volcanic glass (Fig. 4), broken phenocrysts (plagioclase, clinopyroxene, orthopyroxene, magnetite, and olivine), and lithic fragments of holocrystalline basaltic andesite. The ratio of juvenile to lithic components changed markedly as the explosive eruption progressed. The initial explosions (13 and 14 April) produced lithic-rich tephra [60 percent (by weight)], as shown by the lower layer (Fig. 2). The tephra from subsequent explosions (17 to 26 April) was composed predominantly of juvenile material and contained only about 20 percent (by weight) lithic material. The color difference between the two layers is a reflection of the increase in the content of juvenile glass in the upper layer.

The 1979 eruption had several features typical of phreatomagmatic explosive eruptions. First, very strong circumstantial evidence links the explosive activity to the presence of the crater lake. It is more than coincidence that the explosive activity ceased when all the water from the crater lake had been blasted out. Shepherd and Sigurdsson (*4*) have presented a model for the phreatomagmatic eruption mechanism, which relies on a three-way interaction of magma, lake water, and hot rock of the 1971–1972 island to drive the explosive eruption. Although the model cannot, of course, exclude the participation of juvenile magmatic volatile materials in driving the explosions, such volatile materials are not required to account for the observed phenomena.

Second, the ash deposits themselves provide evidence of phreatomagmatic activity. The base-surge beds near the crater are a characteristic feature of phreatomagmatic eruptions (*5*). Similarly, the small change in Md of the air-fall tephra with distance from source, the fine grain size, poor sorting, and abundant accretionary lapilli are features commonly associated with ph~eatomagmatic eruptions (*6*).

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References and Notes

1. J. B. Shepherd, W. P. Aspinall, K. C. Rowley, J. Pereira, H. Sigurdsson, R. S. Fiske, J. F. Tomblin, *Nature (London)* **282**, 24 (1979).
2. The quantity ϕ is the negative logarithm to the base 2 of the particle diameter (in millimeters).
3. R. K. Sorem, *J. Volcanol. Geothermal Res.*, in press.
4. J. B. Shepherd and H. Sigurdsson, *ibid.*, in press.
5. J. G. Moore, *Bull. Volcanol.* **30**, 337 (1967).
6. S. Self and R. S. J. Sparks, *ibid.* **41**, 196 (1978); R. S. J. Sparks, L. Wilson, H. Sigurdsson, *Philos. Trans. R. Soc. London* **299**, 241 (1981).
7. This work is supported by National Science Foundation grant EAR80-18809.

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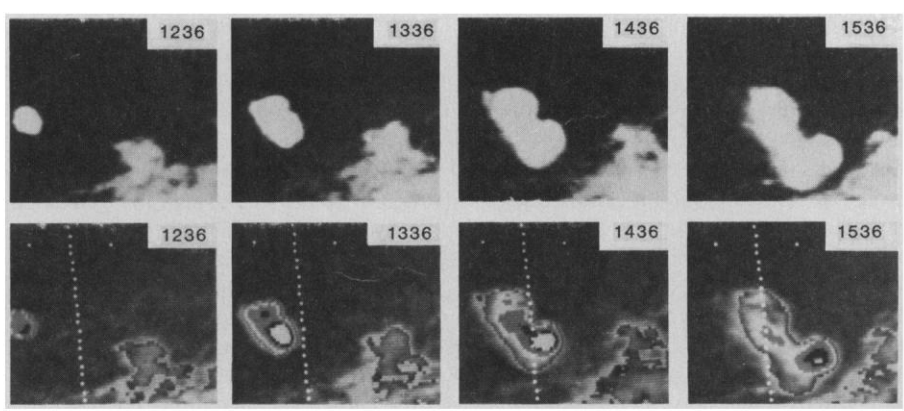
Geostationary Satellite Observations of the April 1979 Soufriere Eruptions

Abstract. *Infrared images from the geostationary satellite SMS-1 were used to study the growth of the eight major eruptions of Soufriere, St. Vincent, during April 1979. These eruptions differed considerably in growth and intensity, the most intense being that of 17 April which formed an ash cloud of 96,000 square kilometers in 4 hours. The weakest eruption formed a cloud of only 16,000 square kilometers.*

Eight of the eruptions of Soufriere Volcano during April 1979 were observed by the SMS-1 satellite, one of a series of geostationary meteorological satellites. This satellite is in a 35,800-km orbit above the equator at longitude 70°W. Because photographs were available at least every half-hour, continuous film loops could be prepared and the eruptions could be viewed by means of a movie projector. On film, the eruptions appeared to grow explosively; in many respects, they resembled the major thunderstorms that form over the American Midwest.

Infrared images from the SMS-1 window channel radiometer (10.5 to 12.5 μm) were particularly useful. Paradoxically, satellite infrared observations of explosive volcanic eruptions indicate these eruptions to be cold. However, only superficial features of the ash cloud can be seen by the satellite. At the edge of the ash cloud, considerable mixing takes place as the cloud rises, and the infrared-sensed temperature approaches the temperature of the environment very quickly.

Generally, the colder the eruption appears, the higher in altitude it should extend. If a nearby radiosonde observation is available, these temperatures can



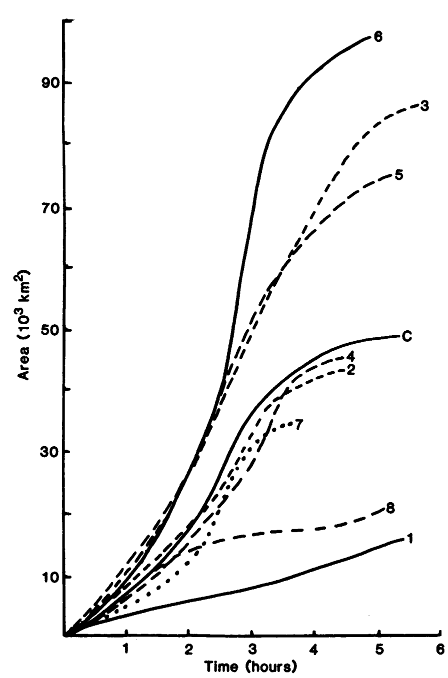


Fig. 1 (above). (Top row) Hourly infrared photographs for the 1150 LCT 14 April 1979 eruption of Soufriere. The times are indicated at the upper right. (Bottom row) Corresponding enhanced infrared imagery. Here the whitest area within the spreading canopy, first appearing at 1336 LCT, corresponds to temperatures colder than −69.7°C, whereas the surrounding black ring represents temperatures between −62.5° and −69.7°C. The nearest radiosonde observation indicates that the central white area represents a growth to altitudes above 14 km. Fig. 2 (right). Growth rates (area as a function of time) for the eight major eruptions of Soufriere that were observed by the geostationary satellite SMS-1. The curves represent eruptions that began at the following times: curve 1, 13 April, 0615 LCT; curve 2, 13 April, 1115 LCT; curve 3, 13 April, 1708 LCT; curve 4, 13 April, 2108 LCT; curve 5, 14 April, 1150 LCT; curve 6, 17 April, 1657 LCT; curve 7, 22 April, 0637 LCT; and curve 8, 25 April, 2353 LCT. Curve C is a composite of these eight eruptions.

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be translated into altitude and the maximum height of the volcanic eruption can then be estimated. This is an important value because the maximum height to which the cloud from an explosive eruption rises is related to (i) the rate at which pyroclastic material is produced and (ii) its thermal power output (*1*).

Satellite observations of an explosive volcanic eruption can be analyzed in the same manner as those of thunderstorms and other convective systems (*2*). Frequently an infrared-enhancement procedure based on a sequence of gray shades (including white and black) is used to emphasize certain ranges of temperature. Figure 1 is an example of this procedure for the 14 April 1979 eruption at 1150 LCT (*3*). The upper series of panels shows hourly infrared images; the lower series shows the corresponding enhanced infrared images. The nearest radiosonde observation was from Guadeloupe; its temperatures indicate that the whitest area represents a growth of the eruption to heights above 14 km. This technique indicated that all the eruptions except the first two extended above this level.

Computer analysis of some of the infrared imagery of the eruptions of 14 April (1150 LCT), 17 April, and 22 April revealed temperatures as low as −80°C. Such temperatures indicate that these ash clouds extended above 18 km and consequently penetrated into the stratosphere. Unfortunately, operational requirements prevented the National Earth Satellite Service from processing images from all the other eruptions.

As these ash clouds grew upward, they extended downstream in long plumes from St. Vincent, usually toward the east or southeast. Growth to altitudes above 14 km generally took place within 1 hour, but the horizontal expansion of the canopy continued for several hours longer. However, considerable variation was seen in the horizontal growth of these eight eruptions, and these differences also reflect the intensities of the individual eruptions.

Figure 2 shows the growth rate for each of the eight eruptions seen by the SMS-1 satellite. Eruptions 1 and 8 appear to have grown at the slowest rate and apparently were the least intense. Eruptions 3, 5, and 6 had the most rapid growth rates, and their ash clouds covered the greatest areas. Usually this horizontal expansion took place in about 4 or 5 hours. The 17 April eruption (eruption 6) is of particular interest because it appears to have been the most intense (*4*). Figure 2 indicates that this eruption resulted in the largest ash cloud, which covered an area of 96,000 km^2 after 4 hours of growth.

After about 4 or 5 hours of horizontal expansion, the ash cloud usually begins to thin out and becomes partially transparent to the infrared radiation originating from lower and warmer altitudes. The infrared temperatures are then unrepresentative because they are no longer characteristic of the ash cloud itself. As the thinning continues, the cloud becomes so diffuse that infrared cannot be used to track it.

These eight explosive Soufriere eruptions were seen very clearly with the infrared sensors aboard SMS-1. In general, explosive volcanic eruptions having columns extending upward at least into the middle troposphere can be observed with these sensors. But weaker eruptions extending only 1 or 2 km above the surface may not be apparent, and consequently three of the Soufriere eruptions could not be observed from the SMS-1. If no clouds are present, weaker eruptions may sometimes be revealed by the visible radiation sensors that are also aboard these satellites.

In light of the infrequency of volcanic eruptions in the Caribbean, it is remarkable that Soufriere experienced eight major explosive eruptions in a 2-week period, all of which could be observed by a geostationary satellite almost directly overhead. Erupting volcanoes have been photographed from satellites before, sometimes with higher resolution than that available from the SMS-1 system (*5*). However, analysis of the continuous time-lapse infrared imagery of the April 1979 Soufriere eruptions made it possible for the first time to trace the growth of a series of major eruptions and to compare their intensities.

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References and Notes

1. L. Wilson, R. S. J. Sparks, T. C. Huang, N. D. Watson, *J. Geophys. Res.* **83**, 1829 (1978); M. Settle, *J. Volcanol. Geothermal Res.* **3**, 309 (1978).
2. R. F. Adler and D. D. Fenn, *J. Appl. Meteorol.* **18**, 502 (1979).
3. All times are local civil time (LCT); add 4 hours for universal time.
4. L. McClelland and R. Fiske, *Eos (Trans. Am. Geophys. Union)* **60**, 469 (1979).
5. J. Friedman and G. Heiken, *Skylab Explores the Earth* (Publication 137, National Aeronautics and Space Administration, Washington, D.C., 1976).
6. I thank H. R. La Porte and M. Young for their assistance in obtaining the high-resolution infrared analysis. I thank W. Replane for measuring the growth rates of all eight eruptions.

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Meteorological Analysis of the Eruption of Soufriere in April 1979

Abstract. *Meteorological upper-air data, in conjunction with satellite imagery, lidar light detection and ranging returns, and aircraft sampling, aid in the determination of plume altitude and transport. The estimated trajectories indicate that the ash was transported eastward across the Atlantic to Africa in 3 to 5 days and that there was modest meridional transport as far as 15° poleward during the first week of travel.*

Volcanoes are of very great interest in atmospheric science because of the documented effects of large emissions on climate and because these emissions function as a natural tracer in the atmosphere. The tracking of volcanic debris has called attention to important properties of the atmospheric motion systems, and investigators have studied small- to medium-scale turbulent diffusion and global-scale transport rates, using volcano plumes as tracers.

Table 1. Power released in the Soufriere eruptions (*9*)

Date in April 1979, time (LCT)	Maximum cloud height (km)	Q (MW)
13, 0500	10	2.7×10^6
13, 1115	12	5.9×10^6
13, 1700	17	2.6×10^7
14, 0100	15	1.5×10^7
14, 1200	18	3.3×10^7
17, 1705	20	5.0×10^7
22, 0635	18	3.3×10^7
25, 2355	15	1.5×10^7

The atmospheric plume from Soufriere, St. Vincent, was not an important climate modifier. The resulting data on plume rise, deformation, and movement, when used in conjunction with meteorological structure, can extend our knowledge of highly energetic buoyant plumes in a stable atmosphere. In this report we explore how conventional meteorological data can be used in interpreting plume motion and in supplementing the special-purpose analyses. Three upper-air-network stations are within 320 km of

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