The eruption of Soufrière volcano, St Vincent April–June 1979

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The Soufrière volcano in St Vincent began to erupt on 13 April 1979 after 10 months of mild premonitory activity. A series of strong vertical explosions between 13 and 26 April generated ash falls, pyroclastic flows and mudflows. From about 3 May onwards basaltic–andesite lava has been accumulating in the summit crater.

ST VINCENT is in the south of the chain of volcanic islands which comprise the Lesser Antilles Island Arc (Fig. 1). The island is 30 km long and the Soufrière volcano constitutes the northernmost third of the island with a diameter of 11 km at sea level. It is a strato-volcano 1,220 m high with an open summit crater 1.6 km in diameter located in the southern part of a 2-km wide somma crater. The summit crater has been occupied by a 1-km wide crater lake throughout most of its history[1–4]. Explosive eruptions occurred in 1718, 1812 and 1902–03; the 1902–03 eruption was preceded by a 14-month period of felt earthquakes, and generated ashfalls, mudflows and pyroclastic flows climaxing on the afternoon of 7 May, 1902, when pyroclastic flows swept down valleys leading to the east and west coasts killing, 1,565 people. The eruption continued intermittently until March 1903 by which time the total volume of uncompacted pyroclastic ejecta is estimated to have been 0.42 km^3 (ref. 5).

In contrast, the eruption of 1971–72[4,6] was aseismic and non-explosive. Between October 1971 and March 1972, $80\times 10^6\ m^3$ of basaltic andesite lava were quietly extruded into the summit crater causing the evaporation of $55\times 10^6\ m^3$ of water out of an original lake volume of $75\times 10^6\ m^3$. During the later part of this eruption seismic activity at the volcano was monitored by three high-gain, short-period seismographs all within 4 km of the crater but no seismic events were recorded other than small surficial events associated with the growth of the lava mass. The number of these events had declined almost to zero by the time that the extrusion of lava ended in March 1972 and they had ceased entirely when the seismograph stations were withdrawn in August 1972.

Activity premonitory to the 1979 eruption

Since August 1972, the nearest seismograph station to the volcano which was in continuous operation was station SVT 19 km to the south. The temperature at the southern edge of the crater lake, which had reached a peak of 81.5 °C in November 1971 was measured twice per month and found to decline steadily until January 1975 when it stabilised between 23 and 26 °C which is 1–4 °C above ambient conditions. The crater lake was inspected about every 3 months. After March 1972, the crater lake and island showed little change other than a gradual erosion of loose material from the island. Fumarolic activity was at first widespread over the island but by 1975 activity was concentrated in a depression of diameter ~20 m in the centre of the island. A bathymetric survey of the crater lake was made in February 1973[7] and surface temperature surveys were made in March 1974 and December 1978. In March 1974, a large yellow stain became visible on the surface of the lake in the south-eastern corner. At this time the temperature around the edge of the lake ranged from 30 to 33 °C, rising to 47 °C close to the lava island. The yellow stain persisted until the start of the 1979 eruption. A similar stain was reported by Senn[8] in 1946 after a series of local earthquakes had been felt in northern St Vincent.

The first signs of abnormal activity which might be related to the present eruption were observed between August and November 1976 when a phreatic eruption of the Soufrière volcano in Guadeloupe 310 km to the north was in progress. Between 11 August and 21 October the water temperature at the southern edge of the lake rose from 23 to 30.5 °C. No other signs of abnormal activity were observed and by 19 January 1977 the temperature had decreased to 25 °C. In February 1978 the temperature began to rise slowly and irregularly, reaching a peak of 31 °C on 21 August 1978. On 2 June 1978 a short-period seismograph linked by radio telemetry to the University of the West Indies in Trinidad was established at Belmont, 9 km south-west of the crater (SVB in Fig. 2) and on 12 June this station began to record events which were tentatively identified as B-type volcanic earthquakes[9]. The events occurred in bursts of up to 20 and their frequency increased throughout June and July reaching a peak on 30 July when 40 events were recognised. Because of the simultaneous rise in lake temperature and increase in seismic activity, the local authorities were advised on 24 August that an abnormal situation might be developing at the volcano. Tilt monitoring stations of the optical tiltmetry type which were first established on the eastern flanks of the volcano in February 1977 at distances of 3 km and 6 km from the crater were re-occupied on 7 March 1978 and again on 17 September 1978. The results showed apparent tilts of order 3–5 μrad, consistent with inflation of the volcano, between March 1977 and September 1978. These were the first optical tiltmetry measurements to be made in St Vincent and the standard error of a single set of measurements was of the order of 4 μrad. The tilt results alone could not therefore be taken as conclusive evidence that the volcano was inflating. Inspection of the crater lake and island showed no significant change but a second telemetered seismograph station established 3 km south-west of the crater on 19 September (SVV on Fig. 2) confirmed that the seismic events originated close to the volcano. From 19 September 1978 to 12 April 1979 these two stations continued to detect B-type events at rates of up to 50 per day but the rate of occurrence showed no tendency to increase or decrease with time. No earthquakes were reported to be felt and only a few of the stronger events were detected by station SVT. During the same period the surface temperature of the lake was measured weekly and fluctuated between 27 and 30 °C up to 11 April 1979 when it was 28 °C. On 24 December 1978 the surface temperature of the lake was measured on one complete circuit of the lake around the island and was found to be a uniform 30 °C except for a hot spot close to the eastern edge of the island where it was 47 °C.

At 07.13 UTC on 12 April a large B-type earthquake was recorded by SVV and SVB and at about the same time continuous tremor became recognisable above the back ground micro-seismic level. For the following 12 h B-type events continued at

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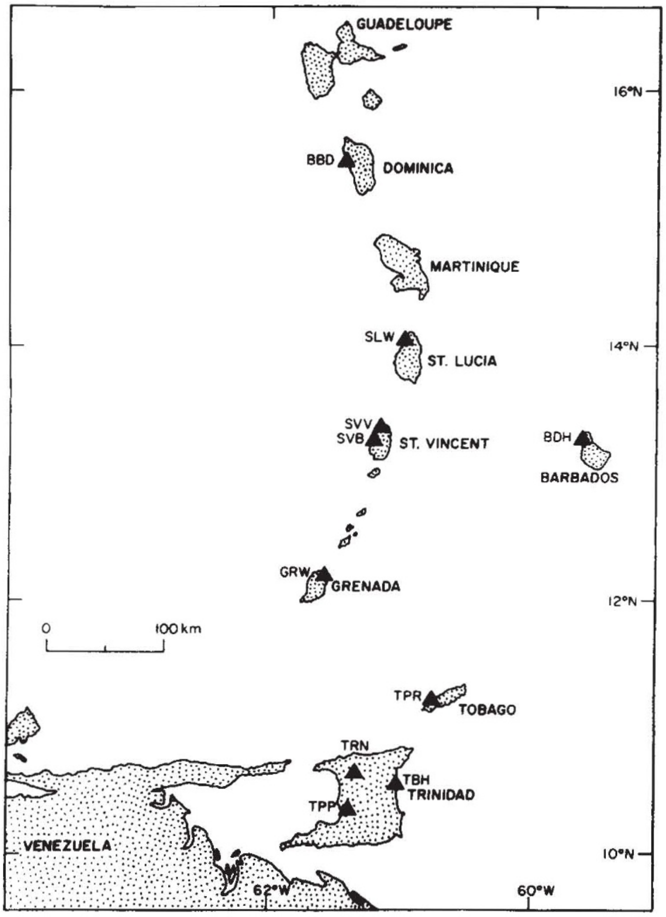

Fig. 1 Regional position of St Vincent in the Eastern Caribbean. The seismograph stations (▲) shown are linked by radio to Trinidad; many other instruments exist in the region.

a mean rate of about one per hour until 19.54 UTC when their frequency began to increase. Between 19.54 and 02.04 UTC on 13 April, 38 events were recorded with generally increasing amplitude and the level of continuous tremor increased steadily. Between 02.04 and 04.30 UTC, 70 events were recorded before continuous tremor saturated both instruments and individual events could no longer be distinguished. At 03.30 UTC (11.30 p.m. on 12 April local time) the government of St Vincent was warned that a highly abnormal situation existed at the volcano, but local residents 6 km east of the crater reported that they had neither seen nor felt anything unusual up to this time. At about 08.00 UTC loud rumbles were heard both east and west of the volcano and shortly afterwards fine ash began to fall at distances of up to 5 km south-east and south-west of the crater. When dawn broke at about 09.30 UTC the volcano was seen to be erupting a column of steam and ash and evacuation of the areas north of the Rabacca and Wallibou rivers (Fig. 2) began immediately. The evacuation was completed smoothly by 20.00 UTC and within the next 24 h about 15,000 people were evacuated from this area.

Early stages of the eruption

Figure 3 summarises the eruptive and associated activity from 12 April to 17 June. From 09.30 to 15.00 UTC on 13 April no one person kept the volcano under continuous observation but from numerous reports we deduce that there was continuous strong steam emission from the crater for the whole of this period, punctuated by powerful vertical explosions which projected ash-laden clouds to heights in excess of 8 km. After the initial outburst further distinct explosive phases were observed at about 10.15 and 15.15 UTC. At 11.20 UTC the eruption column was observed from a commercial aircraft to be at a height of 10 km, 150 km, south-east of the volcano. The column height was then ~8 km and an anvil-shaped cloud extended 80 km to the east. The column was again seen at 12.50 UTC from the same distance and appeared to be unchanged. At 15.00 UTC two of us saw the column from an aircraft approaching St Vincent from the south. When first observed the eruption column and cloud fitted the earlier description, but at 15.15 UTC a dark, cauliflower-shaped cloud was projected upwards above the column and drifted off to the east. At 16.00 UTC we flew low over the eastern and western flanks of the volcano in a light aeroplane and landed briefly at the Rabacca River 7 km south-east of the crater. At this location, fine light-grey volcanic ash was falling lightly but steadily and had formed a layer ~3 mm thick. The aerial inspection showed that a thin layer of ash had been deposited to distances of at least 10 km from the crater. We saw no evidence of pyroclastic flow deposits on the lower flanks, but the uppermost third of the volcano was obscured by falling ash.

After 16.00 UTC the dense steam-and-ash column dispersed although steam continued to pour from the crater. At 19.30 UTC we established an observation post at Belmont (SVB on Fig. 2) and since then the volcano has been kept under continuous visual surveillance. Explosive activity was renewed at 20.05 UTC and further explosive phases began at 21.08 UTC and 23.50 UTC on 13 April and at 01.08, 07.06 and 15.50 UTC on 14 April. The explosive phases varied in duration and intensity but were all broadly similar. Each began with rumbles audible from Belmont followed within 1 min by the emission of a white cloud which rose and expanded rapidly. One to two minutes later the clud became much darker and assumed a distinctive cauliflower shape, rising and expanding rapidly and mushrooming outwards at a height of about 4 km above the crater rim. Ultimate heights of the eruption columns could not easily be estimated from the ground but the eruption clouds generated by the explosions from 21.08 UTC on 13 April onwards were photographed from a NOAA Earth satellite and maximum column heights have been estimated by comparing the temperature at the top of the cloud with standard atmospheric temperatures. By this method the columns from the explosions at 21.08 UTC on 13 April and at 01.08 and 15.50 UTC on 14 April have been estimated to reach heights of 17–18 km. The other eruption columns did not penetrate the meteorological cloud layer and no similar estimates of their heights could be made. The lower part of each cloud drifted to the west in the prevailing trade winds while the upper part drifted to the east in the upper-level westerlies. Transport of the ash-plume resulted in ash fall on Barbados, 180 km to the east on the afternoons of 13 and 14 April. On the western flanks of the volcano air-fall from this series of explosions consisted mainly of fine, light-grey, crystal-rich ash but fresh scoria up to 70 mm in diameter fell on Georgetown, 9 km south-east of the crater. The maximum air-fall thickness at the eastern flank of the volcano 7 km from the crater was 40 mm. All explosive activity originated in the western part of the crater at the approximate location of the island formed in 1971–72.

Pyroclastic flows

During the explosive phase beginning at 21.08 UTC on 13 April we observed a pyroclastic flow which descended the upper part of the Wallibou river valley to the south of the crater. At the Rabacca river crossing 7 km south-east of the crater it was reported that a pyroclastic flow descended part of the way down the Rabacca river valley during the same explosive phase. Further signs that pyroclastic flows were being generated during the phase beginning at 01.08 UTC occurred on 14 April when incandescent material was projected over the crater rim and cascaded down the southern and western flanks. A low-level aerial reconnaissance at dawn (about 10.00 UTC) on 14 April showed a fresh pyroclastic flow deposit in the upper part of the Rabacca valley. The largest pyroclastic flow that we observed descended the 3-km long Larikai valley to the west of the crater at 16.00 UTC on 14 April and continued out to sea for at least 10 km. When inspected on site, 28 h after emplacement, the deposit at the mouth of the Larikai was 1.5 m thick, ~250 m wide and contained scoria blocks up to 600 mm in diameter in a matrix of ash and lapilli. A pyroclastic flow rich in blocks of scroria and carrying trunks and limbs of trees descended the adjacent Roseau valley at about the same time, to within 100 m of the sea.

Subsequent explosive activity

From 17.00 UTC on 14 April to 20.57 UTC on 17 April the volcano was in a state of mildly explosive activity emitting mainly steam but with occasional cauliflower-shaped, ash-laden clouds rising to heights of 1–2 km above the crater rim. On 17 April the lower tilt-meter sites on the eastern flanks were reoccupied and showed tilts of ~4–6 μrad indicating deflation of the volcano since September 1978. At 20.57 UTC on the same day another explosive phase similar to the previous ones began. Pyroclastic flows were again observed to descend the Larikai, Roseau and Wallibou valleys to the west of the crater but none reached the sea. The height of the eruption column was measured from a NASA aircraft near St Vincent and was estimated to be 18.7 km. Ash fall at Belmont was coarser than in previous explosions. Initially it consisted of lapilli up to 10 mm in diameter grading down to fine ash over a period of ~50 min. Coarse scoria again fell on the eastern flanks as far as Georgetown. All these explosions were accompanied by severe electrical storms in which lightning discharges both within the eruption cloud and from cloud to ground occurred at a rate of more than 1 per s. Lightning strikes were observed at distances of at least 9 km from the crater and caused damage to trees 6 km east of the crater. A striking feature observed during the explosion of 17 April was the development of smooth, funnel-shaped bands of condensation around the eruption column immediately below the cauliflower-shaped eruption cloud.

After the 17 April explosion the volcano returned to a state of intermittent, mild explosive activity, generally declining in intensity but punctuated by two further explosive phases beginning at 10.37 UTC on 22 April and 03.53 UTC on 26 April. During the 22 April explosion a small pyroclastic flow descended the Larikai valley. A few minutes later a dilute pyroclastic flow was formed from ash that fell from a billowing cloud of

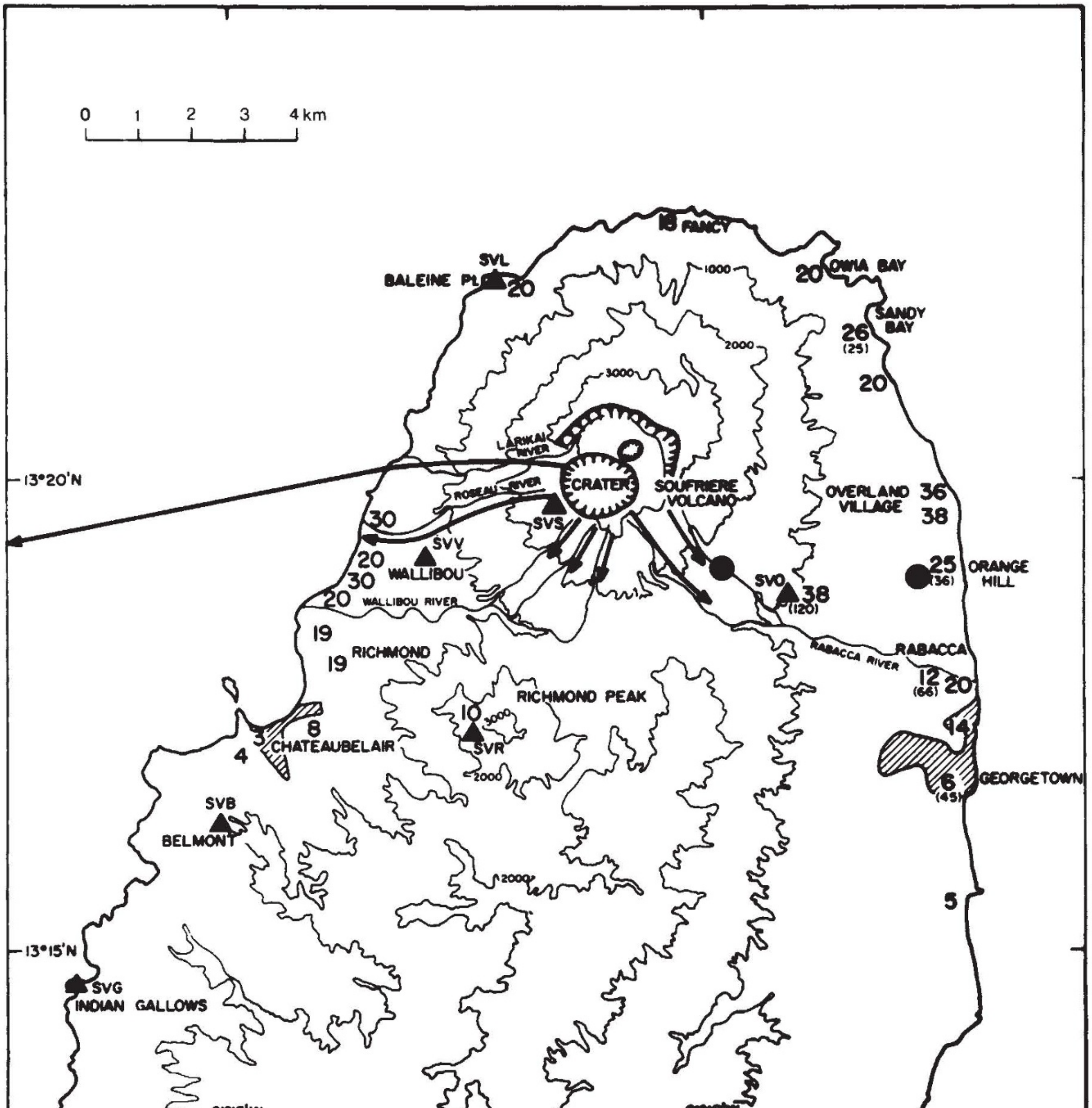

Fig. 2 The northern part of St Vincent island showing the location of the Soufrière volcano, major streams, general topography and two principal towns. The courses of pyroclastic flows known to have taken place in the 1979 eruption are shown as arrows and measurements of ash thicknesses (mm) are given as large numerals. The positions of tiltmeter (●) and seismograph station (▲) are also indicated. Figures in parentheses are maximum bomb dimensions (mm).

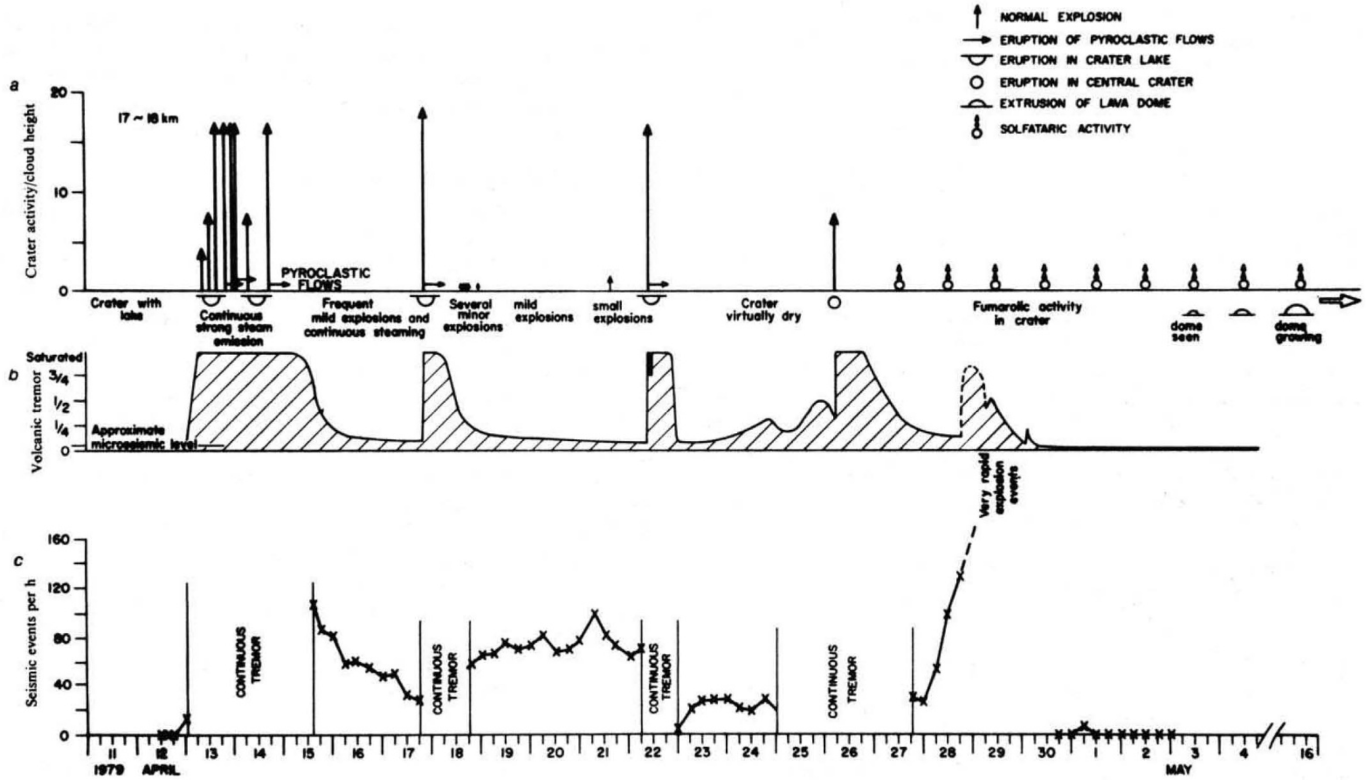

Fig. 3 Chronological summary of the major eruptive events and seismic behaviour of the Soufrière Volcano for the period 11 April–16 May 1979. *a*, The form of activity at the crater; *b*, the approximate level of continuous volcanic tremor; and *c*, the number per hour of discrete seismic events (explosion and B-type earthquakes), when these could be discerned from the continuous tremor.

airborne tephra and this flow, dark grey to black in colour, crossed the coast and spread as far south as Chateaubelair Bay. After this explosion the main axis of ash fall extended east from the crater with maximum total thicknesses along the east coast of the order of 40 mm at Overland Village, thinning to 10 mm at 5 km to the north and south. These figures are lower limits since each ash fall was rapidly eroded by wind and rain soon after deposition. Similarly the pyroclastic flow deposits in river valleys were rapidly reworked by streams and covered by mudflows which began to form on the night of 14–15 April. The final explosion of the series began at 03.53 UTC on 26 April. The height of the eruption column was measured from HMS Gurkha 15 km to the west and was estimated to be 8 km. Wind carried the eruption cloud from this explosion due south and deposited up to 4 mm of ash on Kingstown the capital.

The crater during the eruption

Throughout the explosive period frequent low-level reconnaissance flights were made over the volcano but the continuous steam emission combined with persistent low-level cloud prevented us from seeing into the crater until 17 April at about 13.00 UTC, when a brief view was obtained of the interior of the crater. The 1971 island was still largely intact except to the north where it was breached by a hole approximately 100 m in diameter connected to the crater lake. It was not possible to determine the extent or depth of the crater lake. On 21 April the first clear photographs of the interior of the crater were obtained. About one-quarter of the 1971 island remained, forming a horseshoe shape around a steaming vent. South and east of the island remnant, the floor of the crater was covered with mud and other debris but a portion of the crater lake remained in the northern and western parts, connected to the vent by a breach in the northern part of the island. Persistent heavy cloud at the summit then made aerial reconnaissance extremely difficult but on 30 April conditions improved and it was possible to see that only a fragment of the island remained. Most of the floor was covered with mud around a strongly steaming central depression. On 3 May the presence of a small dome-shaped object in the eastern crater rim was reported to be steaming vigorously. Aerial reconnaissance on 7 May confirmed the presence of a fresh, black, dome-shaped mass of lava ~200 m in diameter rising to ~30 m above the crater floor. The crater itself was infilled with debris to above the level of the pre-eruption lake surface and was apparently dry except for a small pond abutting the northern edge of the new lava mass. Strong steam emission was taking place at the western edge of the lava and at several other places on the crater floor. The lava itself was draped with sediments which eroded rapidly over the next two days. Further aerial inspections were on 8, 9 and 11 May during which time the lava mass increased in size by about 40%. Between 14 and 16 May the lava mass was surveyed from the crater rim and from the crater floor. At this time it was approximately elliptical in plan with major axes 400 m from north to south and 300 m from east to west. Its sides sloped upwards at an angle of about 45° to a flat top with a slight depression in the centre. A small crescent-shaped pond abutted the lava on the north side while to the south-west and south-east two relics of the 1971 island protruded through the new crater floor. During the next month the lava continued to grow, mainly by lateral spreading over the crater floor, at a rate estimated to be $0.5\text{–}1 \times 10^6\ m^3\ d^{-1}$. Growth was most rapid to the north and north-east and least rapid to the south and south-east where the remants of the 1971 lava restricted lateral spreading. The depression on the top of the lava gradually disappeared to be replaced by a slight rise from which several low ridges radiated. On 18 June the diameter of the lava was 715 m from east to west and about 700 m from north to south. Its height was estimated to be 110 ± 10 m and its total volume of order $25 \times 10^6\ m^3$.

Seismological observations

Three short-period vertical-component seismographs were in operation in St Vincent at the beginning of the eruption. Two of these (SVV and SVB in Fig. 2) were linked by radio telemetry to Trinidad where the signals were displayed visually on drum recorders and simultaneously recorded on magnetic tape for later analysis. The third station (SVT) operated with a standard

Table 1 Major oxide analyses of Soufrière samples

Component	Grey glass*	Dark glass*	Scoria block†	Composite ash fall‡	Lava flow§
SiO_2	65.9	57.9	54.9	55.5	55.8
Al_2O_3	13.7	14.3	18.7	19.2	18.4
FeO‖	6.77	9.38	8.23	7.43	8.58
MgO	1.23	2.86	4.08	3.44	4.05
CaO	4.05	6.34	8.94	8.70	9.11
Na_2O	3.34	4.02	3.35	3.43	3.32
K_2O	1.56	1.11	0.56	0.58	0.56
TiO_2	1.08	1.64	1.01	0.97	1.05
P_2O_5	–	–	0.12	0.12	0.11
Total	97.63	97.55	99.89	99.37	100.98

The modal analysis of air-fall ash collected at Grantley Adams Airport, Barbados, 14 April 1979 gave: crystals, 43.5%; grey glass, 33.7%; dark glass, 8.7%; lithics, 13.3%; carbonate and sulphate, <1.0.
* Barbados ash fall, 14 April 1979.
† Larikai pyroclastic flow, 14 April 1979.
‡ Belmont, 17 April 1979.
§ New analysis of sample from lava flow, 13 December 1971.
‖ Total iron oxides reported as FeO.

photographic recorder in St Vincent. On 14 April, a second magnetic tape recorder and visual monitor were set up at Belmont. Initially signals were recorded from SVV, SVB and from SLW, 80 km to the north in St Lucia, BDH, 170 km to the east in Barbados, and BBD, 250 km to the north in Dominica. Other seismograph stations, monitored in Trinidad, were in Grenada, 130 km south of St Vincent and in Trinidad and Tobago. Throughout the eruption the larger network recorded only regional seismic activity at a level known to be normal for this region. In the vicinity of St Vincent the network has a detection capability for earthquakes down to about magnitude (m_b) 2.5, and no earthquake above this magnitude originated within 100 km of the Soufrière throughout the eruption. Between 15 and 21 April four more radio-linked stations were added to the network in St Vincent. On 28 April SVT was linked in to the system and on 12 May a station was established on the crater rim. The final station configuration is shown in Fig. 2. From the time that stations SVV and SVB became saturated by continuous tremor at 04.30 UTC on 13 April they remained saturated until about 13.00 UTC on 15 April (for the entire early period of explosive activity). At about this time the level of continuous tremor had declined sufficiently for individual events to be recognisable, and since then the numbers of events have fluctuated as shown in Fig. 3. A more thorough analysis of these events will be discussed elsewhere but, in the terminology of Minakami[9], they are of two types—explosion-type earthquakes and B-type earthquakes. The relative time control between the stations of the network is $\sim\pm0.02$ s but the continuous background tremor throughout the eruption has made it difficult to identify first onsets to better than 0.1 s. The pattern of arrival times at stations in St Vincent makes it clear that all the events originated within 1 km of the crater, but the emergent nature of the onsets and the station distribution (particularly the lack of a station very close to the crater rim) make it impossible to estimate focal depths by conventional first-arrival techniques to a precision better than ±5 km. A reasonably good correlation was established between some of the larger explosion-type events and actual explosions visible at the crater. Both types of event were propagated with very low phase velocities and attenuated rapidly with distance which suggests they were of extremely shallow origin.

Perhaps the most interesting seismological feature of the eruption has been the continuous tremor. Apart from the initial 57-h period of very strong tremor, there have been several subsequent periods of tremor (Fig. 3). Each major explosive outburst has been accompanied by strong tremor, but no clear premonitory pattern emerged by which we could predict the onset of individual explosions by more than a few minutes. No earthquakes have been reported to be felt during the eruption, but several people who were within 10 km of the volcano on the morning of 13 April reported feeling continuous tremor, and the tremor accompanying the 17 April explosion was reported to be felt at Georgetown.

Petrography and analysis of ejecta

Thin sections of fresh material from bombs and pyroclastic flow deposits show that plagioclase phenocrysts with oscillatory-zoned rims and shadow-zoned cores are the main crystalline phases. Some crystals, the largest of which are 10–12 mm long, contain gas bubbles and inclusions of olivine and glass. Other phenocrysts are pale yellowish-green clinopyroxene with rare and almost colourless orthopyroxene. Accessory amounts of subrounded olivine as well as euhedral amphibole and disseminated magnetite are also present. Fine-grained gabbroic cumulate inclusions 5–20 mm in diameter are common in many of the blocks and bombs. The matrix is glassy to microcrystalline. Tephra collected at Grantley Adams Airport, Barbados, on 14 April 1979 were analysed at the University of Rhode Island and the glasses from the same ashes were analysed by electron microprobe. The results are shown in Table 1. Whole-rock analyses of scoria collected from the 14 April Larikai pyroclast flow and of a composite scoria and ash fall at Belmont on 17 April were carried out at the Smithsonian Institution by electron microprobe. A sample from the 1971 lava was also analysed on the same instrument and all the results are shown in Table 1. The tephra produced in the eruption was found to contain two glass populations of dacitic and andesitic composition. The occurrence of banded scoria blocks in the new air-fall deposits on St Vincent confirm that the 1979 event was a mixed-magma eruption.

Comments

A full assessment of the size and significance of this eruption, the most intensively ever monitored in the Lesser Antilles, cannot be made until all the data have been analysed or indeed until the eruption comes to a definite end. Since 13 April, samples have been collected of the ejecta from each major explosion and the extent and thickness of these deposits have been constantly assessed. After each explosion the air-fall deposits other than those on the uppermost slopes had almost completely vanished within 48 h and the deposits on the volcano itself were partially reworked by mudflows during the same period. These observations illustrate the need for rapid sampling and also suggest that eruptions of the Soufrière which are of great significance from the point of view of public safety may leave little or no permanent stratigraphic record. Several tens of thousands of volcanic earthquakes, as well as many hours of continuous tremor, have been recorded on magnetic tape and most of the individual explosion since 15.15 UTC on 13 April have been extensively photographed, and the explosion of 17 April was particularly well recorded. The air-fall ash thicknesses of Fig. 2 are generally 1–2 orders of magnitude less than the thicknesses reported from the same locations after the explosions of 7–8 May 1902. Similarly the pyroclastic flows seem to have travelled much shorter distances than in 1902 when pyroclastic flows frequently reached the sea both east and west of the crater. Judging by these rough criteria we estimate that the total volume of pyroclastic ejecta in 1979 has been one or two orders of magnitude less than in 1902.

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1. Robson, G. R. & Tomblin, J. F. *Catalogue of the Active Volcanoes of the World*, Part XX (1966).
2. Rowley, K. C. thesis, Univ. West Indies (1978).
3. Anderson, T. & Flett, J. S. *Phil. Trans. R. Soc. Lond.* **A200**, 353–553 (1903).
4. Aspinall, W. P., Sigurdsson, H. & Shepherd, J. B. *Science* **181**, 117–124 (1973).
5. Carey, S. N. & Sigurdsson, H. *Geology* **6**, 271–274 (1978).
6. Shepherd, J. B. & Sigurdsson, H. *Nature* **271**, 344–345 (1978).
7. Sigurdsson, H. *J. Volcanol. Geotherm. Res.* **2**, 165–186 (1977).
8. Senn, A. *Geological Investigations at Soufrière Volcano* (British Union Oil Co. Ltd, Barbados, 1946).
9. Minakami, T. in *Physical Volcanology* (eds Civelta, Gasparini, Luongo & Rapolla) 1–25 (Elsevier, Amsterdam, 1974).