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Seismic characterization of pyroclastic flow activity at Soufrière Hills Volcano, Montserrat, 8 January 2007

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Abstract. A partial dome collapse with concurrent pyroclastic flow (PF) activity occurred at Soufrière Hills Volcano (SHV), Montserrat on 8 January 2007. Pyroclastic density currents were observed to propagate from the Northwest and West sectors of the summit dome into the heads of Tyres Ghaut and Gages Valley, respectively. Between 10:00 and 10:15 UTC pyroclastic flows entered Tyres Ghaut and from there descended into the Belham Valley reaching a distance of about 5 km from the source. Pyroclastic flow activity on the Northwest and West side of the edifice continued at high levels over the following 1.5 h, although run-out distances of individual flows did not exceed 1.5 km. Subsequent observations showed that material had been removed from the lower Northwest side of the dome leaving an amphitheatre-like structure cutting through the old crater rim. The seismic waves excited by the propagation of pyroclastic flows were recorded by the Montserrat Volcano Observatory's network of broadband seismometers. The seismic records show the onset of a continuous signal before 09:30 UTC with gradually increasing amplitudes and spectral energy in the 1–8 Hz band. The signal rapidly increased in amplitude and a characteristic spindle-shaped waveform with broadband energy (1-25 Hz) was observed accompanying large PF that descended along the slopes of the volcano. The main phase was followed by a sequence of individual seismic pulses which correlated well with visual observations of PF. PF are a major hazard at SHV and pose significant risk for the population living in the proximity of the volcano. They can occur with little or no warning and have the potential to reach inhabited areas to the Northwest. The study of the seismic activity associated with the generation and propagation of pyroclastic flows can help to identify characteristic precursory seismic sequences providing valuable information to improve the understanding of the hazards posed by the SHV and to allow better warning to be given to the authorities.

1 Background

1.1 Eruption chronology

Soufrière Hills Volcano (SHV) in Montserrat, West Indies, is an andesitic dome building volcano situated near the Northern end of the Lesser Antilles volcanic arc. The ongoing eruption began on 18 July 1995 (Young et al., 1998; Aspinall et al., 1998) following a three-year period of precursor seismic activity. The eruption has been characterized by the growth of an andesite lava dome with associated pyroclastic flows (PF), vulcanian explosions and debris flows. The twelve-year long eruption can be divided into three periods of dome growth encompassing five distinct eruptive phases interspaced by periods of "residual activity". The first period includes a phase of extrusion from 1995 to early 1998, during which the dome grew and collapsed on a number of occasions followed by a phase of residual activity, from early 1998 to late 1999, without significant lava extrusion but several dome collapses and small-to-moderate size explosions. The second period began in November 1999, with a phase of renewed extrusion and growth of a large lava dome that continued until July 2003. Three major collapses occurred during this period in March 2000, July 2001, and July 2003. A phase of relative quiescence followed, with occasional elevated activity in March-May 2004, April 2005, and June-July 2005 including ash and steam venting, small pyroclastic flows and minor explosions. In August 2005 the fifth phase of the eruption and the ongoing third period of dome growth began. To date (April 2007), there has been one major dome collapse event on 20 May 2006 immediately followed by renewed lava dome growth.

1.2 SHV pyroclastic activity

Pyroclastic flows during the current eruption have originated from a dome located in a horseshoe-shaped crater (formerly known as English's Crater) open to the East with a sloping floor, and ranged from rockfalls through small PF to events involving complete disruption of the lave dome. PF

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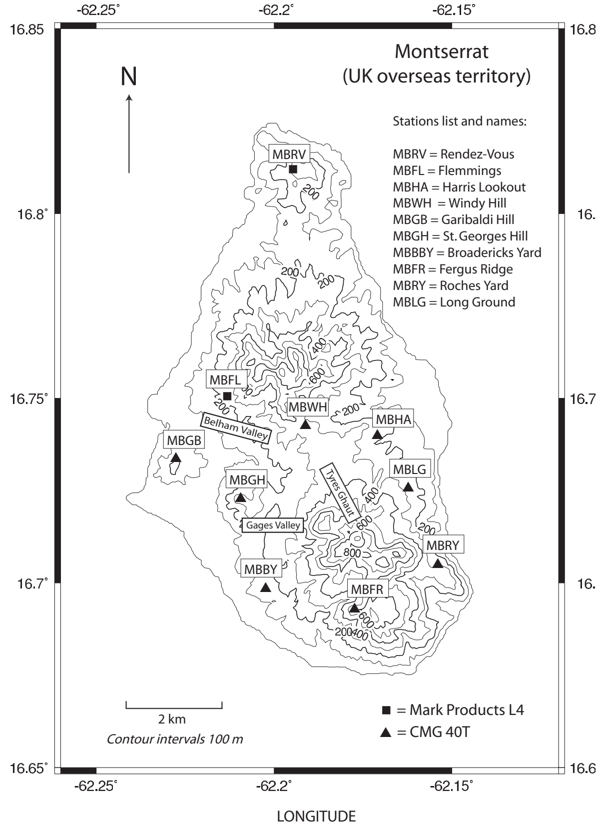

Fig. 1. Topographic map of the island of Montserrat and Soufrière Hills Volcano. The locations of MVO seismic stations are shown (black triangles, broad-band; black squares, short-period). The locations of the areas Northwest and West of the volcano affected by dome collapse and pyroclastic flow activity during the 8 January 2007 event Tyres Ghaut, Gages Valley and the Belham Valley, are also marked.

are distinguished from rockfalls by their larger size and energy, greater run-out distances (>0.5 km) and the presence of turbulent, convecting clouds of fine ash rising above a basal flow of coarser material. They consist of high-density mixtures of hot, dry rock fragments and hot gases moving away from the volcano at very high speeds that can reach up to 200 m/s. Collapses of the summit lava dome at SHV with deposit volumes between $1\times10^6\,\mathrm{mP}^3$ and $210\times10^6\,\mathrm{mP}^3$ have occurred on many occasions, generating more than 10000 rockfalls and over 300 PF with runout distances greater than 2 km (Calder et al., 2002). PF are among the most potentially dangerous and destructive types of volcanic activity as they occur with little or no warning and progress rapidly. On Montserrat, monitoring PF activity is a priority task in order to identify flows that can potentially descend the Northwest flanks of SHV and pose a hazard to population in the inhabited areas around the volcano.

1.3 Seismic monitoring at SHV

Seismic activity at SHV is monitored using a network (Fig. 1) of 8 broadband (T=30 s) three component Guralp CMG-40T seismometers and 2 short-period (T=1 s) Mark Products L4 vertical instruments (Luckett et al., 2007). The seismic signals recorded at SHV are categorised by the Montserrat Volcano Observatory (MVO) as follows: 1) volcano-tectonic (VT), 2) long-period (LP), 3) hybrids, 4) rockfalls, 5) long-period rockfalls. VT earthquakes have impulsive P and S-wave arrivals and are predominantly high frequency (5-10 Hz). They are associated with brittle rock failure and exhibit shear-fault source mechanisms. LP earthquakes have emergent onsets and low-frequency content (1–5 Hz). They can be interpreted as the result of gas or magma movement within the volcano. Hybrid earthquakes share common features with both VT and LP; they have impulsive high frequency onsets but contain significant amount of low-frequency energy in their coda. Hybrids and LP are sometimes considered members of the same family; the same event can be seen as a LP at one station and as a hybrid at another station. They are thought to represent magma forcing its way to the surface (Neuberg et al., 2006). Hybrid earthquakes are often associated with periods of rapid dome growth, sometimes precursory to dome collapse episodes. Rockfall or pyroclastic flow signals are currently the most common types of seismic activity at SHV. They exhibit spindle-shaped and broadband (1–20 Hz) waveforms with very emergent onsets and no clearly defined seismic phases. They are interpreted as due to material falling off the dome and traveling down the flanks of the volcano. Signals associated with PF resemble rockfall seismograms but are generally distinguished by their extended duration and higher amplitudes. Examples of seismic signals recorded at SHV and their Fourier spectra are displayed in Fig. 2.

2 Visual observations

The eruptive event on 8 January 2007 was preceded by sustained rockfall and PF activity over the previous 24 h. Rockfalls and PF were observed to descend from the Northwest sector of the lava dome on the Northwest and West slopes of SHV into Tyres Ghaut and Gages Valley. Between 10:00 and 10:15 UTC 8 January 2007, a moderated-size dome collapse caused large PF to enter Tyres Ghaut and from there the Belham Valley, reaching as far as 5 km away from the volcano (Fig. 3a). An ash cloud was visible from all over Montserrat moving out westwards, reaching a reported height of about 10 km by 10:25 UTC (V.C. Bird International Airport, Antigua). Pyroclastic activity from the Northwest and North sector of the dome continued at high levels over the following 2 h consisting of minor flows (run out <1.0–1.5 km) occurring 5–10 min apart. These flows appeared to be preceded by pulses of ash venting. At about 12:00 UTC, seismicity

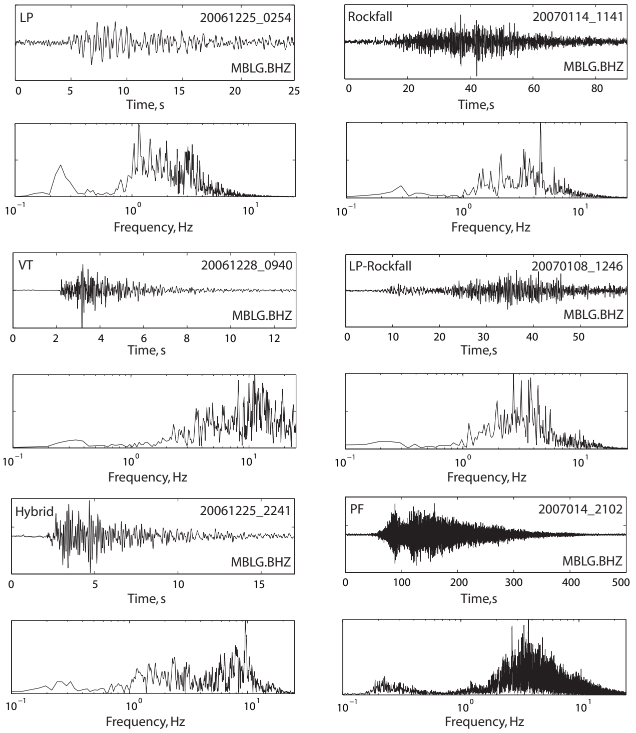

Fig. 2. Examples of volcano seismic signals recorded at Soufrière Hills Volcano at station MBLG (vertical component) and their Fourier spectra (seismic traces and spectral amplitudes are individually normalized).

had returned to background levels. Visual observations of the dome showed that material was removed from the Northwest side of the dome leaving an amphitheatre-like structure cutting through the old crater rim (Fig. 3c). Inspection of photographic images taken from the MVO's remote camera on Windy Hill, about 4.5 km North of the volcano, showed explosive activity on the lower part of the Northwest section of the dome.

Abundant pumiceous material was observed in the flow deposits possibly attesting rapid ascent of gas rich magma at shallow depth and explosive activity. Observations of explosions on the lower Northwest side of the dome, in the images from the MVO remote web camera (Windy Hill) suggest that decompression due to the partial dome collapse might have acted as a trigger for explosive fragmentation of magma.

3 Analysis and interpretation of seismicity

3.1 Precursory period

Seismicity during December 2006 was dominated by rockfalls and small LP earthquakes. The main seismic episode during this period was a swarm of LP events recorded on 25 December 2006 (Fig. 4). The swarm consisted of 88 triggered LP earthquakes (energy in the 1.0–5.0 Hz band) and

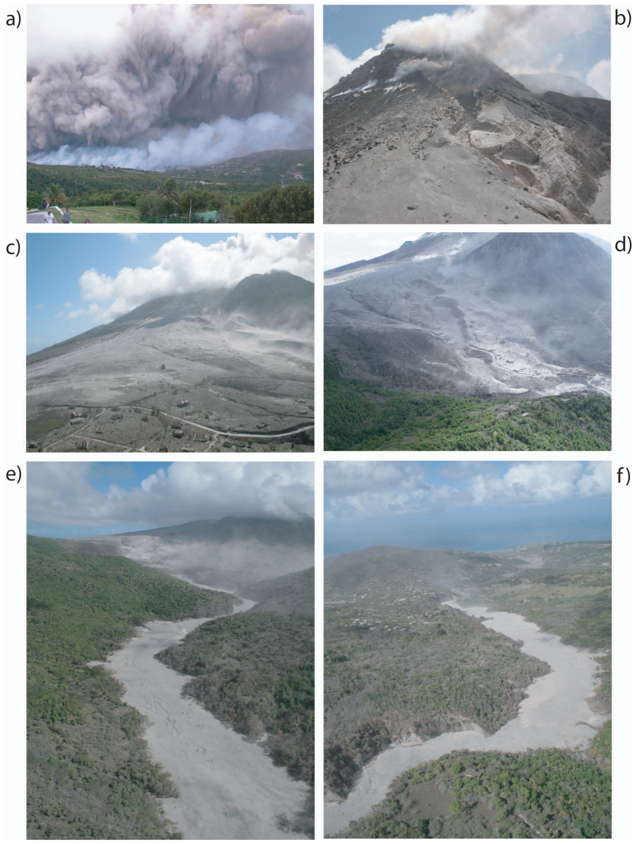

Fig. 3. Photographic record of the 8 January 2007 events at SHV (Copyright MVO/BGS(NERC): **(a)** PF as seen from the Montserrat Volcano Observatory, **(b)** collapse scar cutting through the old crater rim, **(c)** the North flanks of SHV, **(d)** view of Tyres Ghaut from the West, **(e)** and **(f)** flow deposits along the Belham River and reaching the lower Belham Valley after the 8 January event.

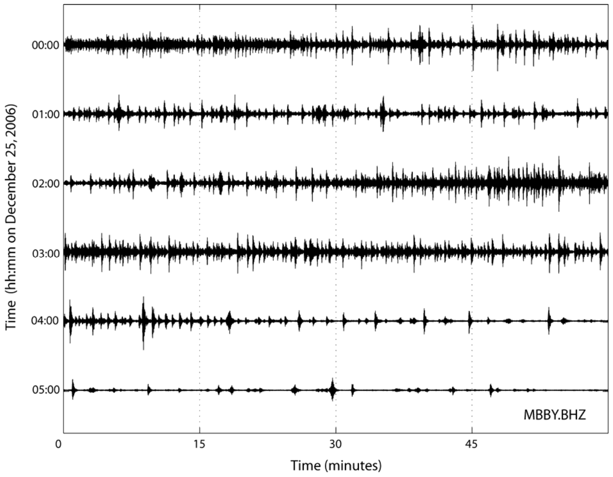

Fig. 4. Seismogram of the swarm of LP earthquakes as recorded at station MBBY (vertical component) on 25 December 2006.

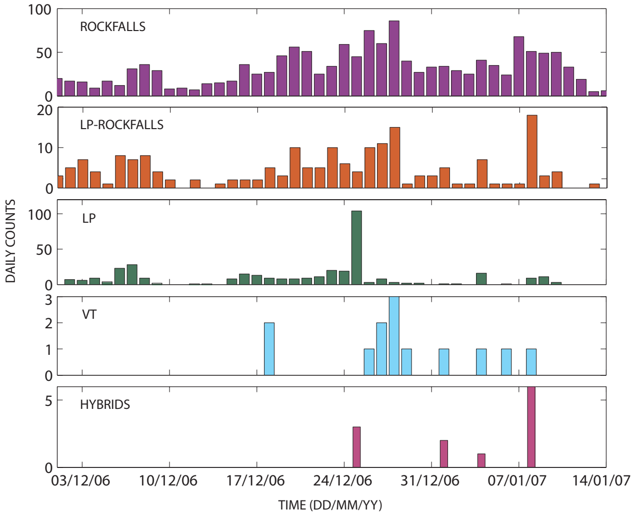

Fig. 5. Seismic activity at Soufrière Hills Volcano between 1 December 2006 and 15 January 2007. From top to bottom, daily seismic counts of rockfalls, lp-rockfalls, lp, vt, and hybrid earthquakes.

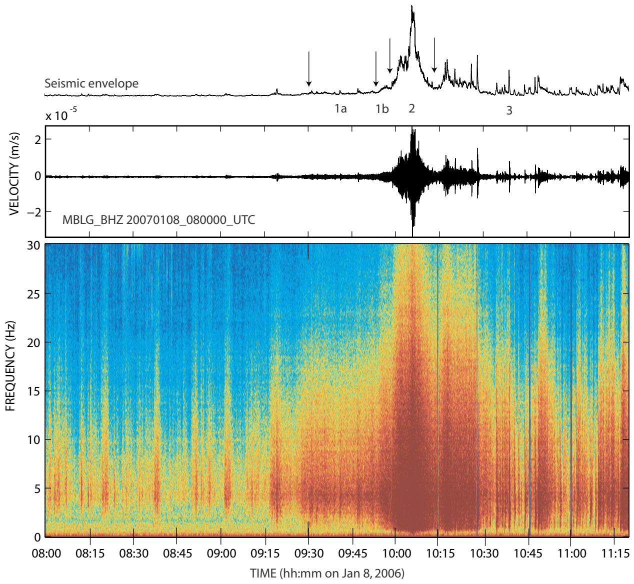

Fig. 6. Seismic envelope (top), velocity seismogram (middle), and spectrogram (bottom) for the signals recorded at station MBLG (vertical component) on 8 January 2007. The envelope is generated from the seismogram as the function $E(t) = \sqrt{S(t) + S_{hil}(t)^2}$ (Kanasewich, 1981), where $S(t)$ is the seismic time series and $S\mathrm{B}_{hilB}(t)$ its Hilbert transform. The spectrogram is obtained by sliding a 1024-sample window along the waveform and calculating the periodogram for 512-sample overlapping positions of the window. The seismogram is divided into different phases according to variable observed activity (see text in the manuscript).

lasted about 6 h (00:00–06:00 UTC). Most of these events were located below the dome at depths between 1–2 km. The LP swarm might represent the arrival of a batch of fresh magma into the conduit and its rapid migration into the dome. The LP earthquake activity was preceded by about 9 h of low-level continuous tremor that accompanyied vigorous ash venting from the western side of the dome. In the hours following the earthquake swarm, the rate of dome growth seemed to have undergone a marked increase, as suggested by rockfall activity and visual observations, and the focus of lava extrusion entirely shifted from the East to the West sector of the dome. A whale-back spine directed towards the Southwest was observed on 26 December as further evidence of the arrival of a batch of fresh magma into the conduit feeding the dome; the spine might, in fact, represent a crystallized portion of the conduit thrown up by the arrival of the new magma. At the same time, the whole West side of the dome could clearly be seen to have been bulked up as the result of magma migration from the conduit into the dome. Rockfalls increased in number during 26–29 December and were clearly visible at night on a sector from the Northwest to the West of the dome confirming the switch in the focus of dome growth. Activity remained at relatively low levels during the following days and picked up again on 7 January, when sustained rockfall seismicity was recorded possibly triggered by the arrival of another batch of fresh magma into the dome. No significant LP seismicity was observed during January although the lack of LP earthquakes could be ascribed to delayed degassing (Scandone et al., 2007). Migration of new magma into the dome is likely to have caused an increased state of internal pressurization. The changes in the state of pressurization and in the direction of dome growth affected its stability eventually leading to the partial collapse of 8 January. Seismic activity at SHV during the period 1 December 2006–15 January 2007 is displayed in Fig. 5.

3.2 The 8 January 2007 event

The event on 8 January, 2007 at SHV was well recorded by the seismic network at SHV. The observed time series can be divided into three main phases as shown in Fig. 6. Phase 1: the onset of a continuous signal is observed before 09:30 UTC. This segment of activity lasted about 30 min characterized by a steady increase in amplitude with time. While phase 1 has energy confined to the 1–15 Hz band, its spectral amplitude evolves; the spectrum, initially peaked between 1 and 8 Hz (phase 1a), becomes rapidly more broadband (phase 1b) towards the onset of phase 2. Phase 2 comprises a strong, broadband (1–25 Hz) signal between 10:00 and 10:15 UTC. This portion of the signal consists of a strong spindle-shaped pulse; the onset is emergent and no clearly defined seismic phases could be recognized in the seismic records. Phase 3 includes a sequence of PF-type seismic pulses with smaller amplitudes than those of phase 2 with an overall duration of 1.5 h. The continuous, emergent, and gradually increasing waveform of phase 1 is characteristic of PF initiated by gravitational dome collapse at SHV (Jolly et al., 2002). Explosively triggered dome collapses at SHV have been often accompanied by more impulsive onsets of the seismic signal. Explosive disruption of the lava dome at SHV can also be anticipated by characteristic patterns of cyclic deformation, and intense long-period and hybrid seismic activity indicative of magma movement and gas pressurization in the upper conduit (Voight et al., 1998; Neuberg, 2000). It is noteworthy that such patterns were not observed before 8 January. We infer that the emergent signal during phase 1a represents the progressive failure of slip zones with variable orientation along the boundaries of an unstable portion of the dome as the result of increased internal pressurization. As the slip became larger and accelerated, the signal increased in amplitude leading to the rapid failure of the unstable front and its fall onto the edifice slopes. A number of individual rockfalls can also be recognized in the seismic records during phase 1a (Fig. 6) possibly reflecting transport of debris during the initial stages of the fracturing process. Phase 2 is thought to represent the fall of the unstable portion of the lava dome, its collision with the slopes of the volcano and resultant fragmentation, and descent of the flows down the flanks of the edifice. The entrainment of volcanic deposits, as the flow progressed, is thought to be partly responsible for the high frequencies observed throughout this phase. During the early stages of phase 3 individual seismic pulses appear to be embedded in a continuous signal possibly due to the re-mobilization of material deposited along the same path by PF during phase 2.

4 Discussion and conclusive remarks

Rockfalls and PFs can be identified in seismic records according to their spindle-shaped waveform envelopes and their extended duration relative to discrete earthquake events such as long-period or volcano-tectonic events (Norris, 1994; Uhira et al., 1994, Calder et al., 2002; Jolly et al., 2002). The seismic time series associated with rockfalls and PF are complex since the wave field at a point receiver is composed of different phase arrivals as they result from multiple moving seismogenic sources (Surinach et al., 2005). Various authors have studied lava dome collapses and PF propagation at SHV. Cole et al. (1998) reviewed pyroclastic flow activity at SHV during 1996-97 describing the characteristics of flows produced by gravitational collapse of the lava dome ranging from discrete pulses to sustained dome collpase events. They observed the occurrence of explosions from flow source areas subsequent to the removal of dome material by collapse and described the pulsatory nature of secondary flows. Calder (2002) presented a study of PF timing, volumes and runout distances for individual collapse events and investigated the influence of magma extrusion rates and dome size on stability and PF generation. Observations of lava dome growth and PF activity at SHV have been documented in a series of papers (Robertson et al., 1997; Voight et al., 1999; Loughlin et al., 2002; Sparks et al., 2002; Voight et al., 2002; Herd et al., 2005) which collectively demonstrate the wide variety of collapse and PF generation mechanisms. Factors controlling the failure of lava domes include intrusion of magma, degassing and rainfall; all these processes can cause extensive fracturing and destabilise the dome leading to a collapse. Collapse of pressurized lava domes can be also triggered by the explosive fragmentation of gas-rich magma in the conduit system. A review of the mechanisms of lava dome collapse can be found in Voight et al. (2000). More recently Scandone et al. (2007) have suggested that dome collapses can be triggered by fast and episodic migration of gas rich magma into the shallow conduit.

The variety of collapse styles and mechanisms corresponds to variable precursory patterns making it difficult to obtain accurate prediction and short-term warnings of incipient events. TCollapse episodes at SHV prior to 2003 were often observed to be preceded by cyclic inflationary tilt of the crater rim, increasing rates of rockfall seismicity, and intensifying LP and hybrid earthquake activity. During these cycles, gas-rich magma was being extruded onto or intruded into a pre-existing dome, leading to rockfalls and collapses from the headwalls of developing lava flow fronts. Whilst it should be noted that no tilt-meters have been installed since 2003, subsequent episodes of dome collapse, have exhibited rather more subtle precursory seismicity; increased rockfall activity and episodic clusters of LP/hybrid earthquakes are typical although there is no evidence of recurring patterns.

In this manuscript the seismic records of a dome collapse episode at SHV on 8 January 2007 have been described and an interpretation put forward. The results of our analyses are consistent with a collapse induced by fracturing of an unstable sector of the dome due to increased internal pressurization. We suggested that intense LP earthquake activity recorded on 25 December 2006 and sustained levels of rockfall activity between late December 2006 and early January 2007 testify the arrival of gas-rich magma in the shallow conduit and its intrusion into the dome contributing to destabilize the lower Northwest side of the edifice. The presence of abundant pumices in the flow deposits seems to confirm that gas-rich magma rapidly migrated at shallow depth into the dome. Observations of explosions in web camera images suggest that explosive fragmentation of magma stored at shallow depth might have occurred triggered by rapid decompression due to the partial dome collapse.

The activity on the Northwest sector of the volcano during December 2006 and January 2007 is unprecedented during the eruption to date, and the 08 January flow which reached Cork Hill is the largest in this drainage. Previously no volumetrically significant flows have occurred in Tyres Ghaut. On the only previous occasion when material entered the Belham Valley, it was during the 25 June 1997 collapse when a portion of the surge cloud detached to travel westwards as far the outskirts of Cork Hill (Cole et al. 1998).T

It is crucial for hazard mitigation in populated areas around volcanoes to identify recurrent patterns of precursory activity and their relation to episodes of dome collapse in order to develop reliable automated alarm systems for use in conjunction with real-time monitoring at volcano observatories. This is paramount at SHV where even relatively small collapses have the potential to generate flows able to reach inhabited areas posing serious risks to the population.

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