GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 19, PAGES 3661-3664, OCTOBER 1, 1998

# Results from the broadband seismic network on Montserrat

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**Abstract.** A digital broadband seismic network has been installed around Soufriere Hills Volcano on Montserrat. While several distinctive types of seismic events with frequencies ranging from 0.5Hz to 30Hz could be identified, the emphasis is on two types of low-frequency events which indicate the involvement of a fluid phase in the source mechanism: the so-called long-period events and the hybrid events. The latter occur in swarms with distinct periodicities of 4 to 12 hours and preceed major dome collapses and explosions. The swarms correlate very well with the tilt observed at the flanks of the volcanic edifice and, hence, can be linked to the pressurization of the magmatic system. Occasionally separate hybrid events merge and form harmonic tremor, which sometimes has a shifting spectral content. This reveals temporary changes in the source parameters. Low-frequency seismic signals on Montserrat are considered to be key parameters for the monitoring of the internal dynamics of the volcano.

## Introduction

In October 1996, a network of five broadband seismometers was installed at the Soufriere Hills Volcano, to operate in conjunction with the short-period seismometer network, installed at the start of the present eruption on 18th July 1995. Seismometer cut-off frequencies of 0.03Hz allow detailed examination of periods up to 30s and longer. Miller et al. [1998] present a detailed discussion of the event classification scheme. Seismicity during the extrusive phase of the eruption has been dominated by low-frequency earthquakes. These events typically have narrow spectral bandwidths, often monochromatic, with distinctive spectral peaks in the 0.5-3Hz range. Observations of similar events at other volcanoes have led to the conclusion that such events are caused by resonant modes of vibrations in the volcanic plumbing system [e.g.*Chouet*, 1988]. Longer duration seismic events with cigar shaped envelopes and frequencies in the range of 1-10Hz have also been observed. These correlate visually with avalanches of material from the lava dome and are referred to as rockfall events. We concentrate in this paper primarily on the low-frequency events as these have been one of the most fascinating aspects of the seismicity observed to date. In contrast to other volcanoes such as Stromboli [*Neuberg et al.*, 1994] or Sakurajima [*Kawakatsu et al.*, 1992] the seismic energy observed on Montserrat to date is confined to frequencies above 0.05Hz. Therefore, the analysis benefits from the wide dynamic range rather than the broadband character of the seismic network.

## Data Acquisition

Data were acquired using a seismic network which originally consisted of five Guralp CMG-40T broadband seismometers arranged in an approximately orthogonal 2-legged array around the volcano [*Aspinall et al.*, 1998]. Three Integra LA100/F seismometers are also included in the network. The data are transmitted to the observatory site as 24-bit digital samples by UHF radio telemetry, and recorded both continuously and in triggered mode. A sampling frequency of 75Hz gives an effective system bandwidth of 0.03Hz to

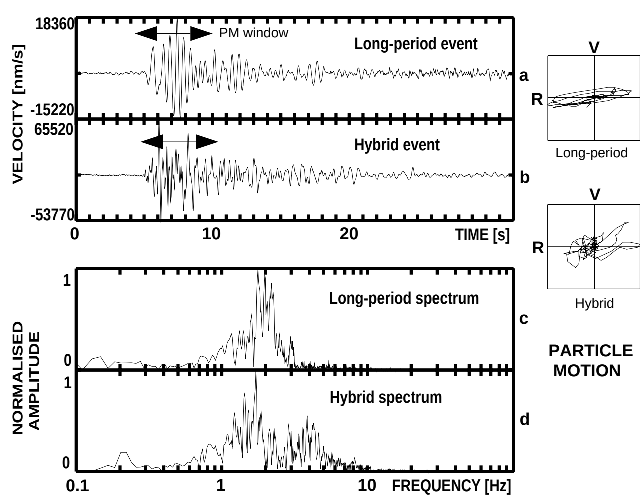


**Figure 1.** Radial component of LP and hybrid event and their amplitude spectra, recorded at station MBGA. Note the similarities and differences of the spectral content. Arrows indicate the time window for the particle motion in the vertical (V) - radial (R) plane.

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Paper number 98GL01441
0094-8534/98/98GL-01441$05.00

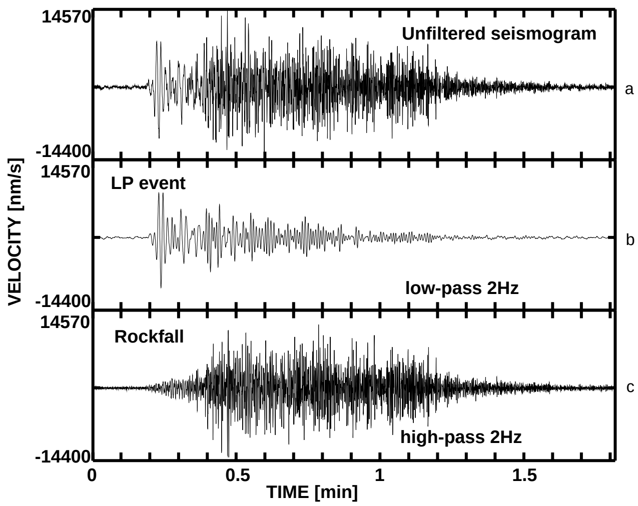


**Figure 2.** Vertical component velocity seismogram of a long-period event with associated rockfall (a); 2Hz low-pass filtered trace to isolate the long-period event, and (c) 2Hz high-pass filtered trace to separate the rockfall signal.

30Hz and dynamic range of up to 145dB for the broadband stations and 1-30Hz and 100dB for the short-period stations. The broadband stations each have three orthogonal sensors to monitor three components of ground motion, thus allowing reconstruction of the full wave-field. The remaining stations have a vertical geophone only.

## Characteristics of Low-Frequency Events

The low-frequency events have been subdivided into two families, long-period earthquakes (LP) and hybrid earthquakes, examples of which can be found in Fig. 1. These two types of events, however, are very similar and share common source processes, thus a continuum exists between these idealised end members. Long-period events are emergent and have monochromatic waveforms with a duration of several seconds. Their dominant frequency varies between 0.7 and 2.0Hz. Hybrid events have, in addition, higher frequency components and often impulsive onsets. The longest lasting hybrid earthquakes have durations of a few tens of seconds. Spectral bandwidths of 0.5Hz - 4Hz are typical. Hybrids have most commonly occurred in swarms and in some cases, with increasing rate of occurrence, discrete events have merged into tremor. In general, the spectral characteristics of the tremor episodes are identical to the spectra of the preceeding hybrid events.

### Long-Period Events

Fig. 1a shows the horizontal component velocity seismogram of a long-period earthquake recorded at the station MBGA (1km from the dome). The emergent signal appears as a modulated envelope of monochromatic energy. The corresponding amplitude spectrum, Fig. 1c, displays strong peaks around 1Hz. The positions of the spectral peaks show small variations at different stations (data not shown) due to both, different path effects and an interference pattern of eigenoscillations of the source, which varies with the receiver position [*Chouet et al.*, 1994]. The analysis of differential travel times gives an apparent horizontal velocity of $1800 - 1900\text{ms}^{-1}$ suggesting a relatively shallow source depth with the energy propagating as surface waves. This is further supported by particle motion analysis an example of which is shown in Fig. 1. The initial phase has a Rayleigh wave particle motion in the radial-vertical plane followed by several more complicated phases. For shallow sources at least some of these additional phases can be explained by the interaction between the seismic wavefield and the stress free surface of the pronounced volcano topography.

### Long-Period Rockfall

Fig. 2a shows the vertical component velocity seismogram of an event recorded at the station MBGE (2.5km from the dome), consisting of a rockfall signal with a well developed long-period precursor. We refer to such events as 'long-period rockfalls'. Rockfall causes high frequency, long duration signals with no obvious separable phases. Filters can be used to isolate two separate components superimposed in these events. The application of a low-pass 6-pole Butterworth filter at 2Hz, Fig. 2b, clearly shows that the long-period signal is a separate event that extends beyond the start of the rockfall signal. In turn, the high frequency rockfall signal is isolated by application of a high-pass filter at 2Hz, Fig. 2c. The LP part of the signal typically begins 10s - 20s before the start of the rockfall. This has been confirmed by using a GPS-synchronised video camera to record the rockfall activity.

### Hybrid Events

Fig. 1b shows the radial component velocity seismogram of a hybrid earthquake measured at the station MBGA, which occurred during a swarm of over 100 similar events. The initial slightly higher frequency impulsive onset is followed by a distinctive long period coda which lasts for several tens of seconds. The spectrum (Fig. 1d) has a narrow bandwidth and displays distinctive peaks between 1 and 2Hz similar to the LP-event, but in addition at 3Hz resulting from the high-frequency onset. Again, these peaks

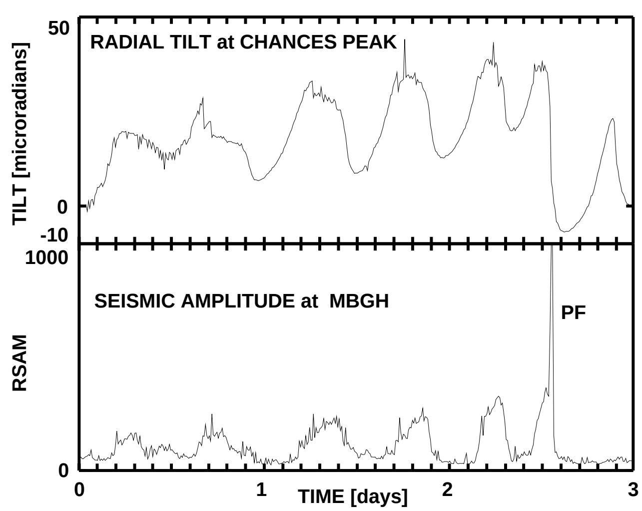


**Figure 3.** Correlation between radial tilt, recorded at Chances Peak, and averaged seismic amplitudes of hybrid events. Positive tilt indicates inflation, negative tilt deflation. The spike in the RSAM represents a pyroclastic flow (PF).

have different values at different stations. Particle motion analysis shows an initial linear P-wave component observed at all stations. This arrival is followed by a higher amplitude surface wavetrain, consisting of several different phases, marked by kinks in the particle motion trajectory. Differential travel-times measured between pairs of stations give a mean apparent horizontal velocity of 3300ms$^{-1}$ suggesting that the hybrid events have a deeper source than the LP events. Event locations yield focal depths ranging from 2-3km below the dome (at 1000m altitude).

## Results

### Hybrid Swarms

The hybrid events described in the last section occur mainly in swarms of seismic signals with very similar if not identical waveforms. The swarms preceed major dome collapses, occur with periodicities of 4 to 12 hours, and correlate very well with the radial tilt of the flanks of the volcano. This indicates several points:

(i) The occurrence of hybrid swarms is associated with the pressurisation of the magmatic system [*Chouet et al.*, 1994] and the corresponding inflation of the volcanic edifice. Fig. 3 shows the mean seismic amplitude with a radial tilt signal observed at Chances Peak at a distance of 700m from the dome. The subsequent pyroclastic flows correlate with the deflation (negative tilt) of the volcano [*Miller et al.*, 1998]. The periodicity of the swarms indicates an oscillating system of fluid charge and discharge with varying cycles of 4 to 12 hours.

(ii) The seismic source location does not change during a swarm. In order to reproduce the same waveform at a single seismic station the source location can only vary within a quarter of the dominant wavelength of the signal from one event to the next. This yields a source area of 200m diameter for the trigger event that ecxites the fluid resonance.

(iii) The trigger mechanism is repeatable. Propagating rock fracture is a very unlikely trigger mechanism to cause the seismic signal because it would alter the source location with each event. In order to construct a regularly repeatable source at the same location, only the involvement of a fluid can provide a mechanism that produces pressure fluctuations without altering or destroying the source area. This suggests the rapid and repeated opening of cracks by excessive gas pressure.

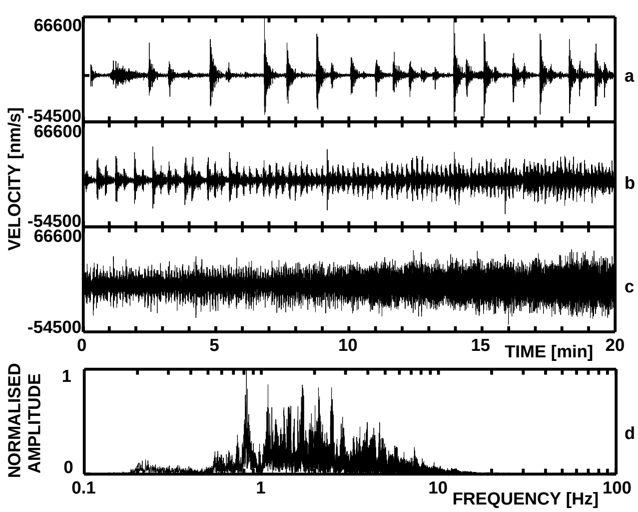


**Figure 4.** Consecutive time windows of 20 minutes showing the transition from single hybrid events (a) to tremor (b,c). Vertical component velocity trace at station MBGA; (d) Amplitude spectrum of tremor in trace (c).

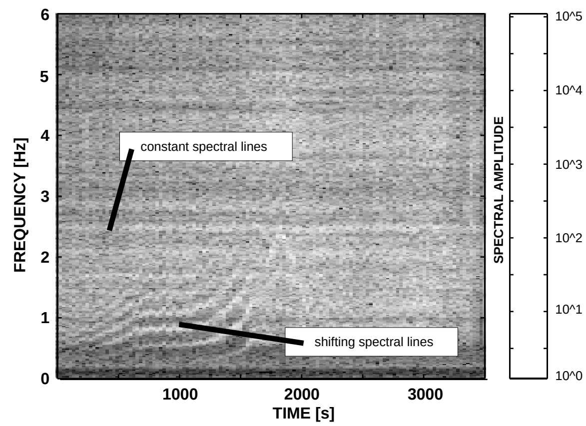


**Figure 5.** Spectrogram of seismic tremor episode, recorded at MBGA, showing shifting and constant spectral lines; sliding time window: 27.3s, overlap: 13.7s.

### Hybrids and Tremor

One of the most striking features observed during a hybrid swarm is the steadily increasing frequency of their occurrence until a stable value is reached (Fig. 4a-c). The superposition of the densely and regularly occurring hybrid events results in a signal with a stationary, peaked spectrum (Fig. 4d) which is usually referred to as harmonic tremor. This demonstrates that harmonic tremor on Montserrat can be considered a superposition of regularly occurring single hybrid events. One has to distinguish between the trigger frequency (or frequency of occurrence of the single events) and the resonance frequency of the volcanic plumbing system. The interference of these frequencies shapes the peaked spectrum in Fig. 4d. Fig. 5 is a spectrogram which shows an episode where the spectral lines shift in time in such a way that they remain evenly spaced. This has been observed on other volcanoes (e.g. Arenal [*Benoit & McNutt* 1997, ]). It demonstrates that the frequency shift can be attributed to a variation in the resonance frequency which is controlled by the geometry and parameters of the fluid-solid interaction. While this is clearly a source effect, the constant spectral lines in Fig. 5 represent the site resonance. Benoit & McNutt [1997] chose a 1-D resonator model and explained the frequency shift by the change of gas content and corresponding seismic velocity. For Montserrat, however, a 2-D model as described by Chouet et al.[1994] must be employed because, within the set of shifting frequencies the dominant spectral lines show variations at different stations.

## Discussion and Conclusions

The monochromatic nature of the LP- and hybrid events seems indicative of damped oscillations or resonances of the volcanic system, involving an interaction between a fluid and an elastic medium. Particle motion analysis suggests that these signals are composed of several seismic phases such as

P- and S-waves, as well as interface waves [*Ferrazzini & Aki.*, 1987] which dominate the signal. The similarity of consecutive waveforms implies a non-destructive source mechanism that kick starts the resonances in a fixed source location and therefore suggests the involvement of pressure changes in a fluid rather than propagating rock fracture. The existence of seismic events intermediate in nature between the long-period and hybrid types suggests that they may both have similar source mechanisms but originate from different depths. Two mechanisms explain the varying fraction of high-frequency energy in the hybrid signals and their relation to origin depth: For shallow locations (down to 300m depth) the seismic signal even at the nearest station on the flank of the volcano is dominated by surface waves and does not show any high frequencies due to the travel path being close to the free surface. Alternatively, the high frequencies could be attenuated on their way through loose and/or partially molten dome material. For deeper events, the high-freqency part of the signal propagates through less attenuating country rock. Together with the source location of the hybrid signals at 2 to 3km depth this favours the idea of a trigger mechanism which acts from the bottom end of the fluid-filled resonator rather than from the top end [*Benoit & McNutt* 1997, ].

The dissimilarity in spectra between individual seismic stations can be explained by a combination of different path effects [*Gordeev*, 1992] and a non-isotropic radiation pattern of the two-dimensional source due to the interference of the different eigenmodes of resonance [*Chouet et al.*, 1994]. This is evident from tremor signals where shifting and constant frequencies allow the separation of source and path/site effects, respectively: different stations see different dominant frequency peaks generated by the source.

The transition between a swarm of hybrid events and tremor demonstrates that both have the same source mechanism. Furthermore, if the LP-events are only a sub-class of (shallow) hybrid events, all low-frequency seismic energy observed on this volcano has one single source mechanism. Models which allow for the strongly depth-varying parameters of the fluid-filled conduit, as well as the location of the trigger mechanism in relation to this resonator are required for future progress.

**Acknowledgments.** This paper is published by the permission of the Director of the British Geological Survey (NERC). JN is grateful to the Institute of Geological & Nuclear Sciences, Wellington, New Zealand, for the kind support during his sabbatical. The comments of two anonymous reviewers are highly appreciated.

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(Received November 21, 1997; revised January 26, 1998; accepted February 18, 1998.)