Seismic Monitoring of the Soufrière Hills Volcano, Montserrat

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INTRODUCTION

The seismicity caused by an active volcano is a useful indicator of its current and future activity. However, it is a challenge to maintain a seismic network in such an environment and to obtain the most significant information possible. This article describes the seismic network and acquisition systems on Montserrat in the West Indies, which have recently undergone an upgrade after more than 10 years of monitoring.

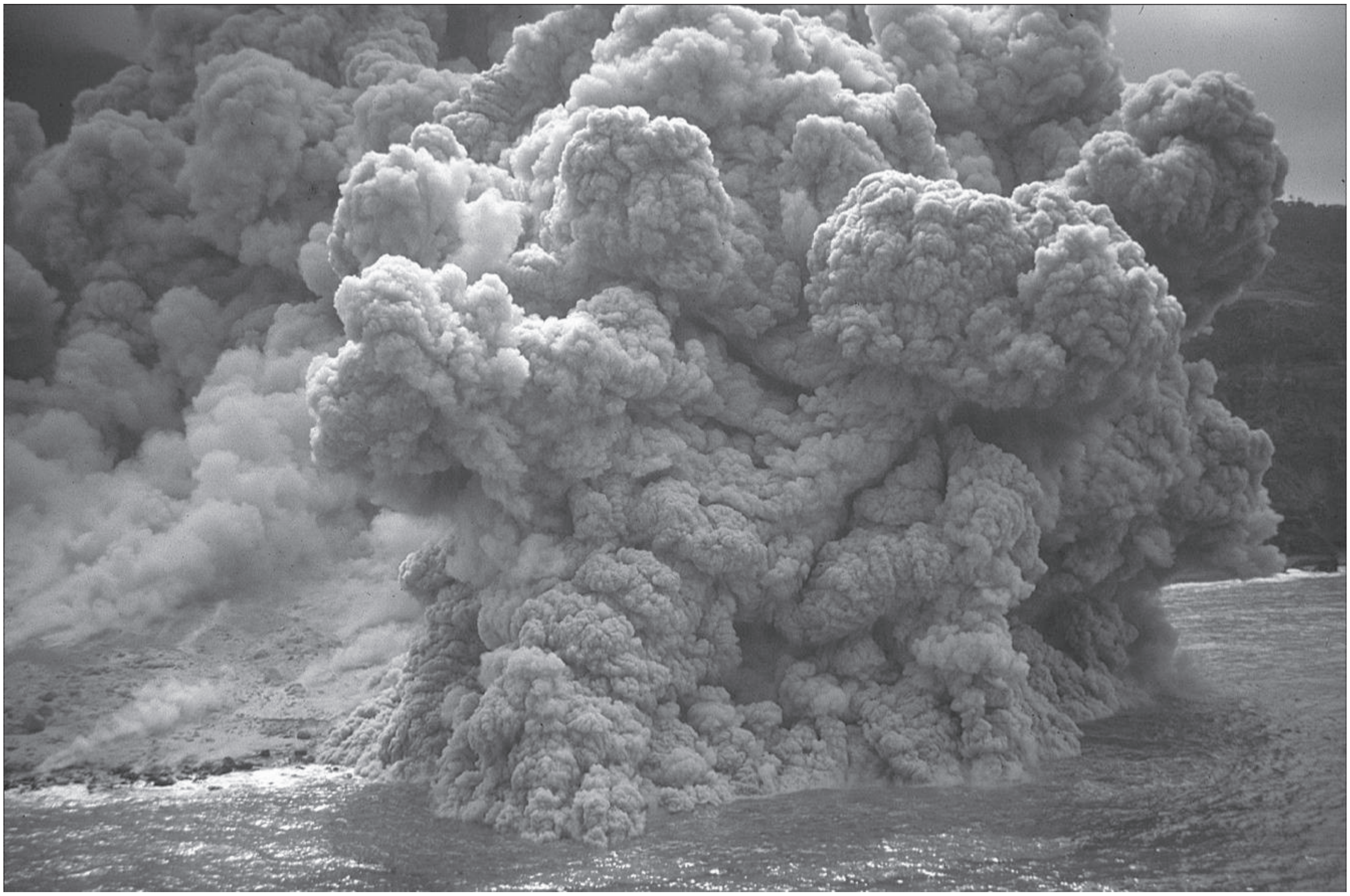
Soufrière Hills Volcano on Montserrat is an andesitic dome-building volcano. Heightened seismicity was noted in 1992, and the current eruption started in 1995 (Young *et al.* 1998) with a dome growing within the crater at the top of the existing volcanic edifice. Since then there have been three main phases of dome growth: July 1995 to March 1998, November 1999 to July 2003, and August 2005 to present. Between these phases were periods of residual activity with much reduced seismicity and occasional explosions. The dome is growing with average lava extrusion rates of approximately 2 m^3/s, but almost constant small dome collapses reduce the size of the resulting dome. There have also been a number of very large dome collapses where the whole dome has been removed. The largest of these was in July 2003 when a dome greater than 210 million m^3 was destroyed over the course of 18 hours. The main hazard from this type of eruption is the pyroclastic flows resulting from partial or complete dome collapse (figure 1). These are mixtures of boulders, ash, and gas that form extremely mobile landslides with temperatures up to 500 °C and can travel in excess of 100 km/hr (Cole *et al.* 1998). The only casualties of the eruption so far were the result of pyroclastic flow activity (Loughlin *et al.* 2002). Areas on the southern half of the island that were deemed likely to be impacted were evacuated early in the eruption, including the capital city of Plymouth. Many of these areas have since been destroyed either by pyroclastic flows or mudflows. The population has resettled in the northern part of the island, which is not threatened by the volcano.

The Montserrat Volcano Observatory (MVO) is responsible for advising the authorities and population of Montserrat on the status of the Soufrière Hills volcano. It was formed in 1995 when the Seismic Research Unit (SRU) of the University of West Indies in Trinidad set up an operational base on the island (Aspinall *et al.* 2002) and has since become a statutory body of the Government of Montserrat, run under contract by the British Geological Survey. The observatory uses many monitoring tools, including permanent networks of GPS receivers and spectrometers designed to measure sulphur dioxide flux. However, besides direct observation of the dome, analyzing seismicity remains the principal monitoring method. In 2005, the current seismic network was upgraded after 10 years of constant use.

HISTORY OF THE SEISMIC NETWORK

Before the eruption, Montserrat was monitored seismically by the SRU at two sites on the island as part of its regional network. In 1994, increased seismicity prompted the SRU to deploy a temporary network with an additional four stations. Once surface activity had begun, the U.S. Geological Survey Volcano Disaster Assistance Program became involved and in July 1995 it contributed three more stations (Power *et al.* 1998) and installed a PC-based acquisition system similar to that previously used on Mt. Pinatubo in the Philippines, (Murray *et al.* 1996) which incorporated the IASPEI PC-SEIS software (Lee 1989). The resulting network of nine short-period, mostly vertical, single-component, analog instruments formed the backbone of the initial volcanic monitoring. Data from this network has been analyzed in several publications (*e.g.*, Aspinall *et al.* 1998, Power *et al.* 1998). The principal problem was the narrow dynamic range imposed by the analog telemetry. This meant that even moderately sized volcanic events were "clipped," which made magnitude calculation or *S*-wave picking impossible. Also, the acquisition system did not record continuous data, limiting analysis to triggered events.

In October 1996 the British Geological Survey installed a new network of digitally telemetered stations in parallel with the existing analog network (Neuberg *et al.* 1998). This comprised five broadband, three-component instruments (Guralp CMG-40T) and three 1 Hz vertical instruments (Integra LA100/F), many co-located with instruments from the existing network. The data was sampled at 75 Hz at each site using Earth Data Ltd 2430 24-bit digitizers and telemetered back to the observatory with Earth Data UHF 100 mW radios. At the observatory, data



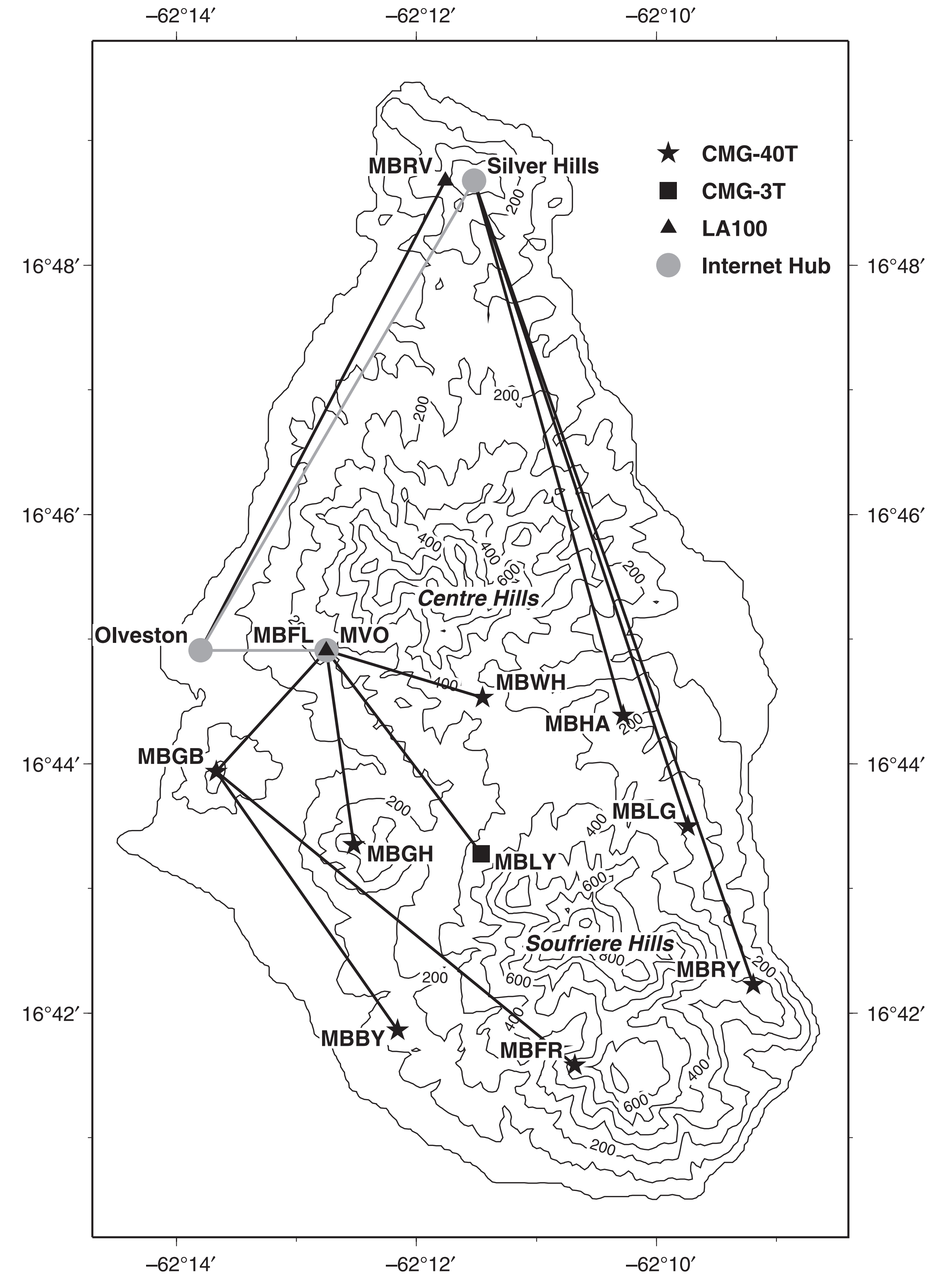
▲ **Figure 1.** Pyroclastic flow entering the sea on the east coast of Montserrat in June 1997. *Photo © Montserrat Volcano Observatory.*

from across the network was synchronized and time-stamped by an Earth Data interpolating line interface. This new network had a greatly improved dynamic range and allowed even the largest events to be recorded without clipping. It also allowed seismologists to see whether the volcano was producing signals at lower frequencies and to carry out analyses, such as particle motion, that require three-component data. Acquisition was done using SEISLOG (Utheim and Havskov 1997) under an OS9 multitasking operating system and analysis carried out using SEISAN (Havskov and Ottemoller 2005). The archiving of continuous data also began at this time.

Over the next eight years there were several changes to the digital network, which continued to form the basis of monitoring at the MVO. In 1997, three of the broadband sites were destroyed by pyroclastic flows. One was later replaced at a nearby but less vulnerable site (MBBY, figure 2). The other two destroyed sites were too dangerous to reinstall and instead of replacing them, the short-period instrument at MBRY was replaced with a CMG-40T in 1998. Telemetry was made more complex in 1997 by the forced relocation of the observatory to a safer location at the northern end of the island. In 2001 SEISLOG was replaced as the acquisition system by a combination of SA24 and Earthworm, a change precipitated by changes in computer hardware (Thompson 2000). Two stations were installed on Montserrat by outside agencies that became part of the MVO monitoring network. The MULTIMO (Multi-Disciplinary Monitoring, Modelling and Forecasting of Volcanic Hazard) project installed a Guralp CMG-3T at MBLY in 2000 (Green and Neuberg 2005), and in 2002 a team from Pennsylvania State University installed a CMG-40T at MBHA. Also in 2002, station MBRV was installed on the northern tip of the island to allow better discrimination between regional and volcanic earthquakes. In January 2003 the MVO moved to the current, purpose-built premises about 6 km northwest of the volcano and telemetry again had to be changed.

CURRENT NETWORK AND ACQUISITION

In 2005 the network (figure 2) was upgraded. One new station was installed at the new observatory (MBFL) and another was moved from a site to the south of the volcano, where telemetry to the new observatory had proved to be difficult, to a nearby ridge with better radio access (MBFR). Two of the 1 Hz instruments were replaced with CMG-40T broadband seismometers (MBLG and MBWH) and the short-period sites (MBFL and MBRV) now have Mark Products L4s, which have lower instrumental self-noise than the Integra. All of the digitizers and radios were replaced. Guralp DM24 24-bit digitizers were installed at all of the sites, each with its own GPS clock to allow time stamping to take place at each outstation; the sampling rate was changed



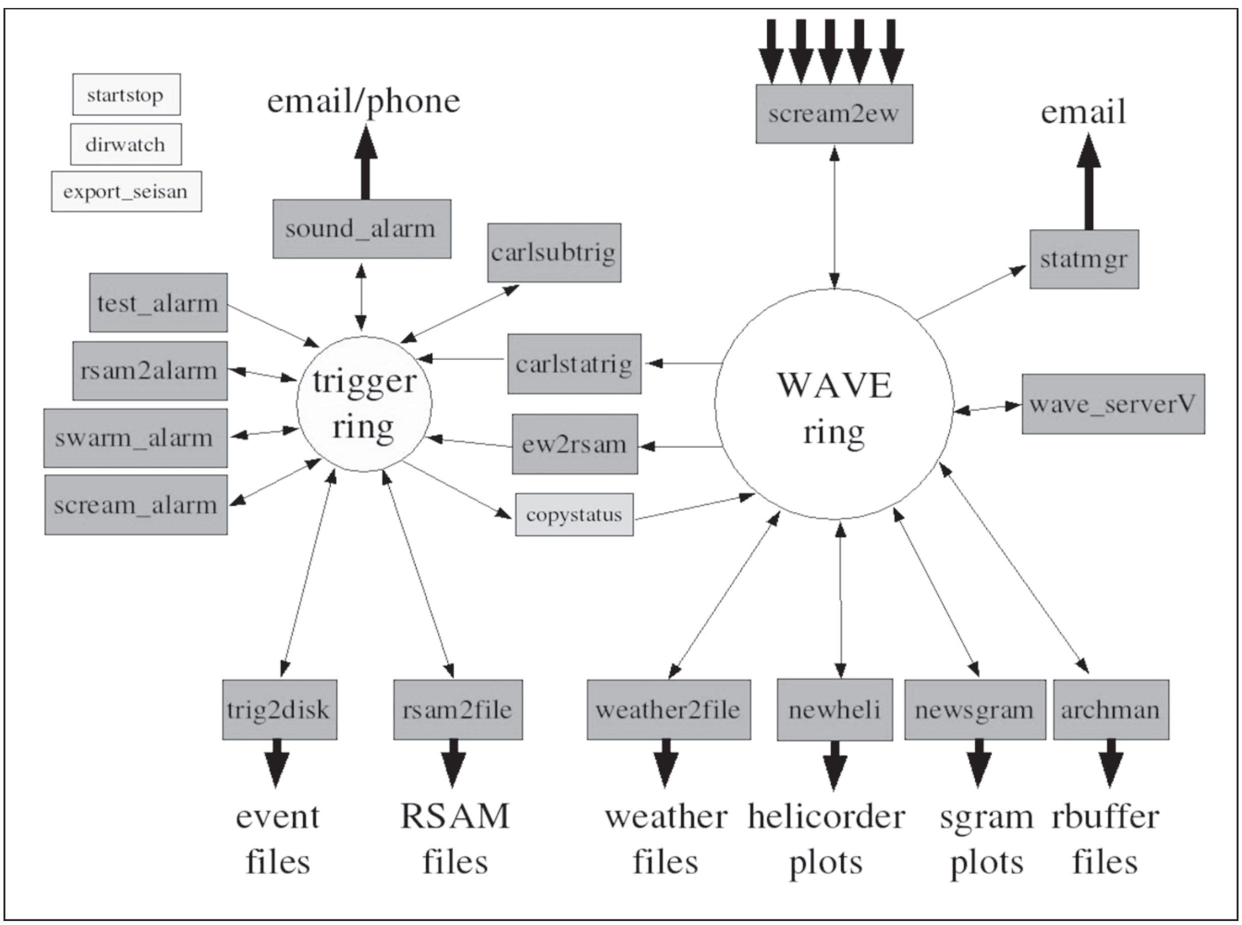
▲ **Figure 2.** MVO seismic network from April 2006.

to 100 Hz. Spread spectrum Freewave radio modems operating at about 900 MHz were used to telemeter data from the sites because, in recent years, interference in the previously used 450 MHz range had become more problematic (possibly due to unknown new transmitters on Antigua) to the point where stations in the east of the island were rarely receivable. Further improvement is achieved through the ability to retransmit data packets, which was not the case with the previous system. Two repeater sites were required because of the island's rugged topography and the new observatory's location in the shadow of the Centre Hills. These repeater sites (Silver Hills and Olveston in figure 2) have mains power and serial-to-IP converters that allow the seismic channels to be connected to the observatory LAN via microwave TCP/IP routers. In the observatory, the Guralp acquisition software SCREAM! collects the data and allows communication with the digitizers in the field.

From SCREAM! the data is fed into an Earthworm system (Johnson *et al.* 1995), the configuration of which is shown in figure 3. Earthworm consists of modules to import, process, and archive data. These modules interact via regions of shared memory known as rings, and this allows them to communicate while being independent of each other. The flexibility of such a system makes it easy to add new functionality, and many of the modules in figure 3 were written at the observatory. Thus, for example, the standard EARTHWORM module scream2ew is used to input data while in-house module sound_alarm is used to alert observatory staff to changes in activity. SEISAN continues to be used for analysis of event and continuous data.

USE OF SEISMIC DATA FOR MONITORING

Throughout eruption, as on other volcanoes, many escalations in volcanic activity or potentially hazardous events have been preceded and/or accompanied by changes in seismicity. For example, swarms of hybrid earthquakes preceded dome collapses in 1997 (Miller *et al.* 1998). This has made seismic monitoring the prime tool for short-term monitoring of activity and the method for sounding alarms. Such alarms are vital because the observatory is not staffed on a 24-hour basis unless volcanic activity is already high. There are several alarms in Earthworm that either detect amplitudes exceeding given thresholds (real-time seismic amplitude measurement or RSAM, Endo and Murray 1991) or the number of triggered events in a given time interval exceeding a threshold (swarm alarms). When an alarm condition is met, an e-mail is sent to the mobile phone of each of the observatory staff explaining the alarm criteria exceeded. Staff are then automatically telephoned in case they are asleep. In addition, there are alarms that sound if either SCREAM! or Earthworm fails, and a test



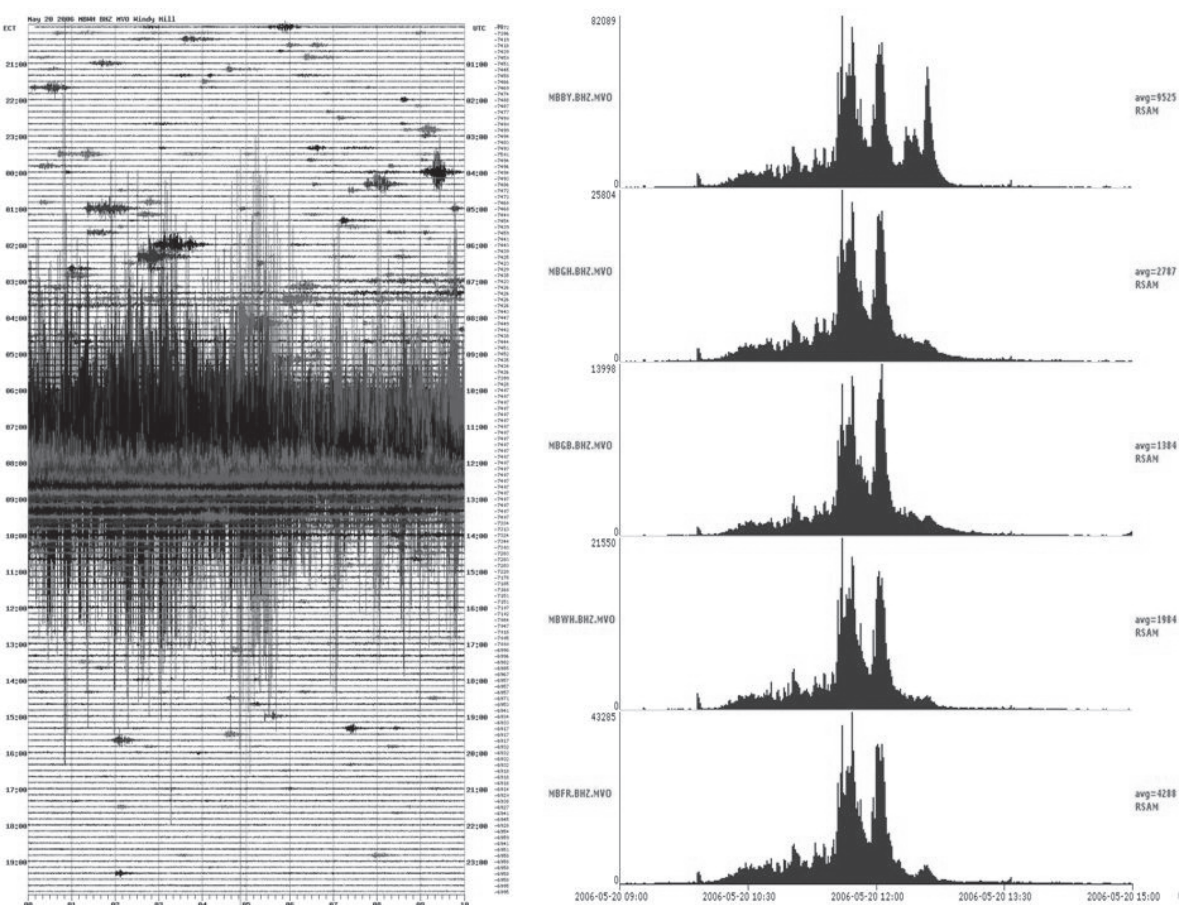
▲ **Figure 3.** Configuration of Earthworm as used at the MVO. The rings are shared memory regions used for communication between modules.

alarm that fires every day at the same time to confirm that the telecommunications are working properly.

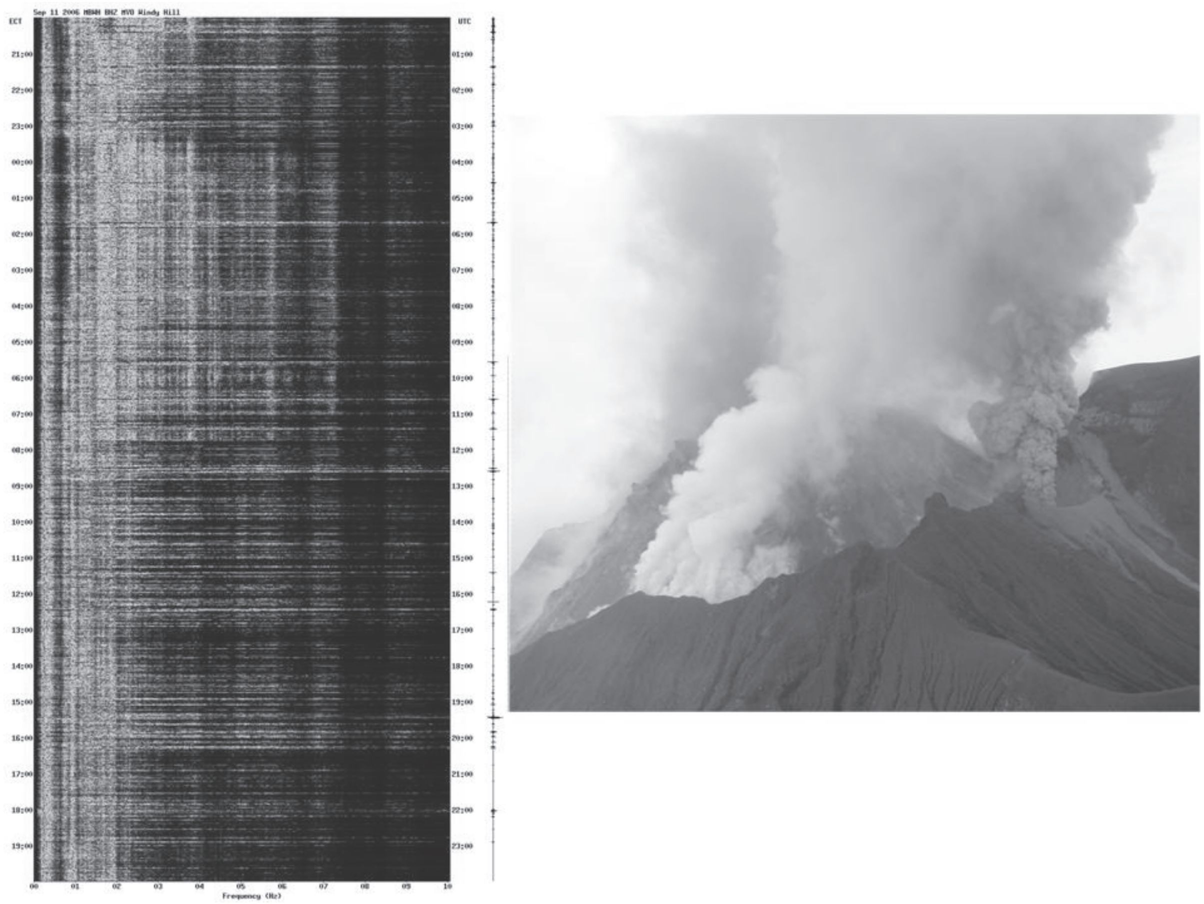
The real-time data products produced by Earthworm are accessible on a secure part of the MVO Web site, http://www.mvo.ms, allowing staff to check on activity from outside the observatory. Figure 4 shows two of these products: a seismicity plot and an RSAM plot for the large dome collapse on 20 May 2006, when a dome of almost 100 million m^3 collapsed into the sea over the course of a few hours. Real-time seismicity plots are the principal tool used to display seismic activity. It can be seen from the example here that there were no seismic precursors to this collapse, unlike many similar events in the past. The RSAM display is useful in that it shows distinct peaks in the activity. The two spikes on the first peak, for example, correspond to explosions caused by decompression of the conduit. We know this because the time difference between the peaks is the same as the time difference between falls of lithics more than 10 minutes later. Another example of the real-time data available to MVO staff is shown in figure 5. This is a 24-hour spectrogram plot that shows the tremor associated with a vent opening on 11 September 2006 as high-amplitude vertical bands in the frequency range between 1 Hz and 3 Hz. Such tremor is typical of venting on Montserrat, but the photograph in the figure is not typical—it's very unusual for the dome to be so clear. Often the existence of tremor on the spectrograms is the best indication that such vigorous venting is underway.

Apart from looking at current seismicity as in the examples above, one of the principal methods of gaining an impression of the relative severity and type of activity of a volcano has always been the classification and counting of triggered events (*e.g.*, Lahr *et al.* 1994). The event types used on Montserrat (figure 6) were first described in Miller *et al.* (1998). Briefly, these are as follows:

- **Volcano-tectonic earthquakes** are interpreted as normal rock-fracture double-couple earthquakes in the country rock caused by intrusion of magma. They have impulsive *P*-wave and *S*-wave arrivals and most energy between 5 Hz and 10 Hz.
- **Long-period events** are monochromatic, emergent signals with frequencies between 1 Hz and 2.5 Hz on Montserrat. They are considered to be related to pressurization of the volcanic plumbing system (Neuberg 2000) and are often



▲ **Figure 4.** Two of the real-time monitoring displays available to staff over the MVO Web site, http://www.mvo.ms, a real-time seismicity plot and an RSAM plot. As an example, a large dome collapse starting at about 10:00 on 20 May 2006 is shown. The helicorder plot shows 24 hours running top to bottom, with each line representing 10 minutes. The RSAM plot is for 9:00 to 15:00 and shows the same time interval as the busy part of the helicorder plot, when the collapse was taking place. The seismicity seen on the helicorder plot before the collapse is typical background with a few rockfall signals; there is no precursory activity.



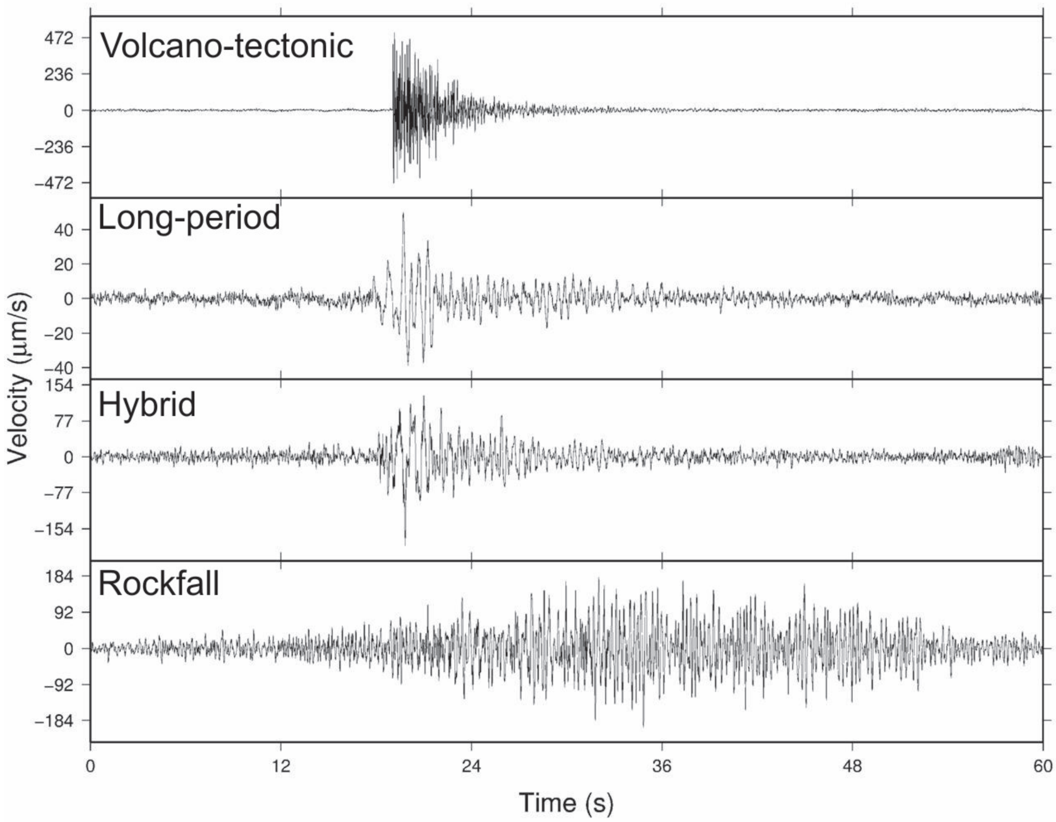
▲ **Figure 5.** Another Earthworm real-time display, a spectrogram. The time window is again 24 hours plotted from top to bottom for comparison with a helicorder plot such as that in figure 4. The x-axis is frequency with 0 Hz at the left and 10 Hz at the right. The tremor clearly shown by the light vertical bands between 1 and 3 Hz is associated with the venting in the photograph. *Photo © Montserrat Volcano Observatory*.

associated with venting from the surface of the dome, and thus with rockfalls (Luckett *et al.* 2002).

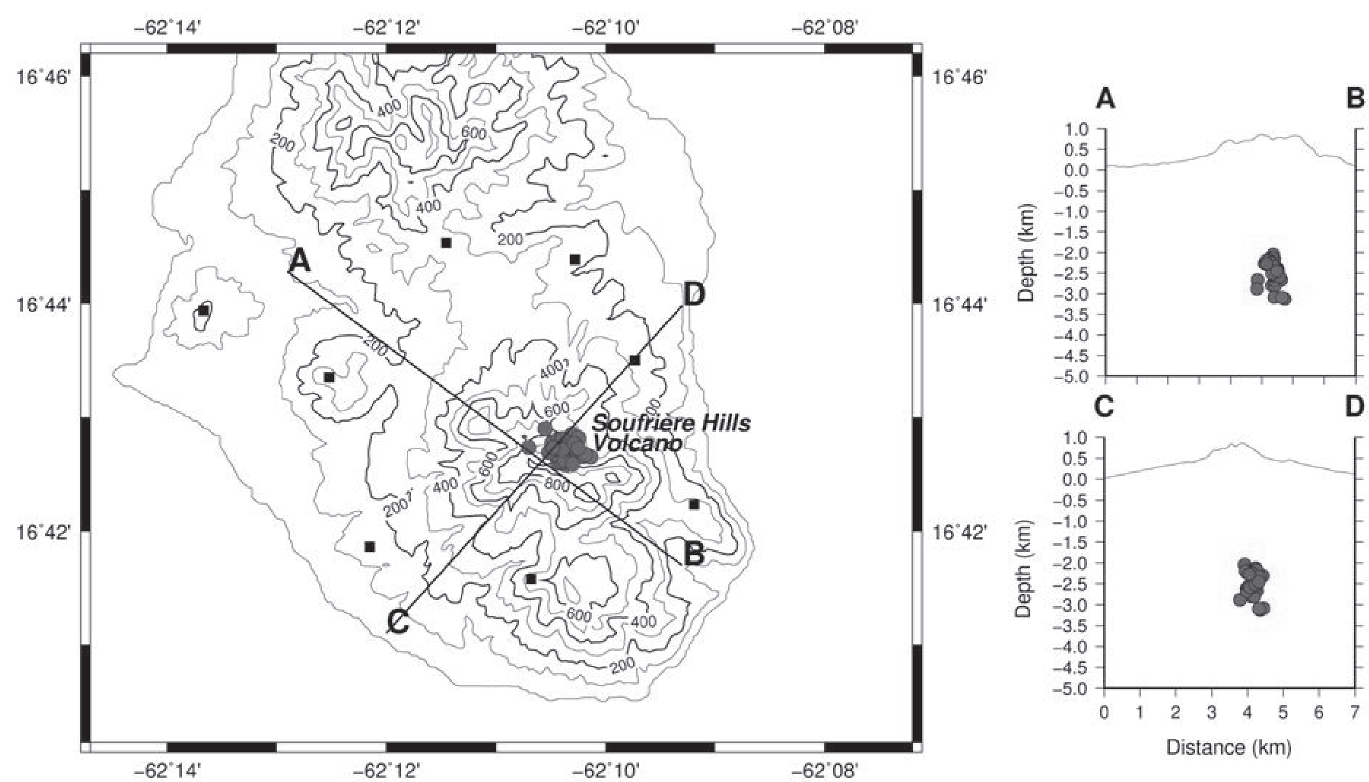
- **Hybrid earthquakes** are a mixture of the previous two event types. They have an impulsive high frequency start with a clear *P*-wave arrival followed by a monochromatic coda with frequencies similar to a long-period event. These events have similar interpretations to long-period events and they are often considered together.
- **Rockfall events** are emergent signals containing a wide range of frequencies and are normally longer in duration than any of the other types. They can often be visually correlated with rockfalls or pyroclastic flows from the dome.

Classification of these events is undertaken daily by analysts at the observatory using SEISAN, which has the facility to record volcanic subtypes. The number of each type of event is then included in the weekly report produced by the observatory. Since the start of the eruption, the relative importance of different event types has changed. In 1997 up to 1,000 hybrids a day were recorded, and these were often clearly associated with magma movement beneath the dome, as shown by correlation with tilt-meter data and dome collapses (Voight *et al.* 1999), but since the current dome started growing in 2005 relatively few hybrids have been recorded, despite occasionally very rapid (> 10 m^3/s) magma extrusion rates. This change in behavior is not understood but may be connected to a widening of the conduit, as inferred from the increase in the diameter of spines (pillar-shaped extrusions of more viscous lava thought to retain the cross-section of the conduit). The vast majority of triggered events are now either long-period events or rockfalls, both of which are probably related to degassing and collapses of the dome itself rather than movement of magma below.

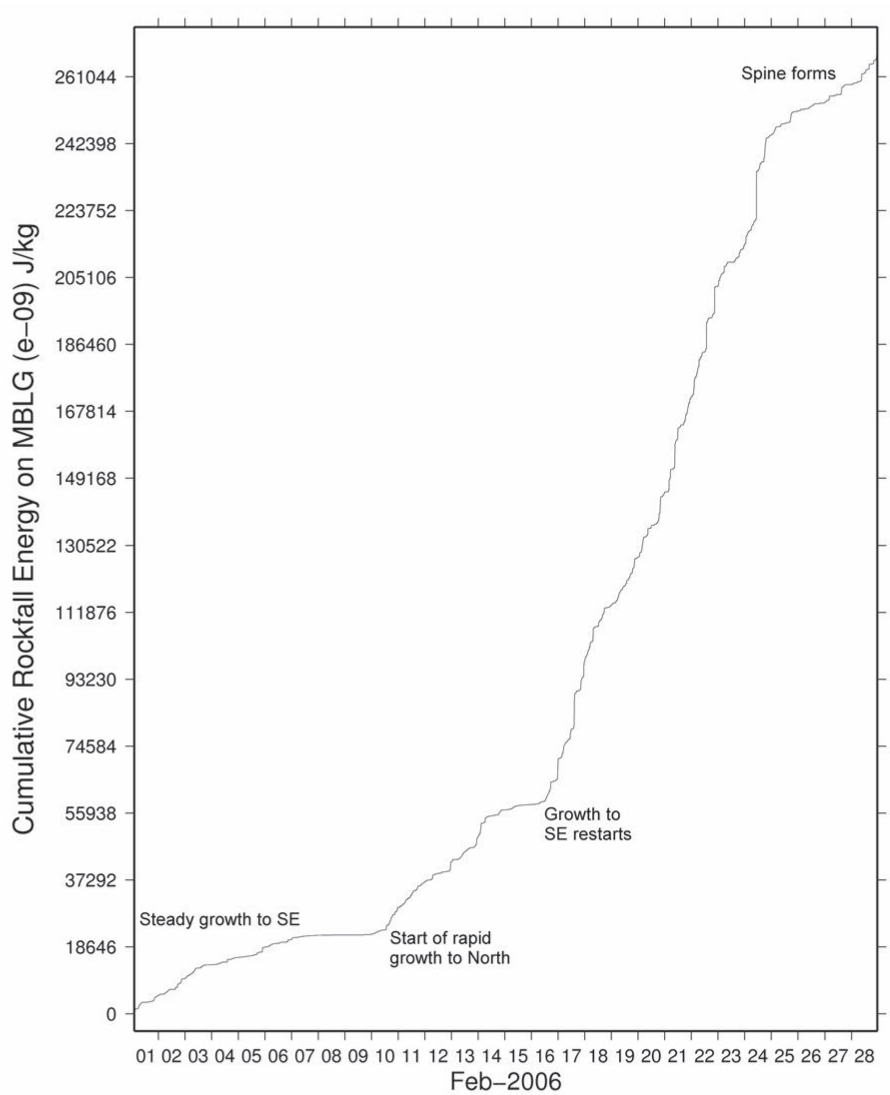
Location of events with impulsive phases (hybrids and volcano-tectonic earthquakes) is a routine task at the observatory. Location is carried out within SEISAN using the "hypocenter" location program (Lienert *et al.* 1986), which applies an iterative least-squares algorithm using a simple one-dimensional velocity model. Before the start of the eruption, locations were scattered beneath the southern part of the island (Aspinall *et al.* 1998), but since dome building was established, hypocenters have almost all been clustered beneath the dome at depths rarely greater than 4 km and most often between 1 and 3 km. Figure 7 shows as an example all those hybrids located in September 2006. The constancy of source area is confirmed by high cross-correlation between the waveforms of events. Such cross-cor-



▲ **Figure 6.** Common types of volcanic events as classified at the MVO. All recorded at MBLG in September 2006.



▲ **Figure 7.** Locations of all 57 locatable hybrid events in September 2006. The black squares are the stations used to calculate these locations.



▲ **Figure 8.** Cumulative energy per unit mass at station MBLG for events classified as rockfalls triggered during February 2006. February was chosen because unusually good dome visibility allowed comparison with visual observations.

relations were used by Rowe *et al.* (2004) to show that hybrids in 1995 and early 1996 were clustered beneath the dome at a depth of 2 km. Fault-plane solutions of volcano-tectonic earthquakes are routinely determined at the observatory. Changes in the inferred stress orientation have been linked to changes in volcano behavior such as the start of dome growth episodes (Roman *et al.* 2006).

Event data is further routinely analyzed by the calculation of energy in each event and of the proportion of this energy in different frequency bands. This parametric data is stored along with any arrival time picks or location information. Plotting this data has been useful in a number of situations and often gives a better understanding of changes in recorded seismicity. As an example, figure 8 shows the cumulative energy of all those events classified as rockfalls. At this time there were very few hybrid earthquakes although the dome was growing. The sharp changes in the slope of the line in figure 8 (which are repeated on similar plots for other stations) correlate with abrupt changes in dome growth rate and direction as indicated by the labels. In terms of hazard the change in focus of dome growth from the east to the north is particularly important. Pyroclastic flows to the east run off harmlessly into the sea while a flow to the north could, in extreme cases, still affect an inhabited area. For the month shown here the changes in dome growth were directly observed, but this is not usually possible as the volcano is often obscured by clouds for days or weeks. In such conditions of no visibility, the possibility to detect sudden changes in dome behavior is very important, even if the nature of the change may not be fully understood.

CONCLUDING REMARKS

The seismic network on Montserrat has been an important part of monitoring the Soufrière Hills volcano for more than 10 years. In this time it has been upgraded and improved, and the quality and quantity of data for monitoring and research has increased markedly. With ongoing changes in the nature of seismicity at the volcano, the seismic data continues to be of utmost importance in our efforts to understand this eruption. The current activity of Soufrière Hills volcano is reported at the observatory Web site, http://www.mvo.ms.

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REFERENCES

Aspinall, W. P., A. D. Miller, L. L. Lynch, J. L. Latchman, R. C. Stewart, R. A. White, and J. A. Power (1998). Soufrière Hills eruption, Montserrat, 1995–1997: Volcanic earthquake locations and fault plane solutions. *Geophysical Research Letters* **25**, 3,397–3,400.

Aspinall, W. P., S. C. Loughlin, F. V. Michael, A. D. Miller, G. E. Norton, K. C. Rowley, R. S. J. Sparks, and S. R. Young (2002). The Montserrat Volcano Observatory: Its evolution, organization, role and activities. In *The Eruption of the Soufrière Hills Volcano, Montserrat from 1995 to 1999*, ed. T. H. Druitt and B. P. Kokelaar, 71–91. London: Geological Society London, memoir no. 21.

Cole, P. D., E. S. Calder, T. H. Druitt, R. Hoblitt, R. Robertson, R. S. J. Sparks, and S. R. Young (1998). Pyroclastic flows generated by gravitational instability of the 1996–1997 lava dome of Soufrière Hills volcano, Montserrat. *Geophysical Research Letters* **25**, 3,425–3,428.

Endo, E. T., and T. Murray (1991). Real-time seismic amplitude measurement (RSAM): A volcano monitoring tool. *Bulletin of Volcanology* **53**, 533–545.

Green, D. N., and J. Neuberg (2005). Seismic and infrasonic signals associated with an unusual collapse event at the Soufrière Hills volcano, Montserrat. *Geophysical Research Letters* **32**, 1–4.

Johnson, C., A. Bittenbinder, B. Bogaert, L. Dietz, and W. Kohler (1995) Earthworm: A flexible approach to seismic network processing. *IRIS Newsletter* **14** (2), 1–4.

Havskov, J., and L. Ottemoller (2005). *SEISAN: The Earthquake Analysis Software Version 8.1 User's Manual*. Bergen: University of Bergen, Norway.

Lahr, J. C., B. A. Chouet, C. D. Stevens, J. A. Power, and R. A. Page (1994). 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 The 1989–1990 eruptions of Redoubt volcano, Alaska, ed. T. P. Miller and B. A. Chouet, special issue, *Journal of Volcanology and Geothermal Research* **62**, 137–151.

Lee, W. H. K. (1989). Toolbox for Seismic Data Acquisition, Processing and Analysis, *IASPEI Software Library,* Vol. 1, published by IASPEI in collaboration with the Seismological Society of America.

Lienert, B. R. E., E. Berg, and L. N. Frazer (1986). Hypocenter: An earthquake location method using centered, scaled, and adaptively least squares. *Bulletin of the Seismological Society of America* **76**, 771–783.

Loughlin, S. C., E. S. Calder, A. B. Clarke, R. D. Cole, R. Luckett, M. Mangan, D. Pyle, R. S. J. Sparks, B. Voight, and R. Watts (2002). Pyroclastic flows generated by the 25 June 1997 dome collapse, Soufrière Hills volcano, Montserrat. In *The Eruption of the Soufrière Hills Volcano, Montserrat from 1995 to 1999*, ed. T. H. Druitt and B. P. Kokelaar, 191–209. London: Geological Society London, memoir no. 21.

Luckett, R., B. Baptie, and J. Neuberg (2002). The relationship between degassing and rockfall signals at Soufrière Hills volcano, Montserrat. In *The Eruption of the Soufrière Hills Volcano, Montserrat from 1995 to 1999*, ed. T. H. Druitt and B. P. Kokelaar, 595–602. London: Geological Society London, memoir no. 21.

Miller, A. D., R. C. Stewart, R. A. White, R. Luckett, B. J. Baptie, W. P. Aspinall, J. L. Latchman, L. L. Lynch, and B. Voight (1998). Seismicity associated with dome growth and collapse at the Soufrière Hills volcano, Montserrat. *Geophysical Research Letters* **25**, 3,401–3,404.

Murray, T., J. Ewert, A. Lockhart, and R. LaHusan (1996). The integrated mobile volcano-monitoring system used by the Volcano Disaster Assistance Program (VDAP). In *Monitoring and Mitigation of Volcano Hazards,* ed. R. Scarpa and R. Tilling, 315–362. Berlin: Springer.

Neuberg, J., B. Baptie, R. Luckett, and R. Stewart (1998). Results from the broadband seismic network on Montserrat. *Geophysical Research Letters* **25**, 3,661–3,664.

Neuberg, J. (2000). Characteristics and causes of shallow seismicity in andesite volcanoes. *Royal Society of London, Philosophical Transactions, Series A, Mathematical, Physical and Engineering Sciences* **358**, 1,533–1,546.

Power, J., M. Wyss, and J. Latchman (1998). Spatial variations in the frequency-magnitude distribution of earthquakes at Soufrière Hills volcano, Montserrat, West Indies. *Geophysical Research Letters* **25**, 3,653–3,656.

Roman, D. C., J. Neuberg, and R. Luckett (2006). Assessing the likelihood of volcanic eruption through analysis of volcanotectonic earthquake fault-plane solutions. *Earth and Planetary Science Letters* **248**, 229–237.

Rowe, C. A., C. H. Thurber, and R. A. White (2004). Dome growth behaviour at Soufrière Hills volcano, Montserrat, revealed by relocation of volcanic event swarms, 1995–1996. *Journal of Volcanology and Geothermal Research* **134**, 199–221.

Thompson, G. (2000). *Review of MVO Seismic Monitoring*. Montserrat Volcano Observatory Open File Report 00/02.

Utheim, T., and J. Havskov (1997). *The SEISLOG Data Acquisition System*. Bergen: University of Bergen, Norway.

Young, S. R., R. S. J. Sparks, W. P. Aspinall, L. Lynch, A. D. Miller, R. E. A. Robertson, and J. B. Shepherd (1998). Overview of the eruption of Soufrière Hills volcano, Montserrat, July 18, 1995 to December 1997. *Geophysical Research Letters* **25**, 3,389–3,392.

Voight, B., R. S. J. Sparks, A. D. Miller, R. C. Stewart, R. P. Hoblitt, A. Clarke, J. Ewert, W. P. Aspinall, B. Baptie, E. S. Calder, P. Cole, T. H. Druitt, C. Harford, R. A. Herd, P. Jackson, A. M. Lejeune, A. B. Lockhart, S. C. Loughlin, R. Luckett, L. Lynch, G. E. Norton, R. Robertson, I. M. Watson, R. Watts, and S. R. Young (1999). Magma flow instability and cyclic activity at Soufrière Hills volcano, Montserrat, British West Indies. *Science* **283**, 1,138–1,142.

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