MONTSERRAT VOLCANO OBSERVATORY

GOVERNMENT OF MONTSERRAT

Banded tremor at Soufriere Hills Volcano, July – August 1996

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MVO Open File Report 96/28

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Executive Summary

After a long period of quiescence, activity at Soufriere Hills Volcano escalated on 20 July 1996. The first indications were VT swarms. Other earthquake types (LPs, hybrids and rockfalls) also increased in intensity significantly at this time. On 29 July several pyroclastic flows entered the sea, and similar episodes occurred on 31 July and 11 August. These events surpassed anything seen previously during the current eruption.

Banded tremor was observed for the first time at this volcano on 23 July. Between 29 July and 7 August banded tremor saturated all seismic stations and appeared to be harmonic. Over the next few weeks the tremor decayed in amplitude and lengthened in period. The speed with which magma is intruded / extruded (magma flux) may directly affect tremor amplitude.

RSAM data shows the banded tremor clearly. Correlation of rockfall data with tremor bands demonstrates that the dome was more unstable during tremor bands. Dome collapse affected tremor amplitude, which indicates that tremor amplitude is related to the pressurization of the system.

Banded tremor has the potential to reveal a lot of information about the volcano and it is important that all data are analyzed in detail. There is still much work to do.

1 INTRODUCTION

The present eruption began on 18 July 1995. The volcano-tectonic (VT) activity increased over the next several months, and peaked during November, about the time dome growth began. This phase was characterized by phreatic eruptions. VT activity declined during December.

Between January and mid-July 1996 the seismic activity was low: an average of less than 1 VT event was detected per day. The first major dome collapses occurred between 3 and 6 April leading to pyroclastic flows which reached the road crossing the Tar River.

Continuous hybrid swarming occurred between 10 and 24 April which reached 5 events per minute at its peak; this corresponded to an increase in dome growth rate. Less intense hybrid swarming occured between 2 and 3 May and again between 31 May and 5 June. Pyroclastic flow activity recommenced on 10 May and on 12 May two flows reached the sea. These generated large ash clouds. These were the only notable events to occur between 1 January and 19 July. Towards the end of this period the scientific consensus was that the current eruption was probably reaching its end.

The first indication of elevated activity was the occurrence of VT swarms between 20 to 22 July (figures 0 and 1). These were the first VT swarms to occur since the phreatic phase. This implied an increase in magma flux from a depth of 3 to 5 km. The frequency of other volcanic earthquake types also increased around this time(figure 2).

VT swarms continued to occur over the next few days at shallower depths. As the slopes of the dome steepened, rockfalls grew in intensity and duration and on 28 July pyroclastic flow activity returned with flows reaching the Tar River Estate house and culminating in a large ash cloud at around 6 p.m. local time. The first indication of heightened activity was a signal saturating the Long Ground seismic station (the nearest station to the Tar River valley) between 0913 and 0948 on 28 July. On 29 and 31 July many flows reached the sea, the deposits forming a new delta at the mouth of the Tar River valley, 3 km from the dome. These produced accetionary lapilli as sea water boiled off and mixed with ash. The seismic signal corresponding to these pyroclastic flows saturated all seismic stations for periods of up to 90 minutes. These events were much larger than the 12 May event and involved the collapse of approximately 5 million cubic metres of rock [Shepherd and Stasiuk, 1996]. Collapsed material was replaced at a rate of 10-15 cubic metres per second. This is in contrast to a dome growth rate of 2 cubic metres per second estimated for the period between mid-April and 19 July.

The dominant feature of the seismic activity between 30 July and 7 August was banded tremor (figure 3). Tremor bands were intense enough to saturate all seismic stations and the only thing to distinguish them from major pyroclastic flows in seismic data was that they reappeared about every four hours. Later it became clear that the banded tremor actually began around 23 July and was still occuring on 23 August. Banded tremor is poorly understood phenomenon and most of this report is dedicated to discussing it.

Between 1 and 23 August activity remained high; activity varied daily but was generally decreasing. On 11 August some large pyroclastic flows occured. The last of these reached the sea and produced accretionary lapilli which formed a layer up to 3 cm thick in parts of Plymouth.

At the end of August the VT activity increased to a level exceeding that of late July (figure_1). On 17 September a phreatic explosion occured which destroyed several houses in the Long Ground and Tar River area. This was the biggest event to occur since the eruption began 14 months ago. It seems likely that the increased VT activity and this explosive eruption are connected. The potential for an explosive eruption was reported by Stasiuk in early August based on rock samples which showed increased vesiculation.

2 BANDED TREMOR

A cyclic pattern was first noticed by Rod Stewart in the RSAM data on 29 July (figure 4). John Stix identified this phenomenon as banded tremor after the major pyroclastic flow activity on 29 July subsided and the 4-hour periodicity was seen clearly on the drum records. Later inspection of the RSAM data reveals that banded tremor first appeared on 23 July, with a period of 6 hours. The tremor was strong enough to saturate all seismic stations between 29 July and 7 August. It then decayed and lengthened in period; by 23 August the period had increased to 10 hours.

Tremor bands were very regular and followed the same basic pattern:

1. Tremor bands were often preceded by a VT swarm which occured up to an hour before the continuous tremor emerged. These VT events were not particularly impulsive and lasted longer than normal. This may be because they were generated by the fracturing of hot, loose blocks.

2. Hybrid events occured, indicating gas or magma effusion at the surface, with the events gradually increasing in frequency from about one event per minute over the next 20 or 30 minutes.

3. Eventually the hybrid events merged into a continuous tremor. The continuous tremor lasted for about an hour, before it started to break up.

4. Hybrid events occured less and less frequently and stopped after 20 or 30 minutes.

Between 30 July and 7 August when this signal was the tremor appeared to be monochromatic or at least harmonic. No digital frequency analysis was possible and no digital seismograms of these strong tremor bands exist, since the recording system uses an event trigger. (To record the tremor, the recording system had to be put on a continuous trigger. This was done, but by that time the tremor bands were much weaker and the apparent harmonic nature and frequency doubling had disappeared). Measurements from the paper records indicated that the dominant frequency was ~1.5 Hz. Later, when the tremor had decayed, it looked more like white noise.

The correlation of monochromatic/harmonic tremor with tremor intensity can be interpreted as a resonance phenomenon. The hybrid swarming prior to tremor bands demonstrates that fluid pressure variations are the source of tremor, and as those fluid pressure variations rise they may at some point trigger the fluid column to resonate.

3 RSAM Data Analysis

Although no seismograms of banded tremor exist, RSAM data does exist which provides a continuous record of seismicity with a time resolution of 1 minute. This is sufficient for measuring some general parameters of the banded tremor. The main conclusions are:

- A correlation between amplitude and period of tremor bands exists (figure 5). Generally as the period decreases the amplitude increases. The errors bars are too large to best fit a line to the data, but amplitude roughly behaves as the inverse of the period. This suggests that amount of magma intruded/extruded during each tremor cycle (one period) was about the same. In this model the difference would be the speed with which magma reached the surface -- faster rising magma would result in a larger seismic amplitude and a shorter period.

- Rockfalls occur more frequently during tremor bands than they do between tremor bands; this can be seen in RSAM data in which rockfalls show up as sharp spikes and the banded tremor can be seen as the underlying envelope (figure 6). This suggests tremor bands are related to inflation of the volcano (making the slopes steeper) or with an increased extrusion rate, both of which would increase the likelihood of dome failure.

- Pyroclastic flows interfere with banded tremor. This is best demonstrated by the 31 July pyroclastic flow episode. After the activity on 29 July, tremor bands are seen to increase in amplitude over 10 cycles, until the activity on 31 July occurs (figure 3). Tremor bands then grow again from a low amplitude. The influence of dome collapse on period is not as strong, although there is a discontinuity in period after the 11 August pyroclastic flows. The removal of overburdening material seems to relieve whatever mechanism causes the tremor. One interpretation is that the depressurization of the magma column caused after a dome collapse leads to increased vesiculation, which tends to decouple the magmatic system from the solid rock. Since banded tremor consists of hybrid-like signals, and those are related to magma intrusion/extrusion, it would appear that dome collapse allows magma intrusion/extrusion to occur more easily.

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4 Banded Tremor Elsewhere

Banded tremor is a rare phenomenon but it has been observed for short times at several volcanoes: Karkar, Izu-Oshima, Etna and Nevado del Ruiz [Martinelli, 1990]. At all these volcanoes banded tremor correlates with visible activity and so banded tremor must have a shallow source. In some cases the banded tremor ceased prior to explosive activity, suggesting the volatile components of the magma are in some way related to banded tremor. A similar type of activity occurs continuously at Old Faithful Geyser [Kieffer, 1984] which suggests that banded tremor is related to the dynamics of magmatic or hydromagmatic system. Phreatic activity at Soufriere Hills indicates that water may have an important role.

5 Further Work

There is the potential to learn a great deal about this volcano through a proper study of banded tremor data. The data collected at Montserrat adds considerably to the worldwide database. The digital seismograms of banded tremor recorded by the short-period network that were archived to CD should be analysed properly unless similar data has since been recorded by the broadband seismic network. Unfortunately due to the lack of access to digital data I have not been able to perform a detailed study of this phenomenon. It would be useful to perform a 3-component frequency and particle motion analysis in order to determine the source region and its geometrical properties.

A study based on drum record data was being performed by Levar Cabey and David Silcott although no results have been forthcoming. John Stix, Rod Stewart and William Ambeh may also have done some work on the data.

Even with the limited data I have, there is a great deal more I could do, particularly by comparing the data to those recorded at other volcanoes.

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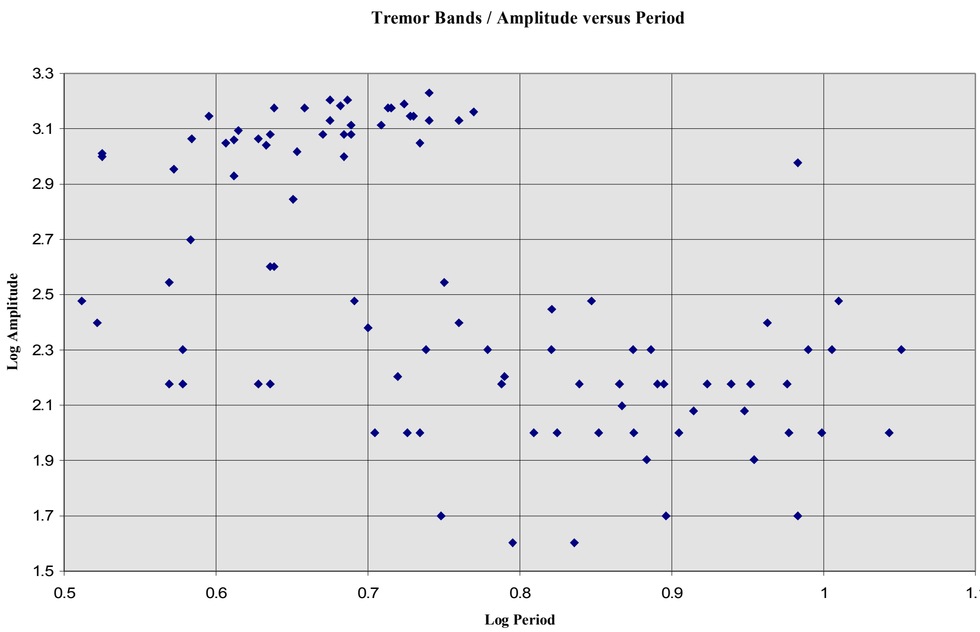
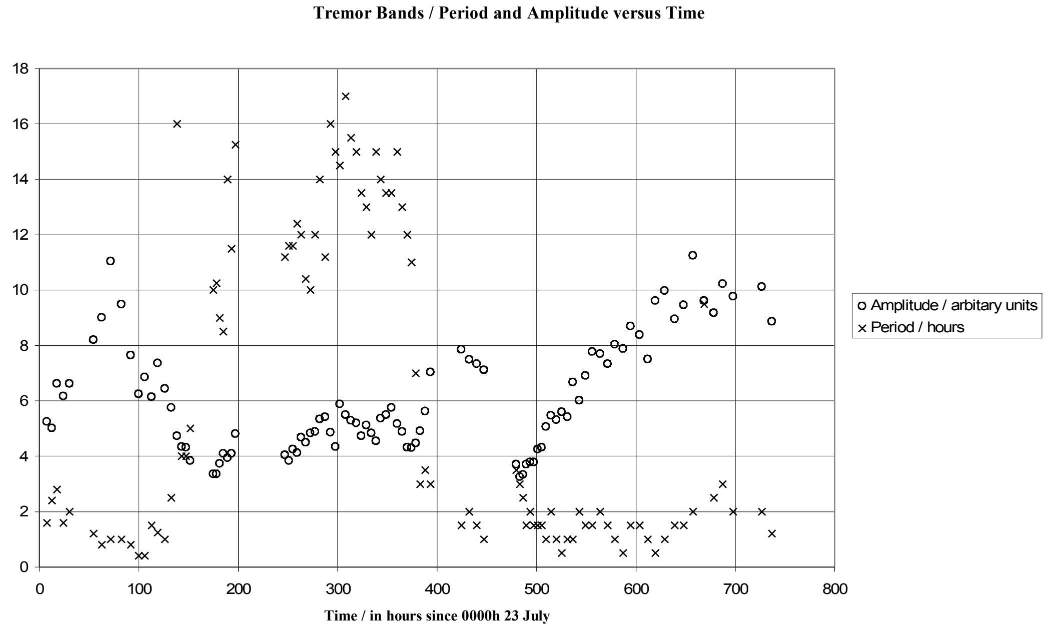
Figure 1: VT activity for the period 29 June 1996 until 18 September 1996. Prior to 20 July 1996 no significant VT activity had occured since December 1995.

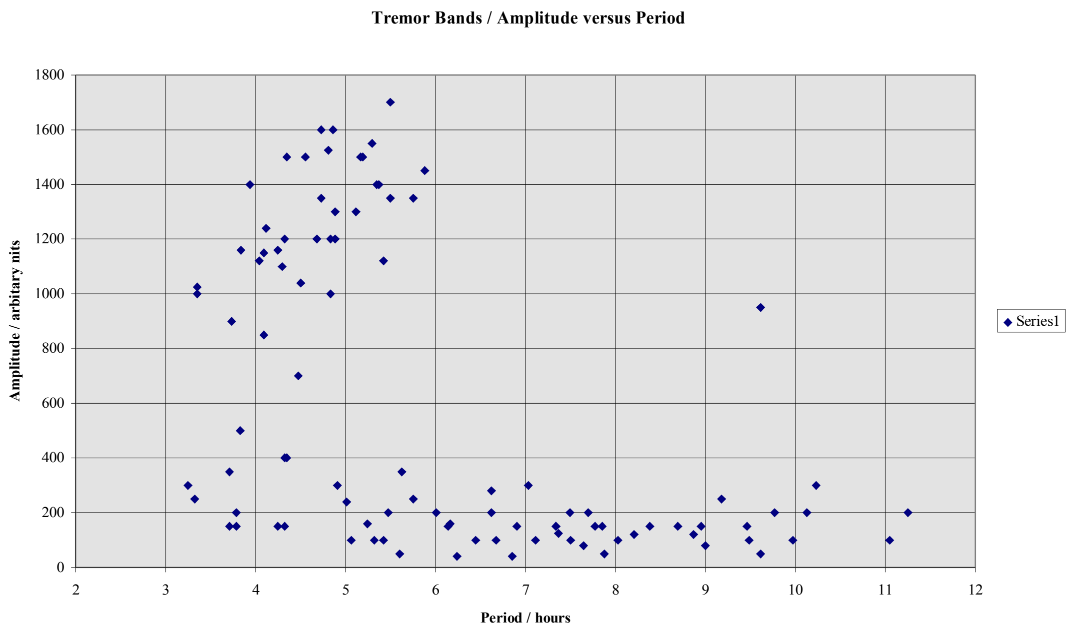
Figure 5a: Plot of tremor amplitude versus time. Some data points are misleading because pyroclastic flow signals are hard to differentiate from banded tremor signals; this applies particularly to points on the 29 and 31 July, and on 11 August.

Figure 5b: Plot of tremor period versus time. Some data points are misleading because pyroclastic flow signals are hard to differentiate from banded tremor signals; this applies particularly to points on the 29 and 31 July, and on 11 August.

Figure 5c: Best fit line to logarithmic graph of tremor amplitude verses tremor period. The gradient is close to -1, suggesting that amplitude is inversely proportional to period.


Tremor Bands / Amplitude versus Period
Log Amplitude
3.3
3.1
2.9
2.7
2.5
2.3
2.1
1.9
1.7
1.5
0.5
0.6
0.7
0.8
0.9
1
1.1
Log Period


Tremor Bands / Period and Amplitude versus Time
18
16
14
12
10
8
6
4
2
0
0
100
200
300
400
500
600
700
800
Time / in hours since 0000h 23 July
Amplitude / arbitary units
Period / hours


Tremor Bands / Amplitude versus Period
Amplitude / arbitary nits
Period / hours
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9
10
11
12
Series1

APPENDIX 1 – DATA SOURCES

There are essentially two types of data used in this report: continuous data and triggered event data.

The seismic activity at all 10 stations is also continuously monitored by a PC-based system. The PC-system provides two important datasets: triggered events and real-time seismic amplitude measurement (RSAM) data. The triggered events are analysed by seismologists and identified as VT, LP, hybrid or rockfall. This provides a second record of the event counts. These are always summed over a 24-hour period from local midnight each day.

Seismic data from 4 stations is continuously plotted on paper drum records. At 16:00 every day the helicorder records are changed and a Seismic Analyst classifies and counts the events recorded on that 24 hour helicorder record. These counts are then stated in daily reports covering the same 24 hour reporting period.

The RSAM data is the most informative dataset of all, since it provides a continuous and completely objective record of the intensity of the seismicity. These are also recorded using local time, but timed with a computer clock which drifts.

So to summarise, the three datasets used in this study are:

1. event counts as reported in the daily reports (measured from drum records over a 24-hour period ending at 16:00 each day).

2. event counts as triggered by the PC-system (measured over a 24-hour period ending at 24:00 each day).

3. RSAM data, which is totally objective, and can easily be plotted graphically.

Advantages and disadvantages:

(i) Triggered event data:

The triggering algorithm provides a constant benchmark, which assures that comparisons made with trigger data are very meaningful.

Triggered data are fine unless there is a high level of background activity. During bands of high amplitude tremor observed in late July and early August few events triggered. The trigger data can therefore show an apparent lull in activity when large amplitude continuous seismicity is occuring. At such times it is better to rely on the other datasets.

(ii) Drum counts:

In general drum counts are higher than triggered data. This is because smaller events, easily identified on the drum records, do not trigger. The pattern of activity shown in these datasets should be similar though.

(iii) RSAM data:

RSAM data is the best indicator of the level of seismic activity, but it cannot be used to distinguish individual events because it has a time resolution of 1 minute. In contrast to the two methods of counting discrete events, this dataset is continuous and includes the background tremor too.

APPENDIX 2 – MONITORING VERSUS RESEARCH

At the MVO the main activity is short term monitoring of activity and there is a tendency to avoid research, which is a mistake. Scientific meetings at the MVO focus on observations and defining hazard maps but scientific questions are rarely discussed.

As a seismic consultant at the MVO most of my work was to classify earthquake events and keep records, but noone was urged to consider the implications of trends in the earthquake activity. There was a general lack of discussion.

There are many monitoring programs in operation at the MVO: GPS, EDM, dome growth, COSPEC, FTIR, microgravity and seismic. Of these seismic collects by far the most amount of data, as data are collected continuously at 10 stations (including 2 three-component stations) at a sampling frequency of 100 Hz; seismic data is potentially the most powerful tool at the MVO. However, the seismic network is used only as a record keeping tool (counting earthquakes), and very little work is done to try to understand the volcano, and rare phenomena which do not fall into the pattern of 'normal' activity are largely ignored.

In particular the imminent installation of a broadband seismic network is welcomed. Broadband seismometers are not handicapped by such a poor frequency range and can be used to detect very low-frequency tremor and events.