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

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Abstract. 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 m^3/s), we identified 2-6 week discharge pulses that 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 Mm^3 occurred during the third episode (on May 20, 2006) as a new magma pulse entered the dome and coincided with heavy rainfall.

1. Introduction

The ongoing eruption of the andesitic Soufrière Hills Volcano (SHV) began in 1995 and up until April 2008 there had been three 2-3 year long episodes of lava dome growth. During the third episode, there were higher average discharge rates (~5.6 m^3/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].

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

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 [eg *Melnik and Sparks*, 2002, 2005; *Costa et al.,* 2007].

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 & 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 m^3/s) resulted in fluid lava capable of axisymmetric lateral spreading ('pancake' lobes), moderate rates (2-7 m^3/s) in the formation of shear lobes, and low rates (<2 m^3/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 ~1 km of the surface where there is a smooth transition to a cylindrical conduit (assuming constant source pressure).

3. Monitoring data and methods

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 (Fig. 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

Based mainly on evidence from time-lapse photographs, helicopter photographs and other observations, we identified 15 dome growth stages including 9 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 (eg shear lobe, megaspine or pancake lobe). Discharge rates declined towards the end of each cycle.

The first growth stage began on August 1, 2005 and was characterised by average discharge rates increasing to 4 m^3/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. 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 m^3/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 m^3/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 6) at high discharge rates. Later pulses were again dominated by subvertical shear lobes and megaspines (Table 1).

Dome growth ended on April 4, 2007, leaving a dome of volume 203 Mm^3 (non-DRE) and height ~ 370m [*Ryan et al.,* 2010].

5. Seismic characteristics

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

There was a steady increase in cumulative rockfall energy from February until early May 2006 (Fig. 2). On May 6, the extrusion direction switched to the southwest, where 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.

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 (Fig. 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 (Fig. 2).

The relationship between extrusion rates and rockfall counts is not straightforward (e.g. Ryan *et al*., 2010) 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

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

A pulse began on May 20 2006 and at 05:52, a large LP earthquake immediately preceded the start of the collapse and occurred at the peak of rainfall intensity on Garibaldi Hill (Fig.1). The seismograms from five seismic stations show a prolonged buildup to the collapse lasting c. 90 minutes, two marked peaks including high and low frequency signals, followed by a rapid decline over c. 30 minutes (Fig. 4). The collapse intensified at 07:32. 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 (<6 cm at Olveston). 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].

The total collapse volume was 97 Mm^3 *,* comprising 85.2 Mm^3 dome and talus measured on May 18, 0.7 Mm^3 lava extruded between 18-20 May (assuming average discharge rates, *Ryan et al.,* 2010), and 11 Mm^3 older dome and talus remnants. The collapse resulted in the rapid release of c. 200 ktons of SO_2 into the stratosphere [*Prata et al.,* 2006; *Carn et al*., 2006]. There was a gas-to-collapse-volume ratio of ~2.0 kt SO_2 per Mm^3 collapsed material. This compares to ~0.4kt SO_2 per Mm^3 collapsed material at previous dome collapses [*Edmonds et al.*, 2003].

6.2 June 30, 2006

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 Mm^3 andesite from the dome.

6.3 January 8, 2007

A switch in discharge direction began on December 24, 2006, with vigorous ash venting and dome-collapse pyroclastic flows 200-300 m down Tyer's Ghaut (Fig. 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 [*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. Melt inclusions in pumice from this collapse contain 6.2 wt% H_2O [*Humphreys et al.*, 2009] significantly higher than previous analyses (4.5 wt% H_2O, *Barclay et al.*, 1998) and suggests magma storage at high pressures.

7. Discussion

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.,* 2009]. 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 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 [eg *Melnik and Sparks,* 2005].

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 ~30 Mm^3, whereas these shorter pulses produced on average 20 Mm^3. We speculate that some threshold excess pressure necessary for extrusion of the pulses is now lower. Assuming that total magma chamber pressure remained constant and the magma retains more gas relative to previous episodes due to rapid ascent, it would be less dense and therefore more overpressured near the chamber top. Rapid ascent would inhibit gas separation and most degassing would then occur nearer the surface. 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.

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 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 (eg 5-7 minutes on 8 January 2007) appeared to relate to explosive activity.

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 SO_2 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 [eg *Taisne & Jaupart,* 2008]. Alternatively, there may have been an unusually large mass of SO_2 associated with the new magma pulse.

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References

Barclay, J, Rutherford, M. J., Carroll, M. R., Murphy, M. D., Devine, J. D., Gardner, J. and Sparks, R. S. J. (1998), Experimental phase equilibria constraints on pre-eruptive storage conditions of the Soufriere Hills magma. *Geophys. Res. Lett. 25*, 3437-3440.

Calder, E. S., R. Luckett, R. S. J. Sparks, and B. Voight (2002), Mechanisms of lava dome instability and generation of rockfalls and pyroclastic flows at Soufriere Hills Volcano, Montserrat, in *The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999*, edited by T. H. Druitt and B. P. Kokelaar, pp. 173-190, Geological Society, London, Memoirs, 21.

Carn, S. A., N. A. Krotkov, K. Yang, R. M. Hoff, A. J. Prata, A. J. Krueger, S. C. Loughlin, P. F. Levelt, (2007). Extended Observations of Volcanic SO_2 and Sulfate Aerosol in the Stratosphere. *Atm. Chem. Phys. Disc., 7*, 2857-2871.

Costa, A., Melnik, O., Sparks, R. S. J. and Voight, B. (2007). Control of magma flow in dykes on cyclic lava dome effusion. *Geophys. Res. Lett., 34,* no. 2, Lo2303.1-L02303.5

De Angelis, S., V. Bass, V. Hards, G. Ryan. (2007). Seismic characterization of pyroclastic flow activity at Soufriere Hills Volcano, Montserrat, 8 January 2007. *Nat. Hazards Earth Syst. Sci., 7,* 467-472.

Denlinger, R. and Hoblitt, R. P. (1999). Cyclic eruptive behaviour of silicis volcanoes. *Geology, 27*, 459-462.

Edmonds, M., Oppenheimer, C. M., Pyle, D. M., Herd, R. A., Thompson, G. (2003). SO_2 emissions from Soufriere Hills Volcano and their relationship to conduit permeability, hydrothermal interaction and degassing regime. *J. Volcanol. Geotherm. Res.*, *124 (1-2),* 23-43. DOI:10.1016/SO377-0273(03)00041-6.

Edmonds, M. and Herd, R. A. (2005). Inland-directed base surge generated by the explosive interaction of pyroclastic flows and seawater at Soufriere Hills volcano, Montserrat. *Geology, 33,* 245-248. DOI: 10.1130/G21166.1

Hards, V., Strutt, M., De Angelis, S., Ryan, G., Christopher, T., Syers, T. And Bass, V. (2008). *Report to the Scientific Advisory Committee, April 2008*. Montserrat Volcano Observatory Open File Report.

Taisne, B. and Jaupart, C. 2008. Magma degassing and intermittent lava dome growth. *Geophys. Res. Lett. 35*, L20310 DOI10.1029/2008GL035432

Humphreys, M. C. S., M. Edmonds, T. Christopher, and V. Hards (2009), Chlorine variations in the magma of Soufrière Hills Volcano, Montserrat: Insights from Cl in hornblende and melt inclusions, *Geochim. Cosmochim. Acta*, *73(19),* 5693-5708.

Jones, L. D. (2006), Monitoring landslides in hazardous terrain using terrestrial LiDAR: an example from Montserrat. , *Q. J. Eng. Geol. Hydrol*., *39,* 371-373.

Loughlin et al. 2006. *Report to the Scientific Advisory Committee, August 2006*. MVO Open File Report 07/06.

Luckett, R., Baptie, B. and Neuberg, J. (2002). The relationship between degassing and rockfall signals at Soufrière Hills Volcano, Montserrat. In. Druitt, T.H. and Kokelaar, B.P. (eds.) *The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, 21, 595-602.

Luckett, R., S. Loughlin, S. De Angelis, and G. Ryan (2008), Volcanic seismicity at Montserrat, a comparison between the 2005 dome growth episode and earlier dome growth, *J. Volcanol. and Geothermal Research*, *177(4),* 894-902.

Melnik, O., and R. S. J. Sparks (1999), Nonlinear dynamics of lava dome discharge, *Nature*, 402(6757), 37-41.

Melnik, O. and Sparks, R. S. J. (2005). Controls on conduit magma flow dynamics during lava dome building eruptions. *J. Geophys. Res., 110,* B02209, doi:10.1029/2004JB003183.

Prata, A. J., S. A. Carn, A. Stohl, J. Kerkmann. (2007)**.** Long range transport and fate of a stratospheric volcanic cloud from Soufriere Hills volcano, Montserrat *Atmos. Chem. Phys., 7,* 5093-5103.

Ryan, G. A., Loughlin, S. C., James, M. R., Jones, L. D., Calder, E. S., Christopher, T., Strutt, M. H., and Wadge, G. Growth of the lava dome and discharge rates at Soufriere Hills Volcano, Montserrat West Indies: 2005-2008, *Geophys, Res. Lett.,* (*this issue*).

Sparks, R. S. J., et al. (1998), Magma production and growth of the lava dome of the Soufriere Hills Volcano, Montserrat, West Indies: November 1995 to December 1997, *Geophys. Res. Lett., 25 (18),* 3421-3424.

Sparks R. S. J.and S. R. Young, (2002) The eruption of Soufriere Hills Volcano, Montserrat (1995-199): overview of scientific results. In *The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999*, edited by T. H. Druitt and B. P. Kokelaar, pp. 115-152, Geological Society, London, Memoirs, 21.

Voight, B., Hoblitt, R. P., Clarke, A. B., Lockhart, A. B., Miller, A. D., Lynch, L. and McMahon, J. (1998). Remarkable cyclic ground deformation monitored in real-time on Montserrat, and its use in eruption forecasting, *Geophys. Res. Lett., 25 (18),* 3405-3408.

Voight, B. *et al*., (1999), Magma flow instability and cyclic activity at Soufriere Hills Volcano, Montserrat, B. W. I., *Science, 283,* 1138-1142.

Wadge, G., *et al*. (2008), Lava dome growth and mass wasting measured by a time series of ground-based radar and seismicity observations., *J.Geophys. Res., 113*, B08210, DOI: 10.1029/2007JB005466.

Watts, R. B., R. A. Herd, R. S. J. Sparks and S. R.Young (2002), Growth patterns and emplacement of the andesite lava dome at the Soufrière Hills Volcano, Montserrat. In *The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999,* edited by T. H. Druitt and B. P. Kokelaar, pp. 115-152, Geological Society, London Memoirs, 21.

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

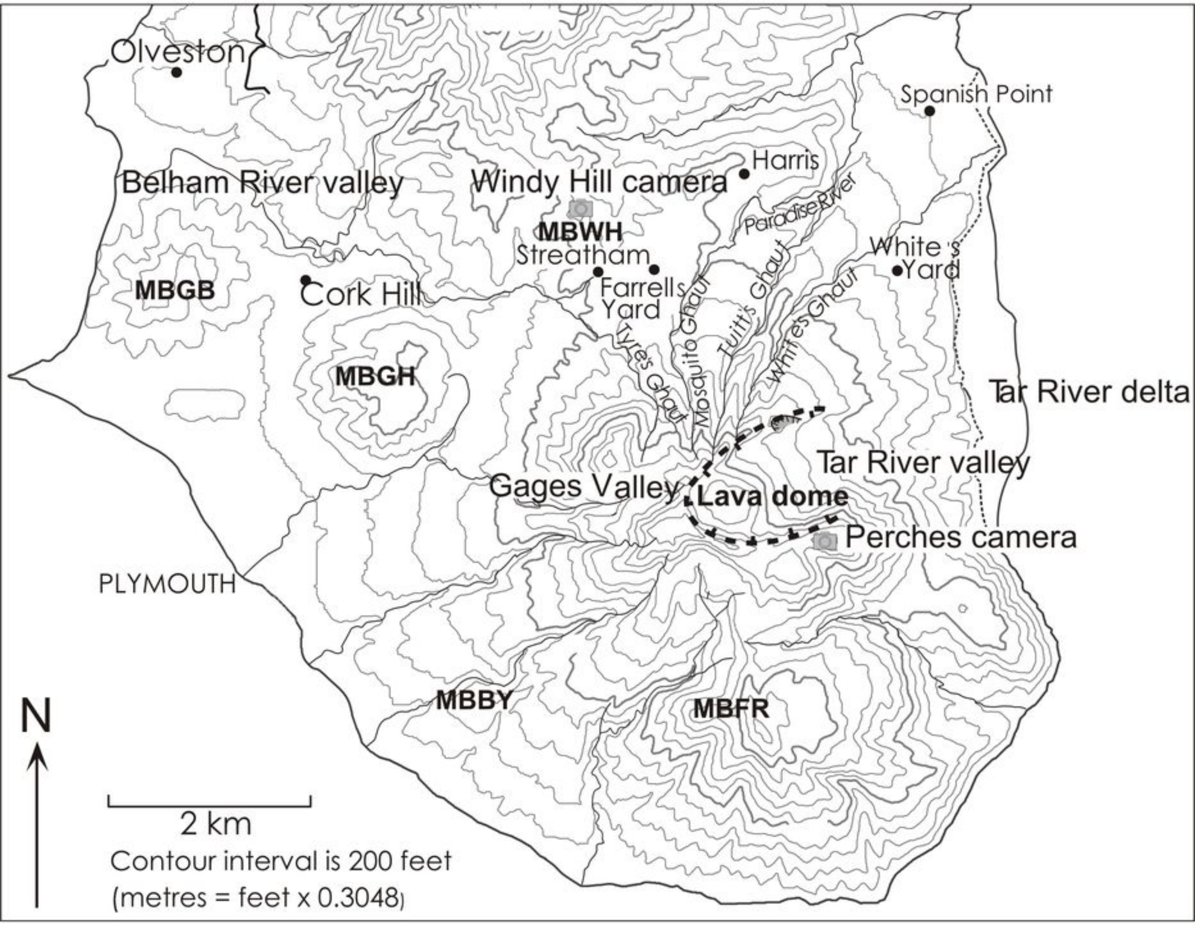
Figure 2. Rockfall counts and cumulative rockfall energy showing major eruptive events and growth stages, August 1, 2006 to April 30, 2007.

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

Figure 4. Seismograms from May 20, 2006 dome collapse showing two low amplitude/high energy signals interpreted as vertical explosions.

GROWTH STAGE	TIME PERIOD DD/MM/YY	DURATION (DAYS)	APPROX. VOL. (x $10^6 m^3$)	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**	**~17***	**Pancake lobe**
10	**21/9/06-5/11/06**	**46**	**~35***	**NE/E lobe**
11	**6/11/06-11/12/06**	**36**	**~28***	**N lobe**
12	**12/12/06-23/12/06**	**12**	**~9***	**SW lobe**
13	**24/12/06-20/1/07**	**27**	**~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

Table 1. Growth stages with estimated duration and volume, major eruptive cycles in bold. Volumes 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.


Olveston
Spanish Point
Harris
Belham River valley
Windy Hill camera
Paradise River
MBWH
White's Yard
Streatham
MBGB
Cork Hill
Farrells Yard
Tyre's Ghaut
Mosquito Ghaut
Tuitt's Ghaut
White's Ghaut
MBGH
Tar River delta
Tar River valley
Gages Valley
Lava dome
Perches camera
PLYMOUTH
MBBY
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2 km
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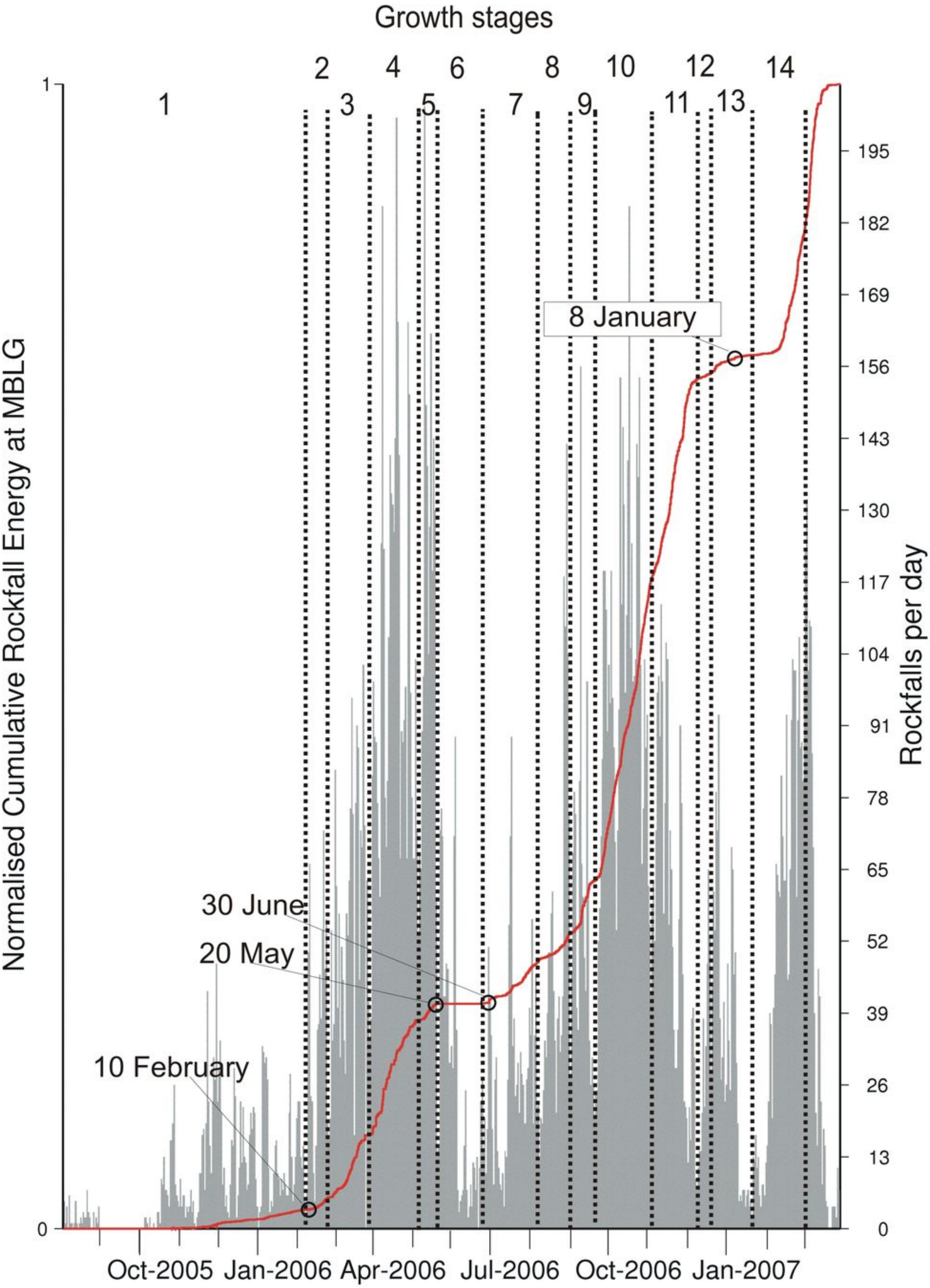
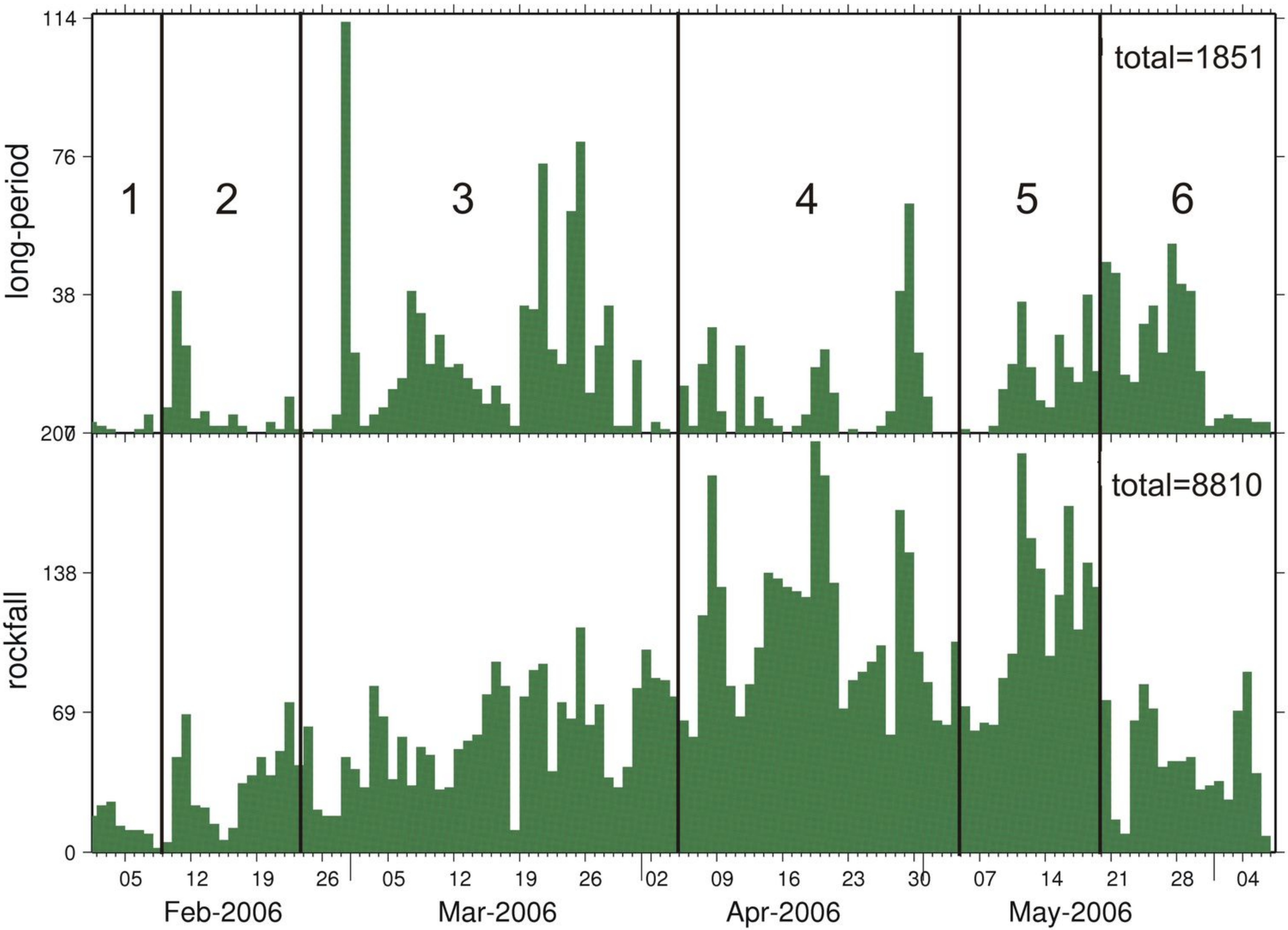
(metres = feet x 0.3048)



Growth stages
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Normalised Cumulative Rockfall Energy at MBLG
Rockfalls per day
10 February
20 May
30 June
8 January
0
1
195
182
169
156
143
130
117
104
91
78
65
52
39
26
13
0
Oct-2005
Jan-2006
Apr-2006
Jul-2006
Oct-2006
Jan-2007



114
76
38
207
138
69
0
long-period
rockfall
1
2
3
4
5
6
total=1851
total=8810
05
12
19
26
05
12
19
26
02
09
16
23
30
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14
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28
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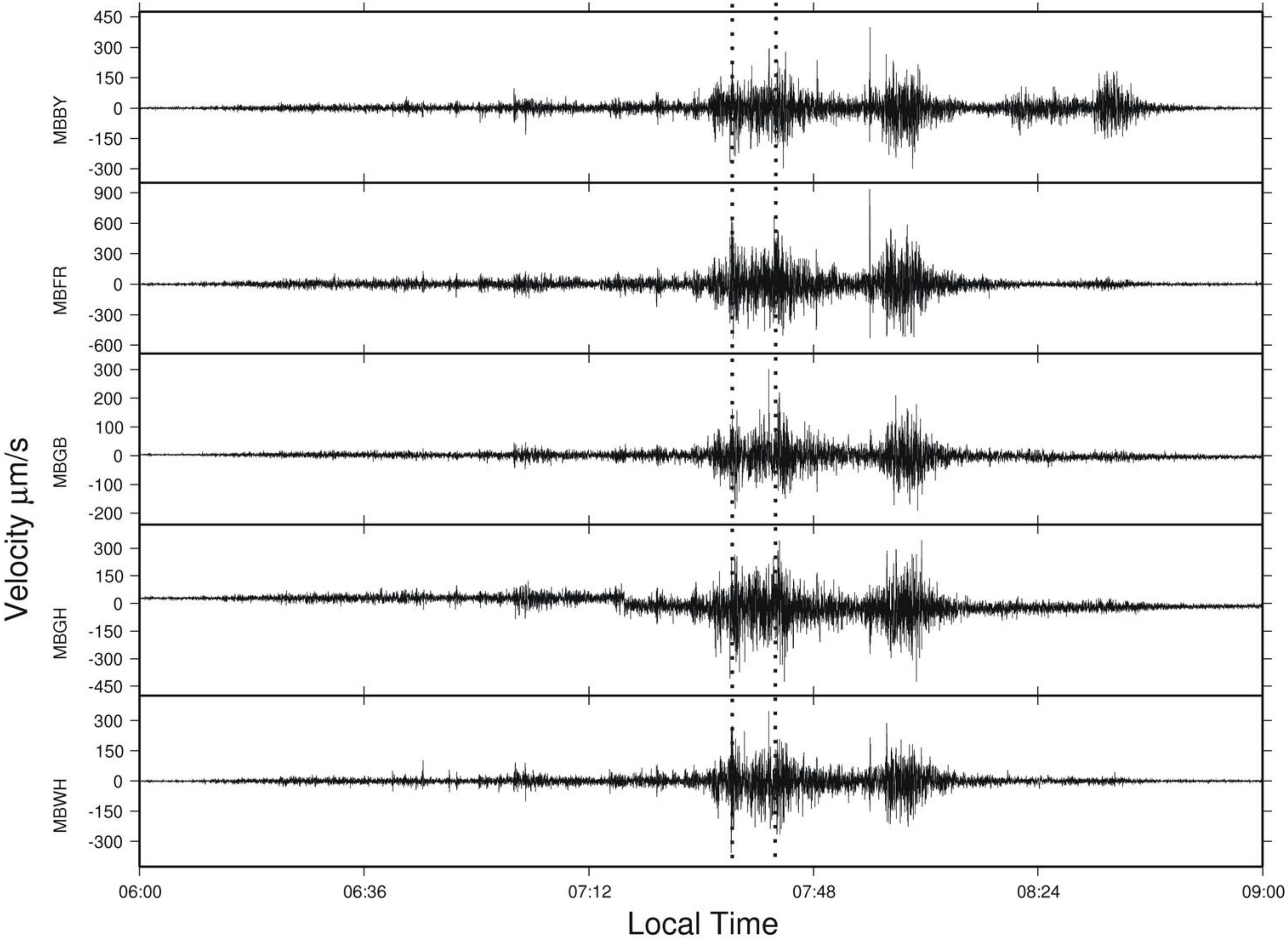
Feb-2006
Mar-2006
Apr-2006
May-2006



MBBY
MBFR
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Velocity μm/s
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300
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0
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06:00
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Local Time