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THE 1975—1977 CRISIS OF LA SOUFRIERE DE GUADELOUPE (F.W.I): A STILL-BORN MAGMATIC ERUPTION

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ABSTRACT

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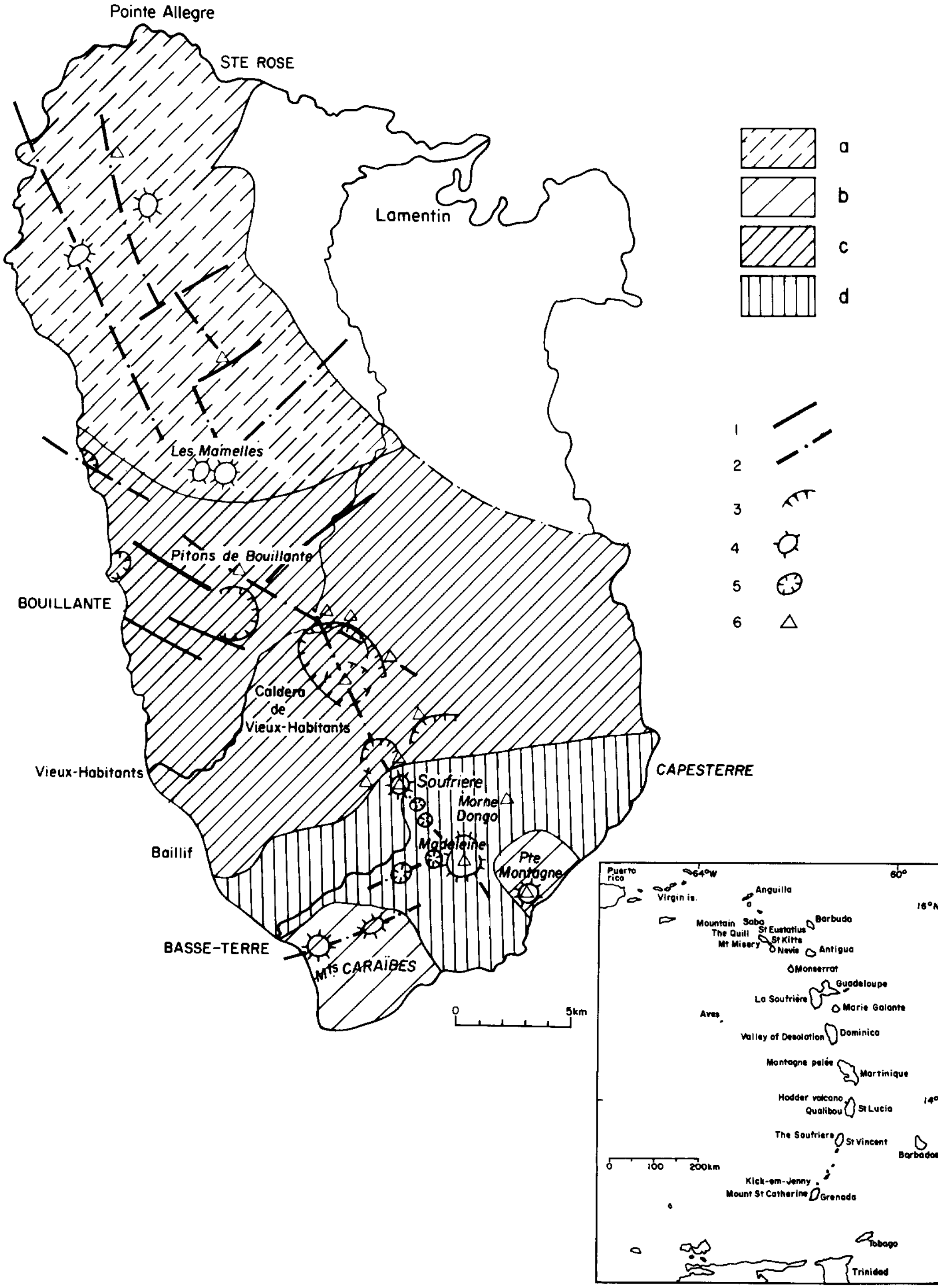
On July 8, 1976, eruptive activity broke out at la Soufrière de Guadeloupe (F.W.I) after about one year of increasing seismic activity. Seismic activity continued to increase until August 1976, reaching more than 1500 events (a 200-fold increase over the preceding quiet period of a few years) and an energy output of about 10^{17} ergs in a day. A total of 26 major phreatic eruptions similar to the July 8 outburst took place during an eight-months period. The steam blasts that characterized the eruptions gave rise to particle- and sometimes block-charged plumes that deposited an estimated 10^6 m^3 of solids. The H_2O-rich gases emitted during the blasts presumably contained other gases (H_2S, SO_2, CO_2 . . .) that were partly adsorbed on solid particles. All material was erupted at temperatures of the order of 100° to 200°C.

The observation of vertical migration of earthquake foci in less than a few hours and over about 6 km depth, and of abnormal variations of the geomagnetic field, indicate a deep energy source for the phreatic eruptions. A small proportion of the gases adsorbed on solid particles had a magmatic origin. However, most of the steam and the tephra seemed to originate from superficial levels of a hydrothermal system. Similar phreatic eruptions have occurred several times in recorded history. In the case of la Soufrière, the origin of the phreatic eruptions is best described by an abnormal energy input (versus steady-state) from a crustal magma chamber. The occurrence of truly magmatic eruptions is presumably inhibited by an extensive hydrothermal system. The abrupt release of more power from the magma chamber could have resulted in an explosive pyroclastic eruption.

Substantial improvement of the Guadeloupe volcano observatory has followed the 1975—1977 crisis. Permanent telemetered geophysical networks and regular geochemical observations have provided a five year data base of the volcano behavior in its non-eruptive state which can be compared to crisis situations.

GENERAL SITUATION AND HISTORICAL RECORD

The Basse-Terre island of Guadeloupe (Fig. 1) is situated along the recent


Pointe Allegre
STE ROSE
Lamentin
Les Mamelles
Pitons de Bouillante
BOUILLANTE
Caldera de Vieux-Habitants
Vieux-Habitants
Baillif
Soufriere
Morne Dongo
Madeleine
Pte Montagne
CAPESTERRE
BASSE-TERRE
Mts CARAÏBES
0
5km
a
b
c
d
1
2
3
4
5
6
Puerto rico
64°W
60°
16°N
14°
Virgin is.
Anguilla
Mountain Saba
The Quill
Mt Misery
St Eustatius
St Kitts
Nevis
Barbuda
Antigua
Monserrat
Guadeloupe
La Soufrière
Marie Galante
Aves
Valley of Desolation
Dominica
Montagne pelée
Martinique
Hodder volcano
Qualibou
St Lucia
The Soufriere
St Vincent
Barbados
0
100
200km
Kick-em-Jenny
Mount St Catherine
Grenada
Tobago
Trinidad

Lesser Antilles island arc as defined by Martin-Kaye (reviews of geological, geochemical, geophysical data may be found in Malfait and Dinkelman, 1972; Tomblin, 1975; Brown et al., 1977; Briden et al., 1979; Le Mouel et al, 1979; Dagain et al., 1981). The arc is characterized by slow subduction (2cm/yr) and infrequent calc-alkalic volcanism. The relative motion between the Caribbean plate and the underthrust South-American plate (Minster and Jordan, 1978) is oblique to the arc segment between Martinique and Guadeloupe and therefore gives rise to a large strike-slip component. The slope of the active Wadati-Benioff seismic zone is close to 45° in the Guadeloupe area (Dorel et al., 1971; Tomblin, 1975; Dorel, 1981). The underthrust slab is reached at a depth of 70 to 80 km under the arc and it becomes seismically inactive below 200 km.

In Basse-Terre island, the Quaternary volcanic history may be subdivided into four main phases of activity (Fig. 1) (Westercamp and Mervoyer, 1976; Briden et al., 1979):

(1) the early Pleistocene calc-alkalic complex of the northern half of the island;

(2) the slightly younger volcanic Mounts Caraibes of island-arc tholeiitic affinity in southern west Basse-Terre;

(3) the approximately one million year old central massif;

(4) the Pleistocene to Recent Madeleine-Soufrière complex.

The volcanic activity of phases (1), (3) and (4) is generally similar in character and has generated products from basic andesite to dacite in composition.

La Soufrière lava dome is the highest mountain of the Lesser Antilles (1467 m) and was apparently emplaced during the last magmatic eruption that took place in 1580 ± 50 A.D. (Semet and Vatin-Pérignon, 1979; Vincent et al., 1979; Semet et al., in press). This eruption was similar in character to historical eruptions of Soufrière, St Vincent (Aspinall et al., 1973; Shepherd et al., 1979). It started with pyroclastic falls and flows that were emitted during the reopening of a crater and were followed by the extrusion of a dome. According to Semet et al. (in press), the eruption was triggered by injection and mixing of a new batch of magma in a superficial (~ 6 km deep) chamber.

The historical record, starting with european settlement in 1635, contains several accounts of eruptive episodes very similar to the minor 1956 event and the 1975—1977 crisis. All of these eruptions were of phreatic (steam-

Fig. 1. Map of the Basse-Terre island of Guadeloupe showing the principal volcanic structures: *a* = the early Pleistocene calc-alkaline complex of the northern half island; *b* = the slightly younger volcanic Mounts Caraibes of Island Arc tholeiitic affinity in southwest Basse-Terre; *c* = the approximately one million years old central massif; and *d* = the Pleistocene to recent Madeleine-Soufrière complex . The symbols represent major faults (*1*), compression axes (*2*), calderas (*3*), domes (*4*), scoria cones (*5*), and major summits (*6*). The inset shows the situation of Guadeloupe in the Lesser Antilles island arc.

blast) type. Of these, minor eruptions took place at the following dates (see Lacroix, 1904; Robson and Tomblin, 1966): around 1690; 1809—1810; December 3, 1836 to February 1837; October 20 to 24, 1956 with continuing seismic activity through December (Jolivet, 1958). Similar in many respects to the 1975—1977 crisis, a major well-documented outbreak took place over the period 1796—1798 (Rapport, 1798). Felt seismic activity preceded the first vapor and ash emission by about a year. Semi-permanent fumarolic activity, mostly situated around the base of the dome and in summit fractures, has seemingly decreased irregularly since the 17th century.

In the Quaternary, la Soufrière shows patterns distinclty comparable to those of other volcanoes in the Lesser Antilles (Robson and Tomblin, 1966). Tomblin (pers. commun., 1978) and Shepherd et al. (1979) have shown that volcanoes that have a geological record of recent pyroclastic flow emission have emitted flows some time after the onset of historical eruptions in 5 out of 16 cases. In at least two instances devastating "nuées ardentes" were emitted less than two days after the onset of eruption. This was a reason for concern when la Soufrière entered an eruptive phase on July 8, 1976.

THE 1975—1977 SEISMO-VOLCANIC CRISIS

Since the October 1956 event, and until 1975, only minor seismic activity was observed. Fumarolic activity in the dome area was limited and irregular. The seismic data for both felt and detectable quakes is inadequate until 1963 (see next section). A histogram of the number of recorded quakes per year from 1963 to 1981 shows two contrasting trends (Fig. 2). From 1963

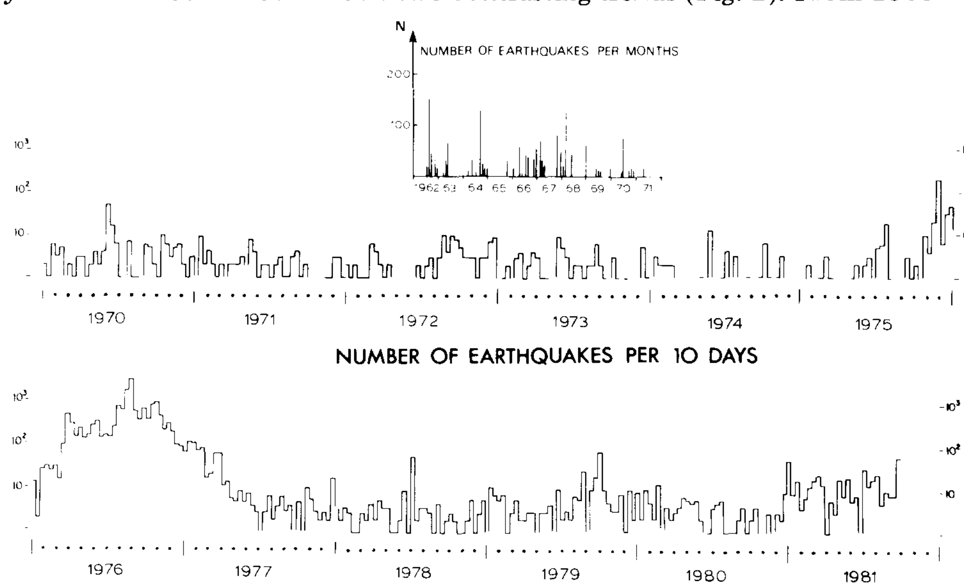


Fig. 2. Histogram of the number of recorded quakes from 1962 to 1981. The upper inset shows the monthly earthquake frequency for the 1962 to 1971 period. Frequencies per 10 days in the period 1970—1981 are shown with a logarithmic scale.

to 1968 (inclusive), the average number of quakes per year is over 230, whereas from 1968 to 1975, this number decreases steadily to reach 47 quakes per year in 1974 and 21 during the first half of 1975; stresses were possibly building up at depth during the seven years preceding the seismic events preceding the 1976 volcano crisis.

Increasing seismic activity beginning in June 1975 (see next section for details) preceded the July 8, 1976 outburst. The only surface precursor to the eruptive phase was a minor landslide occurring on June 9, 1976, along the Ty Fault (Fig. 3) which is known to be active. Then, on July 8, 1976 the volcano entered the eruptive phase with one of the most violent phreatic eruptions of the whole crisis. It was accompanied by a 48 mn tremor, the reactivation of three major radial fractures in the south-eastern part of the dome (Fig. 3), H_2S-rich vapor and ash emissions, and landslides and mud flows ("lahars"). In the next few weeks, the seismic activity increased to its maximum (1257 recorded quakes on August 24) as the major eruptive centers moved from the tip of the south-east fracture zone in the dome to its upper central parts. The period of high seismic activity lasted over four months (mid-July to November) and corresponded to a time of intensive surface activity. It is referred to as the first period. Phreatic eruptions, generally accompanied by tremors, ash and block projections followed each other at irregular intervals (Fig. 4) (Sheridan, 1980). However some tremors occurred without any vapor and ash emission. Nearly one out of three phreatic eruptions occurred within two days of an earlier eruption, one out of two within five days and one out of three between 12 and 16 days.

On November 10, after five eruptions in 10 days, phreatic eruptions and tremors stopped for a period of 56 days, which we call the second period. During this quiet period, the only surface manifestations were semi-permanent emissions of H_2O vapor-rich gases, minor ash projections, and loud noises resulting from gas decompression in a crater located in the southern part of the dome.

Then on January 5, 1977, while the seismic activity had diminished to a small fraction of the August—September 1976 level, a sequence of phreatic eruptions with tremors started again and lasted until March 1, projecting ash and blocks, and occasionally producing landslides and mudflows (Fig. 4). Although the eruptions of this third period were sometimes as violent as those of the first, the total tephra emission was only half that of the earlier period.

In total, during the eruptive phase which lasted eight months, twenty-six major, phreatic eruptions and thirty-five tremors were observed (cf Dorel and Feuillard, 1980). An estimated 10^{10} kg H_2O-vapor and 10^6 m^3 ash and blocks were emitted (Le Guern et al., 1980) at low temperature (100—200° C). After the last phreatic eruption (March 1, 1977), low-level seismic activity continued for a few months at a decreasing rate until June 1977, a date retrospectively designated as the end of the crisis on the basis of quake frequency or energy histograms. After this date, the seismic activity returned

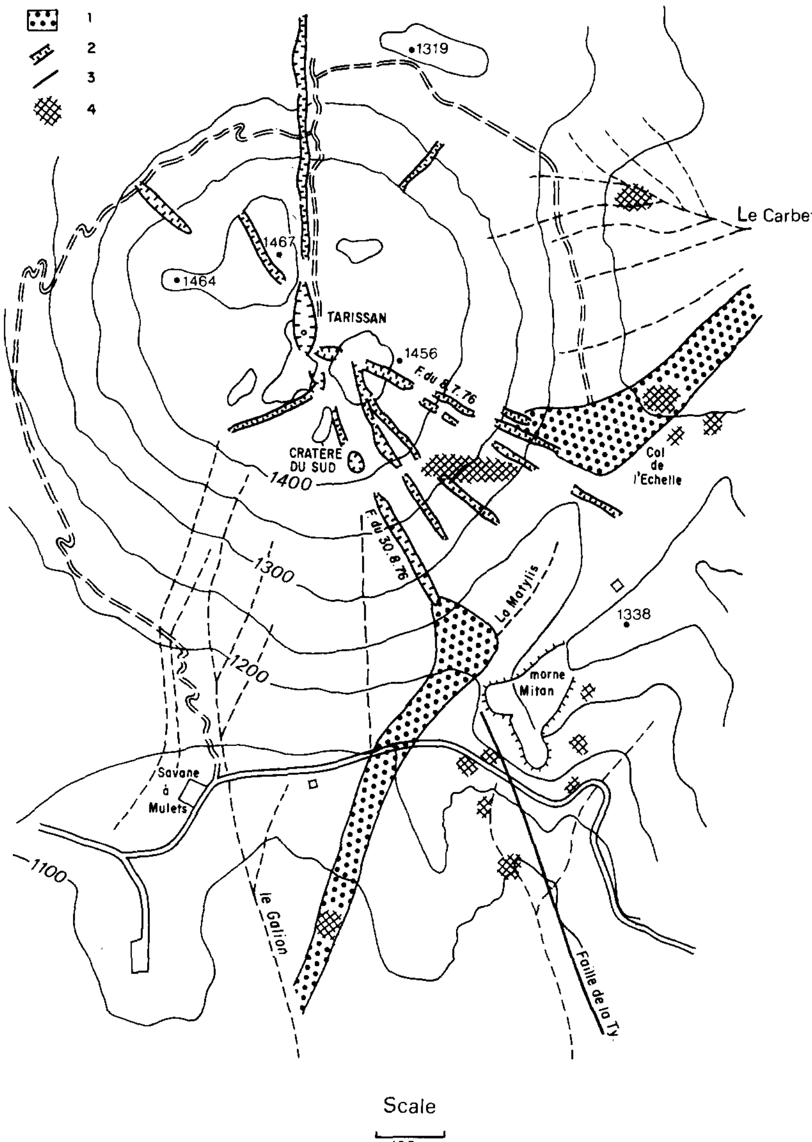


Fig. 3. Schematic volcano-tectonic map of la Soufrière summit area. Lahar are indicated by a stippled pattern (*1*); fractures that were opened or re-activated during the 1975—1977 crisis are indicated by (*2*); the active Ty Fault is indicated by a heavy line (*3*); areas of active fumarolic activity are shown by a cross-hatched pattern (*4*).

to a level comparable to the pre—crisis one. However, small outbursts of seismic activity occurred in 1979 and 1981 and will be briefly described below. The fumarolic activity in fractures on the upper part of the dome also decreased to its pre-crisis level.

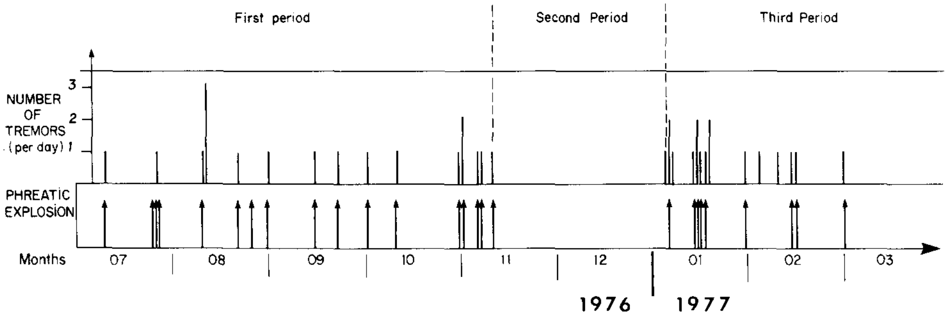


Fig. 4. Time distribution of the 26 phreatic explosions and 35 tremors during the crisis. The first period lasted from July 8 to November 10, 1976; the second period is defined by the absence of tremors and phreatic explosions and lasted from November 11, 1976, to January 4, 1977; the third period is comprised between January 5 to March 1, 1977. Note that phreatic explosions are not always accompanied by tremors and conversely.

SEISMIC ACTIVITY

A permanent recording station was installed close to la Soufrière volcano in June 1949. Since then, a seismic network comprising several stations was progressively installed so that at the beginning of the present crisis (mid 1975) 5 stations distributed over an area of about 5 km in diameter had been working for some years semi-permanently (Dorel and Feuillard, 1976, 1980). During the crisis, 5 more stations were installed. Furthermore, a temporary network of 15 stations was set up over a larger area between September 1—16, 1976.

The permanent activity at la Soufrière is characterized by periods of a few weeks duration in which a number of small unfelt events are recorded separated by quiet periods lasting a few weeks to a few months (Fig. 2). However, over 16000 events were recorded during the 1975—1977 crisis, among which 150 were felt. Figure 5 presents the number of quakes occurring daily during the 1975—1977 period.

Except for the volcanic tremors that accompany major phreatic eruptions the seismic activity is poorly correlated with the eruptive pattern. Thirty quakes of magnitude greater than 3 are not preceded or followed by more intense eruptive activity over a few days interval. No particularly large quake could be connected with the eruption of July 8, 1976. The largest quake of the crisis (magnitude 4.2 of August 16, 1976) followed four days of more or less continuous vapor and ash emission accompanied by tremors.

The maximum seismic energy output in a day was of the order of 10^{17} erg and the total output for the 1975—1977 period was only on the order of 2×10^{18} erg (Dorel and Feuillard, 1980).

Focal determinations were plagued by several limitations of the seismological network (small aperture and a gap to the north of the volcano) and poor knowledge of the local structure and of the topographical corrections. Figure

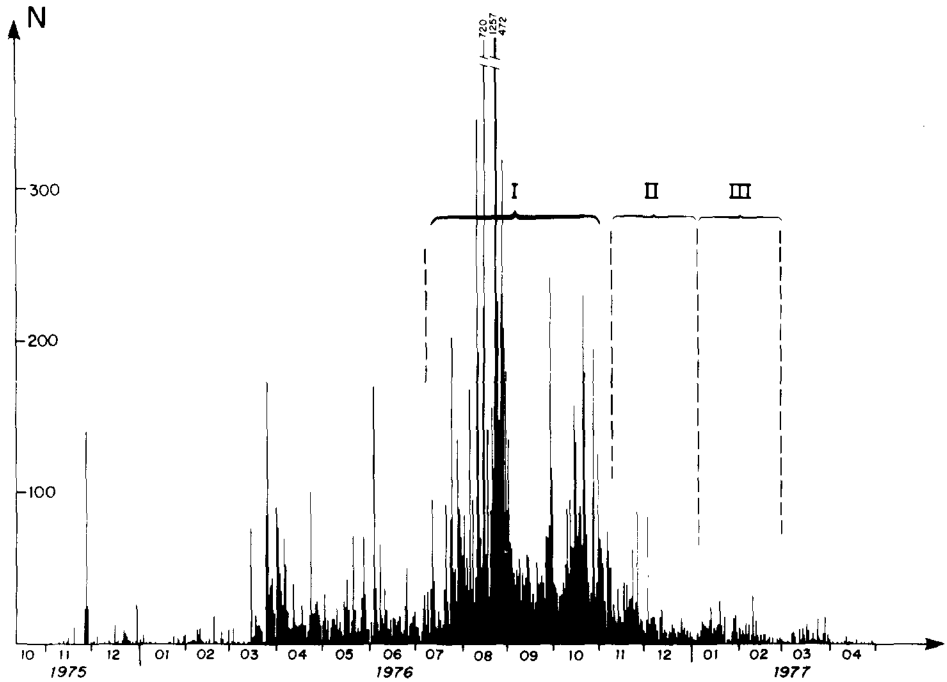


Fig. 5. Daily earthquake frequency during the 1975—1977 crisis. Roman numerals define the three periods referred to in figure 4. Note the decreasing seismicity during the third period, although phreatic explosions and tremors were still occuring until March 1, 1977.

6 illustrates the location of the best determined epicenters during the crisis. They are spread over an elliptical area of approximately 10 × 6 km, elongated in the NW—SE direction, and centered 1 km NW of la Soufrière dome. A number of representative events have been chosen for the determinations, utilizing the differences between P and S arrival times. Comparison of the determinations from the permanent local network with those of the temporary network of 15 stations indicates a precision of about 1.2 km in epicenter location.

Focal depths (Fig. 7) computed with a tabular model are restricted to a zone shallower than 10 km below sea level and cluster in the 1—5 km range. *Long-term* vertical migration of the hypocenters over the 1975—1977 crisis has been suggested previously (Dorel and Feuillard, 1980); but a more accurate analysis of the data shows that in fact monthly-averaged depths stayed constant within the estimated errors. On the contrary, Hirn and Michel (1979) convincingly showed that *short-term* migration of the hypocenters occurred for several major earthquakes swarms: shocks migrate from a depth of about 6 km toward the surface over periods of a few tens of minutes to a few hours.

Computation of focal mechanisms generally gives unstable solutions. Nevertheless, a simple explosion mechanism seems to be excluded by the

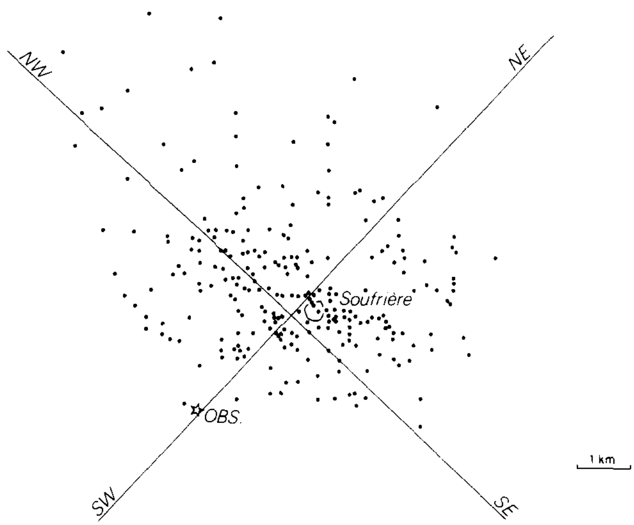


Fig. 6. Earthquake epicenter locations for the period 1975—1977. See text for details.

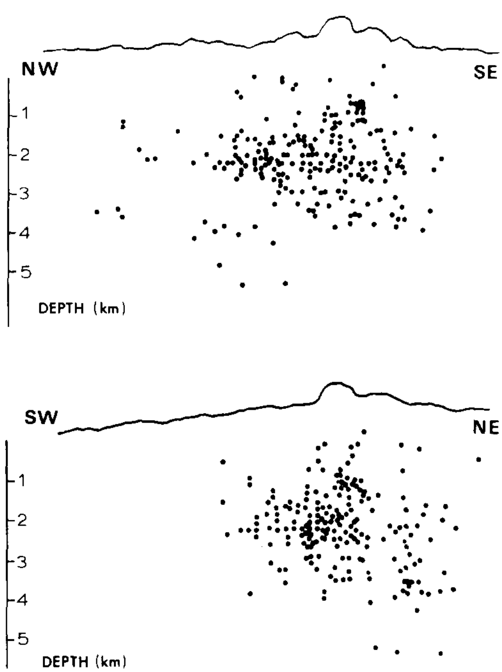


Fig. 7. Projection of the earthquake foci on the main NW—SE and SW—NE vertical sections. The maximum earthquake frequency is located between 1 and 3 km below sea level.

observation of dilation and compression of the first P arrivals on the well-calibrated temporary network. WWSSN stations further indicate for the large August, 16, 1976 event (M ~ 4.2) a normal fault mechanism associated with a large strike-slip component.

MAGNETIC OBSERVATIONS

Abnormal variations of the geomagnetic field intensity were observed during the crisis between August 1976 and April 1977 (Le Mouel, 1976; Pozzi et al., 1979). In the second half of August 1976 about 15 repeat stations were installed in an area of approximately 100 km² centered on the volcano (Fig. 8). Total field intensities were measured with a proton magnetometer on the whole network, at least every other day. Two permanent recording stations were installed, one in Fort Saint-Charles and the other, operated by a C.E.A. (Commissariat à l'Energie Atomique) team, in Matouba.

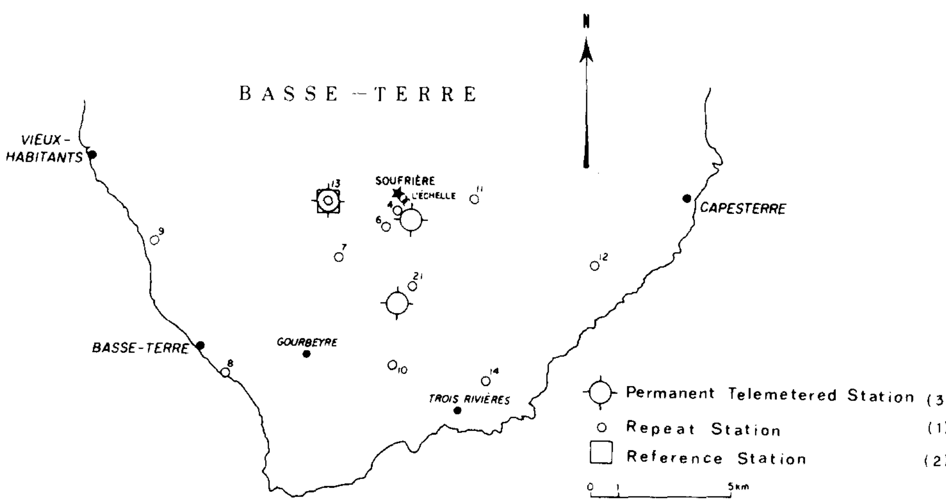


Fig. 8. Magnetic stations in Southern Basse-Terre island. During the crisis the network was composed of 15 repeat points (1) and a recording references station (2). After the crisis three permanent telemetered stations (3) were installed.

The differences between total intensities at the repeat station S_k and at the recording station O, at the same time t: $\Delta B(S_k, O,t) = B(S_k,t) - B(O,t)$ were computed. Significant ΔB variations of up to 15γ ($1\gamma = 1$ nT), were observed (Fig. 9). The non-uniformity of transient variations may account for half of the observed variations. The remaining part was attributed to volcanic activity resulting from stress-induced variations of the magnetization of rocks below la Soufrière massif. The following tentative model that fits the data has been worked out. Hydrostatic pressure variations occur in an active magma reservoir whose depth is about 6 km. Stresses induced by the pressure variations are then computed from elasticity theory. For reasonable piezomagnetic coefficients (Zlotnicki et al., 1981), the pressure variations needed to generate the observed ΔB variation are found to be of a few hundred bars.

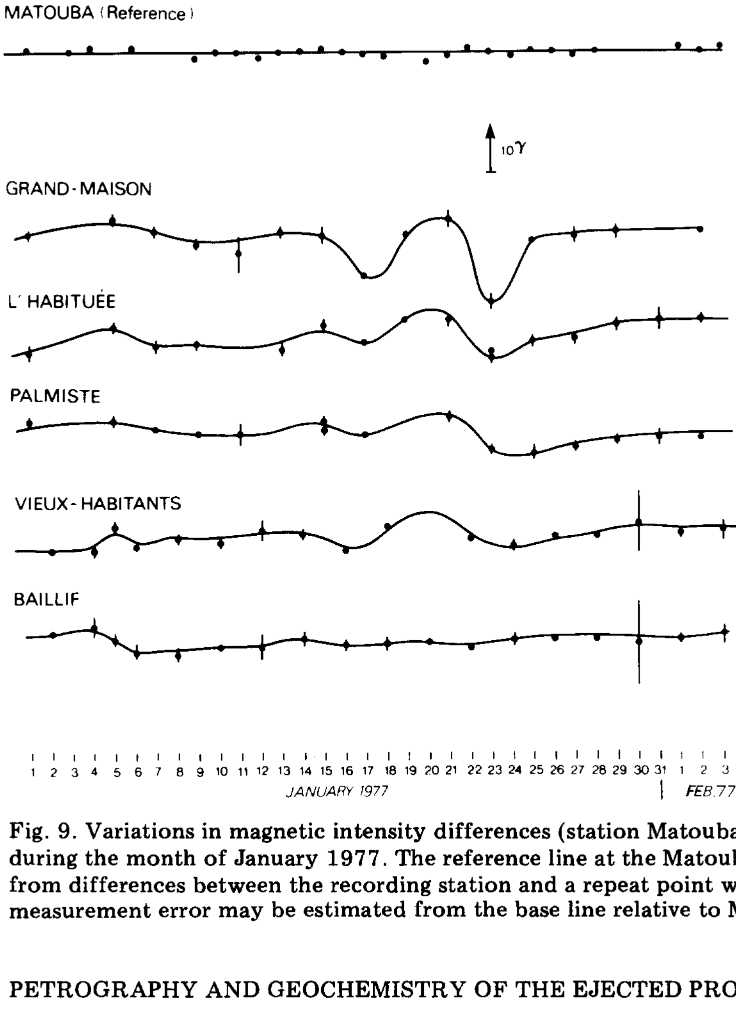


Fig. 9. Variations in magnetic intensity differences (station Matouba) for 5 repeat stations during the month of January 1977. The reference line at the Matouba station was obtained from differences between the recording station and a repeat point within 200 m from it. The measurement error may be estimated from the base line relative to Matouba.

PETROGRAPHY AND GEOCHEMISTRY OF THE EJECTED PRODUCTS

Solid ejecta of the various phases of the eruption consisted mainly of lapilli and ash with a median grain size of 10 to 40 μm. Silt and clay size particles were quite abundant whereas some of the most violent explosions projected blocks of up to several tens of dm^3 to distances of up to 1.5 km. The latter ejecta are readily attributed to fracturing and erosion of the dome fissures by the powerful gas streams of the major phreatic eruptions. Fine-Grained ash consisted mostly of variously altered fragments. A small amount of fresh (unaltered) vitreous andesite was invariably present (Semet and Shimizu, 1976) and is discussed below. Microscope examination of the tephra, combined with S.E.M. and microprobe analyses of selected samples, show them to be an inhomogeneous mixture of crystal and rock fragments variously altered to clay minerals, Ca-sulfates, pyrite, opalites and water soluble salts. Texturally the tephra are muddy or accretionary aggregates of the various components. The clay assemblage is characteristic of hydrothermal alteration in an acid medium at temperatures of 100° to 200°C and low pressure (B. Velde, pers. commun., 1977).

Leaching of the ash not affected by rainfall after deposition has shown (see below) that a variety of soluble products are present. Gypsum is sometimes abundantly present (several wt %) as a "cement" in pea-size accretionary lapilli-type ejecta. Most if not all of the soluble products are thought to represent products that were adsorbed from the gas phase during the eruptive decompression similar to what is observed for higher temperature eruptions (e.g. see Taylor and Stoiber, 1973).

Variable low amounts (<10%) of unaltered glass and glassy scoriaceous fragments is present in the tephra (Marinelli, 1976; Brousee et al., 1977; Heiken et al., 1980; Semet et al., in prep.). The reports of larger amounts of this component during the crisis resulted from confusion of clay aggregates with glass when samples were cursorily examined at the observatory. A juvenile magmatic origin of the unaltered glassy fragments, first considered, was abandoned after similar material was found in the immediate surrounding of the volcano. An accidental origin then seemed most probable.

Major and trace elements have been determined on selected bulk samples of the tephra by X-ray fluorescence and instrumental neutron activation (I.N.A) (Treuil et al., 1976). Sr and Pb isotopic composition were measured on a few samples by high-accuracy solid-source mass spectrometry (Dupré et al., 1976). Many chemical elements have variable abundances in the suite of samples (mobile elements). Others, mostly corresponding to elements that are not mobilized in alteration processes, remain quite constant (refractory elements). The relatively constant abundances of most refractory elements strongly indicate that the tephra originate from a single volcanic horizon located somewhere below la Soufrière dome. The constancy of Sr, and more conclusively, Pb isotopic composition reported in Table I also supports such

TABLE I

Sr and Pb isotopic compositions of 1976 tephra from la Soufrière and 16th century eruption samples[1]

Sample	$^{87}Sr/^{86}Sr$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
8-12-76	—	19.251	15.745	39.10
8-18-76	—	19.240	15.731	39.09
8-22-76	0.70376	—	—	—
8-27-76	0.70372	19.236	15.725	39.07
8-30-76	0.70387	19.254	15.751	39.16
Avg. 16th century	0.70377	19.174	15.674	38.88

[1] Isotopic analyses by M. Polvé-Malod and B. Dupré, Laboratoire de Géochimie et Cosmochimie, Univ. P.M. Curie, Paris 7. Average 2σ errors are 8, 20, 20, and 6 on the last decimal places for $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$, respectively.

a localized origin. Variations in the mobile element abundances are taken to be due to hydrothermal alteration processes. Semet et al. (in prep.) have modeled these variations by variable mixtures of three components: an unaltered andesite, an altered andesite, and gas condensates. Their results are summarized below. Arsenic, which is a good indicator of hydrothermal alteration, has been used to cross-correlate the other chemical elements. The unaltered rock composition obtains for As $\sim$ 0 and the altered pole for As $\sim$ 5 ppm. In the mixing model, Si, Fe, K, Ti, Cr, Co, Cs, La, Hf, Ta, Th and U behaved as refractory elements; mobile elements that were leached out in the process were (in order of decreasing mobility) Na, Mg, Tb, Ca, Al, Ba, Eu, Sr, Mn, Ce, Sc, Rb. Relatively high analytical uncertainties for Zr leave no conclusive answer; S, Sb and obviously As have been imported by the hydrothermal alteration brines. SO_4, Cl and Br behave as adsorbed components during eruptive decompression. Distilled water leaching of the tephra shows that soluble compounds of F, SO_4, Cl, K, Mn, Co, Fe and Br are present. In addition, step-wise heating of bulk samples indicates that Cl desorbs almost completely between 150° and 300° C.

The chemical composition and trace-element abundances deduced for the unaltered andesite are closer to volcanics of l'Echelle (cf. Fig. 3) than to those of la Soufrière. The source of most of the 1976-77 tephra may thus be found in hydrothermally altered underground deposite of l'Echelle.

Most of the hydrothermal transformations are compatible with alteration by a hot (150—200° C) liquid brine rich in soluble and volatile components. Sea-water contamination of the brine is probably minimal as shown by Sr isotopic compositions; tephra have a low $^{87}Sr/^{86}Sr$ of 0.7036 comparable to fresh rocks whereas sea-water ($^{87}Sr/^{86}Sr = 0.709$) addition would rapidly raise the ratio. Volatiles that acidify the thermal brines (Cl, Br, S, etc. . .) are therefore thought to be a juvenile magmatic component.

Fumarolic gases have been analyzed by gas chromatography for a number of samples taken during relatively quiet periods of the crisis (for evident safety reasons). The analyses are, however, plagued with biases introduced by reaction of the gas species in the sample vial during and after sampling (positive identification of activity related changes in composition were not obtained).

A number of easily accessible thermal and non-thermal springs around the volcano were sampled and chemically analyzed for a number of parameters. It was thought that their compositon might reflect variable volcanic activity because water tables are likely sinks for juvenile volatile constituents. Strong and systematic variations in pH and dissolved species were observed for some of the springs close to the volcano (St-Claude, Matouba, Basse-Terre) in contrast to the stable behaviour of more remote stations (Capesterre, Gourbeyre, Sainte-Rose, Vernon and Prise d'Eau). Significantly F and Cl increased during July and August, 1976 over their previous values. As was pointed out above these volatiles may have a juvenile magmatic origin.

MODEL OF THE PHREATIC ERUPTION

Geological and geochemical arguments summarized in the preceding paragraphs indicate that the last magmatic eruption at la Soufrière occurred during the 16th century and was fed from a magma chamber about 6 km below the surface. The chamber has most probably remained active since that time. The increased seismic activity, starting in July, 1975 and culminating in violent vapor and ash eruptions in July, 1976, was apparently related to modifications in the activity of the magma chamber. This may be a consequence of (1) steady-state magmatic differentiation reaching a "critical" point, (2) feeding of the superficial chamber by a new magma batch. Seismic and magnetic activity during the crisis strongly point to a source of energy located approximately at the depth of the presumed magma chamber.

Overpressures sufficient for fracture initiation must have been generated in the chamber by the pressure built-up due to differentiation or new magma injection. All the successive seismic swarms of 1975—1977 probably were similar to those of July 26 and August 16—17, 1976 for which Hirn and Michel (1979) have determined a vertical migration of foci over approximately 6 km. It seems likely therefore that these seismic swarms represent upward propagation of fractures from a depth of about 6 km; the top of the presumed magma chamber. Because upward migration occurs in a few tens of minutes to several hours, crack propagation has probably been effected by magmatic gases that eventually mixed with deep hydrothermal fluids. Injection of magma from the chamber towards the surface, if it occurred at all, must have remained of limited extent.

The subsurface structure of la Soufrière massif although not known in any detail may be imagined as a succession of strata or tongues of porous and more massive units similar to other volcanic edifices (e.g. Keller et al., 1979). A thermally activated convection system involving circulation of groundwaters and/or vapor and leading to superficial fumarolic activity must no doubt exist at depth (Norton and Knight, 1977). Except for a small number of disturbances corresponding to episodes of phreatic eruptions that have occurred over the last three centuries, convection seems to have proceeded at constant rates.

The theory of phreatic eruption mechanism has been studied by Goguel (1953, 1975, 1977). The most straightforward mechanism is one by which a heated superficial aquifer is brought out of hydrostatic equilibrium by a drop of pressure. This drop may be due to the opening of a fissure in the roof of the aquifer or other effects like geyserian activity in a water column equilibrated with the aquifer. The pressure drop will initiate vaporization of the aquifer and eventually unload deeper aquifers that may themselves be vaporized. The porous host rock is disrupted during vaporization and is entrained to form dust clouds. The eruptive phenomenon is strengthened by active heat exchange between the hot dust and the fluid somewhat similarly to pyroclastic eruption and flow (Heiken et al., 1980).

Such a mechanism is possible at la Soufrière where local thermal gradients up to several °C/m have been measured (Feuillard, 1976). It does not, however, explain fundamental aspects of the crisis which are the associated deep geophysical effects. In particular, seismic activity deeper than about 1 km cannot be due to explosive vaporization of H_2O in a context of high geothermal gradient (Goguel, 1953). We are thus led to consider a model in which disequilibrium in the superficial aquifers is brought about by rapid thermal energy transfer from a deep source.

Around July 1975, the pressure in the magma chamber underlying la Soufrière massif had increased sufficiently to induce a traction stress greater than the σ_2 compressive stress. During the time interval between July 1975 to the end of the crisis the re-opening of tensile subvertical fractures accompanied by seismic activity allowed injection of either hot fluids or less likely magma in the vapor-saturated country rocks. The propagation of fractures and energy transfer towards the surface was effected progressively until the level of the H_2O critical pressure was attained. At this stage energy transfer by a vaporization-condensation mechanism generating tremors becomes possible until an aquifer that can directly communicate with the atmosphere is affected. This is taken to have occurred for the first time on July 8, 1976, and has led to the sequence of phreatic eruptions. The time lapse between eruptions depends on deep thermal energy supply and the rate of aquifer recharge by diffusion. Note in this regard that the last phreatic eruption of March 1, 1977 had an intensity comparable to the others, indicating that the power output of each eruption mostly depends on the behaviour of the most superficial aquifers. The model readily accounts for the apparent contrast between the superficial and non magmatic origin of the eruptive material ($<$ 1 km) and the fact that it is contaminated by gases of presumed deep origin. It is also compatible with the observation that no significant ground deformation took place during the crisis; an overpressure of a few hundred bars in a 6 km deep magma chamber of radius 1 km is sufficient to initiate fractures but will not induce measurable superficial deformation. The intrusion of a relatively small magma neck comparable in size to some volcanic dykes will likewise not produce measurable changes at the surface. Differential geomagnetic effects if accountable to a piezomagnetic effect may also be explained by shallow (although deeper than a few km) stress sources that are not large enough to induce ground deformation. Most importantly the model accounts for deep seismic activity having preceded and accompanied the sequence of phreatic eruptions.

Clearly our model is qualitative. Work in progress utilizing all observations during the crisis should allow more quantitative estimates of the most critical parameters.

CONCLUSION AND POST-CRISIS DEVELOPMENTS

We have argued that the 1975—1977 crisis resulted from an enhancement of the energy supplied by the magma chamber that either reached a critical differentiation stage or was fed by a new magma batch. Phreatic eruptions resulted from transfer of this "abnormal" supply towards the surface. Had the power supplied by the magma chamber to the surrounding hydrothermal system been larger and not buffered by it, the crisis might have evolved towards a truly magmatic eruption. We therefore consider that the 1975—1977 seismovolcanic crisis was a still-born magmatic eruption.

After the crisis and following recommendations of an international panel the equipment of the Guadeloupe observatory was greatly improved (I.P.G., 1977, 1978, 1979, 1980, 1981).

After five years of continuous observation we now have a good knowledge of the volcano's behaviour in its non-eruptive state. Details will appear elsewhere. The seismic activity is never at a zero level; it is characterized by the apparently random occurrence of a few small-magnitude events per week and small crises where the number of events increases to a few per day and last a few days (Fig. 2). Fumarolic activity on top and around la Soufrière dome, although at a still lower level than in June 1977, has been continuous. A fumarole that reached about 180° C during the 1975—1977 crisis returned to the water saturation temperature (96° C) in January 1979. Gas analyses of the fumaroles show that the magmatic gas contribution to the hydrothermal system does fluctuate. The chemical composition of spring water around the massif indicate that volatile contributions from deep sources have on the whole decreased since 1977.

We think that the assesment of hazards in an impending volcanic crisis can now be made on a much more satisfactory data base.

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