Deformation Studies on Soufriere, St. Vincent, Between 1977 and 1981

Abstract. *Dry-tilt measurements at two stations indicate that Soufriere Volcano gradually inflated at least 10 microradians prior to the initial explosions of April 1979 and then rapidly deflated more than 20 microradians after the activity got under way. The tilt measured at the station 6.5 kilometers from the summit was about twice that measured at a distance of 2.5 kilometers. This finding suggests the existence of a magma chamber at a depth of more than 10 kilometers.*

In March 1977, more than 2 years before the explosive eruptions of April 1979, two tilt-monitoring stations were established on the east flank of Soufriere, St. Vincent (Fig. 1). These stations formed part of a reconnaissance network of similar stations established in 1976 and 1977 on Soufriere Hills, Montserrat; La Soufrière, Guadeloupe; and Montagne Pelée, Martinique (*1*). The stations are of the optical tiltmetry type, suitable for the use of the "dry tilt" technique developed at the U.S. Geological Survey's Hawaiian Volcano Observatory in the early 1970's. In applying this technique, one uses a Wild N-3 level and Invar surveying rods to determine the altitude differences (to a tolerance of ±0.06 mm) between an array of four, three, or two bench marks, 40 to 50 m apart, set in the configuration of a square, triangle, or line. One obtains altitude differences between the bench marks by averaging 8 to 18 foresight-backsight measurements. One can measure changes in these differences, or the ground tilt, by reoccupying the stations at later points in time.

Time limitations in 1977 permitted the installation of only two tilt stations on Soufriere. Furthermore, because of topographic restrictions and the scarcity of solid-rock outcrops in which to set the bench marks, each of these stations consists of four bench marks, defining two nearly parallel lines oriented essentially radially to the volcano (Fig. 1). We assumed that the point of maximum inflation or deflation would be near the center of the summit crater and therefore that the ground tilt measured at each station could only be expected to yield a component of radial tilt. Thus, no unique tilt vectors were obtained, but the redundancy afforded by the measurement of two independent lines at each station helped to confirm that the observed components of tilt were real.

The data obtained from ten complete or partial occupations of the two stations are presented in Table 1, and the changes in ground tilt, projected onto lines drawn radially from the summit of the volcano, are shown graphically in Fig. 2.

For the first 12 months of observation, February 1977 to February 1978, gradual inflation was recorded by both lines at each station. During the next 7-month period, February to September 1978, both lines at station B continued to record inflationary tilt, whereas the lines at station A recorded no change and slight deflation, respectively. Measurements were not made between September 1978 and the onset of explosive activity in mid-April 1979, but we have assumed, and have shown by dashed lines in Fig. 2, that the deformation trends measured prior to September 1978 continued until the eruption began.

Deflation was recorded at both stations after the eruption got under way, and we have inferred (again, as shown by dashed lines in Fig. 2) that the onset of rapid deflation coincided with the explosive activity of mid-April 1979. Measurements made in June and September 1979, during the period of quiet dome emission, document lower rates of deflation. Interestingly, deflation continued at least until late 1980, a year after eruption at the surface ended—perhaps because of continuing high-level intrusion beneath

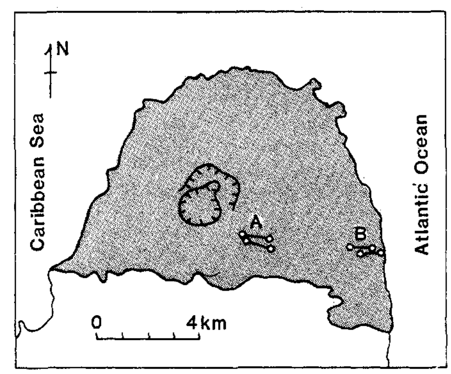

Fig. 1. Map showing the configuration of Soufriere Volcano (stippled area) at the northern end of St. Vincent; *A* and *B* indicate the approximate locations of the tilt-monitoring stations. The two lines at each station are about 40 m long, but their lengths on this map have been greatly exaggerated.

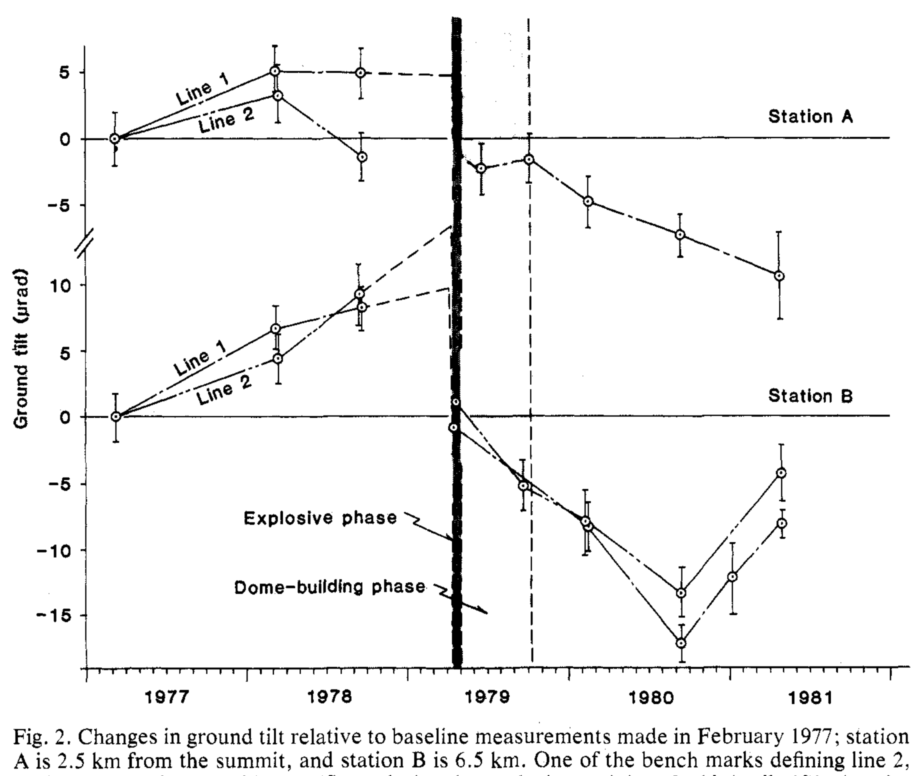

Fig. 2. Changes in ground tilt relative to baseline measurements made in February 1977; station A is 2.5 km from the summit, and station B is 6.5 km. One of the bench marks defining line 2, station A, was destroyed by mudflows during the explosive activity of mid-April 1979; data for this line are therefore available only through September 1978.

the surface of the crater floor. Measurements at station B in 1981 suggest that the volcano has begun to reinflate, although this is not confirmed by measurements at the one line remaining at station A. Additional observations will be necessary to determine whether the volcano is, in fact, again inflating. In any case, the overall configuration of the curves in Fig. 2 suggests that Soufriere inflated gradually during the 26 months before the 1979 eruption and then deflated rapidly after the eruption began.

Although the available data are meager, it seems significant that the 20-μrad deflation measured at station B (6.5 km from the summit) was nearly twice that measured at station A (only 2.5 km from the summit). In an effort to interpret this observation, we have used the theoretical tilt curve of Eaton (*2*) to construct a family of curves showing the relation of theoretical ground tilt to magma-chamber depths of 1, 2, 4, 10, and 20 km. For the tilt at station B to be about twice that at station A, the magma chamber would have to be located at a depth of more than 10 km. For purposes of comparison, a recent petrologic and thermodynamic study of crystal cumulates contained in blocks ejected during Lesser Antillean eruptions has suggested crystallization (for example, magma chamber) depths at St. Vincent of about 15 km (*3*).

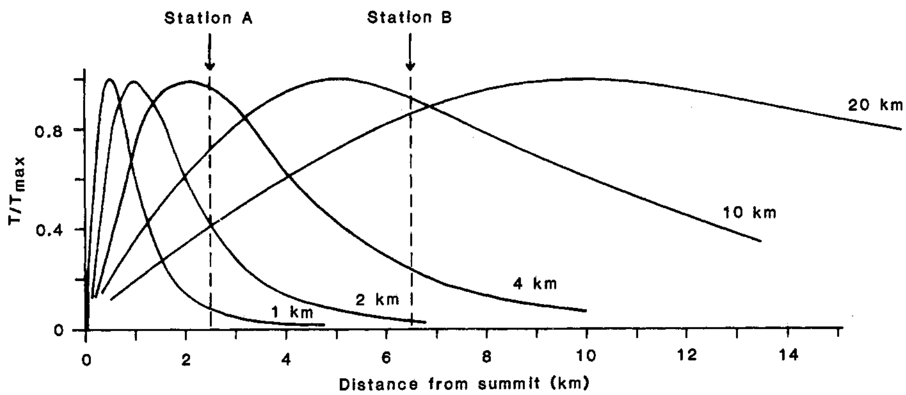

Fig. 3. Theoretical curves relating T/T_{max} to the distance from the summit of a volcano. The position T/T_{max} = 1.0 (maximum tilt) is located farther from the summit for models having progressively deeper magma chambers, but the magnitude of the maximum tilt decreases as the model depth increases. The location of tilt stations A and B is shown by the dashed lines.

Table 1. Dry-tilt data. I, inflation; D, deflation.

Date measured	Altitude difference between bench marks (mm)	Change in altitude difference (mm)	Change in ground tilt (μrad)	Number of foresight-backsight measurements
	Station A, line 1			
7 March 1977	−(380.51 ± 0.04)			13
10 March 1978	−(380.75 ± 0.08)	−(0.22 ± 0.08)	5.1 ± 1.9 I	8
19 September 1978	−(380.74 ± 0.06)	+(0.01 ± 0.08)	0.2 ± 1.9 D	10
15 June 1979	−(380.44 ± 0.05)	+(0.30 ± 0.08)	7.1 ± 1.9 D	10
2 October 1979	−(380.47 ± 0.08)	−(0.03 ± 0.08)	0.7 ± 1.9 I	18
16 February 1980	−(380.33 ± 0.05)	+(0.14 ± 0.08)	3.3 ± 1.9 D	10
12 September 1980	+(373.19 ± 0.05)*	+(0.11 ± 0.07)	2.5 ± 1.6 D	10
30 April 1981	+(373.32 ± 0.11)	+(0.13 ± 0.14)	3.1 ± 3.3 D	12
	Station A, line 2			
7 March 1977	+(689.69 ± 0.04)			10
10 March 1978	+(689.57 ± 0.07)	−(0.12 ± 0.08)	3.3 ± 2.2 I	10
19 September 1978	+(689.74 ± 0.06)	+(0.17 ± 0.07)	4.6 ± 1.9 D	10
	Station B, line 1			
7 March 1977	−(1462.13 ± 0.05)			8
11 March 1978	−(1462.43 ± 0.07)	−(0.30 ± 0.07)	6.8 ± 1.6 I	8
19 September 1978	−(1462.49 ± 0.03)	−(0.06 ± 0.07)	1.4 ± 1.6 I	8
17 April 1979	−(1462.10 ± 0.09)	+(0.39 ± 0.09)	8.9 ± 2.0 D	8
13 February 1980	−(1461.77 ± 0.08)	+(0.33 ± 0.08)	7.5 ± 1.8 D	10
13 September 1980	−(1468.60 ± 0.03)*	+(0.35 ± 0.06)	8.9 ± 1.4 D	12
3 January 1981	−(1468.82 ± 0.10)	−(0.22 ± 0.12)	5.0 ± 2.7 I	8
29 April 1981	−(1469.00 ± 0.08)	−(0.18 ± 0.14)	4.1 ± 1.0 I	12
	Station B, line 2			
7 March 1977	−(1752.39 ± 0.05)			8
11 March 1978	−(1752.58 ± 0.08)	−(0.19 ± 0.08)	4.5 ± 1.9 I	9
19 September 1978	−(1752.79 ± 0.08)	−(0.21 ± 0.10)	4.7 ± 2.4 I	8
17 April 1979	−(1752.45 ± 0.08)	+(0.34 ± 0.10)	8.0 ± 2.4 D	8
3 October 1979	−(1752.18 ± 0.07)	+(0.27 ± 0.08)	6.4 ± 1.9 D	18
14 February 1980	−(1752.06 ± 0.08)	+(0.12 ± 0.10)	2.8 ± 2.4 D	10
13 September 1980	−(1675.76 ± 0.06)*	+(0.22 ± 0.08)	5.2 ± 1.9 D	14
29 April 1981	−(1676.14 ± 0.05)	−(0.38 ± 0.09)	8.9 ± 2.1 I	10

*Improved bench marks were installed and measured in February 1980; these became the new reference points in September 1980.

From the standpoint of assessing volcano hazards, the results reported here indicate that the dry-tilt technique has important practical advantages for Soufriere and other similar volcanoes. If, as the data suggest, a central magma chamber lies at a depth of more than 10 km, inspection of the 10- and 20-km curves shown in Fig. 3 would suggest the existence of a broad and extensive deformation field. Presumably, measurable tilts could have been observed if one had used the same technique at distances of 8, 10, or even 12 km from the summit of the volcano. From the standpoint of site selection for dry-tilt stations, suitably flat terrain is always easier to find low on the flanks of stratovolcanoes than it is high on the upper slopes. Perhaps even more important, from the standpoint of ensuring the safety of field observation teams, the experience gained on St. Vincent in 1979 makes it clear that meaningful measurements could have been made farther southeast and southwest—in areas even beyond the slopes of the volcano. Stations in these areas would have been far removed from the small pyroclastic flows and mudflows produced during the activity of 1979, and they would even have escaped destruction from the obviously larger and more devastating pyroclastic flows that accompanied the infamous eruption of May 1902.

RICHARD S. FISKE

Smithsonian Institution, Washington, D.C. 20560

JOHN B. SHEPHERD

University of the West Indies, St. Augustine, Trinidad

References and Notes

1. R. S. Fiske, G. Jezouin, W. T. Kinoshita, K. Rowley, J. B. Shepherd, L. Siebert, J. F. Tomblin, J. P. Viode, unpublished abstracts of papers presented at the Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior, Durham, England, August 1977, p. 235.
2. J. P. Eaton, *Bull. Seismol. Soc. Am.* **49**, 301 (1959).
3. R. J. Arculus and K. J. A. Wills, *J. Petrol.* **21**, 743 (1980).

4. We thank the Barnard family, Orange Hill Estates, St. Vincent, for logistical support. This work was funded by the Agency for International Development's Office of U.S. Foreign Disaster Assistance and the University of the West Indies.

24 July 1981; revised 11 January 1982