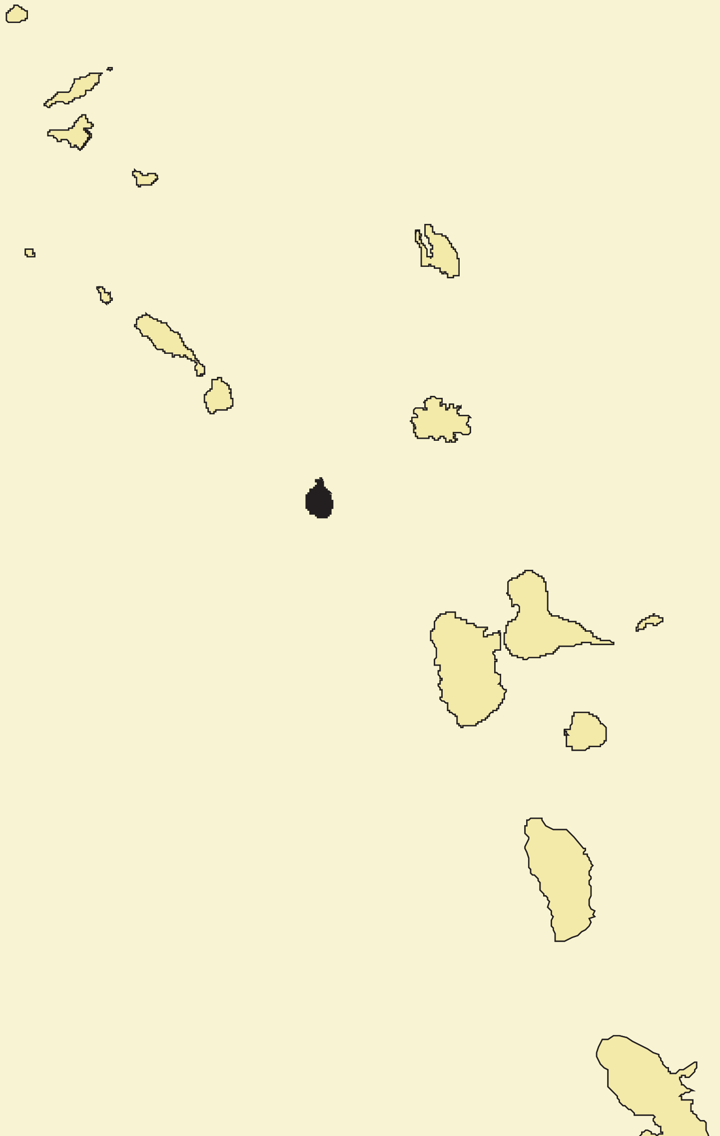
Montserrat



Thea Hincks[1], Steve Sparks[1],
Peter Dunkley[2] and Paul Cole[3]
[1]*Department of Earth Sciences, The University of Bristol, U.K*
[2]*Montserrat Volcano Observatory, Montserrat, West Indies.*
[3]*School of Science and the Environment, Coventry University, U.K.*

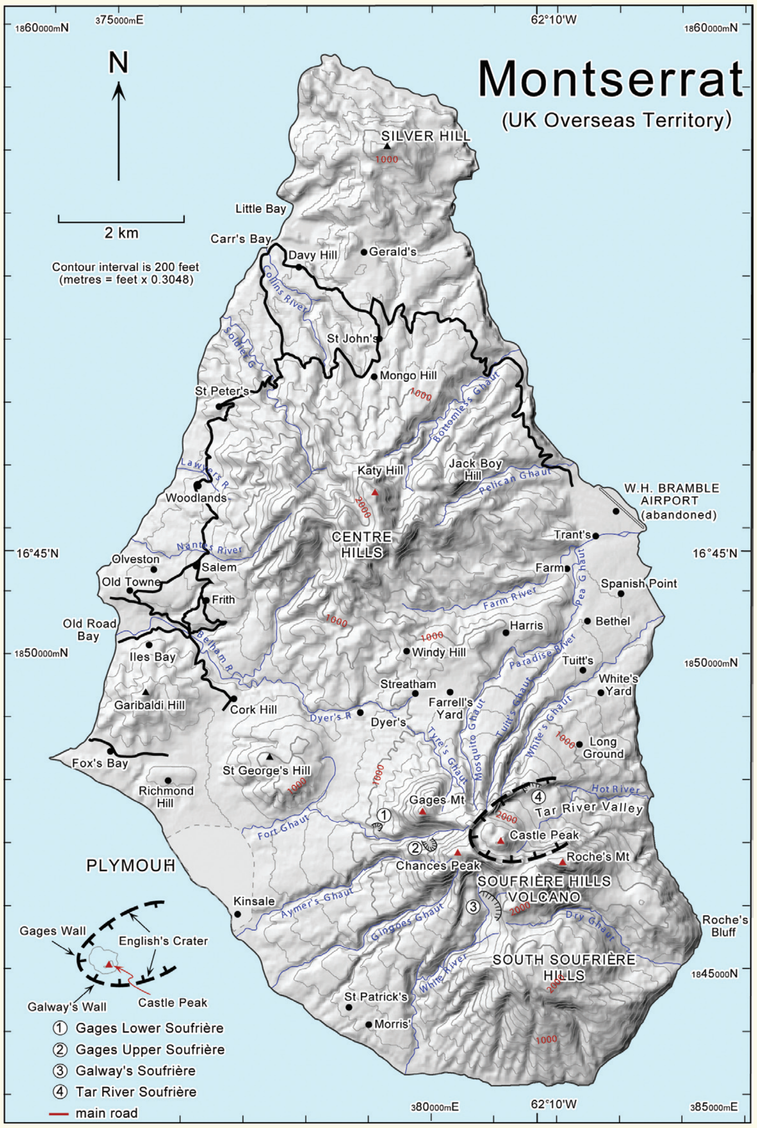
Abstract

Montserrat has one active volcanic centre, the Soufrière Hills Volcano. The volcano is formed of a cluster of andesite domes with flanks of associated pyroclastic deposits and volcaniclastic sediments and has an active history that can be traced back at least 175 ka. A major volcanic eruption started in July 1995 and has continued through to the time of writing (December 2004) with production of 0.5 km^3 of andesite. It is one of the largest volcanic events in historical times in the Caribbean and the first eruption on Montserrat since settlement by Europeans in 1632 AD. The eruption has been characterised by formation of a dome of hornblende andesite associated with pyroclastic flows (generated both by dome collapse and Vulcanian explosions), copious ash fall and reworking of pyroclastic deposits by mudflows, floods, and wind. Other significant activity includes a small sector collapse of the southwest flanks on December 26, 1997, which formed a debris avalanche and lateral volcanic blast. Scientists at the Montserrat Volcano Observatory (MVO) have closely documented the eruption, employing a wide variety of techniques to monitor seismicity, ground deformation, dome growth, gas emissions and environmental impacts. The eruption has caused extensive social and economic upheaval on Montserrat. Much of the island’s infrastructure has been destroyed, about two-thirds of the island now lies abandoned (including the capital Plymouth) and the population has dropped from a pre-eruption high of 10,500 to about 4,300. An exclusion zone has been defined to encompass the area of highest hazard, with the boundaries being occasionally adjusted to reflect changes in volcanic activity.

Geographical setting

Montserrat (latitude 16^{o} 45’N, longitude 62^{o} 10’W) is situated towards the northern end of the Lesser Antilles island arc. With a total land area of 100 km^2 (length approximately 16.5 km north-south, width 10 km east-west) it is one of the smaller islands of the Antilles. Built almost exclusively of volcanic rock, Montserrat is largely mountainous with small areas of coastal lowland. With the exception of areas devastated by the recent eruption, the interior is densely vegetated with tropical rain forest. Rock exposures are generally limited to road cuttings, coastal areas, quarries and the steep inland cliffs. There are few beaches and no inland bodies of water. Before the eruption, the highest point on the island was Chances Peak (part of the Soufrière Hills volcanic complex) at 914 m a.s.l. The dome reached its maximum summit height of 1098 m in March 2003, and on April 22, a spine reached a record height of 1163 m.

Relief Map of Montserrat



The capital, Plymouth, is situated on the coast due west of Chances Peak. It was largely destroyed by volcanic activity in 1997 and is now abandoned. A new centre is being developed in the Little Bay area at the NW end of the island. Following the destruction of the airport terminal (located on the east coast) in 1997, access to the island is by ferry or helicopter from nearby Antigua.

The island encompasses four distinct volcanic massifs: Silver Hills, Centre Hills, Soufrière Hills and South Soufrière Hills. These range in age from about 2.6 million years to the present. Soufrière Hills is the youngest and only active massif. At each of these centres, the old dome structures have been extensively eroded, and deep valleys, known locally as ghauts, are prominent features of the landscape. Garibaldi Hill and St George’s Hill form two smaller, isolated topographic peaks on the western side of the island.

Centre Hills has extensive coastal cliffs, with heights up to 140 m on the east and 75 m on the west. The mountainous interior is covered in dense rainforest. About two-thirds of the island has been abandoned and forms the Exclusion Zone, an area considered as too hazardous for permanent settlement while the volcano remains active. Most of the island settlements lie on an arc around the Centre Hills, from the new housing estates in the north to Old Towne in the west.

In contrast to the lush Centre Hills, the relatively low-lying Silver Hills is covered with scrub woodland and meadow. Much of the new housing and public services buildings are located in the corridor between Silver and Centre Hills.

Before the eruption the Soufrière Hills consisted of a cluster of hills (prehistoric lava domes) and a prominent horseshoe-shaped depression known as English's Crater, which opened to the east into the Tar River valley. The walls of English's Crater ranged from 100-150 m high with a north-south width across the crater of about 800 m. A small lava dome known as Castle Peak occupied the floor of English's Crater, with a moat between the dome and the crater walls. The volcano's upper flanks were cut with several deep ghauts that fed rivers on the outer flanks.

The ongoing eruption has had a significant impact on the landscape of the Soufrière Hills Volcano and the adjacent South Soufrière Hills. In many places vegetation has been destroyed or damaged by pyroclastic flows, ash fall and acidic gas, and much of the tropical rainforest has disappeared. Large flank areas have been buried by pyroclastic flows, lahars and ash falls, particularly in the ghauts and low-lying areas. Many of the major ghauts have been filled with pyroclastic deposits, and deposition at the mouths of several ghauts has constructed new areas of land, extending the coastline.

The Soufrière Hills massif, viewed from the northeast (March 28, 2000)

Marine setting

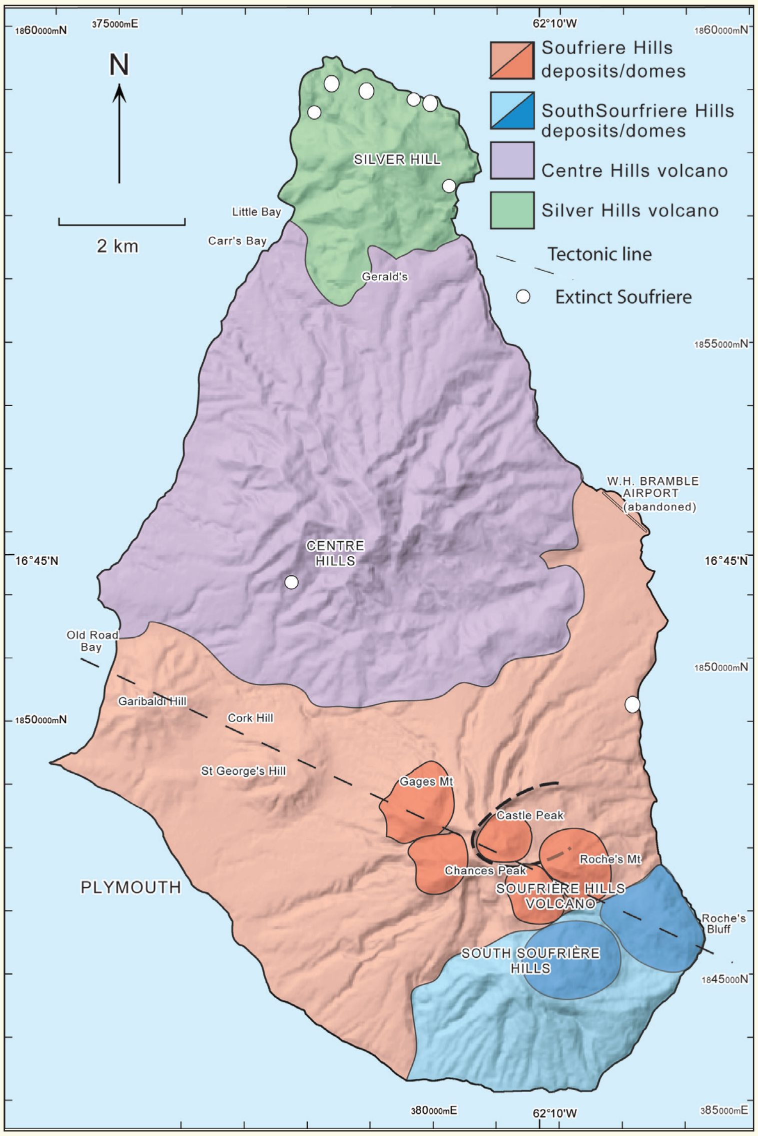
Montserrat lies at the western edge of the relatively shallow platform between the extinct outer arc of the Limestone Caribbees and the active inner arc of the Volcanic Caribbees. The island has a shallow (less than 140 m) submarine shelf, with steep margins that fall off to the Granada Basin in the west and to the Atlantic in the east. The shelf is particularly well developed in the north, and prominent submarine canyons have been identified on the western flanks. The sea floor around Montserrat displays numerous fault-scarps and some volcanic coves. Large areas of hummocky topography off the east, south and west coast have been identified as debris avalanche deposits due to major volcanic landslides (Deplus et al. 2001).

Previous work

Before the 1995 eruption geological interest in Montserrat had been limited, and there was only a small literature. The most notable pre-1995 papers include descriptions of the island's geology by MacGregor (1938) and Rea (1974), the latter including a geological map, and investigations of seismic crises by Powell (1938), Perret (1939) and Shepherd et al. (1971). Baker (1985) and Wadge and Isaacs (1988) made significant contributions to hazard assessment.

The eruption led to a major increase in interest and research publications on Montserrat. Many of the contributions can be found in Geophysical Review Letters 25 (1998), Geological Society of London Memoir 21 (2002) and the MVO website. The most recent synopses of the eruption by Robertson et al. (2000) and the geological evolution of the island by Harford et al. (2002) are recommended reading for general background. Sparks and Young (2002) provide a summary of the main scientific results related to the eruption up to 2001.

Geological map of Montserrat



Geology

Four distinct volcanic massifs have been identified on Montserrat. The erosional maturity of the four massifs decreases progressively from the north to the south, suggesting a simple southward migration of volcanism with time. This conclusion is supported by $^{40}Ar/^{39}Ar$ geochronology (Harford et al. 2002), which indicates sequentially younger ages for the massifs from north to south. With the exception of the neighbouring South Soufrière Hills - Soufrière Hills, there is no temporal overlap of activity, suggesting that eruptive phases at the centres were separated by periods of dormancy. Migration appears to have taken place at a time averaged rate of ~6 km/Ma parallel to the trench, and ~2 km/Ma perpendicular to and away from the trench, with the long axis of the island aligned approximately north - south.

^{40}Ar/^{39}Ar ages for volcanic centres on Montserrat (Harford et al. 2002)

Volcanic Centre	Age (in thousands of years)
Silver Hills	2580 ± 60 to 1160 ± 46
Centre Hills	954 ± 12 to 550 ± 23
Soufrière Hills	174 ± 3 to the present
South Soufrière Hills	128 ± 27

Silver Hills

The Silver Hills massif was active between 2.6 and 1.2 Ma. It is built of massive porphyritic hornblende andesitic lava, in the form of eroded lava domes and sequences of volcaniclastic beds (formed from pyroclastic fan deposits around the lava domes and debris avalanche deposits). Extensive areas of the Silver Hills have been hydrothermally altered, a notable example being Yellow Hole (a bay on the east coast). The highest point is on Silver Hill itself, at 403 m a.s.l. The submarine shelf is particularly well developed around Silver Hills. It is believed that this represents the eroded remains of what was once a much more substantial volcanic massif, of a size comparable to that of the Centre Hills or Soufrière Hills (MacGregor 1938).

Centre Hills

The interior mountains of Centre Hills are formed of massive porphyritic hornblende andesitic lava: the remnants of lava domes that collapsed to produce the pyroclastic deposits on the flanks. The highest peak in the complex is Katy Hill at 741 m a.s.l. Centre Hills has moderately sloping flanks (typically less than 10°) formed of andesitic volcaniclastic deposits. The material is predominantly pyroclastic flow deposit, with lesser amounts of pumice-and-ash-flow, pumice-fall, lahar, debris-avalanche and fluvial deposits. Ages have been determined from 954 to 550 ka (Harford et al. 2002).

Roche's Bluff

Roche's Bluff occurs on the southeast side of the volcano and consists of steeply dipping (up to 50°) submarine volcaniclastic rocks associated with thin limestones. Ages of fossils (corals and foraminifera), a single ^{40}Ar/^{39}Ar age of 1009±15 ka and the coarse grained nature of the deposits indicate deposition in a shelf environment offshore from an andesite centre at around one million years ago, consistent with a link to the Centre Hills volcano. The rocks of Roche's Bluff are cross cut by numerous faults, and it is interpreted as being an uplifted beach.

South Soufrière Hills

The slopes of the South Soufrière Hills are formed of lava flows and volcaniclastic beds (mainly breccias, with some scoria-fall deposits). The lavas and pyroclastic deposits from South Soufrière Hills are of basaltic to basaltic-andesite composition. The summit area encompasses at least four horseshoe shaped structures, representing earlier dome collapse scars. The highest point is 756 m a.s.l. Four ^{40}Ar/^{39}Ar ages indicate the volcano was active around 130 ka.

Soufrière Hills Volcano

Soufrière Hills Volcano is a Peléen-type volcano, and the only active volcanic massif on the island. Before the eruption it was built of five steep-sided andesitic lava domes: Gages Mountain (the oldest), Chances Peak, Galway's Mountain, Perches Mountain and Castle Peak. Castle Peak occupied the horseshoe shaped English's Crater until it was buried in the early stages of the eruption in 1995. Aprons of shallow dipping volcaniclastic deposits flank the four remaining old domes. These deposits are predominantly pyroclastic flow deposits related to dome collapse and lahar deposits, with subsidiary debris avalanche deposits, pumice flow deposits, fluvial deposits, stratified fallout tephras and paleosols. Three debris avalanche deposits have been identified on the lower submarine flanks of the Soufrière Hills Volcano: offshore from the Tar River valley, White River valley and Plymouth (Le Friant et al. 2004).

Gages Mt. (left) and Chances Peak (right) - August 1995

For the Soufrière Hills Volcano, samples with ages greater than 150 ka are dominated by two-pyroxene andesite, whilst those younger than 110 ka are dominated by hornblende-hypersthene andesite (Harford et al. 2002). The transition appears to coincide with a period of basaltic volcanism at the Soufrière Hills at about 130 ka. Over the last 175 ka, the time averaged magma production rate from the Soufrière Hills and South Soufrière Hills complexes is estimated as being approximately 1.5 x 10^{-4}km^3 per year, or 0.005 m^{3}s^{-1} (DRE).

Garibaldi Hill and St George's Hill

St George's Hill and Garibaldi Hill are areas of distinctive geology on the flanks of the Soufrière Hills. They are composed of andesitic lavas, lahars, laharic breccias, pumice fall deposits and pyroclastic flow deposits. Garibaldi Hill is cut by numerous faults, and the pyroclastic deposits have been tilted to dips of up to 30°; these observations indicate that the hill has been uplifted by volcano-tectonic processes. An ^{40}Ar/^{39}Ar age for Garibaldi Hill of 282±8 ka is consistent with it being either a late product of the Centre Hills or an early product of the Soufrière Hills. The similar sequences of St George's Hill suggest that this is also an uplifted area of similar origin.

Volcano monitoring

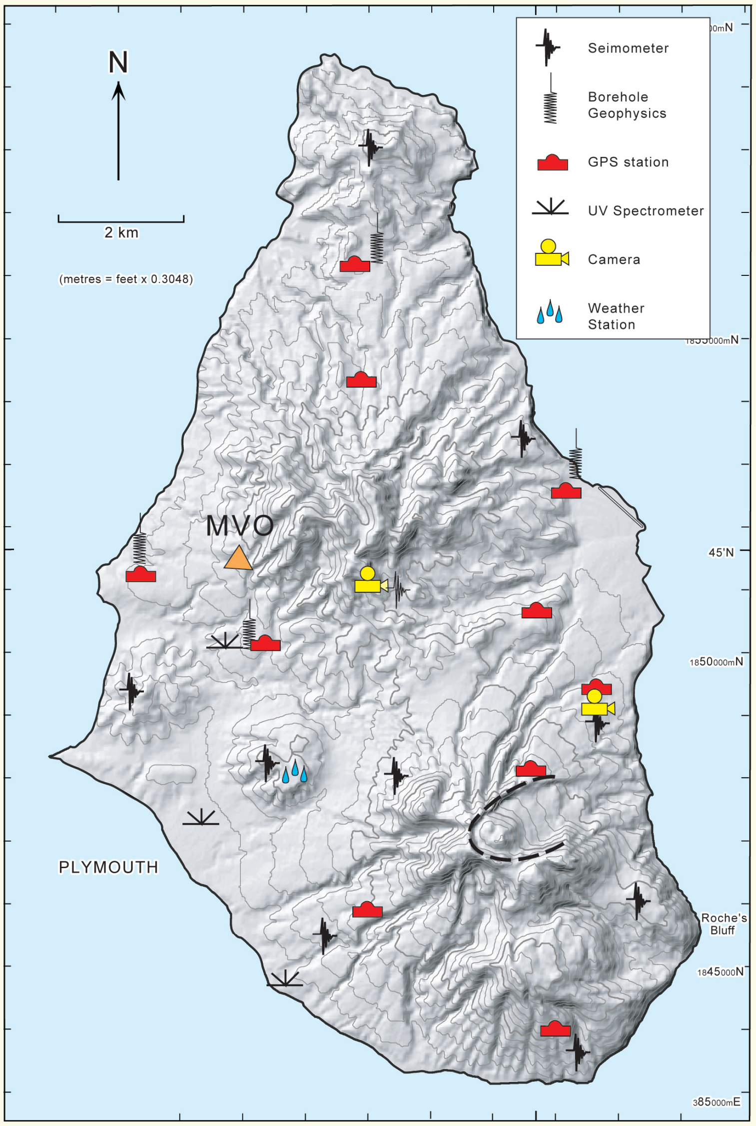
Pre-1995 Monitoring

In 1936 C.F. Powell and A.G. MacGregor were sent to Montserrat by the Royal Society of London. MacGregor (1938) produced the first detailed description of the geology of Montserrat and

Powell (1938) set up a seismograph network, which operated until 1951. Following an increase in the number of felt earthquakes in January and February 1966, the Seismic Research Unit of the University of the West Indies (SRU) installed four seismograph stations and began a programme of ground-deformation measurement. From 1967 to 1980 seismograph recording in Montserrat reverted to the operation of a single, vertical component seismograph station, but the network was reinforced whenever a build-up of local earthquakes occurred.

In 1980 an automatic station was installed on St. George's Hill. A sequence of earthquakes near the island of Redonda between March 1985 and 1986 led to the establishment of two extra stations in mid-1989. The entire network was destroyed by Hurricane Hugo later that year and was not restored until 1992. From then until the onset of eruptive activity in 1995 the number of seismic stations progressively increased.

Volcano monitoring network on Montserrat



Post-1995 Monitoring

Following the onset of the eruption in 1995 the Montserrat Volcano Observatory (MVO) was established to provide intensive monitoring of the volcano. Through the early stages of the crisis (1996-1999) the MVO was staffed by a consortium of scientists from the British Geological Survey (BGS), UK Universities and the SRU working with a local technical team. Since 1998 the scientific operations of the MVO have been managed by the BGS. In February 2003 the MVO moved into a purpose-built observatory at Flemmings, in full view of the volcano.

Methods used to monitor activity at Soufrière Hills include seismic, deformation, gas emission, visual and environmental monitoring.

Seismic monitoring

Seismic monitoring is the main continuous monitoring tool employed at the MVO. There are currently two networks operating simultaneously - one digital (with 6 stations) and one analogue (with 7 stations). Solar cells and car batteries power the remote stations, and signals are telemetered back to the MVO by UHF or VHF radio. At the MVO, continuous and triggered (event) data from both networks are recorded to a computer network, automatically merged and analysed.

Up to four seismograph signals are also written to paper helicorder records. These provide an immediate visual record of the current seismic activity and allow warnings to be sent by radio from the MVO to teams in the field. Independent automatic computer-triggered alarm systems operate on both networks and are used to contact staff by telephone and pager when there is a significant increase in seismic activity.

MVO scientist setting up a camera for remote monitoring of the Soufrière Hills Volcano

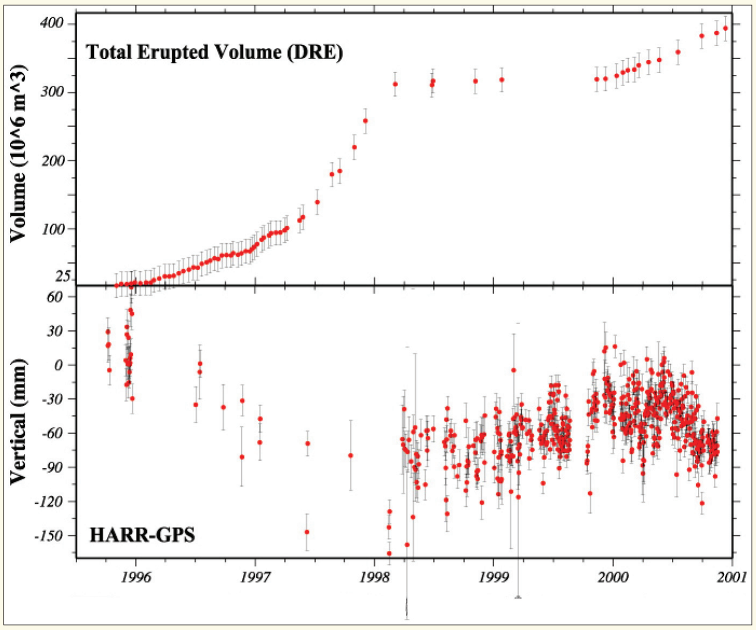
Visual Monitoring

Visual monitoring techniques include aerial and ground based photography, remote digital photography and topographic surveying of the lava dome by theodolite and photometric methods. A brief description of methods of determining dome volumes is given in Sparks et al. (1998). Visual observations are made daily, and two remote digital cameras return images every minute. Such observations provide valuable information on rates of extrusion of lava from the dome, and are essential for hazard assessment.

Deformation Monitoring

Deformation of the flanks of the volcano is measured using Global Positioning System (GPS) measurements, Electronic Distance Measurement (EDM), tilt and crack measurements. There are 6 permanent GPS receivers stationed around the volcano, with an additional 20 temporary sites to provide wider coverage when required. Data from the stations are telemetered to the MVO for processing, where the position of a remote station can be obtained to an accuracy of a few millimetres.

Total erupted volume and ground deformation for the period 1996-2001



Data sources: Mattioli et al. (1998); Sparks et al. (1998); Wadge et al. (2004)

Electronic and dry-tilt have also been used periodically during the eruption. Electronic tilt was particularly successful during periods of rapid dome growth when cyclical activity with time periods of 8 to 24 hours showed repetitive inflation and deflation. During 1996 and early 1997, measurements of the width of cracks on Chances Peak were made both manually and electronically with an extensiometer. Some of the deformation results from the first phase of the eruption can be found in Shepherd et al. (1998) and Voight et al. (1999).

MVO scientist undertaking maintenance at a permanent GPS station

Four borehole observatories were emplaced in February 2003, equipped with strainmeters, tiltmeters, GPS and seismometers.

Gas Monitoring

From July 1995 to December 2001 sulphur dioxide emission rates were measured using a correlation spectrometer (COSPEC). COSPEC analyses light in the UV region, (245 nm – 380 nm), where SO_2 produces distinct spectral absorption lines. Measurements were typically taken 2-5 times per week, using car, boat or helicopter as a platform for horizontal traverses beneath the volcanic plume, as well as scanning from fixed locations on the ground.

A new technique for measuring sulphur dioxide emission rates was developed at the MVO in 2002. The setup comprises three permanent, automated scanning UV spectrometers positioned 3 – 4 km to the west of the volcano. A rotating prism performs a horizon-to-horizon motorised scan thereby transmitting UV light through a telescope and spectrometer where the light is diffracted over a CCD array. It takes around 3.5 minutes to produce a complete scan of the plume. The SO_2 absorption features are obtained by Differential Optical Absorption Spectroscopy (DOAS). Plume height and width are constrained by comparing data from the sites. Plume speeds are derived from wind measurements and from video/photographic data. This method is unique in that it provides nearly continuous measurement during daylight hours.

Gas monitoring with a portable COSPEC

Mass ratios of sulphur dioxide and hydrogen chloride are measured routinely using an open-path Fourier Transform Infra-Red spectrometer (OP-FTIR). The most recent summary of the results of gas studies is given in Edmonds et al. (2001).

Environmental Monitoring

Environmental parameters that are monitored include the concentration of fine dust particles in the air, ambient sulphur dioxide concentrations at ground level and the pH of rainwater. Rainwater collected beneath the plume often has pH as low as 2 (strongly acidic).

Ash plume from the Soufrière Hills Volcano - February 26, 2002

Active volcanic centres

Soufrière Hills volcanic centre

Past eruptive activity

Recent stratigraphic work by Wadge and Isaacs (1988) and Roobol and Smith (1998) indicates that there were major pyroclastic flows from the Soufrière Hills Volcano between 31000 and 16000 years BP After a long period of quiescence, activity resumed circa 4000 years BP, resulting in the formation of English's crater by sector collapse. Prior to 1995, the last eruption of Soufrière Hills appears to have taken place around 300 years ago (Shepherd et al. 1971; Young et al. 1996; Shepherd et al. 2003) with small eruptions of dense andesite, forming the Castle Peak lava dome in English's Crater (Young et al. 1996).

Seismicity

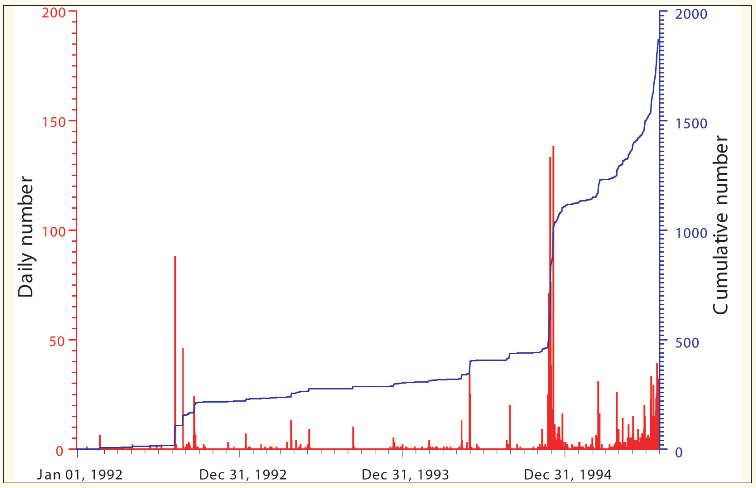
Pre-1995

Perret (1939) gives an account of a sequence of earthquakes in the 1890s based on interviews with the islanders. Between April 23 and 27, 1897, a series of severe earthquakes damaged a number of buildings and caused general panic (Shepherd 1992). Earthquakes continued until either 1900 or 1902 depending on the account.

T. Savage English reported 3290 earthquakes between March 1933 and the end of 1937 (Shepherd et al. 2003). 480 earthquakes were reported in November 1935, however this figure includes a large regional earthquake (magnitude 6.5) and a number of strong aftershocks. As well as the tectonic aftershocks, the earthquake triggered a rapid sequence of strong volcanic earthquakes (Perret 1939). After this, the monthly numbers of felt earthquakes tailed off rapidly, but the seismic network established by Powell (1938) located about 200 local earthquakes between May 1937 and May 1938 with two main centres of activity under the Soufrière Hills and St. George's Hill. This pattern repeated almost 30 years later, with an increase in the number of felt earthquakes over the period January - September 1966 (Shepherd et al. 1971). Activity began to decline from October 1966, and by November 1967 it was no longer thought necessary to continue intensive monitoring.

All these periods of elevated seismicity were accompanied by increased activity at the soufrières, and are interpreted as failed attempts by magma to rise to the surface (Shepherd et al. 1971; Robertson et al. 2000).

Daily and cumulative numbers of volcanic earthquakes in Montserrat 1992-1995 (Shepherd et al. 2003)

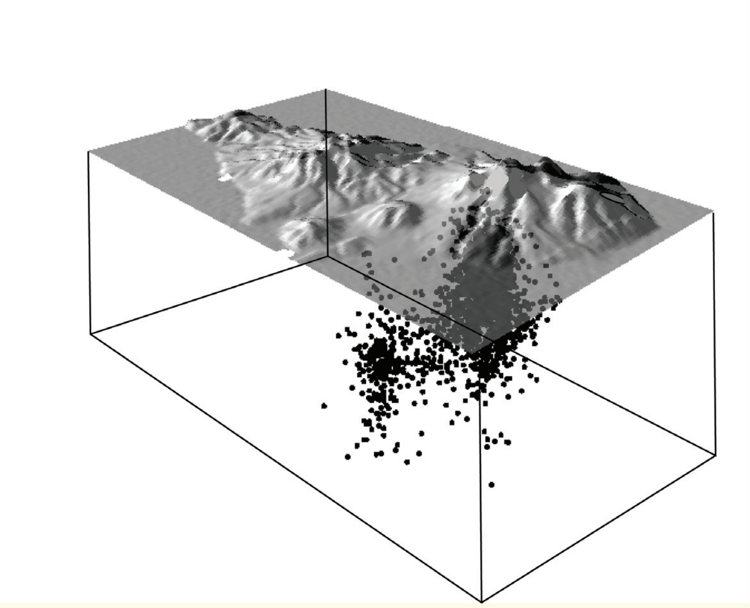


In 1992, after decades of relative quiescence, earthquake activity increased substantially. From January 1992 to July 1995 the average daily number of earthquakes was higher than at any time since 1938.

Post 1995

The 1995–1999 phase of the eruption was dominated by low frequency volcanic earthquakes (LP and hybrid) typically in the region 0.2 to 5 Hz (Baptie et al. 2002). By 1996 most seismic events were originating within a zone of about 2 km in diameter and extending to a depth of about 3 km from the summit. Unpublished work by Baptie suggests that hypocentres for the swarms of low frequency earthquakes in 1997 were tightly clustered under the lava dome at depths as shallow as 1 km. The low frequency events typically occur in swarms, lasting for many hours and containing hundreds of individual earthquakes. Occasionally low frequency events merge to form a continuous signal (Luckett et al. 2002). Swarms of low frequency earthquakes have also coincided with inflation of the volcano (Voight et al. 1999), suggesting a connection with pressurisation in the upper conduit.

3D perspective of earthquake hypocentres for the period July 28, 1995 to end October 1996



Intense rockfall activity on the northeast flanks of the Soufrière Hills Volcano. Photograph taken by remote camera on March 25, 2002

Soufrière Hills Volcano - Typical Seismic Signals

Five main types of seismic signal have been recognised from the Soufrière Hills Volcano: volcano-tectonic earthquakes, long period earthquakes, hybrid earthquakes, rock fall or pyroclastic flow signals, and explosion signals (Miller et al. 1998).

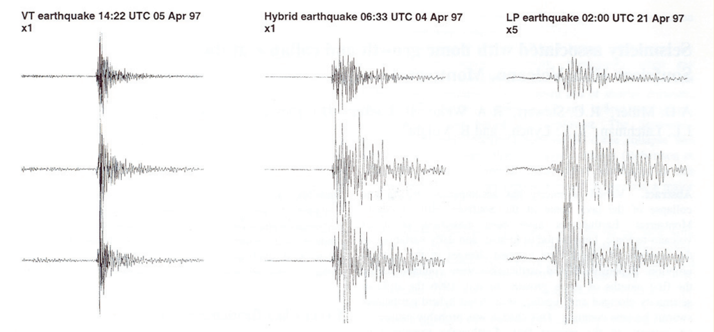
Volcano-tectonic earthquakes (VTs) yield high frequency signals (>2Hz) with impulsive starts followed by a rapid decrease in amplitude. They often occur in swarms and are interpreted as being due to rock fracturing related to magma movement.

Long period (LPs) and Hybrid earthquakes are low frequency events (Neuberg 2000). LPs have a more emergent start and generally low, narrow-band frequency content (1-2 Hz). These are interpreted as either due to resonance of gas or the movement of seismic waves through bubbly magma inside the volcanic conduit. Hybrid earthquakes tend to have impulsive starts but contain significant amounts of low frequency signal. They are observed to be common during magma ascent and dome extrusion, occasionally occurring before major dome collapses or a switch in the direction of lava extrusion.

Rock fall or pyroclastic flow signals are characterised by an emergent start followed by a gradual reduction in amplitude towards the end of the signal and a wide frequency range. Mudflows produce a similar signature, although are typically of lower amplitude and longer duration.

Explosions have a long period component (1-2 Hz) at the start of the signal which is due to the initial gas burst and resonance of the conduit. This component is typically superposed with a high-amplitude mixed-frequency signal related to pyroclastic flows formed by column collapse. The pyroclastic flow signal is rapidly attenuated, leaving a long period wave (associated with low-level ash-venting).

The main types of seismic signals observed at the Soufrière Hills Volcano



Geothermal activity

Before the 1995 eruption, the upper flanks of the Soufrière Hills had several active fumarolic areas at Tar River, Galway's, Upper Gages and Lower Gages. Nugent described "Galloway's" (Galway's) soufrière in 1811, and it seems to have changed little between then and its destruction in December 1997. The Upper Gages Soufrière formed in 1843, following major earthquakes on Montserrat and Antigua. In MacGregor's (1938) description of the geology of Montserrat, seven major hot springs were identified on the flanks of the Soufrière Hills Volcano.

The 1890 earthquake sequence may have been accompanied by geothermal activity, but scientific accounts of this are fragmentary. Perret (1939) refers to an increase in activity at the soufrières, and MacGregor (1949) noted that the Tar River soufrière was either created or re-activated at this time. There also appears to be a correlation between seismic and geothermal activity: during the 1933-37 period of elevated seismicity, heat flux from the soufrières approximately doubled (Shepherd et al. 1971).

Following the onset of the eruption in 1995, activity at the fumarolic fields surrounding the Soufrière Hills began to decline. Geothermal activity outside the dome complex ceased around April 1997, and many of the soufrières on the flanks became buried by debris from the eruption. During the eruption the dome complex has become the focus of intense hydrothermal activity (principally degassing).

Chronology and description of the ongoing eruption

The current eruption has extruded lava at an average rate of about 2.5 m^3s^{-1}, giving a total volume of nearly 0.5 km^3 by October 2002. The new lava is a porphyritic andesite (58.5 to 62 % SiO_2 by weight), which contains phenocrysts of plagioclase, hornblende, orthopyroxene and oxide (Murphy et al. 2000).

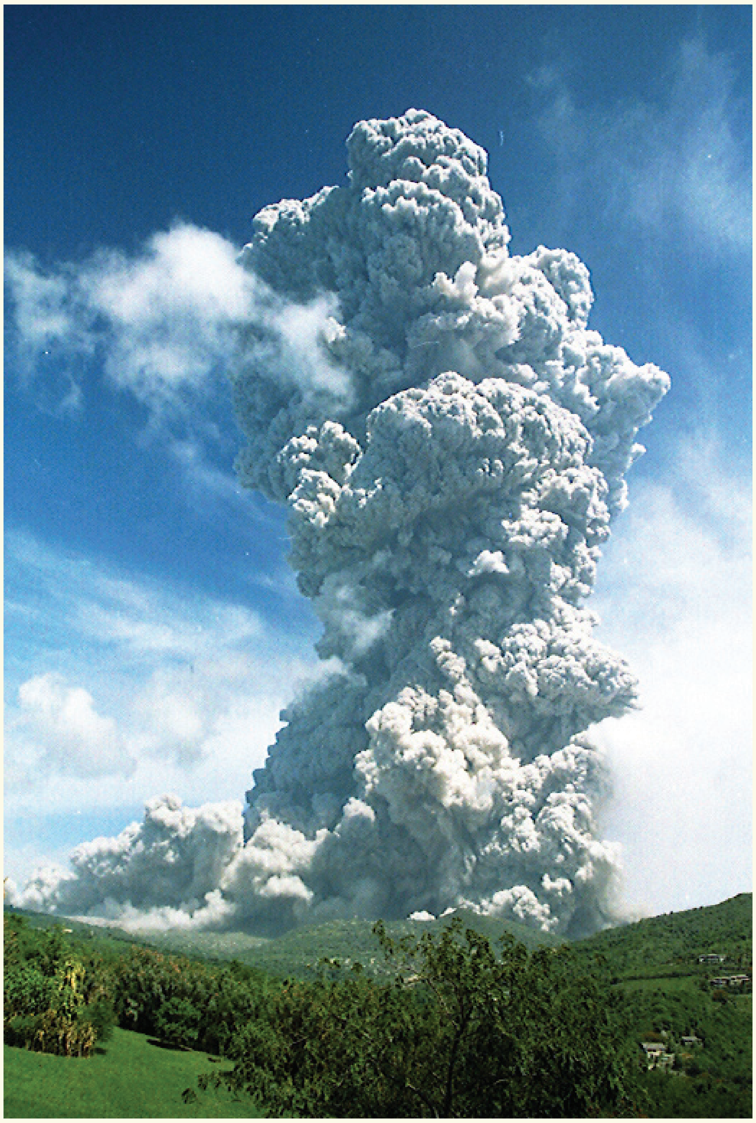
English's Crater during the first period of dome growth, February 1996

First period: initial activity and dome growth (July 1995 - March 1998)

The eruption began with a burst of phreatic activity on July 18, 1995. Small explosions were followed by ash and steam emission from a vent on the NW flank of Castle Peak dome. On August 21, large phreatic explosions generated cold base surges, engulfing Plymouth and prompting the first evacuation of the capital. In December incandescent material was observed in English's Crater, increasing concern for public safety and prompting a major evacuation of southern Montserrat. The first pyroclastic flows began in late March 1996, increasing in magnitude over the subsequent months. The direction of growth switched periodically, and high magma production rates (around 3-5 m^3s^{-1}) led to a number of major dome collapses. A massive collapse on September 17, 1996 removed about 40% of the dome, triggering the first magmatic explosion of the eruption.

The Tar River valley immediately following September 17, 1996 collapse

A second phase of dome growth began in October 1996, and continued with several small dome collapses until June 25, 1997 when 5 million m^3 of dome material collapsed to the east. Sustained pyroclastic flows down Mosquito Ghaut travelled up to 6.5 km, devastating many of the central and eastern villages and stopping within 50 m of the Bramble Airport terminal buildings. Tragically, there were 19 deaths as a result of this event.



Vulcanian explosion from the Soufrière Hills Volcano, August 1997

Night-time photograph of the Soufrière Hills dome showing its incandescence, December 29, 1998

On August 3 and 4, 1997, massive pyroclastic flows down Fort Ghaut destroyed much of central Plymouth and triggered the first series of Vulcanian explosions which continued over the following week. A second series of 75 Vulcanian explosions over one month followed a major dome collapse on September 21 (14 million m^3). On December 26, the Galway's Wall and Soufrière area of the upper flanks failed producing a debris avalanche, triggering an energetic volcanic blast and generating a small tsunami. An area of 10 km^2 to the southwest was devastated by the associated pyroclastic surge, including the village of St Patrick's. Seismic activity declined in the aftermath of this event. Dome growth ceased in March 1998.

Second period: residual activity (March 1998 - November 1999)

During this period there was no apparent growth (Norton et al. 2002), and the dome became continually degraded by small collapses, rock falls and pyroclastic flows. On July 3, 1998, about 25% of the dome (20 - 30 million m^3) collapsed to the east down the Tar River valley. Major pyroclastic flows ensued, and ballistic blocks were discovered at distances up to 1 km from the dome, suggesting explosive activity. Subsequent activity remained at low levels, until periods of heavy rain in September, November and December resulted in extensive mudflows down all flanks of the volcano. Activity increased again in March and May 1999 with a series of explosive ash-venting episodes, some of which were associated with fountain collapse pyroclastic flows. A large dome collapse took place on July 20, resulting in ash fall as far north as the island of Saba. Further mudflows

Collapse scar on the Soufrière Hills dome, December 12, 1998 followed the passage of Hurricane Floyd (September 10) and Hurricane Lenny (November 17–19). Small explosions occurred in the wake of both these events, possibly related to the heavy rain.


The old clocktower at Plymouth, February 1998


The old clocktower at Plymouth with the Soufrière Hills Volcano in background, September 1, 2002


The old clocktower at Plymouth, completely buried, November 10, 2003

Third period: dome growth (November 1999 - present)

On November 27, 1999 a new lava dome was observed in the base of the old dome crater; the first sign of extrusive activity for about 20 months. After several months of growth, sizeable pyroclastic flows from the new dome began to spill down the Tar River valley in February 2000, and a period of heavy rain on March 20, triggered a major collapse (20 million m^3). Dome growth continued at moderate levels into 2001 (with small collapses, pyroclastic flows and rock falls), although it appeared to cease around mid March. Growth resumed on May 18 with the extrusion of a new lobe to the south. In the following months a massive headwall began to develop above the White River valley, resulting in almost continuous rock fall activity.


North flank of the Soufrière Hills, February 27, 2001

The second major collapse of the new dome (45 million m^3) occurred on July 29, 2001, following a day of torrential rainfall and mudflows down the Belham River. The 9-hour event produced near-continuous pyroclastic flows down the Tar River valley and out to sea, and ash fall reached Puerto Rico and the Virgin Islands. The direction of growth switched from east to west in November 2001, although activity remained low for the rest of the year. Activity in late February 2002 was characterised by the extrusion of a number of large spines. One 90 m spine appeared overnight on February 25, reaching an altitude of 1080 m.

Rock fall and seismic activity escalated throughout March and April 2002. Activity declined again at the end of May, remaining at low levels until July 21 when a new lobe began to form on the north face. By the end of September activity was elevated with dome growth focused above the northern flanks of the volcano. Several small collapse events generated pyroclastic flows that reached the east coast. Growth switched to the northeast in early October 2002, prompting an evacuation from the margins of


Photograph taken by remote camera at Whites, October 1, 2002

Chronology and description of the ongoing eruption of the Soufrière Hills Volcano (1995-2004)

	Period	Activity
Seismic	1992 - July 1995	Period of pre-eruptive seismic activity. 18 distinct earthquake swarms occur in the south of the island.
Phreatic	July 18 - November 15, 1995	Phreatic explosions associated with heating shallow or ground water. Initial activity: cold pyroclastic surges and steam jets. Earthquake swarms continue, and in late September an oxidised spine appears in English's Crater.
Dome growth and collapse	November 15, 1995 - March 1996	Magma appears at the surface. Lava dome growth starts in English's Crater and develops slowly (0.2–0.5 m^3s^{-1}). Dome growth rate increases in February (~2 m^3s^{-1}). First rock falls and minor pyroclastic flows are observed.
	April - September 1996	The Tar River valley is subjected to increasingly large pyroclastic flows, which reach the coast on May 12. Growth rate increases (3-5 m^3s^{-1}) and a major collapse occurs on July 28.
	September 17, 1996	Explosive activity followed 9 hours of continuous dome collapse and pyroclastic flow generation. 1.5 m diameter ballistic blocks reach Long Ground (2.1 km from the dome) and the eruption plume reaches 14 km.
	October 1, 1996 - February 1997	A new dome begins slow growth in the collapse scar on October 1. Intense earthquake swarms occur in November and early December. Growth rate increases from mid December.
	March - April 1997	A new lobe appears above Galway's Wall, on the SW side of the dome. Major pyroclastic flows move down the White River valley.
	May - June 24, 1997	Dome growth switches to the north and increases substantially (7-8 m^3s^{-1}). The dome has a volume of over 60 x 10^6 m^3 and completely fills English's Crater. In June, the first pyroclastic flows and rock falls move down Mosquito and Tuitts Ghauts on the northern flanks of the volcano.
	June 25, 1997	A major collapse (at 12:55 LT) lasting about 20 minutes releases 6.4 x 10^6 m^3 of material in three pulses. Pyroclastic flows nearly reach Bramble Airport, and ash-cloud surges sweep over Farrell's Plain. A surge-derived flow moves down the Belham River valley.
	June 26 - August 3, 1997	Continued elevated extrusion with dome growth at the head of the valley leading to Plymouth (Fort Ghaut). A major dome collapse on August 3, sends pyroclastic flows through central Plymouth.
Vulcanian explosions	August 3 - 12, 1997	A series of 10 Vulcanian explosions lasting 1-2 minutes occur approximately every 12 hours. Pumice flows extending to 5 km run down drainage channels on the flanks. Ballistic blocks of 1-2 m diameter reach distances of 1.7 km. Pumice lapilli and ash are dispersed over the island. The extrusion rate during this period is about 10 m^3s^{-1}. A 300 m diameter explosion crater is formed.
Dome Growth	August 12 - September 21, 1997	Rapid (7-8 m^3s^{-1}) dome growth resumes. Pyroclastic flows destroy buildings in the Spanish Point area and the terminal building at Bramble airport. A major dome collapse (14 x 10^6 m^3) occurs on September 21.
Vulc.	September 22 - October 21, 1997	Second period of 75 repetitive Vulcanian explosions.
Dome growth	October 22 - December 24, 1997	Dome growth resumes, with two major dome collapses occurring on November 4 and 6. Pyroclastic flows run down the White River Valley to form a coastal fan. Activity is accompanied by earthquake swarms.
Major collapse	December 25 - 26, 1997	Dome volume: 113 x 10^6 m^3. Height: 1030 m. A major hybrid earthquake swarm merges into a continuous tremor by the end of Christmas day. The SW flank of the volcano and the section of the dome in the Galway's wall area suffers a massive collapse at 03:01 LT on December 26, and a debris avalanche (40-45 x 10^6 m^3) cascades down the White River valley. The dome is undermined, and a high-energy pyroclastic surge sweeps out to sea, devastating 10 km^2 of southern Montserrat. This major collapse is referred to elsewhere as the "Boxing Day" event.
Dome growth	January 4 - 16, 1998	Dome growth resumes in the collapse scar. Low seismicity
	January 17 - March 1, 1998	Increase in Seismicity. Rockfalls and ash venting with plumes to 1.8 km. Small pyroclastic flows down White River valley result in ash fall in Antigua. A period of vigorous ash-venting occurs in early February.
	March 10, 1998	Dome growth ceases around March 10, 1998 with extrusion of a prominent summit spine.

	Period	Activity
Dome degradation and residual activity	March 11 - July, 1998	Degradation of the dome and residual activity. Small pyroclastic flows and rockfalls accompanied by small-scale Vulcanian explosions and periods of ash-venting. Seismic activity continues.
	July 3, 1998	Approximately 20% of the dome complex collapses down Tar River valley. A small explosion follows, and the associated ash cloud surge hits Long Ground.
	July 4 - 24, 1998	After a few days of increased activity, the number of rockfalls and VT earthquakes decline to (and remain at) low levels.
	July 25, 1998	Swarm of 68 VT earthquakes. No outward changes to the volcano.
	July 26 - September 20, 1998	Low-level activity. Small pyroclastic flows and rockfalls continue to degrade the dome. On August 19, rockfalls followed by vigorous ash venting produce a tremor lasting 2 days.
	September 20 - 21, 1998	Passage of Hurricane Georges. 15 cm of rainfall overnight results in extensive mudflows on all flanks. Inundation of the Belham bridge, substantial deposits in Plymouth and on the Bramble airport runway.
	October 13 - November 12, 1998	Frequent pyroclastic flows down Tar River and White River. A large scar develops in the dome, slicing it in two.
	November 13 - 28, 1998	Small pyroclastic flows, rockfalls and ash venting.
	November 28 - 29, 1998	Heavy rain resulting in extensive mudflows down all flanks of the volcano.
	December 14, 1998	Dome collapse down Tar River valley.
	December 15 -19, 1998	Rockfalls, small pyroclastic flows and vigorous ash venting. Maximum ash cloud height is 4.6 km. An explosive event triggers a pyroclastic flow down Tar River on December 19.
	December 21, 1998	Vigorous ash and steam venting, with rocks carried to 80 m above the vent. Followed by a relatively quiet period with few rockfalls and small pyroclastic flows.
	December 28, 1998	Mudflows follow heavy rain. The Belham River valley and Plymouth areas are particularly affected.
	December 29, 1998 - February 28, 1999	Continued degradation of the dome by rockfall activity, ash and steam venting. Slight increase in seismicity. Small dome collapse pyroclastic flows between January 13 and 20. Occasional larger pyroclastic flows from the January 21.
	March 1 - May 10, 1999	Increased activity. Small explosions, ash venting and dome collapse pyroclastic flows. Ash clouds to 6.1 km.
	May 22 - 23, 1999	VT earthquake swarm (121 events) followed by a small dome collapse down the Tar River valley. Ash cloud reaches 5.8 km.
	June 5, 1999	Northeast sector dome collapse. A large hole is formed in the dome above Tuitt's Ghaut. The dome continues to be degraded by rockfall activity. Occasional episodes of ash & steam venting.
Major collapse	July 20, 1999	Large dome collapse down Tar River. Ash cloud reaches 10.7 km. The end of July sees slightly elevated levels of activity, with small explosions and pyroclastic flows.
Dome degradation and residual activity	August 1999	Low levels of activity. Reduced gas emissions and ground deformation. Small dome collapses.
	September 3 - 9, 1999	Substantial explosion on September 3, followed by collapse events and enhanced rockfall activity.
	September 10, 1999	Hurricane Floyd passes to the north. The heavy rain triggers a number of mudflows.
	September 11 - October 20, 1999	Low-level activity. Reduced gas emissions and ground deformation. Small dome collapses.
	October 20, 1999	Passage of Hurricane José to the north of the island produces 14 cm of rain in 6.5 hours. Mudflows down all flanks of the volcano.
	November 3 - 9, 1999	Swarm of 213 hybrid earthquakes (the first since March 1998) followed by two explosions on November 8 and 9.
	November 17 - 19, 1999	Passage of Hurricane Lenny. Heavy rain causes mudflows down all flanks.
Dome growth	November 27, 1999 - January 2000	New lava dome observed in the base of the old crater. By mid January the volume of the dome is estimated at 15 million cubic meters.
	February 2 - 11, 2000	First substantial pyroclastic flows from the new dome. Rockfall and seismic activity increase significantly.
Collapse	March 20, 2000	Dome collapse, apparently triggered by heavy rainfall. Almost all the new material collapses down Tar River. Accompanied by small vulcanian explosions and extensive mudflows.

	Period	Activity
Dome Growth	March 21, 2000 - November 2000	Continued dome growth, accompanied by hybrid and long period earthquakes. Small dome collapse on May 6. Small pyroclastic flows down Tuitt's Ghaut and White's Ghaut.
	November 13 - December 2000	Dome reaches 1077 m – the highest altitude to date. On December 7, the total dome volume is estimated at 122 million cubic meters, with an average extrusion rate of approximately 3 m^3s^{-1}.
	January 2001 - February 25, 2001	Dome growth continues into the new year with a new lobe being extruded on the NE flank on February 23 and 24. This is accompanied by sustained rockfall and small pyroclastic flows down Tuitt's Ghaut. A small collapse (<1 million cubic meters) occurs on February 25.
	February 26 - March 2, 2001	Four days of banded tremor followed by increased extrusion to the south.
	March 3 - May 17, 2001	Dome growth appears to cease.
	May 18 - July 2001	Renewed growth of the southern lobe. Activity increases with rockfalls, small pyroclastic flows and a small collapse to the north on June 30. By late July, the dome has a volume of approximately 162 million cubic meters – the largest accumulated volume in the current eruption.
Major collapse	July 29, 2001	Major collapse of the eastern flank following a day of torrential rainfall and mudflows down the Belham River. The event started at 17:00 LT and lasted 8-9 hours. Near continuous pyroclastic flows run down the Tar River to the sea. Long Ground affected by pyroclastic surges. Strong SE winds blow ash as far as Puerto Rico and the Virgin Islands. 45 million cubic meters of material is removed from the dome, and the summit region lowered by 150 m.
Dome growth	August 3 - October 2001	Dome growth resumes in the collapse scar. A 2-month period of almost continuous banded tremor begins on August 14, followed by rockfalls and small pyroclastic flows. Small collapse events on October 14 and 16.
	November 9 - December 2001	Direction of extrusion switches to the west. The summit region is dominated by a number of vertical spines. An increasing number of rockfalls and small pyroclastic flows occur towards the end of the year. Small collapse on December 28.
	January - February 2002	High levels of activity, with spectacular incandescence observable at night.
	February 25 – 26, 2002	A 90 m spine is extruded overnight, with the apex reaching an altitude of 1080 m
	March 2002	Rockfall and seismic activity increases, and a succession of large spines are extruded at the summit. Pyroclastic flows reach the sea at the Tar River fan.
	April - May 2002	Dome growth switches to the SE in the second week of April. Seismic activity increases. Massive lobe formation and tallus accumulation with rockfalls and pyroclastic flows to the east. Decline in activity towards the end of May.
	June - July 2002	Growth rate continues to decline (approx. 0.1 m^3s^{-1} by the end of July).
	July 21 - August 29, 2002	New lobe develops on the north face (approx. 0.86 m^3s^{-1}). Increased rockfalls to the north and small pyroclastic flows down Tuitt's and White's Ghauts. NE buttress and part of the central buttress are buried.
	September 2002	Around September 24, direction of growth switches briefly to the west resulting in pyroclastic flows down the western flanks. After a few days growth switches back to the north. On September 29, a minor (2-3 million m^3) dome collapse generates pyroclastic flows that reach the sea at Spanish Point.
	October 2002	On October 2, ~4 million m^3 of dome material collapses to the east, possibly triggered by heavy rainfall. A moderate mudflow in the Belham Valley is followed by 6 hours of sustained pyroclastic flows. On October 8, areas on northern side of the Belham Valley are evacuated. Intense rainfall on October 22, produces large mudflows down the Belham valley. Activity declines towards the end of October.
	December 2002	A 4-5 million m^3 dome collapse down White's Ghaut occurs on December 8, followed by a marked increase in SO_2 emission rates. Activity increases throughout December, with pyroclastic flows and rockfalls affecting the N and NE flanks. A large spine is extruded during the night of December 26 - 27. Incandescence observable at night.
	January - March 2003	Dome growth continues to the NE with pyroclastic flows and rockfalls occurring in White's Ghaut, Tar River Valley, Tuitt's Ghaut and the top of Tyre's Ghaut and Farrell's Plain. By March the summit of the dome is at 1098 m, the highest recorded in the history of the eruption.
	April - May 2003	In April, dome growth is focused to the SE, with pyroclastic flows confined to the Tar River. On April 22 a spine extruded from the dome reaches a record height of 1163 m. In May growth switches to the NE before becoming directed to the centre.
	June - July 2003	A new easterly shear lobe develops, followed by two weeks of vigorous pyroclastic flows. Around mid June growth slows (possibly ceasing altogether). A prominent hybrid earthquake swarm begins on the 9 July, merging into continuous tremor on July 12.

	Period	Activity
Major collapse	July 12 - 13, 2003	Third large dome collapse of 1999-2003 dome. The collapse volume is approximately 120 million m^3 - the largest volume event of the current eruption. Large vertical explosions generate ash clouds up to 15 km height. Major pyroclastic flows travel down Tar River to the sea, producing phreatic explosions. Heavy ash fall affects the whole island with the deepest deposits to the NW of the volcano (150 mm in Lime Kiln Bay).
	July 13 - 15, 2003	Three discrete vertical vulcanian explosions deposit pumice and lithic clasts across the island. Ash clouds reach up to 12 km height.
Cessation of dome growth	July 2003 - August 2003	A brief period of dome growth occurs from July 21 - 28, followed by intense ash venting on August 1. Dome growth ceases in early August, and activity declines.
	September 2003 - March 2003	A hybrid earthquake swarm (over 200 events) occurs on September 27, followed by a period of ash venting and tremor on September 30. The volcano is quiet and seismic activity low.
	March 3, 2004	Explosion and dome collapse event. Pyroclastic flows down Tar River reach the sea at the Tar River Fan. Ash clouds associated with the explosion reach altitudes of about 7 km. Low-level tremor for about 18 hours. A further small explosion on March 5 is followed by a period of ash venting.
	March 6, 2004 - Present	Moderate to low tremor continues from late March to May. Intense rain on May 21, triggers large mudflows in the Belham Valley with standing waves up to 2 metres high. No evidence of further dome growth.

the Belham Valley on October 6. Dome growth continued into 2003, predominantly directed to the north and northeast. The dome reached a height of 1098 m in March 2003; the greatest altitude recorded in the history of the eruption, and by July had reached a volume of around 220 million m^3.

The third and largest collapse of the 1999-2003 dome occurred on July 12-13, 2003, with an estimated collapse volume of approximately 120 million m^3. Prolonged and heavy rainfall early in the morning of July 12 triggered mudflows in the Belham Valley. Low volume pyroclastic flows began to travel down Tar River around 0930 hours, increasing in frequency and intensity throughout the day. Many large flows reached the sea, producing phreatic explosions, and an estimated 1.2 million tonnes of ash fell over the populated areas of Montserrat. Pyroclastic flow activity began to decline in the early hours of July 13. Three post-collapse Vulcanian explosions produced ash clouds up to 15 km and deposited small pumice and lithic fragments over Olveston and Old Towne. Towards the end of July a small dome formed in the explosion crater. Tremors and minor ash venting continued sporadically until March 3, 2004, when an explosion and dome collapse event sent pyroclastic flows down the Tar River to the sea and ash clouds to altitudes of about 7 km. Moderate to low tremor continued from late March to May 21, 2004, when intense rain triggered large mudflows in the Belham Valley with standing waves up to 2 metres high. Since May 2004 there has been no evidence of further dome growth.

Pyroclastic flows from the Soufrière Hills, July 27, 2001

Pyroclastic flow down the Tar River valley, January 3, 1999

Pyroclastic flow entering the sea at Tar River, October 5, 2001

Volcanic hazards

The main hazards associated with the ongoing eruption of the Soufrière Hills Volcano are pyroclastic flows, volcanic blasts, explosions, tephra fall and mudflows. The dome-forming character of the eruption is a major factor in determining the level of hazard across the island, as the rate and direction of extrusion are subject to (often rapid) fluctuations. The topography of the summit region and flanks also alters as new material builds up, and the ghauts are either infilled by pyroclastic deposits or eroded.

Pyroclastic flows and surges

Pyroclastic flows are high-speed, gravity-driven flows of hot particles and gas, generated either by explosive activity or collapse of the active lava dome. Pyroclastic flows constitute a major hazard on Montserrat, causing much devastation, and on June 25, 1997 resulted in 19 deaths. The route of a pyroclastic flow is largely constrained by topography, putting river valley regions at greatest risk. However, the more energetic surges may surmount valley walls and topographic highs, and have the potential to threaten much wider areas.

During the eruption, temperatures of over 400^{o} C have been measured in dome collapse pyroclastic flow deposits (Cole et al. 2002). The June 25, 1997, flows reached speeds of approximately 40-60 m s^{-1} near the dome and 10 m s^{-1} at the nose of the flow. A temperature of 640^{o}C was measured at Trant's, 20 days after the event. Deposit volumes from individual flows have reached up to 5 x 10^{7}m^{3}, and run-out distances have extended up to 7 km from the dome. In 1997 the first pyroclastic flows reached Plymouth and have been a major contributing factor in the burial of the town. Flows have entered the sea in several places, notably off the Tar River and White River.

Dome collapse

Two mechanisms have been recognised as causing major dome collapses and large pyroclastic flows. In an endogenous collapse, internal forces within the volcano destabilise the dome by causing a surge of lava. These collapses have always occurred in the direction of dome growth (Watts et al. 2002), and this mechanism characterised all the major dome collapses in the 1995-1998 period. The second mechanism is rainfall-induced collapse. Intense rainfall has preceded large collapses of the dome down the Tar River (Matthews et al. 2002; Matthews and Barclay 2004), and has happened three times in the second and third phases of the eruption since March 1998.

Ballistics

Large ballistics from Vulcanian explosions are a significant hazard in areas within 2.5 km of the dome, although the smaller fallout has a much wider effect. On impact, the hot ejecta may also cause fires. On September 17, 1996, 1.5 m diameter blocks reached the village of Long Ground (2.1 km from the dome).

Volcanic blast

There has been one major volcanic blast, which happened on December 26, 1997 and involved a large collapse of the dome triggered by a failure of the southwest flanks of the edifice (Sparks et al. 2002). The blast devastated 10 km^{2} of southern Montserrat, had a peak speed of over 300 km h^{-1} (90 m s^{-1}) and completely destroyed the evacuated village of St Patrick's.

Roof collapse due to ash loading in Plymouth

Tephra Fall

Although not the most immediate threat to human life, tephra fallout is the most widespread volcanic hazard. Large plumes generated by phreatic explosions (e.g. October 30, 1995); pyroclastic flows (e.g. June 25, 1997) and explosions (e.g. September 17, 1996) have resulted in numerous incidences of tephra fallout all over Montserrat. On a number of occasions light ash fall has been reported as far away as Puerto Rico. Ash clouds are a serious hazard to aviation, as the particles can damage aircraft turbines, resulting in engine shutdown. A Canadian passenger jet lost an engine while passing through the ash cloud of September 16, 1996.

The extent of the damage caused by tephra is dependent on the weather as well as the severity of the event. With Montserrat's predominantly easterly low-level wind (to heights of about 6 km), much of the ash is blown to the west, away from currently inhabited areas (Bonadonna et al. 2002a). As a result, many buildings in Plymouth have suffered roof collapse due to ash overloading. Heavy ash fall has also destroyed large areas of vegetation, and the damage is intensified if deposits are not cleared by wind and rain. Occasionally less common wind directions cause significant ash fall and occasional fall of rock

Mudflow deposits at Trants, April 2, 1998

fragments in populated areas. The Vulcanian explosions of August 1997 produced pumice fallout over much of southern Montserrat.

Volcanic ash is also a potential respiratory health hazard (Baxter et al. 1999). Ash deposits from Montserrat have been shown to contain between 3% and 12% respirable particles (sub 4 µm) including cristobalite, a form of crystalline silica (Horwell et al. 2003), which can lead to silicosis. Further toxic effects of ash fall include the contamination of water supplies and the health risk to livestock ingesting ash settled on vegetation.

Mudflows in the Belham River valley, September 29, 2001

Mudflow

Mudflows (lahars) are triggered when intense rainfall mobilises loose deposits on the flanks of the volcano, and therefore constitute a significant hazard in the wet season (June - November). The flows transport particles ranging in size from fine silt (~tens of µm) to blocks several meters in diameter, burying buildings and roads, and cutting off essential services. Near the mouth of the Belham River deposits are approximately 3 m deep, and mud transported down Fort Ghaut continues to bury central Plymouth. Drainage systems on all faces of the volcano are subjected to mudflows, and even when eruptive activity ceases many areas will remain at risk due to the large volume of accumulated material on the flanks.

Assessment of hazard and risk

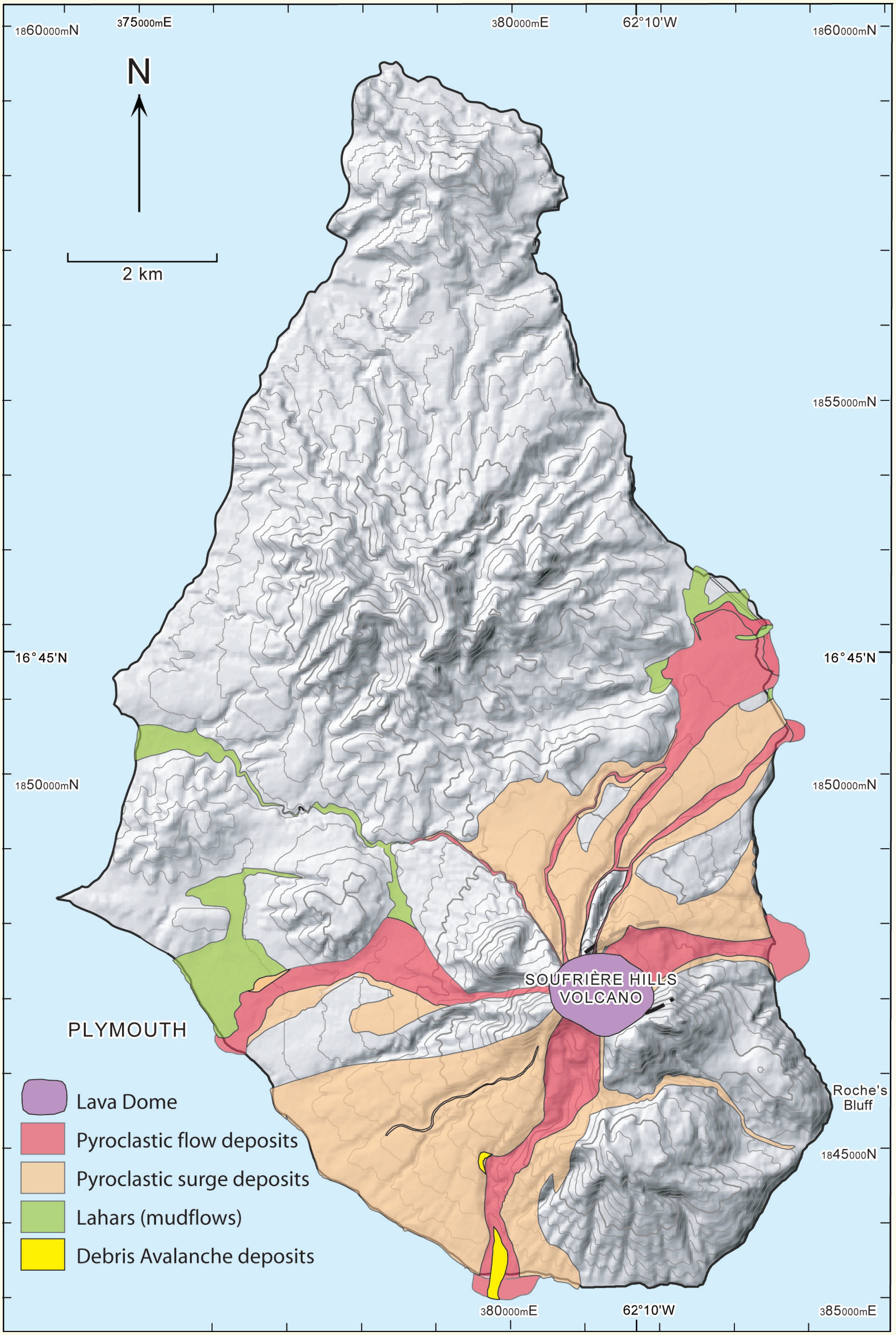
To keep abreast of the changing conditions, hazard and risk assessments are carried out at six-month intervals by a panel comprised of MVO personnel and scientific advisors. This system has been in place since December 1997. The panel's conclusions are reported to the Governor of Montserrat, and form the basis of decisions regarding the extent of the exclusion area and emplacement of emergency procedures. Some hazards can be quite accurately modelled and forecast using quantitative models (e.g. tephra fall; Bonadonna et al. 2002b). Others are less well understood and have to rely more on empirical models and the experience of the observatory team.

A Monte Carlo risk estimation procedure is used to assess the impact of volcanic events on the population. The model employed comprises a range of generic hazard types, selected to be representative of the eruptive characteristics of the volcano (typically based on real scenarios from the recent eruption).

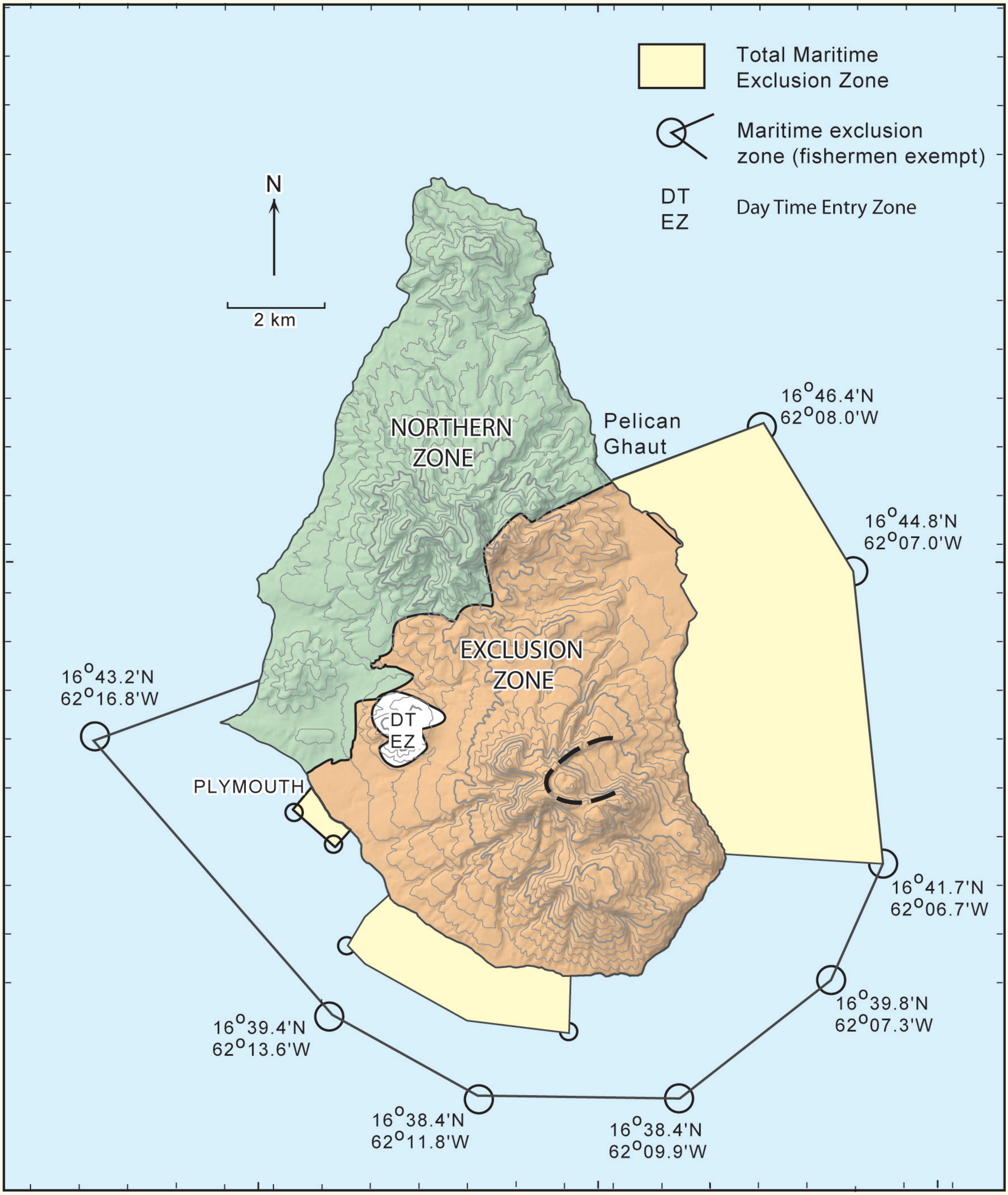
It is assumed that for each hazard scenario there is an associated probability distribution representing the likelihood of occurrence. There is also a set of conditional probabilities associated with the directionality of the event, and the potential impact on identified population centres. The values of these probabilities and the distribution parameters are either obtained from numerical models (where available) or determined by the panel using the process of expert elicitation. A risk exposure is then attributed to each of the designated 'hazard zones' based on the expected annualised risk to life of a person living in that zone.

View of Plymouth with the Soufrière Hills in the background, December 1997

Volcanic deposits/hazard map for the Soufrière Hills Volcano



Volcanic risk map for the Soufrière Hills Volcano, 1st August 2004



Implications for ongoing and future volcanic activity

The ongoing eruption has been similar in style to previous activity at the Soufrière Hills. There has been no major explosive activity for at least the last 170 ka history of the Soufrière Hills or South Soufrière Hills. The only Plinian style eruption recorded in the geological record was an early (~174 ka) small event that produced a one-metre thick pumice fall deposit approximately 3 km from the probable vent in the central Soufrière Hills. On the basis of activity over the past 170 ka, future activity at the Soufrière Hills is likely to pose similar hazards to the ongoing activity.

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Seismic Research Unit, University of the West Indies:

http://www.uwiseismic.com

World Organization of Volcano Observatories (WOVO):

http://www.wovo.org

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