

An overview of lava dome evolution, dome collapse and cyclicity at Soufrière Hills Volcano, Montserrat, 2005–2007

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[1] The third episode of lava dome growth at Soufrière Hills Volcano, Montserrat was characterised by higher average magma discharge rates than either previous dome growth episode at this volcano and yet fewer collapses. During sustained dome growth at moderate-high average rates ($>6 \text{ m}^3/\text{s}$), we identified 2–6 week discharge pulses that each supplied c.20 Mm^3 magma from depth. Our observations are consistent with some existing models but we explain discrepancies by a combination of higher volatile contents and higher ascent rates. Cycles of c. 11–16 days were evident in rockfall, LP rockfall and shallow LP earthquake counts related to dome growth and degassing. We speculate that degassing at the conduit margins together with stick-slip conduit flow may drive these cycles. Only one major collapse $>10 \text{ Mm}^3$ occurred during the third episode (on May 20, 2006) as a new magma pulse entered the dome and coincided with heavy rainfall. **Citation:** Loughlin, S. C., R. Luckett, G. Ryan, T. Christopher, V. Hards, S. De Angelis, L. Jones, and M. Strutt (2010), An overview of lava dome evolution, dome collapse and cyclicity at Soufrière Hills Volcano, Montserrat, 2005–2007, *Geophys. Res. Lett.*, 37, L00E16, doi:10.1029/2010GL042547.

1. Introduction

[2] The ongoing eruption of the andesitic Soufrière Hills Volcano (SHV) began in 1995 and up until April 2008 there had been three episodes of lava dome growth. During the third episode, there were higher average discharge rates ($\sim 5.6 \text{ m}^3/\text{s}$) than either previous dome growth episode [Ryan *et al.*, 2010], yet there were fewer dome collapses. There were also fewer hybrid earthquakes and the 20 May 2006 dome collapse had no hybrid precursors [Luckett *et al.*, 2008].

[3] Recognising cycles as the magmatic system evolves and understanding what controls them is critical if scientists are to effectively forecast eruptive activity. We identify cyclic activity on various scales from minutes to months based mainly on observational data and seismic data (rockfall counts) and test these against existing models. Our

paper provides an overview of the third episode of dome growth in terms of observed extrusion cycles, related seismicity and dome collapses. The implications for magma supply and volcanic hazards are discussed.

2. Previous Cyclic Activity and Dome Growth at SHV

[4] Modelling the dynamics of magma flow in conduits has shown that periodic behaviour over weeks to years is to be expected as a result of non-linear processes related to degassing, gas exsolution, pressurisation and rheological stiffening in the shallow conduit [e.g., Melnik and Sparks, 1999, 2002, 2005; Costa *et al.*, 2007].

[5] Voight *et al.* [1998] described short cycles in 1997 defined by tilt, seismicity and eruptive activity over periods of 4 to 36 hours. They were explained by pressurisation in the upper conduit related to non-linear dynamics of magma flow with stick-slip flow [e.g., Denlinger and Hoblitt, 1999; Voight *et al.*, 1999; Wylie *et al.*, 1999]. Eruptive cycles over 6–7 weeks were recognised in 1997 and were commonly associated with major dome collapses [Sparks and Young, 2002; Watts *et al.*, 2002]. Watts *et al.* [2002] demonstrated how fluctuating discharge rates during these pulses related to emplacement of specific features in the dome. High discharge rates ($>7 \text{ m}^3/\text{s}$) resulted in fluid lava capable of axisymmetric lateral spreading ('pancake' lobes), moderate rates ($2\text{--}7 \text{ m}^3/\text{s}$) in the formation of shear lobes, and low rates ($<2 \text{ m}^3/\text{s}$) resulted in the formation of spines and megaspines. Costa *et al.* [2007] explained these 6–7 week cycles by modelling magma flow through an ellipsoidal dyke in an elastic medium extending from a magma chamber at a depth of 5 km to within $\sim 1 \text{ km}$ of the surface where there is a smooth transition to a cylindrical conduit (assuming constant source pressure).

3. Monitoring Data and Methods

[6] We use seismic data from the Montserrat Volcano Observatory (MVO) broadband network [Luckett *et al.*, 2008] and photographs of the dome taken every minute by fixed cameras at Perches Mountain 1 km to the SE and Windy Hill 3 km to the N (Figure 1) to identify cyclic activity. Dome volumes were calculated using photo methods [Ryan *et al.*, 2010] and ground-based LiDAR [Jones, 2006]. All volumes and discharge rates are dense rock equivalent (DRE) as calculated by Sparks *et al.* [1998] and Ryan *et al.* [2010]. All times are local.

4. Cycles of Lava Dome Growth

[7] Based mainly on evidence from time-lapse photographs, helicopter photographs and other observations, we

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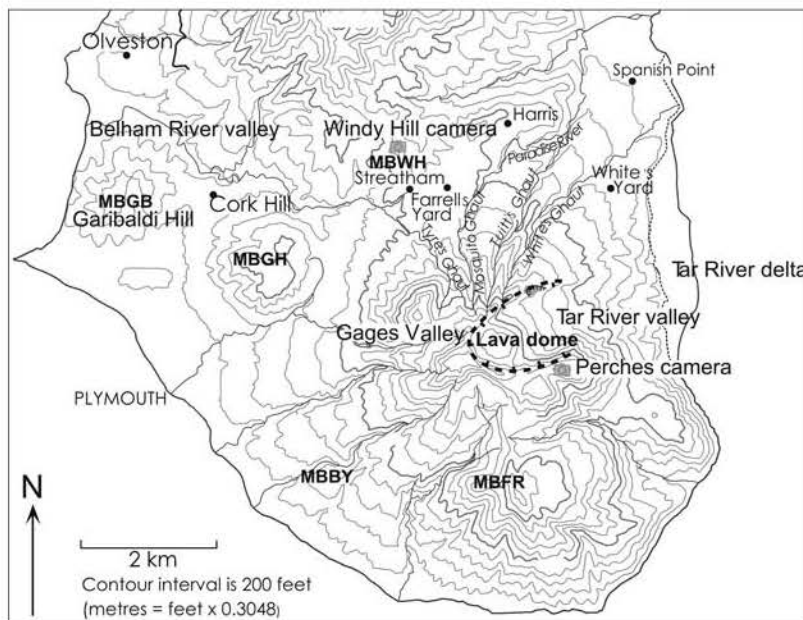


Figure 1. Map of Montserrat showing seismic and camera monitoring sites and locations referred to in the text.

identified 15 dome growth stages including 10 major 2–6 week pulses in discharge rate (Table 1). The onset of each major pulse was characterised by a switch in extrusion direction, a sudden increase in discharge rate and emplacement of a new feature (e.g., shear lobe, megaspine or pancake lobe). Discharge rates declined towards the end of each cycle.

[8] The first growth stage began on August 1, 2005 and was characterised by average discharge rates increasing to c. $4 \text{ m}^3/\text{s}$ in January 2006 [Ryan *et al.*, 2010]. By January 27, 2006, 23 Mm^3 of magma had been discharged [Ryan *et al.*, 2010] and the dome had a height of 170m above its base. On February 9, very vigorous ash venting and degassing from a single vent marked the onset of a major eruptive pulse (growth stage 2). From February 10, fluid lava was discharged at high average rates ($>15 \text{ m}^3/\text{s}$) forming a flat-topped pancake lobe that raised the dome height by over

50 m. Subsequent major pulses (growth stages 3–5) comprised emplacement of subvertical shear lobes and megaspines at average rates $>6 \text{ m}^3/\text{s}$. Following a total dome collapse on May 20, 2006 when the dome had reached a height of 328m, dome growth resumed almost immediately. Very vigorous ash and gas venting on August 31 preceded another pulse of fluid lava (growth stage 9) at high discharge rates. Later pulses were again dominated by subvertical shear lobes and megaspines (Table 1).

[9] Dome growth ended by April 20, 2007, leaving a dome of volume 203 Mm^3 (non-DRE) and height $\sim 370\text{m}$ [Ryan *et al.*, 2010].

5. Seismic Characteristics

[10] Rockfalls, long period (LP) rockfalls and LP earthquake signals dominated dome growth seismicity [Luckett *et*

Table 1. Growth Stages With Estimated Duration and Volume, Major Eruptive Cycles in Bold^a

Growth Stage	Time Period (DD/MM/YY)	Duration (days)	Approximate Volume ($\times 10^6 \text{ m}^3$)	Main Feature
1	1/8/05–8/2/06	192	~ 23	Pulsatory, shear lobes, spines, pancake lobes, endogenous growth
2	9/2/06–24/2/06	15	~ 17	Pancake lobe
3	25/2/06–5/4/06	40	~ 11	NE/E lobe
4	6/4/06–5/5/06	30	~ 21	N/summit lobe
5	6/5/06–19/5/06	14	~ 14	SW lobe
6	20/5/06–27/6/06	38	~ 27	Pulsatory, endogenous
7	28/6/06–8/8/06	42	~ 24	Pulsatory, shear lobes, spines, pancake lobes, endogenous growth
8	9/8/06–30/8/06	22	~ 16	E and W lobes
9	31/8/06–20/9/06	21	$\sim 17^*$	Pancake lobe
10	21/9/06–5/11/06	46	$\sim 35^*$	NE/E lobe
11	6/11/06–11/12/06	36	$\sim 28^*$	N lobe
12	12/12/06–23/12/06	12	$\sim 9^*$	SW lobe
13	24/12/06–20/1/07	27	$\sim 21^*$	NW lobe
14	21/1/07–28/2/07	39	~ 25	SW lobe
15	1/3/07–(4–20)/4/07	35+	~ 12	E/summit lobe

^aVolumes are estimated using average 2–4 week discharge rates [Ryan *et al.*, 2010]. Volumes estimated using a 6 month average discharge rate so subject to greater uncertainty.

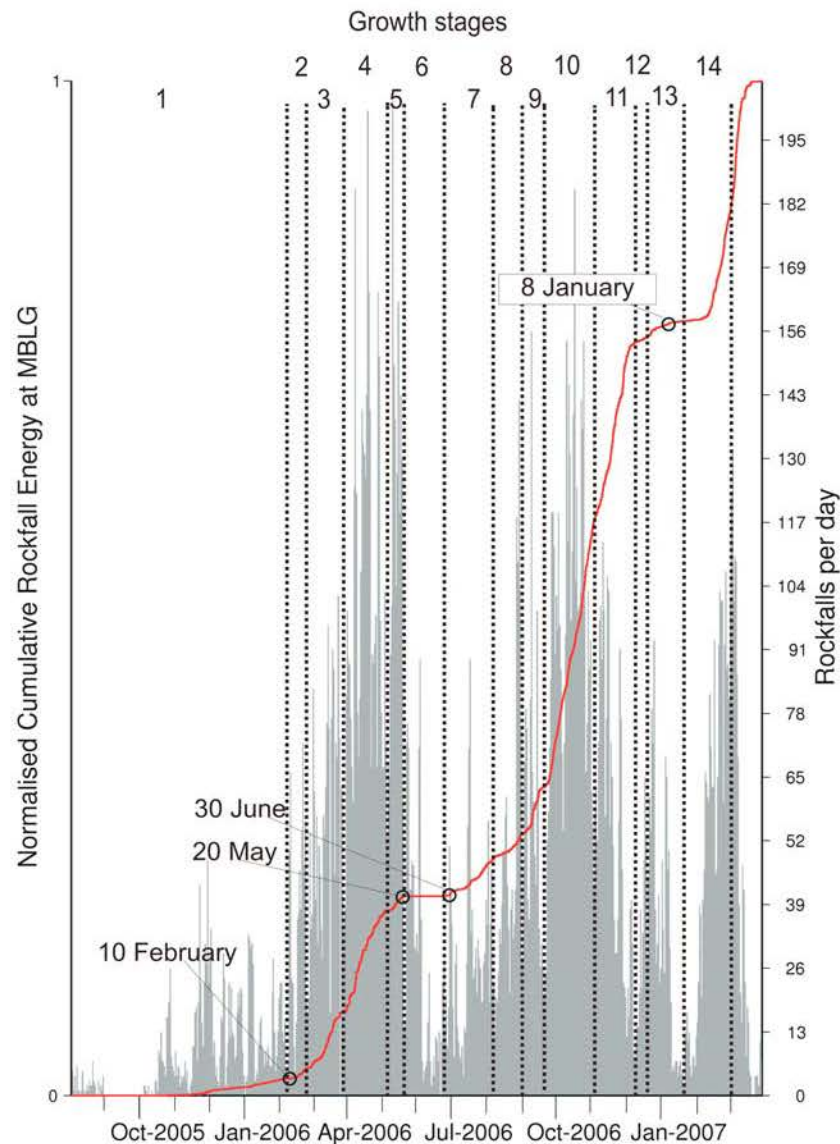


Figure 2. Rockfall counts and cumulative rockfall energy showing major eruptive events and growth stages, August 1, 2006 to April 30, 2007.

al., 2008]. LP rockfall signals are thought to be caused by violent degassing at the surface of the dome that triggers a nearby rockfall [Luckett *et al.*, 2002, 2008]. LP earthquakes are interpreted as pressurisation in the conduit.

[11] There was a steady increase in cumulative rockfall energy from February until early May and from September to mid December 2006 (Figure 2). On May 6 and December 12, the extrusion direction switched to the southwest, where rockfall runout length is restricted by the crater wall. The May 20, 2006 and January 8, 2007 dome collapses both followed a switch from southwest to northerly extrusion.

[12] Cycles in seismic data were on a time scale of days and were therefore independent of the 2–6 week cycles in discharge rate. A 10–11 day rockfall periodicity was evident from February 1 2006 until June 4 2006 (Figure 3). These cycles broke down (and counts reached low levels) on June 8, 2006. Similarly, from July 1 2006, a c.16 day cycle began from August 29 to January 2007 (Figure 2).

[13] The relationship between extrusion rates and rockfall counts is not straightforward [e.g. Luckett *et al.*, 2008] and depends on dome morphology and the location of lava extrusion. For example, there may be a short lag between the onset of high extrusion rates at the summit and increased rockfall activity (e.g. April 5–7, 2006) [Wadge *et al.*, 2008].

6. Dome collapses

[14] Dome collapses typically took place during or soon after the sudden onset of a 2–6 week pulse in discharge rate and change in extrusion direction.

6.1. May 20, 2006

[15] A switch to northerly extrusion began early on May 20 2006. At 05:52, a large LP earthquake immediately preceded the start of this total dome collapse and occurred at the peak of rainfall intensity on Garibaldi Hill (Figure 1). The seismograms from five seismic stations show a pro-

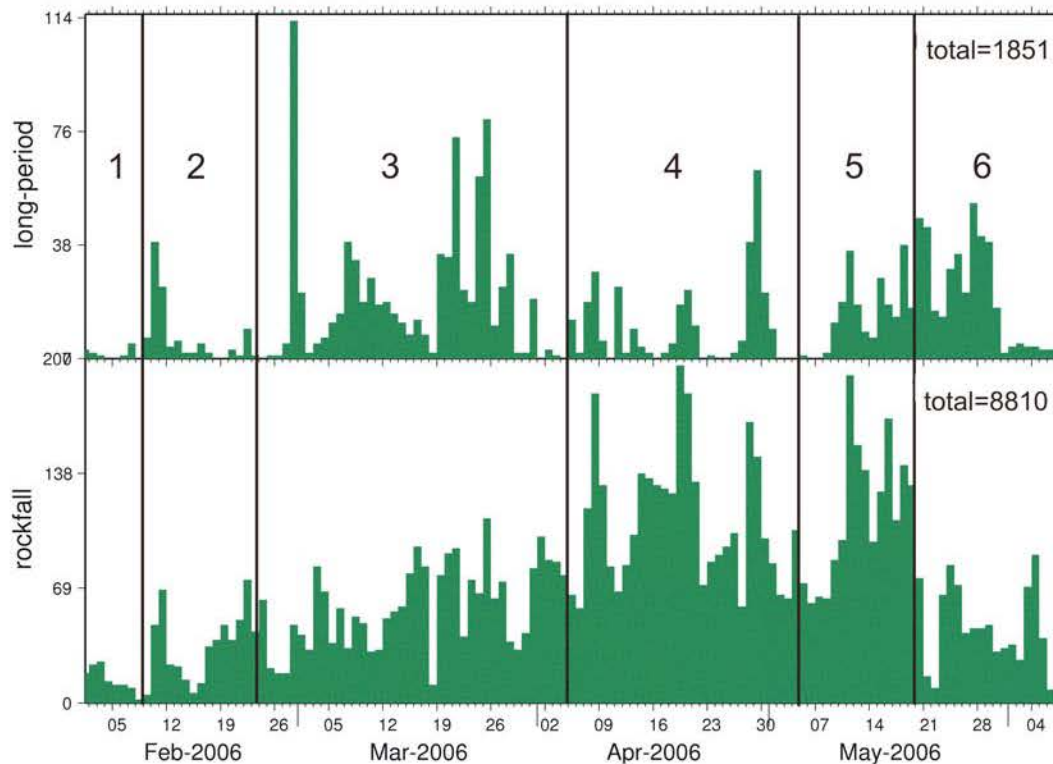


Figure 3. Rockfall, LP rockfall and LP earthquake counts and growth stages, February 1 to June 8, 2006.

longed buildup of increasingly large block-and-ash flows lasting c. 90 minutes. The collapse was intense between 07:32 and 08:07 with two marked peaks including high and low frequency signals, followed by a rapid decline over c. 30 minutes (Figure 4) [Loughlin *et al.*, 2006]. Two sharp low amplitude/high energy release signals at 07:36 and 07:43 are interpreted as vertical explosions that resulted in observed showers of lithic and rare pumice fragments (<5%) over northern parts of the island (lithics <6 cm at Olveston). Block-and-ash flows mainly travelled down Tar River Valley and surges swept up to 3 km northwards from Tar River delta reaching Spanish Point and White's Yard in a similar manner to the 2003 collapse [Edmonds and Herd, 2005].

[16] The total collapse volume was 97 Mm³, comprising 85.2 Mm³ dome and talus measured on May 18, 0.7 Mm³ lava extruded between 18–20 May (assuming average discharge rates) [Ryan *et al.*, 2010], and 11 Mm³ older dome and talus remnants. The collapse resulted in the rapid release of c. 200 ktons of SO₂ into the stratosphere [Prata *et al.*, 2007; Carn *et al.*, 2007] and an ash plume to c. 17 km. There was a gas-to-collapse-volume ratio of ~2.0 kt SO₂ per Mm³ collapsed material. This compares to ~0.4 kt SO₂ per Mm³ collapsed material at previous dome collapses [Edmonds *et al.*, 2003].

6.2. June 30, 2006

[17] Two swarms of small LP earthquakes occurred June 25–27 and June 29–30, accompanied by frequent rockfalls. The second swarm culminated in a partial dome collapse into Tar River valley. The collapse started at 12:51 LT and pyroclastic flows reached the sea at 12:58. It lasted just 18 minutes and removed ~2 Mm³ andesite from the dome.

6.3. January 8, 2007

[18] A switch in discharge direction began on December 24, 2006, with vigorous ash venting and dome-collapse pyroclastic flows 200–300 m down Tyr's Ghaut (Figure 1). There was vigorous ash venting from 05:30 on January 8, followed by three audible explosive pulses at 06:04–06:05, 06:05–06:10 and 06:15, the last of which coincided with the largest pyroclastic flow [Hards *et al.*, 2008; De Angelis *et al.*, 2007], which travelled c. 5.5 km down the Belham Valley reaching Cork Hill for the first time since September 1997. Flows also travelled down Paradise River to Harris and surges swept across Farrells to Streatham and Harris. Flows included dense andesite and pumice (much more pumice than May 20, 2006) consistent with rapid decompression of the freshly emplaced lobe interior. The ash plume rose to c. 10 km. Subsequently, activity continued with pyroclastic flows of 1.5 km runout every 5–7 minutes for the next 90 minutes. Each flow was preceded by a small pulse of ash venting. Plagioclase-hosted inclusions in pumice from this collapse contain 6.2 wt% H₂O [Humphreys *et al.*, 2009] significantly higher than previous analyses (4.5 wt% H₂O) [Barclay *et al.*, 1998] and suggest magma storage at high pressures.

7. Discussion

[19] The volume of magma erupted during 2005–7 was similar to that in 1995–8 but it was discharged at higher average rates [Ryan *et al.*, 2010]. Emplacement of fluid pancake lobes accompanied by vigorous degassing was more common, implying these pulses had high magma ascent rates and limited degassing-induced crystallisation. Subsequent pulses produced megaspines or shear lobes

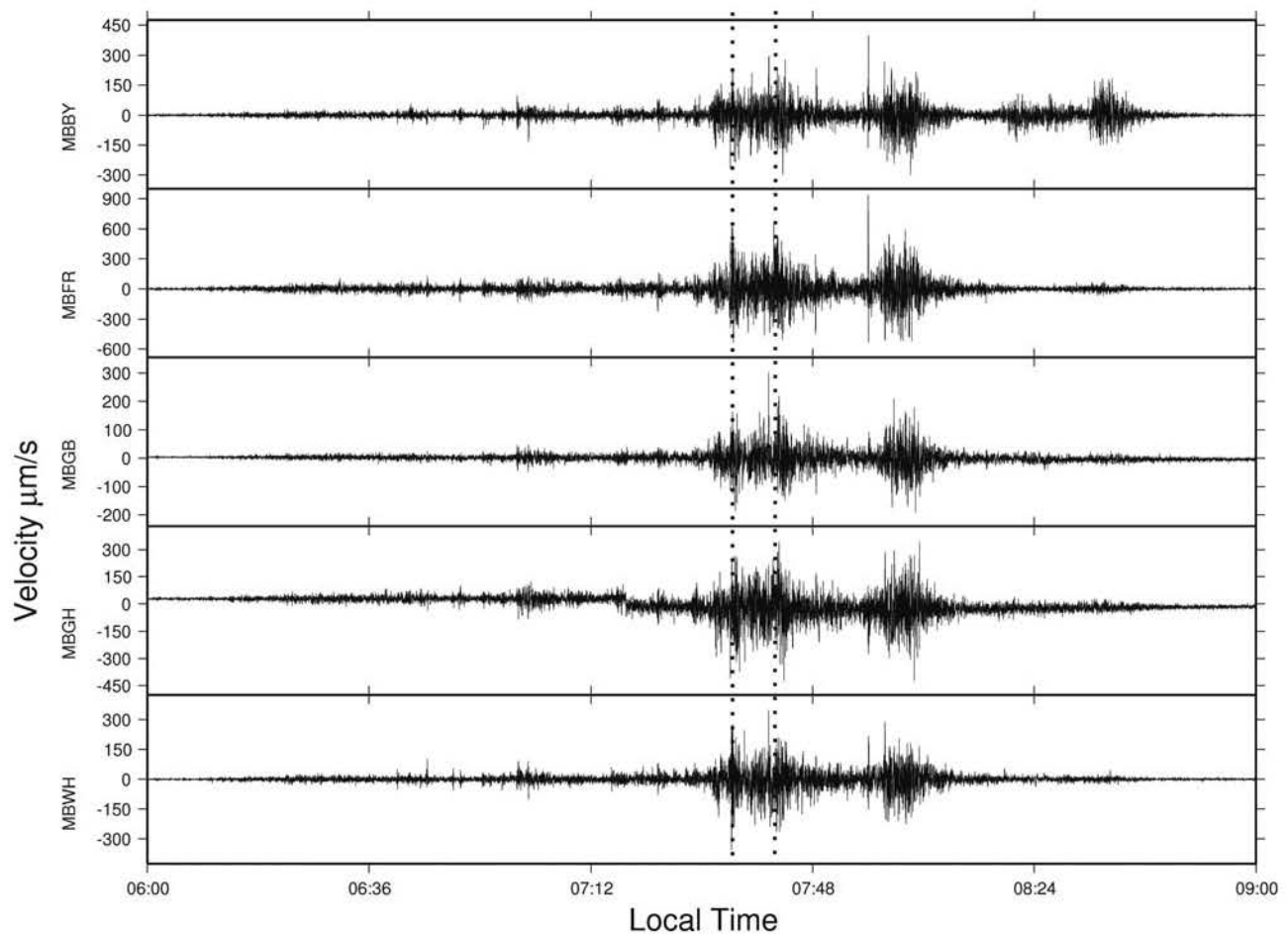


Figure 4. Seismograms from May 20, 2006 dome collapse showing two low amplitude/high energy signals interpreted as vertical explosions and two peaks during the most intense parts of the collapse (07:32 to 08:07).

characterised by extensive degassing-induced crystallisation. Such significant changes in the magma dynamics can be explained by slight changes in a single parameter such as volatile content [e.g., Melnik and Sparks, 2005].

[20] The 2–6 week pulses identified here on the basis of extrusion morphologies and discharge rates are probably equivalent to 6–7 week cycles defined by tilt, hybrid earthquake swarms and eruptive activity in 1997 [Sparks and Young, 2002]. In 1997, each pulse produced an average volume of $\sim 30 \text{ Mm}^3$, interpreted as an excess volume in the magma chamber or cyclic overturn of gas-rich magma [Sparks and Young, 2002], whereas these shorter pulses produced on average 20 Mm^3 . An excess volume in the magma chamber may have been reduced by crystallisation. There were more mafic inclusions in the andesite during the third episode of dome growth confirming that magma mixing has taken place during the eruption and the system is continuously re-invigorated from depth [Barclay et al., 2010] so cyclic overturn of gas-rich magma is also a possibility. Slightly higher volatile contents and temperatures are likely, leading to higher average ascent rates. Higher ascent rates inhibit gas separation, so the conduit contains less dense magma (requiring less excess pressure to drive it upwards). Many dome samples are vesicular implying high gas contents on extrusion. Most pulses were capable of

raising the dome height by c.50 m, suggesting a roughly constant excess pressure of about 1.5 MPa (assuming a lava density of 2400 kgm^{-3}) that must build up before each pulse is released. Costa et al. [2007] stated that the periodicity of flow through a dyke depends on parameters such as influx rate and aspect ratio of the dyke, with periodicity typically decreasing with larger aspect ratios. This is consistent with lower excess pressures and a subsequently thinner dyke.

[21] The periodicity in shallow LP earthquakes, LP rockfalls and rockfall counts every 11–16 days must relate to a regular and pulsatory supply of gas into the dome during growth. Based on average discharge rates [Ryan et al., 2010] each 11–16 day cycle relates to the flux of c. $6–11 \text{ Mm}^3$ lava through the conduit system. Cycles over several days are more likely to be controlled by processes in the conduit than the dome, possibly related to shear at the conduit margins where gas separation can occur and there is possible stick-slip flow. Shorter pulsations in pyroclastic flow activity (e.g., 5–7 minutes on 8 January 2007) appeared to relate to explosive activity.

[22] The onset of a pulse in discharge rate combined with a change in extrusion direction raises the likelihood of a dome collapse as observed early in the eruption [Calder et al., 2002]. On May 20, 2006 heavy rainfall coincided with

the pulse onset and a 10–11 day peak in rockfall activity (degassing) was due. The high SO₂ release during the May 20, 2006 dome collapse may be attributed to a higher porosity in the dome than previously. Loading by the dome may also have closed the fractures in the conduit wall inducing storage in the upper conduit [e.g., Taisne and Jaupart, 2008]. Alternatively, there may have been an unusually large mass of SO₂ associated with the new magma pulse.

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