Guadeloupe

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Abstract

The volcanic island of Basse-Terre, which is part of Guadeloupe, consists of 7 main eruptive fields each composed of several volcanic centres. Based on current data, the Grande Découverte-Soufrière volcanic complex is the only centre to have been active in the last 10,000 years. The last magmatic eruption, which occurred about 560 years ago, was a complex eruption that had many similarities with the ongoing Soufrière Hills eruption on Montserrat. It culminated in the formation of the current Soufrière dome. All historical hydrothermal activity and the six phreatic explosive eruptions of 1690, 1797-98, 1812, 1836-37, 1956 and 1976-77 AD have taken place from fractures and vents on this dome. La Soufrière of Guadeloupe is a well-monitored active volcano located within the Parc national de la Guadeloupe and just 5 km N of the town of Saint-Claude (population 10,000). In the last decade the volcano observatory has recorded a systematic progressive increase in shallow low-energy seismicity, a slow rise of temperatures of some acid-sulfate thermal springs closest to the dome, and, most noticeably, a significant increase in summit fumarolic activity associated with HCl-rich and H_2S acid gas emanations. Permanent acid degassing from two summit high-pressure fumaroles has caused vegetation damage on the downwind flanks of the dome and required closure to the public of parts of the most active areas since 1999. No other anomalous geophysical signals have been recorded. Apart from the most likely phreatic eruptions, dome eruptions generating pyroclastic flows (7 in the last 15,000 years) and partial edifice-collapses generating debris avalanches and blasts (10 in the last 15,000 years) represent the major eruptive events most likely to occur in the future from the Soufrière dome area. Such events would directly threaten about 72,000 people and cause widespread destruction to most of southern Basse-Terre, and require a total evacuation. The region and nearby islands could also be affected by ash fall and tsunamis.

Introduction

Much of the information in this contribution has been compiled from past studies of Soufrière of Guadeloupe volcano which have been carried out mainly in the last 25 years by numerous researchers from different universities in France under the leadership of the Institut de Physique du Globe de Paris (IPGP), by the Bureau de Recherches Géologiques et Minières (BRGM) as well as by a few international scientific teams. Funding for this work has come primarily from various sources of the French Government, the European Community, as well as local Caribbean funding agencies.
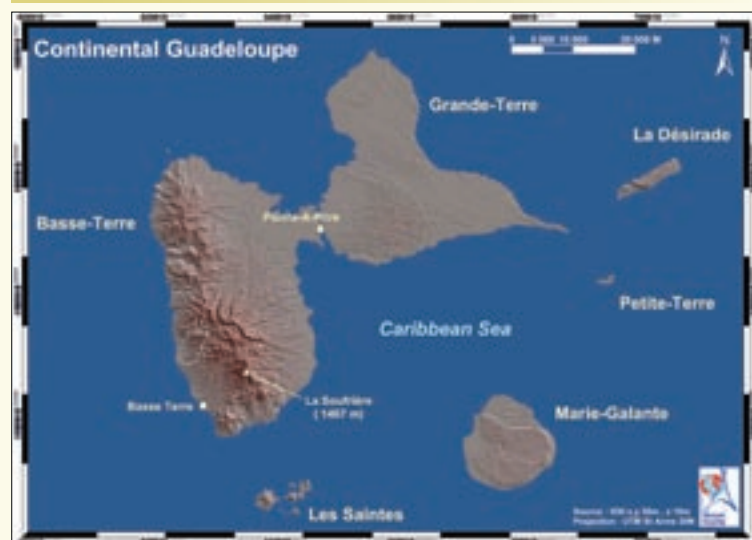
Geographical setting

The island of Guadeloupe is situated in the central region of the Lesser Antilles. It is one of the four overseas departments of France (Guadeloupe, Martinique, Guyane, La Réunion). Administratively Guadeloupe consists of 9 different islands (Basse-Terre, Grande-Terre, La Désirade, Petite-Terre, Marie-Galante, Terre-de-Haut, Terre-de-Bas, Saint-Barthélémy, Saint-Martin) with a total surface area of 1703 km^2 and a total population of 438,500 and a demographic density of 258 inhabitants/km^2. A natural marine channel, the Rivière Salée, separates the largest two islands of the archipelago, Basse-Terre (848 km^2) and Grande-Terre (590 km^2). Basse-Terre, the highest island of the Lesser Antilles with the active Soufrière of Guadeloupe volcano (1467 m a.s.l.), and Les Saintes (309 m a.s.l.) are mountainous islands formed entirely of Tertiary and Quaternary volcanic rocks. Grande-Terre (135 m a.s.l.), Marie-Galante (204 m a.s.l.) and Petite-Terre islands are composed of Pleistocene reef limestones overlying an older pre-Miocene volcanic substrate. La Desirade island (273 m a.s.l.) forms a tilted limestone elongated plateau of lower Pliocene age overlying Upper Jurassic or Lower Cretaceous igneous rocks. The islands of Saint-Barthélémy and Saint-Martin are located 200 km NW of Guadeloupe sensu strictu and just North of Saba and Saint Eustatius, the northern-most active volcanoes of the Lesser Antilles arc. They consist of Tertiary volcanic and plutonic rocks of Lower Eocene age locally overlain by younger Tertiary limestone platforms.

Previous work

The geology of Guadeloupe has been the subject of a vast number of general as well as detailed studies (see bibliography, and references therein). The earliest descriptions of La Soufrière volcano date back to the discovery of Guadeloupe by C. Columbus in his second voyage to the Americas on November 4, 1493 as related by Dr. Chanca, member of the second voyage (Chanca 1494). In this text, Dr. Chanca describes the impressive Chute du Carbet waterfalls as viewed from his ships stationed a few kilometres out in the Caribbean Sea SE of Guadeloupe. He also describes a high peak in the middle of the volcano as viewed from the SE, which could be interpreted to indicate that the volcano's morphology was different at the time of Chanca's observations compared to the current view, due to some unknown modifying event that would have occurred since 1493 AD. Unfortunately, there are no descriptions of the volcano between 1493 AD and the arrival of the first settlers in 1635 AD. Despite what has been sometimes interpreted in the past, there is no clear mention in

Shaded relied map of Guadeloupe (data © IGN)
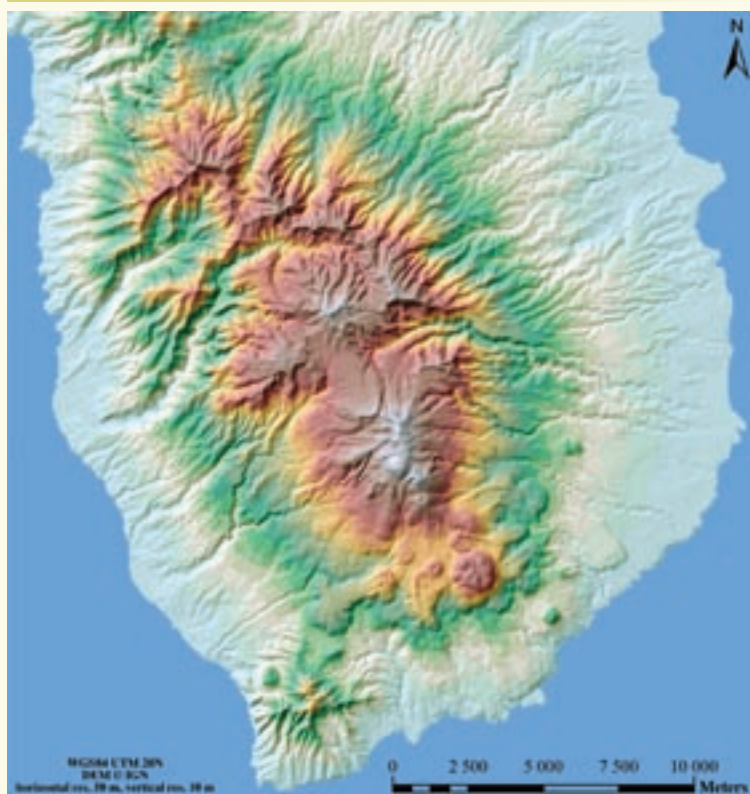
this early record of any residual fumarolic activity that may have been related to the last magmatic eruption of the volcano dated at 1440 AD.

The various missionaries that came to Guadeloupe after colonization in 1635 provided additional descriptions of the volcano (Breton 1647; Breton 1665; Du Tertre 1654; 1667-1671) and the fumarolic activity at the summit (Labat 1732). These early descriptions were followed by numerous other written accounts (see section on Historical eruptions) and geological investigations (see Bibliography). The first geological map of Basse-Terre was published at a scale of 1:50,000 by De Reynal de Saint-Michel (1966).

Overall there exists a good knowledge of the general geology of the different islands of Guadeloupe, which is synthesised in revised geological maps published by the BRGM at scales ranging from 1:20,000 to 1:50,000 since 1979. Additional geological work is presently being undertaken by researchers at the Institut de Physique du Globe de Paris and the Université d'Orsay. The paucity of rock exposure, the extensive vegetation cover, significant relief, the deeply dissected drainage network and lack of road access renders detailed mapping and studies of the volcanic geology of Basse-Terre very difficult.

The geologic map of the volcanic island of Basse-Terre at a scale of 1:50,000 (de Reynal de Saint-Michel 1966) is now obsolete; the BRGM is thus considering preparing a new map in the near future, in collaboration with several university research teams. The volcanic geology of Guadeloupe is known in detail at a scale of 1:20,000 only on the Grande Découverte-Soufrière volcanic complex (Boudon et al. 1988) and on the islands of Les Saintes (Jacques and Maury 1988). However, numerous studies have been carried out locally on volcanic rocks of southern Basse-Terre (see Bibliography, references therein). Recently Bissainte (1995) completed a d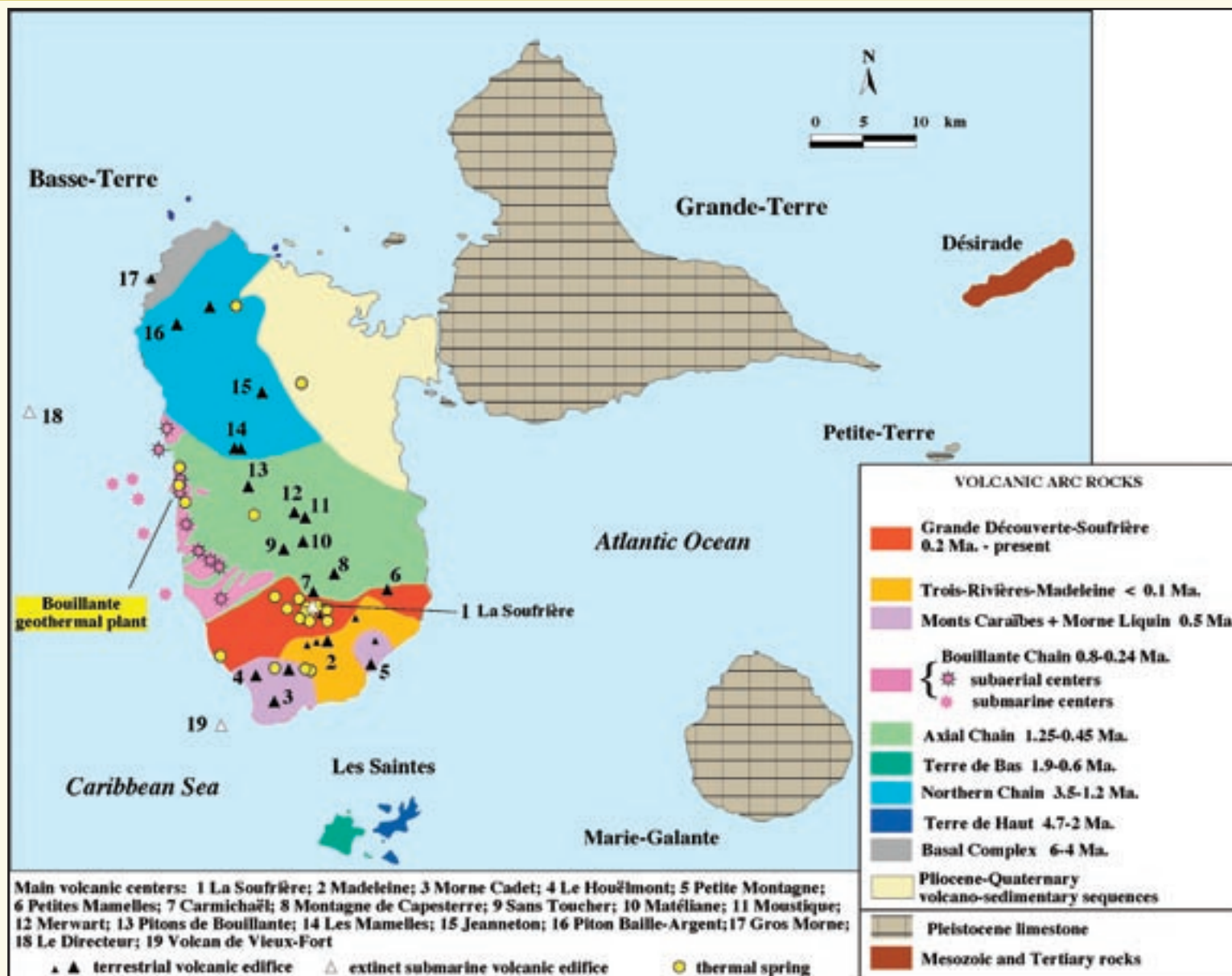etailed study of the Monts Caraïbes volcanic complex of southern Basse-Terre. Feuillet (2000), Feuillet et al. (2002), and Feuillet et al. (2004) have studied in detail the structural geology and tectonics of Guadeloupe.

Geology

The islands of what is called "Continental Guadeloupe" (Grande-Terre, Basse-Terre, La Désirade, Petite-Terre, Marie-Galante, and Les Saintes) have developed as a result of the growth of several distinct volcanic arcs and their associated carbonate platforms. La Desirade comprises the remnants of a Mesozoic ophiolitic complex and an associated silicic magmatic complex of Upper Jurassic age (145 Ma) (Westercamp and Tazieff 1980; Bouysse et al. 1990) overlain by andesitic lava flows, breccias and associated intrusives belonging to an old Oligocene volcanic arc (Westercamp and Tazieff 1980). The islands of Petite Terre, Grande-Terre, and Marie-Galante are composed of reef and detrital carbonate platforms of Pleistocene age, up to 200 m thick on Marie-Galante. Quaternary deformation resulting from the oblique convergence between the North American and Caribbean plates has led to the formation of several uplifted coral terraces, tilting of the carbonate platforms, and the formation of a network of active normal oblique faults oriented generally E-W to N140° E (Feuillet et al. 2002; 2004).

Soufrière of Guadeloupe degassing with 1st and 2nd Carbet waterfalls viewed from Capesterre, 1999. A view decribed by C. Colombus when he discovered Basse-Terre in 1493 (© JC. Komorowski/IPGP)

Geological sketch map of Guadeloupe with volcanic centres and thermal springs (Modified after Bouysse et al. 1985; Barrat, 1984; Brombach et al. 2000; Maury et al. 1990)

VOLCANIC ARC ROCKS

Grande Découverte-Soufrière 0.2 Ma. - present

Trois-Rivières-Madeleine < 0.1 Ma.

Monts Caraïbes + Morne Liquin 0.5 Ma.

Bouillante Chain 0.8-0.24 Ma.
❋ subaerial centers
✴ submarine centers

Axial Chain 1.25-0.45 Ma.

Terre de Bas 1.9-0.6 Ma.

Northern Chain 3.5-1.2 Ma.

Terre de Haut 4.7-2 Ma.

Basal Complex 6-4 Ma.

Pliocene-Quaternary volcano-sedimentary sequences

Pleistocene limestone

Mesozoic and Tertiary rocks

Main volcanic centers: 1 La Soufrière; 2 Madeleine; 3 Morne Cadet; 4 Le Houëlmont; 5 Petite Montagne; 6 Petites Mamelles; 7 Carmichaël; 8 Montagne de Capesterre; 9 Sans Toucher; 10 Matéliane; 11 Moustique; 12 Merwart; 13 Pitons de Bouillante; 14 Les Mamelles; 15 Jeanneton; 16 Piton Baille-Argent; 17 Gros Morne; 18 Le Directeur; 19 Volcan de Vieux-Fort

▴ ▲ terrestrial volcanic edifice   △ extinct submarine volcanic edifice   ◯ thermal spring

Regional seismicity affecting Guadeloupe is related to oblique subduction of the North American plate below the Caribbean plate as well as to movements along normal faults and has been responsible for damaging shallow-depth M ≥5 earthquakes in 1851 and 1897. Although this is still subject to some debate, Feuillet et al. (2001; 2002) have proposed that the young and active Grande-Découverte and Soufrière volcanic complex formed within and at the western tip of a prominent E-W oriented graben whose normal faults extend from the prominent Marie-Galante rift system.

Activity of the inner or recent volcanic arc since the upper Pliocene, about 4 to 3.5 Ma ago (Bouysse et al. 1990), has led to the formation of the island of Basse-Terre (950 km^2), the second largest island of the Lesser Antilles, as well as the small group of volcanic islands of Les Saintes to the south.

The islands of Les Saintes were formed between 4.7 Ma and 0.6 Ma ago by effusive and explosive subaerial as well as submarine volcanism (Jacques et al. 1988) that produced predominant calc-alkaline andesites with subordinate basaltic andesites and dacites. The youngest effusive and pyroclastic products (1.9 to 0.6 Ma) were erupted on Terre de Bas (Jacques et al. 1988).

Basse-Terre consists of 7 main eruptive fields (from oldest to youngest): the Basal Complex, the Northern Chain, the Axial Chain, the Chaîne de Bouillante, the Monts des Caraïbes, the Trois-Rivières-Madeleine complex and the active Grande Découverte-Soufrière massif. They each contain many distinct eruptive centres that form a continuous 55 km-long volcanic chain trending N-NW, up to 25 km in width, and reaching a maximum elevation of 1467 m on the Soufrière dome, which formed during the last magmatic eruption dated at ca. 1440 AD. Volcanism in Basse-Terre is thought to have begun about 3 Ma ago (Samper et al. 2004) with the construction of the Basal Complex and then of the Northern Chain to the North of Basse-Terre. Age determinations by Blanc (1983), Carlut et al. (2000) and Carlut and Quidelleur (2000) have constrained the timing of volcanism on Basse-Terre during the last million years. The Axial Chain formed south of the Northern Chain between 1 Ma and 0.445 Ma, in part contemporaneously with the onset of volcanism of the Bouillante Chain. Between about 0.6 Ma and 0.25 Ma three volcanic complexes were active in southern Basse-Terre; the Axial Chain, the Chaine de Bouillante, and the Monts Caraïbes. Activity at the Grande-Découverte Soufrière volcanic complex began around 0.2 Ma or even earlier (Carlut

Simplified geological map of Soufrière massif 1:20 000 (Modified after Boudon et al. 1988)
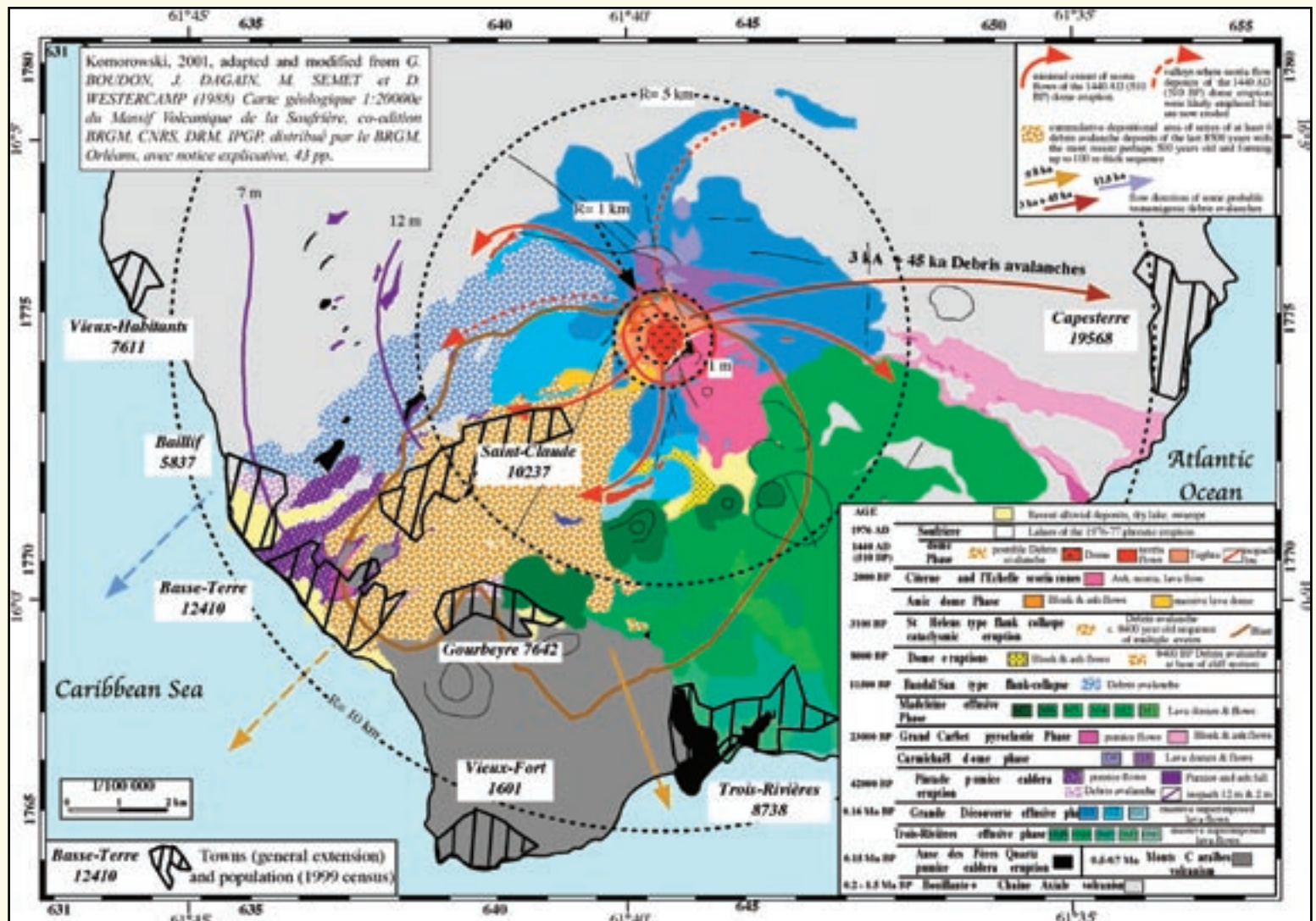
et al. 2000) and is still continuing at present with the Soufrière volcano. Precise chronologic constraints are still missing, but current stratigraphical constraints indicate that the Madeleine Trois-Rivière volcanic complex is the most recent complex to have begun its activity in Southern Basse-Terre, after the onset of the Grande Découverte-Soufrière complex and probably within the last 0.15 Ma.

The Basal Complex
The oldest units of Basse-Terre, thought to be 6 to 4 Ma in age (Maury et al. 1990), consist of massive highly weathered lava flows that outcrop as the Basal Complex at the northern-most part of the island in the Piton St Rose area. The submarine Le Directeur volcano located about 10 km offshore west of Pointe-Noire and Les Mamelles are thought to belong to the Basal Complex. Unpublished geochronological data from ongoing extensive studies by Samper et al. (2004) indicate that the onset of volcanism in Basse-Terre, starting with the Basal Complex, may have in fact started about 3 Ma ago.

The Northern Chain
The calc-alkaline Northern Chain forms about one third of Basse-Terre and was active between 3.5 and 1.2 Ma according to published data compiled by Maury et al. (1990). It consists of a succession of voluminous lava flows and domes of andesitic and dacitic composition including a quartz-dacite episode associated with pyroclastic activity. Activity started in the

North with Piton Baille-Argent, Gros Morne, progressed south with Morne Jeaneton, and ended with the Les Mamelles dacite domes (Westercamp and Tazieff 1980).

The Axial Chain
Between 1.25 and 0.45 Ma ago activity migrated further south to form the prominent 15 km-long Axial Chain along a series of WNW-ESE trending fissures. Extensive voluminous hyaloclastitic units were later covered by voluminous and extensive lava flows that formed several large edifices with elevation greater than 1000 m, such as the Pitons de Bouillante, Morne Moustique, Sans Toucher, Mateliane, and the Montagne de Capesterre. Repetitive large-scale edifice collapses that characterise the evolution of the Axial Chain volcanic field have formed three main imbricate, south-facing, prominent, horseshoe-shaped escarpments within which successive younger volcanic edifices were built (Boudon 1987; Boudon et al. 1992). Activity of the Axial Chain ended with the Sans Toucher volcano whose youngest lavas erupted about 0.445 Ma ago (Blanc 1983; Carlut et al. 2000).

The Bouillante Chain
The Bouillante volcanic chain was formed between 0.8 and 0.25 Ma essentially by phreatomagmatic activity that built a series of small submarine as well as subaerial monogenetic vents that extend from the Petites Mamelles dome on the eastern coast of Basse-Terre near Capesterre to the western Caribbean coast

of Basse-Terre from north of Vieux-Habitants to just south of Pointe-Noire (Blanc 1983). The recent age of this volcanic field is attested by the occurrence of the prominent Bouillante high-enthalpy geothermal field as well as by numerous submarine hydrothermal springs lying offshore south and north of Bouillante.

A wide range of magma compositions characterises the Bouillante volcanism; olivine basalts, andesites, dacites and quartz-bearing rhyolites were erupted from both effusive and explosive vents. Although this is the subject of debate and will likely be revised, the final stages of activity of the Bouillante Chain are thought to have produced andesitic, dacitic to rhyolitic explosive eruptions of unknown source associated with several distinct pumiceous pyroclastic flow and fall units that outcrop scarcely but over a wide area of southern Basse-Terre. In this interpretation the Danoy eruption (dated at 0.244 Ma) associated with the Vieux-Habitants caldera, or the undated Blanchette sequence that disconformably overlies the Plessis 0.6 Ma-old lava flow, would be part of the Bouillante Chain. Pre-Columbian populations used obsidian from the rhyolitic eruptive centre of Le Tuff eruption dated at 0.325 Ma (Blanc 1983) to make hunting tools (Delpuech 2001).

The Monts Caraïbes
The Monts Caraïbes form the southern-most volcanic province of Basse-Terre that was active mostly around 0.5 Ma ago (Blanc 1983), in part contemporaneously with the Chaine de Bouillante and perhaps the waning stages of the Axial Chain. Activity was largely submarine and phreatomagmatic, but the final stages show a transition to explosive subaerial eruptions and include plinian deposits of dacitic composition. Lava flows are locally intercalated in the pyroclastic sequence. Erupted products belong to two different calc-alkaline series and a tholeiitic series (Bissainte 1995).

The Trois-Rivières-Madeleine Complex
The activity of the Trois-Rivières-Madeleine volcanic complex is presently not well constrained geochronologically. Activity was dominantly effusive and produced a sequence of voluminous (km^3) and thick (up to 100 m) variably viscous domes, lava flows, and dome flows of porphyritic massive basaltic andesite including the prominent Madeleine complex, the Palmiste lava flow, and prominent lava flows that reached the Atlantic Ocean in the Trois-Rivières area. Minor pyroclastic block-and-ash flows, surges, and scoria flows are locally associated with some of the lava domes. Numerous rock petroglyphs were carved by pre-Columbian Amerindians (Saladoid period 300-600 AD; Delpuech 2001) on boulders and vertical walls of andesitic lava flows in Basse-Terre, particularly in the Trois-Rivière area. The most recent activity is represented by morphologically young scoria cones (Gros Fougas, Morne Lenglet) overlying the lava flows and isolated phreatomagmatic deposits characteristic of monogenetic explosive volcanism, dated at 0.0127 Ma. The age of the scoria cones is unknown but can be constrained stratigraphically between 0.020 Ma and 0.010 Ma.

An extensive geochronological study of effusive volcanism in Basse-Terre by K-Ar and TL dating is underway (Samper et al. 2004) and will provide valuable new constraints on what could be another potentially active volcanic field in Basse-Terre with

Holocene eruptive activity. Feuillet (2000) and Feuillet et al. (2002) have suggested that eruptive vents of the Madeleine Trois-Rivière complex formed above a W-SE oriented tectonically-controlled fracture that is linked to the propagation on Basse-Terre of west striking normal faults of the Marie-Galante rift.

The Grande Découverte-Soufrière Complex
The Grande Découverte-Soufrière (GDS) composite volcano was built on a sequence of older lava flows from the Sans Toucher composite volcano of the Axial Chain (Boudon et al. 1988). Prominent quartz-rich red clay deposits that formed as a result of prolonged alteration of the widespread Anse des Pères quartz dacite pumice flow deposit (0.140 Ma) and the Montval quartz dacite pumice flow deposit (0.108 Ma) constitute a prominent marker between the older volcanic complexes discussed above and the onset of GDS activity. K-Ar ages of older lava flows (Blanc 1983) together with stratigraphic and petrological arguments led Boudon et al. (1989; 1992) to suggest that activity of the GDS volcano started at about 0.2 Ma. This was confirmed by Carlut et al. (2000) who published a K-Ar age date of 0.2 Ma for a lava flow from the upper section of the Grande-Découverte volcano. The last magmatic eruption at this volcano occurred in 1440 AD, and the most recent activity is represented by non-magmatic phreatic eruptions in 1976-77. Based on published data, the GDS is the only active volcanic complex of Guadeloupe; this centre is discussed in more detail below.


New Observatoire Volcanologique et Sismologique de la Guadeloupe (IPGP) on Mount Houëlmont (Gourbeyre) and Soufrière volcano in the background (8 km) (© JC. Komorowski/IPGP)

Volcano monitoring
The Institut de Physique du Globe de Paris is legally in charge of the scientific study and operational surveillance of active French volcanoes, namely La Soufrière of Guadeloupe, Montagne Pelée in Martinique, and Piton de la Fournaise in Réunion. These tasks are carried out and coordinated by the office of the Observatoires Volcanologiques et Sismologiques of the IPGP. They are responsible for staffing and operation of volcano observatories that have been established in Guadeloupe, Martinique, and Reunion Island with major funding from the INSU of the CNRS, the French Government, and from the local elected assemblies on each island, namely the Conseil Général and the Conseil Régional.

A basic geophysical laboratory was created in 1948 in Saint-Claude on the flanks of Soufrière volcano and was responsible for installing and maintaining a handful of seismic stations.
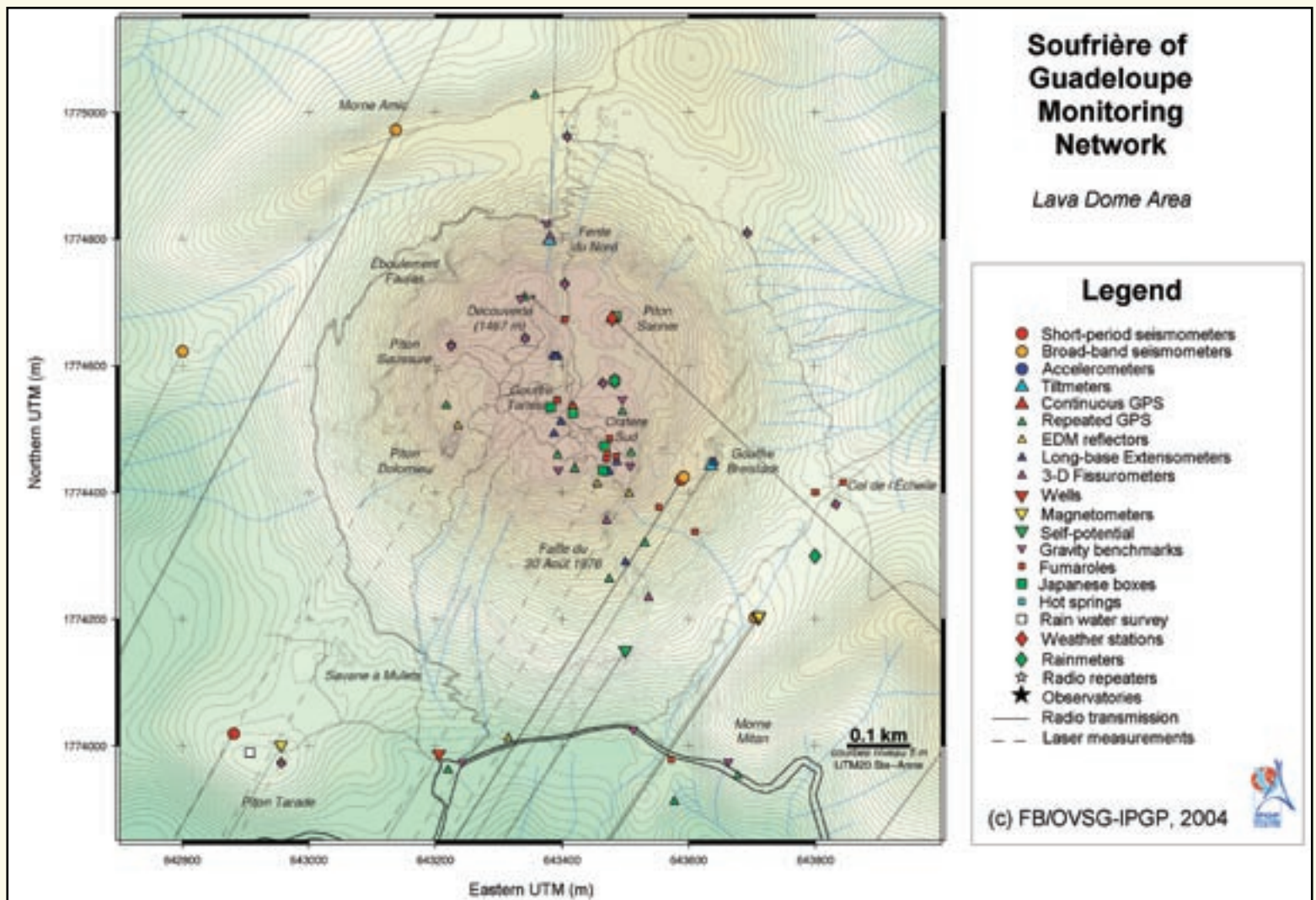
Upgrade and modernisation of the volcano monitoring network began with the onset of significant seismic unrest in 1975 that turned out to be premonitory to the violent and long-lasting phreatic eruption of 1976-1977. As a result of this eruption, the consequences of which could have been much more severe, a substantial programme of basic volcano research as well as a comprehensive multidisciplinary volcano monitoring network has been supported since then by the French Government.

During the 1976 eruption, seismic monitoring was moved to a crisis site near the sea in the thick protective walls of the XVIth century Fort Delgres, while administrative staff mainly stayed in Saint-Claude. The Observatory was finally moved in 1993 to a single operational site on top of the extinct Houëlmont volcanic plug at an elevation of 430 m and at a distance of about 8 km from the active volcano's summit. The current modern Observatory houses all monitoring and data processing installations, an analytical chemistry lab, offices, a small library, a crisis survival cellar, an observational tower, as well as technical lab space and living quarters for visiting scientists. Current staff (about 10 resident, and up to 30 visiting IPGP and university collaborators) include researchers, electronic, chemical, and computer engineers, technicians, and administrative personnel, all part of the French Ministry of Education and Research.

The Soufrière of Guadeloupe Volcano Observatory is responsible for operating and developing the surveillance network and for data processing, analysis, and archiving. The current network includes about 70 telemetered permanent stations with continuous or semi-continuous recording and about 250 sites measured manually in the field with varying periodicities. Short period and broad-band sensors record volcanic seismicity (hypocentres, magnitude and type): volcano-tectonic events due to magmatic sources and shallow events related to hydrothermal activity. Volcano ground deformation is monitored on different scales and sensitivities with tiltmeters, Global Positioning System permanent stations and repetition network (3-D displacements), laser-based distance measurements, and extensometry on

Volcano monitoring digital broadband 3-component seismic station (© F. Beauducel/OVSG-IPGP)
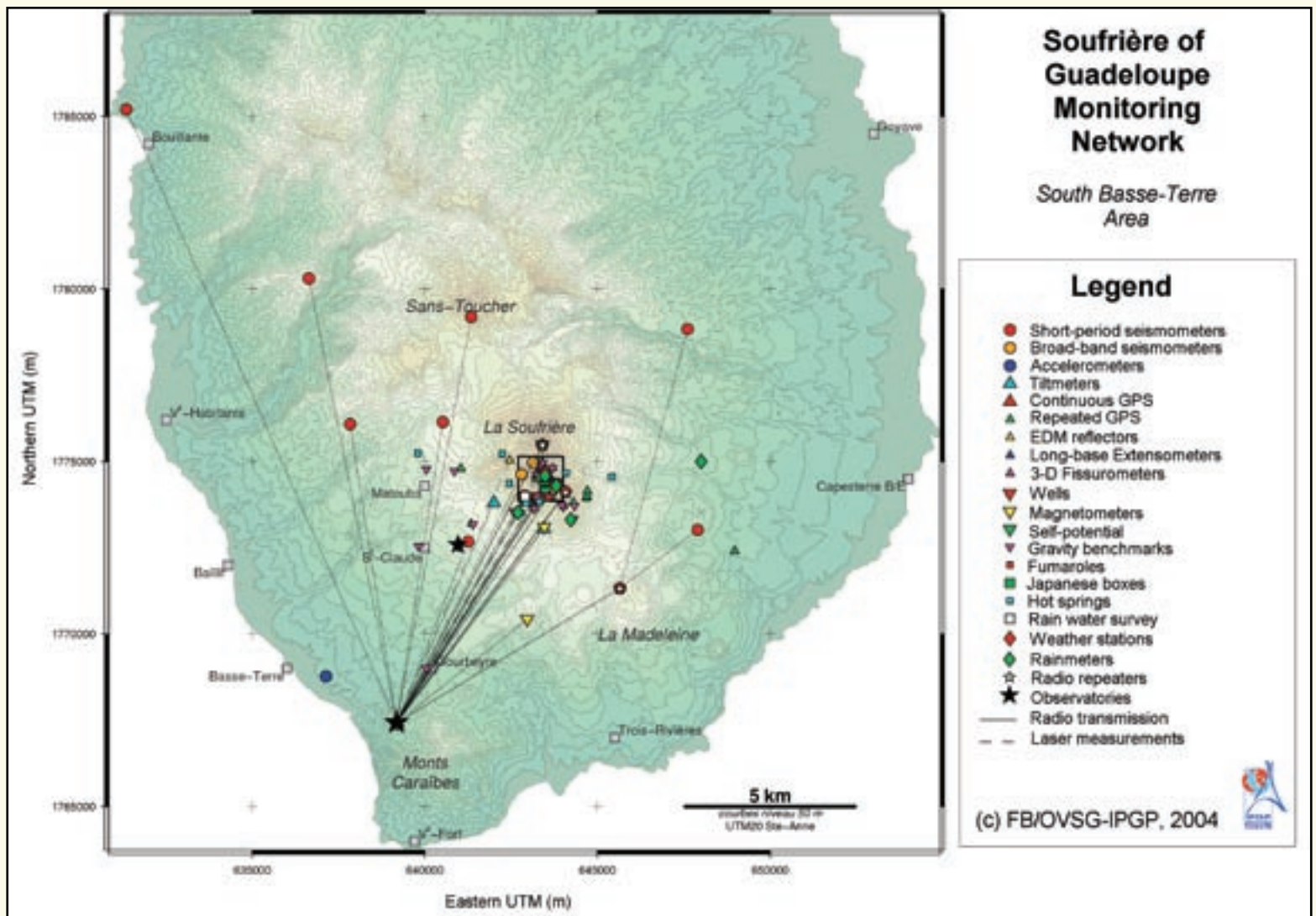
historically active fractures on the dome. Fluid circulation is monitored using physico-chemical analysis of thermo-mineral springs and fumaroles (temperature, flux, pH, conductivity and complete chemical analysis), microgravity surveys, ground self-potential measurements, magnetic field permanent stations, multi-parameter physical sensors in 70-100 m deep wells (temperature, pressure, water level, acoustic noise), closely-spaced surface temperature profiles in the active summit area, and an experimental network of diffuse radon soil degassing. Meteorological data is collected using a complete continuous real-time weather station at the volcano's summit, complemented by a network of rain gauges jointly operated with Météo France. This comprehensive network is complemented with systematic detailed visual observations and photo and video documentation of modifications in superficial activity.

In addition to volcano monitoring, the Observatory is in charge of a regional seismic network of about 20 stations (seismometers and accelerometers) deployed in the Guadeloupe archipelago as well as on Antigua, Montserrat and Dominica islands. This network is integrated with other regional seismic networks, principally in Martinique, but also in Trinidad (Seismic Research Unit), Montserrat, and Puerto Rico. Every year it records between 1,500-2,000 regional and local earthquakes related to the subduction zone, of which about 5 per year are felt by the population in Guadeloupe.

The Observatory maintains an extensive computer network with automatic data processing, storage and transmission to IPGP for all of the telemetered and manual data. A recent development of automated processing routines allows immediate access via an Internet server to the status of the monitoring network, to a complete numerical and graphical data set, as well as to key quantitative indicators of volcano activity.

Scientist sampling gas at the Cratère Sud summit fumaroles (© F. Beauducel/OVSG-IPGP)

View of the Grande Découverte-Soufrière complex from the volcano observatory (© JC. Komorowski/IPGP)

Potentially active centres

The Grande Découverte-Soufrière volcanic centre

The Grande Découverte-Soufrière (GDS) volcanic centre is the only active volcanic centre of Guadeloupe. It is a large complex calc-alkaline stratovolcano that was formed over the last 0.2 Ma (Boudon et al. 1988). It forms a large massif with a diameter of about 8 km, covering most of the southern part of Basse-Terre island. Magma composition is very homogeneous and represented essentially by medium-K calc-alkaline basaltic andesites and andesites. It has produced andesite to dacite (59.4 to 68.7 wt. % SiO_2; Boudon et al. 1988) low potassium lava flows, domes, and associated pyroclastic products. Except for the quartz dacite pumice-rich explosive eruptions of the first phase (68.7 wt. % SiO_2), all other erupted products of the GDS show very little variation in their chemical composition and are andesites with 59-61 wt. % SiO_2 with no definite evolutionary trends between effusive and pyroclastic products.

The complex consists of the remains of three main edifices that were formed either at the same location or roughly on a NW-SE alignment. All the edifices have partially collapsed during sector-collapse eruptions as evidenced by the complex discontinuous NW-SE profile of the massif. Numerous thick lava flows extend up to 10 km from the different edifices. Pyroclastic deposits are not abundant in volume due to significant fluviatile erosion as well as removal by the emplacement of recurrent debris avalanches. Nevertheless the remains of pyroclastic deposits can be found ponded in a few deep ravines along the coastline and in scattered localities higher on the slopes of the massif. The massif has steep slopes, rising from sea level to 1,467 m over a lateral distance of 8 km. It has an overall youthful morphology, particularly the recent Soufrière dome, and is heavily forested except for parts of the Soufrière dome that were affected by historical phreatic eruptions and acid condensates from chlorine-rich degassing that has been ongoing since 1997.

Past eruptive activity

The onset of activity of the GDS complex is a subject of debate. Boudon et al. (1988) proposed a mean date of 0.125 Ma for the substratum over which the GDS complex was built. Carlut et al. (2000) suggested, on the basis of new K-Ar dates of about 0.2 Ma for upper GDS lava flows, that activity began much earlier, which is in agreement with revised interpretations of Boudon et al. (1989; 1992). Although effusive activity accounts for most of the erupted volume of the GDS volcanic complex, Boudon et al. (1988) have proposed an exhaustive reconstruction of the activity, and a 1:20,000 geological map has identified contrasting eruption types and associated deposits. On the basis of Boudon et al. (1988; 1989), together with preliminary results from ongoing unpublished studies, three distinct composite volcanoes make up the GDS volcanic complex. In the following discussion all radiometric ages less than 50,000 years old will be given as ages in years BP (Before Present) (see table with ^{14}C age determinations).

Grande Découverte phase

In the first phase (Grande Découverte phase) that started about 0.2 Ma ago, the Grande Découverte composite volcano was built up by a series of effusive eruptions producing andesitic lava flows that reached 5-10 km from the vent. This dominantly effusive phase was interrupted by three major explosive caldera-forming eruptions that produced widespread pyroclastic pumice flow and associated pumice fallout deposits over all of southern Basse-Terre. These are: (1) the Anse des Pères quartz dacite dated at 0.140±0.014 Ma (Blanc 1983), (2) the Montval quartz dacite dated at 0.108±0.010 Ma, and (3) the Pintade andesite dated by ^{14}C at 42,350+1975/-1585 years BP and at 46,000±6000 years BP by U-Th disequilibrium (B. Villemant, personal communication).
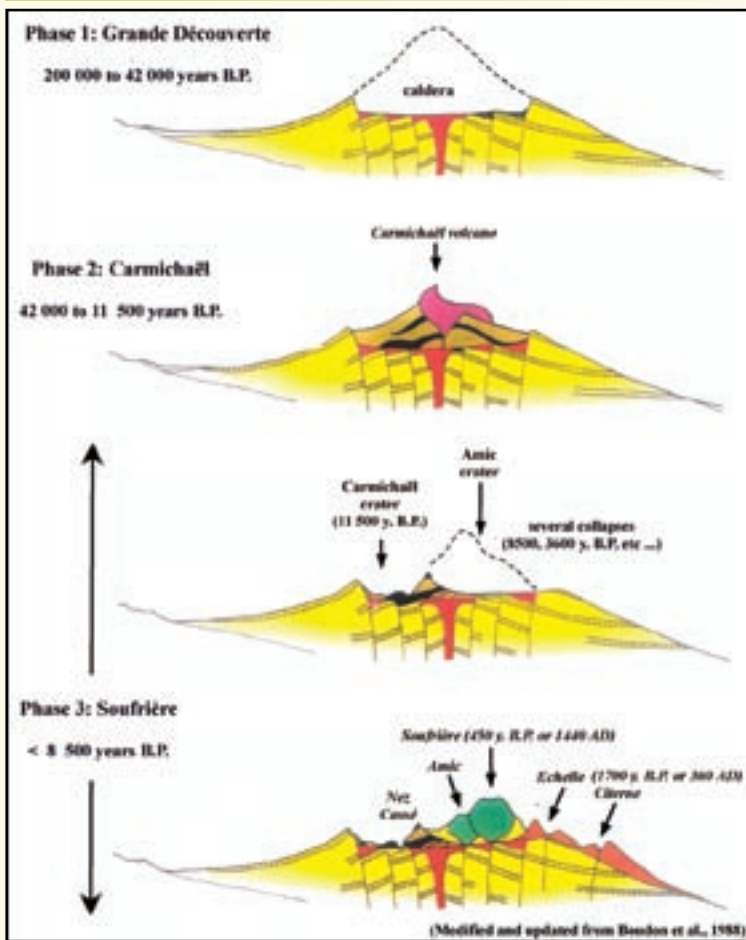

Quarry with 42,000 years BP Pintade pyroclastic pumice flow deposits (© JC. Komorowski)

The Pintade eruption led to the formation of the Grande Découverte caldera (3 km in diameter) and the emplacement of pumice and scoria flows (deposit volume 1-3 km^3) over ca. 120 km^2 of southern Basse-Terre. Thick but limited outcrops of these deposits can be seen mostly in a sector SW of the volcano and particularly in the Basse-Terre, Baillif, and Vieux-Habitants area, but scattered outcrops exist on the SE side of the volcano attesting to the magnitude of these eruptions. In contrast to the older pumice flow deposits, the andesitic Pintade pumice does not contain quartz or hornblende. Several flank collapse events are associated with the evolution of the Grande Découverte volcano including one event directly underlying the 42,000 years BP Pintade sequence (Komorowski et al. 2002).

Carmichaël phase

The second phase (Carmichaël phase) extended from about 42,000 to 11,500 years BP (see age Table) and consisted of the reconstruction of the new Carmichaël composite volcano, within

Simplified geologic cross-sections of Grand Découverte-Soufrière volcanic complex (Modified after Boudon et al. 1988)

about 18,000 and 13,500 years BP, during which a prolonged and extensive hydrothermal system developed and led to pervasive alteration of the volcanic edifice. The Carmichaël phase ends with at least two edifice-collapse eruptions dated at about 13,500 years BP (Komorowski et al. 2002) and 11,500 years BP (Boudon et al. 1984; 1987; 1988; 1989; 1992) which were not associated with a magmatic component nor a laterally-directed blast. A short phase of phreatomagmatic activity dated at about 13,800-12,700 years BP produced explosive breccias and pyroclastic surge deposits in the upper Galion river from monogenetic vents that are geographically within the Madeleine-Trois Rivières volcanic complex but could also correspond to eccentric lateral vents linked to the GDS complex.

Soufrière Phase

The last and current eruptive phase (Soufrière Phase) began after the formation of another edifice-collapse depression (the Amic crater) dated at about 8,500 years BP. It is characterised by a succession of lava dome eruptions as well as prolonged periods of phreatic explosive to non-explosive activity that produced thick phreatic yellow ash fallout deposits particularly between 8000 and 2700 years ago. Pyroclastic products associated with

Thick sequence of 5 debris avalanche deposits ≤ 8500 years BP in a cliff below the Fort Delgrès in the Galion river, Basse-Terre. Insert: 3100 years BP surge/blast deposit above paleosoil and below 3100 y. BP debris avalanche towards the top of this sequence (© JC. Komorowski/IPGP)
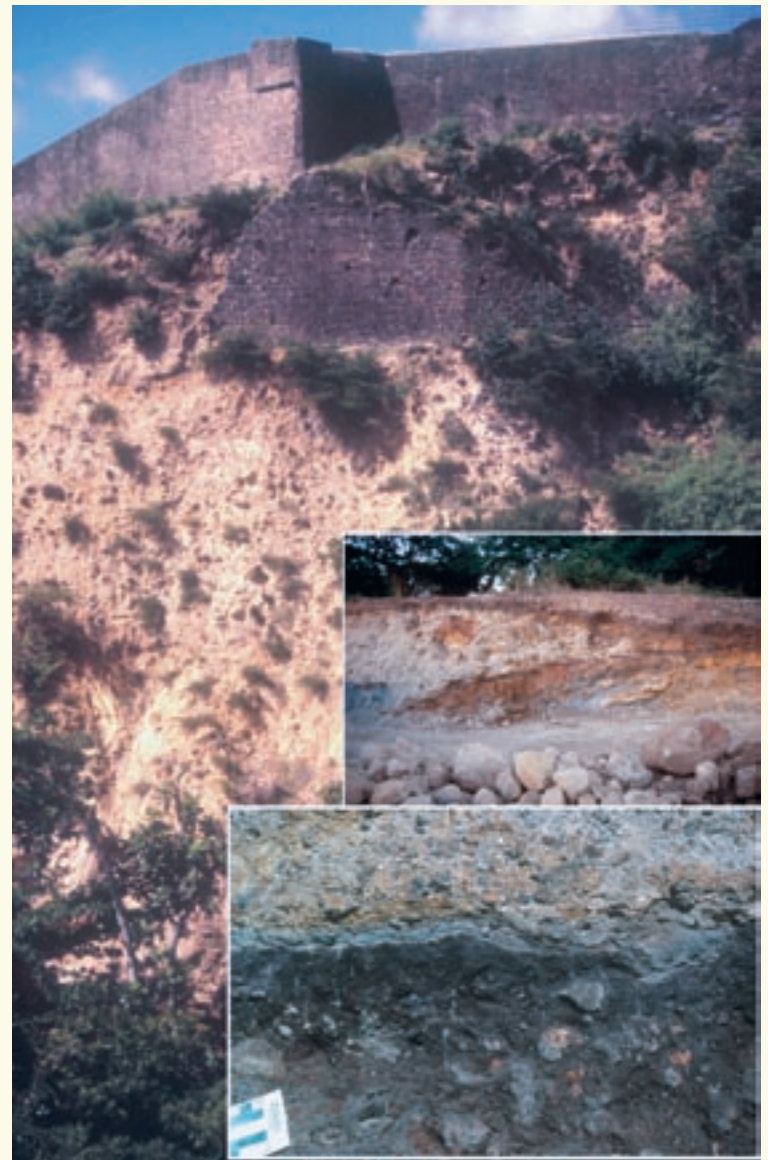
the Grande Découverte caldera, by a succession of lava flows and domes associated with several explosive pyroclastic phases that produced mostly voluminous pyroclastic flow deposits with minor associated Plinian fallout deposits (Dagain 1981; Boudon et al. 1988; Komorowski et al. 2002). Radiocarbon ages for the voluminous pyroclastic flow deposits cluster in 3 groups (Boudon et al. 1988): 1) from 42,000 to 35,000 years BP; 2) from 29,000 to 21,000 years BP; and 3) from 18,000 to 14,000 years BP. These deposits outcrop essentially in the Rivière du Carbet on the E side of the volcano towards the town of Capesterre, in a relict perched outcrop near Dolé (area of Gourbeyre), and in several places in the towns of Basse-Terre (St Phy, Calebassier quarry) and Baillif (Danoy quarry) locally reaching up to 15 m in thickness. They cover an area up to 120 km^2 for the largest event (Pintade eruption, 42,000 years BP), have runout distances of up to 12 km from the volcano, and are characterised by estimated individual deposit volumes between 0.5 to 3 km^3. These are the most widespread pyroclastic deposits of the last 50,000 years of activity of the Grande Découverte Soufrière volcanic complex.

Basse-Terre was covered by at least 2 major eruptions about 42,000 years ago (Pintade eruption) and about 26,000 years ago (St Phy eruption), while the E side of the volcano and principally the Carbet River drainage channelled numerous pyroclastic flows as evidenced by a series of ^{14}C age dates (14 dates) obtained on overlapping and intercalated pyroclastic flow deposits dated from 35,000 years BP to 14,500 years BP that must correspond to several eruptive sequences. A pause in eruptive activity characterises the end of this phase between

these dome eruptions (i.e. pumice and scoria flows, block-and-ash flows, surges, ash and pumice/scoria fallout) are much less widely-dispersed and voluminous that those of the Carmichaël phase that outcrop in the Grand Carbet river. However the pyroclastic eruptive record is likely not complete because of rapid erosive removal of minor pyroclastic deposits linked with past dome eruptions. The remains of at least two lava domes can be seen in the older Amic dome and in the most recent Soufrière dome. The last 10,000 years of activity of La Soufrière, and thus most of the current Soufrière phase, are also characterised by a remarkably high recurrence of (at least 8) small-volume edifice-collapse eruptions. In some cases they are associated with laterally-directed explosions involving either only the shallow hydrothermal system or including also a magmatic component (Komorowski et al. 2002). The best example of such activity is the well-documented 3,100 year BP St. Helens-type event which resulted in the formation or widening of the Amic horse-shoe shape crater (1.7 x 1.3 km) associated with a major laterally-directed magmatic blast that covered at least 100 km^2 of southern Basse-Terre (Boudon et al. 1984; 1987; 1988; 1989; 1992; Besson and Poirier 1994).

Unpublished work in progress (Komorowski et al. 2002) has, over the last 45,000 years, shown that the activity of the GDS volcanic massif has essentially been characterised by a succession of andesite dome eruptions with associated destructional pyroclastic phases and at least 11 collapse events which have contributed to the structural complexity and inherent instability of the current dome. Collapses mostly affected the SW flank of the volcano. Debris-avalanche deposits are separated in time by fluvial erosion levels, paleosols, or pyroclastic units including dilute pyroclastic-flow deposits. Volumes of debris-avalanche deposits are variable but less than 0.5 km^3. The Galion river on the SW flank of the volcano shows the most complete stratigraphic section for the last 8500 years over a total thickness of about 100 m. Debris-avalanche deposits vary in thickness from 15-40 m in valley bottoms to 5-10 m in non-channelled areas. Deposits are almost entirely composed of very hydrothermally altered products. Prolonged and extensive hydrothermal activity and associated frequent phreatic eruptions, as well as the structural characteristics of the volcanic complex, constitute the main geological factors that have controlled recurrent sector collapse of the GDS volcanic complex over the last 50,000 years. With not less than 9 events in the last 15,000 years (including events dated at about 13,500, 11,500, 8500, 3600, 3100, 2700, 1800 and 450 years BP), La Soufrière has a remarkable history of partial collapse. It displays extensive debris-avalanche deposits, which cover the area of the heavily populated cities of St Claude and Basse-Terre. At least 5 and perhaps up to 7 of these events are associated with explosive magmatic eruptions and devastating laterally-directed blasts.

The scoria cones and associated lava flow fields of L'Echelle and La Citerne were formed about 1,700 years ago, beginning with a phreatomagmatic phase (Boudon et al. 1988; Vincent 1994), although no precise age determinations are available.

The Amic dome complex that was formed within the 3100 years BP Amic crater experienced at least 4 small edifice-collapse events that produced debris avalanches (< 0.3 km^3 in size) that sometimes reached the sea 8 km from the vent.

Synthesis of stratigraphy of the last magmatic eruption of Soufrière - 1440 AD
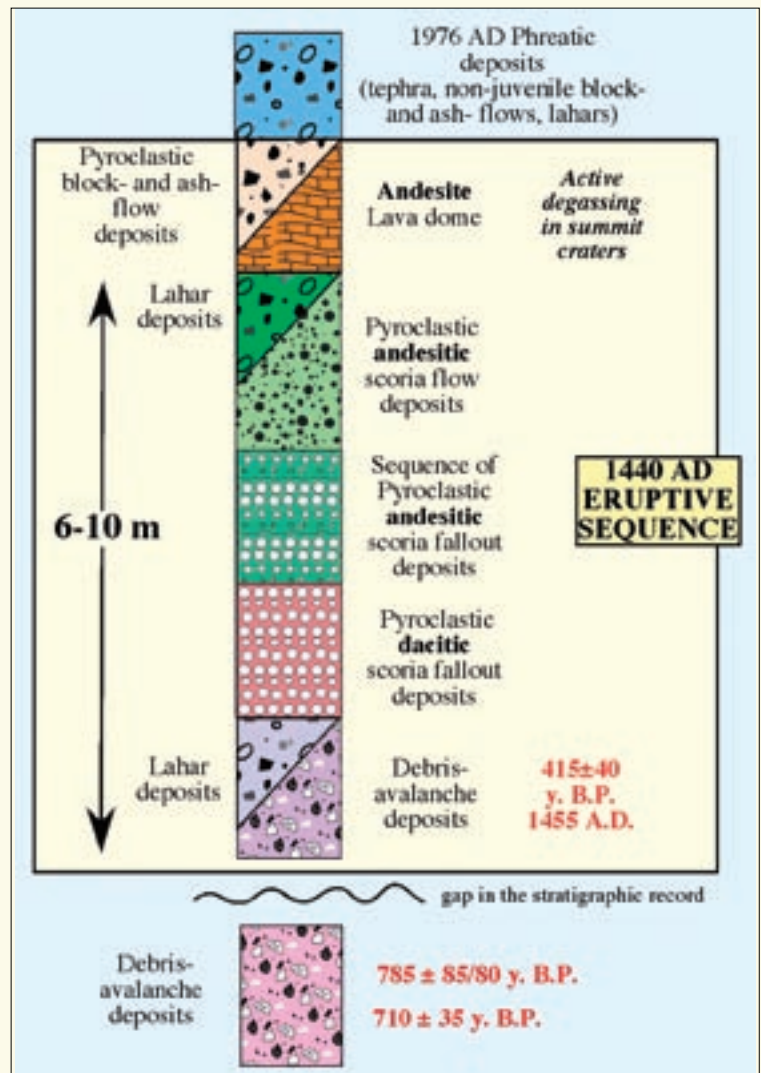
The most recent collapse dated at about 1440 AD (calibrated ^{14}C age) (Komorowski et al. 2002; Semet et al. 2002; Boudon et al. 2003) was directly followed by and perhaps triggered the most recent magmatic eruption of La Soufrière (Semet et al. 1981; Boudon et al. 1988; 2003). In this moderate-sized explosive eruption, eruptive style changed from an initial slope-collapse event, to a vulcanian to sub-plinian phase with emplacement of dacitic to basic andesitic vesicular tephra fall with a 1 m isopach to within 0.7 km from the vent (corresponding to a deposit volume of at least 0.003 km^3). This phase was later followed by associated pyroclastic scoria flows from column collapse (corresponding to an interpolated deposit volume of 0.01 to 0.1 km^3) that reached about 8 km from the vent in several major valleys to the E, S, SW, and NW (Vincent et al. 1979; Semet et al. 1981; 2002; Boudon et al. 2003). The eruption culminated in the growth of the viscous andesite Soufrière dome (about 0.05 km^3) which has been the site of all historical hydrothermal activity and the 6 historical phreatic explosive eruptions. The 1440 AD eruption is peculiar in that the highly porphyritic products are heterogeneous, with a very small volume of acid andesitic to dacitic ejecta in the first stages, followed over a period of time (estimated at days to weeks from crystal growth kinetics) by volumetrically dominant basic andesitic pyroclastics and minor "mixed-magma" fragments (Semet et al. 2002).

Age determinations

Numerous radiometric age determinations have been obtained on volcanic rocks from Basse-Terre since the mid-1970's using K-Ar, thermoluminescence, and ^{14}C techniques. In their compilation of Lesser Antilles K-Ar age dates, Briden et al. (1979) discussed 14 age determinations for rocks from Basse-Terre ranging in age from 0.91 to 2.52 Ma. Blanc (1983) reported 26 K-Ar age dates for rocks from Basse-Terre that correspond to 14 different lava flows. There are important discrepancies between the ages obtained by Briden et al. (1979) and Blanc (1983) on the same lava flows. Over-estimated ages by Briden et al. (1979) are interpreted by Carlut et al. (2000) as a result of potassium loss during rock alteration. Carlut et al. (2000) reported 9 new

K-Ar age determinations as well as paleomagnetic directions on 32 lava flows including the 22 K-Ar dated flows. Carlut and Quidelleur (2000) reported 3 new K-Ar age determinations. Recent K-Ar dating of lava flows from Guadeloupe (Carlut et al. 2000; Carlut and Quidelleur 2000) and on-going studies by Samper et al. (2004) on about 60 new samples including 40 for the southern part of Basse-Terre suggest that many previously published ages by Briden et al. (1979) need to be revised. Therefore only the more recent published ages are included in the table, with the exception of those from Blanc (1983), which were obtained using an early protocol of the Cassignol-Gillot technique (Cassignol and Gillot 1982) improved and used by Carlut et al. (2000), Carlut and Quidelleur (2000), and Samper

Age determinations for Pliocene to Quaternary lavas of Basse-Terre (excluding Les Saintes), Guadeloupe

Description		Location	Age ± error	Method	Ref.
Chaine Axiale Sans Toucher-Matéliane volcanic fields					
H1702 (GU01[a])	Lava flow	Morne Soldat	1. 023 ± 0.025 Ma.[b]	K-Ar	1
G1501	Lava flow	Habitation Grivelière	0. 949 ± 0.020 Ma.[b]	K-Ar	1
D1301 (GU13[a])	Lava flow	Grande Rivière, Vieux-Habitants	0. 784 ± 0.019 Ma.[b]	K-Ar	1
GU11	Lava flow	Morne Marigot	0.785 ± 0.022 Ma.	K-Ar	2
GU10	Lava flow	Morne Marigot	0.781 ± 0.018 Ma.	K-Ar	3
GU09	Lava flow	Morne Marigot	0.777 ± 0.014 Ma.	K-Ar	2
GU22	Lava flow	Beausoleil	0.746 ± 0.013 Ma.	K-Ar	2
D1402a	Lava flow	Morne Davi	0.735 ± 0.047 Ma.[b]	K-Ar	1
J1201 (GU06[a])	Lava flow	Saut d'eau du Matouba waterfall, Matouba	0. 629 ± 0.013 Ma.[b]	K-Ar	1
J1401 (GU07[a])	Lava flow	Morne Montval	0. 620 ± 0.015 Ma.[b]	K-Ar	1
E1101 (GU21[a])	Lava flow	Plessis	0.600 ± 0.017 Ma.	K-Ar	1
GU14	Andesite lava flow	Cascade Vauchelet waterfall, St Claude	0.445 ± 0.006 Ma.	K-Ar	2
	Chaine de Bouillante				
24 (GU12[a])	dike	Tarare-Morantais	0. 863 ± 0.050 Ma.[b]	K-Ar	1
30A	Rhyolite obsidian	Tuf	0. 325 ± 0.008 Ma.[b]	K-Ar	1
F802g1	qtz dacite pumice	Baillif, Danoy Quarry	0.244 ± 0.018 Ma.	TL	1
	Monts Caraïbes				
J301 (GU15[a])	Lava flow	Pointe Mazarin, Vieux-Fort	0. 555 ± 0.026 Ma.	K-Ar	1
J101 (GU20[a])	Lava flow	Pointe Vieux-Fort	0.472 ± 0.016 Ma.[b]	K-Ar	1
GU28	Lava flow	Bel Air	0.400 ± 0.020 Ma.	K-Ar	3
Grande Découverte-Soufrière volcanic field					
GU08	Andesite lava flow	Grande Découverte volcano	0.205 ± 0.028 Ma.	K-Ar	2
K1401 (GU19[a])	Lava flow	Fond Bernard	0.143 ± 0.006 Ma.[b]	K-Ar	1
P301a	qtz dacite pumice	Anse des Pères	0.140 ± 0.014 Ma.	TL	1
S1201 (GU03[a])	Andesite lava flow	3rd waterfall rivière du Carbet	0.129 ± 0.005 Ma.[b]	K-Ar	1
13	qtz dacite pumice	Montval	0.108 ± 0.010 Ma.	TL	1
N1105	Andesite lava flow	Morne Goyavier	0.100 ± 0.010 Ma.[b]	K-Ar	1
GU29	Lava flow	Ravine Longueteau	0.083 ± 0.002 Ma.	K-Ar	2
GU26	Lava flow	Ravine Longueteau	0.083 ± 0.002 Ma.	K-Ar	3
GU02	Andesite lava flow	waterfall rivière du Galion, St Claude	0.079 ± 0.003 Ma.	K-Ar	2
GU04	Andesite lava flow	Rivière Grosse Corde, Trois-Rivières	0.077 ± 0.004 Ma.	K-Ar	2
GU05	Andesite lava flow	Rivière Noire, St Claude	0.047 ± 0.021 Ma.	K-Ar	2
	Andesite scoria	Pintade eruption, Danoy Quarry	0.046 ± 0.006 Ma.	U-Th	4
	Madeleine-Trois Rivière volcanic field				
1	Lava flow	Schoelcher	< 0.035 Ma.	K-Ar	1
1A	Lava flow	L'Habituée	< 0.010 Ma.	K-Ar	1

Ma = million years; TL = Thermoluminescence; K-Ar = Potassium Argon; U-Th = Uranium Thorium; a = sample number of paleomagnetism study of Carlut et al. (2000) for the same eruptive unit as dated by Blanc (1983); b = age given is mean of 2 different age determinations on same sample; c = K-Ar ages obtained with the Cassignol-Gillot technique (see Carlut et al. 2000; Cassignol and Gillot, 1982)
References: 1 = Blanc (1983); 2 = Carlut et al. (2000); 3 = Carlut and Quidelleur (2000); 4 = Villemant, unpublished data, personal communication

Description		Location	Age[a] y. BP	Age Cal[b]	Error± years	Ref
GB7	paleosoil	Ravine Chaude	>38,500			1
GB21	ash	Grand Carbet	>38,500			1
GB38	lahar	Galion	>38,500			1
GB42	pumice flow	Baillif (Danois)	>38,500			1
JJJ nº 10	pumice flow	Basse-Terre (Pintade)	>37,400			2
GB6	clay above ash	Ravine Chaude	>37,000			1
DW77	paleosoil	Ravine Chaude	>37,000			1
GIF3014	pumice flow	Basse-Terre (Pintade)	>35,000			1
GIF3013	pumice flow	Basse-Terre (Pintade)	>35,000			1
GB17	pumice flow	Grand Carbet	>30,000			1
PIN91	pumice flow	Basse-Terre (Calbassier)	42,350		+1975/-1585	1
GS80.17	pumice flow	Basse-Terre (Calbassier)	35,000		1700	1
GIF4346	block and ash flow	Grand Carbet	29,800		800	1
JJJ no 9	pumice flow	Basse-Terre (St Phy)	26,235		2008	2
GB14.1	argilized clay	Grand Carbet	25,800		785	1
GIF3016	block and ash flow	Capesterre (La Fontaine)	25,500		500	1
GB20	ash cloud	Grand Carbet	24,300		740	1
GB26	block and ash flow	Grand Carbet	24,200		600	1
GB27	lahar	Grand Carbet	23,800		500	1
GB31	lahar	Morne Dongo	23,450		600	1
GB34	reworked pumice	Grand Carbet	23,200		600	1
JJJ nº 8	ash fall	Grand Carbet	22,911		403	2
GB30	ash cloud	Grand Carbet	22,600		650	1
V1120	ash cloud	Grand Carbet	21,960		420	1
GIF3032	ash	Grand Carbet	21,340		550	1
GS80.24	block and ash flow	Grand Carbet	21,210		720	1
GB30	block and ash flow	Grand Carbet	20,900		450	1
GIF4347	block and ash flow	Grand Carbet	17,800	-19,275	400	1
IGF3015	pumice flow		14,950	-15,925	200	1
GB33	clay above ash	Morne Dongo	14,500	-15,425	200	1
GB11.1	debris avalanche	Galion	13,850	-14,675	250	1
GB32	stratified ash	Morne Dongo	13,800	-14,575	260	1
GB11.2	debris avalanche	Galion	13,420	-14,125	250	1
GIF4345	pyroclastic surge	Galion	12,700	-13,025	230	1
H902b	debris avalanche	Rivière des Pères	11,670	-11,675	195	1
K1302c1	lahar	Rivière St Louis	11,470	-11,425	145	1
K1320inf	lahar	Rivière St Louis	11,270	-11,225	185	1
GG9a	fluvial sand	Matouba	10,500	-10,475	170	1
GB27	lahar	Galion	8500	-7520	100	1
GG9d	debris avalanche	Matouba	8400	-7460	1500	1
42G	phreatic yellow ash	Soufrière	8070	-7080	480	3
GB36	debris avalanche	Galion	7700	-6450	140	1
GB25	block and ash flow	Morne Dolé	4600	-3360	80	1
K1111	phreatic yellow ash	La Marguerite	4560	-3250	80	1
GB24	clay	Morne Dolé	4400	-2960	110	1
GB43	debris avalanche	Rivière Grande Anse	3600	-1940	100	1
GG9j	debris avalanche	Rivière Grande Anse	3600	-1940	100	1
GB2	lahar	Rivière Grande Anse	3500	-1820	90	1
GB14.2	argilized clay	Rivière Grande Anse	3480	-1800	70	1
O 702	phreatic yellow ash	Grand Fond	3465	-1730	60	1
GIF3035	lahar	Galion	3450	-1730	100	1
JJJ n° 6	lahar	Galion	3300	-1530	110	2
GB22	lahar	Rivière aux Herbes, BT	3200	-1460	60	1
GB4	ash cloud / block and ash flow	Morne Matouba	3200	-1460	100	1
K 1101	debris avalanche	Riv. Noire, ST Claude	3135	-1370	55	1
JJJ n° 7	debris avalanche	Gros Morne Dolé	3066	-1370	84	2
N 701 b2	debris avalanche	Rivière Grande Anse	3030	-1260	140	1
JJJ n° 4	debris avalanche	Galion	3000	-1220	50	2
N 701 b1	debris avalanche	Galion	2980	-1190	85	1

[14]C Age determinations (n=88) for Quaternary pyroclastic deposits of Basse-Terre, Guadeloupe

Description		Location	Age[a] y. BP	Age Cal[b]	Error± years	Ref
PMV 80	lahar	Riv. Noire St Claude	2970	-1165	105	3
JJJ n° 5	lahar	Galion	2910	-1090	100	2
GB28	debris avalanche	Grand Carbet	2850	-980	70	1
SOU-9704-I-a	ash cloud	Blanchet, Gourbeyre	2840	-980	60	1
GIF3034	lahar	Morne Dolé	2800	-920	100	1
N 804 d	blast	Morne Désiré/Palmiste	2800	-920	100	1
GS 83.07 (L 1206)	phreatic yellow ash	St Claude/Papaye	2720	-860	65	1
GB44	debris avalanche	Galion	2700	-820	60	1
GB10	lahar	Riv aux Herbes/BT	2550	-780	60	1
GB5	debris avalanche	Ravine Chaude	1800	+270	100	1
GG91	fluvial sand	Riv. Grande Anse	1700	+370	75	1
GS 80.41	lahar	Galion	1545	+510	65	1
GB50	peat in lake clays	Valkanaers, Gourbeyre	1370	+660	100	1
GB47b	reworked pumice	Galion	690	+1330	90	1
GB47a	reworked pumice	Galion	680	+1330	60	1
GS 80.40	pumice/scoria flow	Galion	670	+1330	60	1
GB48	pumice/scoria flow	Galion	650	+1340	50	1
O 1111 b	pyroclastic surge	Soufrière/Matylis	640	+1340	40	1
Bruet, 1953	pumice/scoria flow	Bassin Bleu/Galion	550	+1370	150	3
JJJ n° 3	block and ash flow	Riv. Grand Carbet	479	+1440	50	2
GB9	lahar	Soufrière/Matylis	460	+1440	90	1
GB49	pumice/scoria flow	Savane à Mulets/Soufrière	450	+1440	60	1
GGB1	pumice/scoria flow	Bassin Bleu/Galion	430	+1440	40	1
JJJ n° 2	pumice/scoria flow	Bassin Bleu/Galion	421	+1455	50	2
GIF225	pumice/scoria flow	Bassin Bleu/Galion	370	+1480	120	1
L 1204	ash	Matouba/Papaye	370	+1480	70	1
O 1114 a	lahar	Galion	350	+1550	40	1
GGB2	pumice/scoria fall	Savane à Mulets/Soufrière	335	+1600	35	1
M 1004	pyroclastic surge	Parnasse/St Claude	280	+1590	45	1

NB: Recent unpublished studies (Komorowski et al. 2002) since 1995 have yielded about 51 new ^{14}C calibrated dates which will be published elsewhere. We report here a compilation of ^{14}C ages acquired up to 1988 and published largely in Boudon et al. (1988). a = y. BP or « years before present », ie. years before AD 1950; b = years before Christ BC; + = years after Christ, AD (ano domini, birth of Christ)
References: 1 = Boudon et al. 1988; 2 = Jérémie, 1979 ; Jérémie, 1980; 3 = Bruet and Aubrat, 1950; Bruet, 1953

et al. (2004). A few age determinations were obtained on quartz-rich dacite pumice by thermoluminescence by Blanc (1983). Unfortunately because of the low-K composition of andesite lavas from Basse-Terre, Blanc (1983) was unable to provide a precise date for morphologically-young lava flows of Schöelcher and of L'Habituée from the Trois-Rivière Madeleine complex. They are thought to be younger than 0.035 Ma and 0.010 Ma respectively (see Table).

The first radiocarbon age date for volcanism in Basse-Terre was obtained in 1950 (Bruet and Aubrat 1950; Bruet 1953) on charcoal fragments of the last magmatic eruption of Soufrière volcano dated at ca. 1440 AD (Vincent et al. 1979). A large number (84) of radiocarbon age determinations on a diversity of pyroclastic products of the last 0.05 Ma of activity of the GDS volcanic complex have been obtained between 1978 and 1995 (e.g. Paterne 1980; Jérémie 1980; Dagain 1981; Boudon et al. 1988) and published in the compilation by Boudon et al. (1988). An additional 51 radiocarbon ages obtained since 1995 (Komorowski et al. unpublished data; Komorowski et al. 2002) complement the database, particularly for the last 10,000 years and for the period from 0.042 to 0.035 Ma, now accessible to radiocarbon dating. Only a sub-sample of the most significant radiocarbon ages from the published compilation of Boudon et al. (1988), representative of all the main eruptive phases of the GDS volcano for the last 0.05 Ma, is presented here in the age table.

Historical eruptions

The majority of ^{14}C age determinations and stratigraphic data on the most recent magmatic pyroclastic products confirm that they can all be attributed to the 1440 AD eruption. In addition, calibrated ^{14}C age dates have been obtained on a lahar deposit (1550 AD), a pyroclastic surge deposit (1590 AD), and a pumice/scoria fall deposit (1600 AD) (Boudon et al. 1988; see Table), which suggests that some magmatic and/or phreatic eruptive activity might have occurred between the first description of La Soufrière by C. Colomb in 1493 and the arrival of first settlers in 1635 AD and the first more detailed written accounts of eruptive activity.

Historical eruptive activity since 1635 AD has consisted exclusively of 6 phreatic explosive eruptions, with minor events in 1690, 1812, 1836-37, 1956, and major events in 1797-98 and most recently in 1976-77. Nevertheless, the earliest written accounts of fumarolic activity were given by several catholic missionary priests in the XVIIth century, often with such imaginative poetic detail as to erroneously suggest explosive eruptive activity. Breton (1647; 1665) describes active fumaroles from the summit and the presence of sulphur-rich deposits including crystalline varieties used for firearms. Du Tertre (1654) and (1667-1671) gives written accounts of an ascent to the summit in 1647 during which he observed fumarolic activity from several craters. Although he mentions seeing "fire flames"

in the fumarolic gas plumes, his rather romanticised account is interpreted as evidence only of vigorous non-eruptive phreatic degassing.

The 1690 phreatic explosion

In his detailed history of Guadeloupe, Ballet (1899) mentions the existence of written evidence that, following a violent regional earthquake in 1680 but more likely after the April 5, 1690 St Kitt's (M ≥7) earthquake (Feuillard 1985; Bernard and Lambert 1988; Feuillet et al. 2002), part of the Piton Saussure or the Piton du Nord lava spine present at the summit collapsed and a new fissure opened to the NE towards the Fente du Nord main fracture, generating some detonations and projections of ash and blocks. This description is thus interpreted as evidence that a mild explosive phreatic eruption occurred in 1690 AD probably similar in magnitude to that observed in 1956 AD (Jolivet 1958).

J-B Labat (1732), a dominican priest that lived in Martinique and Guadeloupe between 1693 and 1705, gives a vivid account of the fumarolic activity and the general morphology of the summit area following his visit on April 8, 1696. Realistically, his account indicates that in April 1696 the volcano was in state of vigorous yet non-eruptive degassing from numerous summit craters and vents, many of which exhibited extensive fumarolic alteration minerals including sulphur-rich deposits. Fumarolic plumes likely contained hydrogen sulphide (H_2S). Several craters were described as venting dark ash, although non-explosively. The thick whitish ash deposits with a sulphurous odour may actually correspond to the products of the 1690 phreatic explosion rather than to any more recent phreatic eruption (Boudon et al. 1988). The account also provides evidence that the ground emitted vapour and was hot in numerous locations of the summit area in addition to the more active vents.

Aerial view (April 1997) from the S above Matylis river of Soufrière dome nested in the 564 year-old flank-collapse structure. In foreground and to the lower right notice the La Ty normal fault trace that prolongates into a fracture that opened on the SE flank of the dome on August 30, 1976 (© JC. Komorowski/IPGP)

The 1797-1798 phreatic eruption

The 1797-1798 eruption was the first major phreatic explosive eruption of the historical period and is comparable in terms of both magnitude and duration to the 1976-77 eruption. It was described in detail by Hapel-Lachênaie et al. (1798), whose

One of the oldest drawing of La Soufrière volcano and it's myths and legends (taken from JB Labat, 1722, Nouveau Voyage aux Iles de l'Amérique 1693-1705, Theodore Le Gras Edition, Paris, vol. 4)

remarkable report (summarised below) constitutes the first detailed scientific account of an eruption of La Soufrière. Interpretative summaries of this report were given by Barat (1986) and Boudon et al. (1988), and extensive parts are reproduced in Adelaide-Merlande and Hervieu (1996).

For several decades and perhaps up to a century prior to the eruption, fumarolic activity showed no significant and systematic increase, and was perhaps even declining, although fumaroles were emitting large volumes of vapour with sufficient pressure to eject small stones placed above the vent (Hapel-Lachênaie et al. 1798). In the years prior to the eruption fumarolic activity was concentrated in the NW part of the summit plateau, perhaps at the Cratere Sud (Peyssonnel 1767; Lacroix 1904), and part way down the eastern flank at the bottom of the Breislack

peak and not within the main N-S fracture. The July 27, 1735 (M = 6.5) Guadeloupe earthquake did not cause any changes in morphology or activity at La Soufrière as was the case in 1690. However, felt seismicity seemed to have increased in frequency and magnitude a few years before the eruption; particularly strongly felt was an earthquake that occurred on January 31, 1797.

The eruption began on September 28, 1797 at around 1800 hrs with a loud rumbling noise heard in all of Basse-Terre, accompanied by a felt earthquake at about 2000 hrs. The rumbling increased in loudness until it sounded as if a canon had been shot, after which time it subsided. Around 2400 hrs a loud howling sound, similar to what can be heard during a hurricane, was heard, and at around 0230 hrs on September 29 a dense dark ash cloud was observed moving towards the west. In the Matouba area within 2-3 km of the volcano and extending to Baillif on the Caribbean coastline about 10 km downwind of the vent, strong rainfall was accompanied all night by significant ash fallout which had a strong sulphurous odour and covered the ground; vegetation was also bent by the weight of the wet ash. Ash clouds were seen propagating down the deep Vieux Habitants river canyon to the west and for several kilometres out to sea. Sediment load in the rivière Rouge (the river draining the volcanic massif to the west) increased markedly for the next 12 hours. The river smelled strongly of H_2S and was more viscous than usual. Starting at about 1000 hrs on the morning of September 29 the temperature of the muddy waters of the Baillif river near the coastline started to increase abnormally so as to become unpleasant to drink. Ash continued to fall to the west accompanied with rumbling noises of varying intensity and a strong unpleasant sulphurous odour up until the afternoon of October 1 when the eruption ended.

Lifting of the thick, black, ash-laden vapour clouds that had engulfed the volcano during the 3 days of the eruption revealed that a prominent spine and promontory of the summit area had collapsed. Two white vapour plumes could be seen emanating vertically from two distinct vents before coalescing and forming a dense cloud that descended the volcano's flanks. A scientific team visiting the volcano on October 4 noted a gravel-like fallout deposit which was coarser closer to the vent. At the base of the dome (Savane à Mulets) the dense gas plume descending the volcano's flanks had an unpleasant sulphurous odour (i.e. H_2S). Five to six small new craters emanating dilute jets of vapour of variable intensity were observed at the base of the Breislack fumarolic field on the upper eastern flank of the volcano. Further rumblings were heard on October 6, and on October 7 a trip to the summit via the SE route revealed that an important peak (Piton Breislack or Dent de l'Est) had collapsed towards the east as well as towards the summit plateau. Furthermore, a large fracture had opened from the centre of the summit plateau towards the N-NW, and this, together with a fracture just above the Dent de l'Est collapse (i.e. probably the southern part of the Napoléon fracture), was emitting voluminous pressurised vapour emissions rich in H_2S. Surrounding the fractures, in particular upwind to a distance of 1 km, damaged vegetation and thick deposits of muddy, sulphurous ash and gravel were observed. It is thought that the bulk of the 1797 eruptive products were emitted from the new N-NW fracture.

Several additional phreatic explosions occurred up until April

1798, producing ash falls even to the east above Capesterre town. On April 22 at 1400 hrs a violent explosion occurred that produced a rumbling sound lasting about 2 minutes and that was heard in the town of Basse-Terre, 8 km away. No ash fall was reported, and the volcano was engulfed by dense vapour clouds for 3 days. When the weather cleared, a new fracture was seen to have opened to the NW about 50 m below the N-NW fracture active in 1797. Large meter-sized blocks of dense old dome lava together with a large volume of smaller-sized debris had been ejected ballistically over a distance of several tens to hundreds of meters to eventually form a voluminous rock fall and rockslide that flowed into and filled the upper parts of the Amic river as a cold block-and-ash flow for up to a few kilometres. Lherminier (1837) reported some evidence that a significant volume of water was mixed with the solid debris, and that this eventually contributed to triggering an overflow in the rivers affected by the event. The south flanks of the Amic dome that faced the new fracture were described as having been stripped of vegetation and ploughed, probably by a small laterally-directed explosion laden with lava blocks. The upper rivière Noire was dammed for three days, stopping the discharge of the rivière des Pères further downslope to the SW. Lacroix (1904) suggested that the 1797-1798 eruption produced a "nuée ardente" and thus some sort of pyroclastic density current although no details are given. We interpret the rockslide as having being produced initially by a laterally-directed low-temperature explosion or blast from a pressurised area of the dome which later transformed into a cold, non-magmatic, block-and-ash flow and eventually into a debris flow. This event would be very similar to that described by Sheridan (1980) which occurred on September 14, 1976 as part of the 1976-1977 phreatic eruption. The new fracture and associated debris field of April 1798 was named the Eboulement (rockslide) or Voie (roadway) Faujas. Viewed from Basse-Terre it looked like a white flat-topped road going up the Rivière Noire valley and splitting in two segments towards the vent (i.e. probably the upper Amic and upper Marchand rivers). The April 1798 explosion marks the end of the 1797-1798 phreatic eruption.

Mild phreatic ash venting of 1812
Fumarolic activity increased progressively between 1809 and 1812 with new fumaroles in the N-NW zone of the summit plateau, widening of the NW fracture by slumping, and the formation of a variety of hydrothermal minerals (Lherminier 1837). Between April and May 10, 1812 increased fumarolic activity accompanied the formation of new W-E-trending fractures during explosions that ejected rock fragments and fine ash that covered the surrounding vegetation. This activity was accompanied by a continuous crackling noise in the Fente du Nord fracture, as well as by the dull sound of intermittent detonations. Although there is clear evidence for an increase in the intensity of the fumarolic activity and for the ejection to small distances of ash and small rock fragments, this activity did not lead to any paroxysmal phreatic explosion.

The 1836-1837 phreatic eruption
After an increase in the number of felt earthquakes over a period of about 10 years since 1825, a phreatic explosion occurred on December 3, 1836 at 1400 hrs or 1500 hrs (note that the eruption is erroneously dated at 1837-1838 in Lacroix 1904). A propagating

rumbling noise similar to a running torrent or a heavy loaded horse cart was heard for about 3-4 minutes and was followed by emission of ash with a sulphurous odour detectable as far as Basse-Terre, 8 km downwind. Ash fall was reported as far as Vieux Habitants, located 15 km W of the vent on the Caribbean coast, as a well as several kilometres over the sea. The eruption started from a vent located within the lower portion of the SE fracture (Lacroix and Napoléon fumaroles and Cratère Sud), as shown on an old drawing, and propagated up into the central fracture of the summit plateau (Gouffre Tarissan, Gouffre Dupuy). It did not reach the N-NW fracture nor the Fente du Nord which had been very active in the previous 1797-1798 eruption (Lherminier 1837). Blocks up to 20-25 kg were ejected by the initial explosion, and ash is described as having descended down a valley as far as the upper parts of Saint-Claude and Matouba about 2.5-3 km from the vent. Biot et al. (1837) observed that torrents of ash mixed with rocks and gravel were projected at great distances and that large masses of rock were detached from the flanks of the dome and flowed downslope into the forest. These observations indicate that, as observed repeatedly, historical phreatic eruptions of La Soufrière generated laterally-directed explosions involving depressurisation of gas reaching up to 1 km from the vent, followed by emplacement of cold phreatic block-and-ash flows that later transformed into a more water-rich debris flow. Ash was reported being emitted over several months and carried by winds to the west. The eruption ended on February 12, 1838 after the Faujas fracture of 1798 (or a new fracture in its immediate vicinity in this NW part of the dome) opened, releasing a large volume of water (Biot et al. 1837; Lherminier 1837) that formed a major debris flow similar to (and that followed the path of) the Faujas 1798 debris flow down the Amic and Noire rivers, which subsequently overflowed. Muddy water is said to have reached up to a height of 2 metres, thus entraining down flow a large number of boulders. Thus phreatic eruptions can be associated with a sudden rise and resurgence via active fractures of the superficial water table or perched aquifers. This has been observed elsewhere, for example during the 1902 eruption of Montagne Pelée (Lacroix 1904) and at the beginning of the ongoing Soufrière Hills, Montserrat eruption in 1995 (G. Hammouya, personal communication).

Engraving by Daver depicting the December 3, 1836 phreatic eruption of Soufrière characterized by emission of vapour, ash and "torrents of ash, mixed with rocks and gravels ejected at great distances" from a new fracture located on the SE flanks of the volcano (taken from Biot et al. 1837)

Soufrière dome with fumeroles from fractures reactivated and formed in the 19 October phreatic eruption as viewed from the North on October 21, 1956. © Macall, taken from Bruet, unpublished report and Barrabé and Jolivet (1958)

The 1956 phreatic eruption

Only a few precursory phenomena were observed before the 1956 phreatic explosion. In the few years preceding the eruption the activity of peripheral fumaroles located at the base of the dome from the SE to the N remained stable overall, whereas several of the summit fumaroles (Fente du N, Napoléon) and the S flank (Lacroix) became totally inactive (Jolivet 1958; Barrabé and Jolivet 1958). Moreover, the frequency to which a dilute H_2S-rich gas plume could be detected in Basse-Terre and Saint-Cloud either by an unpleasant smell or by the blackening of silverware (common in 1951) decreased noticeably until 1955 (Jolivet 1958) suggesting an overall decrease in gas flux from the volcano. Nevertheless, a new fumarole appeared on the SE flank of the dome near the Lacroix fumaroles followed a few months later by a new weakly active fumarole near the Napoléon crater on the summit plateau, exactly on the trace of the eruptive fracture that would form during the October 1956 eruption. Between January and October 1956 there were only two locally felt earthquakes, certainly no increase compared with previous years (7 in 1951; 1 in 1952; 3 in 1953; 2 in 1954; 4 in 1955). However, a large number of low-amplitude local earthquakes were recorded by a single one-horizontal component seismometer located about 3 km from the volcano, but these could not be properly localised.

The eruption began suddenly on October 19 at 2339 hrs local time with a series of detonations that were recorded as explosive, moderate-amplitude signals on the seismometer and heard only by campers located within 1 km S of the dome. The next morning a thin layer of ash (enough to cover the ground in Saint-Claude) was visible over an area extending WSW from the dome up to the Caribbean coast in Baillif and Basse-Terre. The same area was affected by a dilute plume of irritating SO_2 that caused an abnormal increase in the recorded cases of eye and throat irritation in the population. This temporary nuisance thus did not warrant the evacuation of the population in Matouba and Saint-Claude (Jolivet 1958). Ash fell throughout the morning of October 20, and a tall vapour plume could be seen rising 500 m above the volcano. However, the great Souffleur fumaroles located at the eastern base of the dome, which for

the last several years had characteristically emitted a very tall pressurised vapour plume reaching up to 200 m, became suddenly virtually inactive. Over the next 4 days, as ash venting progressively decreased, the Souffleur fumarole progressively regained its original pressurised flux. On October 24 at 1800 hrs local time, a violent emission of ash occurred generating a dark, dense ash-laden cloud that descended very rapidly toward the sea and deposited ash in 15 minutes over a very narrow sector between the volcano, Saint-Claude, Baillif and Rocroy excluding Vieux-Habitants and Basse-Terre. This can be interpreted as the emplacement of a cold dense ash-cloud surge as was witnessed in the early phreatic phases of the eruption of Soufrière Hills on Montserrat in 1995 (Young et al. 1998). After this paroxysmal phase, ash emissions decreased progressively and ended on October 27.

An increase in volcanic seismicity started on November 27, 1956. This was locally felt within a distance of 3 km from the dome by a few people, and accompanied by a thunder-like rumble. A series of 5 volcanic earthquakes of which 2 were felt were recorded on December 17 at 07h00 local time (intensity MSK II and II-III) by the population of SW Basse-Terre within an area bounded by Baillif, La Soufrière, Trois-Rivières and Vieux Fort. This felt seismicity was not accompanied by any particular external volcanic phenomena. Seismic signals recorded prior the explosive phases as well on December 17 were short-period high-frequency signals (Type I of Jolivet 1958) associated with rock fracturing. However, abundant signals of another type (Type II of Jolivet 1958) were recorded during the crisis between the two main explosions and before and during all phases of increased fumarolic degassing even without ash venting. These signals consist of a series of generally impulsive short-period signals (0.25 s) with fast decay, in which P and S waves are indistinguishable, separated by a few seconds to tens of seconds. The complex multiple impulse signal can last up to 2 minutes.

The October 20 explosion led to the formation of a new fracture trending NW-SE from the Tarissan crater at the centre of the summit plateau to the base of the SE flank of the volcano through the Roche Fendue (broken rock) to finish at a place called the Venus cave at the Col de l'Echelle in line with the Souffleur fumarole. An ash-rich mudflow was emplaced through this fracture, flowing down the Matylis river and towards the upper Galion river. As a result the Napoléon, Tarissan, and Dupuy craters became very active and emitted large quantities of vapour, SO_2, and H_2S gas. The Fente du Nord, the NW fracture, the Cratere Sud, and the Lacroix fracture remained unchanged and did not reactivate except for the appearance of the low-activity lower Lacroix fumarole. Abundant ballistic blocks of old dome lava up to 10 kg were projected to the SE to a distance of about 0.6 km in a 30° sector, reaching the N flanks of L'Echelle.

Following the October 24 explosion, the Napoléon crater and the SE fracture were widened and covered by about 0.5 m of ash. A new fracture formed between the SE fracture and the S fracture. Ballistic blocks reached the N flanks of l'Echelle as well as about 1 km to the S, but did not reach the Galion hot spring. As a result of the eruption several areas of the dome experienced marked ground slumping and subsidence, in particular around the Napoléon and Tarissan craters in the area of the old Lacroix fumaroles on the SE fracture and below the S fracture. Ash

emitted during the paroxysmal October 24 explosion reached up to 3-5 cm near Matouba, 3-4 km from the vent. The 1956 eruption thus affected only a restricted SE sector of the cone of about 60° starting with the central part of the dome. Elsewhere the vegetation remained intact. With the exception of the Souffleur fumaroles on the E periphery, whose flux increased significantly since the eruption, the activity of all other fumaroles located outside the active sector remained unchanged. Several fumaroles remained active after the eruption in the summit area (Fente du Nord, Tarissan, Dupuy, Napoléon) and on the flanks (1956, Lacroix, Collardeau, Carbet-Echelle, Chaudières-Souffleur). The total volume of ejecta was estimated at about 0.1×10^6 m³ (Barrabé and Jolivet 1958). The eruption did not trigger any modification of the physico-chemical characteristics of hot springs related to the volcano's hydrothermal system (e.g. Galion or Chute du Carbet hot springs). Phreatic ash was very fine grained with a maximum particle size of 2-3 mm, vitric as well as crystal-rich with abundant quartz (or silica polymorphs), with unmeasured traces of sulphur-rich species and chlorine (Barrabé and Jolivet 1958).

The 1976-1977 phreatic eruption

The last phreatic eruption was particularly violent, complex and prolonged, starting in July 1976 and lasting 8 months to end in March 1977. The lack of a comprehensive and integrated monitoring network prior to and during the crisis, the limited knowledge of the eruptive history of this active andesitic volcano, which had been in a state of magmatic eruptive repose for 500 years, and the memory of the devastating eruptions of the past century in the Caribbean from similar volcanoes all rendered the study and management of this eruptive crisis particularly difficult for scientists, the local and national authorities, and the local population. A major controversy emerged among the scientific community as to whether fresh juvenile magmatic components could be recognised in the eruptive products, thus raising the probability of a transition from phreatic to magmatic eruptive activity. This controversy had various lasting effects on national and international volcanology (Tazieff 1977, 1979, 1980; Bostok 1978; Sigvaldason 1978; Fiske 1984). However, positive consequences included a major increase in funding for development and maintenance of comprehensive monitoring networks and for initiating and developing new research programmes on French volcanoes. In terms of crisis management the eruption served as a test for a variety of approaches and

Aerial view of the Soufrière dome and the active eruptive fumaroles, 1976 (© M. Feuillard/IPGP)

methodologies which led to significantly improved crisis management as early as the 1979 St. Vincent eruption as well as elsewhere in the world.

Soufrière dome with active fumaroles and fractures during the 1976-1977 phreatic eruption as viewed from the north on October 25, 1976. The dome is located on the 3,100 years BP sector collapse depression. © OVSG-IPGP

In contrast to previous phreatic eruptions of La Soufrière and elsewhere in the Caribbean, a significant period of steadily increasing volcanic seismicity was recorded and felt in Guadeloupe starting in July 1975 about 1 year prior to the onset of the eruption. The pre-eruptive seismicity was exceptional in number of recorded and felt events, in the magnitude of the events, and in the occurrence of 3 distinct successive pre-eruptive earthquake swarms of increasing magnitude. The mean number of recorded volcanic earthquakes between 1963 and 1968 was 230, but decreased systematically to 47 for the period between 1969 and 1975 to reach a low of 47 shocks in 1974 and 21 shocks between January and June 1975 (Feuillard et al. 1983). Over the same period the mean number of felt volcanic earthquakes was characteristically on the order of 0 to 3 shocks per year. A pronounced increase in recorded seismicity occurred in July 1975, with the first swarm recording 30 shocks, one of which was felt. Seismicity declined until the second swarm of 209 shocks, recorded in November 1975. Background monthly recorded volcanic seismicity remained higher than normal in December (87 shocks), January 1976 (39 shocks), and February 1976 (93 shocks), until a third major and prolonged swarm occurred between March and June 1976 with about 600-750 shocks per month.

The eruption began on July 8, 1976 with up to 1,220 shocks recorded in July 1976, including 20 felt events. Starting in March 1976 felt volcanic seismicity increased very markedly with a total of 57 shocks and a monthly mean of 16 shocks from March to June (Dorel and Feuillard 1980). This unprecedented increase in recorded and in particular felt seismicity was not accompanied by any major modification in the fumarolic activity of the volcano. Since the Fente du Nord fumarole vanished in 1970 at the summit, only fumaroles located at the periphery of the dome (Collardeau, Carbet-Echelle, Chaudières-Souffleur, Morne Mitan) were still active at the time of the eruption. The only surface precursor to the onset of the eruption was a minor landslide that occurred on June 9, 1976 on the La Ty fault located SE of the dome. The following descriptions are taken essentially from IPGP (1976), Dorel and Feuillard (1980), Le Guern et al.

(1980), Heiken et al. (1980), Sheridan (1980), Westercamp and Tazieff (1980), Feuillard et al. (1983), Barrat (1986), and Boudon et al. (1988).

The eruption began at 0855 hrs local time with one of the most violent explosions of the entire crisis from vents located on the lower portion of the 1956 fracture just above the Col de l'Echelle. This explosion produced 60% by volume (0.6×10^6 m^3) of the total ejected solids during the entire 1976-1977 crisis. Seismic tremor was recorded for 48 minutes, and as the activity developed, three fractures were reactivated in the SE sector of the dome. Large blocks were projected several hundred meters away, with a maximum ejection speed of 30 m/s, and a cold rock avalanche formed from the vent and transformed into a debris flow that reached the 3rd waterfall on the Carbet River to the E for a distance of about 3.5 km, leaving a deposit front about 30-50 m wide and 15-20 m deep. Large and vigorous ash-laden H$_2$S-rich vapour plumes developed, blackening the sky for 20 minutes in Saint-Claude and causing ash and lapilli fall. The eruption frightened and surprised the population, leading to a partial spontaneous evacuation. On July 12, 13, and 14 water was ejected in geyser-like activity from the active vents. Three other explosions occurred on July 24 and 25. Seismic activity continued to increase to reach a maximum of 1,257 earthquakes recorded on August 24, while explosions occurred on 9, 21, 25 and 30 of August. Seismicity reached its peak of the entire eruption in August with 5,989 earthquakes recorded of which at least 41 were felt. The largest earthquake (magnitude Md =4.2,

Phreatic ash on vehicle, 1976 (© R. Fiske)

intensity MSK VI) was felt even in Pointe-à-Pitre more than 50 km away on August 16. On August 18, 1,000 shocks were recorded.

On August 15, the emergency plan was put in action by the authorities following the concern by scientists that the systematic increase in seismicity and magnitude of the explosions could be precursory to a more paroxysmal magmatic phase with generation of devastating pyroclastic flows and surges. At that time the scientific evidence and limited monitoring data could not resolve the question of whether juvenile products were being erupted and whether the violent degassing that contained H_2S, SO_2 and other trace elements provided an indication that magma was ascending closer to the surface. About 70,000 people were evacuated from the entire southern Basse-Terre area from the town of Vieux-Habitants to the W on the Caribbean coast to the town of Saint-Marie, just N of Capesterre on the Atlantic coast without their knowing that they would not return until December 15, 1976.

A spectacular explosion occurred on August 30, when an entirely new major fracture opened in the extension of the La Ty fault onto the S-SE flank of the volcano. The fracture propagated rapidly over several hundred meters to the summit plateau and centre of the dome to trigger a violent explosion from the Tarissan crater that surprised a party of scientists. They took shelter within a few tens of meters of the vent and managed to escape without serious wounds from the ballistic shower that passed over them, projecting blocks that weighed up to 1.5 tons. A rock avalanche and cold block-and-ash flow was emitted from the 30th August Fracture. It flowed into the Matylis river over about 0.7 km. In September 1,776 earthquakes were recorded, and explosions occurred on September 14 and 22 with ash reaching up to 1500

m above the vent. Sheridan (1980) described in detail the small laterally-directed explosion or blast that followed the explosion on September 14 and triggered a directed ballistic shower that reached up to 0.9 km from the dome.

It stripped the vegetation, and led to the generation of another cold block-and-ash flow down the Matylis river that later transformed into a debris flow that reached the Bassin Bleu in the Galion river at a distance of about 3.5 km from the vent. Explosions occurred on October 2, 10, and 30 and 2,315 shocks were recorded. The first phase of the eruption, characterised by intense seismicity and 17 explosions, ended on November 10 after explosions on 1, 6, 7, and 10 of November and about 1,040 recorded shocks in November.

Phreatic explosion on September 22, 1976 with ash reaching up to 1500 m above the vent viewed from Basse-Terre (© M. Feuillard/IPGP)

IMPACT OF THE 1976-1977 ERUPTION ON THE LOCAL POPULATION

The 1976-1977 eruption engendered significant and recurrent nuisances and risks to the population (Le Guern et al. 1980; Feuillard 1979; unpublished internal reports) largely due to: 1) frequently and strongly felt volcanic seismicity; 2) the contamination of the atmosphere by acid gases (H_2S, SO_2) and fine corrosive volcanic dust rich in acid condensates and Ca-sulfate that sometimes also contained non-negligible quantities of silica polymorphs; 3) the contamination of spring waters from the volcano, used as the main source of potable water, and water tanks by soluble acid condensates (including halogens such as fluorine, chlorine, bromine) and other trace elements adsorbed on the surface of the erupted ash; 4) chemical and mechanical consequences of the contamination by acid condensates of crops and fields used for cattle grazing, in particular fluorine, and other trace elements adsorbed on the surface of the erupted ash. For example, an ambient air concentration of 14 ppm of H_2S was detected on July 14 1976 in the then un-evacuated town of Saint-Claude. The accepted Threshold Limit Value - Short Term Exposure Limit (a 15 minute time-weighted average exposure which should not be exceeded at any time during a work day, and should not be repeated more than 4 times a day) is 10 ppm for H_2S. Painted surfaces developed iridescence and/or darkening after prolonged exposure to H_2S-contaminated atmosphere up to a distance of 5 km from the volcano (Feuillard 1979; unpublished internal reports), as was reported also for the 1956 eruption (Jolivet 1958). The acid corrosive atmosphere damaged telephone switch lines, corroded water distribution pipes and caused numerous other nuisances. Even in January and February 1977, after the population had returned to their homes, the pH in potable public water frequently reached values of 4.1 to 4.5 whereas the sulfate SO_4^{2-} content after treatment of the water reached values of 700 mg/l 3 days after the last March 1 explosion, almost three times the maximum official acceptable values at the time and barely acceptable values one month after the last eruption (Feuillard 1979; unpublished internal reports).

The evacuation of about 70,000 people from a large area for at least 6 months engendered severe socio-economical difficulties for the population in southern Basse-Terre as well as for the remainder of Guadeloupe, having a profound and prolonged influence on society continuing long after the crisis had subsided. However, regardless of the interpretation of the eruption (purely phreatic vs potentially magmatic), for all of the reasons discussed above the evacuation of the population in the areas closest to and downwind from the erupting volcano was necessary. Because of the significant growth of all towns on the flanks of the volcano and the future development plans for southern Basse-Terre, a new 1976-77 style eruption is likely to generate a crisis that will remain difficult to manage by authorities and decision makers despite the presence of a highly sophisticated monitoring network and the vast knowledge subsequently acquired about La Soufrière volcano. One complicating issue is the perception by a portion of the population that, following the conflicts among the scientists involved in 1976, the evacuation was either entirely unnecessary or largely exaggerated to the extent that response might be limited in the event of a future call for a preventive evacuation.

The second phase of the eruption, from November 10 to January 4, 1977, was characterised by decreased seismicity (399 shocks in December) and a lack of explosions and recorded seismic tremor. Only permanent vapour degassing, minor ash venting, and loud noises from gas decompression in the Cratere du Sud could be observed. Although seismicity reached its lowest level (312 shocks in January) since March 1976 during the third phase of the eruption (January 5 to March 1, 1977), a series of explosions began on January 5, 1977 associated with tremor, ash emissions (50 % less volume than in the first phase), projections of ash, mud, and blocks associated with minor landslides and mud flows towards Col de L'Echelle (e.g. on January 14 and 15). The second most violent explosion of the entire crisis occurred on January 29, 1977. It ejected the second largest volume of rocks with the highest ejection speed of 150 m/s. An explosion occurred on February 13. The last explosion was observed on March 1, 1977 and produced the third largest volume of rocks. Seismicity continued to decline with 179 shocks in February, 153 in March, 32 in April, 19 in May, and 15 in June 1977, which was defined as the end of the 1976-1977 eruption, with seismicity returning to almost normal levels based on numbers and energy released.

The explosive and non-explosive ash venting phases of the eruption ejected material consisting essentially of lapilli and ash with a mean grain size of 10 to 40 mm. In several explosions, particularly those of July 8, August 30, September 14, 1976, and January 29, 1977, dense blocks torn from the walls of the active craters and fractures with sizes of 0.3 to 1 m in diameter were ejected distances up to 1.5 km. Phreatic ashes consisted essentially of old hydrothermally altered material from the dome and paleo-pyroclastic fragments from the nearby Echelle scoria cone. The invariable presence of up to 10 % by weight of fresh unaltered vitreous andesitic fragments in the phreatic products as reported by several authors (Marinelli 1976; Brousse et al. 1977; Heiken et al. 1980) led to a major scientific controversy as to whether such products represented the first signs of the participation of fresh magma from depth and thus of the potential transition to a more violent magmatic eruption. The increase in F and Cl concentrations during July and August 1976 in some of the thermal springs closest to the volcano compared to pre-crisis values was also interpreted to be compatible with a juvenile magmatic origin for these volatiles (Feuillard et al. 1983).

During the 1976-77 eruptive crisis (Feuillard et al. 1983), 16,000 volcanic earthquakes were detected of which 150 were felt. Excluding volcanic tremor, recorded seismicity was poorly correlated with eruptive phenomena. Focal determinations using a crisis network of 7 stations were problematic and thus epicentres formed an area 10 x 6 km centred 1 km N of the dome and oriented NW-SE. Hypocentres cluster in a zone 1-5 km below sea-level and did not reach a depth greater than 10 km. No systematic vertical migration of earthquake hypocentres were detected on the long term, but Hirn and Michel (1979) clearly evidenced a migration of earthquake foci from a depth of 6 km upward on a time scale of tens of minutes to a few hours. Starting in July 1975 seismic energy released increased with each earthquake swarm and after the beginning of the first explosion in July until reaching a peak in August 1976. Afterwards it began a systematic overall decrease that continued over the

next 6 months until the end of the crisis. The 26 explosions that lasted between 10 to 40 minutes alternated with 31 non-explosive ash venting events that produced a total of about 1 x 10^6 m^3 of non-juvenile tephra. The crisis was accompanied by significant morphological changes in the dome, the opening of two new major sets of fractures in the dome, and the widening and deepening of historically old craters and fractures. Ballistic blocks weighing a few kilograms to several tons were ejected up to 1.6 km from the vent during the explosions. The eruption was accompanied by significant low-temperature (100-200° C) degassing of H_2O (1010 kg) and minor quantities of CO_2, H_2S, SO_2, as well as acid condensates (HCl, HF, Br) and minor ash fall up to 10-15 km distance. During the eruption and until May 1977 significant fumarolic activity was observed on all N-SE sites around the periphery (Collardeau, Carbet-Echelle, Chaudières-Souffleur, Morne Mitan) as well as on a SE sector of the summit area from the Fente du Nord, Dupuy, Tarissan to the Cratère Sud, and on the SE flanks (Lacroix, July 8 and August 30 fractures).
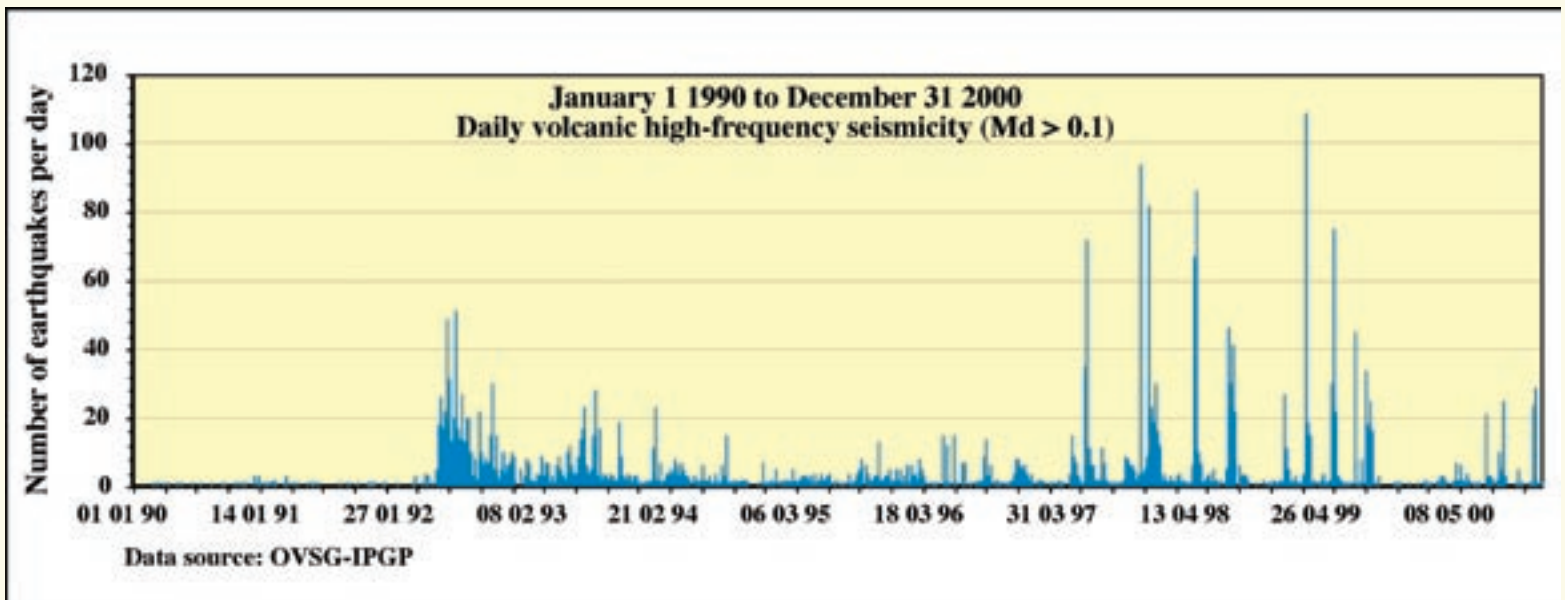
Based on seismic and magnetic data the 1976-1977 eruption is interpreted to have originated from a depth of 6 km (Feuillard et al. 1983), a depth compatible with that of the magma chamber that was involved in the last magmatic eruption of the volcano dated at 1440 AD.

Mixed banded dacite and basaltic andesite vesicular clast from the 1440 AD fallout sequence (© M.P. Semet/IPGP)

Two models have been proposed to explain the explosive phenomena. The first model (Feuillard et al. 1983) suggested that ongoing differentiation processes in the magma chamber and/or small-volume injections of less differentiated hot magma into the chamber would have triggered overpressures of a few hundred bars that could have triggered crack initiation and upward migration of magmatic gases into a fracture propagating into the deep and then superficial hydrothermal system. The model proposed by Zlotnicki et al. (1992) does not imply that physico-chemical changes occur in the magma reservoir. Indeed overpressures could develop in the deep aquifers (>1 km) as the result of insufficient heat transfer by convection from deep sources to the various superficial aquifers that would have become isolated, partially sealed by structural readjustments or deposition of hydrothermal minerals. A phreatic eruption can then occur only when the uppermost superficial sealed aquifer located above the phreatic level is fractured.

Soufrière of Guadeloupe daily volcanic seismicity between 1990-2000 (OVSG-IPGP)

January 1 1990 to December 31 2000
Daily volcanic high-frequency seismicity (Md > 0.1)

Data source: OVSG-IPGP

Seismicity

Seismicity related to historical eruptions is discussed in detail above. We will concentrate here on a general description of seismicity since 1977. Since the end of the 1976-1977 eruption, several volcanic seismic swarms associated with La Soufrière have been recorded (Feuillard 1989, unpublished internal report) namely on the January 7-8, 1981, on November 22-24, 1982, on January 8-9, 1983, October 16-17, 1983, and on October 15, 1984. Shocks were mostly magnitude ≤ 2 with a total of only 8 felt shocks. Earthquake foci were all determined to be less than 5 km below sea level. With the exception of this heightened seismic activity, volcanic seismicity generally declined (in total number, number of swarms, number of felt shocks, and energy released) from 1978 to gradually reach a total low number of 32 recorded shocks two years in a row in 1990 and 1991. There was no felt seismicity between 1986 and 1991, a period characterised by the lowest level of seismic energy released since 1970. Correlated to a significant decrease in fumarolic activity, the 1990-1991 period represents the lowest level of overall activity of the volcano since 1956.

Soufrière of Guadeloupe volcanic seismicity since 1955-2003 (OVSG-IPGP)
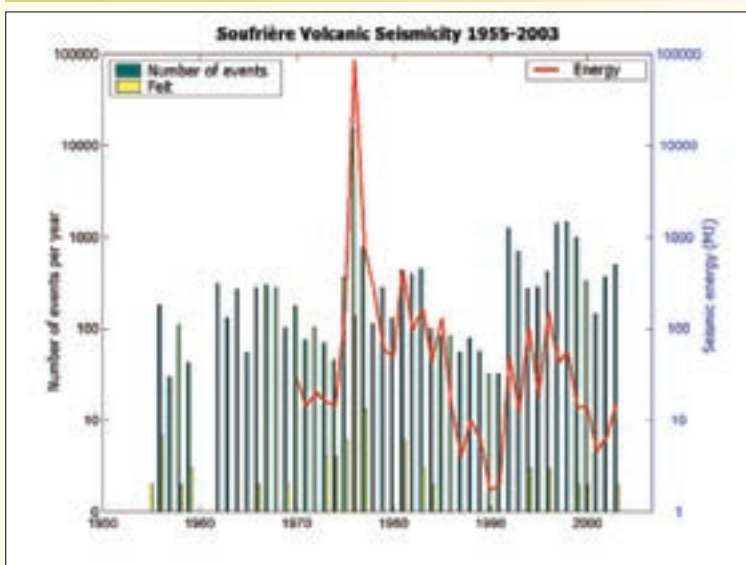
A new phase of variably elevated seismic activity associated with systematic increased fumarolic activity began in 1992 and is still currently ongoing. However, the peaks in recorded earthquakes and counts of felt earthquakes are not exactly correlated with the yearly peaks in seismic energy released nor fumarolic activity. A major seismic crisis produced 1,259 recorded shocks between May 21 and December 12, 1992 (8 separate swarms) but with no felt shocks. This crisis was associated with significant reactivation of the previously extinct Cratere Sud fumarole, appearance of a new warm-spring at the S base of the dome (Pas du Roy), and reactivation of the Tarade warm-spring S of the dome. Seismic activity remained high between 1992 and 1999 with energy peaks in 1994 (2 felt shocks, 275 shocks in the year), 1996 (2 felt shocks, 418 shocks in the year). Fumarolic and thermal reactivation of the Napoléon summit fracture and slow intensification of degassing at Cratere Sud fumarole corresponded to the 1996 seismic unrest. Since 1996, seismic energy released has slowly decreased although recorded number of earthquakes continued to markedly increase until 1999 (1997: 1401; 1 felt shock, the highest number of earthquakes recorded yearly since 1977; and 1998: 1455; 1 felt shock; 1999: 974; 1 felt shock). Seismic energy and counts began to decrease in 2000 (337; 1 felt) to reach another low level in 2001 (140) similar to that of 1990. Since 2002, seismic energy and counts have been increasing gradually (2002: 307 shocks in 2 swarms: 2003: 484 shocks in 6 swarms, 1 felt; 2004: 596 recorded in 5 swarms). Volcanic seismicity consists essentially of high-frequency low-energy earthquakes often grouped in series of multiple events. For the first time in decades, 5 signals with a low-frequency (long-period) component were recorded on August 21, 1998 (A. Nercessian, personal communication) following a large high-frequency swarm. A few long-period signals were also recorded in 2002 and 2003. Over the last 10 years, earthquake foci have remained characteristically shallower than 6 km below the summit with an epicentral area generally centred below or slightly N of the dome.

Currently the variable but shallow-depth low-energy high-frequency seismicity recorded since the end of the 1976-1977 phreatic eruption can be interpreted as evidence for

Soufrière of Guadeloupe Seismicity
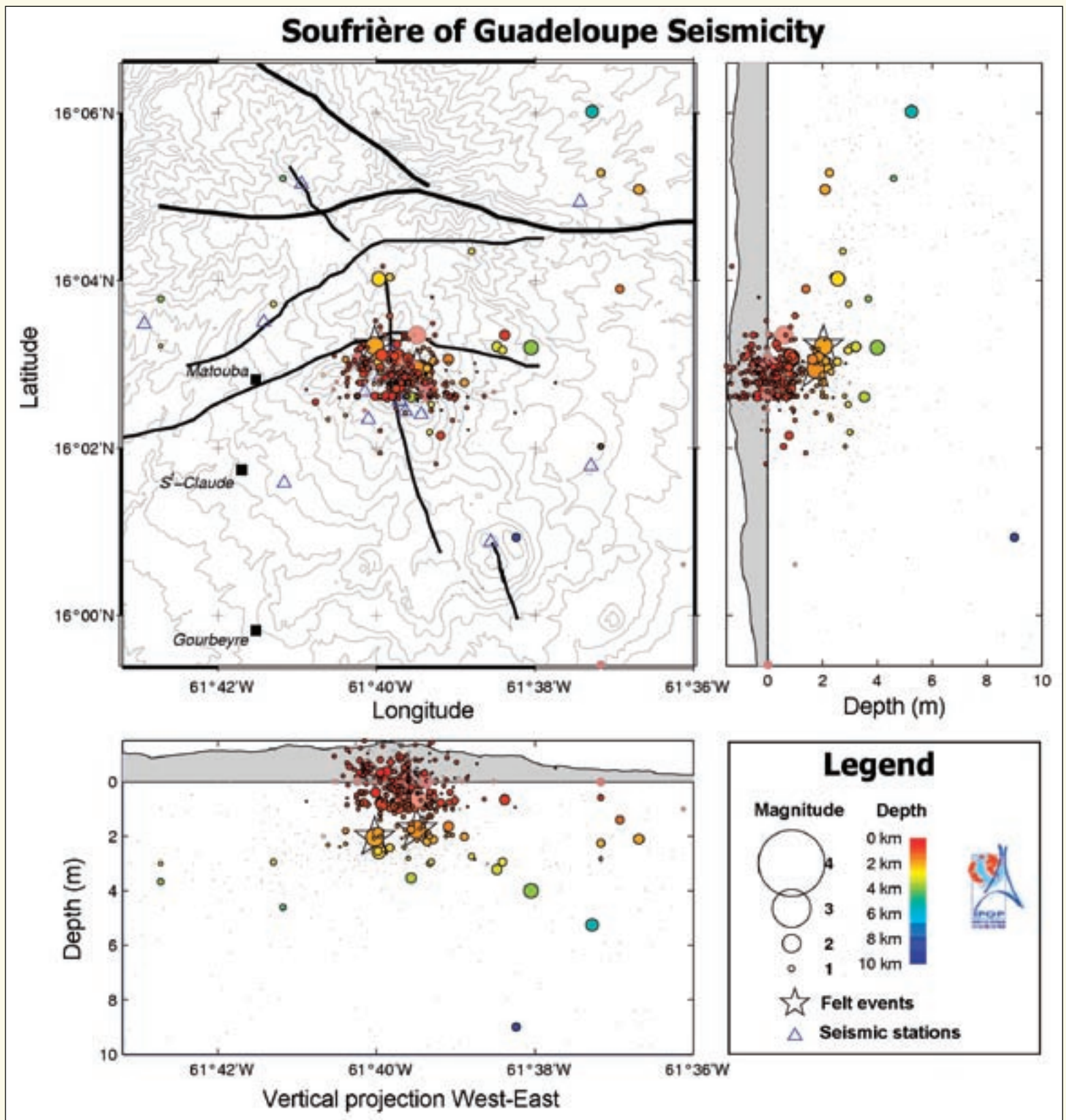
microfracturing of locally very altered mechanically weak host-rocks of the superficial hydrothermal system (<5 km below the summit) by hydrothermal fluids heated by a variable heat and gas flux coming from the deeper magma reservoir but without injections of magma to very shallow depths. The general decrease and even disappearance over the last decades of peripheral fumaroles to the benefit of a few major summit fumaroles suggests that a general self-sealing of the host-rock surrounding the dome and within which the fast-recharge superficial aquifers are located is taking place. Associated modification of the permeability of the water-saturated host-rock could promote build up of pressure and microfracturing. The relationship between the rate of sealing, the state and rate of recharge of the superficial aquifers, the geometry of the fracture conduits and the heat flux from below are amongst the factors that will control whether such pressure buildup can lead to critical superheating of shallow sealed aquifers and a new phreatic eruption.

Geothermal activity
La Soufrière

Apart from the Bouillante area (see below), the most important and widespread manifestations of geothermal activity (thermal springs, fumaroles, areas of hydrothermally altered rocks) are linked with the Soufrière massif. Active fumaroles are currently limited to the dome itself with the exception of a small fumarolic area in the Matylis and La Ty river at the SE base of the dome. Numerous thermal springs are located from the base to within 5 km of the dome. Historical observations show that the nature, distribution, and intensity of these geothermal manifestations has fluctuated considerably over time.

High-pressure degassing from Cratère Sud Nord, November 2003 (© JC. Komorowski/IPGP)

Phases of fumarolic reactivation were reported in 1737-1766, 1809-1812, 1879, 1890, 1896, 1899 and 1902-1903 (Peysonnel 1767; Lherminier 1815; Lacroix 1904). Between the end of the 1976-77 eruption and 1984 there was a phase of progressive decline in fumarolic activity in all areas on the summit (Tarissan, Cratère Sud, Fente du Nord, Cratère 1956), on the flanks (disappearance of the Lacroix fumaroles in 1984) and at the base of the dome (disappearance of the Carbet fumaroles in 1979; the Collardeau fumaroles in 1982; and the Col de l'Echelle fumaroles in 1984). A phase of minimum fumarolic activity occurred between 1984 and 1992, with no fumaroles at the summit and only minor degassing along the SW regional La Ty fracture that intersects the base of the dome (fumaroles of the Route de la Citerne and of the Morne Mitan). A phase of systematic progressive increase in fumarolic degassing with reactivation of summit fumaroles began in 1992 at Cratère Sud, continued in 1996-97 at Napoléon Fracture/Crater, to finally involve Tarissan crater starting in 1997 and increasing in 1999 (Komorowski et al. 2001 see box). There is no significant fumarolic activity at the base of the dome except weak non-pressurised emanations from the stable areas of Morne Mitan and Route de la Citerne. Contemporaneously, three acid-sulfate thermal springs showed significant development at the SW base of the volcano (reappearance of Tarade spring after a long absence, formation of new Pas du Roy spring, increased flux and new resurgence sites for the major Ravine Marchand spring).
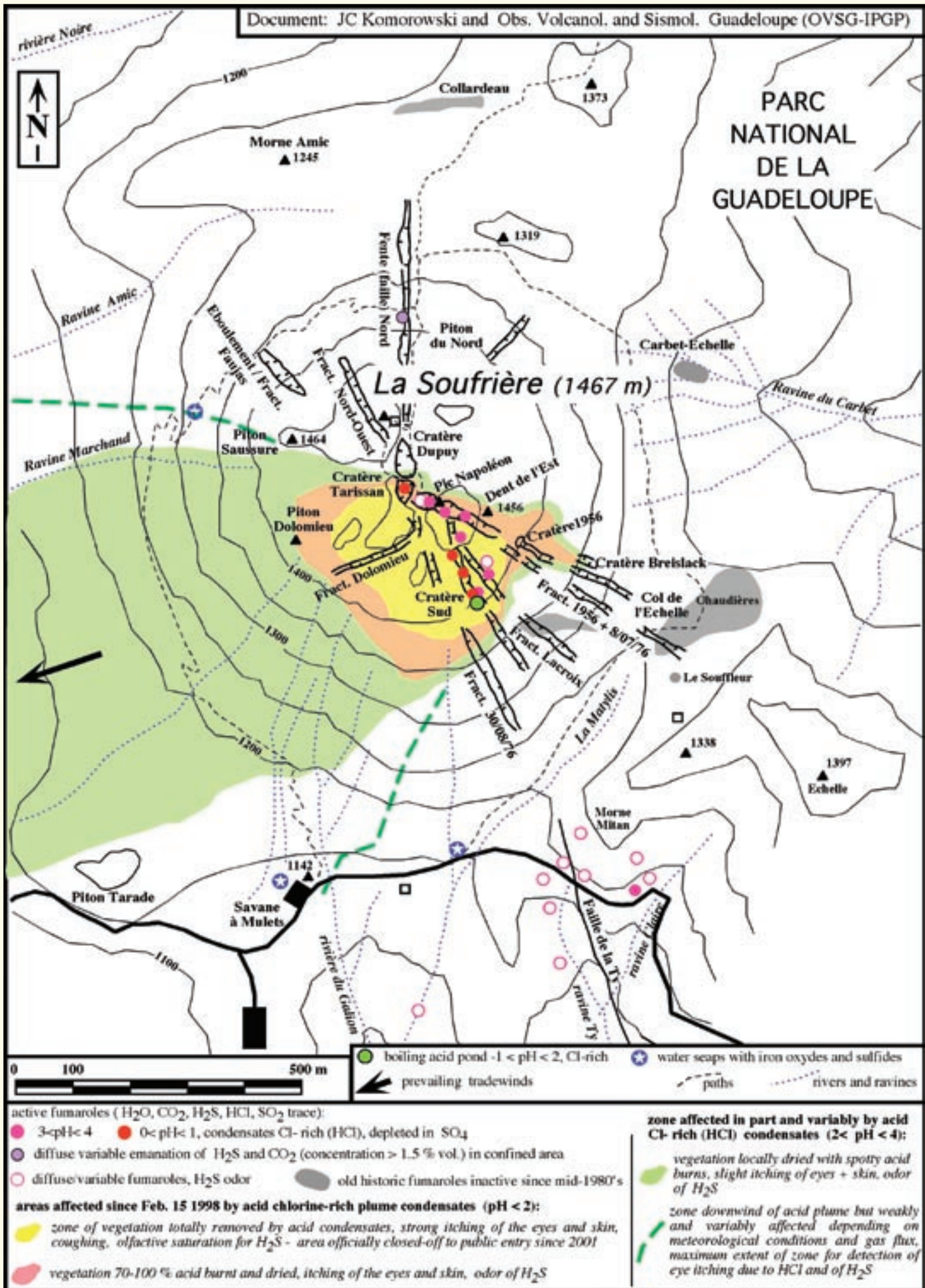
Other geothermal areas

In addition to those of the active Soufrière volcano, there are numerous subaerial as well as submarine surface manifestations of high heat flux in other areas of Basse-Terre, which are testimony to its volcanic past and which feature in a comprehensive study by Brombach et al. (2000). The most extensive geothermal field is that of the Bouillante area located on the western Caribbean coast about 25 km NW of Soufrière volcano and in the central part of Basse-Terre island, a field mentioned in the earliest descriptions of Guadeloupe. Numerous warm to hot thermal springs are located inland of the coastline as well as within shallow waters along the coast. Both high salinity Na-Cl as well as Na-HCO$_3$ thermal springs are present. Due to geothermal exploration since the 1986, the maximum outlet temperature in the Bouillante field is about 74° C, but hotter submarine outlets were sampled at a temperature of 92° C and a depth of 23 m (Traineau et al. 1997). Steaming ground is also present in the Bouillante area. Four exploratory geothermal wells were drilled in the 1970's to depths of 350-2500 m. A temperature of 242° C was encountered at 338 m depth in a Na-Cl high salinity aqueous brine. Currently only one main well (BO2) is exploited to operate a 4.8 MW power plant, which represents about 10 % of the electricity needs of Guadeloupe. Current plans are to upgrade to 10 MW and ultimately 25 MW. Experiments involving the pumping of cold seawater into an old well (BO4) down to depths where it can be reheated before resurfacing have shown great potential (Traineau et al. 1997) and may result in an increase in productivity of the plant.

Boiling hyper acid (-1<pH<1.5) pond at the bottom of the Cratère Sud Sud (1998) (© JC. Komorowski/IPGP)

Map of the Soufrière dome with place names and synthesis of current fumarolic activity

Document: JC Komorowski and Obs. Volcanol. and Sismol. Guadeloupe (OVSG-IPGP)

PARC NATIONAL DE LA GUADELOUPE

La Soufrière (1467 m)

0   100   500 m

🟢 boiling acid pond -1 < pH < 2, Cl-rich   ✪ water seaps with iron oxides and sulfides

↙ prevailing tradewinds   ---- paths   ······ rivers and ravines

active fumaroles (H_2O, CO_2, H_2S, HCl, SO_2 trace):

● 3<pH< 4   ● 0< pH< 1, condensates Cl- rich (HCl), depleted in SO_4

◉ diffuse variable emanation of H_2S and CO_2 (concentration > 1.5 % vol.) in confined area

○ diffuse/variable fumaroles, H_2S odor   ▬ old historic fumaroles inactive since mid-1980's

areas affected since Feb. 15 1998 by acid chlorine-rich plume condensates (pH < 2):

🟨 zone of vegetation totally removed by acid condensates, strong itching of the eyes and skin, coughing, olfactive saturation for H_2S - area officially closed-off to public entry since 2001

🟧 vegetation 70-100 % acid burnt and dried, itching of the eyes and skin, odor of H_2S

zone affected in part and variably by acid Cl- rich (HCl) condensates (2< pH < 4):

🟩 vegetation locally dried with spotty acid burns, slight itching of eyes + skin, odor of H_2S

▬▬ zone downwind of acid plume but weakly and variably affected depending on meteorological conditions and gas flux, maximum extent of zone for detection of eye itching due to HCl and of H_2S

Since December 1997 there has been significant degassing of HCl in summit fumaroles leading to a plume pH oscillating between 0 and 2.7. Vapour flux and temperatures at the Cratère Sud have increased, and the Cratère Sud is now characterised by degassing from four distinct vents, three of which form moderately-sized plumes clearly visible from a distance of tens of kms, and the presence since April 1997 of a boiling pond of extremely acid water (pH between -1.5 and 1.5) present over extended yet variable time periods. An area of high heat flux and abnormal ground temperatures extends for a few tens of meters around the Cratère Sud area. During the 1976-77 phreatic eruption the Crater Tarissan had been particularly active, but following the eruption permanent visible degassing ceased. In late 1998 this crater reactivated, and since April 1999 vapour-flux, heat flux, and acidity have slowly yet steadily increased to form an almost permanent plume that, since August 2000, has also been clearly visible from several tens of km away. Monitoring by the observatory has revealed an increase in the acidity of Tarissan plume condensates since 1999 as well as the presence since 2001 of a boiling acid pond at a depth of 120 m. The Napoléon fracture at the summit has also shown signs of reactivation with the presence of low pressure fumaroles. Finally, since 1992 the temperature of some acid-sulfate thermal springs at the immediate base of the dome has shown a slow but systematic increase regardless of temporary or seasonal fluctuations in water discharge. Interestingly, no significant evolution in the major and trace element geochemistry of fumarolic gas and thermal springs has been detected.

Degassing from Tarissan crater, Soufrière dome, June 2000 (© JC. Komorowski/IPGP)

Currently, degassing consists predominantly of H_2O, CO_2, H_2S and HCl with only very minor traces of SO_2, which is typical for a superficial low-temperature hydrothermal system strongly buffered by meteoric water. Since 1994, however, the concentration of H_2S in monitored fumaroles has doubled. The significant chlorine degassing directly through the summit (ongoing since late 1997) has resulted in a clearly visible and significant degradation of the vegetation on the dome and its immediate surroundings (0.5 km) as well as irritation and burns to eyes, skin and respiratory pathways of people within a few tens to 200 meters downwind of the summit fumaroles.

Seismicity remains of low energy and shallow depth, and there has been no increase in the currently very low rate of felt seismicity (1 event every 1-2 years). There is no significant deformation of the massif and the dome, although since its installation in 1995 the extensometric network has documented

minor (2-14 mm) opening of certain summit fractures, in part correlated with the increased fumarolic activity. Variations over several years in the amplitude and spatio-temporal distribution of ground self-potential anomalies on and around the dome (Zlotnicki et al. 1992; 1994; personal communication) and chemical tracing of hydrothermal discharges (Bigot et al. 1994) are compatible with a model for progressive sealing at the periphery of the dome, associated with an increase of hydrothermal fluid flow to the south-west along a zone of weakness that may correspond with one of the recent edifice collapse structures, as well as with an increase in the thermal and hydrothermal fluid upflow centred on the dome itself.

Vegetation damage and soil erosion downwind from the HCl-rich gas plume of Soufrière, 2000 (© JC. Komorowski/IPGP)

The recent increase in geothermal activity together with low-energy shallow seismicity since late 1996 has prompted a significant upgrade in the staffing and monitoring network of the OVSG (IPGP), an enhancement of national research programmes, mitigation and emergency planning by Civil Protection authorities, and public awareness campaigns, including a monthly public activity bulletin on internet. Access to the entire summit was initially closed by the Prefet and the Parc National de la Guadeloupe in August 1999. In 2001 a revised delimitation of only parts of the summit area subjected to the acid plume was officially closed to the public. There are no current instrumentaly recorded signs that magma is rising or located near the surface. Nevertheless, because of the slow systematic increase in the seismic, fumarolic and thermal activity of the volcano, as well as the fact that some minor historical phreatic eruptions (1836; 1956) were not preceded by major noticeable changes, La Soufrière remains in a state of scientific and instrumental vigilance at alert level 2 (vigilance: increasing activity) and yellow on a four colour code.

HCl-rich degassing from Cratère Sud (right) and Tarissan craters (left) viewed from Basse-Terre, August 20/08/2000 (© JC. Komorowski/IPGP)

Numerous thermal springs occur on the Sans Toucher volcanic massif as well as within the Trois-Rivières Madeleine volcanic field. There are no major relict fluid discharges associated with the Monts Caraïbes volcanic field. Several sites with thermal springs are used for therapeutic purposes such as Ravine Chaude (33° C) near the town of Lamentin, Sofaïa near the town of Sainte-Rose, and the large Eaux Vives clinic in Saint-Claude Matouba on the SW flanks of the Soufrière volcano.

Future eruptions

Based on reconstruction of the eruptive activity of the GDS over the last 15,000 years we define five most likely eruptive scenarios in order of decreasing probability of occurrence: 1) Intense prolonged fumarolic activity; 2) Phreatic eruptions; 3) Edifice collapse eruptions; 4) Effusive and explosive dome-forming eruptions; and 5) Large explosive eruptions.

Scenario 1 (non-eruptive): Intense prolonged fumarolic activity.

Although this scenario does not involve a true eruption we believe it warrants consideration as the intense fumarolic activity that developed on several occasions in the historical period represents the most common activity at Soufrière volcano. Moreover, the moderate reactivation (in terms of nuisances and hazards) ongoing since 1998 has created some difficult issues for the authorities, who had not evaluated the risks and actions needed to mitigate minor non-eruptive phenomena of long-term duration. This recent reactivation provides a relevant analogue, although on a much lower scale, of what can be expected from Scenario 1. Effects of this reactivation have essentially been limited to a distance of 0.5 km from the vents, but some farmers complained of acid burns on their crops in Matouba at the height of the acid degassing phase (e.g. February to May 1998). They also reported unpleasant H_2S smells and tingling of the eyes in the Matouba-Papaye area (2.5 km SW and downwind from the dome) that coincided with days when the pH of fumarole condensates measured by the volcano observatory (OVSG, internal reports) were very low, and when visual observations confirmed that the gas plume was denser and hugging the topography on the SW slopes of the volcano. Although these phenomena were limited in time and thus their effects were very localised and minor, no thorough study of the environmental effects of this acid degassing has been made so far.

An intensification of the fumarolic activity can affect either or both peripheral and summit fumaroles. Intense prolonged fumarolic activity is likely to generate fumaroles with high gas flux and temperatures, increased concentrations of toxic gases such as H_2S and SO_2, accumulation of CO_2 in confined areas, and formation of corrosive and aggressive acid to extremely acid aerosols and condensates, affecting eyes, skin and respiratory pathways. A variety of factors could also lead to minor ash venting from high-pressure fumaroles and ejection of small rock fragments (like in the 1809-1812 period), and formation of boiling acid water pools. This activity will only affect areas within a few tens of meters from the active vents to a maximum of a few hundred meters immediately downwind from the vent. Except in the case of non-explosive phases of a phreatic eruption (scenario 2 discussed below), potential ash emissions linked to Scenario 1 will be of limited volume and should not cause significant problems in the atmosphere.

Finally, the prolonged degradation and even removal of vegetation on the Soufrière dome in areas subjected to acid degassing and condensates will cause enhanced erosion of the soil and steep unstable pyroclastic talus slopes of the dome already deeply incised by surface runoff from up to 10 m of annual rainfall. Small-volume slumps, rockslides, rockfalls and debris flows can be expected to form on the S-SW lower slopes of the dome, especially above the visitor's parking lot, at times of torrential rains, during the rainy season, following the passage of hurricanes, or following strong shallow-depth and nearby regional earthquakes, as was the case following the magnitude M = 6.4 Les Saintes shock of 21 November 2004, located about 25 km SW from the dome.

Recurrence rate of certain eruption types from the Grande-Découverte-Soufrière volcanic complex - excluding the Trois-Rivières-Madeleine volcanic complex

Eruption type	Number of events in 15,000 years	Estimated preliminary Eruption Return rate in years	Most recent eruption.
Edifice collapse with debris avalanches	10	1500[1]	1440 AD (564 years ago)
Dome with pyroclastic scoria/pumice	7	2143	1440 AD (564 years ago)
Distinct event with preserved blast / surge deposits	5 or 7	3000 - 2143	2550 years BP
Eruption with scoria cone and lava flows	≥3	≤5 000	11,600-1700 years BP ??
Phreatomagmatic eruptions	1	15,000[2]	1600-1700 years BP ??
Phreatic eruptions since 1635 AD	6 in 370 years	62[3]	1976-77 AD (28 years)
Large explosive eruptions	at least 3 in 50,000 years	16,600[4]	14,000-17,000 years BP

[1]   recurrence rate is smaller in the last 8500 years with 8 events giving a return rate of 1 eruption per 1,062 year
[2]   we include here the Citerne pre-scoria cone phreatomagmatic phase but EXCLUDE the phreatomagmatic eruptions of the Upper Galion dated at 12,700 years BP and associated with the Trois-Rivières-Madeleine volcanic complex (Boudon et al. 1988)
[3]   return rate based on historical record of 370 years since arrival western civilization in the Lesser Antilles in 1635 AD. Since all magmatic as well as flank-collapse eruptions will be associated with phreatic eruptions, and there is a return rate of one phreatic eruption every 2 years of non-magmatic historical activity, we can estimate based on the above table that at least about 264 phreatic eruptions might have occurred in the last 15,000 years
[4]   return rate is based here on a larger time interval for the last 50,000 years. Uncertainties exist because ^{14}C dates on pyroclastic and scoria flows form three clusters in the last 50,000 years (Boudon et al. 1988): 1) ca. 42 350 to 35 000 years BP; 2) 29,000 to 21,000 years BP; and 3) 17,000 to 14,000 years BP. Currently we are unable to determine how many distinct eruptions were responsible for this distribution of ^{14}C age dates

View (January 2005) of unstable southern flanks of Soufrière dome with prominent rockslides, slumping scars, and erosion of the upper devegetated slopes caused by the combined effects of HCl-rich degassing on vegetation since 1998, the exceptional rainfall of November 2004 and especially the 21 November les Saintes M = 6.4 regional earthquake

Scenario 2: Phreatic eruptions.

Scenario 2 is the most probable of all eruptive phenomena at the Grande Découverte-Soufrière volcano based on the historical record (6 phreatic eruptions, in 1690; 1798-98; 1812; 1836-37; 1956 and 1976-77) and on an extrapolation over the longer time frame of 15,000 years over which other eruption type return rates have determined. All magmatic eruptions will begin with a phreatic phase. Most phreatic eruptions, however, will not lead to a magmatic phase. This constitutes one of the major and most challenging issues to resolve in hazard and risk assessment on any volcano and particularly on La Soufrière of Guadeloupe. Phreatic eruptions do not involve magma but can lead to loss of life and pose very significant risk to life for a large population living within 10 km of the vent. Indeed, they involve violent explosive phases, emit acid and toxic gases, and release fine ash composed of altered volcanic rocks into the atmosphere that can sometimes contain concentrations of hydrothermal minerals (sulphates, sulphides, silica polymorphs), whose particle-size could reach that of the respirable fraction and more importantly the respirable fraction. Phreatic eruptions are generally short-lived, but the 1797-98, 1836-37, and particularly 1976-77 events on La Soufrière show that they can pose significant problems and warrant at least partial evacuations for an extended period. Long-lasting eruptions will likely include several intense phases with more frequent explosions separated by repose periods characterised by non-explosive degassing and ash venting that can lead very suddenly and with little premonitory signs to new explosive phases.

Although they share many common aspects, the historical phreatic eruptions of La Soufrière are characterised by different eruption sites, duration, magnitude of the phenomena, type and magnitude of precursory phenomena, origin, and monitoring data. Scenario 2 will thus be defined in general terms and will need to be re-evaluated when pre-eruption monitoring data becomes available. A new phreatic eruption at La Soufrière will most likely occur from a vent located on one or several of the fractures on the dome that were active in the previous historical eruptions. The direct effects will likely be limited to a zone of about 1.5-2 km radius from the vent and up to 3-4 km down the main course of a few of the rivers that drain directly from the dome (Carbet, Galion, Amic, Marchand, Noire). In this proximal area we can expect locally directed ballistic showers with blocks up to a few tens of kilograms ejected up to about 1.5-2 km from the vent, small directed-blasts of mixed vapour and rock fragments causing severe removal of vegetation up to ≤1 km from the vent, and cumulated cold, non-juvenile ash and lapilli fallout deposits of up to 0.5 m to a distance of 1 km from the vent and particularly downwind but decreasing in thickness afterwards. Explosion breccias will form proximal rock avalanches and cold block-and-ash flows up to a few meters thick that include individual blocks weighing several tons and would flow up to 0.5-1 km from the vent before transforming into more water-rich debris flows. They could reach up to 3-4 km downslope in the deep valleys that drain the volcano to the E, S-SE, and SW, forming potential debris dams that could burst suddenly and generate secondary water surges and debris flows much further downstream. These debris flows would thus directly threaten some of the main tourist areas of the Parc National de la Guadeloupe. As witnessed in 1797-98, 1836-37, and 1976, the rise of the water table, usually during the early phase of the eruption, will generate primary water-saturated debris flows or lahars directly from the vent that will flow downstream and which could pose serious problems much further downstream than any other phenomena linked to Scenario 2. Landslides and slumping will be common on the steep flanks of the dome devegetated due to the presence of toxic and acid gas plumes and associated condensates.

Elsewhere, the significant potential impact on life in the area will be largely due to the indirect effects of the presence of ash and gases in the atmosphere. Accumulated downwind ash thickness could reach up to 5-15 mm in Saint-Claude town. Basse-Terre could be exposed to about 0.5-3 mm of cumulated ash. Occasional and usually not persistent reversed wind patterns may lead to communities to the E of the volcano being affected by up to 0.5 to 1.5 mm of fine ash as far as Capesterre on the Atlantic coast, about 15 km E of the vent. Environmental contamination effects discussed above for both Scenario 1 and 2 (see Box) will be more severe, widely dispersed, and long-lasting in the case of Scenario 2, and will peak after each explosive phase. Although phreatic eruptions should not have a significant impact on international air traffic routes around Guadeloupe and in the Caribbean, the presence of ash in the atmosphere will have to be carefully monitored and assessed. Energetic phreatic explosions are likely to generate cold, dense mixed ash-and-vapor clouds that form at the vent and behave as cold density currents. They can propagate down deep river valleys (e.g. Rivière Noire, Rivière des Pères) with velocities of 10-25 metres per second before reaching the sea, where they will expand laterally and slow down (e.g. October 2 1976 event described by Heiken et al. 1980). Finally, swarms of numerous and occasionally strongly felt volcanic earthquakes are likely to precede and will accompany the explosive phase of the eruption. They can cause severe damage and have to be considered a permanent serious hazard even when the volcano is not erupting.

It is also possible that phreatic eruptions could lead to sector collapse (see Scenario 3) of a very small portion (0.01 to 0.025 km^3) of the current dome (currently 0.05 km^3) and lead to the emplacement of a small-volume debris avalanche consisting of highly hydrothermally altered material and not associated with an explosive magmatic eruption as was repeatedly the case over the last 8500 years. This transition from Scenario 2 to Scenario 3 must be regarded as the most serious of all Scenario transitions, given the magnitude of the associated phenomena and the significant increase in the threatened areas and because precursory phenomena might go unnoticed.

Scenario 3: Edifice collapse eruptions

This is the next most likely eruptive scenario and also one of the most potentially devastating based on the eruptive record of the last 15,000 years. Indeed, at least 10 flank collapses have occurred for the Grande Découverte-La Soufrière complex in the last 15,000 years, of which 8 have occurred in the last 8,500 years. In addition, the last magmatic eruption (in 1440 AD) began with a small flank collapse which led to emplacement of a debris avalanche that probably stopped within 2 km of the Caribbean Sea. Evidence from the geological record indicates that in the last 15,000 years the frequency of partial edifice collapse has increased although the volume of the collapses has decreased. Structural factors (fractures, faults, etc.), morphological constraints (steep slope), the pervasive extensive hydrothermal alteration of parts of the Soufrière dome, the presence of a ring of thermal springs (discharge rate that can reach several kilograms per second) at the base of the dome, and the reactivation of the hydrothermal system involving acid fluids, all suggest that the Soufrière dome is predisposed to flank instability.

Past debris avalanches (volume <<1 km^3) were emplaced mostly to the S-SW, occasionally reaching the sea 8 km from the vent and covering up to about 34 km^2. A few events, including the 2500 years BP eruption, affected the eastern flanks of the massif, reaching the Atlantic coast and the town of Capesterre about 15 km from the vent. Within about 5 km from the vent, small volume avalanches (0.02-0.05 km^3) have been mostly channelled in the main river valleys (e.g. Galion River) to reach up to 50-60 m in thickness for individual events. Larger volume avalanches (0.05-0.5 km^3) have overflowed the paleo-river valleys and impacted a much wider area. These non-channelised debris avalanches deposits can reach a thickness of 5-10 m. The

towns of Saint-Claude and Basse-Terre and part of Gourbeyre are built on the 8 debris-avalanche deposits of the last 8,500 years. In addition, the towns of Capesterre and Trois-Rivieres were affected in part by at least one event. Depending on the volume involved and the sector of the dome that collapses (the S-SW sectors being the most likely candidates), any new sector collapse will cause widespread devastation over an area of about 20 to 40 km^2 of southern Basse-Terre. The most probable scenario involves collapse of part or all of the present small Soufrière dome, and most of the avalanche is therefore likely be channelled in the Galion river. It is likely to affect an area more limited than the maximum area affected by all debris avalanches of the last 8,500 years.

There is a high probability that edifice collapse will trigger laterally-directed explosions (between 2 and 5 of the 8 edifice collapses of the last 8,500 years generated laterally-directed blasts). Associated turbulent devastating blasts have the potential of covering an area of 30 to 80 km^2 in southern Basse-Terre, particularly if they are associated with a magmatic eruption and thus involve high-temperature gases and rock debris, as was the case in the largest of these events about 3,100 years ago (Boudon et al. 1984).

The entry of a debris avalanche into the sea will generate a hazardous tsunami that could have direct effects on the population concentrated near the Caribbean coast (most likely) or the Atlantic coast (least likely) of southern Basse-Terre, as well as the rest of coastal Guadeloupe and elsewhere in the Caribbean.

Material from debris avalanches that ponded in one or several river valleys will be remobilised by debris flows for a long time following the eruption. Depending on the magnitude of the collapse and whether a blast is associated with it, a significant ash cloud could be generated by the avalanche, thus affecting a large area downwind. The eastern part of Guadeloupe and perhaps other nearby islands could be affected by minor ash in the atmosphere if ash reaches above the altitude of 5-8 km where westerly counter-trade winds prevail. This would cause concern for aviation safety in the area.

The Boxing Day event on December 26, 1997 of the Soufrière Hills volcano on Montserrat (Sparks et al. 2002; Voight et al. 2002; Young et al. 2002) is a very good analogue for the small-volume

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MAIN ENVIRONMENTAL INDIRECT EFFECTS COMMON TO ALL ERUPTIVE SCENARIOS

Long-term emanations of gases (SO_2, HCl, HF, H_2S) are likely to cause some indirect nuisances to crops, cattle, and disturbances to the population or even infrastructure because of the highly corrosive properties of the associated acid condensates (HCl, F, H_2SO_4) and acid rainfall. The extent of these nuisances will depend on many factors including the gas chemistry and flux, the number of vents and their location, meteorological factors and the duration of the crisis. Not all of the hazards discussed below will be present, but this should serve as a guide to some of the potential problems that will need assessment and monitoring in all scenarios, including the non-eruptive Scenario 1 which may last for a long time with potential chronic although non-acute effects. Agricultural crops and animal feeds are likely to be contaminated to

varying degrees downwind of the volcano and up to a distance of a few kilometres, including the very rich agricultural fields of the Matouba-Saint Claude area. The springs, including those used for bottled water, streams and water collection tanks that are used for water consumption in Guadeloupe could be affected, and would have to be monitored closely for potential contamination by acid compounds (F, HCl), sulphates, and other trace metals that could be associated with acid gaseous emissions. Roofs made of corrugated metal sheets could be corroded by acid rains and thus contaminate rain water. Persistent exposure to low-concentration SO_2, H_2S and HCl aerosols as well as hazardous mineral dusts (e.g. silica polymorphs) may cause health problems in the local population.

avalanche described above for Scenario 3, which represents the most hazardous of the high-probability future events of La Soufrière of Guadeloupe. Moreover the eruptive record clearly indicates that they have occurred as part of phreatic eruptions (Scenario 2) as well as dome-forming eruptions (Scenario 4) or large open-crater explosive eruptions (Scenario 5).

Scenario 4: Effusive and explosive dome-forming eruptions

Although the eruptive record for such eruptions is the least widely preserved, at least 7 dome-forming eruptions have occurred over the last 15,000 years in the Grande Découverte-Soufrière volcanic complex. This is considered the second most-likely scenario for a major volcanic eruption in Guadeloupe. Based on the eruptive record, the most likely vent location will be over or within a radius of 0.5 to 1 km from the Soufrière dome. The precise location cannot be determined until precursory signs such as earthquake swarms, phreatic activity, and ground deformation are recorded. It will, however, have a major influence on which sector of southern Basse-Terre will be most threatened. The main hazards associated with dome eruptions are the formation of pyroclastic flows and surges linked to oversteepening and gravitational collapse of the dome. Eruption of less degassed rapidly ascending magma during vulcanian to subplinian explosive eruptions will develop eruption columns that will collapse and produce more energetic pumice or scoria pyroclastic flows with associated ash and pumice/scoria falls and turbulent pyroclastic surges. Because this is the most frequent magmatic eruption type in the Caribbean for the last century, this scenario has been described, studied, and monitored intensely for example at Montagne Pelée, St. Vincent, and most recently at Soufrière Hills (Montserrat) (see this volume for other descriptions).

The most serious consequence of a dome eruption is the generation of laterally-directed explosions from the base or from sectors of a fast growing pressurised dome which will then trigger highly devastating density currents or blasts best exemplified by the explosive "nuées ardentes" of the May 8, 1902 Montagne Pelée eruption (see Martinique, this volume). These blasts consist of very rapidly expanding (on the order of 100 m/s or more) turbulent hot mixture of gas and dome fragments (mm to cm size) that descend the slopes of the volcano regardless of topography and cause total devastation in a few seconds.

There are three principal variations of a dome-forming eruption scenario: 1) The dome eruption could involve passive non-explosive formation of a dome as in the case of the St Vincent 1971-72 eruption (See St. Vincent, this volume), 2) The dome eruption could proceed like the 1902 Montagne Pelée eruption, with paroxysmal explosive events occurring in the initial phases of the eruption after only a few days of dome growth (see Martinique, this volume), although dome growth might continue for 3 to 4 years, and 3) Dome growth could proceed in an essentially effusive manner with pyroclastic flows progressively increasing in runout distance, eventually leading to a paroxysmal blast-type event well after the onset of the crisis. This is best exemplified by the nearly decade-long complex dome eruption of the Soufrière Hills, Montserrat (see Montserrat, this volume), which is characterised by phases of gradual increase in the intensity of the eruption that culminate with gravitational collapses of large parts of or almost the entire

dome resulting in pyroclastic flows, surges, and tephra falls, which are separated from phases of new dome growth by repose periods of a few days to up to a year. On Montserrat the first and most violent explosion of the dome occurred on December 26, 1997, more than 2 years after the onset of dome growth (Sparks et al. 2002).

The overall spatio-temporal intensity pattern of any future dome eruption at La Soufrière of Guadeloupe will strongly control the magnitude and extent of associated hazards. The majority of edifice collapses in the last 15,000 years have led to the formation of a marked poly-phased collapse crater oriented to S-SW towards the most populated areas of Basse-Terre and Saint-Claude. All dome activity in the last 8,500 years has developed within this structure. Thus depending on the position of the new dome and its evolution throughout the eruption, the most likely direction for pyroclastic flow and surges is towards the most populated areas. As in most scenarios, significant hazards threaten towns of Saint-Claude, Basse-Terre, and Gourbeyre to the SW of the volcano, where several deep rivers will likely channel pyroclastic flows to a significant distance and thus further towards the lower elevation and more populated areas. Pyroclastic surges will likely pose a significant threat to most of the town of Saint-Claude area, but the most energetic pyroclastic surges could reach the lower part of Saint-Claude and upper part of Basse-Terre to a distance of about 6-7 km. A marked notch in the topography of the volcano could help surges cross over onto the W-SW parts of the volcano in the Matouba-Papaye area and towards the lower Rivière St-Louis area. The next most hazardous area is to the E of the volcano towards the town of Capesterre, which is located at the mouth of the Carbet river system and is not shielded by any significant topography. The topographic relief of the Trois-Rivières-Madeleine volcanic field (Madeleine dome, Palmiste plateau) will provide some protection to Trois-Rivières, although pyroclastic flows could descend at least partly down the Rivière Grande Anse and Rivière Petit Carbet. Magmatic blasts related to laterally-directed cryptodome or major dome explosions are likely to reach up to 5-8 km from the vent, devastating an area of up to 70-100 km^2.

Dome eruptions will also produce significant quantities of more or less vesicular material that will be carried by prevailing easterly winds to the W-SW. Any material injected into the atmosphere above the altitude of the tropopause in the region (5-8 km) will then be transported by counter-trade winds (westerlies) over eastern regions of Guadeloupe and other parts of the Caribbean thus causing concern for civil aviation as well as environmental contamination. Downwind environmental effects discussed previously (see the box) will be most pronounced, widespread, and persistent in the case of dome eruptions that tend to last several years and can involve significant magma production with associated gas and ash emissions (e.g. Soufrière Hills eruption). Cumulative thicknesses of up to 1 m of tephra can be expected within 1 to 1.5 km from the vent, rapidly decreasing to 2-5 cm in the Basse-Terre area depending on the magnitude of the eruption. Debris flows in all river valleys affected by pyroclastic flows and tephra fall will continue to pose hazards to the population and the infrastructure several years to decades after the cessation of eruptive activity.

A dome eruption (Scenario 4) at La Soufrière could involve a

partial edifice collapse (Scenario 3) at the onset of the eruption or during the eruption, as was the case in 1997 at Soufrière Hills (Montserrat), thus increasing the magnitude and extension of the hazards. Entry of debris avalanches and associated pyroclastic flows into the sea is likely to generate tsunamis whose hazards must be evaluated for the coastlines of Basse-Terre, the rest of Guadeloupe and other nearby islands. Pyroclastic flows from a large dome collapse of Soufrière Hills on July 9, 2003 (Montserrat Volcano Observatory report) generated a tsunami that had local effects on the E coast of Montserrat (A. Le Friant, personal communication) but also upturned several fishing boats in the port of Deshaies in northern Basse-Terre island, Guadeloupe.

Scenario 5 (least likely): Large explosive eruptions
Based on past distribution of widespread pyroclastic deposits Scenario 5 is the worst-case scenario for the Grande Découverte Soufrière volcanic complex. It is likely to be associated with a larger crater or caldera collapse event and could involve up to 1-2 km^3 of magma. Regional pyroclastic flows associated with energetic pyroclastic surges would cover most of the southern Basse-Terre area, draining first in all major rivers before expanding on the lower elevation flatter coastal areas. The topographic relief of the Trois Rivières-Madeleine complex would likely offer the Trois-Rivières area some partial protection in an otherwise extensive pyroclastic flow fan. Associated ash and vesicular tephra fall could reach up to 2 m in thickness to a distance of 8 km downwind from the vent for the largest event (e.g. Pintade 42,000 years BP eruption) to a minimum of 15 cm at the same distance for much smaller eruptions (e.g. St Phy 26,000 years BP eruption). Tephra would be injected high in the atmosphere and would cause widespread disturbances to regional and international aviation routes in the area as well as nuisances that could reach several tens to hundreds of kilometres from the eruption site. All other environmental effects discussed previously, as well as debris flow and tsunami hazards, would be magnified and more probable, with more widespread effects in the area. Although this is the least frequent, least probable scenario, Scenario 5 has the most violent and devastating local and regional effects (Maximum Potential Event). The estimated preliminary recurrence rate of 1 event every 16,600 years that can be initially proposed for Scenario 5 may increase with further studies. It is important to bear in mind that the time period that has passed (i.e. 14,500 years) since the most recent large explosive pumiceous pyroclastic-flow eruption of the type described in Scenario 5 is similar to the conservative estimate of the return rate of 1 every 16,600 years for such events based on a 50,000 year record.

Integrated Volcanic Hazards Zones
The areas most likely to be affected in the five eruptive scenarios defined for an eruption from a vent on or within 1 km the Soufrière dome and within the S-SW oriented most-recent edifice collapse depression and with the assumption of the presence of easterly trade winds between 0 and 5-8 km altitude have been used to determine 4 integrated hazard zones for southern Basse-Terre island only. This provides an indication of overall hazard for that part of the island.
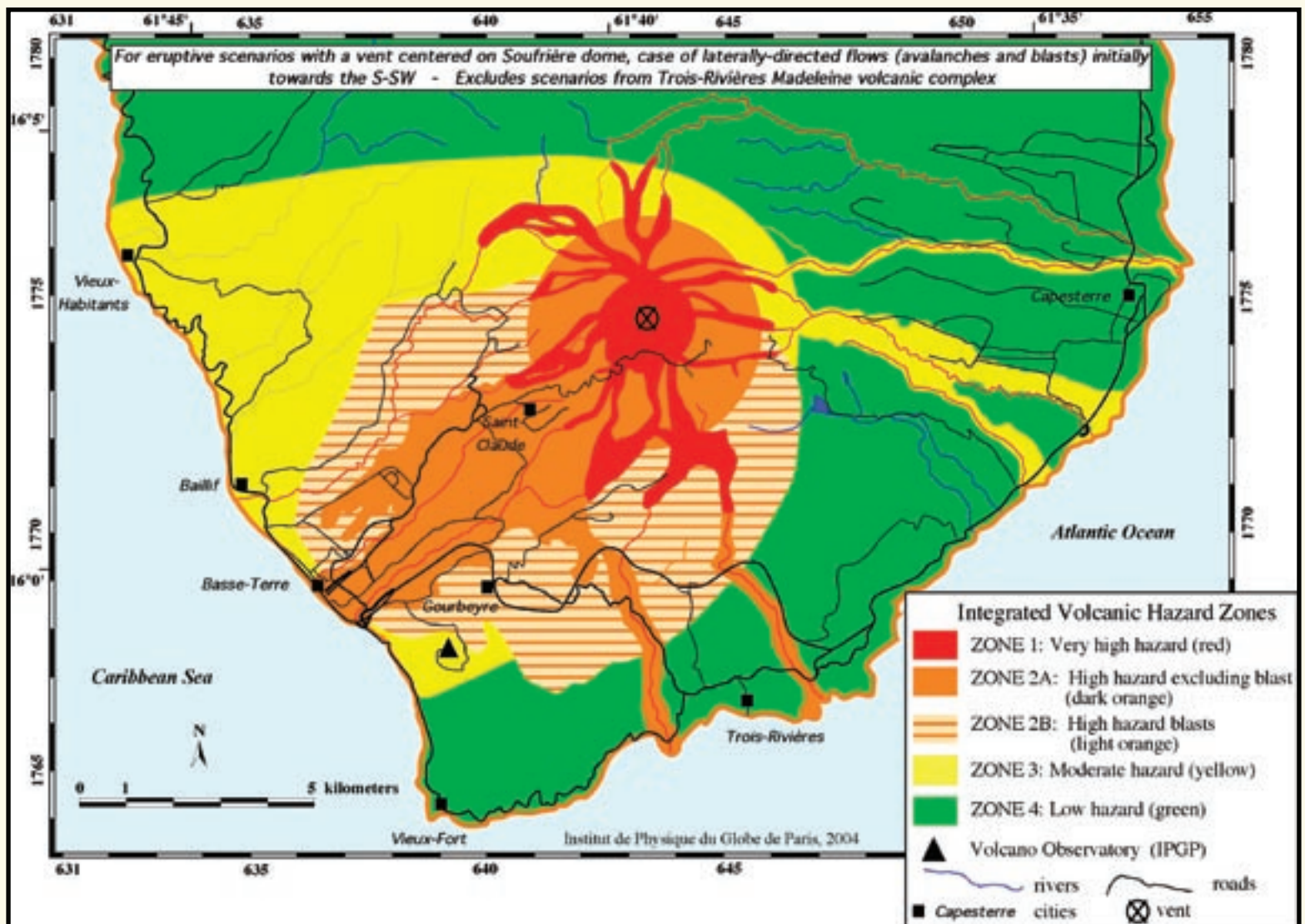
The rest of Guadeloupe sensu largo could be indirectly affected: 1) by minor ash falls that could present a hazard to civil aviation,

a nuisance to the population and a low environmental hazard because they are likely to contain minor amounts of volcanic mineral dusts (e.g. cristobalite, sulphates) and acid condensates; 2) by felt volcanic earthquakes; and 3) by minor tsunamis. We have analysed the eruptive record (recurrence, intensity, dispersion, nature of the phenomena), evidence from other well-studied eruptions, and general geographical knowledge of the area to determine the various hazard zones for each scenario. We have determined 5 different integrated hazard zones that take into consideration all phenomena likely to affect that area as well as their recurrence and intensity.

We deliberately chose not to present a hazard map for each of the 5 scenarios because eruptions of Soufrière are complex events that frequently evolve from one scenario to another and lead to a superposition of phenomena and deposits in basically the same areas. Moreover there exist many possibilities for a vent location and for the overall magnitude of the eruption and the temporal-volcanic intensity pattern, such that any map would represent an oversimplification in the absence of more robust physical modelling data and simulations. In addition, for many eruptions the pyroclastic eruptive record consist of scattered outcrops which do not allow scenarios to be determined in as much detail as would be hoped.

Zone 1 (red) is the area of very high hazard. This is the area that will most likely be affected by a new dome-forming eruption generating pyroclastic flows and surges (Scenario 4). It is also the area subjected to ballistic fallout from an eruption column that could reach 5-10 km in height and experience periodic collapse, as well as fallout of a few tens of centimetres up to 1 m of ash or vesicular fragments. Zone 1 will also contain areas that can be reached by cold block-and-ash flows, small directed blasts, and directed ballistic showers during phreatic eruptions (Scenario 2). Any valley affected by pyroclastic flows as well as areas of significant tephra deposition are likely to generate debris flows (lahars) that can travel downstream much further that the pyroclastic flow terminus. Depending on the integrated hazard, rivers valleys likely to be affected by debris flows are shown in the colour according to level of hazard characterising the upslope pyroclastic-flow source areas. Phreatic water-rich debris flows can also be generated directly from the vent during phreatic eruptions. In the advent of such an eruption, zone 1 will have to be evacuated before the eruption begins. Areas on the periphery will have to be ready to evacuate on very short notice or might be evacuated preventively as soon as the eruption data suggest that a laterally-directed dome explosion (blast) could occur thus affecting a wider area.

Zone 2 (orange) is the zone of high hazard. We have subdivided this zone into 2 zones of equal level of hazard but linked to very different phenomena. Zone 2A is the maximum area likely to be affected by debris avalanches (Scenario 3) generated in a future partial edifice collapse of the Soufrière dome, associated debris flows, as well as the most energetic pyroclastic flows and surges that would accompany such eruptions or large dome eruptions (Scenario 4) but excluding any laterally-directed blasts. This zone was determined using the maximum hazard zones for debris avalanches that have occurred from the Soufrière area in the last 15,000 years together with the areas likely to be affected by ballistics ejecta, thicknesses of 5 cm to a few tens

Integrated volcanic hazards zones for southern Basse-Terre (Guadeloupe) based on eruptive scenarios 1-5

of centimetres of tephra from dome eruptions, and the most energetic pyroclastic flows from dome eruptions. Because of its current limited size, any future edifice collapse is likely not to affect this entire area. Debris avalanches will probably be channelled in a few of the deepest valleys depending on the orientation of the collapse. This zone also includes a narrow band of a few meters to perhaps of few tens of meters all along the coastline of southern Basse-Terre that could be affected by tsunamis generated upon entry in the sea of large volumes of debris from debris avalanches or pyroclastic flows. Zone 2A is also the area where the most serious environmental effects related to any scenario (1-5) are expected to be experienced with varying intensity and duration depending on the scenario and possibly extending to zone 2B.

Zone 2B (crosshatched light orange) is the zone that is likely to be affected by laterally-directed blasts and the most violent pyroclastic surges either associated with edifice collapse and emplacement of debris avalanches (Scenario 3) or with violent Montagne Pelée 1902 or Soufrière Hills Boxing Day type dome explosions (Scenario 4).

Zone 3 (yellow) is a zone of moderate hazard. It was defined using the zone where tephra falls from dome eruptions will be less than 5 cm thick in case of normal prevailing winds. More importantly this zone could be affected by the least likely

but worst-case scenario (Scenario 5). We feel it is important to include this scenario in the hazard map because: 1) this scenario is the least well-constrained by eruption data, but ^{14}C ages of regional pyroclastic flow deposits from such a scenario extend from 42,000 years BP to more frequent and recent dates fall between 29,000 and 14,800 years BP, and 2) in the most conservative hypothesis, already 14,000 – 17,000 years have passed since the last-dated such eruption, a value equal to our estimate return rate (which could be reduced in the future pending new age dates). These voluminous pyroclastic flows are likely to affect the major Rivière du Carbet drainage to the E of the volcano, thus posing a hazard to the large town of Capesterre but primarily again to the area of Basse-Terre where they have accumulated up to 10-15 m for individual ponded flow units. Although the least frequent, the fact that these eruptions affect a wide area with intense phenomena justifies the inclusion of their effects within the moderate hazard zone. Occasional individual tephra falls associated with these eruptions can lead up to accumulation of 1 m at a distance of 8 km to up to several meters closer to the volcano and downwind. Thus zone 3 also includes the hazard zone associated with such rare tephra falls.

Zone 4 (green) is the zone of low hazard. It includes the area that could be affected by distal thin ash falls and the most widespread of the environmental ash and gas plume hazards.

All hazard zones are likely to be affected by moderately to strongly felt earthquakes that can occur repeatedly in swarms of several events in a short time and for several months thus posing a hazard to houses, other structures and lifelines, as well as generating psychological stress in any portion of the population that would not have been evacuated.

The boundaries of the integrated hazard zones must never be considered sharp, narrow precise lines as shown on the map. The boundaries will vary slightly depending on the specific vent location, weather conditions, as well as the chronology and evolution of the eruption. This hazard map will be revised periodically as new field, analytical, and modelling data provide us with a better understanding of eruptive processes from Soufrière volcano, and regularly in the event of a significant reawakening of the volcano. This hazard map only concerns the southern part of Basse-Terre island. In the event of an eruption, hazard zones will also be evaluated for the maritime area surrounding the volcano as well as for regional effects of the eruption on nearby islands and the rest of Guadeloupe as mentioned above. Pyroclastic flows and surges can travel over water, and ash falls are likely to be significant on the downwind western side of the volcano. Particular attention will be paid to the problems resulting from the presence of volcanic ash in the atmosphere and the potential propagation of tsunamis which could generate waves of varying run-up heights on the populated low-lying coastal areas of nearby islands.

Conclusion

Potential future reactivation of La Soufrière volcano of Guadeloupe will pose significant hazards and risks for the ca. 73,000 people (1999 census) which reside within 15 km of the volcano in southern Basse-Terre island. They represent 17 % of the population of the entire Guadeloupe region including nearby island dependencies and up to 20 % of the Guadeloupe mainland population excluding all dependencies. At least 10,000 people live within an area affected by scoria flow of the AD 1440 dome eruption, and more than 63,000 live within 10 km of the volcano in an area affected by at least 8 debris avalanches from repetitive edifice collapse in the last 8,500 years, at least one of which was associated with a magmatic blast about 3,000 years ago. Moreover, the indirect consequences of a Montserrat-like eruption would be significant for the remainder of Guadeloupe as well as for nearby islands.

View (January 2005) of Soufrière from the centre of Basse-Terre located 9 km SW and downwind from the volcano

Phreatic eruptions (Scenario 2) are the most frequent and most probable on Soufrière volcano. The next most frequent eruptions in the last 15,000 years are the highly damaging edifice collapse events (Scenario 3) which can actually occur in all scenarios, including a major phreatic eruption without involvement of magma. Scenario 3 is the most hazardous probable eruption to the populations of Saint-Claude, Basse-Terre, Gourbeyre and Trois-Rivières for a total estimated population of about 39,000 and up to about 58,600 if collapse affects not only the SW but also the SE flanks of the volcano. This area does not include population that could be affected by tsunamis triggered by debris-avalanches entering the sea; such events could affect the coastline of southern Basse-Terre and nearby islands, and potentially reach further. Probable dome eruptions (Scenario 4), such as the 1440 AD eruption of La Soufrière or an eruption similar to the Soufrière Hills eruption in Montserrat, will also directly or indirectly threaten most of the southern part of Basse-Terre island.

These facts must be taken into consideration in the long term planning of land-use and development of the Basse-Terre area, particularly in terms of lasting infrastructures (industry, education, health, crisis management centres, roads and bridges) as well as in terms of life-lines (e.g. water resources). The current volcanic crisis rescue plans must be updated to take into consideration the concept of transitional and evolutionary volcanic eruptive scenarios and probabilistic risk assessment.

Volcanic crises can last for a long time and require long-term management as is shown by the 10-year long eruption of the Soufrière Hills of Montserrat. Finally it is also important to note that, based on the current expansion of land-use and demographics in southern Basse-Terre and the socio-economic demands and expectations of the population, eruptive as well as prolonged non-eruptive intense phases of fumarolic degassing are likely to have lasting effects and pose nuisances on life in the Basse-Terre area. Although no signs on an impending eruption can be detected, the current slow but systematic increase in seismic, fumarolic, and thermal activity of La Soufrière volcano must stand as a reminder that it remains an active volcano capable of developing on a human time scale either of several potential eruptive scenarios. Each would pose a wide array of significant risks to life and property that also affect the long-term development of the southern part of the island already struggling to recover from the socio-economic consequences of the 1976-77 phreatic eruptions.

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