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Eruption of Soufrière Volcano on St. Vincent Island, 1971–1972

This study of the latest activity and review of historic eruptions suggests a two-stage volcanic cycle.

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The catastrophic eruption of 7 May 1902 established the Soufrière of St. Vincent Island, West Indies, as one of the world's most destructive volcanoes. In the early stages of the eruption 1565 people were killed by pyroclast flows which swept down all the major valleys leading from the volcano to the east and west coasts. The volcano occupies the northernmost third of the island (Fig. 1), and in 1971 the crater lake contained 75 million cubic meters of water. A major contribution to the loss of life in 1902 was the fact that all roads leading from the settlements on the flanks of the volcano to the south of the island cross either the Rabacca River, which flows to the east coast, or the Wallibou River, which flows to the west coast, and at the onset of the 1902 eruption both of these rivers were made impassible by boiling water and mud ejected from the crater. The news of renewed activity in the Soufrière on 31 October 1971 was therefore received with great concern and apprehension by the population of St. Vincent (96,000), of whom approximately 7500 lived in the area of maximum risk. Although there was no time during the eruption at which violent activity seemed imminent, a gradual exodus from the area started at the beginning of November and the area was officially evacuated on 7 December. Scientists from the University of the West Indies maintained continuous surveillance of the volcano from 1 November onward. This article summarizes our investigations of this event.

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Setting and Historic Activity

St. Vincent is in the southern part of the chain of volcanic islands comprising the Lesser Antilles (Fig. 1). The island, which is 30 kilometers long, is made up of Pliocene to Recent basalts and andesitic basalts, with lavas predominating over pyroclast deposits, originating from largely unknown and strongly dissected centers (*1*). The Soufrière volcano constitutes the northern third of the island, with a diameter of 11 km at sea level. It is a stratovolcano 1220 m high, with an open summit crater 1.6 km in diameter, located in the southern part of a 2-km-wide somma crater (Fig. 1). Robson (*2*) has related the formation of the prehistoric somma crater to the eruption of extensive deposits of Pleistocene ashes, widely distributed along the east coast of St. Vincent. These pyroclast deposits are in turn overlain by late-Pleistocene subaerial ash deposits, which reach thicknesses of up to 40 m and mantle much of the island of St. Vincent (*3*).

The first historic eruption of the Soufrière began on 26 March 1718 when the island was inhabited only by Carib Indians, but reports from passing ships indicate that a large volume of pyroclasts was erupted during the 3 days of the event (*4*). The earliest account of the Soufrière dates from 1784, when James Anderson descended into the crater. His descriptions convey a picture of conditions remarkably similar to those in the Soufrière today: a mile-wide crater with a large central cone nested on the crater floor, partly surrounded by two lakes (*5*). The 1812 eruption, which was preceded by 11 months of earthquake activity, started on 27 April with the eruption of large volumes of pyroclast flows, mudflows, and ash. A new crater was formed in this eruption, immediately northeast of the old crater, but both vents were active during the event, which killed 56 people before coming to an end on 9 June. A small eruption seems to have taken place on 9 January 1814, when rocks were thrown from the crater to a distance of half a kilometer (*4*). One report indicates that in 1880 the lake was hot and underwent a major rise in water level, scorching all vegetation in and around the crater (*4, 6*).

Following a 14-month period of local earthquakes, the eruption of 1902 to 1903 generated ashfalls, mudflows, and pyroclast flows on 7 May, but activity had already started in the crater on 6 May, when the lake was boiling and steaming strongly (*4*). A description of "stones" in the center of the crater lake on that day strongly suggests that a large mass of lava had already been extruded under water. The eruption reached its climax in the afternoon of 7 May, when pyroclast flows swept down valleys leading to the east and west coasts, causing the deaths of 1565 persons. The eruption continued intermittently until March 1903, when the uncompacted volume of pyroclast ejecta amounted to about 2 km^3 (*1*).

A lake with a volume of 75×10^6 m^3 formed in the elliptical Soufrière crater after this eruption, and soundings carried out in 1958 showed that the crater had the form of an inverted truncated cone (*1*) with a maximum water depth of 180 m and a floor 560 m below the northern part of the crater rim. The

40°.

After the occurrence of a swarm of local earthquakes between November 1945 and February 1946 (*7*) the annual mean temperature of the lake rose to about 28°C in 1948 to 1949 (Fig. 2), returning to its 1946 value by 1954. Thereafter there was a continued but less marked drop in lake temperature so that by the mid-1960's the temperature was almost at that expected from ambient conditions. The annual mean level of the crater lake dropped by about 1 m in the period 1946 to 1949 (Fig. 2), which corresponds well with the estimated increase in evaporation resulting in the rise in water temperature. This implies that no large body of magma was introduced into the crater in 1945 to 1946 (a body of magma produced the large change in lake level observed in the recent activity). From 1960 the volume of the lake increased, probably reflecting diminished evaporation from the cooling water.

Much of the vegetation on the

and plant succession of the Soufrière after the eruption was studied by Beard (*6*), using data from 1886, 1912, and 1942. He established a succession of montane rain forest, hurricane forest, and elfin woodland, with alpine meadow and tundra at the highest levels, and demonstrated an upward migration of the elfin woodland by 300 m in the period from 1912 to 1942.

Chronology of Events

The exact date of the beginning of the 1971–1972 eruption cannot be fixed with certainty, but 19 September 1971 was the last date on which the crater lake was visited by an experienced observer and found to be normal. An aerial photograph taken on 28 September 1971 also showed no steam or discoloration of the lake water, but on 31 October 1971 the pilot of a light airplane noticed that the lake was discolored and steaming. As a consequence of his report the

Subsequently it was discovered that a party of tourists had visited the lake on 17 October and had noted that the lake was steaming and giving off a sulfurous smell. Unfortunately this abnormal state of affairs was not reported, but from photographs taken at the time it has been possible to estimate that the water level was approximately 13 m above normal. Thus, it can be concluded that activity at the crater began between 19 September and 17 October, most probably between 28 September and 10 October. On 3 November we descended the southern inner wall of the crater and found the surface temperature of the water to be 81.5°C and the water level 26 m above normal. The entire lake surface was shrouded by steam, which also filled most of the crater, and the normally clear blue lake was now an unpleasant mustard-yellow color. From that date on the lake temperature and level were generally measured every second day; the data are summarized in Fig. 3.

Until 20 November it was not known whether the rise in temperature and level of the lake was caused by large-scale fumarolic activity on the floor of the lake or by injection of lava into the lake (*8*). However, on 20 November a lava island appeared in the lake; it rose initially at a rate of 2 to 3 m per day and subsequently at a diminishing rate, until 20 March 1972, when growth of the island appears to have ceased (Fig. 4). When the island emerged above the lake surface the water level, which had risen to 28 m above normal on 20 November, began to drop, and the water temperature, which had fluctuated between 79° and 82°C up to 20 November, also declined steadily from that date on (see Fig. 3).

The sheltered but steep slopes inside the crater are covered with dense vegetation, mainly of ferns, shrubs, and grasses, but the 1971–1972 eruption led to the total destruction of a 30-m-high belt of vegetation which was swamped by the near-boiling crater lake. A conspicuous brown band of dead vegetation surrounds the crater lake today, after the lowering of lake level, but rare clumps of grasses and ferns were observed on 2 June 1972, marking the first return of vegetation. The eruption had no visible effect on vegetation elsewhere inside the crater, in spite of the prolonged presence of

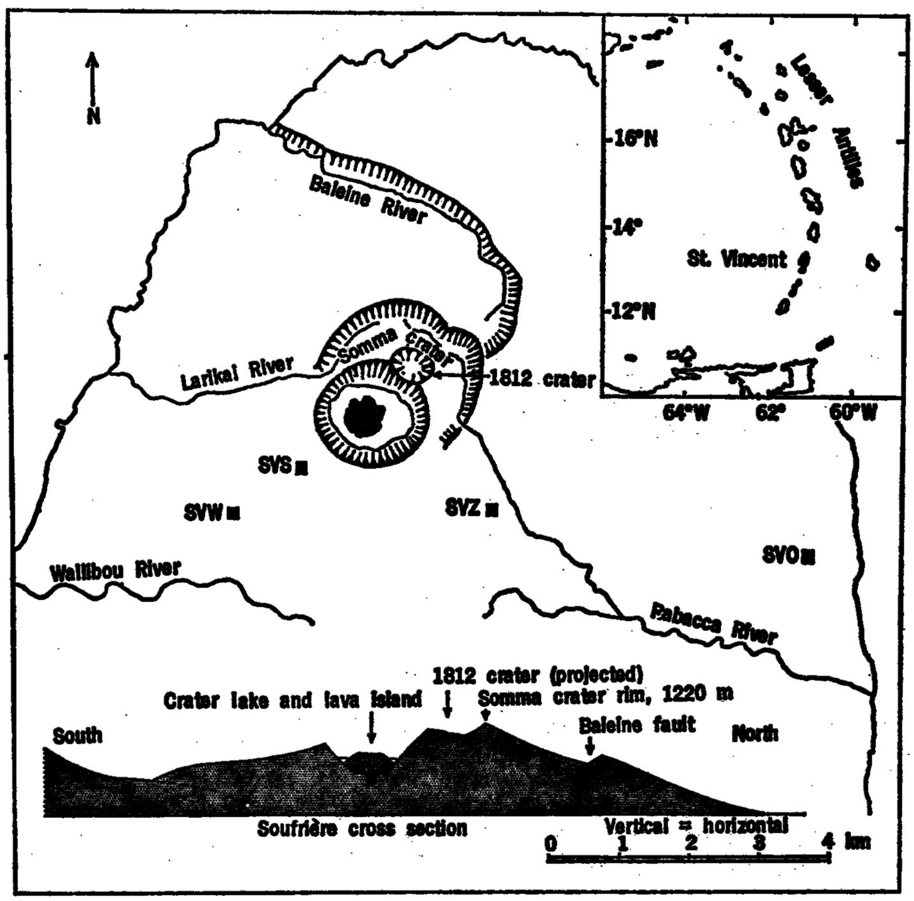

Fig. 1. Schematic map of the Soufrière volcano and the northern part of St. Vincent Island. The cross section is roughly north-south. The black squares indicate the locations of seismograph stations installed during the 1971–1972 eruption.

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hot and somewhat sulfurous steam. Some years before the 1971–1972 eruption the crater lake had been stocked with fish, and ducks were occasionally seen on the water. It seems certain that all biological forms were killed in October 1971, and the lake probably remained sterile until March 1972, when the water temperature dropped to 50°C. Toward the end of March the lake turned blue-green in color, as green algae started to appear in abundance, eventually accumulating as green slime on the crater walls below water level. By June 1972 the green algae were even more evident, both in suspension in the lake and contributing increasingly to the bottom layer of slime, which was then 5 cm thick. Plants were first reported from the new lava island on 6 June 1972, when a group of 20 fern plants, 2 to 3 cm high, was spotted growing in reddish silt on the northern shore of the island, at a time when the lake temperature varied from 39°C near the crater walls to 60°C near the new island.

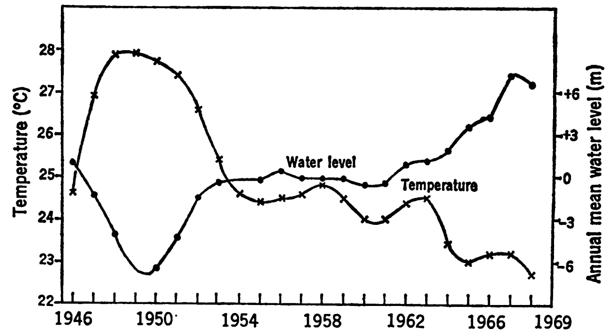
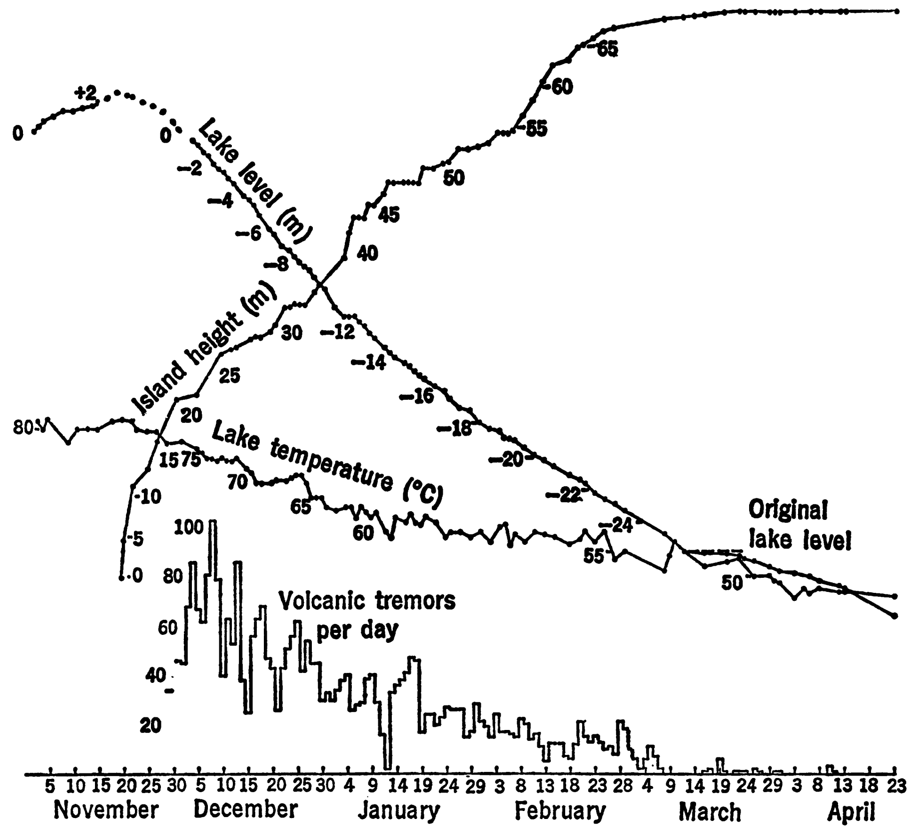


Fig. 2. Variations in annual mean water level and temperature in the crater lake for the period 1946 to 1968. The water level is referred to the datum of 5 April 1946. The drop in water level in the period 1946 to 1950 is a consequence of increased evaporation due to elevated water temperature.



The Crater Lake during the Eruption

Although obscuring for some time the chief subject of our study, the crater lake served as an excellent monitor of several aspects of the eruption, and information about lava volumes was deduced from changes in the lake level in October and November (Fig. 5). The crater lake also acted as a gigantic condenser of volcanic gases from the vent before the lava mass reached the surface, and regular sampling has demonstrated major changes in the water chemistry (*9*). The variation in water level (Fig. 3) is related to several factors: lava extrusion below water level, evaporation from the lake surface (and later from steam vents on the lava island), seepage through the crater walls, and addition of rainwater. Since the lake level has shown only small fluctuations in the past it is

Fig. 3 (center). Variations in lake level, water temperature, and height of the new lava island during the eruption. Also shown is the daily frequency of volcanic tremors recorded by the summit seismograph station (SVS in Fig. 1). The water level and island height data are relative to the water level datum of 3 November 1971. Fig. 4 (bottom). A view from the crater rim looking north over the lake on 22 March 1972, 2 days after the eruption stopped. The island is some 95 m in height above lake level and 650 m in diameter.

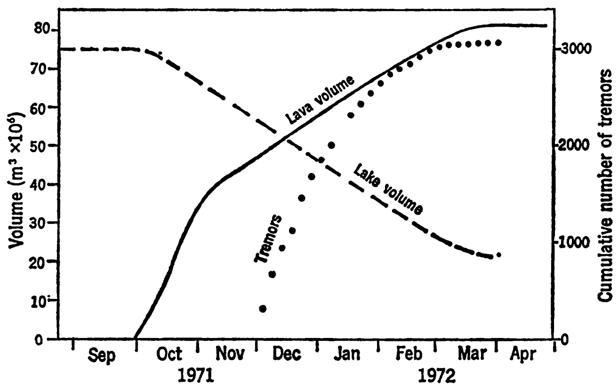


Fig. 5. Calculations of the volume of erupted magma are based on the amount of water displaced in the crater lake (corrected for evaporation) up to 20 November 1971, when lava broke the water surface. Subsequent volume estimates are based on triangulation surveys and aerial photographs of the lava island. The cumulative tremor graph shows a correlation between the rate of lava production and the number of crater tremors.

assumed that seepage and precipitation are roughly equal, and they are therefore ignored in the following discussion. Repeated temperature checks in rivers and streams around the volcano did not reveal any thermal anomalies which could be related to seepage from the crater. The daily drop of 20 to 30 cm in water level is thus almost entirely attributed to evaporation from the steaming lake surface. Theoretical calculations (*10*) of the rate of evaporation under the atmospheric conditions in the Soufrière crater give an average value of 0.8 gram per square centimeter per hour, or an approximately 20-cm lowering of the lake surface in 24 hours, which is equivalent to a daily water loss of 200,000 m^3. The observed changes demand a higher rate of water loss, and overall daily evaporation was probably nearer to 300,000 m^3 in the first half of the eruption, but by 20 March 1972 the lake was reduced to less than a third of the preeruption volume.

Studies of water chemistry (*9*) show that the content of dissolved solids increased at a much higher rate than can be predicted from evaporative concentration. For example, the chlorine content went from 280 parts per million (ppm) on 3 November 1971 to 769 ppm on 25 January 1972, an increase of 175 percent, when the water loss amounted to only 45 percent. Thus, other processes of enrichment must have operated, the most likely one being influx of volcanic gases from the magma, condensed and taken into solution in the lake water. Chlorine was the most abundant component in the lake during the eruption; the others, which were similarly enriched throughout the eruption, were, in order of abundance (parts per million): sodium (200), sulfate (140), magnesium (120), silicon (80), calcium (80), potassium (28), and iron and manganese (2 to 3). The bicarbonate ion in the lake, on the other hand, showed a very rapid decrease from 240 to 10 ppm during the eruption, coinciding with a drop of *p*H to a slightly acid condition, probably reflecting oxidation of hydrogen sulfide from the volcanic gases and liberation of carbon dioxide.

Throughout the eruption the lake was in a state of strong convective overturn, which manifested itself in a number of ways. Large amounts of minute mineral fragments and silt particles were carried in permanent suspension by the convective movement, rendering an unpleasant muddy mustard-yellow color to the lake. Convection also resulted in a higher water temperature in the surface layer than at depths in the peripheral parts of the lake, and convective flow away from the island was strong enough for us to notice while rowing in our fiber glass dinghy, as hot water welled up along the sides of the lava mass. The data in Fig. 3 show the temperature at the southern edge of the lake, whereas the water temperature near the island was generally 10° to 25°C higher.

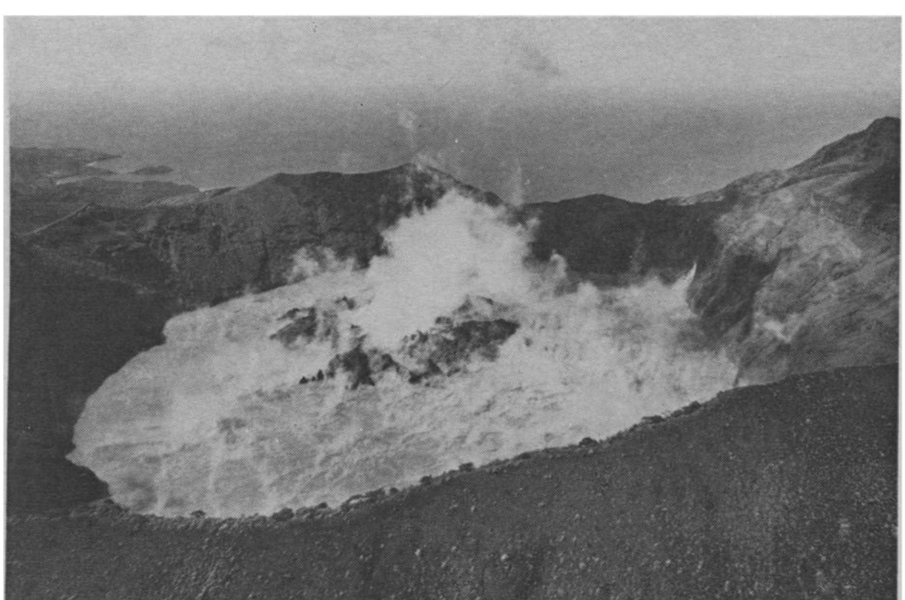


Fig. 6. Aerial view of the crater lake and new lava island on 13 December 1971, looking west-southwest. On that same date a boat trip was made to the island and samples were collected.

The Lava Island

Before 20 November there was no definite evidence that lava was being erupted into the lake, and speculations about the causes of the heating of the lake and the rise in water level (*8*) included large-scale fumarolic activity on the lake floor, producing steam which on condensing added to the lake volume. We were delivered from the realm of speculation on the morning of 20 November when a lava island started to emerge through the lake surface. It was then clear that an eruption had been in progress for some time, resulting in the extrusion of a lava mass 230 m thick. Judged by the volume of displaced water on 20 November (corrected for loss by evaporation), the volume of lava extruded on that date was 43×10^6 m^3, or approximately half of the final total erupted volume, and the rate of production up to 20 November must have been close to 10^6 m^3/day (Fig. 5).

The island mass rose at a rate of 1 m/day up to 9 January 1972 and at a rate of 0.5 m/day from January to mid-February, and when growth finally ceased altogether on 20 March the lava mass had attained a thickness of 295 m on the former crater floor. The island emerged initially as a series of long, narrow ridges of lava radiating from a central depression, reminiscent of the petals of a flower (see cover photograph). As the water level dropped and the island was uplifted further out of the lake, the ridges gradually coalesced and formed a roughly circular, relatively flat-topped and steep-sided island (Fig. 6) some 600 m in diameter. The radial ridges were the chief morphological features, but they gradually lost their form through crumbling and rockfalls off the crests, which resulted in the formation of extensive scree and talus slopes throughout the island.

Internally, the ridges consist of inclined lenticular slabs or sheets, half a meter thick and up tens of meters in lateral dimensions. These slabs may represent units separated by cooling joints, but on joint surfaces the lava is often brownish, oxidized, vesicular, and with a sharkskin texture. Surfaces frequently show low-angle flow or scour marks. Shatter zones or true slickensides have not been observed in joints, but each cooling unit usually contains successive vesicular zones parallel to the outer edge. Small-scale columnar jointing perpendicular to the slabs is well developed locally, and radial jointing, reminiscent of pillow lavas, is common in the western and northern parts of the island (Fig. 7).

Fig. 7. One of the pillow-like structures on the lava island, exhibiting radial jointing, concentric vesicular zones, and a frothy external rim.

Petrochemistry

The lava from the 1971–1972 eruption is a dark-gray basaltic andesite with numerous large phenocrysts of plagioclase but rarer olivine and pyroxene. The fine groundmass contains abundant brownish interstitial glass. Plagioclase in the new lava forms large, often euhedral phenocrysts of bytownite, An_{80} to An_{85} (80 to 85 mole percent anorthite) (*11*), zoned to labradorite margins (An_{60}), whereas in comparison the plagioclase in the 1902–1903 ejecta is calcic labradorite (An_{65} to An_{70}). Clinopyroxene phenocrysts and microlites show only minor compositional variation, ranging from $Wo_{50}En_{41}Fs_{9}$ (50 mole percent wollastonite, 41 enstatite, 9 ferrosilite) to $Wo_{40}En_{41}Fs_{19}$, or identical to calcium-rich clinopyroxenes in the ejected gabbroic cumulate blocks from the Soufrière (*12*). Interesting features of the microprobe data on clinopyroxenes are the limited chemical range, including phenocryst cores and microlites, and the highly calcic composition. Orthopyroxenes form euhedral phenocrysts (rarely rimmed by clinopyroxenes) ranging from En_{63} to $En_{67.5}$ with a wollastonite content of 2.7 mole percent. Hypersthene laths form a rare groundmass phase. Olivine occurs as phenocrysts only (70 to 75 mole percent forsterite) and is usually associated with or enclosed in clusters of pyroxene, plagioclase, and magnetite phenocrysts. Some olivines show corrosion features where they are in contact with liquid (groundmass). Coarse-grained xenoliths are common in the new lava and the type most frequently encountered is a plagioclase-olivine cumulate or plagioclase-olivine-clinopyroxene cumulate. In addition we have found xenoliths of a plagioclase-orthopyroxene-clinopyroxene rock with a granular texture, probably metamorphosed igneous rock.

The lava erupted in 1971 to 1972 is a basaltic andesite with a silica content of 54.1 percent and is chemically closely comparable to products of previous Soufrière eruptions (Table 1). Available analyses of ejecta from the 1902–1903 eruption give a silica content in the range of 50.5 to 57.8 percent, but a good deal of this variation is due to aeolian differentiation, as pointed out by Flett (*13*). Most volcanic ash consists of a mixture of crystals and glass shards. While airborne, the denser crystals fall at a considerably greater rate than the lighter glass fragments, which tend to be carried by air currents farther away from the vent. The effect of such aeolian differentiation on the chemical composition of ash is to lead to the accumulation of a fraction relatively low in silica near the vent and a silica-rich glassy portion at great distances from the vent. Hay (*14*) demonstrated the effect of this type of differentiation in the pyroclast flow deposits from 1902, where concentration of crystals over glass fragments took place in the ash column, and referred to scoria bombs as representative of the magma. It is also our opinion that the best approximation to the composition of the first magma erupted on 6 to 7 May 1902 is given by two analyses of pyroclasts: a vitreous bomb with 56.7 percent silica (*15*), and pumice with 55.6 percent silica (*16*). Unfortunately, no other well-dated samples are available from the early stages of the 1902–1903 eruption, but four samples from deposits believed to be 1902 pyroclast flows give an average of 53.1 percent silica,

Table 1. Chemical analyses of the 1971–1972 Soufrière lava and products of the 1902–1903 eruption. The symbols H_2O^+ and H_2O^- stand for absorbed water and water of crystallization, respectively. (A) Basaltic andesite from the new lava island in Soufrière crater, 1971 to 1972. The composition is the mean of two analyses by D. Seupersad, University of the West Indies. (B) Vitreous bomb from Soufrière, 7 May 1902 (*29*). (C) Pumice from Soufrière, 7 May 1902 (*6*). (D) Pyroclast flows from Soufrière, 1902; the composition is the mean of four analyses (*30*). (E) Scoria from the west rim of Soufrière crater, erupted March 1903 (*30*).

Component	A	B	C	D	E
SiO_2	54.10	56.71	55.64	53.14	50.51
Al_2O_3	18.70	18.80	18.21	18.71	17.52
Fe_2O_3	2.03	3.12	3.63	3.20	3.18
FeO	6.75	5.30	4.83	5.65	5.83
MgO	3.94	3.62	3.48	3.48	7.28
CaO	8.25	8.06	8.14	9.79	11.27
Na_2O	3.60	3.65	3.55	3.05	2.09
K_2O	0.54	0.77	0.58	0.51	0.43
H_2O^+	.13	.11	.54	.82	.59
H_2O^-	.12		.20	.26	.10
TiO_2	1.04	.77	.98	.90	.83
P_2O_5	0.12	.08	.11	.11	.10
MnO	.18	.05	.19	.18	.16
Totals	99.50	101.04	100.08	99.80	99.89

whereas scoria erupted in March 1903, collected from the west rim of the crater, contains 50.5 percent silicon dioxide. The composition of the pyroclasts ejected in the 1902–1903 eruption thus varied from andesite (56.1 percent SiO_2) in the initial stages, to basalt (50.5 percent SiO_2) in the final explosions of March 1903. The Soufrière lavas and pyroclasts are somewhat richer in sodium than basaltic andesites from the islands of Martinique, Guadeloupe, Montserrat, and Nevis, but are comparable to those of St. Kitts. However, the basaltic andesites of Dominica and Nevis show a higher potash content, whereas those of Grenada contain much higher total alkalis than the Soufrière products.

Seismological Investigations

The most striking seismological feature of the eruption was the absence of true volcanic earthquakes. The eruptions of the Soufrière in 1812 and 1902 were preceded and accompanied by a series of felt earthquakes (*4*), as were the eruptions of Mt. Pelée on the neighboring island of Martinique in 1902 and 1929 (*15, 17*). The minor eruptions which have occurred in the Lesser Antilles in the 20th century at the Soufrière of Guadeloupe (*18*) and at Kick'em Jenny submarine volcano (*19*) have also been accompanied by earthquake phenomena, and series of strong local earthquakes attributed to movements of magma below the volcanoes occur regularly throughout the region (*20, 21*). Because of these facts, seismic monitoring is relied on heavily to provide advance warning of Lesser Antillean eruptions, and before the 1971–1972 eruption this method was the only one in continuous use in St. Vincent. The permanent St. Vincent seismograph (SVT) is located at Camden Park, 19 km south of the volcano, and is equipped with a short-period Willmore seismograph of the vertical component type, operating at a peak magnification of 23,000 at 0.2 second. This station was out of commission for the period 13 to 31 October but was reactivated on 1 November, and on 2 and 21 November additional stations with similar characteristics were established 6 km southwest of the crater (SVR) and 6 km east of the crater (SVO in Fig. 1). Throughout the eruption none of these stations recorded any earthquakes other than regional tectonic events.

From 20 November it was definitely known that a true eruption was in progress, and in view of the earthquake activity that had accompanied previous Lesser Antillean eruptions the absence of earthquakes was surprising. Three more stations (SVS, SVZ, and SVW in Fig. 1) were therefore established close to the crater itself between 29 November and 13 December. These stations immediately began to record seismic signals, initially at a rate of 60 to 110 per day, but as the rate of growth of the island decreased the number of events also decreased, virtually to zero after 20 March. The signals were of extremely small amplitude and bore little resemblance to the signals usually generated by earthquakes close to Lesser Antillean volcanoes at times of increased activity. Generally, these earthquakes have been indistinguishable from small tectonic earthquakes (*21*): they have shown clearly developed *P* and *S* phases, many of them have been felt, and they have been detectable at distances of up to 10 to 20 km from the volcanoes. In contrast to this, the St. Vincent events were emergent packets of energy 10 to 15 seconds in duration (Fig. 8) in which phases could not be recognized, with one possible exception none of them were felt, and they were detectable only within 2 to 3 km of the crater itself. Many of the events were remarkably sinusoidal with a predominant frequency of 2.5 hertz, and there are similarities both to the volcanic (B type) earthquakes observed at Mt. Asama, Japan (*22*), and to sinusoidal tremors recorded in the Aeolian Islands, off Sicily (*23*). Although all stations shared a common time control, the fact that the signals emerged slowly from the background and were recorded only at three closely spaced stations make it extremely difficult to estimate the points of origin of the events with any accuracy. However, from the time delays between arrivals at stations SVS and SVW it has been possible to estimate that the disturbances propagated at a velocity not greater than 2.7 km/sec. A number of the more clearly recorded events were examined, and from the relative arrival times at the three stations and the above velocity it was estimated that the events occurred in a hemisphere of approximate radius 0.5 km, centered on the crater floor.

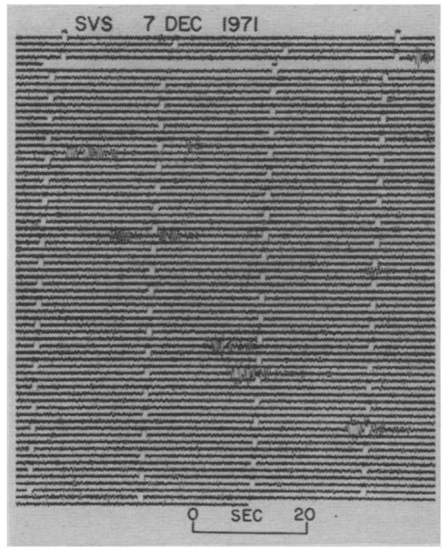


Fig. 8. Part of a seismogram written by the instrument closest to the crater, illustrating the kind of events recorded during the lava eruption. The microseismic background level is about 3 nanometers.

The conclusion that the events were generated within the crater itself was reinforced by visual observations. The rate of occurrence of the events was greatest when the rate of growth of the island was greatest (Fig. 3), at which time there were frequent falls of rock from the island. Simultaneous observation both of the rockfalls and of the output from the seismometer closest to the crater showed that almost all of the seismic events were accompanied by rockfalls, although not all rockfalls were accompanied by seismic events. This suggests that some of the rockfalls were triggered by the same process that generated the seismic events and that this process occurred close to the surface of the lava mass. The magnification of the seismograph nearest the crater (SVS) was about 21,000 at period 0.1 second, and the maximum ground displacement in any event was about 100 nanometers. This corresponds to a total energy release of the order of 5×10^6 ergs, so that at the time of maximum occurrence of the tremors the daily energy release was only about 6×10^8 ergs. The small amount of energy involved and the rapid attenuation of the signals with distance make it unlikely that the events were generated by large-scale movements of magma in the throat of the volcano, and the noninstantaneous source mechanisms make it unlikely that they were generated by fracturing either in the country rock or in the solid carapace of the lava mass. One possible explanation is that they were generated by minor steam explosions within the crater lake, caused by hot lava coming into contact with the lake water. Many of the rockfalls, especially at the ends of the radial ridges of the island, were immediately preceded by the appearance of a patch of boiling water close to the island, from which a red-brown stain spread, presumably consisting of stirred-up sediments from the lake bottom. We believe that such minor explosions provide the most plausible explanation for the seismic disturbances, but whether or not this particular mechanism is the correct one, the fact remains that the only seismic events which were recorded during the eruption were minor ones associated with processes in the crater. The 1971–1972 eruption is thus unique among historic Lesser Antillean eruptions in that it occurred completely aseismically.

Discussion of the Eruption

West Indian volcanic eruptions are traditionally considered to be highly explosive and are associated with andesitic magmas and glowing avalanches. The unusual behavior of the Soufrière in 1971 therefore proved a source of great apprehension until it was realized that we were dealing with a nonexplosive basaltic andesite magma. The slow rate of extrusion of lava and the complete lack of seismic activity were additional indications that this eruption was of a type different from any which had previously been described in the West Indies.

The possibility that the materials erupted in 1971 to 1972 and in 1902 to 1903 represented the same magma —that is, that the 1971–1972 events were the last phase of the earlier eruption—has been considered, but we feel that this is not likely to be the true explanation. The differences between composition and zoning in plagioclase phenocrysts from the two eruptions suggest that the 1971–1972 events belong to a new magmatic event, and it is difficult to suggest a reason why the eruption should stop for 68 years and then continue.

A second possibility which we considered was that the eruption was similar to the second halves of the eruptions of neighboring Mt. Pelée in 1902 and 1929. Each of these eruptions began explosively with the generation of glowing avalanches and frequent earthquakes, but subsequently settled into relatively quiet eruptions in which domes of extremely viscous andesitic lava were extruded. Although there are similarities between these episodes and the 1971–1972 eruption, we believe that these similarities are more apparent than real. The Pelean dome-building periods were preceded by periods of up to 2 years of felt earthquakes and 6 months of explosions and pyroclast flows (*15, 17*). The domes were extruded as blocky, highly viscous or near-plastic lavas, and their growth was accompanied by differential vertical movement of the blocks resulting in striations on their surfaces, by the extrusion of narrow vertical spines which usually crumbled rapidly, and by frequent significant explosions and minor glowing avalanches. The mode of extrusion of domes at similar volcanoes in other parts of the world has almost invariably followed this pattern, some recent examples including Merapi (*24*), Mt. Lamington (*25*), Bezymianny (*26*), Hibok-Hibok (*27*), and Santiaguito (*28*).

In contrast to this mode of growth, the 1971–1972 lava was extruded without any preceding or accompanying earthquakes and there were no explosions other than extremely minor underwater steam explosions. Throughout the period when the lava mass was visible it rose as a single unit without significant relative vertical movement other than falls of rock; no spines were extruded and the tension cracks separating blocks of lava on the island show no signs of striations or slickensiding to indicate relative movement of rigid or semirigid units. In addition, the Pelean dome lavas, and the majority of other West Indian dome lavas, are considerably more andesitic than the 1971–1972 lava. There is no direct evidence concerning the viscosity of the 1971–1972 lava, but the difference between its silica content (54.1 percent) and that of the 1903–1904 Pelean dome lava (62.75 percent) (*29*) suggests that the 1971–1972 lava should have a considerably lower viscosity. Thus, although the steep sides of the lava mass may indicate that the lava was extruded in a viscous or near-plastic state, it is equally likely that the lava was extruded in a fluid state and that the steep sides result from the fact that the lava was quenched by the lake water and restricted by the steep sides of the crater before any significant lateral flow could take place. The distinctive columnar jointing and structures similar to pillow lava which are visible on the mass (and are absent from other West Indian domes) tend to support this interpretation. In view of these gross differences between the 1971–1972 eruption and the previous dome-building episodes observed in the West Indies we believe that it is misleading to compare the two types of eruption, and we prefer to regard the 1971–1972 lava simply as a basaltic andesite lava flow which reached its dome-like shape because of the peculiar conditions of a slow rate of eruption into a steep-sided water-filled crater.

The fact that the 1971–1972 eruption occurred aseismically and without any explosions or other phenomena which were audible or visible at the foot of the volcano led us to investigate the possibility that other such eruptions had occurred in the past and had gone virtually unnoticed. A close examination of the literature shows that there have been two occasions on which this may have happened. In 1784 the presence of a youthful, steaming mass of lava in the crater was reported (*5*), which strongly suggests that an eruption similar to that of 1971–1972 had occurred subsequent to the catastrophic eruption of 1718. Again in 1880 vegetation in and around the crater was reported to have been destroyed by activity in the crater (*4, 6*), and it is possible that a body of magma entered the crater at this time. The sequence of known eruptive events at the Soufrière is therefore as follows:

1718	Explosive eruption
1780's	Extrusion of lava
1812	Explosive eruption
1880	Extrusion of lava?
1902	Explosive eruption
1971	Extrusion of lava

The most important fact to emerge from this investigation is that the Soufrière is capable of at least two distinct types of eruption:

1) The "traditional" Soufrière eruption, which is preceded by frequent strong earthquakes and is highly explosive in nature. The rate of production of new material is extremely rapid and volumes of the order of 2 km^3 may be produced in the form of pyroclast flows and ashfalls.

2) The 1971–1972 type of eruption, which is not preceded or accompanied by earthquakes, is nonexplosive, and in which material is erupted at a much lower rate and in much smaller amounts.

From the available historical records it appears that these two types of eruption alternate and that eruptions of type 1 are followed by 60 to 70 years of inactivity and eruptions of type 2 by 20 to 30 years of inactivity. It is tempting, therefore, to ascribe a cyclic behavior to the Soufrière and to extrapolate the cycle to predict an explosive eruption 20 to 30 years from now. However, in view of the scanty data from the earlier historical period we believe that it would be unwise to make such predictions at the present time.

Summary

The Soufrière volcano in St. Vincent erupted from October 1971 to March 1972, as 80×10^6 m^3 of basaltic andesite lava was quietly extruded inside the mile-wide crater. The eruption was largely subaqueous, taking place in the 180-m-deep crater lake, and resulted in the emergence of a steep-sided island. The mild character of the eruption and the absence of seismic activity stand in direct contrast to the highly explosive character of the eruption of 1902 to 1903.

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Clinical Psychopharmacology in Its 20th Year

Late, unanticipated effects of neuroleptics may limit their use in psychiatry.

George E. Crane

The use of neuroleptic drugs (*1*) for the treatment of mental disorders began in the early 1950's and has increased steadily. According to one estimate (*2*), 250 million people had received these drugs by the end of 1970. In the last decade, hospital beds have been increasingly phased out, and, to take their place, new community mental health centers have been opened or existing facilities have been expanded throughout the nation. According to the medical profession, this new program for the treatment of the mentally ill would not have been possible without neuroleptics. Psychiatrists, sociologists, and professionals in allied fields have emphasized the advantages of maintaining the mentally ill in the community. On the other hand, it is acknowledged that a large proportion of patients released from hospitals are incapable of meeting the demands of society. Inadequate programs for the management of these mentally handicapped persons have created new and unexpected problems, and, in an effort to solve them, the psychiatric community has become more and more dependent on the use of neuroleptic agents. One of the consequences of this reliance on psychopharmacology has been the tendency to minimize the potential danger of long-term exposure to powerful chemical agents. Thus, permanent neurological disorders have become very common among patients treated with neuroleptics, but little effort has been made to come to grips with this problem.

Use of Neuroleptic Agents

Physicians prescribe neuroleptic drugs on a long-term basis for mental disorders such as schizophrenia, psychosis due to mental deficiency, paranoid states of adulthood and senility, chronic brain syndromes, mania, hyperactivity in disturbed children, addiction to narcotics, excessive anxiety as observed in neurosis, and physical illness. The National Research Council of the National Academy of Sciences has recently reviewed the data on the effectiveness of some of the neuroleptics (*3*), but it has not confirmed claims that such agents are indicated for the treatment of mental conditions other than schizophrenia and related diseases.

There are few schizophrenic patients now living in the United States and Europe who have not received a phenothiazine or a butyrophenone at one time or another. In the last 15 years, neuroleptic agents have replaced most forms of treatment for psychoses and other serious mental ailments. Electric shock therapy and various types of psychotherapy have survived, but the former is seldom used in institutions, and the latter play a subordinate role in the total management of psychotic individuals. The fact that these drugs reduce overt psychopathology without causing excessive sedation, euphoria, or addiction explains, in part, their

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