Soufrière of Guadeloupe 1976-1977 Eruption – Mass and Energy Transfer and Volcanic Health Hazards (*)

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ABSTRACT

The Soufrière volcano in Guadeloupe island delivered a phreatic eruption that commenced on July 8th, 1976 and lasted until March 1st, 1977. This eruption was similar to the 1797, 1798, 1809 and 1956 outbreaks. Phreatic activity ejected blocks derived from the fissure walls and fine pyroclasts produced by hydrothermal alteration of the old dome's rocks. Field observations and measurements allowed the present authors to calculate the mass and energy transfer of steam and ashes: 10^7 tons of water (very low considering that on the mountain summit the annual precipitation is 10 tons m^2),10^6 m^3 of ashes. The most important energy transfers was thermal: about 5×10^{20} ergs for each phreatic eruption. The total kinetic energy output was 2×10^{19} ergs for a total thermal energy output of 64×10^{20} ergs.

The gases and fine pyroclasts did pollute the atmosphere, waters and soils and consequently affected the population living on the slopes of the volcano.

INTRODUCTION

The Soufrière of Guadeloupe is a strato volcano with a crater filled by a dome, located on the southern end of Basse Terre Island of Guadeloupe (West Indies, lat. 16°03′ North, long. 61°40′ West). Its top is 1467 m a.s.l. and 2560 m above the sea floor (Fig. 1, 2 and 3).

Pyroclastic flows have been emitted by the Soufrière during precolombian times but all the historical eruptions were phreatic and of short duration (a few days to a few months). The previous one occurred in 1956 when less than 10^5 m^3 of ashes and blocks were erupted (ROBSON and TOMBLIN, 1966).

During the past decades, towns and village grew closer to the top (2 km) and this created new socio-economic problems, which had to be faced during the 1976-1977 crisis.

In July 1975, abnormal seismic activity began, the intensity of which grew with time, and was eventually followed by a phreatic eruption on July 8th 1976. Haroun Tazieff organized the monitoring of these events after having identified their phreatic nature.

During July, the fractures of the old dome (over 1300 m in elevation on Fig. 3) degassed with a constant and stable steam flow of approximately 15,000 to 20,000 tons/day.

(*) Presented at the following meeting:
— Naples, 23-25 June 1977: Informal meeting on volcanic gases and volcanic hazard, disturbance on the environment.
— Durham, August 1977 workshop U.N.E.-S.C.O.: Hazard to human and animal health from toxic products of volcanic activity (Soufrière of Guadeloupe 1976-1977 eruption)
— Orsay: 6éme Réunion annuelle des Sciences de la Terre, 1978: Soufrière de la Guadeloupe éruption 1976-1977: évaluation phénoménologique.
Soufriére de la Guadeloupe éruption 1976-1977 influence sur l'environnement.

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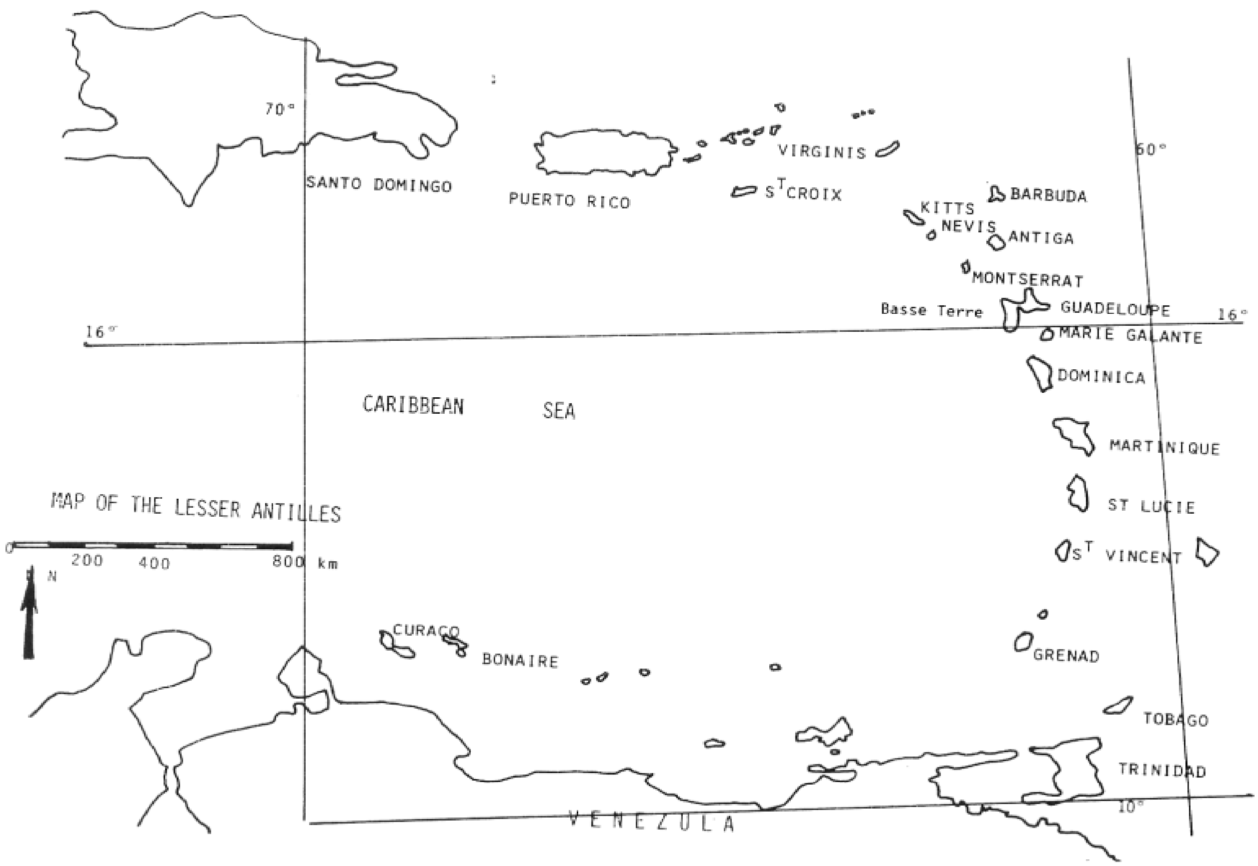

FIG. 1 – Map of the Lesser Antilles.

In August, the ash fall, recorded seisms and steam flow continuously increased; the authorities in charge at that time in Guadeloupe decided to evacuate the whole population.

Due to difficult field conditions, extremely high rainfall and lack of good field monitoring systems, a reliable quantitative evaluation of the mass and energy transfer from the volcano to the atmosphere could not be carried out.

Using field observations, photographs and testimonies collected by us and the policemen in all the area, affected by the eruption, the quantities of gas, water, ash and rocks emitted during the crisis were evaluated to within one order of magnitude, and the thermal and kinetic energy liberated during the main phreatic eruption was estimated. Through the results obtained, it was possible to establish the orders of magnitude of water and pyroclastic outputs.

These results helped to survey health hazards in the area where the population was eventually allowed to return, three and a half months after having been evacuated, but three months before the eruption end.

DESCRIPTION OF THE VOLCANIC ACTIVITY

Since the previous (1956) eruption, vegetation had grown again on the dome summit. Mild fumarolic activity was located around the «Col de l'Echelle» (Fig. 3).

The 1976-1977 crisis was characterized by a variable flow of steam and ashes, occasionally decreasing to a almost as low flow as the precrisis one (scarce fumaroles without any pressure), between the big phreatic explosions.

From July 8, 1976, to March 1, 1977, a score of phreatic eruptions occurred, each lasting up to 50 minutes, which emitted large amounts of ashed and blocks and destroyed the forest on the upper parts of the mountain.

The eruption may be divided in four successive stages:

1° – The phreatic explosion of July 8th. It occurred after one month of increasing seismic activity and was the biggest one of the whole crisis, producing more than one half of the total ash volume delivered. The steam blew out water, clays and rocks, reopening the whole system of fissures and inducing the only important «lahar» of the entire crisis (Fig. 3). On July 12th, 13th and 14th, water was still continuously blown geyserlike from the active fissures, but in decreasing intensity. It is impossible to evaluate the volume of water emitted during this phase of the eruption. The exclusively phreatic nature of this eruption was ascertained by TAZIEFF (1976) and the total unlikeliness of any nuées ardentes occurrence demonstrated. This was later ascertained by the International Experts Commission (CNRS, 1976).

2° – July, August, September. At the end of August the steam flow increased steadily. The number of recorded seisms increased rapidly to reach a maximum in mid-August: 1220 in July, 5920 in August and 1716 in September. The phreatic eruptions succeeded with increased energy and the gas flow between the phreatic events remained considerable during August, decreasing only at the beginning of September (Fig. 4).

3° – October, November, December. The seismic crisis diminished, the gas flow was moderate and dry steam was occasionally observed (184°C, SABROUX, personal communication). No phreatic eruptions occurred.

4° – January, February, March. The permanent gas flow was less important than in July, August and September but phreatic eruptions recommenced: on Juanuary 13th three explosions, in-

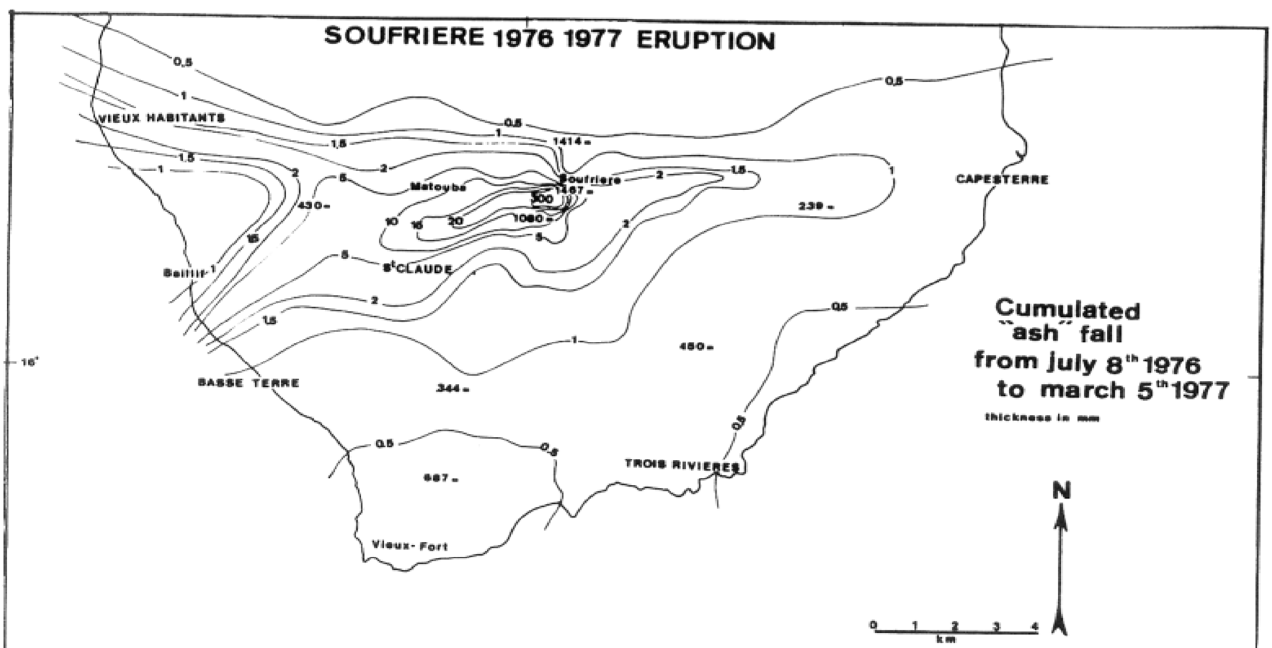

FIG. 2 – 1976-1977 Soufriére eruption: cumulated «ash» fall from July, 8th March, 5th 1977.

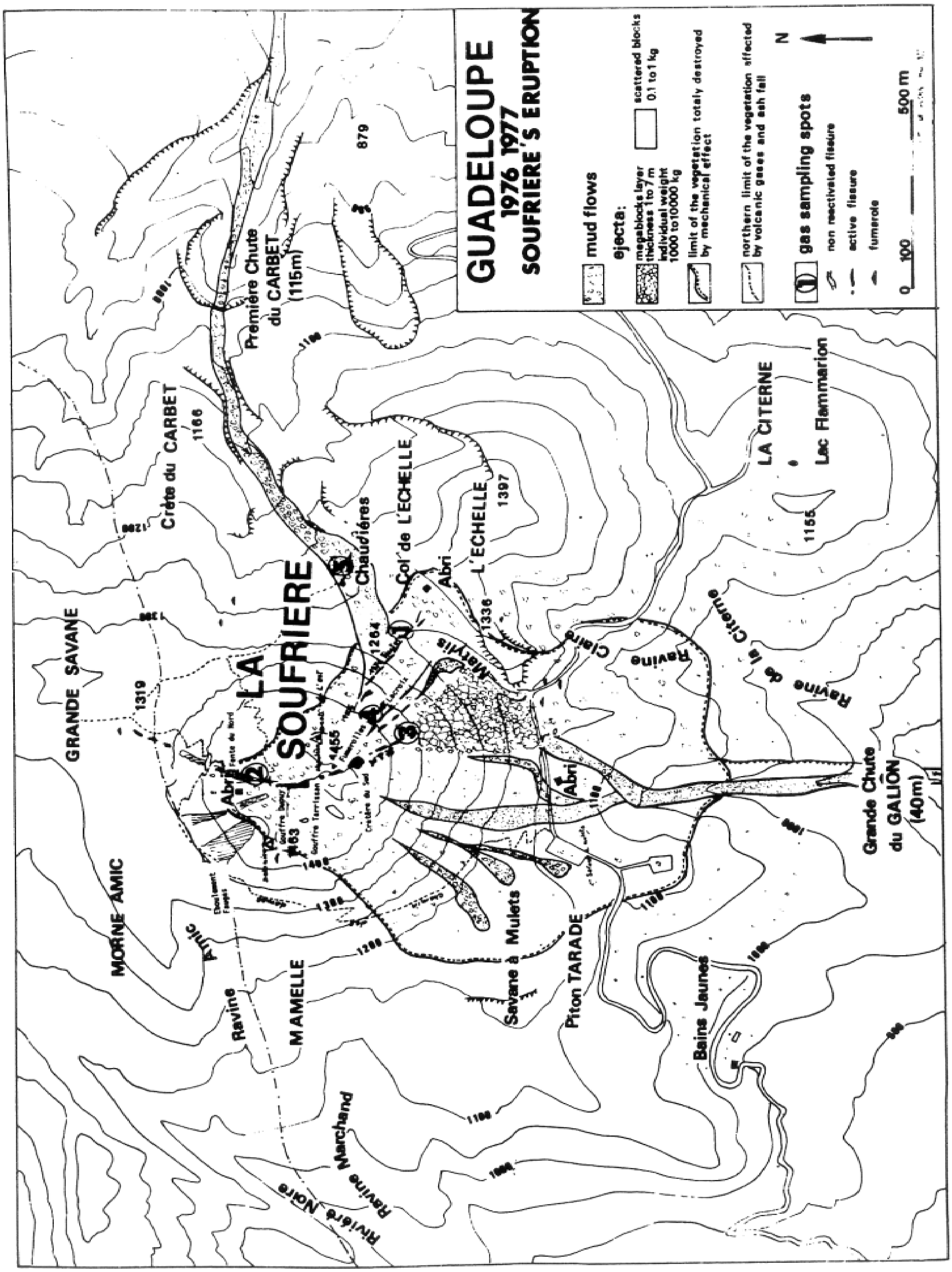

FIG. 3 – Guadeloupe 1976-1977: Soufriére's eruption.

FIG. 4 – Soufriére de la Guadeloupe: 1976-1977 eruption: diagram of phenomenology.

creasing in intensity occurred within a few hours; during this period, on January 29th and March 1st (which was the last outburst of the 1976-77 eruption), the largest (except the July 8th one) volume phreatic outbursts occurred. The 30th of August we were able once to observe from only a few meters from the eruptive vent a big phreatic eruption. It had been described by TAZIEFF (1978). The gas and fine ash emission, which had been considerable on the previous days (40,000 ton/day, Fig. 4), fell down to a few tons only few hours before the eruption. We were collecting samples on the eruptive fissures rim when suddenly the gas started to flow at high speed without any warning and reached its maximum intensity in two to three minutes with ground vibrations and strong degassing that lasted for about 13 min. (tremor were recorded by the seismographs). Twenty meters from the fissures, we were trapped for these 13 min and we could observe the phenomena. Two increases in the gas flow happened, that ejected blocks 100 to 1500 kg a piece. The first maximum flow occurred during the first half of the steam emission. The second one 6 to 7 minutes later. The violent event stopped suddenly just after this second outburst (see Fig. 4). Ash fell only during the first part of the eruption.

Clasts can be divided into fine and blocky ejections.

Fine clasts were sporadic and always occurred during high steam flows: *i.e.* phreatic eruptions or strong continuous activity (July 8, August 1976, February, March 1, 1977). Based on the field observations made by scientists as well as by policemen and inhabitants, maps have been drawn of the measured or observed ash thicknesses between July 8th 1976 and March 1st 1977, date of the last phreatic eruption. Since measurements were often carried out under poor conditions, many figures gives just orders of magnitude only.

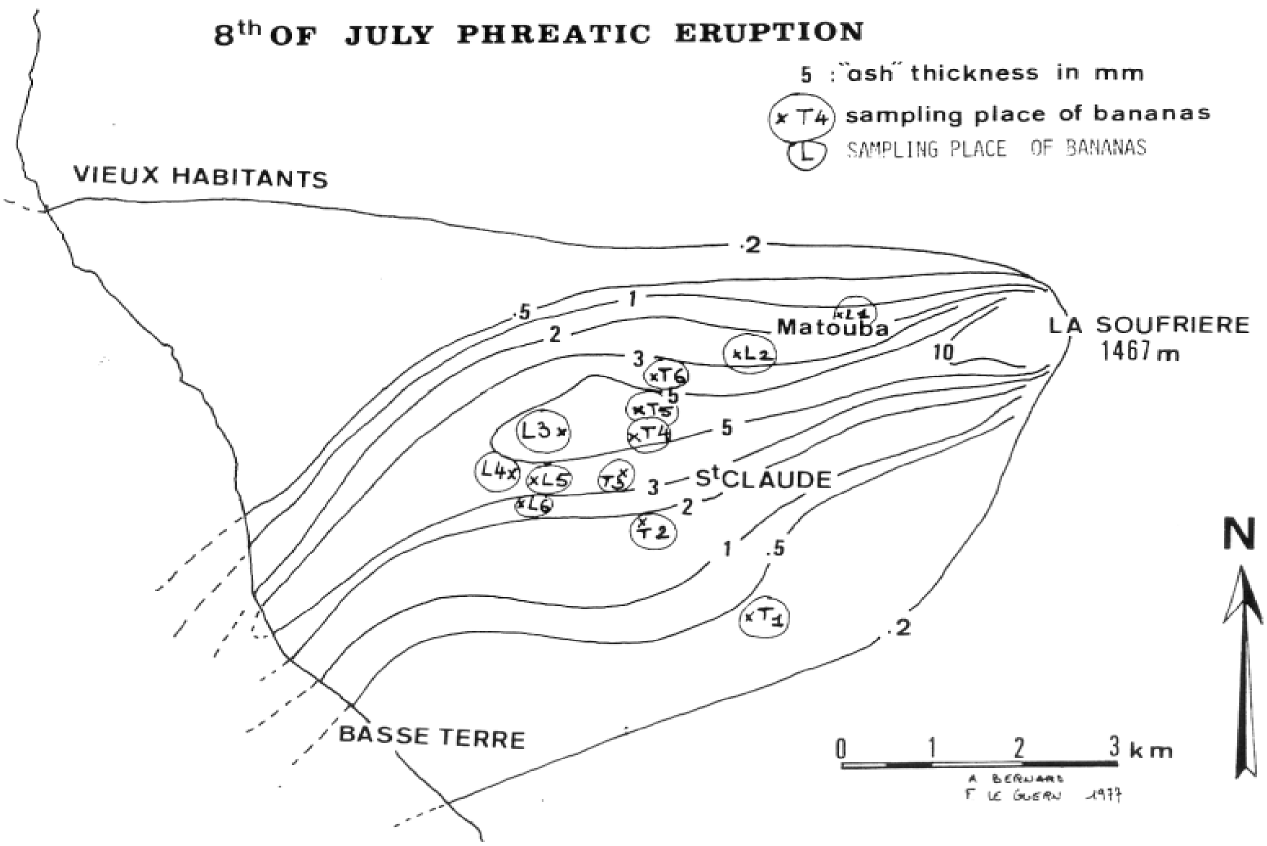

FIG. 5 - July 8th phreatic eruption.

However, these approximations provide a fair estimation of the steam and ash transfer during the crisis. By superimposing the 37 maps thus obtained, the cumulative ash fall for the 1976-1977 crisis has been determined (Fig. 2). Figures 5 and 6 give the ash thickness for individual eruptions according to reliable field observations. During phreatic eruptions, the kinetic energy of the fine pyroclasts is rapidly lost by drag in the atmosphere. The constant trade winds blew the fine particles westwards; the ashes observed south and east of the summit were carried by opposite winds blowing for few days during a precyclonic period end of August.

The error due to the lack of data concerning ash which had fallen into the sea can be estimated 10 to 15% for the bigger phreatic eruptions.

Petrological and geochemical studies of the ashes have shown them being clays produced by hydrothermal alteration of the old dome (Observation volcanologique, La Soufrière de la Guadeloupe, Nov. 1976 Avril 1977), (INSTITUT DE PHYSIQUE DU GLOBE, 1976; MARINELLI, 1976; HEIKEN *et al.*, 1976).

During the phreatic eruptions, blocks a few kgs to a few tons heavy were hurled out up to 1.6 km from the fissure reaching the «Grande Chute du Galion» (Fig. 3). They were ejected by the steam jet from the upper part of the fissure walls during the steam outbursts:

1) During two amongst the most spectacular phratic eruptions (August 30th, September 14th), the volume of the open fissure was approximately the same that the total volume of ejected blocks.

2) Observations made between phreatic eruptions inside the «Gouffre Tarrissan» showed several tenths of cubic metres wide 30 to 40 m below the surface.

3) Most of the big blocks ejected showed oxydations and pyrite deposits due to the gases.

4) During the August 30th phreatic eruption, field observations made from the «Col de l'Echelle» showed that many explosion craters opened along the fissu-

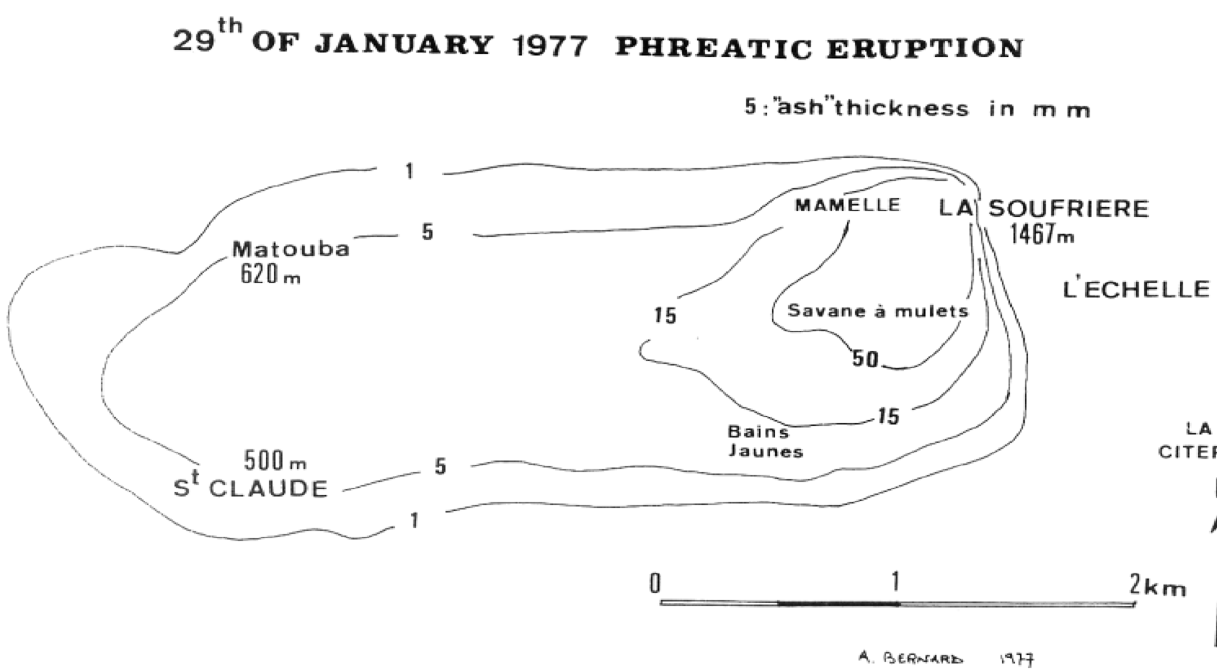

FIG. 6 – January 29th, 1977 phreatic eruption.

res and around them, in areas where nothing had been observed before because of the vegetation.

5) On numerous occasions (August 30th, September 14th, September 22nd, January 14th) fallen blocks not ash covered were observed: the ashes were always emitted during the opening phase of the phreatic eruptions.

TEMPERATURE MEASUREMENTS

Field measurements were possible only between the phreatic eruptions. The average measured temperature in the fumaroles was 96 to 97°C (boiling point of water at the considered altitude). During the crisis, dry steam over the «Col de l'Echelle» was observed in December 1976 (184°C, SABROUX, personal communication). This measurement coincides with the results obtained from geochemical studies on the ashes, and the mineralogical composition of the «ashes» ejected during the eruptions, which were clays resulting from hydrothermal alteration of rock, giving a temperature of about 200°C (TREUIL and SEMET, I.P.G., 1976). That temperature is in quite good agreement with the injuries made by hot rock pieces during the 30th of August phreatic event, to the people staying close to the «Gouffre Tarissan» (TAZIEFF, 1978).

EVALUATION OF THE MASS AND ENERGY TRANSFER

Initial Velocity of Blocks during a Phreatic Eruption

Several evaluation methods have been used:

1) Direct observation carried out from, respectively, 10 and 20 m distance at the «Gouffre Tarissan» on August 30th, gave an estimation 5 to 10 m above the ground surface of 150 to 200 m/s for block velocity (TAZIEFF, personal communication).

TABLE 1 - 1976-1977 Soufrière (Guadeloupe) eruption: Mass and energy transfer during the phreatic eruptions.

Dates	Ash volume (m^3)	Ash weight (grammes)	total blocks fall volume (m^3)	total weight of blocks fall (grammes)	weight of water in 10^9 gr.	duration of tremor (minutes)	estimated initial velocity of ejectas (m/s)
8.07.76	600 000	$1.2\ 10^{12}$	100	$2.5\ 10^8$		48	30
25.07.76					4		
9.08.76	10 000	$2\ 10^{10}$			10	11	50
22.08.76			300	$7.5\ 10^8$	13	10	90
30.08.76	10 000	$2\ 10^{10}$	600	$15\ 10^8$	19	24	100
14.09.76	2 500	$5\ 10^9$	4 000	$100\ 10^8$	22	9	130
22.09.76	3 000	$6\ 10^9$	500	$12.5\ 10^8$	19	19	130
2.10.76					3		
4.10.76							
10.10.76					10	1.3	
30.10.76					10	9	
1.11.76					5	20	
1.11.76					6	4	
14.01.77					5		90
14.01.77					6		
15.01.77	700	$1.4\ 10^9$			10	59	100
29.01.77	38 000	$7.6\ 10^{10}$	500	$12.5\ 10^8$	22	9	150
13.02.77					3		90
01.03.77	27 000	$5.4\ 10^{10}$			22		

2) Film equipement was installed at the end of August a few kilometers away from the summit. Speeds of fine particles, some 10 to 50 m above the summit were measured 70-80 m/s (HEIKEN, 1976).

3) An attempt was made to estimate the velocity from ballistic trajectories measured in the field: the distance a block is thrown in the atmosphere depends on:

- the initial velocity
- the ejection angle
- the mass
- the cross section area
- a drag coefficient, which is depended on the atmospheric density and the roughness of the projectile.

The distance of ejection was measured in the field. By estimating the four others parameters, the minimum ejection velocity can be evaluated (FUDALI and MELSON, 1971). The calculations were carried out with the data obtained in the field (Fig. 3) and the results are shown in Table 1 and 2.

Evaluation of the Steam Transfer during the Phreatic Eruptions

Lack of equipment during the crisis made it impossible to measure the speed of plume and the gas concentrations within. Neverthless, thanks to films, photographs and direct field observations, the order of magnitude of the steam ejection could be evaluated.

Technical Evaluation — The top of the volcano was usually hidden by clouds, but during some phreatic eruptions the weather was sufficiently fair to allow good photography. On September 22nd, a series of pictures was taken, one every 30 seconds (photos by Guillaume); the weather was good, windless and the plume was expanding in the atmosphere into cumulus and cumulonimbus shapes, finally stopping in equilibrium with the atmosphere. Estimate of water content in

TABLE 2 - 1976-1977 Soufriére of Guadeloupe eruption: Mass and energy transfer during the phreatic events.

DATE	KINETIC ENERGY IN ERGS			TOTAL KINETIC ENERGY ERGS	THERMAL ENERGY IN ERGS				TOTAL THERMAL ENERGY ERGS
	ASHES	BLOCKS	WATER VAPOUR		SOLIDS cp =25 cal/g	STEAM COOLING	CONDEN-SATION	WATER COOLING	
8 07 76	$1 \; 10^{19}$	$1 \; 10^{15}$			$2 \; 10^{21}$				
25 07 76						$8 \; 10^{18}$	$9.2 \; 10^{19}$	$1.1 \; 10^{19}$	$1.1 \; 10^{20}$
9 08 76	$2.5 \; 10^{17}$		$1.2 \; 10^{17}$	$3.7 \; 10^{17}$	$4 \; 10^{17}$	$2 \; 10^{19}$	$2.3 \; 10^{20}$	$2.8 \; 10^{19}$	$3.2 \; 10^{20}$
22 08 76		$3 \; 10^{6}$	$5 \; 10^{17}$	$5.5 \; 10^{17}$	$1.5 \; 10^{10}$	$2.6 \; 10^{19}$	$3 \; 10^{20}$	$3.7 \; 10^{19}$	$3.6 \; 10^{20}$
30 08 76	$1 \; 10^{18}$	$7 \; 10^{16}$	$9 \; 10^{17}$	$2 \; 10^{18}$	$4.3 \; 10^{19}$	$3.8 \; 10^{19}$	$4.4 \; 10^{20}$	$5.5 \; 10^{19}$	$5.8 \; 10^{20}$
14 09 76	$4 \; 10^{17}$	$8.5 \; 10^{17}$	$2 \; 10^{18}$	$3 \; 10^{18}$	$3 \; 10^{19}$	$4.4 \; 10^{19}$	$5.1 \; 10^{20}$	$6.3 \; 10^{19}$	$6.5 \; 10^{20}$
22 09 76	$5 \; 10^{17}$	$1 \; 10^{17}$	$1 \; 10^{18}$	$2 \; 10^{18}$	$1.4 \; 10^{19}$	$3.8 \; 10^{19}$	$4.4 \; 10^{20}$	$5.5 \; 10^{19}$	$5.5 \; 10^{20}$
2 10 76						$.6 \; 10^{19}$	$6.9 \; 10^{19}$	$9.5 \; 10^{18}$	$8.4 \; 10^{20}$
4 10 76									
10 10 76						$2 \; 10^{19}$	$2.3 \; 10^{20}$	$2.8 \; 10^{19}$	$2.8 \; 10^{20}$
30 10 76						$2 \; 10^{19}$	$2.3 \; 10^{20}$	$2.8 \; 10^{19}$	$2.8 \; 10^{20}$
1 11 76						$1 \; 10^{19}$	$1.2 \; 10^{20}$	$1.4 \; 10^{18}$	$1.4 \; 10^{20}$
1 11 76						$1.2 \; 10^{19}$	$1.4 \; 10^{20}$	$1.7 \; 10^{19}$	$1.7 \; 10^{20}$
14 01 77						$1 \; 10^{19}$	$1.2 \; 10^{20}$	$1.4 \; 10^{19}$	$1.4 \; 10^{20}$
14 01 77						$1.2 \; 10^{19}$	$1.4 \; 10^{20}$	$1.7 \; 10^{19}$	$1.7 \; 10^{20}$
15 01 77	$7 \; 10^{17}$		$5 \; 10^{17}$	$1.2 \; 10^{18}$	$2.8 \; 10^{18}$	$2 \; 10^{19}$	$2.3 \; 10^{20}$	$2.8 \; 10^{19}$	$2.7 \; 10^{20}$
29 01 77	$8.5 \; 10^{18}$	$1 \; 10^{17}$	$2.5 \; 10^{18}$	$1 \; 10^{19}$	$1.5 \; 10^{20}$	$4.4 \; 10^{19}$	$5.1 \; 10^{20}$	$6.3 \; 10^{19}$	$7.7 \; 10^{20}$
13 02 77						$0.6 \; 10^{19}$	$6.9 \; 10^{19}$	$8.6 \; 10^{18}$	$8.3 \; 10^{19}$
01 03 77					$1.1 \; 10^{20}$	$4.4 \; 10^{19}$	$5.1 \; 10^{20}$	$6.3 \; 10^{19}$	$7.3 \; 10^{20}$

clouds varies with various authors and different climates ranging from 1 to 8 g/m^3 (BRICARD, 1963; ROULLEAU *et al.*, 1958). The phreatic gas emission contains definitely more than 95% water and a low percentage of CO_2, SO_2, H_2S, CO, H_2, CH_4. The other «dry gases» can be dismissed. Assessing volumes from the photographs, it is possible to measure the order of magnitude of the water droplet content, which was estimated to be 19,000 m^3 on September 22nd.

Unfortunately, the other phreatic eruptions were not photographed because they occurred during cloudy weather, but comparisons of the damage in the field, testimonies collected, films and field slides allow to classify the different phreatic eruptions on a five degrees scale. The estimates thus obtained are shown in Table 1.

Energy Transfer — With the measurements and estimates previously described it was possible to evaluate the energy transfer with the techniques described by YOKOYAMA (1957), NAKAMURA (1974) and FUDALI and MELSON (1971).

Thermal energy transported by one gram of ejecta:

$$E_{\text{ths}} \text{ (erg/s)} = T \times C \times J$$

where: T is the temperature difference between the ejecta and the atmosphere in °C;

C is the specific heat (0.25 cal/g/°C);

J is the thermal equivalent of calory (4×10^7).

Thermal energy trasported by the gases (water vapour):

Water represents far more than 95% of the gases emitted during the phreatic eruptions. The superheated steam has a specific heat of 0.5 cal/g/°C (GOGUEL, 1953). If we assume that the temperature of emission is 200°C as described before (TREUIL and SEMET in IPG, 1976), the cooling of the gases provides 0.5×100 calories per gram of water vapour (SETTLE, 1978) or $0.5 \times 100 \times 4 \times 10^7$ ergs. Heat of vaporisation of water is 580 cal/g, the thermal energy used in vaporisation can only be recovered by condensation of steam partially compensated by the mixing of air into the column during condensation (WILSON, 1976; WILSON *et al.*, 1978) the condensation of one gram of steam provide: 580 cal or $580 \times 4\ 10^7$ ergs. The cooling of the plume to 28°C provides about 72 calories per gram or $72 \times 4\ 10^7$ ergs/gram to the atmosphere: so we obtain the thermal energy calculated in Table 2.

Kinetic energy:

The kinetic energy can written: $V^2/2$ in erg/s, V being the initial speed of ejecta in cm/s. Table 1 shows the results obtained for the different phreatic eruptions: the thermal energy reached 10^{19} to 10^{20} ergs.

During the crisis, the energy of the different phreatic explosions increased (Table 2), due to the opening of the fissures and or to the deepening of the phreatic eruption sources. In the field, it was observed that ash emission occurred exclusively during phreatic eruptions. The fast decompression of hot, porous, water impregnated ground, has been described in detail (GOGUEL, 1953) and is a satisfactory model for the interpretation of phreatic crises of this nature.

VOLCANIC HEALTH HAZARDS

Before and after evacuation, in July, August and December 1976, January and February 1977, the population living near the summit of La Soufrière suffered from the harmful effects of the erupting volcano:

— the atmosphere was contaminated by sulfuric gases and fine dust;

— condensates from the ashes dissolved in the drinking water;

— crops were damaged or destroyed in the fields and cattle feedstuffs at times contaminated.

What were the origins of these contaminations and how can they be controlled?

Atmospheric Contamination by the Volcanic Gases

The previous evaluations give 10^7 tons of water emitted during the crisis. from an analysis of the composition of the gases emitted from the fissures, it is possible to evaluate that the amount of carbon dioxide and sulfuric gases represent 1 to 5% of the total gases, water being 95 to 99%.

In July 1976, the population in St Claude complained of headaches and insomnia, due to sulfuric gases.

S.T.E.P.A.M. and C.N.R.S. teams measures the atmospheric concentration by pumping air through reactive tubes for one to two hours. The results obtained are shown in Table 3. The major problem was to establish whether such permanent concentrations would prove hazardous to the health of the population.

Table 4 shows the olfactive threshold, the lethal dose, and the maximum permanent concentration allowed. On active volcanoes, the main atmospheric contaminations are due to sulfuric gases: SO_2 and H_2S; chlorine and fluorine. In Guadeloupe, only the sulfuric gases were sufficiently concentrated to cause pollution. In the comparison of Table 3 and 4, the following comments can be made:

— for H_2S, the olfactive threshold is the same as the maximum concentrations permanently acceptable (Germany, U.S.A., U.S.S.R. in Table 4). In Guadeloupe, the measured concentrations are sporadically above these values.

— SO_2 is present in the gases emitted from the summit, but its concentration in the atmosphere is negligible.

Gases created discomfort for the popu-

TABLE 3 – H_2S atmospheric concentration in urban area.

Date	H_2S (ppm)	Sampling site and remarks
7/19/76	0.2	St Claude
7/20/76	0.05	"
7/21/76	0.04	"
7/22/76	0.06	"
7/26/76	non detectable	population complained about a headhache and a strong SO_2 odour
7/27/76	0.1	St Claude
7/29/76	0.004	a strong SO_2 odour.
8/05/76	0.16	population complained about a headhache
8/08/76	0.16	St Claude
8/09/76	0.15	some people had breathing difficulties
8/13/76	0.10	Matouba
8/14/76	0.10	Matouba
8/21/76	80	SO_2 20 ppm, CO 2 ppm : analyses carried out on the summit of the volcano, working site of the scientific team.

TABLE 4 - Information on toxics (gases).

Gases	Olfactive threshold (ppm)	Lethal dosage (ppm)	Working site standards (7 to 8 hours per day and 40hours per week)			Permanent atmospheric standards	
			U.S.A. (ppm)	U.S.A. (mg/m^3)	U.S.S.R. (mg/m^3)	Germany (ppm)	U.S.S.R. (ppm)
SO_2	3.4	400	5	13	10	0,2	0,5
H_2S	0,1	700	10	15	10	0,1	0,03
Cl_2	0,02	900	1	3	1	0,1	0,1
CO_2	odourless	200.000	5.000	9.000			
CO	odourless	30.000	50	55	20		6
HCl			5	7		0,5	
F					0,03		

lation and oxidised paintwork and metal (telephones were damaged by oxidation of the switches).

Atmospheric Contamination Due to the Dust

The maximum «ash» emission occurred on July the 8th 1976 when 6×10^5 tons of ash were emitted, *c.f.* 10^6 tons for all the eruption (1976-1977). This dust, produced by the hydrothermal alteration of the volcanic rocks of the «old dome of La Soufrière, upset transport and agriculture. Certain people in the villages nearest to the summit, where we were living, experienced breathing difficulties. The disturbance were both mechanical (small in dimension) and chemical (high sulfate content).

Contamination of the Drinking Water

La Soufrière is 1,460 m a.s.l., with high annual rainfall (10 m) on the summit. The water for the surrounging villages and towns is impounded from the volcano itself.

This water has different origins:

1) Condensation of steam from the active volcanic fissure. During the daily gas collections, water was collected by condensation of steam. Analyses were carried out on the spot (Table 5). There were important fluctuations in composition, and a decrease in pH was observed during the first days of the crisis (July 1976). After the destruction of the collection system during the phreatic eruption on August the 22nd and 30th, we visited the fissures less frequently.

2) Matylis river (Fig. 5): this river, which flows down from the Col de L'Echelle, gathers water flowing down the Dome, as well as condensates from the fissures. The water is very acid, with a high sulfur and chlorine content. The drinking water impounded one to two kilometers below the summit is sufficiently diluted by rain water to eliminate the effect of condensate from the summit.

3) Water from impounds: contamination of impounds is most serious, since it occurs after the ash falls when the rain water is in contact with the condensates and sublimates adsorbed on the surface of the fine particles. Results of analysis are scarce; some example are given in Table 6. After the January ash fall, the pH reached unacceptable values for drinking water and acidic water began to dissolve drain tubes leading to the reservoir. The only way to prevent these disturbance was

TABLE 5 – Results of water analysis on the summit of Soufriére volcano.

	Condensation of "Echelle" steam				"La Matylis"				"Bains Jaunes"			
DATE	S total : équivalent SO_2 mg l^{-1}	Cl^- gl^{-1}	F^- mg l^{-1}	pH	SO_2 mg l^{-1}	Cl^- mg l^{-1}	F µl^{-1}	pH	SO_2 mg l^{-1}	Cl^- mg l^{-1}	F^- µl^{-1}	pH
14.7.76	700	11,9		1,1								
15.7.76	700	5,3		2,4								
16.7.76	580	3,9	2,5	3,2								
17.7.76		qq ppm		4 à 5								
18.7.76				4 à 5								
19.7.76				4 à 5		9.6 10^3		1				5
20.7.76	320			5		13.7 10^{+3}		1				5
21.7.76	390	49 10^{-3}	0,2	4 à 5		16.9 10^{+3}		1		65		5
22.7.76	390	25 10^{-3}	0,16							60		5
23.7.76	190	7 10^{-3}	0,4	3 à 4	150					62		5
24.7.76												
25.7.76	320	11 10^{-3}		3 à 4		1.7 10^3		2 à 3		60		5
26.7.76				3 à 4	510	0,71 10^3		4				5
27.7.76		23 10^{-3}		3 à 4	1800	15,2 10^3		1		60		
28.7.76		12 10^{-3}		1 à 2	2600	24,9 10^3		3	< 25 mg/litre	60	5 10^{-5} µl^{-1}	5
29.7.76	320	26 10^{-3}	1,6	4	1900	25,5 10^3		1				
30.7.76	510	11 10^{-3}		4 à 5		9,9 10^3		2 à 3				
31.7.76	900	55 10^{-3}	0;3	4	2200	28 10^3		1		58		5
1.8.76	260	52 10^{-3}	0;14	4	2100	20,6 10^3		1 à 1.5		61		5
2.8.76	280	213 10^{-3}			2000	13,5 10^3		1,5 à 2		61		5
3.8.76	115	26 10^{-3}		3	1100	94		5		58		5
4.8.76	510			2à2,5		2,5 10^3		3		59		5
5.8.76	1400	131 10^{-3}		1,5à2	1100	14 10^3		1,5 à 2		56		5
6.8.76												
7.8.76	320	9 10^{-3}		5								
8.8.76					960	1,1 10^3		1 ,5		60		5
9.8.76	130	6 10^{-3}	1,0	4,5	700	2,52 10^3		4,5		59		5
10.8.76												
11.8.76	64	5 10^{-3}	0,2	5		5						
12.8.76	51											
13.8.76					2200	10 10^3		4		56		
14.8.76	290	3 10^{-3}	0,4	2,5								
15.8.76	150	3 10^{-3}	0,4	2,5								
16.8.76												
17.8.76	51			5								
18.8.76												
19.8.76									< 25 mg/litre		5 10^{-5} µl^{-1}	
20.8.76												
21.8.76												
22.8.76	Sampling tube destroyed by a phreatic eruption											
23.8.76	160			3,5								
24.8.76	380	79	0,6									
25.8.76	150	0,7	0,12									
26.8.76	64	4,6 10^{-3}	0,08									
27.8.76	260	4,6 10^{-3}	0,76									
28.8.76		3,5 10^{-3}	0,03									
29.8.76												
30.8.76	Sampling probe destroyed by a phreatic eruption											
31.8.76												

to collect water on the neighbouring mountains unaffected by «ash» falls.

4) contamination of cistern water: accumulating «ash» from one phreatic eruption to another rapidly made the water undrinkable and of no use for agriculture.

Contamination of Crops

The following phenomena occurred in the zone affected by the «ash» falls:

— mechanical effects: on the summit vegetation was totally destroyed by rocks falls.

— chemical effects: on the summit vegetation was destroyed by acid gases.

At the beginning of the eruption, an attempt was made to detect fluorine contamination. Fluorine content is very low in the Soufrière volcano gases, but it is detectable in condensates from the fumaroles (Table 5) and in the ashes (Table 7). In July 1976, we collected banana fruits and leaves in the zone affected by the phre-

TABLE 6 – Water analysis: sampling in the water-catchment stations around Soufrière volcano.

Date			4.03.77	4.03.77	28.02.77	7.03.77	7.03.77
Place			Morne Houel	Gourbeyre	St Claude*	St Claude*	"Gourbeyre"
Aspect			Clear	Clear	Slightly opalesc.	Slightly opalesc.	Clear
Turbidity			14	15	32	38	13
Odour			Odourless	Odourless	Odourless	Odourless	Odourless
Resistivity Ω /m			720	1460	1900	1530	1280
pH			7.2	5.6	7.3	6.0	5.1
Oxidability with heat O_2 KmO_4		mg/l	0.6	0.4	0.4	1.0	0.6
Ammoniac Nitrogen	N	mg/l					
Nitreous Nitrogen	N	mg/l					
Nitric Nitrogen	N	mg/l	< 0.5	< 0.5	< 0.5		
Alkalinity	CaO	mg/l	8	3.5	10	3.4	1.4
Chloride	Cl^-	mg/l	105	55	28	46	75
Sulfate	SO_4^{--}	mg/l	700	265	200	275	340
Total Hardness (French degree)			83	33	27	35	44
Silica	SiO_2	mg/l	53	78	72	60	69
Free Carbonic Gas	CO_2						
Sodium	Na^+	mg/l	34	28	22.8	21.5	26
Potassium	K^+	mg/l	9.6	6.2	5.4	5.4	7.6
Cyanide	CN^-	mg/l	0	0	0	0	0
Fluorine	F^-	mg/l	1.14	0.22	0.38	1.14	0.505
Reduced Sulfide	S^{2-}	mg/l	0.8	0.6			
Sulfide	S^{2-}	mg/l	0.07	< 0.01			
Thiosulphate	S^{2-}	mg/l	0.2	0.16			
Sulfites	S^{2-}	mg/l	0.00	0.00			
Sulfur	S^{2-}	mg/l	0.25	0.20			
Mn		g/l	1.24	1.60		0.6	
Ba		g/l	2.5	1.0	< 0.5	0.8	1.2
Sc		g/l	0.30	< 0.05		0.10	0.07
Hg		g/l	< 0.3	< 0.3	0.0004	0.3	0.3

* Morne Houel

atic eruptions of July the 8th (Fig. 3). The analyses were undertaken at the Centre d'Etude Nucleaire de Grenoble (GARREC *et al.*, 1977; FAIVRE PIERRET *et al.*, 1977). The results are summarised in Table 8. The banana pulp contained only 0.7 µg of fluorine per gram of dry material, the fluorine being dangerous over 30 µg per g of dry material (Fluor et Santé, Organisation mondiale de la santé, série monographie N. 59, 1972). For the fluorine content of the leaves, it might be necessary to carry out analysis outside the zone affected by the eruption, to establish the ordinary fluorine contribution from the volcanic rocks in the soil. Nevertheless, ash falls caused black spots on the peel, which made the bananas unfit for marketing.

However, all the seedlings were destroyed by the ash fall during the phreatic eruption before they could be transplanted. This affected the market gardeners of Matouba Papaye, unable to harvest their crops while the neighbouring volcano remained active. Four head of cattle died through lack of water after grazing grass covered with ash.

TABLE 7 – Fluorine content of ash samples.

Samples	Sampling site			Fluorine content in ppm (mgF/Kg of dry material)
77/15	Papaye	ashes	1/05/77	692
77/25	Savane à Mulet	"	1/29/77	725
134	Dôme summit	"	2/13/77	625
141	Chemin des Dames	"	3/01/77	537
131	Papaye		2/08/77	550
140	Parnasse		3/01/77	800
143	Valeau	ashes	7/08/76	625
144	Valeau	"	1/29/77	690

CONCLUSIONS

The 1976-77 eruption was an exclusively phreatic one. The endangered area had a radium smaller than 1 km.

The order of magnitude of ash, rock, and gas flows provides an idea of the true impact of the eruption: 10^6 m^3 of ash represents a cube of $100 \times 100 \times 100$ m. If this volume is distributed along a fissure 700 m long and 3,000 m deep, it is only 46 m wide. The water output of 10^3 tons is very small, specially if it is taken into account the fact that on the top of that mountain the annual precipitation is 10 tons per square meter.

The 1976-1977 crisis was similar to the historical Labat eruption of 1969; the steam and ash ejections described re-

TABLE 8 – Fluorine content in the bananas. µg per g of dry material.

Sampling site	Description	Fluorine content
L1	Banana leaves	30
L2	"	30
L3	"	8
L4	"	35
L5	"	18
L6	"	20
T1	"	16
T2	"	19
T3	"	27
T4	"	22
T5	"	32
T6	"	33
	Banana pulp	24
	Banana peel	7
8127	Volcanic ash	727

Banana leaves = 4th leaf of each banana

semble the August 1976 activity. In 1797, a phreatic eruption occurred on September 29th, the activity culminating with the explosion of April 26th, 1798, which opened the «Eboulement Faugas» similar to the opining of fissures observed from the «Col de l'Echelle» during the August 30th 1976 phreatic event. On December 3rd 1837, a big phreatic eruption began, ending on February 12th 1838, with considerable ash emissions and mud flows on the summit, similar to the «lahar» and «ashes» produced by the first July 8th of the 1976 eruption. In 1809 and 1956, small eruptions were observed, similar to the November December 1976 activity (BARRABÉ and JOLIVET, 1958).

However, because of the population expansion over the slopes of the volcano past centuries, minor problems developed into serious ones. Volcanological riscks usually take into account only destruction due to violent eruptive activity but problems connected with a population living in the vicinity of strong fumarolic activity are usually neglected. The considerable increase in population in the volcanic areas during the past decades must be taken into account and, as shown in Guadeloupe, populations can be affected even by a moderate volcanic activity. Monitoring can be carried out with techniques used to survey urban and industrial pollution. In France, however, legislation only stipulates acceptable values at the source of pollution, without defining a threshold for general atmospheric pollutions for a heterogeneous population, as it is the case in Germany or the U.S.S.R. It is very difficult to obtain continuous measurements in the crater of an active volcano. The experience of the Soufrière 1976-1977 eruption has stressed the importance of being prepared for a similar situation by adapting agriculture to volcanic activity and impounding water from a zone non affected by the volcanic activity.

TABLE 9 – Report, Volcanological Mission to Soufriere Volcano (13-24 July 1976) by H. Tazieff

The aim of our mission was to carry investigations on the volcano in order to provide the administrative authorities with reliable information allowing them to decide what precautions to take.

Mainly chemical, these investigations have provided information which compared with the seism logical information and with the phenomelological one allowed to forecast an almost certainty that no immediate eruption was to be feared.

The arguments for such diagnostics were as follows:

1. Historical argument.
   - 1.1. Lack of any violent historical eruption of the Soufrière.
   - 1.2. Occurrence of volcano seismic crisis, sometimes frightening ones, in the Caribbean, without any eventual eruption (*e.g.* Montserrat).
2. Geological argument.
   Comparatively small (less than 25%) proportion of nuées ardentes or pumice flow deposits in the Soufrière edifice.
3. Volcano-seismic argument.
   - 3.1. The seismic crisis that started in July 1975 and did not stop for more than one year, sometimes highly active (up to 600 shocks a month), sometimes comparatively quiet, has not been affected by the 8 July 1976 eruption event which seems tranquillizing.
   - 3.2. Focal depths, as calculated by the I.P.G. Paris, are between six and two km deep. If we assume a possible error of 1 km, hypocenters are located at the top of an ascending magma column, because the Soufrière's andesitic magmas are very viscous ones,

several months at least, more probably several years be necessary to allow this column to reach the surface.

4. Eruptive mechanism arguments.
   4.1. 8 July 1976 outbreak was very short: approximately 20 minutes.
   4.2. This outbreak occurred through the same fissure that the XIXth century and the 1956 ones, none of which proved terrible. One is therefore allowed to hope that the further outbreaks will not be different.
   4.3. The outbreak that generated an «ash» plume and broke an appreciable volume of rocks, seems to have been due to a subinstantaneous vaporization of ground water and by the sudden expansion of magmatic gases.It is most probable that this eruption was a phreatic one.
   4.4. Plants killed by the eruption, as observed on either sides of the eruptive fissure, show that the gas temperature was low, not over boiling water temperature. Consequently, it is assumed that the proportion of possible high temperature magmatic gases was quite small as compared to the amount of water steam.
   4.5. The «ashes» emitted were old rocky matter exclusively, without any fresh lava at all. As noted by F. Le Guern, these ashes are most probably clays (fumarolized rocks) torn off the fracture's walls by high speed steam.
   4.6. The estimated output of the gas-water mixture emitted through some vents of the eruptive fissure is continuously decreasing.
   4.7. The acidity of water emitted at a constant 95°C temperature is spectacularly decreasing:

	pH
14 July	1.1
15 July	2.0
16 July	3.0
17 July	4.6

   4.8 The gas composition.

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Ms. received Feb. 1979; sent to review Feb. 1979. Revised ms. received May 1980.