Chapter 2

Cyclic phenomena at the Soufrière Hills Volcano, Montserrat

HENRY M. ODBERT1,2*, RODERICK C. STEWART1,2 & GEOFFREY WADGE3
1Montserrat Volcano Observatory, Flemmings, Montserrat, West Indies
2Seismic Research Centre, University of the West Indies, St Augustine, Trinidad & Tobago, West Indies
3Environmental Systems Science Centre, University of Reading, Reading RG6 6AL, UK
*Corresponding author (e-mail: h.odbert@bristol.ac.uk)

Abstract: Cycles of eruptive activity are generally interpreted as evidence of one or more mechanisms operating in equilibrium. Modulation of cycle characteristics thus reflects changes in the conditions affecting those mechanisms. This kind of semi-deterministic behaviour at the Soufrière Hills Volcano has occurred on multiple timescales and with a range of eruptive intensity. By documenting cyclic phenomena, it is possible to investigate the mechanisms that modulate the state of the eruption and examine conceptual models. Pattern recognition and model development allows some degree of short-term forecasting ability for volcanic activity. We report the cyclic eruptive phenomena that have occurred at the Soufrière Hills Volcano and the underlying processes that are responsible for variability in the eruptive process. The result is a rich, but fragmented record of some of the cyclic events at SHV, both to demonstrate their occurrence and to provide information to constrain the nature of those processes driving the eruption and to better understand future behaviour of the volcano.

The eruption of the Soufrière Hills Volcano (SHV), Montserrat, has been characterized by significant variations in surface activity at multiple timescales. The eruption was preceded by several ‘seismic crises’ at about 30 year intervals (Wadge & Isaacs 1988). During the eruption, phases of lava extrusion lasting from months to years (Phases 1–5) have been interrupted by periods of relative quiescence of similar duration (Wadge et al. 2014b). Within each activity phase, variations in surface lava flux have been observed at scales of hours (Voight et al. 1999) and weeks (Sparks & Young 2002; Costa et al. 2007). The occurrence of these and other examples of cycles have been associated with systematic processes; that is, processes that are derived intrinsically from non-random systems or mechanisms in the volcano. Observing and analysing cyclic phenomena in eruptions can thus serve to provide information to constrain the nature of those processes driving the eruption and to better understand future behaviour of the volcano.

Volcanic systems involve the generation and buoyant rise of magma, its storage and eruption. These systems are complex with some evidently non-linear processes involved (e.g. crystallization-induced rheological stiffening: Melnik & Sparks 1999), and the deterministic behaviour shown by cyclic behaviour at volcanoes like SHV is susceptible to divergent evolution caused by small variations in source conditions. This underlying tendency to chaotic dynamic behaviour renders prediction of future states impossible (Schuster & Just 2005). One of the concepts used in the mathematical analysis of such chaotic systems is that of intermittency, in which the time series follows a periodicity for some time but then fluctuates randomly from it, only to return to the periodic state later. This type of behaviour is apparent at times in sub-daily activity at the SHV.

Before discussing the evidence of various cyclic phenomena in detail, we must define what should be regarded under this umbrella term. For the purposes of this study, we consider a single cycle to be defined as a systematic variability through time in any observable parameter (e.g. number of seismically detected events) from an initial state, at an initial time, eventually returning to that state and followed by repeating behaviour. Recurrence may imply the existence of a mechanism or process that is able to reset and/or recharge at the end of each cycle (Odbert & Wadge 2009). In the simple case where a measured observable value oscillates in time like a sine wave, the cycle period could thus be measured, for example, from one peak to the next. In natural systems, of course, one would not necessarily expect the variation to be perfectly sinusoidal and often it is not (e.g. Melnik & Sparks 2005). Indeed, the shape and other characteristics of cycles, and how they change in time, may themselves be used to infer information about the source mechanism and its equilibrium state (Odbert & Wadge 2009). We revisit this topic in more detail later, with respect to observations made at the SHV.

Cycles might be observed at volcanoes through visual observations (usually at short timescales) but are often only clearly defined and quantified through visual or numerical inspection of time-series data. The eruption at the SHV is notable both for its duration and for the scrutiny with which it is routinely monitored by the Montserrat Volcano Observatory (MVO) and studied by the wider research community. The result is a rich, but fragmented collection of time-series data including seismic, deformation, gas, lava flux, thermal imagery and visual observation datasets. Where possible, we use a multi-parameter approach to define cyclic events at SHV, both to demonstrate their occurrence robustly and to understand their characteristics. The high sampling rate and sensitivity of the seismic monitoring network allows for short period (hours to months) cycles to be identified and analysed quantitatively. Seismic data are manipulated to generate derivative time-series data, such as Real-time Seismic Amplitude Measurement (RSAM: Murray & Endo 1992) with minute-scale resolution, and automatically or manually derived event counts of, for example, rockfall or long-period (LP) earthquake occurrence.

Other monitoring data can be integrated to characterize the nature of cyclic behaviour. The time resolution and sensitivity of available monitoring techniques are important considerations for recording and finding evidence of cyclic events. Tiltmeter measurements made in 1996–1997 (with a 10 min sampling...
interval) provided valuable geophysical evidence of cyclic processes (Voight et al. 1998). Deformation monitoring via permanent and episodic global positioning system (GPS) surveying, with daily resolution, has been used widely to interpret cycles at timescales of months to years (Odbert et al. 2014). The use of Electronic Distance Meter (EDM) measurements to assess baseline length changes around the flanks of SHV (typically at weekly to monthly intervals) has corroborated and complemented GPS deformation observations, especially in the near-field (Odbert et al. 2014). Routine sulphur dioxide (SO₂) monitoring has been undertaken onMontserrat since 1996 (Watson et al. 2000; Christopher et al. 2010) and has provided an average daily value, although higher-frequency sampling is possible during daylight hours at the cost of value uncertainty. Atmospheric SO₂ measurements can also be made via satellite remote sensing (Carn & Prata 2010) at daily intervals. The flux of erupting lava has been estimated using a variety of techniques (Odbert 2009), with an operational frequency of about 20 days for photogrammetric methods. Higher-frequency (c. hourly) volumetric flux monitoring has been demonstrated using all-weather Volcano Topography Imaging Sensor (AVTIS), a ground-based imaging radar (Wadge et al. 2014c) with regular visible and infrared imagings, and sampled frequently (c. 2 Hz) and assessed quantitatively or qualitatively. Often a combination of observations from multiple monitoring techniques is desirable for robust detection of eruptive cyclicity. We note specifically the value of visual observation logs in assimilating the other evidence, as well as sometimes serving as a quasi-quantitative dataset in their own right.

Often, the most easily measured property of a cycle is its period – the time from one point in a cycle’s phase to the same point in the next cycle. The period (or, inversely, the frequency) of a cycle is sometimes the only metric that can be gleaned in absolute terms from the available data. In cases where quantitative data are available, the amplitude (the difference between the lowest and highest parts of the signal) and the shape of the cycle can also be measured, although care must be taken to account properly for the background noise that is inherent in most volcanological data. This is often accomplished using an appropriate filtering scheme. The amplitude of cycles corresponds to the intensity of activity, which, in turn, may be interdependent on cycle period. The shape of a cycle (e.g. how skewed or asymmetric it is) may also be used to characterize the process(es) driving periodic behaviour. A number of techniques may be used to ascertain cycle properties. Spectral analysis of a time series via the Fast Fourier Transform (FFT) can be applied to demonstrate the relative contribution of cyclic signals with different frequencies, and numerous algorithms exist to test results statistically against hypothetical noise models (Percival & Walden 1993). A drawback of FFT analysis of volcanic data is the assumption that the time series under analysis is stationary (i.e. the spectral content does not change in time); an assumption that is sometimes untruth at SHV. Spectrogram analysis uses FFT analysis over a series of contiguous or overlapping short time windows. Stationarity is then only required for the duration of each time window, and the spectral content of a window may be compared independently to that of the next window. Wavelet analysis provides a means of analysing a time series over a range of frequencies and time intervals, and requires no implicit assumption that a time series is stationary. Where possible, we use a combination of complementary time-series analysis tools to identify the presence and properties of cycles in time-series data. We make no attempt here to analyse cyclicity in seismic data at waveform timescales (seconds to minutes); instead, we focus primarily on cycles in eruptive phenomena.

The occurrence of cyclic activity at SHV is evidence of systematic processes within the volcano. Achieving a better understanding of when and how these phenomena occur will help us to understand what causes them to start, change and cease. This has the lure of providing a route to being able to model and forecast deterministic or semi-deterministic processes in eruptions numerically. Here, we aim to present evidence of cyclic behaviour at the SHV at a range of timescales, and formally document the timing and characteristics of the cyclic volcanic phenomena. Where new data are available, we present time-series analysis from multi-parameter time-series data, particularly from recent eruptive phases, when cyclic activity has been particularly prevalent. In this chapter, we discuss cycles according to their period: those occurring with periods of the order of hours (sub-daily), weeks to months, years and decades. We then discuss the observations generally, and outline a strategy for capturing and analysing cyclic behaviour optimally.

Sub-daily cycles

On numerous occasions since the onset of lava extrusion in 1995, patterns in activity have been documented that describe regular cycles, with periods of between hours and tens of hours (collectively referred to herein as ‘sub-daily’ cycles). Strong sub-daily cyclicity in 1996–1997 was associated with regular, small–moderate explosions, and generated well-defined ground deformation (near-field tilt) and seismic signals (Voight et al. 1998). Similar sub-daily cycles with approximately 8.5 h average periods were recognized in 1999–2000, and their evidence in seismic tremor and SO₂ data was reported by Young et al. (2003). The authors noted a lag of several tens of minutes from peaks in seismic energy release to peaks in gas flux. Cycles such as these were less evident in subsequent phases of extrusion until Phase 4b (2008–2009) and particularly Phase 5 (2009–2010), when activity was again marked by strong variability at sub-daily timescales (Cole et al. 2010). These cycles in eruptive activity deserve particular attention because they can provide operational insight for short-term hazard mitigation planning, and this has been exploited by the MVO throughout the eruption.

Phase 5 cyclicity: 2009–2010

Sub-daily cycles in the intensity of surface activity (mainly rockfalls and ash venting) developed shortly after the onset of dome growth in October 2009 and, as the cycles continued and intensified, became a defining feature of Phase 5 extrusion. In general, two forms of cyclic seismicity were observed. Figure 2.1 shows typical Phase 5 seismicity, with dominant signals from rockfalls (c. 0.5–5 min duration, cigar-shaped signals), hybrid earthquakes (short, low-amplitude signals) and tremor (c. 20–90 min duration, continuous, low-amplitude signals). Figure 2.1a shows an example of cyclic seismicity that features frequent hybrid earthquake quakes that merge to form continuous tremor. Tremor signals (Fig. 2.1a, b) were often associated with visible venting of ash and gases (so-called ‘ash venting’) around the summit of the lava dome; presumably in the locale of the active lava extrusion vent. Rockfall and pyroclastic flow signals (RF, identified collectively) are generated by mass-wasting events, typically originating high on the lava dome. Figure 2.1 also shows bunching of RF events around the ash-ventilation episode and this combination of surface activity was commonly observed throughout Phase 5. Some example photographs of both types of activity are given by Cole et al. (2014a). Both panels in Figure 2.1 demonstrate the recurrence of ash venting at regular intervals (with c. 7 and 6 h-cycles on 1 November and 17 December 2009, respectively). Contributions from ash-venting-related tremor and RF signals dominated the seismic data stream for most of Phase 5 (see Cole et al. 2010). Peaks in surface activity such as these usually lasted between about 0.5 and 4 h.

To analyse the occurrence and variation in sub-daily cyclicity throughout Phase 5, we consider the RSAM envelope of the seismic signal as a proxy for the intensity of surface activity. Usually it is possible to obtain RSAM from a single, representative
seismic station. However, owing to intermittent failures across the network that are typical during periods of intense activity, we derived a normalized, network-averaged RSAM (or NARSAM; Cole et al. 2010) to obtain a continuous time series. NARSAM is calculated using a weighted average of RSAM data from the seismic network. Weightings are determined through empirical adjustment, aiming to minimize biases in the network and maintain long-term consistency in the NARSAM time series. Figure 2.2a shows the NARSAM time series derived for Phase 5, clearly illustrating the changes in eruption intensity.

The occurrence and characteristics of periodic signals in a time series may be analysed via the Continuous Wavelet Transform (CWT; Percival & Walden 2000; Odbert & Wadge 2009). Wavelet analysis provides a convenient method to measure how well correlated a time series is with the shape of the chosen wavelet in multiple domains (time and frequency). We adopt the Morlet wavelet – shaped like a decaying sine wave – to measure how similar the NARSAM time series is to a sine-wave-like signal for a range of frequencies. Large positive CWT values correspond to strong, positive correlation with the wavelet (i.e. relating to a peak in the time series) and large negative values correspond to strong anti-correlations. Values close to 0 indicate weak correlations. Persistence through time of regular high transform values for a given pseudo-period is therefore evidence of cyclicity in the time series. The CWT value for a fixed pseudo-period thus corresponds with the phase of the cycle in the data. We note that the cycles in the NARSAM time series do not necessarily resemble sine waves but that the choice of wavelet is suitable for such analyses without requiring specific a priori knowledge of the system generating the time series (Trauth 2006).

Figure 2.2b shows the Morlet CWT for the NARSAM time series, indicating strong transform values at a range of pseudo-periods. Occasional elevated CWT values in October and November 2009 show the presence of sub-daily cycles with periods of between about 4 and 14 h. The most intense cycles of Phase 5 developed after 20 November (indicated by a green, dashed line). These had periods of about 5 h for around 2 weeks, at which point the periods began to increase. This is shown by an approximately linear transition of peak transform magnitude up to about 9 h by 8 January 2010, when there was a large Vulcanian explosion (details reported by Cole et al. 2014b). In the week that followed, which included two more explosions on 10 and 11 January, surface activity was markedly less well organized and this is reflected in the reduction of CWT magnitude in Figure 2.2b after 8 January 2010. Cyclic activity resumed at a variable, and generally lower, intensity, with a period of around 6 h from 11 January onwards. The period then began to lengthen once again to approximately 11 h by 5 February. Several isolated Vulcanian explosions occurred throughout this period (8, 10 and 11 January, and 5 and 8 February: Cole et al. 2014b), and there was demonstrable disruption to the sub-daily mechanism following the events on 8 January, and 5 and 8 February. A reduction in cycle period (from c. 10 to c. 7 h) and increase in intensity occurred over the approximately 2 days immediately preceding the partial dome collapse and end of Phase 5 (Stinton et al. 2014b) on 11 February 2010.

Changes in the nature of the cycles can be tracked through Phase 5 by considering asymmetry and relative intensity (‘asymmetry’ is used here to describe the degree to which an RSAM cycle is skewed). Figure 2.2c shows the stages of each cycle during which tremor (and, by proxy, ash venting) was ongoing. As the tremor signal partly defines the RSAM cyclicity, it naturally follows that tremor typically began before the cycle peak and ended after it. However, Figure 2.2c shows that some asymmetry developed in this sequence, particularly in the middle episode of Phase 5. During the period of intense, approximately 5 h cycles, the most intense part of each cycle was towards the end of the

Fig. 2.1. Helicorder seismic trace plots showing vertical broadband seismic signals recorded on (a) 1 November 2009, and (b) 17 December 2009 at the Fergus Ridge seismic station (MBFR, c. 2.2 km from the SHV vent). Each horizontal line shows the seismic trace for 10 min (delimited by faint vertical grid lines); there are six lines per hour, with alternating colours to help visual distinction of overlapping signals.
ash-venting event. It is notable that the severity of this asymmetry diminished gradually before the cycles’ period started to lengthen. The relative intensity of cycles can be analysed by considering the ratio between their peak amplitude and their period. In a case where the time-averaged intensity of the eruption is constant (e.g. constant lava flux), the ratio would remain approximately constant such that a shorter, higher-amplitude cycle could be considered equivalent to a longer, low-amplitude cycle. Following the assumption that each sub-daily cycle was due to the repeating action of the same mechanism(s), the ratio shown in Figure 2.2d may be considered as a proxy of eruption intensity. The general trend indicates a relatively constant background level of intensity that becomes elevated by nearly an order of magnitude around the end of November, immediately before the development of long, asymmetrical ash-venting events. The level of intensity decays to the background level in the latter part of the second episode, as cycles lengthen and become less intense.

The second key contribution to cyclicity in the RSAM record was the seismicity associated with RF events. Visual observations recorded the increased frequency of RFs coincident with ash venting. We can analyse the timing of RF events and ash venting to build up a type description of sub-daily cycles in Phase 5. Figure 2.3 shows the distribution of RF events around their respective RSAM peaks for events between 1 December 2009 and 8 January 2010. The histogram demonstrates the increase in rate of RF events by a factor of 3–4 in time intervals prior to and immediately after the RSAM peak. This demonstrates the variable rate in RF occurrence but is, in part, an intrinsic result of the...
RSAM calculation method. We consider that the peaks in RF frequency identify peaks in surface lava flux; as a batch of lava is extruded rapidly onto the lava dome, the stability of new and pre-emplaced lava masses is reduced compared to when there is little or no supply. The result would be an increase in generation of mass-wasting events from around the vent area.

This argument is corroborated by more detailed evidence recorded during Phase 5. The unprecedented volume and height of the lava dome at this time meant that material could be shed from the lava dome into all major drainages around the volcano (Stinton et al. 2014a). Typically, RFs would occur in a dominant direction at any given time (as discussed later), but on numerous occasions multiple, moderate–large pyroclastic flows were formed simultaneously that travelled in different – often opposite – directions. These observations were a first at the SHV, and we interpret them as being more definitive evidence of RF generation driven by increased lava flux from a vent close to SHV, and we interpret them as being more definitive evidence of RF generation driven by increased lava flux from a vent close to the summit of a nearly symmetrical lava dome. The occurrence of multi-directional RF events was also more common around the summit of the lava dome at this time meant that material could be shed from the dome into all major drainages around the volcano (Stinton et al. 2014a).

Finally, Figure 2.3 shows measurements of the ratio between hydrogen chloride and sulphur dioxide (HCl:SO2) in the volcano’s gas plume, recorded using a Fourier Transform Infrared (FTIR) spectrometer near the end of Phase 5. Each data point is averaged from a session consisting of tens to hundreds of individual scans. Although few data points are available, owing to instrument failure, we note that the highest measurements were made approximately coincident to cycle peaks and the lowest measurements made closer to the cycle trough. Indications from individual scans suggest that, where high ratios are observed, they are only sustained for a short period. Oppenheimer et al. (2002) reported variations in HCl:SO2 from 1996 to 1998, interpreting increases in the ratio as the result of an increase in degassing from an andesite source (generating HCl) and/or a decrease in degassing of a basaltic source (generating SO2). As the basaltic source is typically assumed to be from deep in the system, short-term ratio variations would then tend to be dominated by variable

![Fig. 2.3. Histogram showing the timing of rockfall/pyroclastic flow events (collectively RFs) with respect to the phase of the concurrent RSAM cycle. Phase timings were determined as outlined in the caption of Figure 2.2. The number of events is shown for all RF events (blue bars; N = 1080) and events in which multi-direction RFs were generated simultaneously (red bars, 41 simultaneous events; N = 82 individual RF events). For each record of multi-direction RF events, its proportional contribution to the overall RF count is shown as a percentage. RF timings were derived from a combination of thermal infrared video records and seismic plots for the date range 1 December 2009–8 January 2010. Green crosses show the ratio between HCl and SO2 measured by passive FTIR in the downwind plume over five surveys between 29 January and 10 February 2010. Values represent ratios determined from tens to hundreds of individual scans recorded during an observation session. The horizontal bars indicate the duration of each scanning session in terms of phase, and vertical bars show the uncertainty in the measurement, according to the axis on the right-hand side.](image-url)

Common characteristics of sub-daily cyclicity that were typical (although not ubiquitous) of Phase 5 can be summarized as follows. Background seismicity prior to each cycle would be at a low level – dominated by smaller RF events owing to the instability of the active lava dome. The start of a cycle would be marked by the onset of continuous ash venting from near the summit of the lava dome and concomitant seismic tremor – reflected by increased RSAM. The rate and size of RF events would grow such that the combined activity generated a crescendo in RSAM. The RF frequency and ash-venting intensity then decayed. This decay would sometimes occur more suddenly than the onset, yielding an asymmetrical cycle. The surface activity would then return to the background state with no tremor and occasional RFs. The peak in activity typically lasted between about 0.5 and 4 h, perhaps accompanied by gas efflux with elevated HCl:SO2, and would repeat every 4–14 h. At times when cycle period was short, ash venting from the volcano was near continuous (e.g. early December, Fig. 2.2c).

We interpret this generalized sequence of events to be the surface expression of large variations in surface lava flux over the timescales of minutes to hours. Similar interpretations have been made from observations of sub-daily tilt cycles during 1997 (Voight et al. 1999; Wylie et al. 1999; Sparks & Young 2002; Widiwijayanti et al. 2005; Green et al. 2006; Costa et al. 2007; Lensky et al. 2008; Odbert & Wadge 2009). The mechanisms inferred from tilt data were generally thought of as pressurization in the shallow conduit (Voight et al. 1999) as lava flow is restricted owing to the formation of a viscous lava plug formed by degassing-induced crystalization. At a critical pressure, the plug fails and is ejected from the conduit, often along with vigorous ash emission. The resulting pressure reduction promoted degassing in the conduit lava and the cycle repeated. We consider that the same mechanism would explain the sub-daily cyclicity
observed in Phase 5, and, perhaps, at earlier times in the eruption. The resulting surface observation is a reduction or cessation of lava extrusion from the vent as conduit flow is restricted, followed by a surge in lava flux during the plug-ejection phase. The onset of venting indicates the beginning of plug failure, as trapped gases that have exsolved from the lava plug are released. The structural failure allows the lava to be forced from the vent, generating RF activity. The pressure driving plug ejection is relaxed such that venting and the supply of fresh lava to form RFs subsides, and then the process resets. It appears that the cyclic activity can occur with a range of intensity from those with minimal visible surface activity up to cycles that culminated in Vulcanian explosions (e.g. Sparks & Young 2002).

Given the sequence of events described above, we note particularly that surface efflux of lava varies significantly even during highly active periods of activity on the volcano. Indeed, if it were assumed that all of the lava erupted during Phase 5 (c. 74 Mm3: Stinton et al. 2014a) was extruded in this fashion (i.e. during ash-venting events, which accounted for 20% of the duration of Phase 5) and that the surface flux was 0 between cycle peaks, the actual surface flux of lava during active extrusion cycle, as estimated by a similar pattern to observation rates (Stinton et al. 2013). Cyclic activity is evident in most types of seismicity, with the notable exception of volcano-tectonic (VT) earthquakes. Episodes of continuous tremor have also been cyclic (‘banded tremor’), although many of these actually result from the merging of frequent, small hybrid earthquakes (Neuberg et al. 1998). It has not been possible to analyse the entire eruption using a single dataset, such as a whole-eruption RSAM, owing to frequent changes in the seismic network (changing instrumentation and locations). The properties of the cycles were therefore estimated using shorter periods of RSAM data that were generated from suitable available data or, failing that, hourly counts of various earthquake types.

We identified 42 distinct episodes of cyclic activity, lasting between 1 and 153 days (Table 2.1). Several of these episodes can be divided into separate sub-episodes, characterized by notable changes in either the type of seismicity or the character of the cycles. For each episode or sub-episode (denoted by a lowercase suffix), we list the minimum, median and maximum cycle period. We note a slight tendency for sub-daily cycles to be asymmetric, with the RSAM peak usually closer to the end of the cycle, suggesting a similar pattern to observations from Phase 5.

Figure 2.4 illustrates the occurrence of sub-daily cycles, as summarized in Table 2.1, throughout the eruption. Although the most pronounced cycles occurred in Phases 1 and 5, it is notable that there is evidence for similar events in all of the eruptive phases. Only two episodes of cyclicity took place when no extrusion was ongoing. The first, in September 1995, occurred before any liquid lava had been extruded, although it coincided with the extrusion of an old lava spine. With these exceptions, all of the cycles have been associated with ongoing lava extrusion and later are summarized for each multi-annual cycle. The period of cycles has varied throughout the eruption, as shown in Figure 2.4. There have been occurrences when the average cycle period has varied systematically over a series of sub-daily cycle episodes. For example, in early 1997, the average cycle period increased, indicating an apparent negative correlation with lava flux changes. The opposite correlation has been observed at other specific times in the eruption. However, cycles with shorter periods tend to correspond to periods of high average lava flux in general (Fig. 2.4).

The variety of the cyclic activity listed in Table 2.1 is remarkable, and may be evidence of multiple causal mechanisms or changing conditions under which a single mechanism operates. A common observation to all of the cycles is their association with near-surface activity. Cycles in low-frequency (LF) seismicity (i.e. hybrid and LP earthquakes) in 1996–1997 were associated with near-dome tilt cycles (Voight et al. 1998). Similar deformation has probably occurred at other times during the eruption but has not been captured owing to an absence of near-field deformation monitoring since 1997 (see Odberg et al. 2014). Magma fracturing is interpreted as a trigger for LF earthquakes, generated by interface waves between magma and the conduit walls (De Angelis & Henton 2011; Thomas & Neuberg 2012). Cycles in LP earthquakes located about 1500 m below the lava dome have been associated with stick–slip flow in the conduit (e.g. Neuberg et al. 2006); LF events were observed to occur during the depressurization phase of a stick–slip (no flow–flow) cycle (fig. 3 of Neuberg et al. 2006), although we note that the exact timing of these occurrences in early eruption data may be complicated by instrument clock errors. Cycles in rockfall activity may be generated by deformation of the dome or regular changes in the lava extrusion rate.

The presence and characteristics of sub-daily cycles in activity have been modulated by the occurrence of significant volcanic events, such as explosions or dome collapses. Repeating cycles are evidence of the existence of a system whose boundary conditions are maintained within a certain degree of equilibrium (Odberg & Wadge 2009). Significant disruption to this equilibrium state, and, therefore, to the boundary conditions of the mechanism(s) generating cyclic activity, would therefore have the potential to alter that activity – either by effecting a change in the intensity or period of cycles, or by causing them to stop or start. Regular sub-daily cycles observed in late December 2008–2 January 2009 had a near-constant period of about 4 h. In the few cycles immediately preceding the Vulcanian explosion of 2 January 2009, the period shortened to about 3 h (Stewart et al. 2009). Earlier, we noted lengthening of sub-daily cycles in the weeks preceding the January and February 2010 explosions of Phase 5. Before the dome collapse of 25 June 1997, the sub-daily cycle, measured by tiltmeter, had an average period of about 10 h, which was reduced to about 7 h immediately after (Widiwijayanti et al. 2005). A post-collapse offset in the tilt pattern was interpreted by Widiwijayanti et al. (2005) to result from the additive effects of the unloading of dome surcharge and the pressure drop in the shallow magma system. Costa et al. (2012) modelled such a change in terms of an unloading depressurization forcing a stick–slip mechanism.

Sub-annual cycles

At various times since 1995, observations have indicated the presence of cyclic activity with a period of around 5–8 weeks (collectively considered here under the umbrella term ‘50 day cycles’, although the actual period varied). The first such occurrences were recognized by Voight et al. (1998), who identified two complete cycles, plus part of a third, in near-vent tiltmeter data recorded during Phase 1, between May and August 1997. Sparks & Young (2002) also reported the characteristically abrupt onset of each cycle, often associated with a major volcanic event such as a dome collapse and with intense swarms of hybrid seismicity that gradually decayed in intensity and was commonly followed by explosions. Following the destruction of the tilt network in
### Table 2.1. Episodes of sub-daily cycles at the Soufrière Hills Volcano between 1995 and 2011

| Episode ID (suffix) | Start   | End     | Duration (days) | No. of cycles | Period (h) | Seismic* | Volcanic activity | References† |
|---------------------|---------|---------|-----------------|---------------|------------|----------|-------------------|-------------|
| 19950923            | 23-Sep-95  | 27-Sep-95 | 5               | 10            | 8          | 6.2      | 10.1              | HY          |
| 19951114            | 14-Nov-95  | 16-Nov-95 | 3               | 8             | 3.8        | 3.1      | 5.7               | HY          |
| 19960515            | 15-May-96  | 15-May-96 | 1               | 3             | 6.1        | 6        | 6.3               | HY          |
| 19960728            | 23-Jul-96  | 28-Jul-96 | 5               | 6             | 7          | 4.6      | 10.7              | HY          |
| 19961024            | 24-Oct-96  | 28-Oct-96 | 5               | 4             | 28.9       | 26.8     | 35.2              | HY          |
| 19961222            | 22-Dec-96  | 01-Jan-97 | 11              |               |            |          |                   | Rapid dome growth |
| 19970118            | 14-Jan-97  | 02-Mar-97 | 48              |               |            |          |                   |            |
| 19970310            | 10-Mar-97  | 04-Apr-97 | 26              | 18            | 31.3       | 12.3     | 81.9              | HY          |
| 19970412            | 12-Apr-97  | 16-Apr-97 | 5               | 5             | 24         | 22.3     | 27                | HY          |
| 19970513            | 13-May-97  | 09-Jul-97 | 58              |               |            |          |                   |            |
| 19970731            | 31-Jul-97  | 23-Aug-97 | 24              |               |            |          |                   |            |
| 19970826            | 26-Aug-97  | 12-Sep-97 | 18              | 26            | 11.4       | 7.1      | 29.2              | HY, RF      |
| 19970920            | 20-Sep-97  | 02-Nov-97 | 7               | 19            | 7.1        | 5.3      | 24.6              | HY          |
| 19971027            | 27-Oct-97  | 02-Nov-97 | 41              | 60            | 14.9       | 7.9      | 56.7              | HY, LP      |
| 19971225            | 25-Dec-97  | 28-Dec-97 | 5               | 13            | 8.4        | 5        | 13.8              | HY          |
| 19980128            | 28-Jan-98  | 02-Mar-98 | 34              |               |            |          |                   |            |
| 19991012            | 12-Oct-99  | 14-Oct-99 | 3               | 5             | 8.1        | 4.8      | 17.2              | TR          |
| 20000118            | 18-Jan-00  | 23-Jan-00 | 6               | 11            | 13.3       | 8.3      | 17.1              |            |
| 20000201            | 01-Feb-00  | 07-Feb-00 | 7               | 20            | 7.9        | 5.9      | 11.7              |            |
| 20000216            | 16-Feb-00  | 19-Feb-00 | 4               | 7             | 11.5       | 10       | 13.8              | HY          |
| 20000306            | 06-Mar-00  | 16-Mar-00 | 11              | 18            | 10         | 6        | 47.2              | HY, LP      |
| 20000515            | 15-May-00  | 18-May-00 | 4               | 10            | 7.5        | 5.9      | 17.1              | HY          |
| 20000814            | 14-Aug-00  | 30-Aug-00 | 17              | 17            | 24.6       | 10       | 47.2              | RF          |
| 20000924            | 24-Sep-00  | 27-Sep-00 | 4               | 11            | 11         | 6.8      | 15.9              | RF          |
| 20010112            | 12-Oct-00  | 02-Oct-00 | 9               | 13            | 15.7       | 8.9      | 26.9              | RF          |
| 20011116            | 16-Nov-00  | 04-Mar-01 | 109             |               |            |          |                   |            |
| 20030110            | 10-Jan-03  | 14-Jan-03 | 5               | 4             | 29.8       | 27       | 37.3              | LP          |
| 20030129            | 29-Jan-03  | 06-Feb-03 | 9               | 9             | 23         | 17.3     | 30                | LP          |
| 20050912            | 12-Sep-05  | 15-Sep-05 | 4               | 4             | 15.5       | 14.6     | 18                | HY          |
| 20051017            | 17-Oct-05  | 29-Oct-05 | 13              | 64            | 4.5        | 1.7      | 20.6              |             |
| 20051104            | 04-Nov-05  | 06-Nov-05 | 3               | 10            | 5.6        | 3.6      | 12.5              |             |
| 20051122            | 22-Nov-05  | 26-Nov-05 | 5               | 4             | 21.2       | 19       | 22                |             |
| 20060319            | 19-Mar-06  | 21-Mar-06 | 3               | 5             | 12.2       | 10.6     | 14.7              | LP, RF      |
| 20060713            | 13-Jul-06  | 19-Jul-06 | 7               |               |            |          |                   |             |
| 20060904            | 04-Sep-06  | 08-Sep-06 | 5               | 21            | 2.8        | 1.6      | 13                | HY          |
| 20070108            | 08-Jan-07  | 10-Jan-07 | 3               | 9             | 1.6        | 0.9      | 7.1               | LP          |

(Continued)
August 1997, three further similar cycles were identified by variations in hybrid seismicity, the occurrence of Vulcanian explosions and other surface observations (Table 2.2). Recognition of the emerging multi-week cyclicity in August had led to forecasts of dome collapse/explosion sequences for the following months (B. Voight pers. comm. 2012) such that some of these events (e.g. September, November and December 1997 collapses) were somewhat anticipated (Kokelaar 2002; Young et al. 2002).

There was a notable interaction between the 50 day cycles and sub-daily cycles discussed earlier; the abrupt onset of the longer cycles would coincide with increased amplitude and frequency of inflation cycles, identified in tiltmeter inflation trends and explosion occurrence (Sparks & Young 2002). The observations of 1997 have become recognized as the ‘type’ examples of 50 day cycles, to which other cases are compared hereafter. Similarity in estimated extruded lava volumes recorded for each of the five cycles (Table 2.2) prompted the suggestion that, perhaps, cycles were controlled by a volume capacitor (Sparks & Young 2002).

The overprinting of shorter, sub-daily cycles on 50 day cycles in 1997 demonstrates how it is possible for the surface expression of the longer cycles to be swamped by shorter-term variability. A single ‘50 day’ cycle was identified in Phase 2 from 23 November 1999 to 8 January 2000 (Young et al. 2003), and several were recognized in the Phase 3 data (Loughlin et al. 2010). In the absence of tilt data, 50 day cycles might be indicated by sudden increases in seismic or surface activity; initial earthquake swarms (hybrid, LP or VT); changes in the character of sub-daily cycles, if present; periods during which approximately 30 Mm$^3$ lava is extruded; ground deformation signals; and changes in the orientation of dome growth.

Figure 2.5 shows an illustrative analysis of seismic data recorded during the whole eruption, indicating the occurrences of sub-annual cyclicity. We use the total triggered seismic event count here as an indicator of the daily level of activity during the eruption. This metric is one of the few quantitative measures that can encompass different types of event (e.g. volcanic earthquakes, rockfalls, pyroclastic flows) and was relatively consistently derived throughout the eruption. We note, however, that such simplistic interpretation of these data can be misleading and present these analyses as an indication of activity rather than as a quantitative proxy. The complete seismic count time-series record is shown in Figure 2.5a.

The second panel (Fig. 2.5b) shows the Morlet CWT power of this total event-count time series for pseudo-periods up to 28 weeks. The white dashed line indicates the 50 day pseudo-period.

---

### Table 2.1. Continued

| Episode ID (suffix) | Start Date | End Date | Duration (days) | No. of cycles | Period (h) Med. | Min | Max | Seismic* | Volcanic activity | References† |
|---------------------|------------|----------|-----------------|---------------|----------------|-----|-----|----------|------------------|-------------|
| 20070126            | 26-Jan-07  | 01-Feb-07| 7               | 18            | 10.5           | 2.7 | 22.6| LP       |                  | 17          |
| 20081215            | 15-Dec-08  | 02-Jan-09| 19              | 80            | 4.2            | 1.5 | 15.8| TR       | Growth on north flank of dome | 18          |
| a                   | 15-Dec-08  | 30-Dec-08| 16              | 80            | 4.2            | 1.5 | 15.8| TR       | Terminal explosions (2) | 18          |
| b                   | 31-Dec-08  | 02-Jan-09| 3               | 17            | 4              | 2.9 | 5.8 | TR, RF   |                  | 18          |
| 20091016            | 16-Oct-09  | 08-Jan-10| 85              | 64            | 4.9            | 1.5 | 29.9| TR       |                  | 18          |
| a                   | 16-Oct-09  | 31-Oct-09| 16              | 64            | 4.9            | 1.5 | 29.9| TR       |                  | 18          |
| b                   | 01-Nov-09  | 27-Nov-09| 27              | 105           | 5.3            | 1.4 | 25.5| HY, LP   |                  | 18          |
| c                   | 28-Nov-09  | 04-Dec-09| 7               | 43            | 4.6            | 2.7 | 6.8 | HY, TR   |                  | 18          |
| d                   | 05-Dec-09  | 08-Jan-10| 35              | 135           | 6              | 1.9 | 11  | HY, TR   |                  | 18          |
| 20100111            | 11-Jan-10  | 11-Feb-10| 32              | 51            | 6.3            | 1.7 | 40.7|         | Terminal dome collapse | 18          |
| a                   | 11-Jan-10  | 29-Jan-10| 19              | 51            | 6.3            | 1.7 | 40.7|         |                  | 18          |
| b                   | 30-Jan-10  | 11-Feb-10| 13              | 39            | 7.8            | 1   | 17  |         |                  | 18          |

The lines in italics are totals for the subsections that follow. Episodes are assigned an ID according to the start date. Some episodes are subdivided into sub-episodes, denoted by a suffix. Relevant discussions in the literature are referenced.

*HY, hybrids; LP, long-period earthquakes; RF, rockfalls; TR, tremor.
†1: Gardner & White (2002); 2: Robertson et al. (2000); 3: White et al. (1998); 4: MVO (1996); 5: Miller et al. (1998); 6: Dunkley et al. (2003); 7: Thompson (1996); 8: Thompson (2001); 9: Voight et al. (1998); 10: Voight et al. (1999); 11: Drutt et al. (2002); 12: Calder et al. (2002); 13: McGuire et al. (1996); 14: Bonadonna et al. (2002); 15: MVO Weekly Report 21-12-2001; 16: Hards et al. (2007a; b); 17: Stewart et al. (2009); 18: Cole et al. (2010).
### Table 2.2. Timing and details of individual approximately 50 day cycles since 1995

| Eruptive Phase | Period (days) | Observations | Notes |
|----------------|---------------|--------------|-------|
| **Start (CWT peak)** | **End** | | |
| **Phase 1** | | | |
| 17 May 1997* | 22 Jun 1997* | 36 | Tilt cycles, HY, explosions | 26 Mm³ lava extruded |
| (14 May 1997) | (41) | | | |
| 22 Jun 1997 | 31 Jul 1997 | 39 | Tilt, HY | 25 June 1997 collapse |
| (24 Jun 1997) | (46) | | | |
| 31 Jul 1997* | 21 Sep 1997* | 52 | Tilt, HY | 3 August 1997 collapse |
| (9 Aug 1997) | (43) | | | |
| 21 Sep 1997* | 4 Nov 1997* | 43 | Explosions | 21 September 1997 collapse |
| (21 Sep 1997) | (45) | | | |
| 4 Nov 1997* | 26 Dec 1997* | 52 | HY, switch in dome growth † | 4 and 6 November 1997 collapses |
| (5 Nov 1997) | (50) | | | |
| 27 Dec 1997* | 7 Feb 1998* | 43 | HY | 28 Mm³ lava extruded |
| (25 Dec 1997) | (50) | | | |
| 13 Feb 1998 | | 50 | Periodicity in seismic event count | Strong seismicity and ash venting* |
| **Phase 2** | | | |
| 27 Mar 2000 | 48 | | Periodicity in seismic event count | 1 Mm³ lava extruded |
| 14 May 2000 | 48 | | Periodicity in seismic event count | 6 Mm³ lava extruded |
| 1 Jul 2000 | 60 | | Periodicity in seismic event count | 13 Mm³ lava extruded |
| 30 Aug 2000 | 45 | | Periodicity in seismic event count | 6 Mm³ lava extruded |
| 14 Oct 2000 | 44 | | Periodicity in seismic event count | 11 Mm³ lava extruded |
| 27 Nov 2000 | 45 | | Periodicity in seismic event count | 14 Mm³ lava extruded |
| 1 Jan 2001 | 49 | | Periodicity in seismic event count | 12 Mm³ lava extruded |
| 1 Mar 2001 | 46 | | Peak immediately prior to short pause | No lava extruded |
| 5 Jun 2001 | 50 | | Periodicity in seismic event count | 13 Mm³ lava extruded |
| 25 Jul 2001 | 59 | | Periodicity in seismic event count | 12 Mm³ lava extruded |
| 22 Sep 2001 | 51 | | Periodicity in seismic event count | 20 Mm³ lava extruded |
| 12 Nov 2001 | 46 | | Periodicity in seismic event count | 12 Mm³ lava extruded |
| 28 Dec 2001 | 45 | | Periodicity in seismic event count | 9 Mm³ lava extruded |
| 11 Feb 2002 | 48 | | Periodicity in seismic event count | | |
| 2 Aug 2002 | 52 | | Periodicity in seismic event count | 9 Mm³ lava extruded |
| 23 Sep 2002 | 48 | | Periodicity in seismic event count | 30 Mm³ lava extruded |
| 10 Nov 2002 | 48 | | Periodicity in seismic event count | 27 Mm³ lava extruded |
| 18 Mar 2003 | 49 | | Periodicity in seismic event count | 18 Mm³ lava extruded |
| 6 May 2003 | 62 | | Periodicity in seismic event count | 18 Mm³ lava extruded |
| **Phase 3** | | | |
| 24 Oct 2005 | 25 Dec 2005 | 62 | HY, LP, VT, RF | c. 6 Mm³ DRE lava extruded |
| (18 Oct 2005) | | | | |
| 25 Dec 2005 | 7 Feb 2006 | 44 | HY | c. 22 Mm³ DRE lava extruded |
| 7 Feb 2006 | 5 Apr 2006 | 57 | Ash, high lava flux, VT, LP, RFs | c. 21 Mm³ DRE lava extruded |
| 5 Apr 2006 | 20 May 2006? | 45? | RF | Loughlin et al. (2010) # 2 & 3? |
| (16 May 2006?) | (47) | | | 20 May 2006 collapse |
| 2 Jul 2006? | 30 Aug 2006? | 59 | HY, LP | Loughlin et al. (2010) # 4 & 5? |
| (30 Aug 2006) | (48) | | | |
| 8 Sep 2006 | 5 Nov 2006? | 58 | Ash, high lava flux, VT, LP, RFs | c. 30 Mm³ DRE lava extruded |
| (30 Aug 2006) | (48) | | | Loughlin et al. (2010) # 9 & 10? |
| 25 Dec 2006 | 21 Feb 2007 | 58 | High flux, LP | c. 49 Mm³ DRE lava extruded |
| (2 Jan 2007) | (47) | | | Loughlin et al. (2010) # 13 & 14? |
| 21 Feb 2007 | 20 Apr 2007? | 58? | LP | c. 14 Mm³ DRE lava extruded |
| (27 Feb 2007) | | | | |
| **Phase 4** | | | |
| 8 Aug 2008 | 8 Oct 2008 | 61 | Phase 4a extrusion | |
| 2 Dec 2008 | 3 Jan 2009 | 32 | Phase 4b extrusion | |
| **Phase 5** | | | |
| 9 Oct 2009 | 20 Nov 2009 | 42 | RF, ground deformation, sub-daily cycles | Dome growth focused in the SW to west |
| (18 Oct 2009) | (52) | | c. 34 Mm³ lava erupted§ | |
| 20 Nov 2009 | 8 Jan 2010 | 49 | RF, HY, ground deformation, intense sub-daily cycles | Dome growth focused in the NE and east |
| (9 Dec 2009) | (53) | | c. 32 Mm³ lava erupted§ | |
| 8 Jan 2010 | 11 Feb 2010 | 37 | RF, explosions, sub-daily cycles | Dome growth focused in the west and NE |
| (31 Jan 2010) | (50) | | c. 10 Mm³ lava erupted§ | |

*Dates in italic indicate the 50 day cycle peak ascertained through wavelet analysis of seismic event count data, as described in the text. Corresponding ‘major cycles’ identified by Loughlin et al. (2010) are indicated for Phase 3. Extrusive phases are defined in Table 2.3. Values in italics represent cycles characterized through CWT analysis.

†Refers to cycle numbering allocated by Loughlin et al. (2010), also illustrated in (Fig. 2.6).

§Estimation interpolated from volume series in Figure 2.9: HY, hybrid seismicity; LP, long-period seismicity; VT, volcano-tectonic seismicity; RF, rockfalls; DRE, Dense Rock Equivalent.
At various stages of the eruption there have been repeating cycles with high transform power (yellow–red colours) at these periods. This indicates a strong positive correlation between the time series and a sine-wave-like wavelet with a frequency of $1/50$ days. The peak values in the CWT plot, along the dashed white line, indicate the timing of the ‘peak’ of the cycles in the data. Conversely, the troughs in the time-series cycles correspond to large negative values in the transform, which are not as readily identified using this colour scale. To highlight this point, Figure 2.5c shows the Morlet wavelet transform power of the seismic count time series at a scale equivalent to a 50 day pseudo-period; that is, the transform power along the white dashed line. The peaks, circled in red, indicate the timing of the peak of 50 day cycles, with absolute transform power exceeding 100. However, the period of cycles in the time-series data is not constant; deviation from the 50 day period line reduces transform power at that scale.

Figure 2.5b, c may be used together to assess the existence and significance of 50 day cyclicity in the seismic count data. The five cycles between 17 May 1997 and 7 February 1998 – documented by Sparks & Young (2002) (Table 2.2) – are represented by high-magnitude transform values, showing strong wavelet correlation (Fig. 2.5c). Transform peaks are generally within a few days of the observed cycles (Table 2.2). There is evidence from this analysis of 50 day cycles throughout the eruption, although it is notable that few cycles were identified in ‘real time’ until Phase 5, when the magnitude of the cycles was comparable to those in Phase 1. The cycles identified in Figure 2.5c during Phase 2 are listed in Table 2.2. With the exception of the cycles documented during Phase 1 and one during Phase 2 (discussed above), sub-annual cycles were generally not noted at the time in the MVO observations log, indicating that their surface expression was not well defined. Without such independent observations, the timings in Table 2.2 should be regarded as speculative. The volume estimates for the Phase 2 cycles have a lower average ($c. 14$ Mm$^3$) than the typical 20–30 Mm$^3$ range reported in Phases 1, 3 and 5. This reflects the apparently lower level of average eruption rate during Phase 2 (relative to Phases 1 and 3) and may be an artefact of the observations then (see Wadge et al. 2010) or may represent different dynamic conditions during Phase 2.

Out of a possible 10 or 11 cycles that could have occurred in Phase 3, there is evidence from LF seismic swarms for at least six. These are indicated in black in Figure 2.6. The onset of these cycles was mainly identified using seismic swarms based on evidence compiled from MVO reports for Phase 3 (Bass et al. 2005, 2006; Loughlin et al. 2006; Ryan et al. (2010). Cycles 3, 4 and 5 (Fig. 2.6, Table 2.2) also began with notable increases in lava flux. Banded tremor with 4 h periodicity occurred at the start of cycle 3. The end of cycle 3 is taken as 5 April 2006, which was identified as a point of changed behaviour based on AVTIS measurements and increased rockfall seismicity (Wadge et al. 2009). The three seismic swarms of 20 May, 25 June and 18 August 2006 could mark cycle boundaries (Fig. 2.6), but none is definitive. The wholesale collapse of 20 May 2006 may have changed the system equilibrium. Loughlin et al. (2010) defined 10 ‘major eruptive cycles’ within Phase 3 largely using observed switches in dome growth direction (in red,
Fig. 2.6. Timeline of Phase 3 (labelled monthly) showing potential limits of 50 day cycles. The vertical black lines are the dates (numbers below horizontal line) of evidence from, mainly, LF seismicity and high lava flux for the starts of the cycles (numbered with the DRE (Dense Rock Equivalent) volume in Table 2.2). The cycles identified by Loughlin et al. (2010), mainly on the basis of visual observations, are shown in red (cycle number above the line, date below the line). Grey bars indicate the peaks of wavelet-identified cycles, as in Figure 2.5.

Fig. 2.6. Timeline of Phase 3 (labelled monthly) showing potential limits of 50 day cycles. The vertical black lines are the dates (numbers below horizontal line) of evidence from, mainly, LF seismicity and high lava flux for the starts of the cycles (numbered with the DRE (Dense Rock Equivalent) volume in Table 2.2). The cycles identified by Loughlin et al. (2010), mainly on the basis of visual observations, are shown in red (cycle number above the line, date below the line). Grey bars indicate the peaks of wavelet-identified cycles, as in Figure 2.5.

The cycles had a mean duration of 28 days and a mean estimated erupted volume of 20 Mm$^3$ per cycle.

The wavelet analysis of seismic event count in Figure 2.5 can assist in reconciling these various interpretations, indicating that transform power is elevated at multiple frequencies. In fact, it appears that there is some concordance between the two approaches to identifying cycles, with pairs of the Loughlin et al. (2010) cycles fitting approximately into seismic-swarm cycles 3, 4 and 5. This fit is illustrated in Figure 2.6 and Table 2.2. The peaks of approximately 50 day cycles identified through wavelet analysis are included in Table 2.2 for comparison to those identified through independent compilation of MVO records. Although both sets of dates are based largely on seismic data, there are some notable differences. The 50 day cycles at this time were, again, relatively weakly defined, accounting for much of the ambiguity in defining precise time bounds of each cycle. The wavelet-picked start dates for the cycles tend to be a few days later than those picked based on LF seismicity alone. This is understandable in physical terms if there is a lag in the build-up of rockfall seismicity following increased lava flux at the start of the cycle (e.g. cycles 1, 4, 5 and 6 of Fig. 2.6).

Phase 4 comprised two short periods of lava extrusion, lasting about 62 (poorly constrained) and 33 days. Although these phases were too brief to exhibit multiple occurrences of 50 day cycles, it is reasonable to speculate that a common forcing mechanism controlled the duration of extrusion.

Phase 5 demonstrated marked fluctuations in activity with an approximately 50 day period. It is reasonable to interpret these common process has resulted in modulation of eruptive activity with a period of about 50 days. It is reasonable to interpret these observations as evidence of a persistent capacitor mechanism in the volcanic system that has been able to operate at different
times throughout the eruption. Costa et al. (2007) proposed a model in which the capacitor is an elastic-walled dyke joined to a cylindrical conduit above. Hautmann et al. (2009) modelled the elastic storage and release of magma in a dyke, and demonstrated that such conduit geometry could explain surface flux and deformation data. Recent analyses of SO2 flux time series have revealed comparable 50 day cycles in degassing data (Nicholson et al. 2013). Degassing cycles are offset in time but demonstrably correlated with cycles in seismicity, deformation and lava extrusion, which will provide additional constraint on future models of causative processes.

Multi-annual cycles

A striking feature of the SHV eruption has been the intermittency of lava extrusion (Wadge et al. 2014b). Between 1995 and the time of writing there have been five major phases of extrusion (Phases 1–5: Table 2.3), each followed by a period of repose when no lava was erupted (Pauses 1–5). The ‘on–off’ nature of extrusion on Montserrat is, perhaps, the most obviously apparent cyclic feature of the eruption. Within each phase, lava flux has varied considerably, as we have already discussed, and Phases 2 and 4 were each interrupted by brief periods of no extrusion (Table 2.3). Whether or not these interruptions should be classed as pauses in their own right becomes a matter of semantics, but in this section we shall treat them as secondary to the main extrusive trends. Taking this into account, the average duration of lava extrusion phases has been 1.7 years and the average pause interval (including the current state) has been 1.4 years.

Figure 2.8 gives an overview of some of the key observations made since 1995, showing the frequency of rockfall events (including pyroclastic flows), an example ground deformation time series, earthquake frequency and estimated lava flux. All of the time series show a distinct response to lava extrusion. With the onset of each phase, the continual addition of lava to the dome causes an increase in rockfall frequency, as discussed earlier. The first-order trends in ground deformation (Fig. 2.8b) (Odbert et al. 2014) have been a striking feature of the eruption. Pauses in lava extrusion have been accompanied by near-linear inflation of the volcanic edifice, while near-linear deflationary signals were recorded during extrusive phases. Several authors have used such deformation measurements to investigate the cause of the repeating inflation cycles; these are summarized by Odbert et al. (2014) and will not be discussed in depth here. However, a commonly accepted inference is that approximately 1–3 yearly cycles have been controlled by the recharging of a shallow magma reservoir (top at c. 5 km) until it reaches a state where it is ready to erupt and sustain another extrusive phase (e.g. Foroozan et al. 2011).

An interesting observation of Figure 2.8 is an apparent bimodal distribution in pause and phase duration; Phases 4 and 5, and the pauses preceding them, were each considerably shorter than the three earlier phases and pauses. These observations raise the question of whether the preconceived inferences of shallow reservoir recharge are valid or, alternatively, whether the volcanic system underwent some fundamental change between Phases 3 and 4. Perhaps Phases 4 and 5 are the combined effect of a repetition of the mechanism that triggered the first three extrusive phases. In this case, it would appear that the energy available to drive this
fourth phase of eruption was significantly less than on previous occasions. However, the activity during Phases 4b and 5 was notably vigorous (Wadge et al. 2014b) in comparison to earlier phases, which suggests some change in the mechanisms feeding the eruption.

Figure 2.9 shows the comparative evolution of Phases 1, 2, 3 and 5 in terms of the normalized cumulative volume of lava extruded. While the time series for Phase 5 is less well populated due to the shorter duration of extrusion, it is evident that the onset of lava extrusion had a much higher initial flux. By contrast, Phases 1 and 3 began gradually, with flux becoming about constant in the middle part of each phase (Wadge et al. 2010). Phase 2 had a higher initial flux than 1 and 3 but a lower average flux (Table 2.3), which was maintained at a relatively constant rate. All of these phases showed a period of waning output at the end. Like Phase 5, Phase 4b was short-lived, with high average flux (Table 2.3). The characteristic distinction demonstrated to date, therefore, is that prolonged extrusion phases (1–3) began with low lava flux and continued for 2–3 years, whereas shorter phases (4b and 5) were marked by higher flux but lasted only a few months on average. This distinction would support the conclusion that there was, indeed, some change in the eruptive mechanism between Phases 3 and 4. However, there is no evidence that this will not change again if activity resumes. The elapsed time since the end of Phase 5 has already surpassed the duration of the first two pauses at the time of writing (November 2012).

In addition to the phases of extrusion, there is other evidence of cyclic activity at similar timescales. Nicholson et al. (2013) suggest that LP cycles of SO2 flux may have occurred, with a period of between about 2 and 3 years. The authors note that there has been no apparent correspondence between SO2 and phases of lava extrusion since 1995, and attribute the cycles to storage and release of gas in the volcanic system that is somewhat independent of extrusion dynamics.

**Multi-decadal cycles**

The occurrence of repeating ‘volcano-seismic crises’ at approximately 30 year intervals was noted prior to the onset of the 1995 eruption (Shepherd et al. 1971; Wadge & Isaacs 1987, 1988). Typically, the crises were defined by significant seismic activity and sometimes elevated fumarolic activity. We have revisited the available data and written records, and have identified several other episodes of unrest. It is notable that some misleading inferences pertaining to some of these events have begun to become entrained in recent literature, and we attempt to present...
Table 2.3. Timing and details of 2–3 year extrusive cycles between 1995 and 2010

| Phase | Start          | End            | Duration (days) | DRE volume (Mm$^3$) | Extrusion Rate (m$^3$·s$^{-1}$·d$^{-1}$) | Character (% of days that included sub-daily cycles)          |
|-------|----------------|----------------|-----------------|---------------------|------------------------------------------|---------------------------------------------------------------|
| Phase 1 | 15 Nov 95     | 10 Mar 08      | 846             | 331                 | 4.5                                      | Initial phreatomagmatic explosions and large to moderate collapses common (37%) |
| Pause 1 |               |                |                 |                     |                                          | Increased dome collapses and mild explosive activity after 3 July 1998 |
| Phase 2 | 27 Nov 99     | c. 27 Jul 03   | 1339            | 336                 | 2.9                                      | Largest dome built to date after two major collapses. Late increase in pyroclastic flows, ends in wholesale collapse of dome. Two short intervals of no extrusion (27%) |
| (a) 27 Nov 99 | 2 Mar 01      |                |                 |                     |                                          |                                                                 |
| (b) 10 May 01 | 31 May 02     |                |                 |                     |                                          |                                                                 |
| (c) 20 Jul 02 | 28 Jul 03     |                |                 |                     |                                          |                                                                 |
| Pause 2 |               |                | 735             | –                   | –                                        | Very low residual activity                                      |
| Phase 3 | 1 Aug 05 (+3 days)$^a$ | 4–20 Apr 07   | 627             | 282                 | 5.3                                      | Precursory phreatomagmatic. One wholesale collapse, ends with the largest dome in place (8%) |
| Pause 3 |               |                | 465             | –                   | –                                        | Very low residual activity                                      |
| Phase 4 | 28 Jul 08$^†$ | 3 Jan 09      | 158             | 39                  | 2.9                                      | Two short episodes. Explosions and extrusion on the western flank of the dome (20%) |
| (a) 28 Jul 08$^†$ | 9 Oct 08     |               | (66)$^b$        |                     | (6.8)$^b$                                |                                                                 |
| (b) 2 Dec 08 | 3 Jan 09      |                |                 |                     |                                          |                                                                 |
| Pause 4 |               |                | 273             | –                   | –                                        | Very low residual activity                                      |
| Phase 5 | 9 Oct 09      | 11 Feb 10     | 125             | 74                  | 6.8                                      | Extrusion to the west, south and north. Explosions later. Ends in large north-directed partial collapse (90%) |
|         |               |                |                 |                     |                                          |                                                                 |

At the time of writing, there has been very low residual activity and resumption of lava extrusion since the end of Phase 5.

$^a$Exact date determined due to low cloud cover.

$^†$Or the following day, in Universal time (UTC).

$^b$Averaged over the two periods of active extrusion in Phase 4.

the original evidence for discussion. Montserrat was first encountered by Europeans in 1493 but there is little written record of natural events prior to the nineteenth century. Therefore, there is no evidence to either support or dismiss earlier occurrences. Some of the historical evidence is ambiguous or fleeting in detail and must be interpreted with care.

In this section, we present the evidence of historical seismic crises and attempt to constrain their timing, given the available information (Table 2.4). The differences in how each crisis was monitored and recorded make it difficult to directly compare separate events. However, we are confident that at least three and possibly four seismic crises occurred prior to 1995. Figure 2.10 illustrates the timing of crisis events, and shows the intensity of all seismic events (volcanic and tectonic) felt on Montserrat for the same period. Also shown are two VT swarms that occurred between 1840 and 1850. He speculated that it probably formed as a result of the great regional earthquake of 8 February 1843. This event was probably the last major interplate thrust earthquake in the northern half of the Lesser Antilles subduction zone (Bernard & Lambert 1988). Its likely location is shown in the northern half of the Lesser Antilles subduction zone

This event was probably the last major interplate thrust earthquake as a result of the great regional earthquake of 8 February 1843. The end of the crisis is less clear still, and has been reported variously as 1898, 1899 and 1900. MacGregor (1938) even cited

1896–1900

Evidence of a volcano-seismic crisis around the turn of the twentieth century was recorded in the contemporary newspaper articles and Commissioners’ reports discussed by Sapper (1903) and Perret (1939). Felt and damaging earthquakes were documented at Gages, Tar River, Harris and other parts of the east–west belt between Centre Hills and Soufrière Hills. Most commentators, including Robson (1964), report that seismic activity began on 23 April 1897. However, Milne (1902) documented ‘many small earthquakes’ following heavy rain on 29 November 1896 and went on to note that, ‘For forty years before there had been but few noticeable shocks. Since the rainfall the springs give off more gas, and silver is blackened three miles away’ (p. 152).

Major damage to stone-built churches and houses, and road-blocking landslides were common, particularly in 1898 and on 20 October 1900 (Perret 1939).

The end of the crisis is less clear still, and has been reported variously as 1898, 1899 and 1900. MacGregor (1938) even cited

1840s

There is some circumstantial evidence that a volcano-seismic crisis occurred in the 1840s. English (1930), who more extensively documented some of the early narrative about Montserrat, recorded that the Gages soufrière (fumarole) came into existence between 1840 and 1850. He speculated that it probably formed as a result of the great regional earthquake of 8 February 1843. This event was probably the last major interplate thrust earthquake in the northern half of the Lesser Antilles subduction zone (Bernard & Lambert 1988). Its likely location is shown in the northern half of the Lesser Antilles subduction zone

Evidence of a volcano-seismic crisis around the turn of the twentieth century was recorded in the contemporary newspaper articles and Commissioners’ reports discussed by Sapper (1903) and Perret (1939). Felt and damaging earthquakes were documented at Gages, Tar River, Harris and other parts of the east–west belt between Centre Hills and Soufrière Hills. Most commentators, including Robson (1964), report that seismic activity began on 23 April 1897. However, Milne (1902) documented ‘many small earthquakes’ following heavy rain on 29 November 1896 and went on to note that, ‘For forty years before there had been but few noticeable shocks. Since the rainfall the springs give off more gas, and silver is blackened three miles away’ (p. 152).

Major damage to stone-built churches and houses, and road-blocking landslides were common, particularly in 1898 and on 20 October 1900 (Perret 1939).

The end of the crisis is less clear still, and has been reported variously as 1898, 1899 and 1900. MacGregor (1938) even cited
reports of ongoing activity until 1902 but these were deemed to probably be incorrect by Powell (1937). Feuillet et al. (2011) argued, on the basis of Coulomb stress modelling, that the 1843 earthquake imparted a large stress on the Montserrat–Bouillante Fault System running through Montserrat to Guadeloupe and that this was the source of the trigger for the significant regional earthquake near Guadeloupe on 29 April 1897, and perhaps the initiation of volcano-seismic activity on Montserrat 1 week earlier.

1933–1937

The first seismic crisis to be studied scientifically was the subject of a Royal Society expedition, reported by MacGregor (1938) and Powell (1938). However, by the time the expedition reached Montserrat, in the spring of 1936, the intensity of activity had greatly diminished. Nonetheless, over 1000 felt local earthquakes were reported — some strong enough to damage stone buildings, probably at Modified Mercalli Intensity VIII — making it the most intense of the crises seismically. Perret (1939) studied the crisis from 1934 onwards and noted its similarities to the previous crisis, including increased fumarolic degassing, especially hydrogen sulphide, from the Galway’s and two Gages soufrières. Powell (1938) estimated that the hypocentre locations were spread along an east–west belt to the east of St George’s Hill. The seismic record documented by Perret (1939) shows a gradual increase from 1934, peaking in May 1935. We consider that another, larger peak in the seismic event record in November 1935 must be contaminated by the aftershock sequence of a major regional earthquake, which occurred to the north of Montserrat on 10 November 1935. Perret (1939) reported that this event, and a subsequent sequence of earthquakes were located between Montserrat and the island of Redonda to the NW. He reported damage to buildings on Montserrat and a large landslide on Redonda. Activity declined through 1936–1937 until it reached a very low level and the monitoring instrumentation was withdrawn.

1966–1967

The crisis starting in March 1966 and continuing until November 1967 was monitored using seismometers deployed by the University of the West Indies Seismic Research Unit (Shepherd et al. 1971). More than 700 earthquakes were recorded instrumentally, with locations across southern Montserrat in a WNW-trending band, and with depths between 3 and 13 km. The average depth of earthquakes decreased from 5 to 3 km between April and September 1966, and then increased to about 10 km by November 1967. Fewer than 50 felt earthquakes were reported and there were no reports of damaged buildings, suggesting a significantly lower intensity than the previous two crises.

Tilt measurements made at three sites indicated inflation of the volcanic edifice between July and October 1966, and a deflationary trend from January to March 1967, with rates of up to 0.3 m rad (c. 0.6 mm over 2 km) per day. No changes were reported in fumarolic activity, except that the heat flow decreased by a factor of 4 between late 1966 and 1 year later. Shepherd et al. (1971) interpreted the observations as the ascent of magma beneath SHV (or to its SE) until about August 1966, and subsequent magma descent.

1977–1985

The seismic network deployed in 1966 remained operational after the crisis had ended, and in 1977 it recorded the first of three episodes of VT earthquake swarms, followed by two more in

| Start | End | Period (years) | Crisis duration (days) | Observations |
|-------|-----|----------------|------------------------|--------------|
| 8 Feb 1843 | 1850? | – | ? | Fumarolic activity? |
| 29 Nov 1896 | 1899 | 57? | Volcano-seismic crisis, Fumarolic activity |
| Apr 1934 | Jun 1936 | 37.3 | 1127 | Volcano-seismic crisis, Fumarolic activity |
| 14 Jan 1966 | Dec 1967 | 31.8 | 716 | Volcano-seismic crisis, deformation |
| 15 Aug 1977 | 16 Aug 1977 | – | 1 | Seismic swarm |
| 31 Mar 1978 | 20 Apr 1978 | – | 20 | Seismic swarms |
| 6 May 1985 | 7 May 1985 | – | 1 | Seismic swarm |
| 24 Jan 1992 | 18 Jul 1995 | 26.0 | 1271 | (Precursory) seismic crisis |
| 18 Jul 1995 | – | – | – | Eruption |

Short-lived seismic swarms, listed in italics, were generally lower intensity and recorded instrumentally following installation of permanent seismometers. Equivalent swarms occurring earlier than 1966 would probably not have been detected.
1978 and 1985 (Latchman 1995). Table 2.4 lists the dates of these swarms individually. The earthquakes were generally lower intensity (only a few were felt) and the VT swarms were much shorter than the earthquake swarms of earlier crises (days rather than years). The largest events of the 1977–1985 crises reached only V on the Modified Mercalli Intensity scale (MMI), compared to MMI VII in the 1933–1937 crisis (Robson 1964). We note that the absence of permanent instrumentation prior to 1966 may have precluded observation of earlier, low-intensity crises such as this because individual or sporadic felt earthquakes are a common occurrence in the Eastern Caribbean generally and would probably not warrant reporting.

1992–1995

The seismic crisis that immediately preceded the onset of the 1995 eruption at SHV was monitored instrumentally, but there were few other observations of the soufrières or deformation, for example. The seismicity of the crisis has not been reported in detail, although it has been summarized by numerous authors (Latchman 1995; Ambeh & Lynch 1996; Shepherd et al. 2003). In August and September 1992, there were three earthquake swarms, each comprising tens of individual events. Elevated seismic activity persisted, albeit at a lower rate, into 1994. The pre-eruption crisis reached its peak in November–December 1994 when the event rate exceeded 100 per day. Although earthquakes were more frequent than in the 1930s crisis, they were smaller in magnitude (fewer were felt). As this crisis transitioned into the phreatic eruption (Boudon et al. 1998; Hammouya et al. 1998), the volcano’s hydrothermal system was not involved with the onset of the eruption (Boudon et al. 1998; Hammouya et al. 1998).

Shepherd et al. (1971) concluded that the crises represented ‘failed eruptions’, in which magma did not reach the surface to erupt. This argument was supported by the eventual eruption of the SHV in 1995. There are two main aspects of the periodic nature of these events that are of interest to our discussion: the quasi-regular timing of the crises; and the duration of each episode. Adopting the inferences of Shepherd et al. (1971), the processes driving the intrusion and ascent of magma beneath the volcano were modulated such that the ‘active’ part of each cycle recurred at approximately three-decade intervals. Several authors have drawn an association between large, felt regional earthquakes and volcanic activity on Montserrat. Figure 2.10 shows the timing of all regional earthquakes (MMI > IV) since 1825 and how intensely they were felt on Montserrat. This catalogue incorporates the events reported by Robson (1964) and subsequent updates (L. Lynch pers. comm. 2011). While most of the seismic events occur around the same time as volcanic unrest, the largest events post-date crisis onsets (i.e. in the 1840s and 1930s). We, therefore, reject regional tectonic earthquakes as the direct trigger of seismic crises but do not rule out the likely influence of major earthquakes on the regional stress field and, perhaps, the volcanic system generally.

The long period of recurrence is also indicative of a mechanism in the deep part of the volcanic system. Candidate mechanisms could include crustal (or, perhaps, mantle) processes. Such an example might be the injection or mixing of fresh basic magma into the bottom of the magmatic plumbing system, each time reinvigorating the shallower system, driving buoyant magma ascent and/or seismogenic reservoir or conduit processes. The absence of obvious progression from one crisis to the next may suggest that the three-decade mechanism reflects adjustment to the existing magmatic system rather than the genesis of a new one. After repeat ‘attempts’, these disturbances supply sufficient energy to the system to trigger the eventual eruption. Recurrent seismic crises have been a feature of many arc volcanoes (Lindsay et al. 2005); a greater understanding and record of these observations may serve in the interpretation of events at other potentially active volcanoes.

The duration of each seismic crisis (Fig. 2.10, Table 2.4) was relatively constant, typically about 2–4 years. The consistency of this timing may reflect the process or sequence of processes operating at each occurrence. For example, one might expect that a similar batch of ‘energy’ (e.g. in the form of heat, magma,
gas) was involved for each crisis, resulting in a similar mechanical or hydrothermal response from the volcano each time. The apparent progressive decrease in the seismic energy involved in the crises could reflect a process where the same volume of crust was repeatedly subject to stresses of equivalent magnitude. Alternatively (or additionally), the country rock becoming more ductile (and less seismogenic) could be a result of progressive heating over the course of the repeated crises. Once SHV began erupting, the boundary conditions of the system changed. It is notable that the duration of each seismic crisis is slightly longer but similar in duration to the extrusive phases during the eruption. This may be coincidental, or may reflect a characteristic modulating frequency of the volcanic system between the source and the surface vent.

Conclusions

We have identified and catalogued the existence of cyclic behaviour in eruptive activity at the SHV at four timescales: sub-daily (hours), sub-annual (weeks), multi-annual and multi-decadal scales. Although the source mechanisms of these different cyclic signals are not the same, their existence is evidence of systematic behaviour at the volcano on a range of scales. It is generally understood that longer-period signals at volcanoes correspond to deeper processes, and this is borne out in the observations we have summarized.

Shallow (<1–2 km) conduit processes are responsible for rapid fluctuations in lava flux over hours to tens of hours that have been detected, intermittently, throughout the eruption. These processes may include plug-formation, rheological stiffening, magma fracturing and stick–slip behaviour. Seismic and deformation observations suggest recurrent cycles with a period of around 50 days, and these have been interpreted in term of an elastic-walled dyke at a depth of between 1–2 and 5 km acting as a magma capacitor (Costa et al. 2007; Hautmann et al. 2009). Inflation–deflation cycles associated with crustal (6–19 km) magma reservoirs are highly correlated with lava efflux cycles, with periods of a few years, although we note that this has changed in character some-

high-amplitude, asymmetric character of these cycles (Fig. 2.2) is generally consistent with this.

The influence of a deeper, larger part of the volcanic system on a shallower system seems intuitive. Sparks & Young (2002) speculated that at least some of the cyclic behaviour seen at SHV may be controlled primarily by the volume capacitance of the mechanism(s). In the example outlined above, dyke deflation cycles – each associated with a ‘batch’ of magma approximately tens of million cubic metres in volume – evidently influence the character of cycles. The changing supply rate of magma from the dyke into the shallow conduit alters a critical boundary condition to the plug-process, and can thus affect the change in the rate of plug formation and ejection (e.g. Diller et al. 2006). Disruption to the state of equilibrium in which the cyclic mechanism operates thus precipitates a change in the character of the cyclicity. The reciprocal influence which the development of sub-daily cyclicity may have on deeper processes, if any, is less clear. It is conceivable that the changes in the time-averaged resistance of flow out of the dyke due to conduit mechanisms, for example, may feed back to modulate the development of longer period cycles. Perhaps interactions such as these have controlled the variable intensity of the sub-daily and sub-annual cyclicity throughout the eruption; the most clearly defined examples of both types of behaviour have been coincident (occurring in Phases 1 and 5).

Looking deeper in the volcanic system, the dyke inflation mechanism may interact with the reservoir inflation mechanism that feeds it, although the evidence for such a relationship is less clear. Higher-volume, deeper components of the magmatic plumbing system (e.g. the crustal reservoirs v. the intermediate dyke) are likely to exert greater overall control on the progression of the eruption because of their greater mechanical inertia (Melnik & Costa 2014). However, it is apparent that each of the processes, and the mechanisms by which they are able to feed back to one another, are important in determining surface volcanic activity. Another consideration is that the surface expression of any mechanisms operating on short timescales deeper in the system would probably be damped or buffered by shallower parts of the system and may not be able to generate a coherent or detectable surface signal.

Several key monitoring techniques have been vital to the identification and analysis of cyclic phenomena. Visual indications of varying surface activity often provide the earliest sign of cyclic activity at the volcano. Seismic data then offer a versatile means of summarizing activity at the volcano quantitatively. The time-averaged amplitude of seismicity, represented by RSAM, is an indicator of the eruption intensity during phases of lava extrusion. This has proven to be a useful tool for short-term (hours to months) assessment of cyclicity at sub-diurnal timescales, when contributions from surface activity dominate the signal. Records of individually categorized events, such as rockfalls, tremor and various types of earthquake, have been exploited to demonstrate the existence of cyclic eruptive activity at longer timescales, and we identify numerous cycles that had previously not been detected.

However, seismic data alone cannot unambiguously identify eruptive cyclic phenomena. Evidence from other monitoring techniques and records can be used to corroborate seismic observations and vice versa. As the eruption has continued, the longevity and quality of monitoring data streams on MVO has grown. Recent eruptive episodes have generated a rich, multi-parameter dataset that allows close scrutiny of cyclic events. These observations demonstrate the value of multi-parametric observation. In order to capture cyclic phenomena, it is important to maintain a monitoring strategy with the appropriate coverage, resolution and sensitivity for the phenomena under observation. We have summarized some of the key observations from Phase 5, when strong cyclic activity was apparent at timescales of hours and days. SHV also has a small network of Sacks–Evertson dilometers that have proven to be sensitive to strain transients associated with major explosive/collapse events (e.g. Chardot et al. 2010). Unfortunately, they are apparently located too far (>5 km)
from the upper conduit of SHV to be able to detect any strain signals associated with the sub-daily cycles.

The observation and measurement of cyclic phenomena at volcanoes has obvious appeal. If it appears that the system(s) driving the eruption can operate under a deterministic regime, there exists potential to forecast future cyclic events. This has been achieved to some degree of success at short timescales when, for example, the expectation of an imminent increase in surface activity may be used to guide deployment of equipment or workers in the field. This has become possible in cases where the number of observed cycles has become large enough that some degree of confidence could be placed in simplistic first-order forecasting. However, for longer-term cycles, fewer data points are available on which to form the basis of a statistical forecast model. The continuation of robust and thorough monitoring programme at SHV will assist in strengthening our knowledge and understanding of cyclic phenomena. By understanding this element of activity onMontserrat, we move towards the ability to characterize deterministic mechanisms that control the state of eruption at a range of timescales.

The work reported here is the culmination of careful observations and reporting of volcanic events at SHV. We are indebted to all staff and colleagues of the MVO for their diligence in this regard. We would particularly like to thank M. Hughes, T. Christopher, A. Stinton, S. Loughlin, V. Bass, P. Smith, M. Ripepe, D. Delle Dome, C. Hayer, L. Lynch, J. Latchman, J.-C. Komorowski and P. Cole for the valuable contributions their efforts have made to this report. The paper has benefited from helpful reviews by B. Voight and S. De Angelis.

References

Ambrasey, 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, 9–12 October 1996, Kingston, Jamaica. Volume 1. Unit for Disaster Studies, Department of Geography and Geology. The University of West Indies, Jamaica, 30.

Bass, V., Jones, L. et al. 2005. Montserrat Volcano Observatory Report to the Scientific Advisory Committee, Montserrat, September 2005. Montserrat Volcano Observatory, Open File Report 04/05. Montserrat Volcano Observatory, Flemmings, Montserrat.

Bass, V., Christopher, T. et al. 2006. Montserrat Volcano Observatory Report to the Scientific Advisory Committee, Montserrat, March 2006. Montserrat Volcano Observatory, Open File Report 02/06. Montserrat Volcano Observatory, Flemmings, Montserrat.

Bernard, P. & Lambert, J. 1988. Subduction and seismic hazard in the northern Lesser Antilles: revision of the historical seismicity. Bulletin of the Seismological Society of America, 78, 1965–1983.

Bonadonna, C., Mayberry, G. et al. 2002. Tephra fallout in the eruption of Soufrière Hills Volcano, Montserrat. In: Drutt, T. & Kokeelaar, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 483–516.

Boudon, G., Vilmant, B., Komorowski, J-C., Ildefonse, P. & Semet, M. 1998. The hydrothermal system at Soufrière Hills Volcano, Montserrat (West Indies): characterization and role in the on-going eruption. Geophysical Research Letters, 25, 3693–3696. http://dx.doi.org/10.1029/98GL00885

Calder, E., Luckett, R., Sparks, R. & Voight, B. 2002. Mechanisms of lava dome instability and generation of rockfalls and pyroclastic flows at Soufrière Hills Volcano, Montserrat. In: Drutt, T. & Kokeelaar, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 173–190.

Cole, P., Bass, V. et al. 2010. Report to the Scientific Advisory Committee on Montserrat Volcanic Activity: Report on Activity Between 15 August 2009 and 28 February 2010. Montserrat Volcano Observatory, Open File Report 10-01 2010. Montserrat Volcano Observatory, Flemmings, Montserrat.

Cole, P. D., Smith, P. et al. 2014a. Ash venting occurring both prior to and during lava extrusion at Soufrière Hills Volcano, Montserrat, from 2005 to 2010. In: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, Memoirs, 39, 71–92. http://dx.doi.org/10.1144/M39.4

Cole, P. D., Smith, P. J., Stinton, A. J., Odbert, H. M., Bernstein, M. L., Komorowski, J. C. & Stewart, R. 2014b. Vulcanian explosions at Soufrière Hills Volcano, Montserrat between 2008 and 2010. In: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, Memoirs, 39, 93–111, http://dx.doi.org/10.1144/M39.5

Coleridge, H. N. 1825. Six Months in the West Indies. John Murray, London.

Carn, S. A. & Prata, F. J. 2010. Satellite-base constraints on explosive SO2 release from Soufrière Hills Volcano, Montserrat. Geophysical Research Letters, 37, L00E22. http://dx.doi.org/10.1029/2010GL042509

Charidot, L., Voight, B. et al. 2010. Explosion dynamics and microbarometer observations, Soufrière Hills Volcano, Montserrat: 2008–2009. Geophysical Research Letters, 37, L00E24. http://dx.doi.org/10.1029/2010GL044661

Christopher, T., Edmonds, M., Humphreys, M. C. S. & Herd, R. A. 2010. Volcanic gas emissions from Soufrière Hills Volcano, Montserrat 1995–2009, with implications for mafic magma supply and degassing. Geophysical Research Letters, 37, L00E04, http://dx.doi.org/10.1029/2009GL041325

Costa, A., Melnik, O., Sparks, R. S. J. & Voight, B. 2007. Control of magma flow in dykes on cyclic lava dome extrusion. Geophysical Research Letters, 34, L02303, http://dx.doi.org/10.1029/2006GL027466

Costa, A., Wadge, G. & Melnik, O. 2012. Cyclic extrusion of a lava dome based on a stick–slip mechanism. Earth and Planetary Science Letters, 337–38, 39–46, http://dx.doi.org/10.1016/j.epsl.2012.05.011

De Angelis, S. & Henton, S. M. 2011. On the feasibility of magma fracture within volcanic conduits: constraints from earthquake data and empirical modelling of magma viscosity. Geophysical Research Letters, 38, L19310, http://dx.doi.org/10.1029/2011GL049297

Diller, R. Clarke, A. B., Voight, B. & Neri, A. 2006. Mechanisms of conduit plug formation: implication for Vulcanian explosions. Geophysical Research Letters, 33, L02302, http://dx.doi.org/10.1029/2006GL027391

Drutt, T., Young, S. et al. 2002. Episodes of cyclic Vulcanian explosive activity with fountain collapse at Soufrière Hills Volcano, Montserrat. In: Drutt, T. & Kokeelaar, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 281–306.

Dunkley, P., Edmonds, M., Herd, R. & Thompson, G. 2003. Summary of Volcanic Activity and Monitoring Data, with Particular Emphasis on the Second Phase of Dome Building November 1999 to June 2003. Montserrat Volcano Observatory, Technical Report 03/01. Montserrat Volcano Observatory, Flemmings, Montserrat.

Edmonds, M., Pyle, D. & Oppenheim, C. 2001. A model for degassing at the Soufrière Hills Volcano, Montserrat, West Indies, based on geochemical data. Earth and Planetary Science Letters, 186, 159–173, http://dx.doi.org/10.1016/s0012-821x(01)00242-2

English, T. S. 1930. Records of Montserrat. Manuscript held at Montserrat National Trust.

Feuillet, N., Beauducel, F. & Tappeiner, P. 2011. Tectonic context of moderate to large historical earthquakes in the Lesser Antilles and mechanical coupling with volcanoes. Journal of Geophysical Research, 116, B10308, http://dx.doi.org/10.1029/2011JB008443

Gardner, C. & White, R. 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: Drutt, T. H. & Kokeelaar, B. P. (eds) The Eruption of Soufrière
selective pressurization and stick–slip extrusion. Activity at Soufrie`re Hills Volcano, Montserrat. Geological Society, London, Special Publications, 307, 263–288

Hautmann, S., Syers, S., Christopher, T., Luckett, R., Bax, V., & Syers, T. 2007b. Report to the Scientific Advisory Committee, Montserrat, 8th Meeting, March 2007. Montserrat Volcano Observatory, Open File Report 07/01. Montserrat Volcano Observatory, Flemmings, Montserrat.

Harford, C., Pringle, M. S., Sparks, R. S. J. & Young, S. 2002. The volcanic evolution of Montserrat using 4Ar/3Ar geochronology. In: Drutt, T. H. & Kokelaar, B. P. (eds) The Eruption of Soufrie`re Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 285–297.

Hautmann, S., Gotsmann, J., Sparks, R. S. J., Costa, A., Melnik, O., & Voight, B. 2009. Modelling ground deformation caused by oscillating overpressure in a dyke conduit at Soufrie`re Hills Volcano, Montserrat. Tectonophysics, 471, 87–95, http://dx.doi.org/10.1016/j.tecto.2008.10.021

Kokelaar, B. P. 2002. Setting, chronology and consequences of the eruption of Soufrie`re Hills Volcano, Montserrat (1995 to 1999). In: Drutt, T. H. & Kokelaar, B. P. (eds) The Eruption of Soufrie`re Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 1–44.

Komorowski, J.-C. & Wadge, G. 2009. Chronology of PYROCLASTIC Flow-Related Phenomena – Eruptive Period of Dec 2 2008 to Jan 5 2009. Montserrat Volcano Observatory, Unpublished Report. Montserrat Volcano Observatory, Flemmings, Montserrat.

Latchman, J. 1995. Pre-1995 Montserrat Seismo-Volcanic Activity. Technical Report, Seismic Research Unit, University of the West Indies, Jamaica.

Lenski, N., Sparks, R., Navon, O. & Lyakhovsky, V. 2008. Cyclic activity at Soufrie`re Hills Volcano, Montserrat: degassing-induced pressurization and stick–slip extrusion. In: Lane, S. J. & Gilbert, J. S. (eds) Fluid Motions in Volcanic Conduits: A Source of Seismic and Acoustic Signals. Geological Society, London, Special Publications, 265, 169–188.

Lindsay, J. M., Robertson, R. E. A., Shepherd, J. B. & Ali, S. (eds) 2005. Volcanic Hazard Atlas of the Lesser Antilles. Seismic Research Unit, The University of the West Indies, Trinidad and Tobago, West Indies.

Loughlin, S., Baptie, B. et al. 2006. Montserrat Volcano Observatory Report to the Scientific Advisory Committee, Montserrat, August 2006. Montserrat Volcano Observatory, Open File Report 06/07. Montserrat Volcano Observatory, Flemmings, Montserrat.

Loughlin, S. C., Luckett, R. et al. 2010. An overview of lava dome evolution, dome collapse and cyclicity at Soufrie`re Hills Volcano, Montserrat, 2005–2007. Geophysical Research Letters, 37, L06E16, http://dx.doi.org/10.1029/2010GL042547

MacGregor, A. 1938. The Royal Society Expedition to Montserrat, B.W.I. The Volcanic History and Petrology of Montserrat, with observations on MT Pele, in Martinique. Philosophical Transactions of the Royal Society. London B, 229, 69–90, http://dx.doi.org/10.1098/rstb.1938.0002

Martin, R. 1837. History of the West Indies, Comprising Jamaica, Honduras, Trinidad, Tobago, Grenada, Bahama and Virgin Isles, Volume 2. Whittaker & Co., London.

McGuire, B. J., Norton, G. E., Sparks, R. S. J., Robertson, R. E. & Young, S. R. 1996. Report of the Explosive Event of 17–18 September, 1996. Montserrat Volcano Observatory, Special Report I. Montserrat Volcano Observatory, Flemmings, Montserrat.

Melnik, O. & Sparks, R. S. J. 1999. Nonlinear dynamics of lava dome extrusion. Nature, 402, 37–41.

Melnik, O. & Sparks, R. S. J. 2005. Controls on conduit magma flow dynamics during lava dome building eruptions. Journal of Geophysical Research, 110, B02209, http://dx.doi.org/10.1029/2004JB003183

Melnik, O. & Costa, A. 2014. Dual-chamber-conduit models of nonlinear dynamics behaviour at Soufrie`re Hills Volcano, Montserrat. In: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) The Eruption of Soufrie`re Hills Volcano, Montserrat, from 2000 to 2010. Geological Society, London, Memoirs, 39, 61–69, http://dx.doi.org/10.1144/M39.3

Miller, A., Stewart, R. et al. 1998. Seismicity associated with dome growth and collapse at the Soufrie`re Hills Volcano, Montserrat. Geophysical Research Letters, 25, 3401–3404, http://dx.doi.org/10.1029/98GL01778

Milne, J. 1902. Volcanic Eruptions in the West Indies. Nature, 66, 151–153, http://dx.doi.org/10.1038/066151a0

Murray, T. L. & Endo, E. T. 1992. A Real-Time Seismic-Amplitude Measurement System (RSAM). In: Ewart, J. W. & Swanson, D. A. (eds) Monitoring Volcanoes: Techniques and Strategies Used by the Staff of the Cascades Volcano Observatory, 1980–90. United States Geological Survey, Bulletin, 1566, 5–10.

MVO 1996. Scientific Reports 1 to 31: December 1995 to June 1996. Montserrat Volcano Observatory, Open File Report 96/19. Montserrat Volcano Observatory, Flemmings, Montserrat.

Neuberg, J., Baptie, B., Luckett, R. & Stewart, R. C. 1998. Results from the broadband seismic network on Montserrat. Geophysical Research Letters, 25, 3661–3664, http://dx.doi.org/10.1029/98GL01441

Neuberg, J. W., Tuffen, H., Collier, L., Green, D., Powell, T. & Dingwell, D. 2006. The trigger mechanism of low-frequency earthquakes on Montserrat. Journal of Volcanology and Geothermal Research, 153, 37–50, http://dx.doi.org/10.1016/j.jvolgeores.2005.08.004

Nicholson, E. J., Mather, T. A., Pyle, D. M., Odber, H. M. & Christopher, T. 2013. Cyclical patterns in volcanic degassing revealed by SO2 flux timeseries analysis: an application to Soufrie`re Hills Volcano, Montserrat. Earth and Planetary Science Letters, 375(1–2), 209–221, http://dx.doi.org/10.1016/j.epsl.2013.05.032

Nugent, N. 1811. An Account of ‘The Sulphur’, or ‘Soufrie`re’ of the Island of Montserrat. Transactions of the Geological Society, London, Series 1, 1, 185–190.

Odber, H. M. 2009. Observing and understanding lava flux dynamics. PhD thesis, University of Reading.

Odber, H. M. & Wadge, G. 2009. Time series analysis of lava flux. Journal of Volcanology and Geothermal Research, 188, 305–314, http://dx.doi.org/10.1016/j.jvolgeores.2009.09.005

Odber, H. M., Ryan, G. A., Mattioli, G. S., Hautmann, S., Gottsmann, J., Fournier, N. & Herd, R. A. 2014. Volcano geodesy at the Soufriére Hills Volcano, Montserrat: a review. In: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) The Eruption of Soufrie`re Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, Memoirs, 39, 195–217, http://dx.doi.org/10.1144/M39.1

Oppenheimer, C., Edmonds, M., Francis, P. & Burton, M. 2002. Variation in HCl/SO2 gas ratios observed by Fourier transform spectroscopy at Soufrie`re Hills Volcano, Montserrat. In: Drutt, T. & Kokelaar, B. P. (eds) The Eruption of Soufrie`re Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 621–639.

Percival, D. & Walden, A. 1993. Spectral Analysis for Physical Applications: Multitaper and Conventional Univariate Techniques. Cambridge University Press, Cambridge.

Percival, D. & Walden, A. 2000. Wavelet Methods for Time Series Analysis. Cambridge University Press, Cambridge.

Perrett, F. 1939. The Volcano-Seismic Crisis at Montserrat 1935–1937. Carnegie Institution of Washington, Washington, DC.

Powell, C. 1937. Royal Society Expedition to Montserrat, B.W.I. Preliminary Report on Seismic observations. Proceedings of the Royal Society A: Mathematical and Physical Engineering Sciences, A158, 479–494.
Sparks, R. S. J. & Young, S. 2002. The eruption of Soufrière Hills Volcano, Montserrat (1995–1998): overview of scientific results. In: Drutt, T. & Kokelaar, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 45–69.

Shepherd, J., Tomblin, J. & Woo, D. 1971. Volcano-seismic crisis in Montserrat, West Indies, 1966–67. Bulletin of Volcanology, 35, 143–162, http://dx.doi.org/10.1007/BF02596813

Shepherd, J. B., Robertson, R., Latchman, J. & Lynch, L. 2003. Pre-cursory Activity to the 1995 Eruption of Soufrière Hills Volcano, Montserrat. Seismic Research Unit, Technical Report, University of the West Indies, Jamaica.

Stewart, R., Bass, V. et al. 2009. Report for the Scientific Advisory Committee on Montserrat Volcanic Activity. Montserrat Volcano Observatory, Open File Report, 09/01. Montserrat Volcano Observatory, Flemmings, Montserrat.

Stinton, A. J., Cole, P. D., Odbert, H. M., Christopher, T., Avarid, G. & Bernstein, M. 2014a. Dome growth and valley fill during Phase 5 (8 October 2009–11 February 2010) at the Soufrière Hills Volcano, Montserrat. In: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, Memoirs, 39, 113–131, http://dx.doi.org/10.1144/M39.6

Stinton, A. J., Cole, P. D., Stewart, R. C., Odbert, H. M. & Smith, P. 2014b. The 11 February 2010 partial dome Collapse at Soufrière Hills Volcano, Montserrat. In: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, Memoirs, 39, 133–152, http://dx.doi.org/10.1144/M39.7

Thomas, M. E. & Neuberg, J. 2012. What makes a volcano tick - a first explanation of deep multiple seismic sources in ascending magma. Geology, 40, 351–354, http://dx.doi.org/10.1130/G32868.1

Voight, B., Sparks, R. S. J. et al. 1999. Magma flow instability and cyclic activity at Soufrière Hills Volcano, British West Indies. Science, 283, 1138–1142

Wadge, G. & Isaacs, M. C. 1988. Mapping the Volcano Hazards from the Soufrière Hills Volcano, Montserrat, West Indies, using an image processor. Journal of the Geological Society, London, 145, 541–555.

Wadge, G., Odbert, H. & Macfarlane, D. 2009. An AVTIS-based DEM of Soufrière Hills for October 2008. Technical Report, Informal Report to Montserrat Volcano Observatory.

Wadge, G., Herd, R., Ryan, G., Calder, E. S. & Komorowski, J.-C. 2010. Lava production at Soufrière Hills Volcano, Montserrat: 1995–2009. Geophysical Research Letters, 37, L00E03, http://dx.doi.org/10.1029/2009GL041466

Wadge, G., Cole, P., Stinton, A., Komorowski, J.-C., Stewart, R., Toombs, A. C. & Legendre, Y. 2011. Rapid topographic change measured by high resolution satellite radar at Soufrière Hills Volcano, Montserrat, 2008–2010. Journal of Volcanology and Geothermal Research, 199, 142–152, http://dx.doi.org/10.1016/j.jvolgeores.2010.10.011

Wadge, G., Macfarlane, D. G., Odbert, H. M., Stinton, A., Robertson, D. A., James, R. M. & Pinkerton, H. 2014a. AVTIS observations of lava dome growth at Soufrière Hills Volcano, Montserrat: 2004 to 2011. In: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, Memoirs, 39, 229–240, http://dx.doi.org/10.1144/M39.13

Watson, I. M., Oppenheimner, C. et al. 2000. The relationship between degassing and ground deformation at Soufrière Hills Volcano, Montserrat. Journal of Volcanology and Geothermal Research, 98, 117–126.

Watts, R. B., Herd, R. A., Sparks, R. S. J. & Young, S. R. 2002. Growth patterns and emplacement of the andesite lava dome at the Soufrière Hills Volcano, Montserrat. In: Drutt, T. H. & Kokelaar, B. P. (eds) The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 115–152.

White, R., Miller, A., Lynch, L. & Power, J. 1998. Observations of hybrid seismic events at Soufrière Hills Volcano, Montserrat: July 1995 to September 1996. Geophysical Research Letters, 25, 3657–3660, http://dx.doi.org/10.1029/98GL02427

Wildewiayanti, C., Clarke, A., Elsworth, D. & Voight, B. 2005. Geodetic constraints on the shallow magma system at Soufrière Hills Volcano, Montserrat. Geophysical Research Letters, 32, L11309, http://dx.doi.org/10.1029/2005GL022846

Wylie, J., Voight, B. & Whitehead, J. A. 1999. Instability of magma flow from volatile-dependent viscosity. Science, 285, 1883–1885.

Young, S. R., Voight, B. et al. 2002. Hazard implications of small-scale edifice instability and sector collapse: a case history from Soufrière Hills Volcano, Montserrat. In: Drutt, T. H. & Kokelaar, B. P. (eds) The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. Geological Society, London, Memoirs, 21, 349–362.

Young, S. R., Voight, B. & Duffell, H. J. 2003. Magma extrusion dynamics revealed by high-frequency gas monitoring at Soufrière Hills Volcano, Montserrat. In: Oppenheimner, C., Pyle, D. M. & Barclay, J. (eds) Volcanic Degassing. Geological Society, London, Special Publications, 213, 198–230.