Volcanic seismicity at Montserrat, a comparison between the 2005 dome growth episode and earlier dome growth.

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Abstract

In 2005 Soufrière Hills Volcano on Montserrat started its third major episode of dome growth since the current eruption started in 1995. The style of seismicity associated with dome growth has changed, in particular the events known as 'hybrid' earthquakes have reduced in numbers by an order of magnitude compared to previous dome growth episodes. In the past, hybrid earthquakes have been associated with magma ascent and so it is surprising to observe prolonged periods of rapid dome growth during which very few hybrid earthquakes are recorded. In addition, the frequency of the codas of hybrid earthquakes, as well as of some of the so called 'long-period' events, has changed. The changes in recorded seismicity have had a marked effect on the techniques used to monitor the state of the volcano and those events that continue to be recorded in large numbers ('rockfall events') have been used to assess the state of activity at the volcano.

Introduction

Soufrière Hills on Montserrat in the West Indies is an andesitic dome building volcano. The current eruption started in 1995 (Young et al., 1998) and since then intermittent dome growth has taken place in the crater at the top of the edifice. The first two episodes of such growth were between September 1995 and March 1998 and between November 1999 and July 2003. The third episode started in August 2005. As would be expected, there is a marked difference in the seismicity recorded during episodes of dome growth compared to that recorded during the repose periods between them. There is also a difference in the seismicity typical of each episode of growth. While there are many publications concerning the seismicity associated with the first extrusive episode at Montserrat (e.g. Miller et al., 1998, Aspinall et al., 1998, Neuberg et al., 1998), the more recent episodes are less well documented.

As part of its monitoring program the Montserrat Volcano Observatory (MVO) has maintained an array of digitally telemetered broadband seismometers on Montserrat since 1996. This network was upgraded at the start of 2005 (Luckett et al., 2007) and now consists of 8 Guralp CMG-40T 3 component 30 second seismometers and 2 Mark Products L4 vertical 1 Hz instruments (Figure 1). All stations are digitised and GPS time-stamped at the site using Guralp DM24 digitisers and telemetered to the observatory using spread-spectrum VHF radio-modems. 100Hz, 24 bit seismic data are recorded continuously and a triggering algorithm detects events in real time. Events are classified into a small number of types and the counts of these types are used as a monitoring tool. The event types recognised on Montserrat are volcano-tectonic earthquakes, long-period earthquakes, hybrid earthquakes, rockfall signals and long-period rockfall signals (Miller et al., 1998).

In the years between 1992 and the start of the eruption at Soufrière Hills in 1995 there were several thousand volcano-tectonic earthquakes (Aspinall et al., 1998, Power et al., 1998). Similar seismicity has been observed associated with dome emplacement at many other volcanoes (Zobin, 2003) and has been linked to magma forcing a route to the surface and the associated stresses (Roman et al., 2006). Once dome growth had begun hybrids – events with a similar initial phase to the volcano-tectonic events but with an additional lower frequency monochromatic phase - replaced volcano-tectonic earthquakes as the most common event type. Very large numbers of this type of event continued throughout the first dome growth episode, and to a lesser degree throughout the second episode. In the repose periods there was very little seismicity, although in the first repose period there were regular steam explosions. This report describes the seismicity recorded during the third episode of dome growth and compares it with that recorded during the first. Some speculation is included about the reasons for changes in this seismicity but no modelling is done or hypotheses tested. Rather, observations are presented in the hope that they will be useful to people monitoring other volcanoes. These observations also place some important constraints on the sources of volcanic seismicity associated with dome growth that need to be considered in future models. An example is given of how seismic monitoring has been adjusted to allow for changes in volcanic seismicity.

Chronology of 2005 dome

Between the collapse of the previous dome in July 2003 and June 2005 there was little seismicity associated with the volcano. Averaged over the whole period there were roughly 100 events per month compared with an average of over 2500 events per month for the 3.5 year duration of the preceding dome growth episode. The first significant and sustained increase in seismicity began on April 15th 2005 when a vigorous vent opened on the crater rim, heard throughout the island as a 'jet engine' noise. There were a small number of volcano-tectonic events associated with the

52 venting and from this point seismicity increased, with 9 episodes of volcano-tectonic earthquakes
53 in the next 2 months, each lasting between a few hours and a few days and consisting of one or
54 two events each hour.
55
56 On June 13th, 2005 a thunderstorm over the volcano cleared to reveal vigorous steam and ash
57 venting from several places within the crater, perhaps signifying deeper penetration by meteoric
58 water than usual. This venting was accompanied by an episode of volcano-tectonic events similar
59 in duration and density to those in previous weeks, but this time long-period and hybrid
60 earthquakes were also recorded. For the next two weeks there was elevated venting activity but
61 little seismicity apart from low amplitude tremor with energy in the frequency band between 1Hz
62 and 5Hz and no particular spectral peaks. When the summit could be observed this tremor was
63 seen to coincide with particularly energetic venting. On June 28th there was the first of 5
64 explosions; each of these had an ash cloud higher than 3 km but no juvenile magma was erupted.
65 The explosions had a clear seismic signature with a high amplitude, nearly monochromatic phase
66 at the start. Each explosion had a slightly different frequency for this phase but all had a
67 frequency of less than 1Hz. Each explosion was associated with a small number of volcano-
68 tectonic and hybrid earthquakes that occurred both before and after the explosion itself. These
69 explosions were similar in many ways to those in 1997 (Druitt et al., 2002).
70
71 The new lava dome was first seen on August 8th and from then on its growth was measured using
72 photogrammetric methods (Sparks et al., 1998) and ground-based LiDAR (Light Detection And
73 Ranging: Jones, 2006). The accuracy of the growth rates given here is estimated to be 15% or
74 better. For the first 2 months of dome growth there was very little seismicity, with an average of 5
75 events per day triggering the network (compared with a background level of 2 events per day in
76 March). The growth rate for the new dome was estimated to be 0.5 m^3s^{-1}. The pattern changed in
77 October when about 650 small hybrid earthquakes were recorded over an interval of 3 weeks. The
78 number of rockfall signals increased markedly and a slight increase in long-period seismicity was
79 also observed. For the next 3 months there was an average of 15 events each day, an average of
80 12 of which were rockfalls. Over this period the growth rate was, on average, 2.4 m^3s^{-1}. On
81 February 9th, 2006 another venting episode signalled an acceleration in extrusion rate to over 10
82 m^3s^{-1}. The number and energy of rockfall signals again increased with an average of 80 each day
83 for the next 3 months. The number of long-period earthquakes recorded also increased to more
84 than 10 a day.
85
86 On May 20th there was a major dome collapse that removed the whole dome and some remnants
87 from previous domes (approximately 112 million m^3 (DRE) of material, Loughlin et al., 2008). The
88 only seismic precursor for this collapse was a single high amplitude long-period event about 3
89 hours beforehand. The collapse led to explosions and an SO_2 cloud that reached a height of 20
90 km and had a mass of 200 kilotons (Carn et al., 2007). This is far more gas than in a previous,
91 larger collapse on 12-13 July 2003 (Herd et al., 2005). A new lava dome started to grow within
92 hours of the collapse. By 27th June the new dome had a volume of about 26 million m^3 and was
93 growing at an average rate of 8 m^3s^{-1} (Loughlin et al., 2008).
94
95
96 **Seismicity associated with 2005 dome**
97
98 Figure 2 shows daily counts for the different event types for the 8 months preceding the May 20th
99 2006 collapse. For comparison, 8 months of 1996/1997 are also shown when the dome was
100 growing at a similar rate (Sparks et al., 1998). The main difference between the two intervals is
101 the almost complete lack of hybrid earthquakes in 2005/2006. The various event types are
102 discussed here in turn.

103
Volcano-tectonics
105 Very few volcano-tectonic earthquakes were recorded during the growth of the 2005 dome, being
106 mainly restricted to two episodes in the last week of September 2005 and on February 7th 2006.
107 These events were located using the same method as the hybrids, as described below, and were
108 found to have similar locations.
109
Hybrids
111 There has been a very marked decrease in the number of hybrid earthquakes on Montserrat.
112 Throughout 1997 an average of 1600 events were classified as hybrids each month. These
113 hybrids often occurred in swarms that were correlated with tilt data indicating short term increases
114 in pressurisation within the conduit (Voight et al., 1999). Pyroclastic flows often followed such
115 swarms and so seismicity could be used in short term forecasting. As might be expected, this type
116 of event almost disappeared in the two repose periods and started again when dome growth
117 resumed each time. However, they failed to reoccur in similar numbers during either of the more
118 recent dome growth episodes. In particular, there were fewer than 150 hybrids a month recorded
119 on average between the start of the 2005 episode and the May 20th collapse. The lack of hybrids
120 had a considerable effect on monitoring, with very high estimated magma ascent rates (for
121 example over 10 m^3s^{-1} in February 2006) having virtually no accompanying seismicity that could
122 be attributed directly to the movement of this magma. The May 20th 2006 collapse, the second
123 largest known at this volcano, effectively had no seismic precursors to give warning of such a
124 major event.
125
126 The dominant frequency of hybrids in 2005/2006 was different to that earlier in the eruption (Figure
127 3). Although the frequency of the long-period part of hybrids in 1997 varied, it was predominantly
128 between 1Hz and 2Hz, the same frequency as the few long-period earthquakes that were
129 recorded at that time. The hybrids recorded during the growth of the 2005 dome have typically had
130 codas with energy in the region of 3Hz or 4Hz. Figure 4 shows a comparison between a typical
131 1997 hybrid and an example from 2005. The higher dominant frequency was also observed in
132 many events identified as long-period events in 2005/2006 but, as discussed below, other long-
133 period events continued to be recorded with frequencies between 1Hz and 2Hz.
134
135 Most of the hybrids recorded in 2005 and before May 20th in 2006 were too small to reliably pick
136 arrival times, so relatively few were located. Of those routinely located the 120 events with the
137 best signal-to-noise ratio were reanalysed. Cross-correlation shows that waveforms at a given
138 station are extremely similar from event to event, indicating a single source area. Accordingly, a
139 Joint Hypocentre Determination (JHD) method similar to that used for previous Montserrat data by
140 Rowe et al. (2004) and Ottemoller (2008) was used to relocate the events. The resulting locations
141 (Figure 5) cluster beneath the dome at a depth of approximately 2 km below sea-level. This source
142 region is the same as that found for hybrids throughout the eruption. Changes in the waveforms of
143 hybrid events are thus not due to differences in path from different source regions.
144
145 Hybrid and long-period earthquakes have generally been treated together in terms of source
146 modelling and much work has been done in this field, starting with Aki et al. (1977). Many models
147 have concentrated on interface waves in the boundary between a fluid and country rock (e.g.
148 Chouet, 1988, Neuberg et al., 2000) and resonance in a gas-filled dike was put forward by
149 Schlindwein et al (1995). The trigger needed to initiate such sources has been described as an
150 ash injection into cracks (Molina et al., 2004) or the brittle failure of magma as it passes through
151 the glass transition (Neuberg et al., 2006). These models can accommodate the slight changes in
152 frequency observed at Montserrat through reasonable changes in initial conditions but it is more
153 difficult to explain the almost complete lack of such seismicity when magma extrusion rates are

154 known to be high. Petrological studies show that the magma being erupted has changed very little
155 over the last 10 years (J. Divine pers. Comm.) but something must have changed in the volcanic
156 system to explain the differences in seismicity being recorded. One explanation is that the country
157 rock surrounding the conduit is fractured to such a degree that changes in stress due to rising
158 magma can be accommodated without further failure. However, for this to explain the lack of
159 hybrids the trigger for hybrids would have to be a brittle fracture in the vicinity of the conduit. This
160 model has problems explaining the repeatability that is an observed property of hybrid
161 earthquakes (Neuberg, 2000). Another explanation is that a change in the geometry of the conduit
162 is in some way responsible for the relative lack of seismicity. This could also explain the change in
163 frequency of the hybrid codas, although the modelling to show this is beyond the scope of this
164 paper.
165
166 **Rockfalls and Long-periods**
167 Throughout the eruption there has been a strong link between some long-period events and
168 rockfalls, with the two types of event often occurring consecutively to form events known as long-
169 period rockfalls (Figure 6). Rockfall signals have often had 1Hz to 2Hz peaks in their spectra and
170 discrete long-period events occur during or just after rockfall signals, as well as before the rockfall
171 as is most often the case. In 1997 long-period rockfall events were investigated using a pressure
172 sensor (Luckett et al., 2002). It was shown that the long-period part of long-period rockfalls
173 correlates with an acoustic wave, indicating that the signal is linked to gas escaping violently from
174 the dome. Although no pressure sensor was deployed in 2006, it was noted that jets of gas and
175 ash were expelled from the dome preceding some rockfalls. The seismic events associated with
176 such rockfalls are similar to long-period rockfalls in 1997, with the long-period part being of similar
177 frequency.
178
179 One of the most interesting things about the long-period earthquakes in 2005 is that while some
180 have the same frequency as hybrids, i.e. between 3Hz and 5Hz, others have the same dominant
181 frequency as previously, i.e. between 1Hz and 2Hz. An example of each is shown in Figure 7.
182 The long-period events with higher frequencies, similar to the frequency of the codas of recent
183 hybrids, could have the same source as hybrid events but have lost their high frequency initial
184 phase due to attenuation, as suggested in Neuberg et al. (1998). However those with lower
185 frequencies must have a different source.
186
187 While not all long-period events with frequency in the 1Hz to 2Hz band occur within a short time of
188 a rockfall signal, most do. These signals have a source that is, at least sometimes, related to gas
189 escaping from the surface of the dome. It seems likely that long-period events with similar
190 frequencies have a similar source. Thus all 1Hz to 2Hz long-period earthquakes, as well as long-
191 period rockfalls, are probably related to degassing. That a considerable volume of gas was
192 trapped within the 2005 dome was shown on May 20th 2006 when satellite images after the
193 collapse showed that 200 kilotons of SO_2 had been released (Carn et al., 2007). This is much
194 more gas than was measured after a larger collapse in July 2003 (Herd et al., 2005). There was
195 no evidence for deep excavation of the conduit during the May 20th collapse so the gas must have
196 largely been contained within the dome, as postulated for previous collapses (Edmonds et al.,
197 2003). Considering that the gas in the dome will act as a buffer between the top of the conduit and
198 the surface it seems unlikely that gas escaping from the conduit can explain the long-period
199 events associated with rockfalls. Rather, these long-period events are related to gas movement
200 within the dome itself. The events were not located because their emergent nature makes it
201 impossible to pick arrival times. However low-frequency events on Unzen were located within the
202 dome (Nakada et al., 1999), supporting such a hypothesis on Montserrat. As discussed above,
203 long-period events have long been associated with the movement of gas within cracks or other
204 structures. Long-period events associated with rockfalls could be caused by resonance in cracks

205 or voids within the dome. The regular occurrence of long-periods both before and after the start of
206 a rockfall signal can be speculatively explained by considering that, while the emergence of a
207 violent jet of gas at the surface can start a landslide, it is also true that such a landslide can cause
208 a localised depressurisation and therefore a movement of gas near the surface. If there was more
209 gas in the 2005 dome than was the case in 1997 then that would explain the increased number of
210 long-period and long-period rockfall events.
211
Monitoring
213
214 Rockfalls and long-period rockfalls appear to be a direct result of lava dome growth, rather than of
215 the movement of magma in the conduit. However, their analysis is the best seismic monitoring tool
216 available when the dome is growing and there is little other seismicity. The best method found so
217 far is to plot cumulative rockfall energy in a similar approach to that used on Mount St Helens in
218 1981 and 1982 (Malone et al., 1983). Seismic energy at any one station is calculated for each
219 rockfall and when these values are added together over time the resulting 'cumulative rockfall
220 energy' is useful for detecting changes in dome growth, whether in extrusion rate, direction or style
221 of growth. The sharp changes in the slope of the line in Figure 8 (which are repeated on similar
222 plots for other stations) correlate with changes in dome growth rate and direction as indicated by
223 the labels. This has important connotations for monitoring volcanic hazard as it gives the MVO
224 warning of potentially important changes when the dome is hidden from sight by cloud (which can
225 be the case for many consecutive days). Most major dome collapses have occurred during or
226 immediately after a change in the direction of growth or extrusion rate (Loughlin et al 2008). Higher
227 extrusion rates may make a collapse or explosive event more likely (Calder et al., 2002) but the
228 highest extrusion rates are not always accompanied by the highest rockfall energy. Monitoring
229 rockfall activity can nevertheless give the first indication of a possible change in direction of dome
230 growth or change in extrusion rate, both of which could lead to increased risk of dome collapse.
231
Conclusions
233
234 Seismicity associated with dome growth at Montserrat has decreased over the duration of the 12
235 year eruption. The reasons for these changes are not understood, but they are reported here as
236 they have important implications for both the modelling of volcanic long-period seismic sources
237 and for volcanic monitoring. In particular the lack of hybrid earthquakes to interpret in terms of
238 increased volcanic hazard, has forced changes in procedure at the MVO. Methods have been
239 developed for using the signals caused by rockfalls on the dome to indicate changes in extrusion
240 rate and/or direction of growth. Thus seismic monitoring remains important to the observatory
241 despite the relative lack of deeper seismicity.
242
243 One explanation for the lack of hybrids is that the rock surrounding the conduit has become so
244 fractured after 10 years of seismic activity that the stresses required for new fractures do not
245 occur, despite considerable forces acting due to rapidly ascending magma. If this were to explain
246 the lack of hybrids then the trigger for such events would have to be a fracture near to the conduit,
247 a model that may fail to explain the repeatability of such events. It has also been suggested that
248 the rock immediately surrounding the conduit has become more plastic due to heating. A
249 consideration of the properties of andesite shows that this is not the case. Assuming a magma
250 temperature of 860°C and thermal diffusivity of $7x10^7$ m^2s^{-1} (Sparks et al., 2000) rock 100 m from
251 the conduit will have increased in temperature by less than 30°C after 20 years. Perhaps the most
252 likely explanation is that the conditions for a trigger within the conduit itself have changed due to
253 changes in conduit geometry. It is possible that conduit changes could also explain the change in
254 coda frequency of those hybrids that are still recorded (Jousset et al., 2003), but the modelling
255 necessary to show this is beyond the scope of this paper. When considering changes to the

256 source of hybrids it must be taken into account that their source has remained in the same place,
257 within measurement uncertainty, throughout the eruption. The locus of extrusion has also
258 effectively remained the same, making any major change in the path taken by magma to the
259 surface unlikely. Any model of the source of long-period seismicity associated with dome growth
260 must allow for aseismic magma ascent to occur at similar rates to that occurring when seismicity is
261 recorded.
262
263 There are two types of long-period event being recorded on Montserrat. One type has similar
264 dominant frequencies to the codas of recent hybrids, with spectral peaks near 3Hz or 4Hz. The
265 other type continues to have frequencies between 1Hz and 2Hz, as was true of both hybrid codas
266 and long-periods earlier in the eruption. The first type of long-period earthquake can be considered
267 to be hybrids for which the initial phase is not recorded, as was previously thought. However the
268 second type must have a different source. Because this second type of long-periods have similar
269 frequencies to previous hybrids, they were probably always present but indistinguishable from the
270 first type, which still have similar frequencies to hybrids now that these frequencies have changed.
271
272 The coincidence of gas jetting at the surface of the dome and long-period earthquakes with
273 frequencies in the 1Hz to 2Hz range, combined with the knowledge that there is a huge quantity of
274 gas stored within the dome, makes it unlikely that these events are connected to processes within
275 the conduit, as is held to be true for hybrid earthquakes. Instead these events seem to be linked
276 to resonances within the dome itself. This explains their close relationship with rockfall signals,
277 either a jet of gas can dislodge loose blocks on the surface of the dome or gravity driven rockfalls
278 can cause a sudden depressurisation near to the surface and a subsequent escape of gas.
279
280 **Acknowledgements**
281

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Figure 1: MVO seismic network from April 2006. The observatory is located near the station MBFL.

Figure 2: Daily seismic network event counts from October 2005 to May 2006. For comparison, counts for a similar time interval in 1996 and 1997 are also shown.

Figure 3: Frequency of the highest peak in the spectra of hybrid events recorded at MBGH. Those events with low signal-to-noise ratio have their highest peak between 0.2Hz and 0.4Hz, at sea microseism frequencies. Otherwise the vast majority of events in 1997 have spectral peaks at near 1.2Hz or 1.7Hz. By comparison, in 2005/2006 hybrids did not generally have spectral peaks below 2Hz.

Figure 4: Hybrids from different years recorded at MBRY. Note the change in dominant frequency from between 1Hz and 2Hz in 1997 to between 3Hz and 4Hz in 2005.

Figure 5: Location of the 120 best recorded hybrid earthquakes from 2005. Horizontal errors in these locations are of a few hundred metres but depth errors are between 1 km and 2 km. The r.m.s. of the residuals are less than 0.1 s for all of these events.

Figure 6: Examples of long-period rockfall signals with the most obvious long-period energy before, during, and after the rockfall. These were all recorded on MBGH.

Figure 7: Comparison between two long-period earthquakes recorded at MBLG, one with dominant frequency near 1Hz and one with dominant frequency near 4Hz.

Figure 8: Cumulative energy at station MBWH for events classified as rockfalls triggered during February 2006. February was chosen because unusually good dome visibility allows comparison with observations.