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# Remarkable cyclic ground deformation monitored in real-time on Montserrat, and its use in eruption forecasting

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**Abstract.** Telemetered high-resolution tiltmeters were installed in Montserrat in summer of 1995, in December 1996, and in May 1997. The 1995 installations, several km from the Soufriere Hills vent, were too distant to yield useful data. However, the 1996 and 1997 installations on the crater rim revealed 6-14 h inflation cycles caused by magma pressurization at shallow depths (< 0.6 km below the base of dome). The tilt data correlated with seismicity, explosions, and pyroclastic flow activity, and were used to forecast times of increased volcanic hazard to protect scientific field workers and the general public.

## Introduction

The eruption of Soufriere Hills volcano on Montserrat began in July 1995 [*Young et al.*, this issue]. Electronic tilt monitoring began soon after the onset of the eruption, with the deployment of 3 tiltmeters at distances > 1.5 km from the vent. Although similar arrays at other volcanoes have yielded useful data, the Montserrat array recovered no clear evidence of deformation through August 1997.

Concern over the possibility of a sector collapse and lateral blast led to the installation of a telemetered tiltmeter on Chances Peak near the south crater rim in December 1996 (Fig. 1). In late December this tiltmeter (CP1) began to display cyclic variations, and by early January it was recognised that these cycles correlated with seismicity and rockfall or pyroclastic flow activity. The system was destroyed in mid-January 1997. Tilt monitoring was reestablished on Chances Peak on May 18 1997 (Fig. 1). The new installations coincided with strong cyclical inflations and deflations, and these cycles enabled correlations with specific styles of swarm seismicity, peak occurrences of rockfalls and hazardous pyroclastic flows from the dome, and degassing. Tilt monitoring was continuous until August 5 when system components were destroyed by a vulcanian explosion that had been forecast on the basis of the cyclical tilt behavior. This paper discusses the tilt installations and shows how the data of 1996-97 provided key insights and constraints on the causative magmatic processes, and enabled forecasts of hazardous volcanic activity.

## Systematics

High-gain tilt sensors were bubble-type biaxial platform tiltmeters with a resolution of 0.1 μrad, set at 0.1 μrad/mV. Digital data telemetry platforms were designed and built by the USGS Cascades Volcano Observatory [*Murray et al.*, 1996]. Radio and antennae systems were added, and power was provided by automobile batteries coupled to solar panels.

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Analog inputs were digitized (A-D sensitivity 12+ bit dual-slope integration) and transmitted by radio to the Montserrat Volcano Observatory (MVO) receiving site at nominal 8 min intervals. Transmissions took less than 10 s, allowing several transmitters to share the same frequency, and were received by radio and relayed through a modem port of a computer for decoding and data storage. The tilt data are stored in unfiltered form in a database but can be analyzed using the interactive, command driven program BOB [*Murray et al.*, 1996]. BOB facilitates near real-time analysis of time-series data from multiple monitoring sources, such as RSAM and triggered seismic events. RSAM measures the average absolute amplitude of seismic signals, using a sampling rate of about 60 samples per second [*Endo and Murray*, 1991]. It provides a simple quantitative measure of seismicity but does not discriminate between various types of seismic events and rockfalls. Triggered events are the number of events recorded at a given station during a 10-min period, counted by recognising sudden jumps in average amplitudes (RSAM units) over successive 2.5 sec increments [*Murray et al.*, 1996].

Whenever possible, platform tiltmeters (the standard type used by the USGS volcano crisis assistance team) should be protected by burial to reduce temperature change and environmental effects [*Dzurisin*, 1992]. However, this type of installation is time consuming and thus can be less favorable for hazardous locations such as Chances Peak. The short base length of the tilt sensor makes it sensitive to local deformations, and once buried, a substantial time period is sometimes required for the system to reach thermal and mechanical equilibration. Some of these problems can be reduced by borehole installations, but this option was not available to us and the site conditions did not favor it. An available alternative was the thick, reinforced concrete floor of an

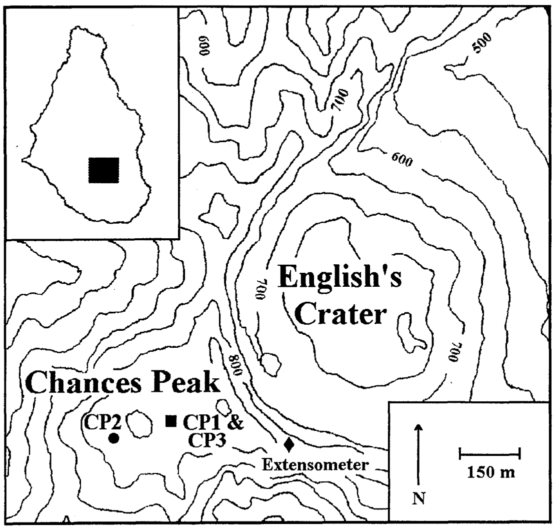


**Figure 1.** Map of summit area of Soufriere Hills volcano, showing locations of tiltmeters. Inset map shows summit area in relation to Montserrat island. X-axis azimuths of the 3 tiltmeters are CP1, 324; CP2, 002; CP3, 099. Subtract 090 for Y-axis azimuths.

isolated room in the Cable-and-Wireless radio communication building near the summit of Chances Peak (CP1, Fig. 1). The room provided protection from weather and modulated temperature fluctuations, the floor provided a large base length for the sensor, equilibration would be rapid because the building had been present for years, installation could be rapid, and the strong concrete walls and roof afforded protection to the sensor, and to the field crew, against some eruption hazards. The CP1 system lasted until January 13 1997 when the room was flooded by rain-mobilized ash.

In May 1997 a tiltmeter was installed inside the Antilles Radio building (CP2, Fig. 1). A waterproof stainless steel tilt sensor was used to avoid potential flood problems. It became operational May 18 and provided usable signals within hours. Four days later a second sensor (CP3) was installed inside the Cable-and-Wireless hut. To avoid flooding, the sensor was placed on a stiff metal bracket bolted to an interior reinforced-concrete wall. The two tiltmeters, at different distances from the vent, complemented each other. However, an important reason for the second installation was redundancy to help maintain a data stream to MVO, given the fragility of electronic tiltmeter systems, and the vulnerability of any installation near an actively growing dome. This decision was validated as CP2 was plagued by malfunctions after May 30 and the redundant system CP3 carried the weight of vital data transmission throughout the eventful summer.

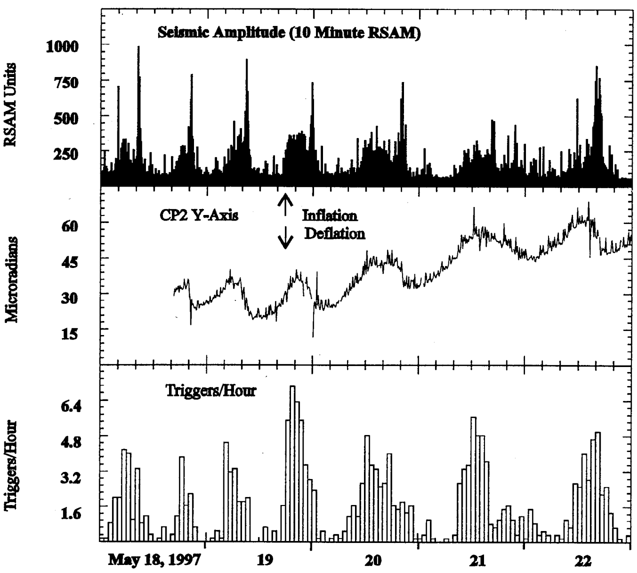


**Figure 3.** Comparison of cyclic CP2 tilt records with RSAM and triggered earthquakes. May 18-22, 1997. The triggered earthquakes are dominated by hybrid events. The largest spikes in RSAM are rockfalls or pyroclastic flows.

## Tilt Cycles, Related Activity, and Forecasts

### December 1996 - January 1997

Signals from tiltmeter CP1 stabilized within a day of its installation on December 9, at the end of a period of hybrid swarm seismicity. A steady, long-term tilt change immediately became evident and continued until about December 20 (Fig. 2), when a tilt inflection point coincided with a shift in the locus of dome growth from the south to the northeast. Two days later the tilt resumed its pre-20 December behavior. The long-term tilt rate of both axes declined on December 30, and convincing, low-amplitude (1-2 μrad) cyclic tilt variations emerged from background noise at about the same time. The cycle period was about 6-8 h, and was clearly correlated with RSAM (seismic amplitude) cycles which had reappeared on December 22. Data from CP1 ceased on January 13, probably due to loss of battery power with water immersion.

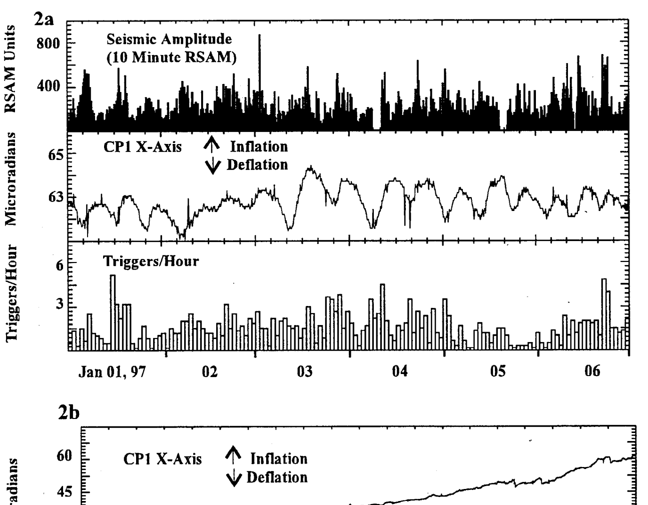


**Figure 2.** (a) CP1 tilt pattern for January 1-6 1997, compared to seismic amplitude, RSAM, and triggered events per hour. (b) CP1 trend leading up January 1.

### May 1997 - August 1997

Within a few hours after installation on May 18 and 22, respectively, tiltmeters CP2 and CP3 began to display a strong rhythmic pattern of repetitive inflation and deflation (Fig.3); cycle amplitudes (10-25 μrad) were much greater than those observed with CP1. Each cycle lasted about 12-18 h, with the deflationary part of the cycle occurring more rapidly than the previous inflationary part. The correlations between tilt, seismicity, and rockfall/pyroclastic flow activity that had previously been recognised were now even better developed. Hybrid earthquakes [*Miller et al.*, this issue], recently reactivated after many weeks of low activity, occurred in increasing numbers as the inflationary part of the cycle progressed, sometimes merged into tremor as inflation approached a maximum, and then declined. Their pattern is indicated in real-time by display of "triggered events" (Fig. 3). Peak rockfall/pyroclastic flow activity occurred with deflations. The latter pattern is apparent from the RSAM data, with the higher peaks in RSAM due to dome rockfalls and pyroclastic flows, and the lower amplitude background caused by hybrid events, tremor, lesser rockfalls, and other seismicity.

The predictive value of the tilt pattern was confirmed after a few days of observation, and tilt data then began to be regularly used to reduce the risk to field parties to pyroclastic flows. Ordinarily the tilt data were used for forecasts in concert with real-time displays of "triggered" events (mostly hybrids). Initiation of the deflation could generally be recognised with high resolution on the tilt record; once an inflation episode began to flatten out, rockfalls and pyroclastic flows could be expected to peak within the next few hours (Fig. 3). The occurrence of such activity could then be confirmed by drum records or RSAM, or by visual observations during good weather. Thus, when possible, field missions by MVO, public officials, animal rescue teams, and others into hazardous areas were scheduled to coincide with the time of early inflation, when likelihood of pyroclastic flows was considered minimal. For much of the summer the public was not widely informed of these forecasts, for reasons pertaining to wise hazard management: first, officials and MVO did not wish to encourage the public to enter hazardous areas at any time, and such forecasts might have inadvertently provided such encouragement; and second, although peak activity could be anticipated, this did not preclude the occasional random occurrence at other times of hazardous pyroclastic flows. However, citizens performing critical work in potentially hazardous areas were continually advised on the state of the volcano, and public forecasts were made on selected occasions.

Tilt amplitudes declined gradually at the end of May, as the number of hybrid earthquakes also declined. Signals from CP2 stopped May 30, so the remaining account is based on CP3. A temporary increase in cyclic tilt amplitude to 16-18 μrad occurred between June 5-14 (period 12-16 h), coincident with a brief increase of shallow long-period (LP) seismicity. Tilt amplitude then declined to 5-10 μrad. Rockfalls into drainages on the northern flank of the volcano had continued throughout this period, generally still synchronized with the tilt cycles. A swarm of volcano-tectonic (VT) earthquakes occurred on June 16. The next day, another brief episode of increased tilt amplitude began, and with its deflation, pyroclastic flows containing sparsely-vesicular pumice occurred with runout to 3.5 km. After a second cycle of elevated amplitude, the tilt again resumed the low-amplitude pattern.

The low-amplitude pattern was broken by an abrupt inflation at 0530 on June 22 (Fig. 4), followed an hour later by a sharp deflation coincident with sustained pyroclastic flows down Tar River. This tilt excursion was the first in a series of 9 high amplitude (~ 30 μrad resultant), short period (8-12 h) cycles that culminated in a major dome collapse event. A VT swarm occurred on June 22, following a brief increase in LP seismicity; thereafter the successive cyclic inflations were accompanied by a buildup of hybrid seismicity, with the events becoming larger and more numerous and the overall deformation trend deflationary (Fig. 4).

By June 24-25 the hybrid swarms became so intense at peak inflations that the overall pattern resembled tremor on the drum records, difficult to distinguish from rockfall signals. The ninth inflation began about 0900 and peaked around 1200. The accompanying hybrid swarm began at 1050 and merged into continuous tremor around 1245, when deflation commenced. Ten minutes later a partial dome collapse occurred (8 million cubic meters) and associated pyroclastic flows swept the volcano's northern flanks nearly to the sea. This, the most lethal event in the volcano's historical record, destroyed about 150 houses and killed 19 people.

The loss of life occurred despite hazard warnings and zonations that since mid-May had repeatedly emphasized the threat of energetic pyroclastic flows and surges on the northern and eastern flanks of the volcano. The recent increase in tilt cycle amplitude and seismicity were interpreted as evidence of increased conduit pressurization, and an increasing pyroclastic flow hazard. Field crews adjusted their operations and schedules in cognisance of the tilt cycles and their relation to pyroclastic flows. On the basis of tilt and cyclic seismicity, field crews were withdrawn, or denied access to, areas that minutes later were swept by pyroclastic flows and surges. Check points into Plymouth were closed at 1230, and at 1245 and shortly thereafter, essential services in Plymouth were advised to evacuate, the siren was sounded, and the duty scientist at the airport was alerted.

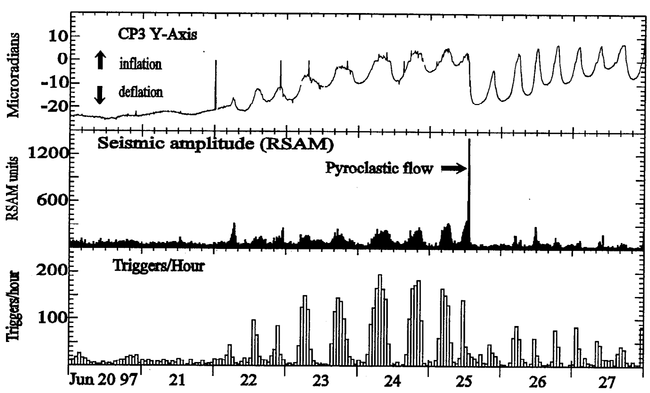


**Figure 4.** Comparison of CP3 tilt record with seismic amplitude, RSAM, and triggered events per hour. June 20 - 27, 1997. Large pyroclastic flows from the partial dome collapse on June 25 destroyed several villages and killed 19 persons. Spikes on tilt record represent noise.

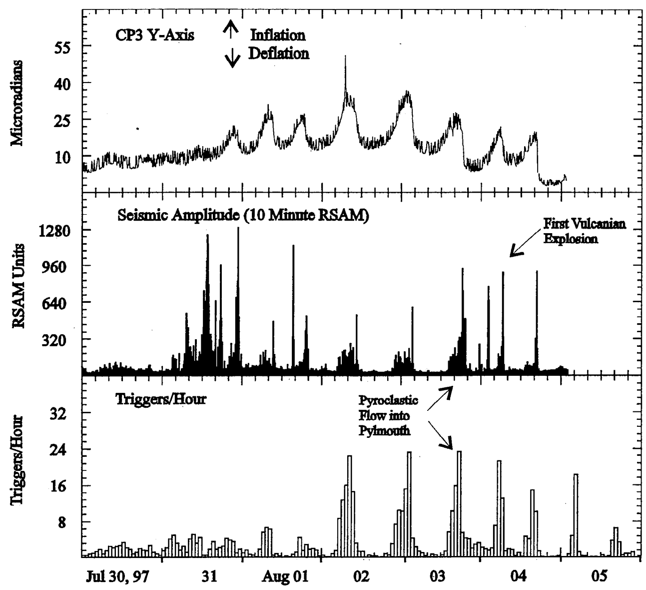


**Figure 5.** CP3 tilt records for the period July 30-August 5, 1997. The tilt system was destroyed by explosions on August 5.

The deflation that coincided with the collapse was more pronounced than for preceding cycles, and succeeding cycles displayed somewhat greater amplitudes to July 8. The peaks of the tilt waveforms changed, from blunt, broadly curving forms to sharp, pointed inflations. By July 10 the tilt pattern had flattened due to low amplitudes (a few μrad) and periods ~ 30 h, although dome growth continued.

Seismicity elevated on July 31, coinciding with development of high amplitude tilt cycles with 10-14 h periods, which continued into August (Fig. 5). At 1800 on August 3 a substantial pyroclastic flow, anticipated from the tilt cycle and the increase of activity in this sector, swept through Gages village into Plymouth, igniting and destroying many buildings. At 1615 the next day, during a deflation, a dark gray jet was seen projecting from the north flank of the dome. This event marked the dome-destruction phase of a series of vulcanian eruptions that occurred at 10-12 h intervals, with collapsing ejecta fountains producing pyroclastic flows down all flanks of the volcano. Each explosion was anticipated on the basis of cyclic tilt and/or associated seismicity, and each was publically forecast: the populace was warned in advance by siren and public radio, and limited temporary evacuations were enforced. The explosion at 0445 on August 5 destroyed the tiltmeter installations and radio towers on Chances Peak. Although the tilt data were no longer available, seismic data (particularly, hybrid seismicity on drum records) served as a proxy to enable identification of the continuing cycles.

## Discussion

Magma is expelled from the conduit in pulses because of two competing processes: (1) exsolution and degassing at the top of the magma column, which increases magma viscosity and strength and thus inhibits magma flow, and (2) pressurization of the magma beneath the degassing plug, which works to push the plug out of the conduit against its flow resistance and the back-pressure of the overlying dome.

Magma melt viscosity and density rise as volatiles escape from the melt, and rise further when the volatile loss causes microlite crystallization. As microlites become abundant they increase the bulk viscosity and strength by particle-to-particle interactions, and by increasing the silica content of the melt phase [*Shaw*, 1972]. The resulting plug of stiff magma retards the flow of less viscous, more volatile-rich magma at deeper levels in the conduit [*Sparks*, 1997; Hoblitt et al., 1996].

The volcano inflates as volatile-rich magma pressurizes under the stiff plug. The pressure rise is due to transfer of overpressure from the magma chamber aided by high-level pressurization of degassing magma under the plug. The hybrid earthquakes are indicators of this pressurization. Eventually the pressure reaches a threshold sufficient to push the degassed plug out of the conduit and into the dome, along with an accompanying slug of magma richer in volatiles. This extrusion relaxes pressure in the upper conduit, causing deflation of the volcano. However, this rapid decrease in pressure also promotes degassing and microlite nucleation in fresh magma rising in the conduit, and a new tilt cycle begins.

The depth of pressurization can be modelled using tilt data as a constraint. In the simplest approximation the pressure source may be treated as an inflating spherical cavity in a homogeneous elastic half space [*Mogi,* 1958]. The source epicenter is constrained by known points of lava effusion and by seismicity. Tilt data from CP2 and CP3 for individual inflations in May, with station radii measured from the assumed epicenter, yield a source depth about 700-800 m. However a cylindrical source is capable of producing similar surface displacement profiles [*Dieterich and Decker*, 1975], and analysis suggests that the top of the conduit pressure source is perhaps only a few hundred meters below the lava dome. This result provides an explanation for the lack of signals discerned at distant tilt stations.

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