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# Observations of hybrid seismic events at Soufriere Hills Volcano, Montserrat: July 1995 to September 1996

Randall A White[1], Angus D. Miller[2], Lloyd Lynch[3] and John Power[4]

**Abstract.** Swarms of small repetitive events with similar waveforms and magnitudes are often observed during the emplacement of lava domes. Over 300,000 such events were recorded in association with the emplacement of the lava dome at Soufriere Hills Volcano, Montserrat, from August 1995 through August 1996. These events originated <2-3 km deep. They exhibited energy ranging over ~1.5-4.5 Hz and were broader band than typical long-period events. We term the events "hybrid" between long-period and volcano-tectonic. The events were more impulsive and broader band prior to, compared with during and after, periods of inferred increased magma flux rate. Individual swarms contained up to 10,000 events often exhibiting very similar magnitudes and waveforms throughout the swarm. Swarms lasted hours to weeks, during which inter-event intervals generally increased, then decreased, often several times. Long-duration swarms began about every two months starting in late September 1995. We speculate that the events were produced as the magma column degassed into adjacent cracks.

## Introduction

Between August 6, 1995 and August 15, 1996, more than 300,000 hybrid seismic events were observed at Soufriere Hills Volcano, Montserrat, West Indies. Hybrid events show a mix of characteristics which fall between brittle-fracture earthquakes, which in volcanic settings are referred to as volcano-tectonic (VT) earthquakes, and low-frequency or long-period (LP) events, which are often observed at active volcanoes, often in association with volcanic tremor. For examples and discussion of waveforms at Soufriere Hills, see Miller *et al., (1998)* and Neuberg et al., (1998). For a more general discussion of the classification of volcano related seismic events, see Chouet *et al.* (1994), Lahr *et al.* (1994), Power *et al.* (1994), and Chouet (1996). At Redoubt volcano, waveforms of hybrid events had a pronounced high-frequency onset (5-10 Hz) with mixed first motions, clear body phases, and a coda which is dominated by a low-frequency (1.5-3.3 Hz) wave train (Lahr *et al.* (1994). Waveforms of hybrid events at Soufriere Hills also had pronounced high-frequency onsets during the early stages of long-duration swarms, may have had mixed first motions, often had clear P and what may be split S phases, and were also dominated by low-frequency wave trains. These hybrid events were more broadband than typical LP events, with considerable energy over the range 1.5 and 4.5 Hz in the near field; being dominantly "long-period" however, these events may termed as lonng-period events by others.

Seismic events exhibiting similar characteristics and behavior have been observed during episodes of dome emplacement at a number of volcanoes including Usu (Okada *et al.*, 1981), Soufriere of St. Vincent (Shepherd and Aspinall, 1982), Mount St. Helens (Fremont and Malone, 1987), Augustine Volcano (Power, 1988), and Mount Pinatubo (Ramos *et al.*, 1996), although the recording instrumentation, analysis techniques, and terminology have differed somewhat for each of these examples. Swarms of small repetitive events with similar waveforms and magnitudes appear to be a common phenomenon associated with the emplacement of lava domes.

Figure 1A shows waveforms of a typical hybrid event during slow dome growth in early January 1996. Figure 1B shows the stack of the velocity spectra for those same waveforms, with energy principally between 1.5 and 4.5 Hz. Within many long-duration swarms prior to May 1996, hybrid events displayed more high-frequency content at signal onset early in the swarm and became more monochromatic later in the swarm, as extrusion began or the rate increased. Thus, early in swarms, events generally had a spectral bandwidth with quality factor $Q$ ~1, where $Q = F_0 / \Delta f$, $F_0$ is the dominant frequency, and $\Delta f$ is the peak spectral width at half power, which often narrowed to $2 < Q < 3$ later in swarms. The events occurred in distinct swarms lasting hours to weeks and occurred at regular intervals with the rate first increasing, then decreasing, often several times, during the swarm. The events often had similar waveforms, which cross-correlated at >0.9 +/-0.1 over 1024 samples (10.24 s), and uniform magnitudes, which varied by <0.3 magnitude units for hundreds of consecutive events.

Swarms of small amplitude hybrid events lasting only a few days were seen as early as August 6, 1995. Starting in late September 1995 when the first small extrusion probably occurred, swarms of larger amplitude hybrid events began at roughly two month intervals (see Figure 2). Prior to November 1995, swarms lasted days and contained many hundreds to a few thousand events, while swarms from November 1995 through April 1996 lasted weeks and contained tens of thousands of events. During the two periods of greatest hybrid event activity in late May-early June and late July to mid-August 1996, hybrid swarms lasting only 1-2 hr, occurred several hours apart, and contained as many as ten thousand events; these swarms were often immediately

[1] Randall A. White, US Geological Survey, Mailstop 910, 345 Middlefield Road, Menlo Park, CA 94025, USA. (email: rwhite@usgs.gov)
[2] Angus D. Miller, British Geological Survey, Edinburgh, EH9 3LA, UK. (email: angus@geowalks.demon.co.uk)
[3] Lloyd Lynch, Seismic Research Unit, University of the West Indies, St Augustine, Trinidad & Tobago. (email: sru@wow.net)
[4] John Power, US Geological Survey, Anchorage, AK 99508, USA. (email: jpower@usgs.gov)



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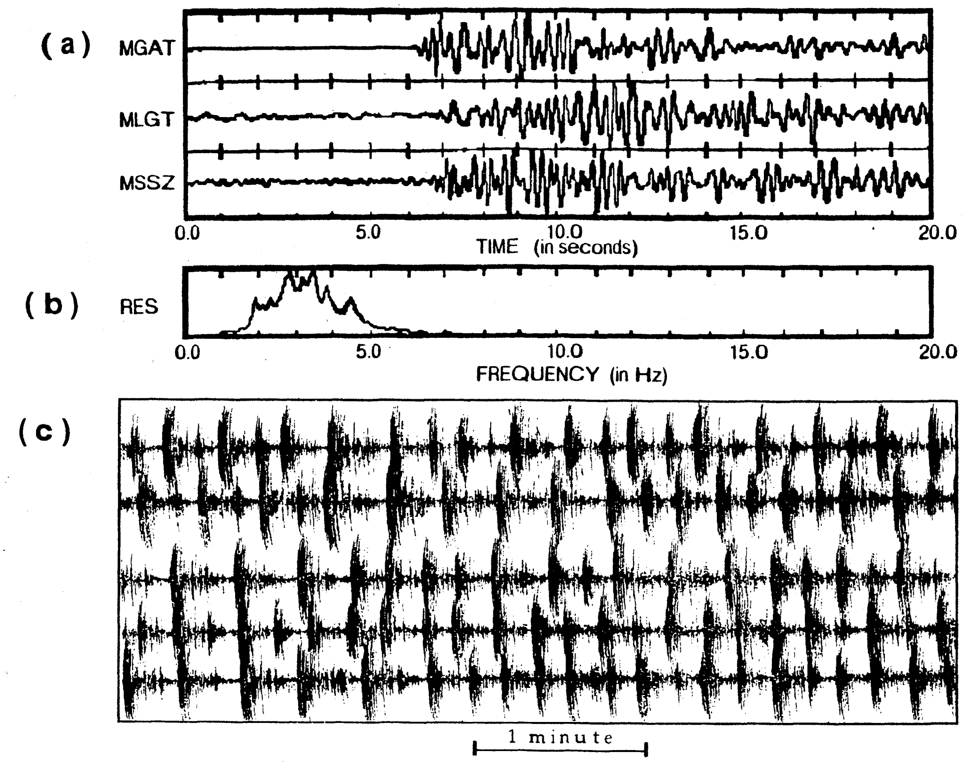


**Figure 1.** a) Waveform of a hybrid earthquake from January 6, 1996 at 08:10:52 from 1 Hz vertical-component velocity sensors located about one km west, 1 km northeast, and 2 km south of English's Crater, respectively; b) stack of the velocity amplitude spectra for the first 10 s of waveform for the same three stations; c) seismogram showing frequent hybrid earthquakes on January 26, 1996, recorded on a portable seismograph deployed on the north rim of English's Crater. Horizontal bar at bottom is 1 minute long. See Miller *et al.* (this volume) for other examples of hybrid waveforms.

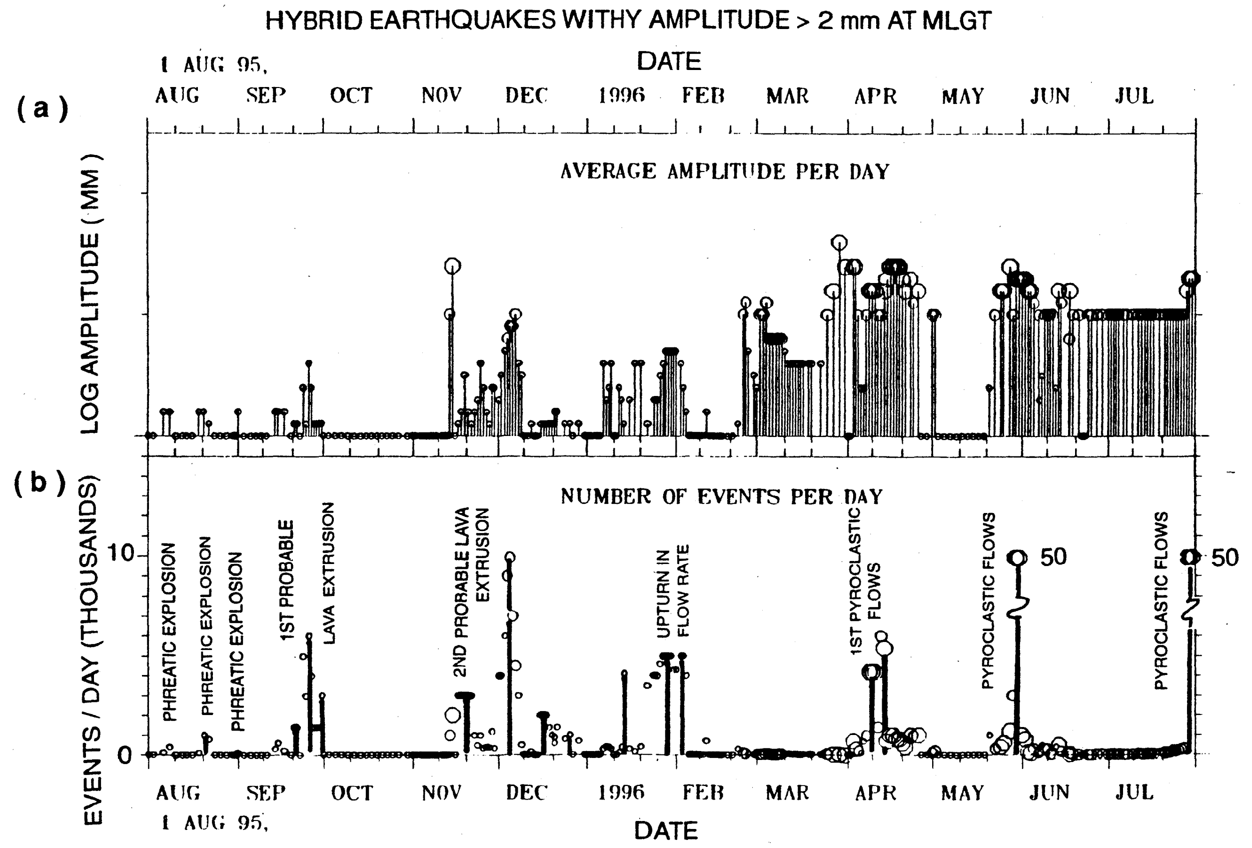


**Figure 2.** a) Average amplitude (in mm) of hybrid events per day at station MLGT. b) Number of hybrid earthquakes per day at station MLGT. The number of events per day for the two large spikes in late May and late July 1996 is complicated by the events merging to tremor, but should be about 5 times larger if the tremor is considered to be produced by hybrid earthquakes occurring at rates of 3 to 6 times per second as we infer (see text).

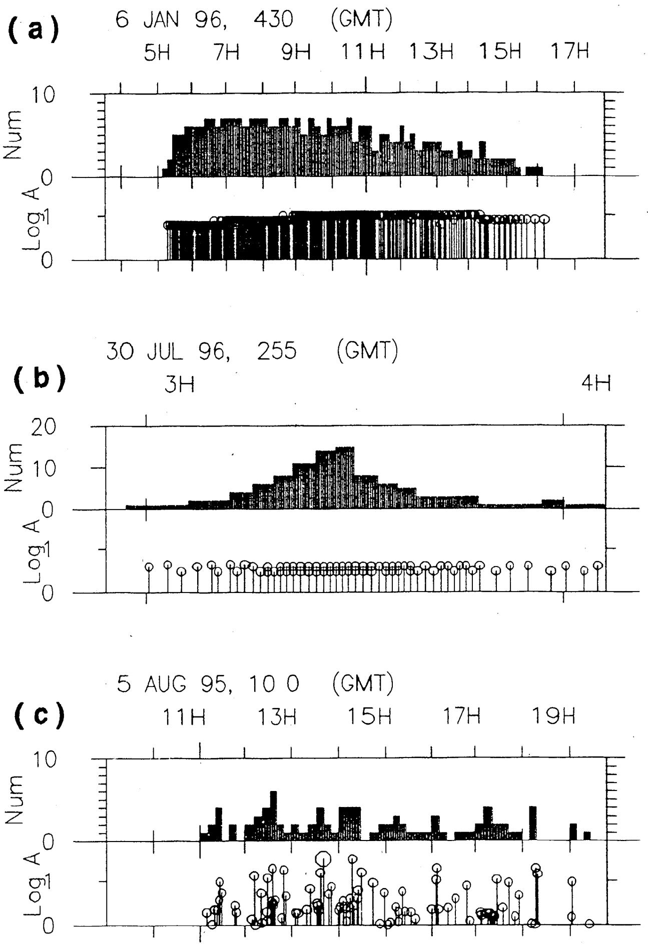


**Figure 3.** a) Log of the maximum amplitude (in mm) at station MLGT and number of events per 10 minutes for a swarm of hybrid earthquakes on January 6, 1996; b) Log of the maximum amplitude (in mm) at station MLGT and the number of events per second, for a swarm of hybrid earthquakes on July 30, 1996; c) Log of the maximum amplitude (in mm) at station MLGT and number of events per 10 minutes for a swarm of volcano-tectonic earthquakes on August 5, 1995.

followed by high rates of rockfall and/or pyroclastic flow signals.

## Hybrid Event Characteristics:

Discrete spectra were calculated for the first 10.24 s of waveform for ten events during each month of August, September, November, and December 1995 and from January and May 1996, for stations located about 2 km northeast, 2 km west, and 2 km south of the crater. These spectra were found to be in good agreement with SSAM spectra, in which spectral amplitudes were calculated for 16 discrete frequency bands between 0.2 and 10 Hz at one minute intervals over the entire study period for the same three stations. The spectra showed that hybrid events at Montserrat had a dominant frequency between 1.5 and 3.3 Hz, with decreasing energy up to about 8 Hz, such that $\sim 1 < Q \leq 3$. Hybrid events that occurred well prior to times of inferred extrusion were broader band, such that $\sim 1 < Q \leq 2$, compared with hybrid events that occurred just prior to or during an increase in magma flux rate.

Particle motions of hybrid events showed that waveforms contained clear P wave arrivals. First motions were often difficult to pick, owing to noise and/or event overlap, but may have had a mix of compressions and dilatations at different stations. Surface wave arrivals have dominantly horizontally-polarized energy, even at stations within 1 km of the crater (see also Neuberg *et al.*, 1998). The events also often contained a phase with the approximate arrival time and amplitude appropriate for an S phase, but with aparticle motion almost purely linear and radial, compatible with shear-wave splitting. Without a clear S phase, it was difficult to establish precise depths for the hybrid events, but standard hypocentral calculations based on P phases alone placed the hybrid events within three kilometers of the surface (Aspinall *et al.*, 1998 and Neuberg *et al.*, 1998).

In contrast to these hybrid events, VT earthquakes at Montserrat had significant energy up to 15 Hz such that $Q < 1$, had clear S-phase arrivals, and occurred at a variety of locations and depths (Aspinall *et al.*, 1998). LP events were observed less frequently than both VT earthquakes and hybrid events, often had clear S phases, and had strongly peaked spectra between 1.0 and 2.6 Hz, such that $Q > 4$. We located several LP events in early February 1996 at 1.7 +/-0.2 km beneath the crater.

During the various hybrid swarms, individual events often occurred at regular intervals which sometimes varied by less than 2% for hundreds to thousands of events over periods of hours to days. Figure 1C shows an example of such regularly spaced events during late January 1996. Swarms generally began with infrequent events, built to a peak rate, and then slowly declined. Often, the size of events within the swarm remained nearly constant. Figure 3A shows the maximum event amplitudes and number of events per 10 minutes for a hybrid swarm which occurred on January 6, 1996. Maximum amplitudes increased slightly at first, and declined slightly at the end, varying in all by less than a factor of 1.5. At the end of May and during July 29-August 10, 1996, swarms were much more brief, but also much more frequent, generally lasting only one to three hours and occurring every several hours. During these swarms, events occurred infrequently at first, attained rates of up to six events per second (as deduced from helicorder and SSAM records; see also Neuberg *et al.*, (1998), then decreased in rate, with amplitudes again remaining nearly constant. Figure 3B shows an example of such a swarm of hybrid events on July 30, 1996. For comparison Figure 3C shows the number of events per 10 minutes and maximum amplitudes for a VT swarm on August 5, 1995. Note the variability in both rate and size of the VT earthquakes as compared to the hybrid swarms.

Often events within individual swarms had virtually identical waveforms. Correlation coefficients were calculated for the first 10.24 seconds (1024 samples) for 40 randomly selected pairs of the 275 events which occurred in the swarm on January 6, 1996; the coefficients exceeded 0.9 +/-0.1 for all but one pair. We have not yet attempted a rigorous cross correlation of waveforms for all swarms; however a visual inspection of waveforms suggests that waveforms do not correlate well from one swarm to another.

## Discussion

Waveforms and magnitudes of individual hybrid events were observed to often be very similar throughout a swarm. The events are so similar that they must have originated within at most a few hundred meters of each other and be generated by a non-destructive source process. Neuberg *et al.* (this volume) believe that this source was at 2 to 3 km depth. The periodicity in both individual events and swarms may result from oscillations in pressure and/or mass flux within the magma column. That many swarms of hybrid events are followed almost immediately by rockfall and pyroclastic flow signals provides evidence linking the occurrence of hybrid events to the migration of magma beneath the lava dome.

We speculate that these observations are compatible with a model in which a deep pressure source acts periodically on the base of a magma column, inducing movement of the column. We speculate that the hundreds to thousands of hybrid events which accompany one of these movements may result from violent degassing of the upper magma column into adjacent cracks. Temporal variations in waveforms and spectra during swarms may result from physical changes due to vesiculation and expansion within the magma column at or just above the hybrid event source. Alternative theories for the hybrid event source include 1) stick-slip motion of the upper magma column sliding upward against the conduit walls, with the variations in waveform envelope and spectral content possibly caused by varying shear modulus of the rising magma and 2) thermally induced hydraulic fracturing (Shepherd and Aspinall, 1982).

## Summary

Hypocentral locations by Aspinall *et al.* (1998) show that hybrid events originate at <3 km depth beneath the crater. Large swarms of these events occurred approximately every two months from late September 1995 through August 1996, possibly reflecting a periodicity in pressurization acting at the base of the magma column.

Swarms began with events becoming gradually both more frequent and larger and ended with events becoming gradually less frequent and/or gradually smaller (see Figures 1 and 2, for example). Rarely, events suddenly became much smaller but much more frequent. Taken together, we speculate that this indicates a pressure source, within the upper magma column, that does not varies slowly with time.

Occasionally, two groups of hybrid earthquakes with different amplitudes and waveforms occurred during the same few hours. During such periods, the inter-event interval was uniform and large between the large events and uniform and small between the small events. Two distinct seismic sources may have been active simultaneously, with each seismic source having a its own pressure source.

During the large hybrid swarm sequences of late 1995 through early 1996, hybrid events were more impulsive and broader band at the beginning of sequences and became more emergent and narrower band during and after the peak in seismic activity. This also seems to be true for the larger sequences of mid-1996. This change in hybrid event waveform seems to correlate approximately with onsets of extrusion, and/or increases in the extrusion rate.

Long duration swarms during late 1995 through early 1996 had many evenly spaced peaks in the energy release rate over time. Intervals between peaks decreased gradually from more than 16 hours between peaks to 3 to 6 hours during the height of the activity, then increased again. This periodicity, and the manner in which it varied, was identical to the periodicity observed between the short, intense pulses of activity during mid-1996. These later peaks seemed to slightly precede increases in dome growth rate.

LP earthquakes were observed to occur at the beginning and end of large hybrid event swarms. LP events were generally larger and much less frequent than hybrid events. One group of LP events originated at about 1.7 +/-0.2 km depth. The LP events may originate from the same process which produced the hybrid events, but at a different depth.

We model the system as follows: a deep pressure source acts on the base of a magma column, inducing upward movement; pressure at the base of the column is temporarily reduced, but rebuilds after periods of about two months; this upward movement of the base of the magma column produces oscillations within the column which results in episodic movement near the top of the magma column and produces the evenly spaced peaks in the seismic energy release rate summarized above; the hundreds to thousands of hybrid events which accompany one of these episodic movements results from violent degassing of the upper magma column into adjacent cracks; the observed temporal variations in hybrid waveform envelopes and spectra during swarms may result from physical changes due to vesiculation and expansion within the top of the magma column.

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