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Seismicity associated with dome growth and collapse at the Soufriere Hills Volcano, Montserrat

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Abstract. Varied seismicity has accompanied growth and collapse of the lava dome of the Soufriere Hills Volcano, Montserrat. Earthquakes have been classified as either volcano-tectonic, long-period or hybrid, and daily variations in the numbers of events have mapped changes in the style of eruption. Repetitive hybrid earthquakes were common during the first months of dome growth. In July 1996 the style of seismicity changed and regular, short-lived hybrid earthquake swarms became common. This change was probably caused by an increase in the magma flux. Earthquake swarms have preceded almost all major dome collapses, and have accompanied cyclical deformation, thought to be due to a build-up of pressure in the upper conduit which is later released by magma moving into the dome.

Introduction

Continuous dome growth began in the crater of the Soufriere Hills Volcano, Montserrat, in November 1995 (Young *et al.*, 1998). In the following 2 years growth of the dome was accompanied by a range of seismic signals, recorded by two local seismic networks (Aspinall *et al.*, 1998; Neuberg *et al.*, 1998). The Montserrat Volcano Observatory (MVO) has monitored the volcano using data from both networks, and in day-to-day monitoring the most useful diagnostic has been the temporal distribution of different event types. The character of the seismicity changed markedly when dome growth started. The bulk of pre-dome seismicity comprised high-frequency earthquakes scattered throughout southern Montserrat (Aspinall *et al.*, 1998), thought to be due to shear failure within the country rock. Since the start of dome growth, most earthquakes have been low frequency, and are attributed to magmatic processes. Collapses of the lava dome, explosions, landslides and lahars have also generated seismic signals. Complex relationships exist between different types of earthquakes and other variables and events, such as the rate of dome growth, deformation and pyroclastic flows. Activity has often been cyclical, suggesting the influence of periodic dynamic processes within the magma system.

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Event Classification Scheme

The main volcano-seismic events have been classified visually into 7 classes. The classification broadly followed the scheme used at other volcanoes (*e.g.*, Lahr *et al*, 1994), with some modifications developed as the eruption progressed. As is common at erupting volcanoes, a wide variety of seismic signals have been recorded, and not all events can be classified easily, or are classified the same way by different operators. Some retrospective re-classification has been attempted. The scheme presented here has been adequate to classify the majority of the seismic signals and to allow the main trends in the seismicity to be identified. The main classes are illustrated in Figure 1.

Volcano-tectonic earthquake (VT). A local earthquake produced by brittle failure (Power *et al.*, 1994) with significant energy above 5 Hz. *P* and *S* waves are generally impulsive. VT earthquakes have been located throughout southern Montserrat with most occurring beneath the volcano at shallow depth (Aspinall *et al.*, 1998).

Long-period earthquake (LP). Volcanic earthquakes with nearly monochromatic waveform and peaked spectra in the range 1-2.5 Hz (Fehler and Chouet, 1982). These earthquakes are not very common in Montserrat, with usually <5 per day. The waveforms are emergent and *P* and *S* phases are not apparent (Neuberg *et al.*, 1998).

Hybrid earthquake. Volcanic earthquakes which occur mostly in swarms, with predominant frequencies between 0.5-4 Hz. They have impulsive first arrivals, a high-frequency start (especially at stations close to the volcano), and a long-period coda. A complicated wavetrain follows a small *P* wave first arrival, with most of the energy in the horizontal plane (Neuberg *et al.*, 1998). Our use of the term "hybrid" follows Lahr *et al.* (1994), who defined hybrids as having "a mix of characteristics between VT and LP events". Whereas Lahr *et al.* (1994) classified hybrid events after detailed spectral analysis, we have not followed this rigorous procedure, and use the term as a useful designation to separate the events from the lower-frequency LP events. Within swarms, the hybrid earthquake are sometimes highly repetitive. They occur at regular intervals (<1 second to tens of minutes) with similar waveforms and magnitudes (White *et al.*, 1998). Non-repetitive hybrid earthquakes also occur, where the inter-event time is irregular and there is no consistent trend of magnitude

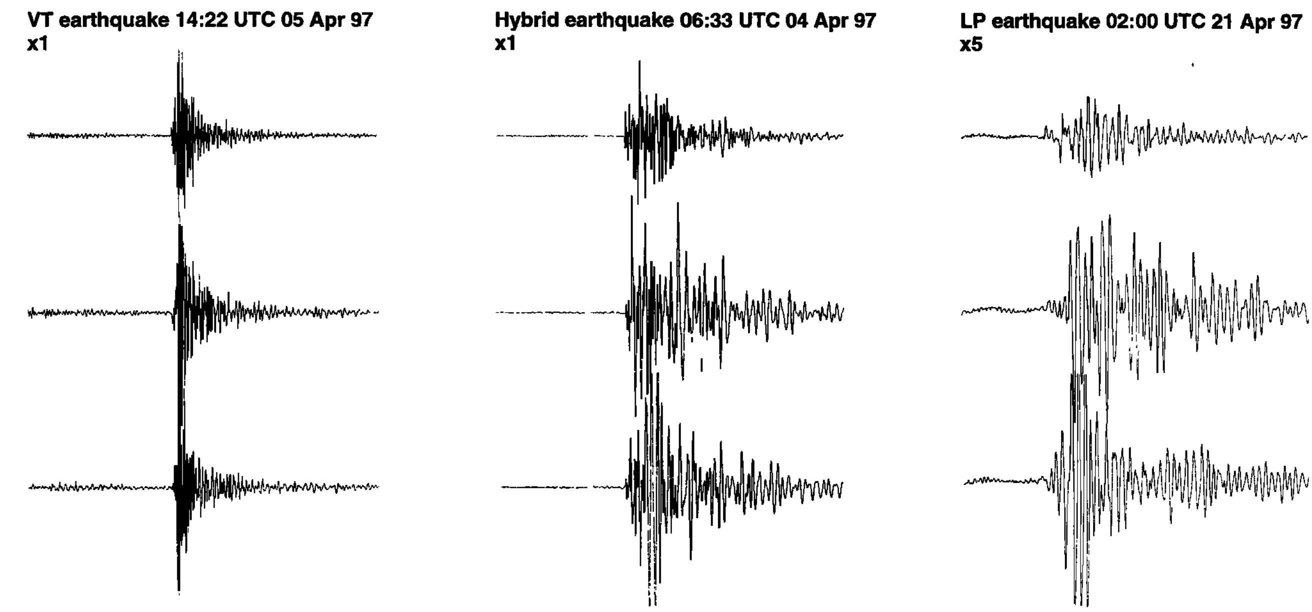

Figure 1. Examples of seismic signals from the Soufriere Hills volcano. Vertical, north-south, east-west components recorded by the Gages broadband seismometer (see Aspinall *et al.*, 1998 for location).

variation. These are generally larger than the repetitive earthquakes, with estimated magnitudes (M_L) up to 3.

Tremor. A continuous seismic disturbance lasting for several minutes. Tremor is sometimes harmonic, and some episodes are preceded by repetitive hybrid earthquakes which become steadily more common until they coalesce to form tremor with frequency spectra similar to those of the preceding hybrid earthquakes.

Vulcanian explosion signals. These signals start with an emergent long-period (1-2 Hz) signal which continues for up to 3 hours after the explosion at reduced amplitude. A high-amplitude, high-frequency signal starts after the long-period signal, and is caused by pyroclastic flows generated by column collapse.

Phreatic explosion signals. Quite impulsive broadband signals lasting for a few minutes, which occurred between July and November 1995. The signals tended to be more monochromatic and low-frequency when explosions vented into the atmosphere.

Rockfall signals. These are emergent, phaseless, high-frequency signals that correlate with observed rockfall and pyroclastic flows from the dome.

Chronology of Dome-Related Seismicity

Swarms of repetitive hybrid earthquakes preceded and accompanied the first local extrusion of magma in September 1995 and the start of continuous dome growth in November 1995 (White *et al.*, 1998). Similar swarms occurred during the first 8 months of dome growth, with up to 8000 small events per day recorded at times (mostly too small to trigger the event recording system). The first pyroclastic flows occurred in late March 1996. The number of VT earthquakes decreased, and from April to mid-July 1996 there generally were less than 5 VTs per week.

The seismicity changed character on 20 July 1996, when swarms of non-repetitive hybrid earthquakes occurred, preceded by a swarm of small VT earthquakes. A week later, regular hybrid earthquake swarms began, which merged into tremor. Each tremor episode lasted for about one hour, and was accompanied by vigorous steam emission, suggesting increased gas release from the dome. The dome grew rapidly and pyroclastic flows were frequent (Sparks *et al.*, 1998). Tremor ceased on 10 August, but short-lived swarms of hybrid earthquakes continued until an explosion on 17 September (Robertson *et al.*, 1998). Most swarms lasted for less than 6 hours, and the recurrence interval varied from 4-20 hours. Prior to the explosion the level of LP earthquakes increased. Immediately after the explosion, the level of seismicity decreased markedly.

Non-repetitive hybrid earthquakes restarted on a month later. Eight prolonged swarms, lasting for 64 hours on average, accompanied deformation of the southern crater rim (Galway's Wall) in November-December 1996. The dome was quiet during the swarms, but landslides of cold rock from the outside face of Galway's Wall, and the extension of nearby crack systems, suggested that the wall was being deformed by intruding magma. Between swarms magma reached the surface, the dome grew and dome rockfalls were common. Following pumiceous pyroclastic flows on 19 December there was another period of frequent, short, high-intensity, hybrid earthquake swarms and tremor (Figure 2), associated with rapid dome growth.

Hybrid earthquake swarms were common in January and February 1997, with many of the swarms terminated in tremor. A typical swarm lasted for 2-4 hours, beginning with non-repetitive hybrids of variable magnitude and followed by repetitive hybrids of lower magnitude, which sometimes merged into tremor. A few large pyroclastic flows occurred in January, each one after a hybrid earthquake swarm.

Rapid dome growth occurred in the southern sector at the end of March 1997, resulting in pyroclastic flows to the south. Unusually, there were no hybrid earthquake swarms during this period of elevated activity. LP activity increased from mid-March (Figure 3). About 50% of the LPs immediately preceded rockfall signals (which we call LP rockfalls), with

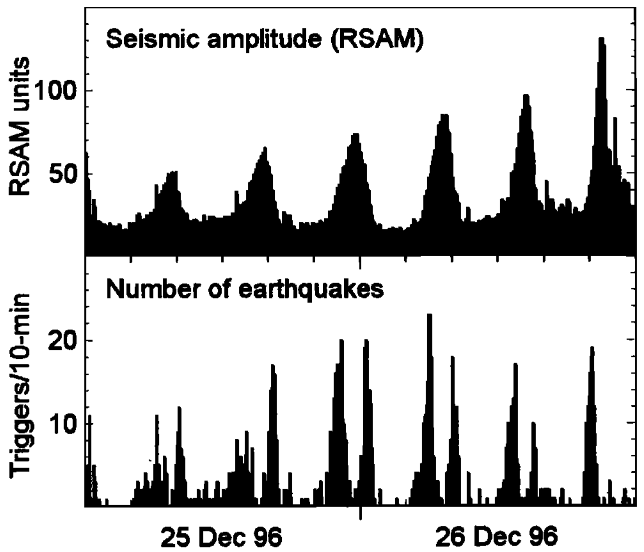

Figure 2. Signal amplitude (top) and number of earthquakes (bottom) for the short-period seismometer at St George's Hill, 25-26 December 1996. Episodes of small, repetitive hybrid earthquakes and tremor occurred every 8 hours. As the series progress, the episodes became close together and increased in intensity. Earthquakes occurred at the beginning and end of each episode, and coalesced to a continuous tremor signal in the middle.

the start of the LP signal preceded the rockfall signal by a few seconds. During LP rockfall signals there is no movement on the dome until the rockfall signal begins (Neuberg *et al.*, 1998), suggesting that the long-period signal is not caused by a surface process, such as the movement of lava blocks. Some LPs were accompanied by puffs of ash or steam from the dome.

Hybrid swarms began again in mid-May 1997 accompanied by cyclical deformation, measured by tiltmeters on the crater rim (Voight *et al.*, 1998). In a typical cycle, inflation of the volcano was accompanied by a hybrid earthquake swarm, which gained intensity as the inflation approached a maximum. Often the swarms graded into tremor. Shortly afterwards, deflation coincided with the end of the swarm and tremor, increased rockfall activity, and occasionally pyroclastic flows to the north. Regular hybrid swarms preceded major pyroclastic flows in late June-early July, and were accompanied by high-amplitude cyclical deformation.

Hybrid earthquake swarms restarted on 31 July 1997, and continued every 3-40 hours (average 13.4 hours) until 25 August. The average swarm duration was 5 hours, and many swarms merged into tremor. The number of LP earthquakes was elevated from 31 July to 3 August. On 4 August, the first of a series of vulcanian explosions occurred with 13 explosions during 4-12 August, all of which occurred during or after hybrid earthquake swarms. VT earthquakes became more common from 25 August, with up to 29 per day.

Following a major dome collapse on 21 September 1997, another series of 76 vulcanian explosions began and lasted until 21 October. The first explosions were preceded by hybrid earthquake swarms, but later VT earthquakes became dominant with up to 75 per day. After the explosions ceased, hybrid swarms were accompanied by above-average numbers of LP earthquakes with up to 55 earthquakes per day. In early November, two major pyroclastic flows occurred at the end of periods of elevated seismicity.

VT Earthquakes During Dome Growth

During dome growth the number of VT earthquakes has been low, and they have been almost exclusively located beneath the crater at 2-5 km depth. From November 1995 to August 1997, there were 7 VT swarms, six of which preceded increases in the level of hybrid seismicity. In some cases a VT swarm was followed by a hybrid earthquake swarm a few hours later. VT earthquakes are probably located in country rock close to the conduit, and caused by changes in the conduit, perhaps an increase in magma flow or the passage of more gas-rich magma which affects the local stress field. As the new batch of magma approaches the surface, hybrid earthquakes are generated.

Hybrid Earthquake Swarms

Hybrid swarms have been the most prominent type of dome-related seismicity, and they have exhibited a variety of features. Swarms prior to July 1996 comprised small, repetitive events, occurring at regular intervals often for days at a time. Since July 1996, non-repetitive hybrid earthquakes have been more common, individual earthquakes have been larger, and most swarms have lasted for only a few hours. The earthquakes are located directly beneath the crater, at shallow depth (<4km) (Aspinall *et al*, 1998).

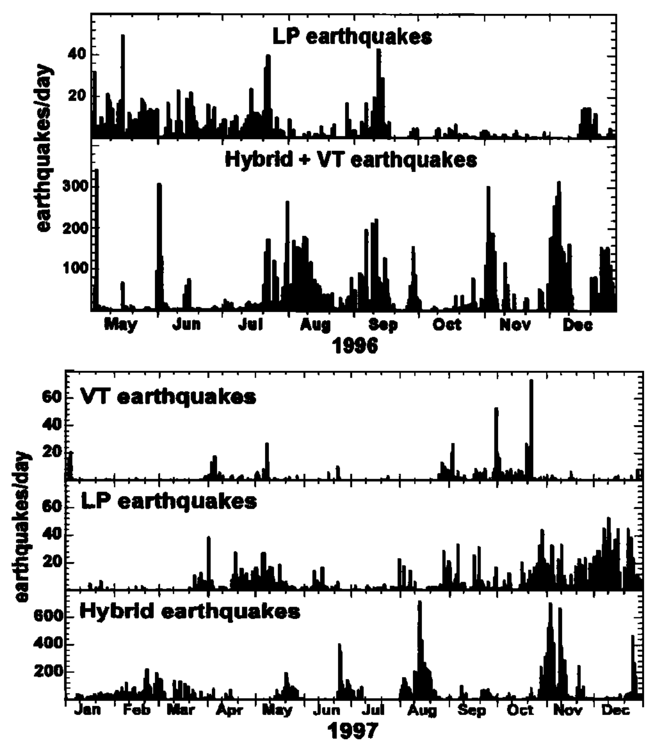

Figure 3. Daily counts of VT, LP, hybrid earthquakes between May 1996 and December 1997. The 1996 data are for earthquakes which triggered the analogue network recording system (Aspinall *et al.*, 1998), when VT and hybrid earthquakes were not discriminated during classification. The 1997 data come from the digital network (Neuberg *et al.*, 1998).

A major change in the volcanic activity occurred in July 1996. This change in activity was probably due to an increase in the magma supply rate, leading to faster dome growth and also an increase in the gas content of the magma close to the surface. This resulted in an increased level of seismicity, and a change in the characteristic patterns, with a decrease in the periodicity from several days or weeks down to a few hours.

There have been several periods since July 1996 where short-duration hybrid swarms have occurred periodically, and have often been followed dome collapses or vulcanian explosions. Whenever tiltmeters have been in operation on the crater rim during these periods, cyclical deformation has been detected (Voight *et al.*, 1998), and it seems likely that this is a feature of all the episodes. During the most recent series of explosions, in September-October 1997, most explosions were not accompanied by hybrid earthquake swarms, suggesting that the underlying process does not always result in hybrid earthquakes. Also, tiltmeters have detected low-amplitude deformation cycles during periods of low seismicity. However, almost all major collapse events have been preceded by hybrid seismicity, which is clearly a useful result for hazard management. In January 1997, swarms were followed by a hiatus of 1-2 hours before pyroclastic flows occurred, but at other times the flows occurred during or directly after swarms.

Hybrid earthquakes are thought to be caused by resonance of the magma column, triggered by the movement of gas released from batches of gas-rich magma (Neuberg *et al.*, 1998; Voight *et al.*, 1998). The near-dome deformation is caused by increased magma pressure which is released as each batch enters the dome complex, resulting in ash venting and rockfalls, and occasionally pyroclastic flows or explosions.

LP Earthquakes

While LP earthquakes have been relatively rare, they have been persistent and observed throughout the period of dome growth (Figure 3). In June and July 1996, there were on average 10 LP earthquakes per day, but the level of LP activity dropped following the change in activity in late July. From then until March 1997 LP earthquakes were much less common, apart from the period before the September 1996 explosion (see below). Many LPs have triggered dome rockfalls and pyroclastic flows. When LPs and hybrids occur close together in time, only the LPs trigger rockfalls, even when the hybrids have larger peak amplitudes. This, combined with other evidence (Neuberg *et al.*, 1998), suggests that LP earthquakes are shallower than hybrid earthquakes, but probably have the same mechanism.

Peaks in the daily number of hybrid and LP earthquakes are negatively correlated for most of the period for which reliable daily counts exist (Figure 3). The main exception to this was the period immediately prior to the September 1996 explosion, when an abnormal number of LPs occurred at the same time as hybrid swarms (Figure 3). There have been a few other short periods when this pattern occurred, including the four days prior to the start of explosive activity in August 1997. Periods of enhanced LP seismicity are not associated with increased SO_2 release, which suggests that LPs are not simply due to increased gas emission. In late 1997 LP earthquakes became more common, and have occurred in above-average numbers at the same time as hybrid swarms, suggesting a change in the system. Another period of enhanced LP seismicity, in mid-March to May 1997, was also a time of growth of the southern sector of the dome. The configuration of the upper conduit and dome in this sector may make LP earthquakes more common when growth occurs there.

It is intriguing that both LP and hybrid earthquakes are present before explosive activity, presumably when gas pressures are elevated. Prior to the September 1996 explosion hybrid swarms became more frequent and of shorter duration, and the peak in the number of LP and hybrid earthquakes occurred six days before the explosion. The September explosion probably occurred because the dome collapse was much larger and deeper than previous collapses (Robertson *et al.*, 1998). High gas pressures may have contributed to this failure, and also made an explosion more likely once a major collapse had started.

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References

Aspinall, W.P., A.D. Miller, L.L. Lynch, J.L. Latchman, R.C. Stewart, R.A. White, J.A. Power and MVO staff, Soufriere Hills eruption, Montserrat, 1995-1997: volcanic earthquake locations and fault plane solutions, *Geophys. Res. Lett.*, in press, 1998.

Fehler, M., and B.A. Chouet, Operation of a digital seismic network on Mount St Helens Volcano and observations of long-period seismic events that originate under the volcano, *Geophys. Res. Lett.*, 9, 1017-1020, 1983.

Lahr, J.C., B.A Chouet, C.D. Stephens, J.A. Power and R.A. Page, Earthquake classification, location and error analysis in a volcanic environment: implications for the magmatic system of the 1989-1990 eruptions at Redoubt Volcano, Alaska. In: T.P. Miller and B.A. Chouet (eds.) The 1989-1990 Eruptions of Redoubt Volcano, Alaska, *J. Volcanol. Geotherm. Res.*, 62, 137-151, 1994.

Neuberg, J., B. Baptie, R. Luckett and R.C. Stewart, Results from the broadband seismic network on Montserrat, *Geophys. Res. Lett.*, in press, 1998.

Power, J.P., J.C. Lahr, R.A. Page, B.A. Chouet, C.D. Stephens, D.H. Harlow, T.L. Murray and J.N. Davies, Seismic evolution of the 1989-1990 eruption sequence of Redoubt Volcano, Alaska, *J. Volcanol. Geotherm. Res.*, 62, 69-94, 1994.

Robertson, R., P. Cole, R.S.J.S. Sparks, C. Harford, A.M. Lejeune, W.J. McGuire, A.D. Miller, M. Murphy, G. Norton, N.F. Stevens, S.R. Young and MVO staff, The explosive eruption of Soufriere Hills Volcano, Montserrat, 17 September, 1996, *Geophys. Res. Lett.*, in press, 1998.

Sparks, R.S.J., S.R. Young, J. Barclay, E.S. Calder, P. Cole, B. Darroux, M.A. Davies, T.H. Druitt, C. Harford, R. Herd, M. James, A.M. Lejeune, G. Norton, G. Skeritt, M.V. Stasiuk, N.S. Stevens, J. Toothill, G. Wadge, R. Watts, Magma production and growth of the lava dome of the Soufriere Hills Volcano, Montserrat: November 1995 to May 1997, *Geophys. Res. Lett.*, in press, 1998.

Voight, B., R.P. Hoblitt, A.B. Lockhart, A. Clarke, A.D. Miller, J. McMahon and MVO Staff, Remarkable cyclic ground deformation monitored in real-time at Montserrat, and its use in eruption forecasting, *Geophys. Res. Lett.*, in press, 1998.

White, R.A., A.D. Miller, L.L. Lynch, J.P. Power and MVO Staff, Observations of hybrid seismic events at Soufriere Hills volcano, Montserrat, West Indies: July 1995 to September 1996, *Geophys. Res. Lett.*, in press, 1998.

Young, S.R., R.S.J. Sparks, W.P. Aspinall, L.L. Lynch, A.D. Miller, R.E.A. Robertson, J.B. Shepherd, and MVO staff, Overview of the eruption of Soufriere Hills Volcano, Montserrat, 18 July 1995 to October 1997, *Geophys. Res. Lett.*, in press, 1998.

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