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Volcano-Tectonic Seismicity of Soufriere Hills Volcano, Montserrat

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Synonyms

A-type volcanic earthquakes; HF earthquakes; High-frequency volcanic earthquakes; The eruption of Soufrière Hills Volcano; Volcano-tectonic earthquakes; VT earthquakes; Montserrat

Introduction

Introduction and Definitions

Volcano-tectonic (hereafter VT) earthquakes, sometimes also termed high-frequency (HF) earthquakes, are a category of volcanic seismic signal. They are local earthquakes that occur in a volcanic setting and possess clear impulsive *P*- and *S*-phases with energy between 1 and 20 Hz, an example of which is shown in Fig. 1.

VT earthquakes are interpreted as resulting from brittle failure or shear fracturing along a fault plane and are therefore indistinguishable from ordinary double-couple tectonic earthquakes. Since VT earthquakes possess the same characteristics as tectonic earthquakes, if they are recorded at sufficient stations, standard seismological methods and tools can be used to determine their hypocenters, magnitudes, and focal mechanisms.

The local stress field in volcanic environments is a combination of the regional tectonic stress and that produced by magmatic and hydrothermal processes. The interaction of these two components leads to the generation of VT earthquakes, which are produced by stress changes, linked to the movement of magma or other fluids. Therefore, VT earthquakes are often linked to magmatic intrusion and are generally regarded as one of the earliest precursors to increased volcanic activity or unrest (Roman and Cashman 2006). VT earthquakes rarely follow the typical mainshock-aftershock sequence seen for tectonic earthquakes, but instead often exhibit different patterns of swarm behavior, with events clustering in time and space without a single mainshock (McNutt 2005). An increase or acceleration in the rate of VT seismicity is often associated with volcanic eruptions, and theoretical models and concepts, such as material failure, have been used to explain these trends and even to produce short-term eruption forecasts.

Magnitudes of VT earthquakes are typically small, $0 < m_b < 3$, and are rarely higher than $m_b 4.5$ (Zobin 2012), but their generally shallow depth can produce locally high intensities close to the source. The relationship between earthquake magnitude and frequency of occurrence is described by the Gutenberg-Richter frequency-magnitude relation, generally expressed by the *b*-value, where *b* is the slope of linear relationship between magnitude and number when written as $\log_{10} N = a - bM$. In tectonically active areas the *b*-value is generally close to 1.0, but in volcanic areas swarms of VT earthquakes can have much higher *b*-values, with many smaller events and fewer larger ones.

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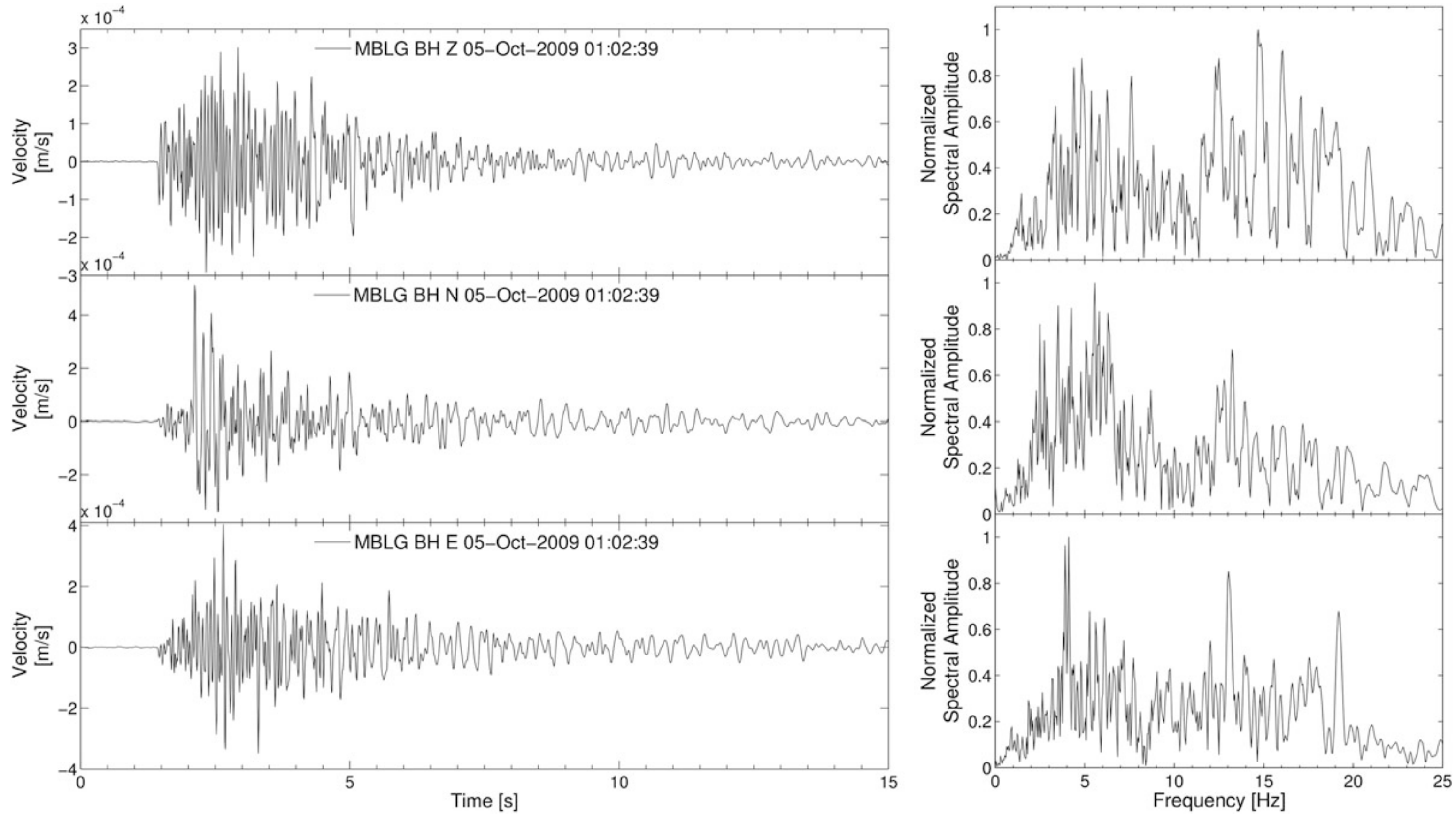

Fig. 1 VT earthquake waveform showing *P*- and *S*-phases and broad amplitude spectrum. This example shows 15 s long three-component velocity seismograms from a M_L2.8 VT earthquake recorded at station MBLG, approximately 3 km NE of Soufrière Hills volcano, Montserrat, on 5 October 2009

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Examples

VT earthquakes can occur before and during volcanic eruptions in a variety of tectonic settings. In basaltic systems such as Piton de La Fournaise volcano, La Reunion, VT earthquakes have been used to track the migration and propagation of magma in an intruding dyke (Battaglia et al. 2005). This behavior is uncommon, however, especially at more silicic volcanoes, and VT seismicity does not usually reveal the path of magma migrating towards the surface prior to eruption. A common precursory feature appears to be the presence of distinct distal clusters of VT earthquakes away from the main volcanic vent, which often disappear with the onset of magmatic activity.

Several examples of this phenomenon have been seen preceding volcanic eruptions in recent years. Each of the last major eruptions at Augustine volcano, Alaska, was preceded by several months of increased and escalating VT seismicity. In the 8 months preceding the explosive eruption in 2006, a cluster of distal VT earthquakes occurred approximately 25 km northeast of Augustine volcano (Fisher et al. 2010). The 1990 eruption of Unzen volcano in southwest Japan was preceded by several years of VT seismicity distributed mainly more than 4 km to the west of the summit (Umakoshi et al. 2001). Two months of VT seismicity also preceded the 1991 eruption of Mount Pinatubo, Philippines. Again, the seismicity occurred in distinct clusters, at shallow depths below the summit and slightly deeper around 5 km to the northwest, with the rate of seismicity accelerating in the days before 7 June eruption. During the early stages of the eruption of Soufrière Hills volcano, Montserrat, in 1995, two main distal clusters of VT earthquakes several km northeast and northwest of the vent were also observed (Aspinall et al. 1998). These are discussed in more detail in the section "► Pre-1995 and Phase 1 VT Seismicity."

Outline

This contribution comprises of a roughly chronological review of VT seismicity at Soufrière Hills volcano (hereafter SHV), Montserrat, chosen because the well-monitored and well-studied ongoing eruption of SHV offers an unparalleled example of the evolution of VT earthquakes during a long-lived multiphase dome-building volcanic eruption.

Section "► Soufrière Hills Volcano" provides some background to the current eruption of SHV, before the VT seismicity is discussed in detail in the following sections. Section "► Pre-1995 and Phase 1 VT Seismicity" discusses the preeruption and early-eruption seismicity, while the relationship between VT seismicity, stress changes, and magmatic intrusion throughout the eruption is examined in the section "► VT Earthquakes and Stress." Some of the more recent VT seismicity at SHV is described in the section "► Recent VT Seismicity at SHV," primarily the short spasmodic bursts or swarms of VT seismicity that have been termed VT "strings."

Soufrière Hills Volcano

Geological Background and Eruptive History

Soufrière Hills volcano is an andesitic volcano occupying the southern portion of the island of Montserrat. The 16 × 10 km island is located in the northern part of the 800 km long Lesser Antilles volcanic arc, a result of the subduction of the North American plate beneath the Caribbean plate at a convergence rate of around 2 cm/year.

Montserrat is made up of three main volcanic complexes, Silver Hills (c.2.6-1.2 Ma), Centre Hills (950–550 ka), and South Soufrière Hills-Soufrière Hills (c.170 ka – present) (Fig. 2), which get progressively younger from north to south. SHV is the youngest and only currently active volcanic center and comprises of a core of several andesitic domes, surrounded by pyroclastic aprons and

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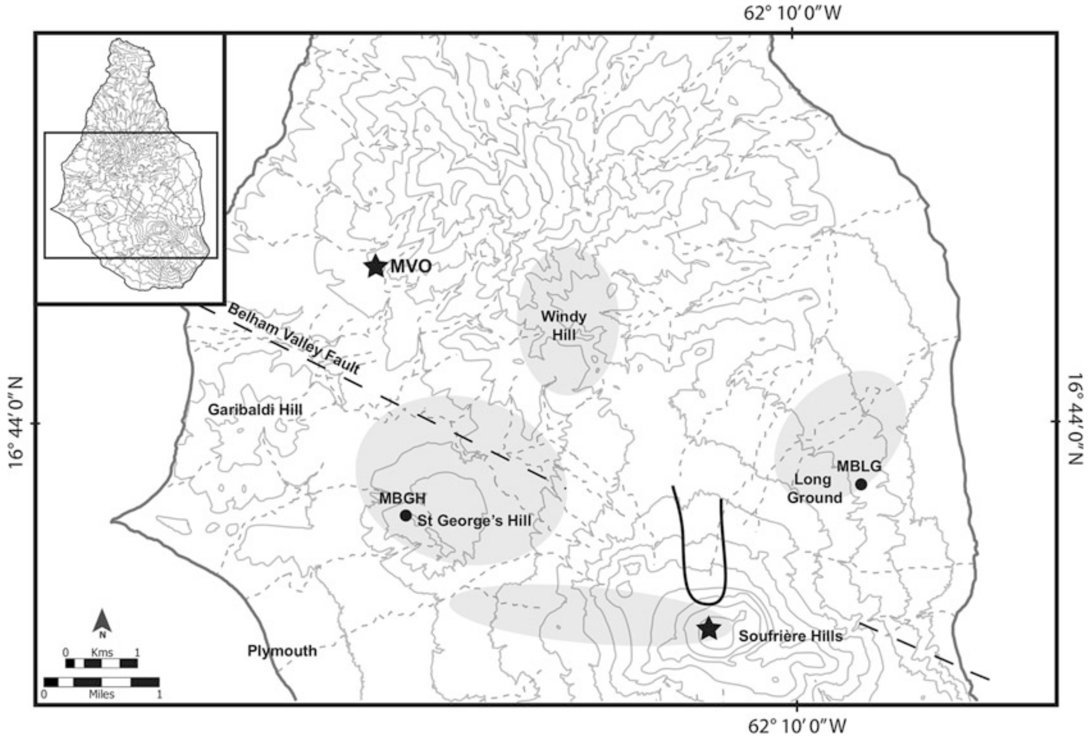

Fig. 2 Map of southern Montserrat showing SHV and other key features. The location of MVO along with two seismic stations, MBGH and MBLG, are shown. The *black star* indicates the explosion crater formed during the 11 February 2010 partial dome collapse, close to the dome summit. The topography shown is pre-collapse, with the approximate location of the 11 February 2010 collapse scar shown in *black* to the north of the dome. The regions of the four distal clusters of VT seismicity in 1995 are shown by the *shaded ellipses*: north of St. George's Hill (Aspinall et al. 1998; Gardner and White 2002; Miller et al. 2010), beneath Windy Hill (Gardner and White 2002; Miller et al. 2010), to the NE (Gardner and White 2002), and to the WNW (Miller et al. 2010). The approximate location of the Belham Valley fault (Feuillet et al. 2010) is also marked

other volcanic sedimentary deposits. South Soufrière Hills is the result of a short-lived period of basaltic to basaltic-andesite volcanism that occurred approximately 120 ka.

The current eruption of SHV has consisted of five phases (Fig. 3) of lava extrusion which have erupted a total of more than 1 km^3 of andesite in the 18 years since 1995. These extrusive dome-building phases have alternated with distinct pauses, during which no lava was extruded but geophysical monitoring data continued to indicate unrest.

Following a period of 3 years of elevated seismic activity (see the section "► Pre-1995 and Phase 1 VT Seismicity"), the eruption of SHV began on 18 July 1995, with several months of phreatic activity followed by the first dome growth in November 1995 (Young et al. 1998). The first magmatic explosion occurred in September 1996 and activity escalated through 1996 and mid- to late 1997, culminating in the destructive lateral sector collapse event on 26 December (Boxing Day) 1997 with associated blast and debris avalanche. The only known fatalities of the eruption occurred during this first phase of extrusion following a significant dome collapse event on 25 June 1997, whose associated pyroclastic flows and surges led to 19 deaths. Since Phase 1, several other whole or partial dome collapses have occurred throughout the eruption, notably in March 2000, July 2003 (the largest recorded collapse of 200×10^6 m^3), and May 2006. The fifth, and most recent, phase of lava extrusion ended on 11 February 2010, with a partial collapse of the lava dome that involved 50×10^6 m^3 of material.

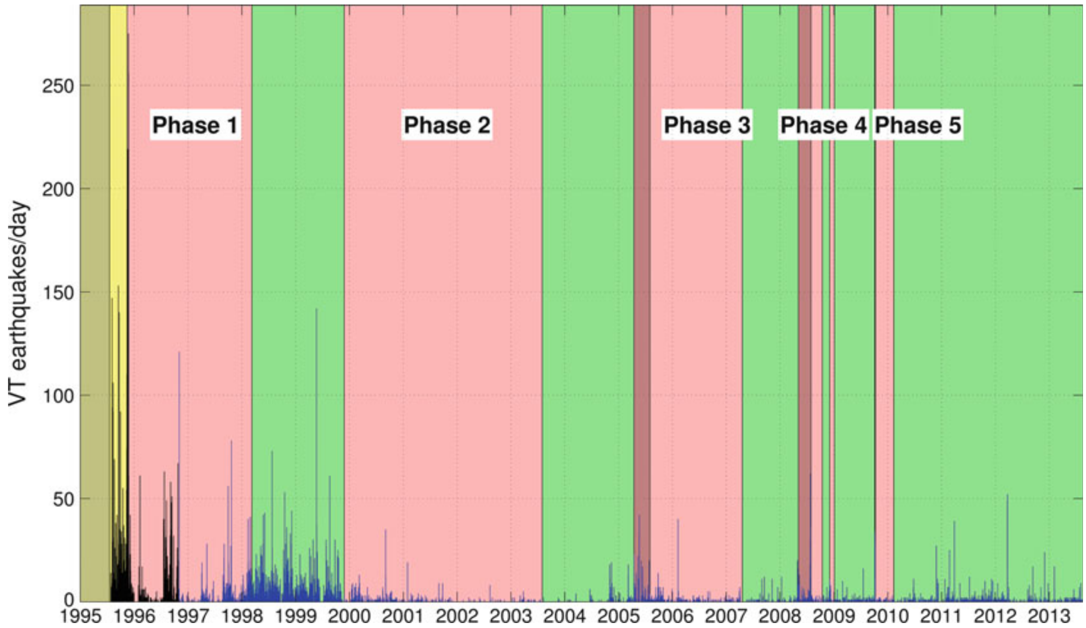

Fig. 3 Daily numbers of VT earthquakes recorded at SHV, Montserrat, from 1995 to present. Earthquake counts from the analogue network are shown in *black* and those from the MVO digital broadband network in *blue*. The five extrusive phases are shown in *pink*, with pauses in extrusion in *green*. *Yellow* indicates the initial phreatic phase in 1995, and the *dark-pink* periods are subsequent transitional, precursory, or phreatic phases

The eruption has caused major social and economic disruption to the island. The former capital Plymouth and much of the island's major infrastructure were destroyed, with the southern two-thirds of the island now a permanent exclusion zone. Many residents were forced to leave the island during the early part of the crisis, although the population has since stabilized. A 2011 census estimated the population at just below 5,000 people, slightly less than half of the preeruption population.

Seismic Crises

Prior to the activity of SHV in July 1995, unpublished evidence from radiocarbon dates of possible volcanic charcoal deposits suggests that the last eruption of SHV occurred during or just before the first European settlement of Montserrat in the early seventeenth century. In later historical times, in the century or so before the onset of the current eruption, there were several volcanic seismic crises on Montserrat, recurring at approximately 30-year intervals. There is very little record of the first in 1897–1898, but more is known of the second, which occurred between 1933 and 1937. Several thousand felt earthquakes were reported, including a large tectonic (i.e., nonvolcanic) earthquake on 10 November 1935, followed by many aftershocks (Perret 1939). As a result of the Royal Society of London expedition to Montserrat to investigate the activity, Powell (1938) established a seismic network of up to eight stations, which operated until 1951. The locations of around 200 local volcanic earthquakes were reported between May 1937 and May 1938, showing several spatial clusters, notably at shallow depths below Soufrière Hills and St. George's Hill to the northwest (Fig. 2). The seismic crisis in 1966–1967 is also well documented. Following felt earthquake reports in early 1966, four seismic stations were installed by the Seismic Research Unit (SRU), Trinidad, and recorded over 700 local earthquakes between May 1966 and the end of 1967. Hypocenters of VT-type earthquakes were located across the south of the island and beneath Soufrière Hills at depths of less than 15 km (Shepherd et al. 1971).

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Increased hydrothermal or fumarolic activity at soufrières surrounding the volcano was observed in association with each of these seismic crises, which have been interpreted as magmatic intrusions that failed to reach the surface.

Pre-1995 and Phase 1 VT Seismicity

VT Seismicity Prior to the 1995 Eruption

After volcanic seismicity on Montserrat waned in late 1967, seismic monitoring on the island was reduced to a single short-period vertical station until 1980, when a real-time telemetered station was installed at St. George's Hill. Between 1967 and 1980 data were recorded locally, and Shepherd et al. (2002) report an average of 3–4 volcanic earthquakes per month, with occasional bursts of greater numbers. A M6.2 tectonic earthquake occurred on 6 March 1985 approximately 20 km N of Montserrat, near the island of Redonda, followed by a large number of aftershocks in 1985–1986. During this time possible local earthquakes were recorded on Montserrat, and in order to distinguish them from tectonic aftershocks, two new seismic stations were established on Montserrat in 1989 (Shepherd et al. 2002).

Following the pattern of the earlier seismic crises of the twentieth century, seismic activity at SHV increased prior to the 1995 eruption. There is perhaps surprisingly little published literature describing this period, but there is consensus that elevated levels of seismicity on Montserrat were observed from January 1992 (Ambeh and Lynch 1996). However, the earlier seismic network was badly damaged by Hurricane Hugo which impacted the island in 1989, and the network was not restored until 1992 (Shepherd et al. 2002). Therefore, it is difficult to assert with certainty that the period of elevated seismicity began in 1992.

Figure 4 shows the volcanic seismicity on Montserrat from 1992 to the beginning of the eruption in mid-1995, with the average daily rate throughout this period higher than at any time since 1938. Little detail of the waveforms is recorded in the literature, but these events are assumed to be mostly high-frequency VT-type earthquakes, located below southern Montserrat at depths of less than 20 km. A total of 18 steadily increasing episodic swarms, lasting from hours to days, were recorded between January 1992 and 17 July 1995 (Ambeh and Lynch 1996). The sharp increase in mid- to late 1994, including many felt events, prompted the installation of four new seismic stations on the island. The rate began to increase further during 1995, and more than 300 events preceded the first phreatic activity in mid-July. The tenfold increase in the daily rate of seismicity before the first magma extrusion in November 1995 has been attributed to slow-rock fracturing as magma approached the surface (Kilburn and Voight 1998).

Distal VT Swarms

In 1995 seismic monitoring consisted of the short-period (analogue) network, comprising of the existing SRU stations supplemented by a network installed by the USGS Volcano Disaster Assistance Program (VDAP) (Aspinall et al. 1998; Gardner and White 2002). These were mostly 1Hz vertical component instruments, with a total of nine stations, although not all were concurrently active. From October 1996 onwards, a network of telemetered digital seismic stations was installed, eventually superseding the short-period network. This initially comprised of five three-component broadband stations and three short-period vertical stations, but has been incrementally upgraded, evolving into the current MVO seismic network of ten broadband and two short-period stations.

VT earthquakes were the dominant type of volcanic seismicity in both the lead up to the eruption and during the initial phreatic phase (Miller et al. 1998), but were replaced by low-frequency

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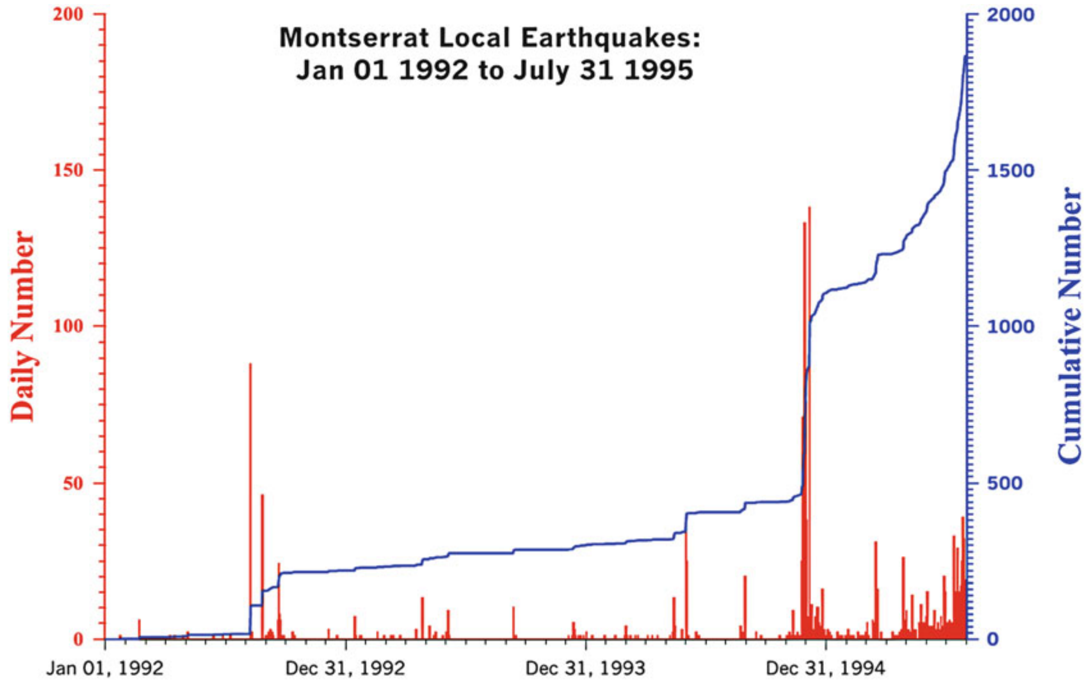

Fig. 4 Daily and cumulative numbers of local volcanic earthquakes recorded on Montserrat between 1992 and July 1995 (Taken from Shepherd et al. 2002)

seismicity and rockfalls once dome growth began. They were also more abundant during the early part of the eruption (Fig. 3) and continued in high numbers during the first pause in lava extrusion between 1998 and 2000.

As discussed in the section "▶ Examples," distal clusters of VT earthquakes, away from the main volcanic vent, appear to be a relatively common precursory phenomenon, particularly in silicic systems. This was also the case during the eruption of SHV, Montserrat, in 1995. In terms of hypocentral locations, the vast majority of VT earthquakes at SHV have occurred in a main proximal cluster, occupying a relatively small seismogenic volume beneath the volcanic vent, at depths typically 1–3 km bsl. However, during the early phreatic stages of the eruption in 1995, there is consensus that at least two other short-lived spatial clusters of VT earthquakes occurred (Aspinall et al. 1998; Gardner and White 2002; Roman et al. 2008).

The first cluster occurred approximately 3 km to the northeast of the volcano, over a 2-day period between 5 and 6 August 1995, prior to the onset of lava extrusion. A second distal cluster, 4 km to the northwest of the volcano and centered almost directly beneath St. George's Hill (SGH), occurred between 12 and 14 August 1995, although occasional further events continued until early 1996. Earlier studies (Aspinall et al. 1998; Gardner and White 2002) found depth ranges of 1–6 km, but more recent work suggests a narrower depth range of 3–4 km bsl (Roman et al. 2008). Gardner and White (2002) also identify a third cluster of distal earthquakes, to the north of SHV below Windy Hill, and in more recent analysis Miller et al. (2010) identify a fourth, extending WNW from SHV (Fig. 2).

This spatial pattern of hypocenters, particularly the cluster beneath SGH to the NW, is qualitatively similar to that observed in the earlier seismic crises at SHV (Powell 1938; Shepherd et al. 1971). Recent work (Roman et al. 2008; Miller et al. 2010) has interpreted these distal clusters, particularly the cluster below SGH, as resulting from stress changes produced by an ascending magmatic dyke, with an NE or NNE trend. The explanation of the distal VT seismicity is that the

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intruding dyke altered the stress distribution in a weakened tectonic zone and oriented ESE across Montserrat, promoting localized fault movements and changes in pore fluid pressure. Geological evidence suggests that SGH is a result of tectonic uplift, rather than a parasitic cone, and the stress transfer hypothesis is preferred to a secondary magmatic intrusion below SGH, where the distal VT earthquakes would have been proximal to the secondary intrusion.

VT Earthquakes and Stress

VT Source Characteristics

Since VT earthquakes are produced by brittle failure or shear fracturing along a fault plane in the same way as tectonic earthquakes, analysis of their source characteristics – their focal mechanisms and moment tensors – can be used to infer information about the local stress conditions.

Full moment tensors describing the inelastic deformation in the source region can be obtained by waveform inversion, but data from VT earthquakes are often too sparse for such methods, so they are often assumed to be a result of a pure double-couple source mechanism. The geometry of the faulting that occurs during an earthquake can be studied by determining the earthquake focal mechanism (or fault-plane solution), since it is the fault geometry that controls the seismic radiation pattern.

Focal mechanisms are usually determined from the polarity of *P*-wave first motions at various distances and azimuths but can also be further constrained by the amplitude ratio between *P*- and *S*-wave arrivals. Sets of focal mechanisms can be combined together in order to invert for a common stress tensor that completely describes the local stress regime. Alternatively, the orientation of the principal axes of the focal mechanism can be used as a proxy for the orientation of the stress field. These are the so-called pressure (P) and tension (T) axes, which represent the maximum and minimum compressive stress, respectively, and are determined by bisecting the dilatational and compressional quadrants.

Studies at several volcanoes have shown that the orientation of the axes of VT fault-plane solutions can undergo systematic changes in response to volcanic activity (e.g., Umakoshi et al. 2001; Roman et al. 2006) and, in particular, in association with changes in the pressurization of magmatic intrusions.

Regional Stress Conditions on Montserrat

Roman et al. (2008) cite evidence from the fault-plane solutions of nearby regional earthquakes and the orientation of dykes mapped on neighboring islands to suggest that the regional stress field around Montserrat is characterized by maximum compressive stress in an arc-normal, approximately NE-SW direction. Recent studies of the local tectonics, arising from offshore seismic reflection profiles, have suggested that, at a local level, the stress regime may in fact be more complex (Kenedi et al. 2010).

Montserrat is located in the northern part of the Lesser Antilles and is a result of oblique subduction of the North American plate beneath the Caribbean plate, which is accommodated by a combination of large-scale sinistral strike-slip faulting and smaller local normal faults perpendicular to the arc. The dominant structural feature on the island is the extensional Montserrat-Havers fault system (MHFS) (Feuillet et al. 2010), along which the andesitic domes of the SHV complex and other uplifted features such as SGH and Garibaldi Hill are aligned. The MHFS includes an ESE-trending lineament that passes south of the Centre Hills and is interpreted as the Belham Valley fault (BVF). The MHFS also extends to the southeast towards Guadeloupe, where Montserrat lies at the northern end of the offshore Bouillante-Montserrat graben structure (BMF). This could imply

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a roughly E-W orientation of minimum compressive stress, approximately normal to the N-S regional extensional trend of the MHFS and BMF structures.

VTs and Stress at SHV

The source mechanisms of VT earthquakes at SHV have been analyzed in several studies in order to improve understanding of the local stress field and the nature and orientation of the magmatic intrusions supplying the eruption.

Roman et al. (2006) analyzed the focal mechanisms from a subset of 551 VT earthquakes at SHV with well-constrained double-couple fault-plane solutions, spanning October 1996 to July 2005, and observed temporal changes in the orientation of the *p*-axes. Several periods of a few months were identified where the dominant orientation of the *p*-axes switched from the predominant NE-SW to a NW-SE trend. This represents a 90° rotation from the assumed arc-normal regional maximum compressive stress. Analysis of seismic anisotropy through study of shear-wave splitting of regional earthquakes recorded on the MVO network has provided further evidence to support the presence of short-term variations in the local stress field at SHV.

Models of the interaction between regional and magma-induced stresses (Vargas-Bracamontes and Neuberg 2012) have shown that VT earthquakes on regionally aligned faults are more easily triggered by lower internal pressures of the intruding magma body. By contrast, pressures much higher than the regional stress field are needed to promote rotated VT earthquakes, supporting observations of their short-lived episodic nature. The presence of such rotated events could therefore indicate significant pressurization of the volcanic system, and hence, the occurrence of these rotated VT events has been interpreted as evidence of stresses induced by the inflation of a NE-SW-oriented dyke beneath SHV. This is broadly supported by the analysis of distal VT focal mechanisms during the early phase of the eruption (see the section "► Distal VT Swarms").

This NE to NNE orientation is somewhat in disagreement with the NW- to NNW-oriented dyke proposed for SHV derived from geodetic or borehole strain data. Kenedi et al. (2010) propose an approximately N-S-oriented feeder dyke as a possible way to reconcile these competing models.

Recent VT Seismicity at SHV

Patterns of VT Occurrence at SHV

VT earthquakes were most numerous at SHV in the buildup to the eruption and during the initial phreatic phase before dome growth began. They also continued in relatively high numbers during the first pause in extrusion, occurring at a rate of around 5 per day between March 1998 and November 1999. Since this period the daily rate has been much lower and has remained roughly constant at an average rate of less than one per day from 2000 to present.

However, short-term increases in VT activity have been associated with the restarts in extrusion during the course of the eruption at SHV, often increasing notably during the short transitional or phreatic phases which preceded renewed lava extrusion. Diffuse episodes of VT earthquakes associated with ash venting and minor explosive activity preceded the onset of extrusion of both Phase 3 in mid-2005 and Phase 4 in mid-2008. A more intense swarm of 24 VT earthquakes on 5 October 2009 heralded the onset of several days of ash venting before the start of Phase 5 extrusion.

Since around the end of Phase 3 in 2007, the character of VT seismicity seen at SHV appears to have changed. Fewer intense swarms have been observed, and instead the dominant feature has been the sporadic occurrence of short bursts of high-frequency VT events termed VT "strings."

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A sequence of repeating VT earthquakes with similar waveforms was also observed in late 2008 and early 2009. The timing of this change in behavior roughly coincides with a departure from the longer extrusive periods of Phases 1–3 to the shorter more rapid extrusion of Phases 4 and 5.

Repeating VTs

An unusual quasiperiodic sequence of seven large ($2.6 < M_L < 3.2$) repeating VT earthquakes was observed at SHV between October 2008 and May 2009, straddling the two brief periods of extrusion that comprised Phase 4. Analysis of arrival times, waveforms, and focal mechanisms suggests a common location and source process for six of the seven events, with inter-event cross-correlation coefficients of 0.75 and above. A composite focal mechanism revealed mostly strike-slip-style faulting, with a *p*-axis orientation of approximately 75°, which does not correspond to either the regional stress aligned or the 90° rotated solutions of Roman et al. (2006).

VT Strings

Description and Characteristics

VT strings, defined as a short, intense swarms of VT earthquakes, a phenomenon occasionally referred to elsewhere as "spasmodic bursts" (e.g., Hill et al. 2002), have become a feature of the eruption of SHV since late 2007. To date, 52 such earthquake sequences have been identified in the 69 months since the first in November 2007, continuing across Phases 4 and 5 of lava extrusion (Fig. 5).

The details of individual strings have varied, but certain common characteristics have been identified. The duration of these sequences has typically been less than an hour, with a mean of roughly 10 events occurring in 30 min, when averaged across all strings. The first event in the swarm is generally not the largest, and thus, VT strings do not represent a mainshock-aftershock sequence, instead exhibiting swarm-like behavior, with events tightly clustered in time and space (see, e.g., Fig. 7). In terms of their waveforms, hypocenters, and focal mechanisms, analysis of individual

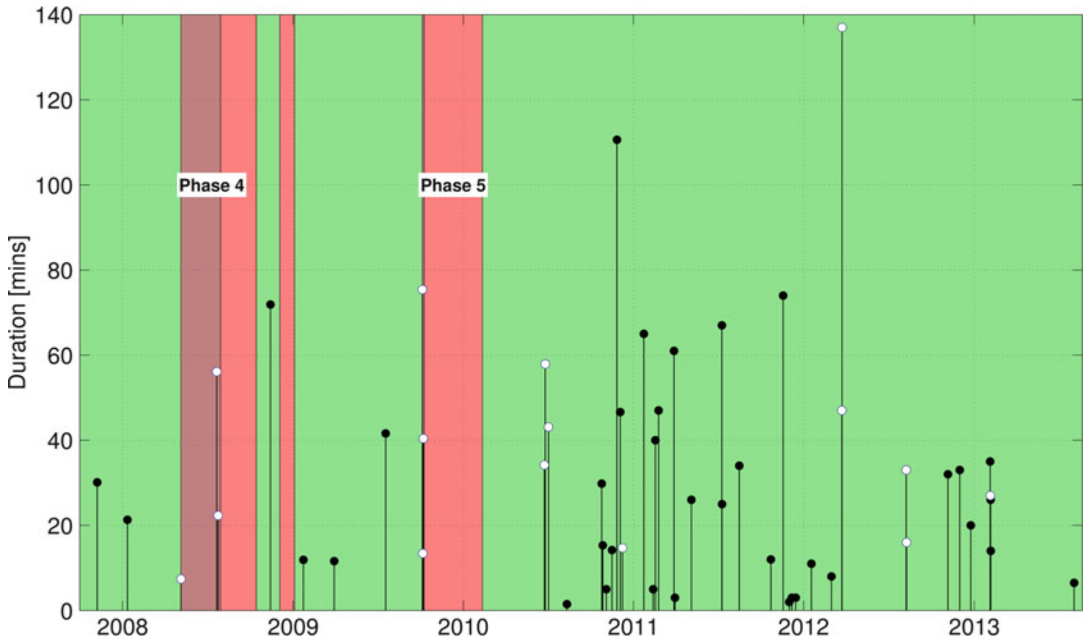

Fig. 5 Duration of all VT strings recorded at SHV, first seen in November 2007. The white circles represent VT strings that were associated with observable activity at the surface. Extrusive phases are shown in *pink* and pauses in extrusion in *green*, and *dark-pink* periods represent the transitional, precursory, or phreatic phases

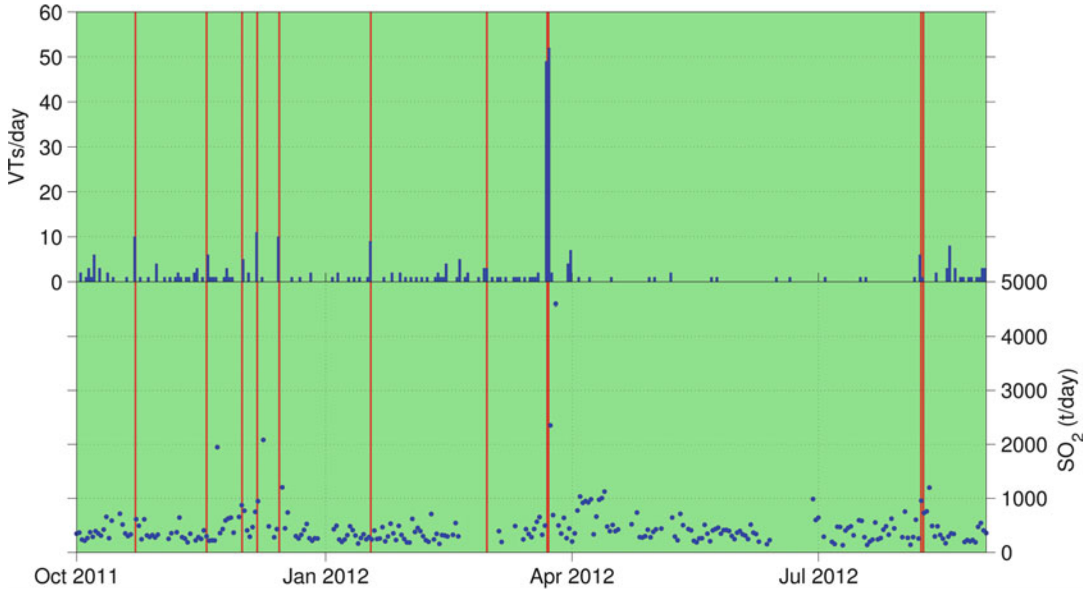

Fig. 6 Correlation between VT strings and SO_2 output at SHV for the period October 2011 to September 2012. The top panel shows daily VT earthquake counts and the bottom the recorded SO_2 flux in tonnes per day. VT strings are indicated by the *red vertical lines*

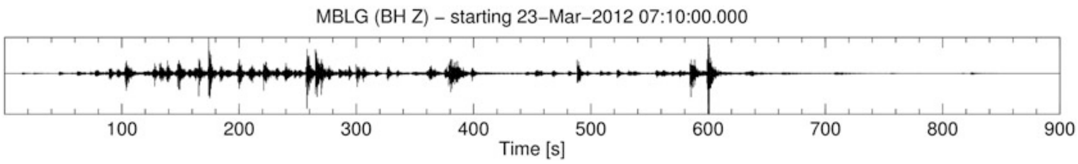

Fig. 7 Normalized waveform showing the most intense phase of the VT swarm that occurred at SHV on 23 March 2012. Shown is a 15-min-long vertical component velocity seismogram recorded at station MBLG. The start time is given in UTC

earthquakes has revealed no clear differences between those occurring as part of strings and ordinary or background VT events.

Approximately a quarter of VT strings have been linked to observed surficial activity such as ash venting or visibly increasing degassing and fumarolic activity. This has led to some speculation as to their predictive capability in forecasting such activity or perhaps even renewed lava extrusion. This relationship is supported by SO_2 flux data from SHV, which show some degree of correlation with the seismicity, with often, though not in all cases, a spike in gas output several hours to days after the earthquakes occur (Fig. 6). This has led to tentative proposals that the seismicity is perhaps driven by gas release and/or hydrothermal processes, although it is clear that this phenomenon is not well understood and that more work is needed to refine the generation mechanism. Similar models have been suggested elsewhere, such as Nishi et al. (1996), who propose a hydrothermal source for spasmodic bursts observed at White Island, New Zealand, based on a mechanism of brittle failure induced by rapid fluid pressure fluctuations in the shallow hydrothermal system.

March 2012

Some of the most significant VT seismicity at SHV occurred on 22 and 23 March 2012, with two swarms of around 50 VT earthquakes each. The second swarm on 23 March was more energetic than

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the first, with local magnitudes of up to M_L3.9: some of the largest VT earthquakes to have been recorded at SHV. The most intense phase of the VT swarm lasted only 15 min (Fig. 7) and was followed by three large hybrid earthquakes. A very-long-period (VLP) seismic signal (below 0.1Hz or 10s period) was also observed across the MVO seismic network during this swarm, coincident with a large amplitude (≈250 nanostrain) strain signal recorded by several borehole strainmeters. The seismicity was followed by mild ash venting several hours later.

As with the explosion and accompanying strain signal on 3 March 2004 (Linde et al. 2010), preliminary analysis of the strain data has suggested the involvement of a shallow dyke or fracture, although in this case there was no emission of magmatic material. The events of 22–23 March 2012 have some broad similarities with the VT strings that have occurred since at SHV since 2007, perhaps hinting at a common driving process. These include the relatively short duration of the VT seismicity and its correlation with ash venting and increased degassing. There was a time lag between the occurrence of the seismicity and the SO_2 output which responded on 24 March (2,400 T) followed by the third highest value ever measured by the spectrometer network of 4,600 T on 26 March. The strong pulse in gas associated with this event is similar to the increase in emissions associated with several other VT strings. However, similar strain signals have not been identified with any other VT strings, although the magnitude of this event was clearly much larger.

Summary

Volcano-tectonic earthquakes are brittle failure events that occur in volcanic environments, sharing many of the properties of tectonic earthquakes. Understanding their characteristics and behavior is of critical importance in monitoring and forecasting efforts, particularly as volcano-tectonic earthquakes are often one of the first signs of volcanic unrest and potential future eruptions. The ongoing eruption of Soufrière Hills volcano, Montserrat, has offered an unparalleled opportunity to observe the evolution of volcano-tectonic seismicity throughout a long-term dome-building eruption.

Several volcano-seismic crises, of presumably mostly VT events, occurred on Montserrat at approximately 30-year intervals throughout the twentieth century, in 1933–1937 and 1966–1967. Volcano-tectonic seismicity was also the most prevalent precursor to the start of the current eruption, with increasing numbers seen in escalating episodic swarms in the 3 years preceding the onset of phreatic activity in 1995. During these initial phreatic stages of the eruption, distal swarms of VT earthquakes several kilometers away from the main summit vent were observed, particularly below St. George's Hill to the northwest of the volcano. This distal cluster is proposed to have resulted from stress transfer through a weakened tectonic zone, rather than a secondary magmatic intrusion. A rapid acceleration in the rate of VT earthquakes, linked to subcritical rock fracturing, also preceded the first magmatic activity and the onset of lava extrusion.

The source mechanisms of VT events can be used to infer the local stress conditions under which they are generated. Analysis of the orientation of the *p*-axes of focal mechanisms of VT earthquakes at SHV has shown systematic temporal changes in response to volcanically induced stresses, in particular the occurrence of events with a 90° rotation from the dominant trend. The presence of these "rotated" events has been interpreted as the result of pressure changes in an NNE- to NE-oriented shallow dyke beneath SHV overprinting the regional stress regime and promoting failure on optimally aligned faults.

A different character of VT seismicity was seen at SHV after the end of the third phase of lava extrusion. VT earthquakes were the dominant seismicity during the short transitional phases that preceded restarts in lava extrusion which were associated with minor explosive activity and

ash-venting episodes. The emergence of short spasmodic bursts of VT earthquakes termed VT "strings" since 2007 has also been linked to ash venting, increased fumarolic activity, and SO_2 output. An intense VT swarm on 23 March 2012 occurred coincident with a very-long-period (VLP) seismic signal and a large step in strain. This seismicity preceded mild ash venting and a large spike in SO_2 release, suggesting the processes driving this event and VT strings may be similar.

Cross-References

- ► Earthquake Magnitude Estimation
- ► Earthquake Mechanism and Stress Field
- ► Frequency-Magnitude Distribution of Seismicity in Volcanic Regions
- ► Earthquake location
- ► Seismic Anisotropy in Volcanic Regions
- ► Seismic Monitoring of Volcanoes
- ► Volcanic Eruptions, Real-time Forecasting of

References

Ambeh W, Lynch L (1996) Seismicity preceding the current eruption of the Soufrière Hills volcano, Montserrat, West Indies. In: Ahmad R (ed) Science, hazards and hazard management – the second Caribbean conference on natural hazards and disasters, vol 1. Unit for Disaster Studies, The University of the West Indies, Kingston, p 30

Aspinall W, Miller A, Lynch L, Latchman J, Stewart R, White R, Power J (1998) Soufrière Hills eruption, Montserrat, 1995–1997: volcanic earthquake locations and fault plane solutions. Geophys Res Lett 25:3397–3400

Battaglia J, Ferrazzini V, Staudacher T, Aki K, Chemin J-L (2005) Pre- eruptive migration of earthquakes at the Piton de la Fournaise volcano (Réunion Island). Geophys J Int 161(2):549–558

Feuillet N, Leclerc F, Tapponnier P, Beauducel F, Boudon G, Le Friant A, Deplus C, Lebrun J-F, Nercessian A, Saurel J-M, Clment V (2010) Active faulting induced by slip partitioning in Montserrat and link with volcanic activity: new insights from the 2009 GWADASEIS marine cruise data. Geophys Res Lett 37(19), L00E15, doi:10.1029/2010GL042556

Fisher MA, Ruppert NA, White RA, Sliter RW, Wong FL (2010) Distal volcano-tectonic seismicity near Augustine Volcano. In: Power J, Coombs M, Freymueller J (eds) The 2006 eruption of Augustine Volcano, Alaska. U.S. Geological Survey, Reston, Virginia, professional paper 1769. pp 119–126

Gardner CA, White RA (2002) Seismicity, gas emission and deformation from 18 July to 25 September 1995 during the initial phreatic phase of the eruption of Soufrière Hills Volcano, Montserrat. In: Druitt TH, Kokelaar BP (eds) The eruption of Soufrière Hills Volcano, Montserrat from 1995 to 1999, vol 21. Geological Society Memoirs, London, pp 567–581

Hill DP, Dawson P, Johnston MJS, Pitt AM, Biasi G, Smith K (2002) Very-long-period volcanic earthquakes beneath Mammoth Mountain, California. Geophys Res Lett 29(10):8-1–8-4

Kenedi CL, Sparks RSJ, Malin P, Voight B, Dean S, Minshull T, Paulatto M, Peirce C, Shalev E (2010) Contrasts in morphology and deformation offshore Montserrat: New insights from the SEA-CALIPSO marine cruise data. Geophys Res Lett 37(19), L00E25, doi:10.1029/2010GL043925

DOI 10.1007/978-3-642-36197-5_93-1

Kilburn CRJ, Voight B (1998) Slow rock fracture as eruption precursor at Soufrière Hills volcano, Montserrat. Geophys Res Lett 25(19):3665–3668

Linde AT, Sacks S, Hidayat D, Voight B, Clarke A, Elsworth D, Mattioli G, Malin P, Shalev E, Sparks S, Widiwijayanti C (2010) Vulcanian explosion at Soufrière Hills Volcano, Montserrat on March 2004 as revealed by strain data. Geophys Res Lett 37(19), L00E07, doi:10.1029/2009GL041988

McNutt SR (2005) Volcanic seismology. Ann Rev Earth Planet Sci 33(1):461–491

Miller A, Stewart R, White R, Luckett R, Baptie B, Aspinall W, Latchman J, Lynch L, Voight B (1998) Seismicity associated with dome growth and collapse at the Soufrière Hills Volcano, Montserrat. Geophys Res Lett 25:3401–3404

Miller V, Voight B, Ammon CJ, Shalev E, Thompson G (2010) Seismic expression of magma-induced crustal strains and localized fluid pressures during initial eruptive stages, Soufrière Hills Volcano, Montserrat. Geophys Res Lett 37(19)

Nishi Y, Sherburn S, Scott BJ, Sugihara M (1996) High-frequency earthquakes at White Island volcano, New Zealand: insights into the shallow structure of a volcano-hydrothermal system. J Volcanol Geotherm Res 72(34):183–197

Perret FA (1939) The volcano-seismic crisis at Montserrat, 1933–1937. Carnegie Institution of Washington, Washington, DC

Powell CF (1938) The Royal Society expedition to Montserrat, BWI. Final report. Philos Trans R Soc A 237:1–34

Roman DC, Cashman KV (2006) The origin of volcano-tectonic earthquake swarms. Geology 34(6):457–460

Roman D, Neuberg J, Luckett R (2006) Assessing the likelihood of volcanic eruption through analysis of volcanotectonic earthquake fault-plane solutions. Earth Planet Sci Lett 248:244–252

Roman D, De Angelis S, Latchman J, White R (2008) Patterns of volcanotectonic seismicity and stress during the ongoing eruption of the Soufrière Hills Volcano Montserrat (1995–2007). J Volcanol Geotherm Res 173:230–244

Shepherd JB, Tomblin JF, Woo DA (1971) Volcano-seismic crisis in Montserrat, West Indies, 1966–67. Bull Volcanol 35:143–163

Shepherd JB, Robertson R, Latchman J, Lynch L (2002) Precursory activity to the 1995 eruption of the Soufrière Hills Volcano, Montserrat, Technical report. Seismic Research Unit, University of the West Indies

Umakoshi K, Shimizu H, Matsuwo N (2001) Volcano-tectonic seismicity at Unzen Volcano, Japan, 1985–1999. J Volcanol Geotherm Res 112(1–4):117–131

Vargas-Bracamontes D, Neuberg J (2012) Interaction between regional and magma-induced stresses and their impact on volcano-tectonic seismicity. J Volcanol Geotherm Res 243–244:91–96

Young SR, Sparks RSJ, Aspinall W, Lynch L, Miller A, Robertson T, Shepherd J (1998) Overview of the eruption of Soufrière Hills Volcano, Montserrat, 18 July 1995 to December 1997. Geophys Res Lett 25:3389–3392

Zobin VM (2012) Introduction to volcanic seismology. Elsevier, London