Field trip on La Soufrière volcano

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The volcanism in Guadeloupe: Basse-Terre and Grande Découverte – La Soufrière Complex

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Geographical and geological 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 last 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.

The Basse-Terre eruptive centres

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 centers that form a continuous 55 km-long volcanic chain trending NNW, 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 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 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 (140 Ma) and the Montval quartz dacite pumice flow deposit (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.

The Grande Découverte-Soufrière (GDS) volcanic center is the only active volcanic center 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 1467 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.

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) suggest, 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 that 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 By U-Th disequilibrium (B. Villemant, personal communication). 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 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 ^{14}C 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 km2 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 channeled 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 characterizes the end of this phase between 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 y BP (Komorowski et al. 2002) and 11,500 y 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 y 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 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 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 yBP 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-channeled areas. Deposits are almost entirely composed of very hydrothermaly 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 well-established history of partial collapse, and displays extensive debris-avalanche deposits which cover the area of the heavily populated cities of St Claude and Basse-Terre. At least 2 and perhaps up to 5 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 1700 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 km3 in size) that sometimes reached the sea 8 km from the vent.

The most recent collapse dated at about 1440AD (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 5 historical phreatic explosive eruptions. The 1440AD eruption is particular 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).

Historical activity and 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 1440AD eruption. In addition, calibrated ^{14}C age dates have been obtained on a lahar deposit (1550AD), a pyroclastic surge deposit (1590AD), and a pumice/scoria fall deposit (1600AD) (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 1635AD and the first more detailed written accounts of eruptive activity.

Historical eruptive activity since 1635AD has consisted exclusively of 6 phreatic explosive eruptions, with minor events in 1690, 1812, 1836-37, 1956, and major events in 1797-98 and 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 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; 45 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 1690AD probably similar in magnitude to that observed in 1956AD (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.

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 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 the eruption, fumarolic activity showed no significant and systematic increase, and was perhaps even declining, although fumaroles were emitting large volumes of vapor 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 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 1800hrs with a loud rumbling noise heard in all of Basse-Terre, accompanied by a felt earthquake at about 2000hrs. The rumbling increased in loudness until it sounded as if a canon had been shot, after which time it subsided. Around 2400hrs a loud howling sound, similar to what can be heard during a hurricane, was heard, and at around 0230hrs 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 signifiant 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 kilometers 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 smelt strongly of H_2S and was more viscous than usual. Starting at about 1000hrs 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 vapor 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 odor (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 center of the summit plateau towards the NNW, and this, together with a fracture just above the Dent de l’Est collapse (i.e. probably the southern part of the Napoleon 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 NNW fracture.

Several additional phreatic explosions occurred up until April 1798, producing ash falls even to the east above Capesterre town. On April 22 at 1400hrs 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 NNW 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 kilometers. 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 plowed, 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 NNW 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 1400hrs or 1500hrs (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 kilometers 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 NNW 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, historic, 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 20 feet, 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 Mount Pelée (Lacroix 1904) and at the beginning of the ongoing Soufrière Hills, Montserrat eruption in 1995 (G. Hammouya, personal communication).

The 1956 phreatic eruption

Only 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 Napoleon 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 2339hrs 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 vapor plume could be seen rising 500 m above the volcano. However, the great Souffleur fumaroles located at the eastern base of the dome that 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 1800hrs 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 undistinguishable, 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 center 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 vapor, 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^o 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, Napoleon) and on the flanks (1956, Lacroix, Collardeau, Carbet-Echelle, Chaudières-Souffleur). The total volume of ejecta was estimated at about 0.1×10^6 m^3 (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 (eg. 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 methodologies which led to significantly improved crisis management as early as the 1979 St. Vincent eruption as well as elsewhere in the world.

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 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 1220 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 x 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, 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_2S-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, 25. Seismic activity continued to increase to reach a maximum of 1257 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 5989 earthquakes recorded of which at least 41 were felt. The largest earthquake (magnitude Md =4.2, intensity MSK VI) was felt even in Pointe-à-Pitre more than 50 km away on August 16. On August 18, 1000 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 60,000 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 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 to the summit plateau and the center of the dome over several hundred meters 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 1716 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, 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 2315 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 1040 recorded shocks in November.

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-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 hydrothermaly 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 epicenters form an area 10 x 6 km centered 1 km N of the dome and oriented NW-SE. Hypocenters 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 hypocenters 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^o C) degassing of H_2O (1010 kg) and minor quantities 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 1440AD. Recent work by Villemant et al. (2005) confirms this hypothseis based on an analysis of the variation of the geochemistry of hydrothermal springs in the last 25 years.

Two models have been proposed to explain the explosive phenomena. The first model (Feuillard et al. 1983) suggests 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.

Impact of the 1976-1977 eruption on the local population

The 1976-1977 eruption engendered significant and recurrent nuisances and risk 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 of crops and fields used for cattle grazing by acid condensates and other trace elements adsorbed on the surface of the erupted ash, in particular fluorine. 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 1997 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.

Volcanic 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 7-8 January 1981, on 22-24 November 1982, on 8-9 January 1983, 16-17 October 1983, and on 15 October 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.

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 1259 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 Napoleon 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 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 centered 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 microfracturing of locally very altered mecanically 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 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.

Hydrothermal activity

Apart from the Bouillante area, the most important and widespread manifestations of geothermal activity in Guadeloupe (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.

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). 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).

Since December 1997 there has been significant degassing of HCl in summit fumaroles leading to a plume pH oscillating between 0 and 2.7. Vapor 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 generally permanent boiling pond of extremely acid water (pH between -1 and 1.5). 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 vapor-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.

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 (2-7 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 centered on the dome itself.

Recent increase in geothermal activity together and 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 National Park in August 1999. In 2001 a revised delimitation of only parts of the summit area subjected to the acid plume was officially closed-off 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, and the fact that 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 ("Increasing activity").

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Field trip on la Soufrière volcano

Departure from Houelmont Observatory towards Soufrière

Stop 1: Galion bridge and Fort Delgrès in Basse-Terre : Outcrops of the sequence of debris avalanche covering the southwestern flank of the volcano.

The debris avalanche deposits outcrop in the cliffs of the Galion River. At least 4 debris avalanche deposits can be observed in the cliffs. The lower is dated around 8500 years BP and the upper deposit is the 565 y old (1440 AD) deposit. The top of each debris avalanche deposits is covered by a paleaosoil and in some cases we can observed at the base of the deposit a small fine-grained deposit interpreted as resulting of a lateral directed blast. It is the case for the 3100 years BP debris avalanche deposit. This deposit can be observed along the road in front of the parking of the Fort Delgrès. The lateral directed blast, generated by the depressurization of the volcanic gases (magmatic and hydrothermal), during the flank-collapse has a higher velocity than the debris avalanche. It arrived at the coast before the debris avalanche.

Stop 2 : If the weather is good, **panoramic view of the Grande Découverte – la Soufrière volcano,** from Basse-Terre city. From this place, we can see a great part of the volcano :

- the north flank of the primitive edifice
- the Carmichaël flank-collapse crater, and the 11500 years BP debris avalanche deposit on the west flank of the volcano
- the Nez Cassé lava dome located between the two flank-collapse craters
- the Amic horseshoe-shaped crater resulting of the 3100 years BP flank-collapse event
- the Soufrière lava dome located inside the Amic crater.

During the transport from Basse-Terre to Saint-Claude, we drive on the sequence of the debris avalanche deposits, generally on the 3100 years BP one, and sometimes on the blast deposit of the 3100 years BP eruption.

Stop 3 : La Savane à Mulets parking.

View of the most recent eruptive centres of the Grande Découverte volcano: l'Echelle scoriaceous cone and the Soufrière lava dome. On the west part, the Piton Tarade is a megablock which slided from the horseshoe-shaped Amic crater (3100 years BP) during the flank-collapse.

Departure to the top of the Soufrière lava dome by the "Chemin des Dames" (Path for Ladies)

Stop 4 : View of the north-west rim of the Amic horseshoe-shaped crater.

Inside this structure, we can see the Amic lava dome, which is cut by the Soufrière Crater. On the Soufrière lava dome, the 1798 fracture formed during the large 1797-1798 phreatic eruption, produced an important rock slide in the little Amic river.

Stop 5 : The “Fente du Nord” or North fault.

It is a great fracture, of N-S direction, which cut the Soufrière lava dome in two parts.

Stop 6 : Top of the Soufrière lava dome; visit of the summit part of the dome.

The lava dome is cut by several radial fractures, formed during the numerous phreatic eruptions since 1680. Some of these fractures are deep (for example Tarissan pit). The Tarissan pit and the “Cratère du Sud” (South crater) has a very important fumarolic activity with acidic gases. Vapor venting significantly increased in 1992 for the Cratère du Sud and in 1998 for the Tarissan pit and also for the Cratère du Sud.

If the weather is good : view of the northern part of the Grande Découverte composite volcano, of the Echelle and Citerne scoriaceous cones and of the south part of the island (St. Claude and Basse-Terre towns, Mont Caraïbes where the Volcanological and Seismological Observatory is constructed.

Stop 7 : Col de l’Echelle

View of the Echelle scoriaceaous cone and of the east part of the Soufrière lava dome, cut by the fractures produced during the 1956 and 1976-77 phreatic eruptions. We can also see a small lahar deposit and the block avalanches formed during the 1976-77 eruption on July 8 and August 30 1976.

Stop 8 : Fumarolic area of Morne Mitan

The south part of the edifice (Soufrière lava dome, Echelle and Citerne scoria cones) is cut by a regional normal fault named “Ty fault” of NNW-SSE direction. This fault was reactivated during the 1976-77 phreatic eruption. The fracture opened in the lava dome during the August 30, 1976 explosion is in alignment with this regional fault.

Return to the Savane à Mulets parking

Stop 9 : Matouba – Morne Savon :

Outcrops of two lateral directed magmatic blast deposits associated to the flank-collapse eruptions of 3100 years BP and 2400 years BP.

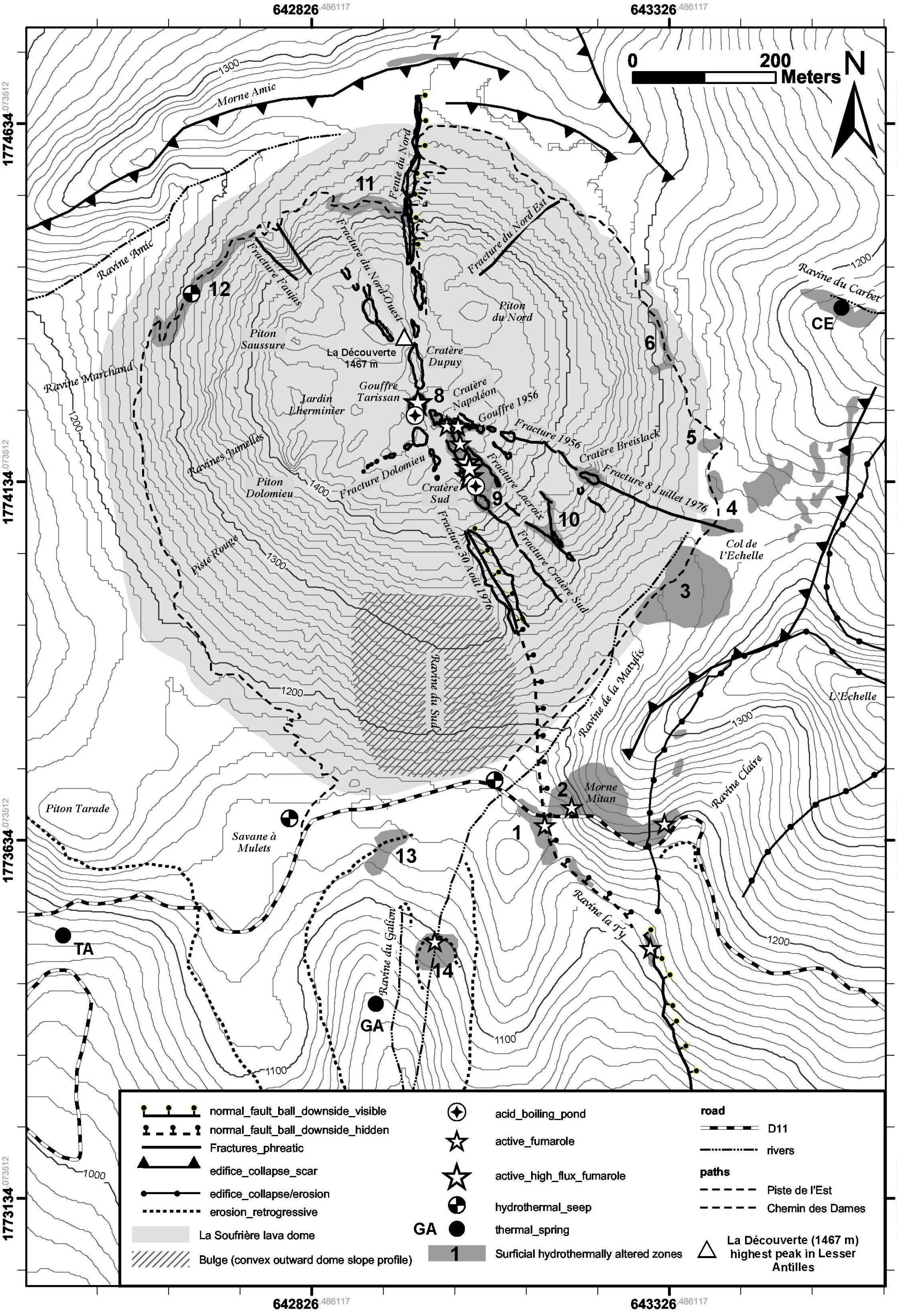
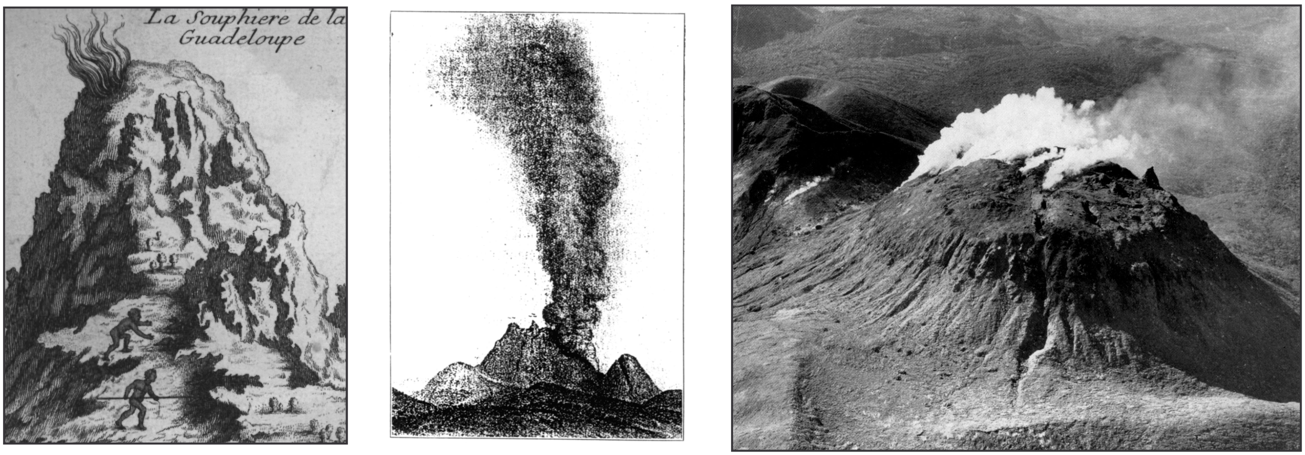


Figure 4. Map of the Soufrière lava dome with place names and synthesis of the current fumarolic activity (from Nicollin et al., 2005)

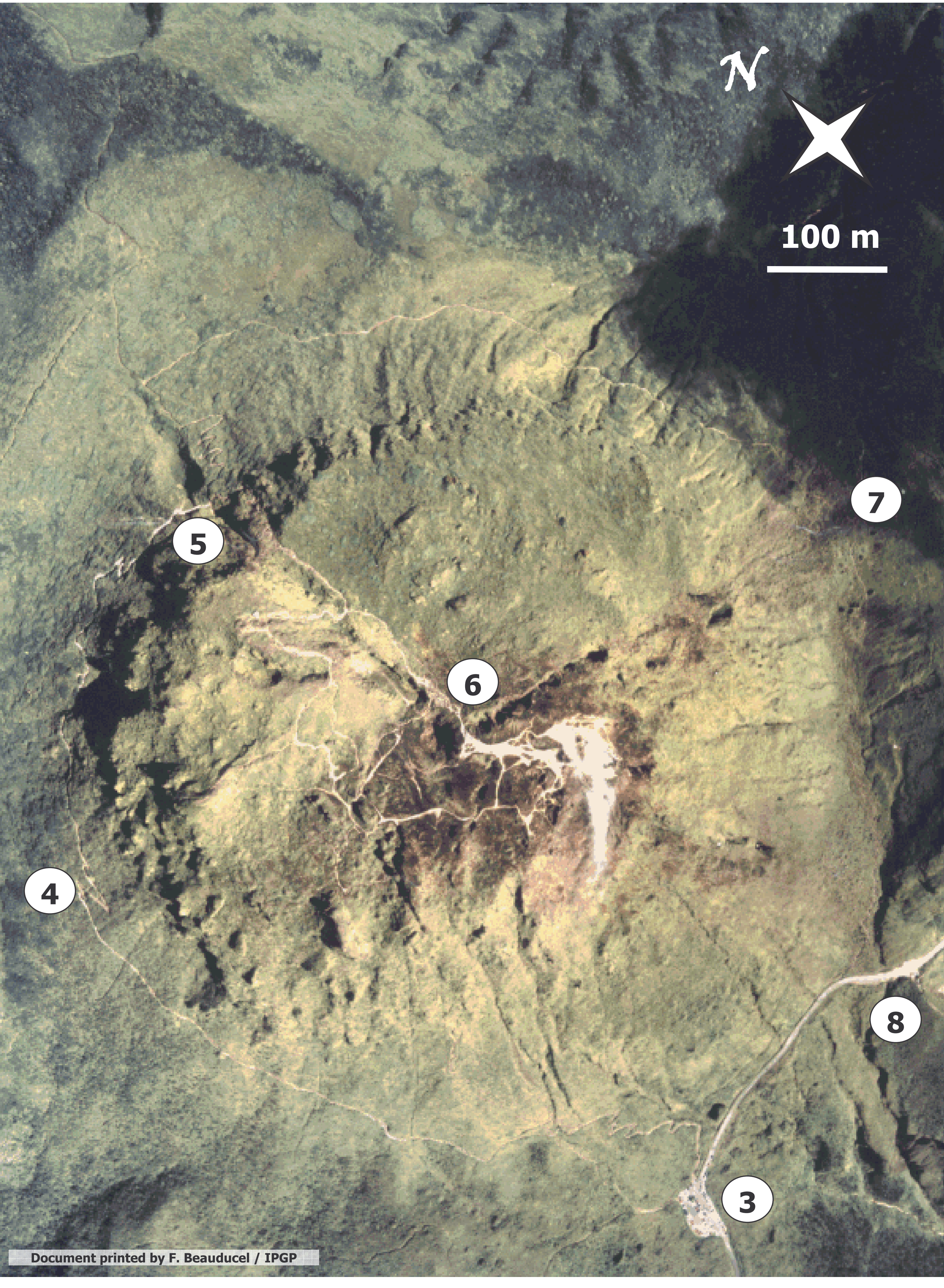


XVII^{e} - XVIII^{e} **1836-1837** **1956**

Photo M. Feuillard / IPGP

1976-1977

Figure 5. Documents relative to historical phreatic eruptions of La Soufrière.



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