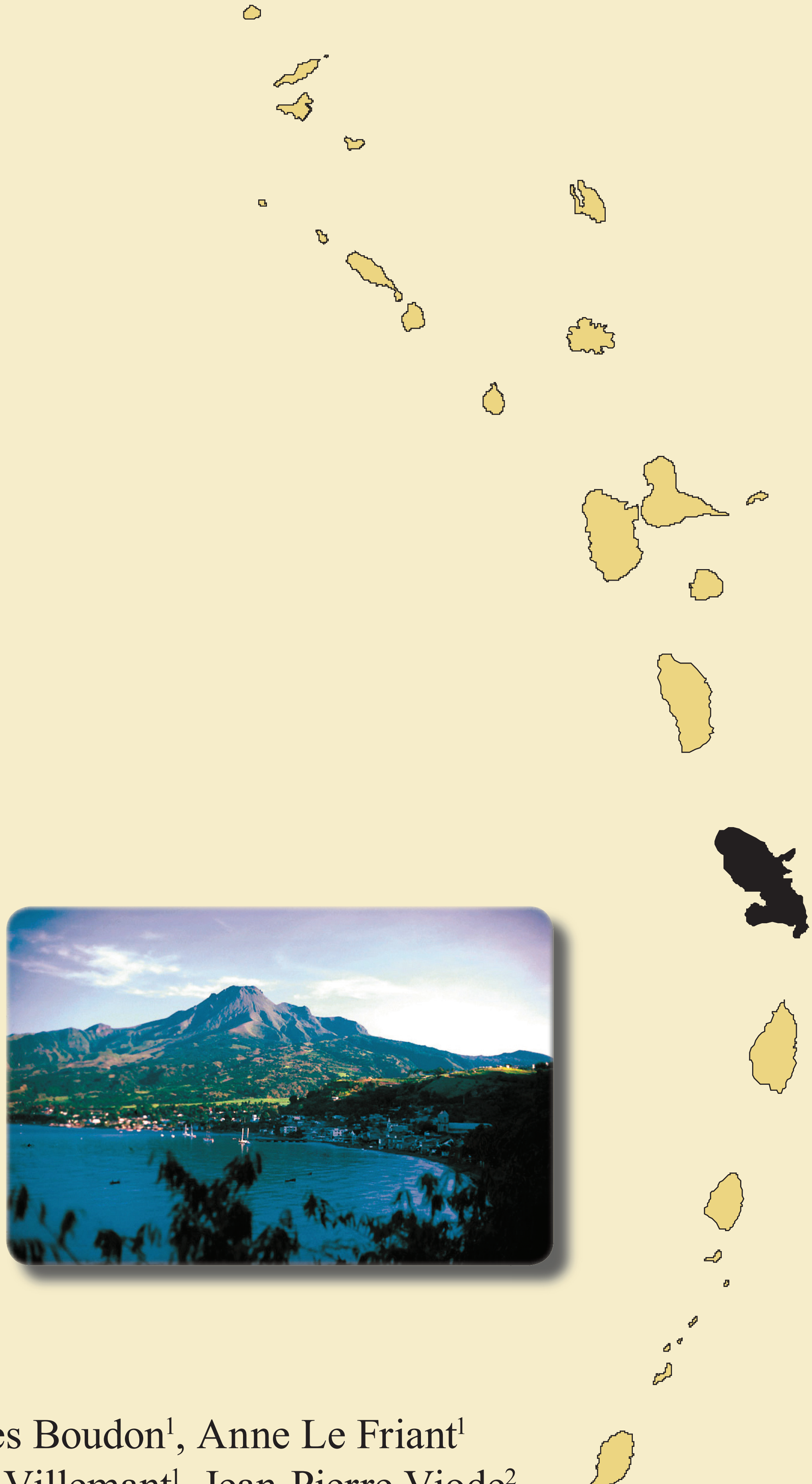
Martinique



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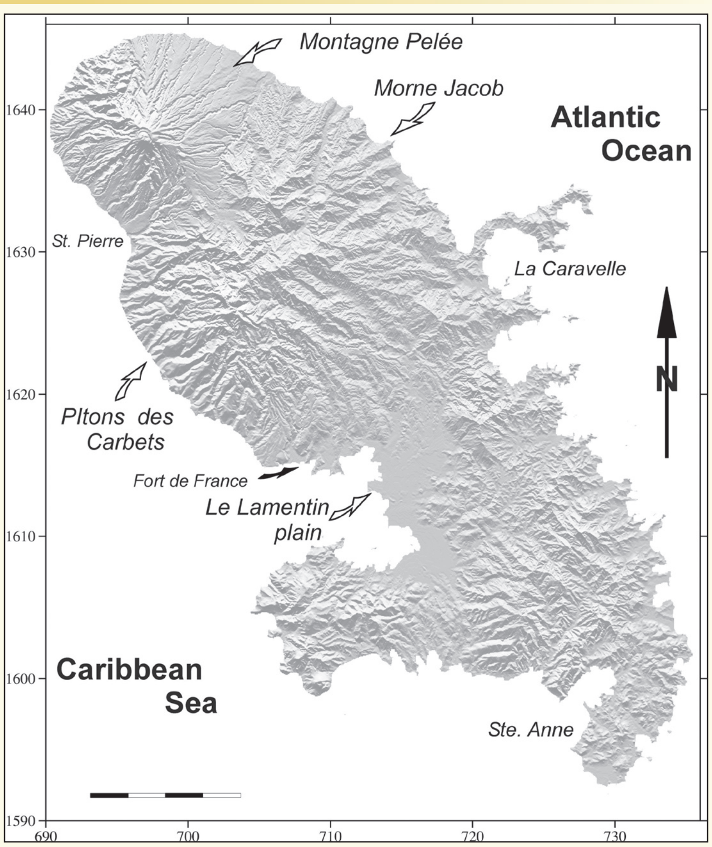
Abstract

Martinique consists of several juxtaposed volcanic centres that belong to the old external arc and the young internal arc (end of Oligocene to present). Montagne Pelée, located in the northern part of the island, is the only active volcano. In the last century there were two magmatic dome-forming eruptions, in 1902-1905 and 1929-1932. The 1902-1905 eruption was one of the most deadly the world has known during recorded history. Although there has been no volcanic activity for 70 years, Montagne Pelée is a very active and dangerous volcano that will produce new destructive eruptions. A future eruption will be located at the summit of the volcano, and will probably be a phreatic event occurring alone or preceding a magmatic eruption. The most likely type of magmatic eruption is a dome-forming event which may generate block-and-ash flows, and, less probably, violent turbulent high-velocity pyroclastic flows. The next most probable type of magmatic activity is an open-vent pumiceous eruption. Even less likely, but highly destructive, would be the collapse of the western flank of the volcano. This could trigger a tsunami that may reach the coast of several of the arc's islands causing widespread destruction. Regardless of the eruptive style, mudflows would be systematically produced during periods of heavy rain. Martinique's Volcano Observatory, part of the Institut de Physique du Globe de Paris, has developed a multidisciplinary surveillance network to monitor the activity of the volcano and to detect precursors of a new eruption.

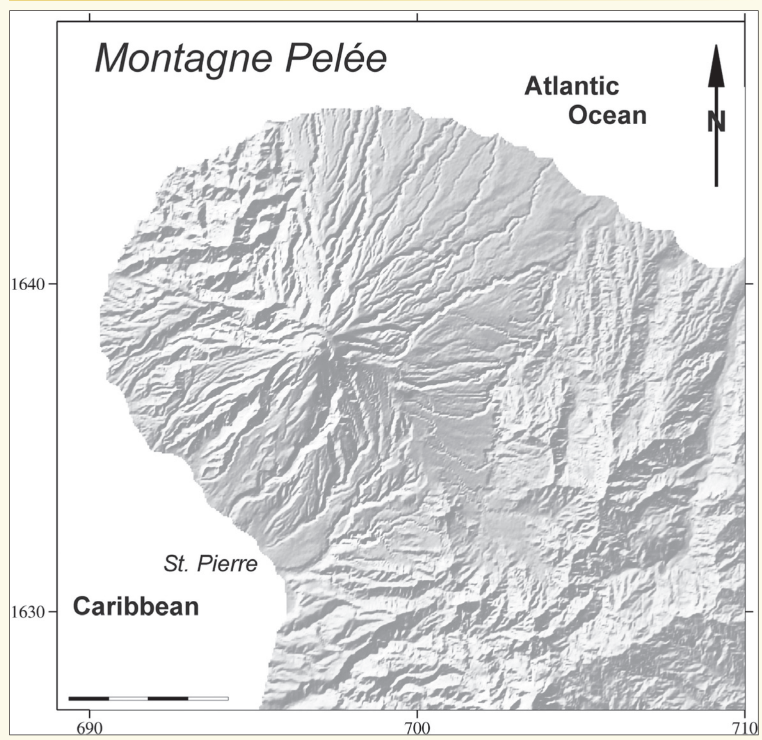
Introduction

Martinique, and particularly the active volcano of Montagne Pelée, has been the subject of abundant studies since the beginning of the 20th century. In 1902, the volcano's violent and destructive eruption killed 30,000 people: it was the most lethal eruption driven by a primary volcanic event in the world that century, and one of the most fatal in recorded history. Since this date, a large number of scientific studies have been undertaken by both the French and foreign volcanological communities. Thus, Montagne Pelée, the 1902-1905 eruption, and the island of Martinique are famous throughout the world. Here we synthesise these studies focusing on Montagne Pelée and the most up to date interpretations of its recent evolution, and thus define new scenarios for future volcanic activity and establish a new volcanic hazard assessment.

Shaded image of topography of Martinique illuminated from N 0°. DEM from IGN, resolution 50 m



Shaded image of topography of Montagne Pelée illuminated from N 320°. DEM from IGN, resolution 50 m



Geographic setting

Martinique is located in the southern part of the Lesser Antilles arc between Dominica and St. Lucia, at 14^{o} 20' – 14^{o} 55' N and 60^{o} 50 – 61^{o} 15 W. Covering an area of 1100 km^2, the island is elongated in a NW-SE direction. It is entirely volcanic and can be divided into three parts. The northern part is mountainous with the most recent volcanic centres: Montagne Pelée, the active volcano, and Mont Conil, Morne Jacob and Pitons du Carbet, centres which have been inactive for several hundred thousand years. The southern part consists of old, partially-eroded volcanic centres. The central part is defined by a NNE–SSW trending graben that opens to the southwest into the large Bay of Fort de France. The island's highest point is Montagne Pelée, at 1397 m. The northern part of the island is covered by rainforest and the southern part by dry scrub. Most of the central plain and the low-lying flanks of the volcano are cultivated with mainly banana and sugar cane. The island of Martinique is one of four French overseas departments (Martinique, Guadeloupe, Guyane, and La Réunion) and has a population of ~390,000. The capital, home to more than half of the population of the island, is Fort de France, located near the sea on the Caribbean coast.

Previous work

Due to an abundance of geological work, Martinique is among the most well-studied active volcanic islands in the Lesser Antilles arc. The first geological work done on the island dates from 1902, the year of the notorious eruption of Montagne Pelée. At that time numerous geologists came to Martinique to study it (Anderson 1908; Anderson and Flett 1903; Heilprin 1902, 1903; Hill 1903; Hovey 1903 1904; Lacroix 1904). In 1929-1932, F. Perret from the Carnegie Institution studied the last eruption of the volcano (Perret 1937), and later Grunevald (1961) published the first geological map of the island (1:50,000) and the map explanation (Grunevald 1965).

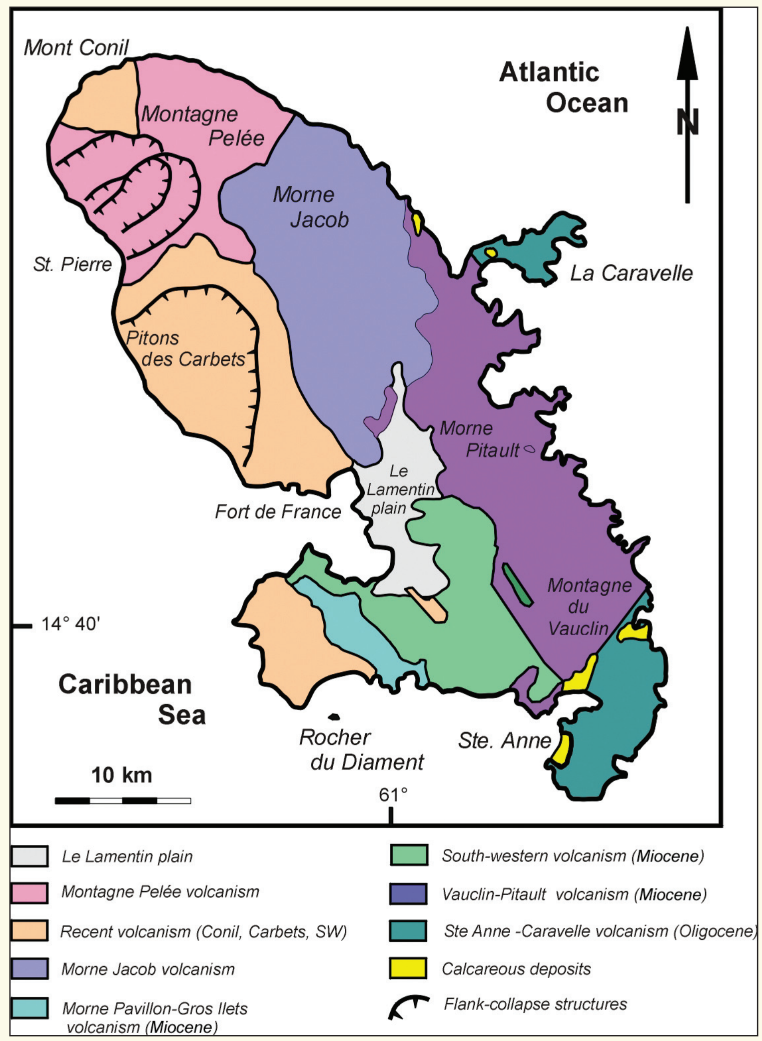
During the 1970's, the most interesting geological work was done by Westercamp et al. who, in 1990, published a more detailed geological map (1:50,000). Since then most work has been focused on Montagne Pelée, and includes: geological mapping (Westercamp and Traineau 1983a); deposit stratigraphy (Bardintzeff et al. 1989; Boudon 1993; Roobol and Smith 1975b; 1976a,b; Smith and Roobol 1976b, 1990; Traineau 1982; Traineau et al. 1989; Vincent et al. 1989; Westercamp and Traineau 1983b); paleomagnetism on the recent pyroclastic deposits and lavas (Genevey et al. 2002); the volcanological interpretation of 1902-1905 deposits (Fisher et al. 1980; Fisher and Heiken 1982; Sparks 1983; Boudon and Lajoie 1989; Bourdier et al. 1989; Charland and Lajoie 1989; Lajoie et al. 1989; Boudon et al. 1990; Tanguy 1994); a comparison with other similar eruptions (MacGregor 1952; Roobol and Smith 1975a; Walker and McBroome 1983); and the petrology of erupted magmas (Bourdier et al. 1985; Dupuy et al. 1985; Gunn et al. 1974; Traineau et al. 1983; Fichaut et al. 1989; Gourgaud et al. 1989; Pichavant et al. 2002; Smith and Roobol 1976a, 1990; Villemant et al. 1996; Villemant and Boudon 1998, 1999).

Previous flank instabilities, which occurred during the formation of the volcano, have also been studied using new offshore and on-land data (Le Friant et al. 2003). As a result of the Aguadomar cruise carried out in 1998-1999 by the Institut de Physique du Globe de Paris on the R/V l'Atlante (Ifremer), several debris avalanche deposits were recognised and mapped off Martinique and all main volcanic Caribbean islands (Deplus et al. 2001; Le Friant 2001). Because of its low seismic activity, only a few geophysical studies have been carried out on Montagne Pelée's structure (Eschenbrenner et al. 1980; Hirn et al. 1987; Zlotnicki et al. 1998).

Geology

On Martinique the volcanic centres of the older external arc and the recent internal arc are juxtaposed (Westercamp et al. 1990). The oldest volcanic rocks are located in the southeastern and eastern part of the island (Ste Anne, Caravelle) and were emplaced during the end of the Oligocene and the beginning of the Miocene. They consist mainly of submarine deposits and some subaerial lava flows of basaltic and andesitic composition. A subaerial block and ash flow deposit, with casts of wood, presumably of Oligocene age, is also recognised on the Caravelle peninsula. The Vauclin-Pitault centre, of Miocene age (14 – 10 Ma) in the southeast of the island is a submarine volcanic chain with a succession of hyaloclastites, breccias, some lava flows and occasional calcareous sediments. Most of the eruptive products are andesitic and some are basaltic. After building this volcanic chain, the activity was displaced to the west and began along fractures of NNW-SSE direction producing a succession of explosive phreatomagmatic and effusive centres of andesitic composition (8.9 - 6.5 Ma). At the end of this phase, the lava dome and lava flow of Gros-Ilets were emplaced (6.5 Ma); the magmas are dacitic in composition with garnet phenocrysts.

Geological sketch map of Martinique (simplified and modified from Westercamp et al. 1990)



After an inactive period of ~1 Ma, the activity was displaced to the north, where it built the Morne Jacob volcano, the largest volcanic edifice on the island (5.5 - 2.2 Ma). This centre is mainly composed of massive lava flows with occasional intercalated pyroclastic deposits. The basement deposits are basaltic, but the main part of the edifice is andesitic. The activity was then displaced again to the southwest, where it developed a series of monogenetic volcanoes with varying dynamics and petrology (2 - 1 Ma). This activity ended in a series of small volcanoes along a NW-SE direction including the small "Rocher du Diamant", a remnant of a dacitic lava dome in the Caribbean Sea. At the same time, the Pitons des Carbets volcano was constructed in the northern part of the island, west of Morne Jacob volcano. An early edifice of andesitic composition was built (~2 Ma) and was then later destroyed by a large flank-collapse event of 30 - 40 km^3. The resulting horseshoe-shaped structure, 11 x 9 km, opens west towards the Caribbean Sea (Boudon et al. 1992). Most of the sea cliffs are made up of debris-avalanche deposits, up to 100 m thick in some places. Inside the structure some pumiceous events occurred followed by the emplacement of many viscous lava domes known as “les Pitons” (~1 Ma). The lava domes are of andesitic composition and rich in large phenocrysts of biotite, quartz and plagioclase. Numerous block-and-ash flows were also associated with their emplacement.

Mont Conil, north of Piton des Carbets, is the most northern peak of Martinique. It is the most recent volcanic centre (1 – 0.5 Ma), not including Montagne Pelée, and is composed of andesitic breccias, lava domes and lava flows. The end of this activity corresponds to the beginning of the building of Montagne Pelée.

The northern and southern parts of the island are separated by the Lamentin plain, which is interpreted as a complex graben-type structure, mainly NE-SW in direction, with unclear boundaries. This structure was active between 14 and 10 Ma, however the low seismic activity registered nowadays suggests that it is still slightly active.

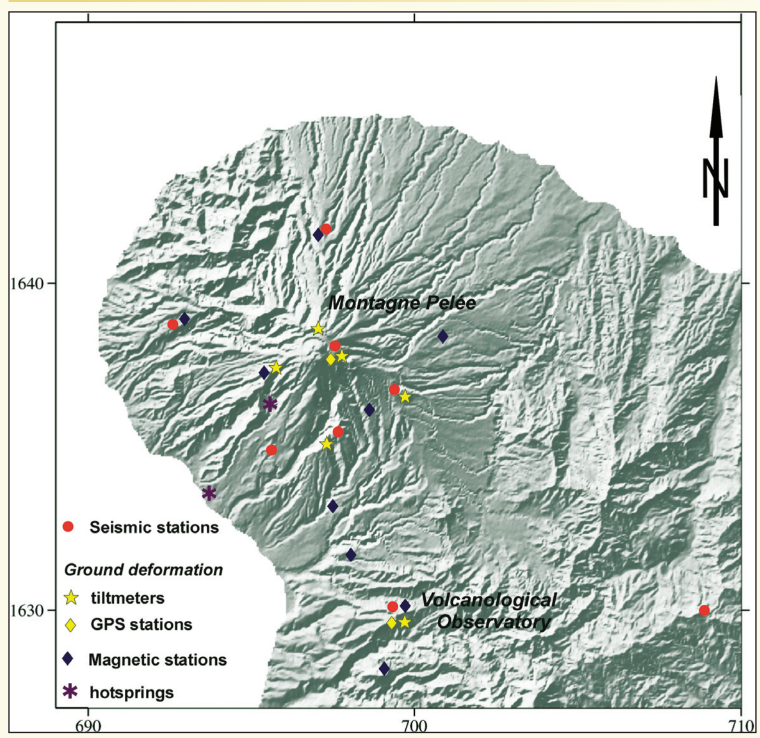
Volcanological and Seismological Observatory of Martinique (Morne des Cadets)

Volcano monitoring

At the end of 1902, on Montagne Pelée, Alfred Lacroix founded the world’s second volcanological observatory; the first being located on Mount Vesuvius. Lacroix had come from the Museum d’Histoire Naturelle de Paris to study the eruption and its effects (Lacroix 1904). The observatory was located on the Morne des Cadets, 8.5 km south of Montagne Pelée’s summit, on the rim of an old flank-collapse structure from the Pitons des Carbets volcano. It was in direct view of the active volcano, on a high point (510 m above sea level) and separated from the southern flank by at least two deep valleys, making it a very secure observation point. This first observatory was partially destroyed by a hurricane in the 1920’s and had not been reconstructed when a new eruption occurred in 1929-1932. After this eruption, the French authorities decided to construct a new observatory which was inaugurated in 1935. For several decades, monitoring was limited to the visual observation of the volcano, a seismic station located in the observatory, and a chemical laboratory for fumarole analysis. After the 1976-77 eruption of la Soufrière de Guadeloupe, the Institut de Physique du Globe de Paris (in charge of the monitoring of active French volcanoes since 1947) decided to improve all volcano monitoring.

At present, monitoring consists of several geophysical networks: all permanent networks being telemetered to the observatory. The seismic network is composed of eight stations, six of which have one vertical component seismometers and are located on the flank of the volcano. The other two have three-component seismometers and are located on the rim of the crater and at the observatory. Three types of ground deformation measurements are performed. Five permanent tiltmeters are telemetered to the observatory, automatic EDM measurements from the observatory to 10 reflectors on the summit and flanks of the volcano are recorded, there are two permanent GPS stations (on the rim of the crater and at the observatory). A temporary GPS network of about 20 points (installed in the summit area and on the western flank of the volcano) is measured annually to monitor ground deformation and flank stability both inside and outside the flank-collapse structures. A permanent network of seven magnetic stations, located on the flanks of the volcano, measures the magnetic field variations for comparison with reference points located near to the observatory. Finally, water from a hotspring and a hot drill hole, located on the western flank, is regularly sampled for geochemical analyses. In the drill hole, temperature, water level, pH and conductivity are continually measured and recorded. In addition to volcano monitoring, a seismological network of sixteen stations (eight seismometers and eight accelerometers) across the island records seismic activity related to subduction and active superficial faults.

Montagne Pelée monitoring network



Potentially active volcanic centres

Montagne Pelée volcano

Montagne Pelée is the only active volcano on the island of Martinique. It is located between two old volcanic centres: Morne Jacob - Pitons du Carbet to the south, and Mont Conil to the north. Due to this location, Montagne Pelée is not a perfect cone, its north-eastern and south-western flanks are more developed than the north-western and south-eastern ones.

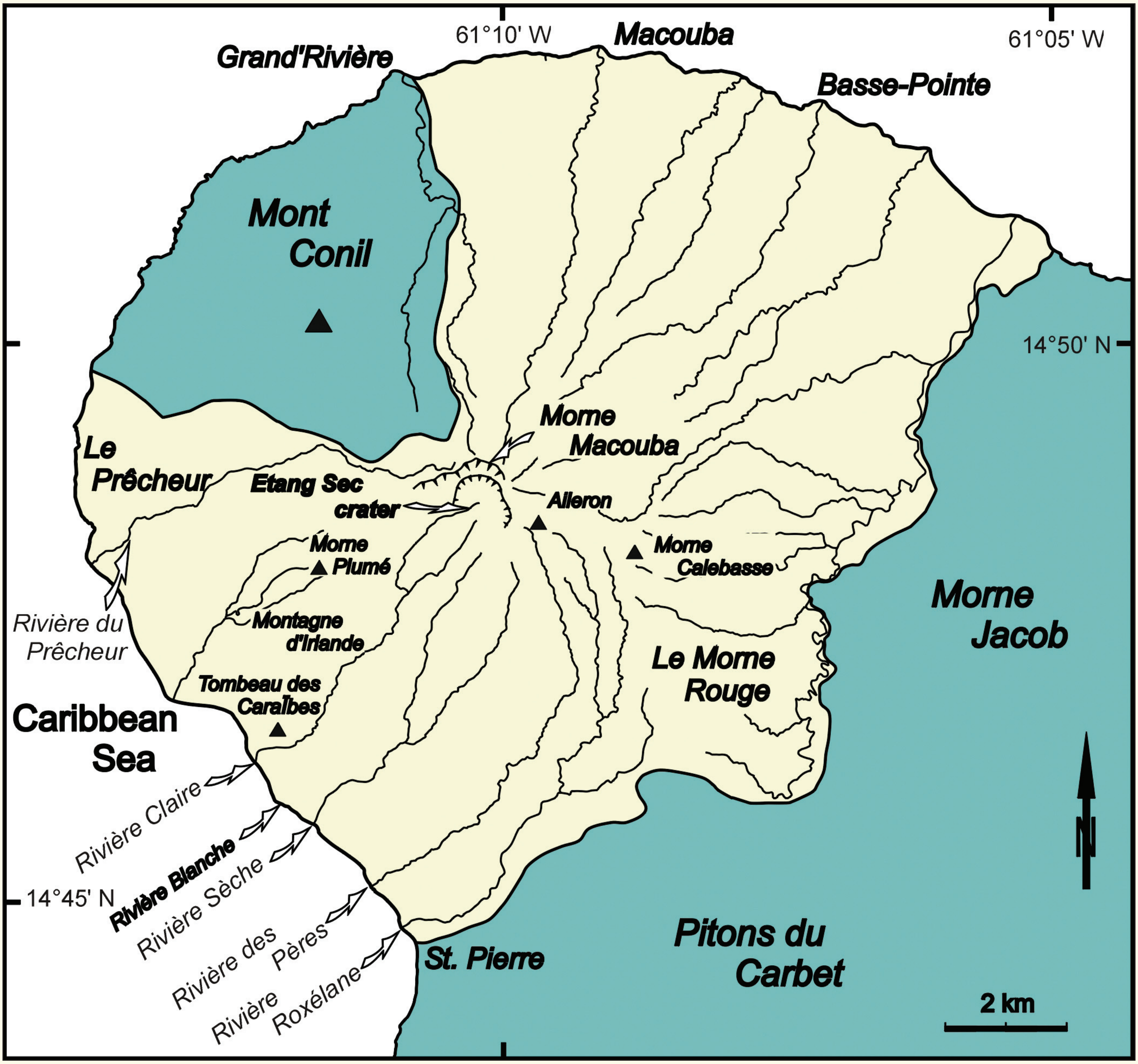
Past eruptive activity

The beginning of Montagne Pelée's activity is not well known, but an age of 0.3 - 0.5 Ma for the earliest activity is generally accepted on the basis of the little K-Ar data available: 0.6±0.1 Ma for a sample belonging to Mont Conil (Nagle et al. 1976) and 0.4±0.2 Ma for breccia from the first stage of cone building at Montagne Pelée (Bellon et al. 1974). The eruptive history of Montagne Pelée may be informally divided into three eruptive periods, according to different authors (Traineau 1982; Westercamp and Traineau 1983a,b; Traineau et al. 1983; Bourdier et al. 1985). Vincent et al. (1989) proposed two main stages: paleo-Pelée and néo-Pelée, the last one including the two most recent periods of activity. It was also accepted that the first stage was followed by a long period of erosion; probably more than 0.1 or 0.2 Ma - (Westercamp and Traineau 1983a) supported by the existence of erosional valleys, several hundred meters deep, which cut early breccias.

Following recent on-land and marine studies, Le Friant et al. (2003) proposed a new evolution of the volcano. This is based on a succession of constructive growth periods and destructive flank-collapse events. The volcano's history is still divided into three main stages in this classification, but the ages and durations of the periods are different.

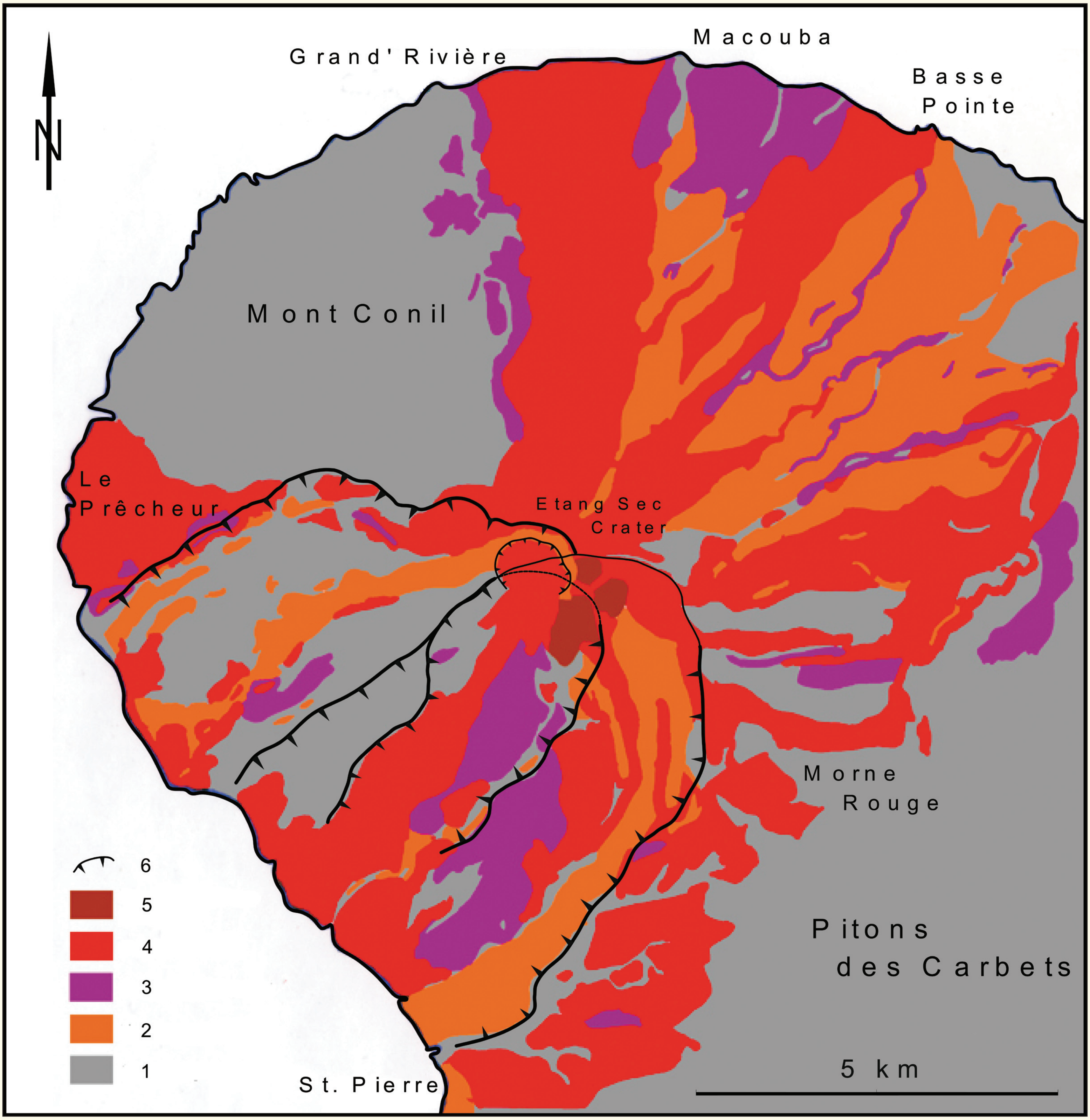
The first stage saw the construction of the primitive volcano, a cone probably comparable in size with the present edifice. It consisted of volcaniclastic breccias and, rarely, lava domes. Distribution of these products indicates that the first edifice was a central volcano, the summit of which roughly coincides with the present summit. Some breccias named "Macouba-type breccias"

Geographic map of Montagne Pelée (yellow) and adjacent centres (green)



principally outcrop on the northern flank of the volcano. They consist of low dipping (5°) compacted stratified breccias, with thick coarse-grained beds (1-3 m thick) and intercalated fine-grained layers (<30 cm thick). They are interpreted by Roobol and Smith (1976b) to be fluvial conglomerates, but Vincent et al. (1989), proposed that they could be a primary volcanic facies formed from brecciated lava flows that were internally bedded by shearing of the laminar flow. It is now considered that the first interpretation is the best one. The western flank of this first edifice was destroyed by a voluminous flank collapse (Le Prêcheur event) producing a debris avalanche, 25 km^3 in volume, which flowed into the Caribbean Sea. It covers an area of 1100 km^2 in the Grenada Basin and extends up to 70 km from the coastline (deposit D1). Only the northern rim of the flank-collapse structure is preserved and forms a curved scarp on the right side of the Rivière du Prêcheur. From the coastline to the summit area, this scarp varies in height between 150 and 500 m. The southern rim was either destroyed or has since been covered

Simplified geological map of Montagne Pelée (modified from Westercamp and Traineau 1983a)

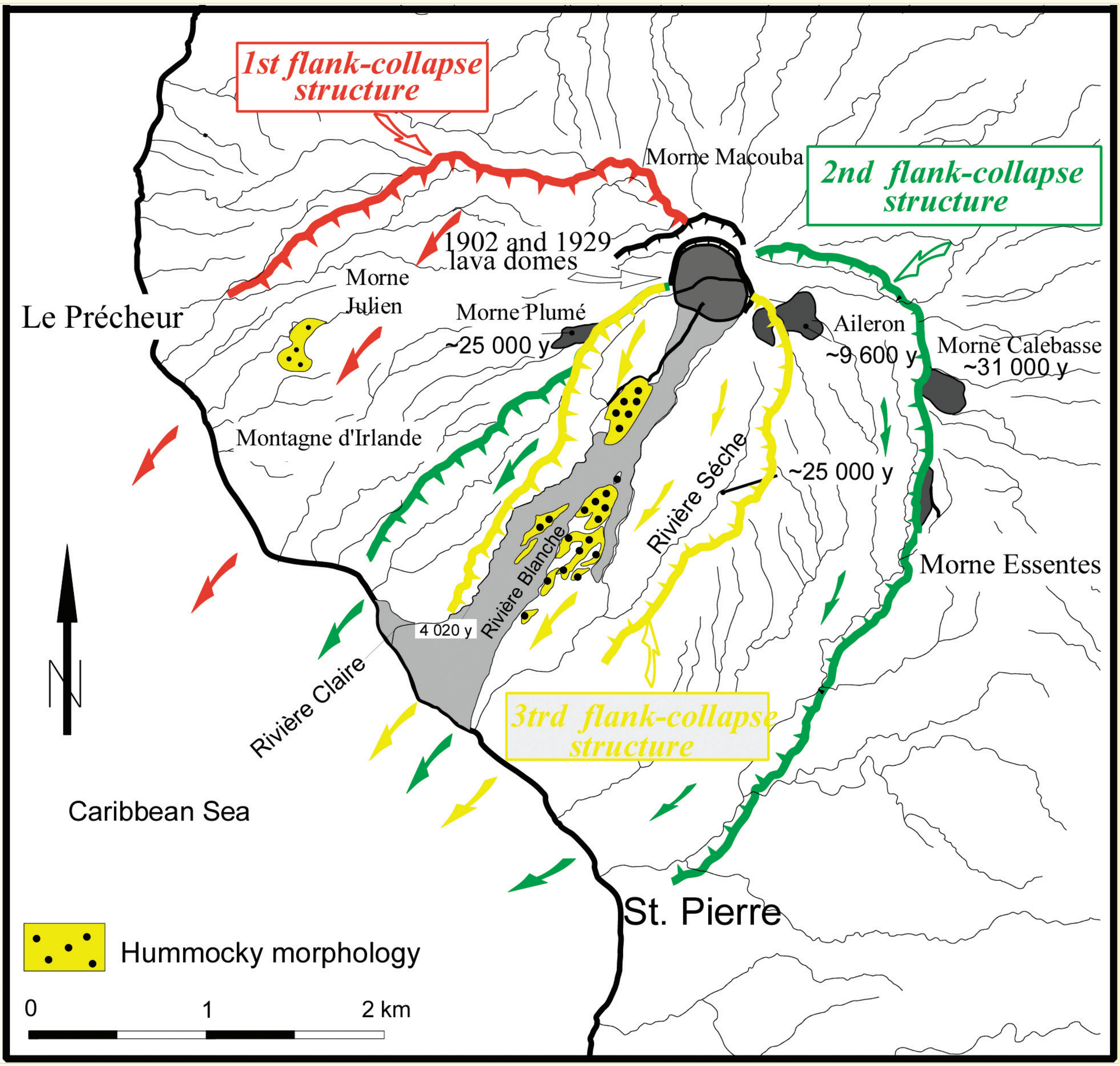


1: substratum (Mont Conil and Pitons du Carbet) and primitive edifice of Montagne Pelée; 2: pumiceous deposits (ash-and-pumice fall and flows); 3: scoria flow deposits; 4: block-and-ash flow deposits including the 1902-1905 and 1929-1932 eruptions; 5: recent lava domes of the summit area; 6: horseshoe-shaped structures and summit crater.

by more recent products. On the basis of the geometry of the northern rim and the lateral extension of the debris avalanche offshore, the structure is probably 8 x 6 km in size. The age of this flank-collapse event is not well constrained, but on the basis of the sediment thickness covering the debris avalanche deposit, Le Friant et al. (2003) propose a minimum age of 100,000 years.

The second cone built up inside the Prêcheur flank-collapse structure and consisted mostly of volcaniclastic breccias and subordinate lava domes and lava flows. Some of these breccias outcrop on the western and southern flanks of the volcano and are known as "breccias of Tombeau Caraïbe type". They are well-hardened breccias and form radial ridges on the western flank and show a succession of coarse-grained poorly-graded flow units several meters thick. Roobol and Smith (1976a,b) and Westercamp and Traineau (1983a) interpreted them as indurated block-and-ash flow deposits similar to the recent ones. However, Vincent et al. (1989) proposed that they could result from mild and progressive mechanical brecciation during the emplacement of lava flows. At present the first interpretation is the preferred one. Magmas emitted during this second stage are mainly acid andesites. A series of ages obtained by U-Th dating on these breccias, and on several lava domes and flows, indicate that they were emitted between 100,000 and 25,000 years ago. The existence of a long period of erosion and inactivity from 0.1 to 0.2 Ma, previously proposed by several authors, was not confirmed by Le Friant et al. (2003).

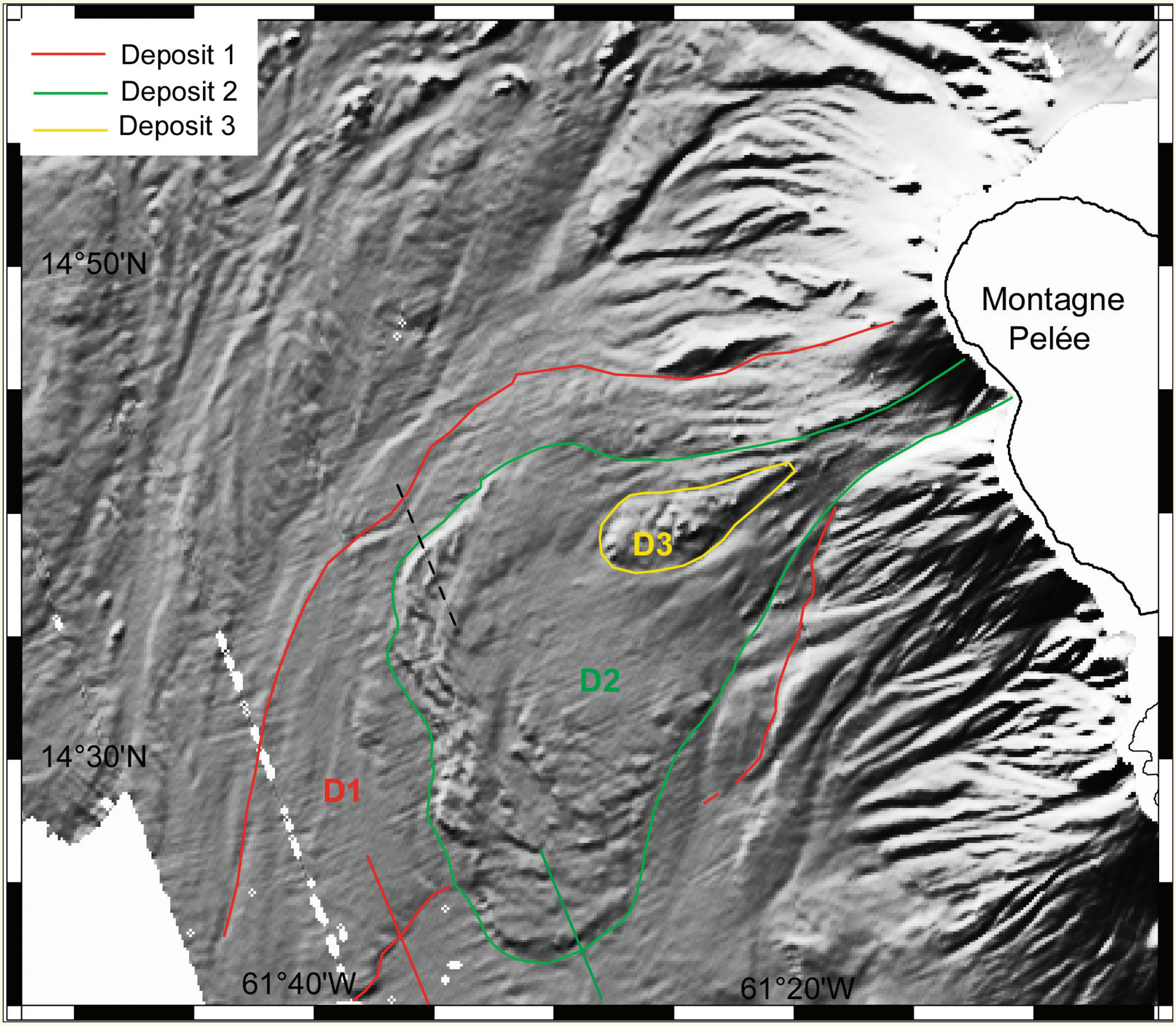
Flank-collapse structures on the western flank of Montagne Pelée (from Le Friant et al. 2003)



This second stage ended with a second flank-collapse event that again destroyed the western flank of the cone (St. Pierre event). It produced a debris avalanche that, like the first, flowed into the Caribbean Sea, this time producing a 700 km^2 deposit (deposit D2). The resulting horseshoe-shaped structure is 6 x 4.5 km and its northern and southern rims are well defined by the 100 to 150 m high cliffs. The rims then disappear under more recent products towards the centre of the volcano. The total collapsed volume has been estimated to be ~13 km^3. Part of the submarine flank of the volcano was eroded by the debris avalanche producing a chute several kilometres long. The two structural rims that reach the sea and the concave shape of the coastline between the rims indicates that the flank-collapse also affected the submarine flank of the volcanic edifice. This collapse has been dated to ~25,000 years ago on the basis of two concordant ages obtained from a lava flow cut by the rim of the structure (Morne Plumé: 25,000±3000 years; U-Th dating) and from a scoria flow filling the structure (25,000±1000 years BP; ^{14}C dating).

A new cone was built inside the horseshoe-shaped structure immediately after the flank-collapse. At the beginning of this third stage the magmas emitted were mainly basaltic andesites, in contrast to the acidic magmas (acid andesites and dacites), which were emitted during the second stage. They produced open-vent eruptions that gave rise to scoria flows (named in the Lesser Antilles "St.Vincent-style eruptions"). These were mainly channelled into the horseshoe-shaped structure but also to a lesser extent down the northern and north-eastern valleys of the volcano. Several of the eruptive sequences show a similar evolution from early acid andesites up to dominantly basaltic andesites, through a series of banded "mixed" products (Traineau et al. 1983; Bourdier et al. 1985). Traineau et al. (1983) and Smith and Roobol (1990) have identified a series of scoria flow deposits with ^{14}C age dates between 27,000 and 20,000 years BP. They proposed that at least 4 to 6 eruptions occurred. Two main eruptions occurred during this period dated at around 25,000 and 22,000 years BP, named respectively SV1

Shaded image of bathymetry illuminated from N320° : The offshore extent of three debris avalanche deposits from Montagne Pelée (from Le Friant et al. 2003)



and SV2 (Traineau et al. 1983). Taking into consideration the analytic errors on the dates, these ages are compatible with our interpretation of a flank-collapse around 25,000 years BP. Other deposits located outside the scar of the flank-collapse structure and interpreted as scoria flow deposits were also dated between 36,070 and > 40,000 years BP (Westercamp and Traineau 1983a; Bourdier et al. 1985). Most of them are reinterpreted as block and ash flow deposits of more acid composition.

The emission of more basic magmas following the flank-collapse event can be interpreted as the result of a reduced load above the magma chamber, as proposed in numerical models by Pinel and Jaupart (2000). After emitting basic andesites for several thousand years, the activity stopped for a period of 4-5 thousand years before restarting about 16,000 years ago. Acid andesites were then predominantly emitted and also occasionally low-silica dacites similar in composition to magmas produced during the second stage. During this period, a succession of 3-4 eruptions per thousand years has been inferred from the ^{14}C record (Westercamp and Traineau 1983a,b).

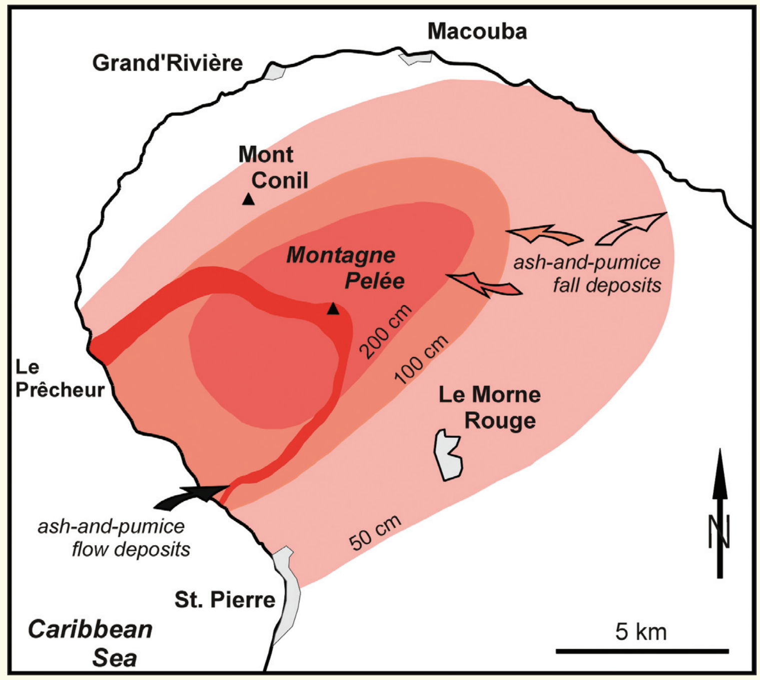
During this last stage, a third flank collapse occurred on the western flank of the volcano (Rivière Sèche event) destroying part of the cone and producing a debris avalanche that flowed, for the main part, down the submarine flank (deposit D3). It formed a lobate shaped deposit with hummocky morphology. Part of the debris avalanche remained on land and can still be seen today as large megablocks that form several hills both inside, and at the opening of, the horseshoe-shaped structure. The volume of the deposits is estimated to be ~2 km^3, of which 1.6 km^3 is offshore. The horseshoe-shaped structure is well preserved with 100 to 300 m high cliffs, west of Rivière Claire and east of Rivière Sèche, and covered in its upper part by products from the recent cone. On the basis of U-Th dating, the age of this third flank-collapse event is estimated to be ~9000 years, and the recent activity of Montagne Pelée is located inside the resulting structure.

View of the southwestern flank of Montagne Pelée

The recent activity of Montagne Pelée

Systematic ^{14}C dating has identified 28 magmatic eruptions during the last 16,000 years (Cal.BP) of the recent stage, 18 of which occurred during the last 5,000 years (Westercamp and Traineau 1983a,b). The preliminary results of tephrochronological studies on piston cores, sampled to the west of Montagne Pelée, indicate that the number of magmatic eruptions identified on land has been largely underestimated. During this period, the volcano

Distribution of the ash-and-pumice falls and flows from the last pumiceous eruption (P1, 650 years BP)



showed a succession of two types of magmatic eruptions: firstly, open-vent pumiceous, mainly Plinian eruptions, that are represented in the geological record as Plinian fallout layers, ash-and-pumice flow deposits, or both, and secondly, dome-forming eruptions inferred from the geological record by the occurrence of block-and-ash flow deposits. Of the 28 magmatic eruptions recorded on-land, 10 are pumiceous while the others correspond to dome-forming activity. An unknown number of phreatic eruptions, probably of mild intensity, are likely to have occurred. Martinique's population has witnessed two minor phreatic eruptions (1792 and 1851) during recorded history, but all magmatic events have also been preceded by phreatic activity leaving thin ash layers at the bottom of the pyroclastic magmatic sequence.

Pumiceous eruptions on Montagne Pelée, named P1 for the most recent (~650±30 years BP) to P10 for the oldest (10,280±180 years BP; ^{14}C ages), show different depositional sequences: the plinian fallout deposits are, in some cases, followed by ash-and-pumice flows. In one case (P3 : 2006±30 years BP), a surge deposit is interbedded in the ash-and-pumice flow deposits. (Traineau et al. 1989). They were relatively mild in magnitude with a total mass of erupted material generally estimated to be ≤1 km^3 per eruption. The last pumiceous Plinian eruption (P1) like the former (P2, dated at around 1640±32 years BP), was probably witnessed by the Pre-Columbian Indians who lived on the flanks of the volcano (Roobol and Smith 1976a; Westercamp and Traineau 1983b).

Numerous dome-forming eruptions were produced during this period, which characterises the recent activity of Montagne Pelée. The last two eruptions that occurred during the 20th century were dome-forming eruptions generally referred to as Peléean eruptions because of the 1902 activity. However, a large number of dome-forming eruptions on Montagne Pelée were not of pelean-type. Two types of pyroclastic activity associated with dome-forming eruptions can be identified, each of which produce different hazards. The first one results from dome collapses that generated block-and-ash flows channelled in the main valleys located at the base of the lava dome. The second one, less abundant, produces superficial and violent explosions at the base of the growing lava dome generating high-velocity turbulent and dilute ground-hugging pyroclastic flows (surges) historically named "peléean nuées ardentes". The two historical eruptions (1902-1905 and 1929-1932) are good examples of these two types of activity. Montagne Pelée, meaning "without vegetation" was named as a consequence of a dome-forming eruption which occurred around 1620 AD, just before the European settlement in Martinique (Westercamp and Traineau 1983b).

Age determinations

A large number of Martinique's volcanic rock formations have been dated, particularly those on Montagne Pelée. A series of more than 100 ^{14}C dates provide the framework for the chronology of the last 40,000 years of activity (Doucet 1997; Roobol and Smith 1976a,b; Smith and Roobol 1976b, 1990; Westercamp and Traineau 1983a,b; Traineau 1982, unpublished data). These were mainly determined from charcoal and soil samples from the base of pyroclastic flows (block-and-ash flows and ash-and-pumice flows) produced by the recent period of activity (<16,000 years). K-Ar dating of fragmented and low K (andesitic) volcanic material is extremely difficult, so none of Montagne Pelée's abundant pyroclastic flows have been dated using this technique. Some dating using U-series disequilibrium on mineral-matrix isochrons has been performed on lava domes, lava flows and breccias that were cut by flank collapse structures or channelled inside. On the older volcanic parts of the island,

^{238}U-^{230}Th ages on Montagne Pelée (internal isochrons, in Le Friant et al. 2003 and unpublished data)

Description	Location	Age±error (ka)
Lava dome	Sans Nom	9±1
Lava dome	Aileron	10±1
Lava flow	Morne Plume	25±3
Lava dome	Morne Calebasse	44±5
Block-and-ash flow	Morntagne d'Irlande	39±5
Scoria flow	Riviere du Precheur	33±5
Block-and-ash flow	Tombeau des Caraibes	63±10

Chronology of the recent magmatic eruptions of Montagne Pelée (from Traineau 1982; Westercamp and Traineau 1983a; Smith and Roobol 1990; Doucet 1997)

Magmatic eruption dated	Type of eruption	Age BP[1] (non-calibrated)	Calibrated Age[2]	Number of samples
1929	D			
1902	D			
NRP3	D	305±27	1511 – 1657 AD	6
P1	P	653±29	1289 – 1398 AD	12
	D	1143±45	784 – 1004 AD	3
P2	P	1670±32	265 – 438 AD	6
P3	D	2006±30	49 BC – 75 AD	12
	D	2269±32	395 – 202 BC	3
P4	P	2466±29	769 – 408 BC	7
NAB2	D	2455±35	768 – 403 BC	4
NAB1	D	2719±57	991 – 797 BC	2
	D	3138±54	1515 – 1264 BC	2
NRS1	D	3710±77	2322 – 1886 BC	2
NRS2	D	3983±46	2585 – 2346 BC	3
P5	P	4034±51	2856 – 2457 BC	3
NPM	D	4430±47	3331 – 2916 BC	4
P6	P	4656±34	3511 – 3351 BC	8
NMR	D	5160±34	4033 – 3822 BC	9
	D	5650±300	5223 – 3804 BC	1
	P	6630±130	5711 – 5283 BC	1
	P	7410±130	6461 – 5975 BC	1
	D	8320±800	9058 – 5591 BC	1
P8	P	7804±54	6755 – 6465 BC	6
	D	8280±370	8036 – 6380 BC	1
	P	9175±110	8427 – 8002 BC	1
	P	10280±180	10641 – 9056 BC	1
NMC	D	11273±128	11544 – 10963 BC	6
NBC	D	13443±256	14813 – 13334 BC	3

28 magmatic eruptions on the basis of 108 ^{14}C dates (data: Traineau 1982; Westercamp and Traineau 1983a; Roobol and Smith 1976a; Grunevald 1965; Traineau unpublished data). D = Dome-forming eruption; P = Open-vent pumiceous eruption; [1] Mean Age with its standard error (± 1σ) given in years BP (Before Present, the reference year being 1950); [2] Calibrated age presented as intervals of calendar years, calculated with the software "Calib v.3.0.3c" (Stuiver and Reimer 1993), given for 2σ (AD: years after Christ, ano domini; BC: years before Christ) numerous K-Ar ages were obtained on the lava flows and domes, permitting the chronological reconstruction of the volcanic activity.

Historical eruptions

During the last few centuries, Montagne Pelée has been one of the most active and hazardous volcanoes of the Lesser Antilles arc. Since European settlement in 1635 AD it has erupted four times: in 1792 and 1851 (minor phreatic eruptions), then in 1902-1905 and 1929-1932 (magmatic dome-forming eruptions preceded by minor phreatic outbursts).

The phreatic eruptions of 1792 and 1851

The first eruption, which was of mild intensity, began in January 1792 and ended three months later. It produced block-and-ash falls that contained old material and were limited in extent to the "Etang Sec", the summit crater. The second eruption, occurring between August and October 1851, was more violent. Several phreatic explosions involved block-and-ash falls which destroyed the vegetation in the summit area and produced a fine ash which fell on the city of St. Pierre, located 5 km away (Lacroix 1904).

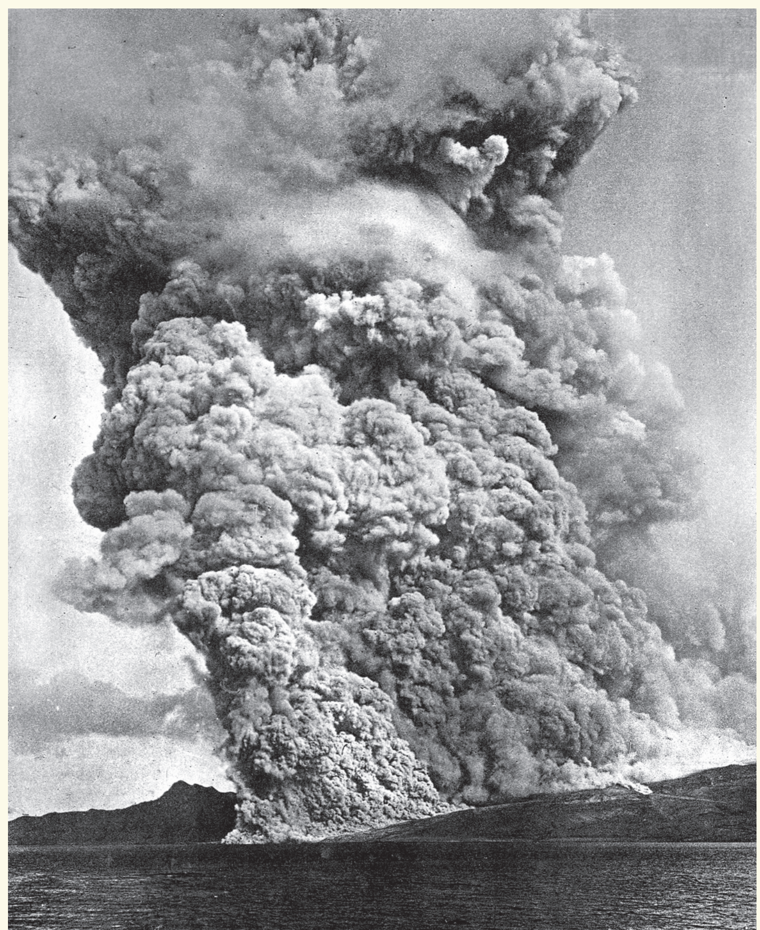
The town of St. Pierre after the 1902 eruption. In the background Montagne Pelée and the spine at the top of the lava dome (from Lacroix 1904)

The 1902-1905 dome-forming eruption

This was one of the most infamous historical eruptions in the world and was described in detail by A. Lacroix in 1904. It can be divided into three main stages:

* The pre-climactic stage: The first precursors probably occurred in 1889, 13 years before the beginning of the eruption, with the emergence of fumarolic activity inside the summit crater. Very few eyewitness accounts describing fumarolic activity exist before 1900. From the beginning of 1902, fumarolic activity increased in the crater, and from April 1902 human activity on the lee side of the volcano became difficult. Then on April 23 the first phreatic explosion occurred. During the following 15 days numerous phreatic events produced a thick ash layer on the western flank of the volcano and a much thinner layer over the city of St. Pierre. On May 5, a lahar generated by the destruction of a natural dam in the Etang Sec Crater flowed down the Rivière Blanche valley towards its mouth killing 23 people in the Guerin factory. They were the first victims of the eruption. During the night of the May 5, a glow was observed by the inhabitants of St. Pierre indicating that the magma had reached the surface inside the crater.

* The climactic stage: Beginning on May 8, at 0802 hours and ending on August 30, the eruption was characterised by a series of at least seven violent and destructive explosions which occurred at the base of the growing lava dome in the Etang Sec crater. The first explosion destroyed the city of St. Pierre and killed all but two of its 28,000 inhabitants. The last explosion, on August 30, partly destroyed Morne Rouge village, located on the southern side of the volcano, killing another 1500 inhabitants. Detailed studies of the 1902 deposits (Boudon and Lajoie 1989; Boudon et al. 1990; Bourdier et al. 1989; Charland and Lajoie 1989; Lajoie et al. 1989) show that these catastrophic events were due to high-energy 'nuées ardentes' erupting through the growing lava dome. These were ejected preferentially in a lateral direction and gained their energy mainly from: the transient depressurisation of magmatic gases within the dome; the magmatic column immediately below; and possibly, from the flashing of the hydrothermal system in the upper part of the volcano. These nuées ardentes were emplaced as high-velocity, highly turbulent and dilute ground-hugging pyroclastic flows (surges) that expanded rapidly in the horizontal plane covering large areas on the south and west flanks of the volcano. Their behaviour, and the sedimentological characteristics of their deposits, resemble those of the 1980 Mount St. Helens' lateral blast. Throughout this stage, the lava dome grew continuously inside the Etang Sec crater, reaching its maximum size in August 1902 (Lacroix and Perret 1904; Tanguy 2004). Contemporaneously, numerous block-and-ash flows were also channelled down the Rivière Blanche valley located on the west side of the volcano.



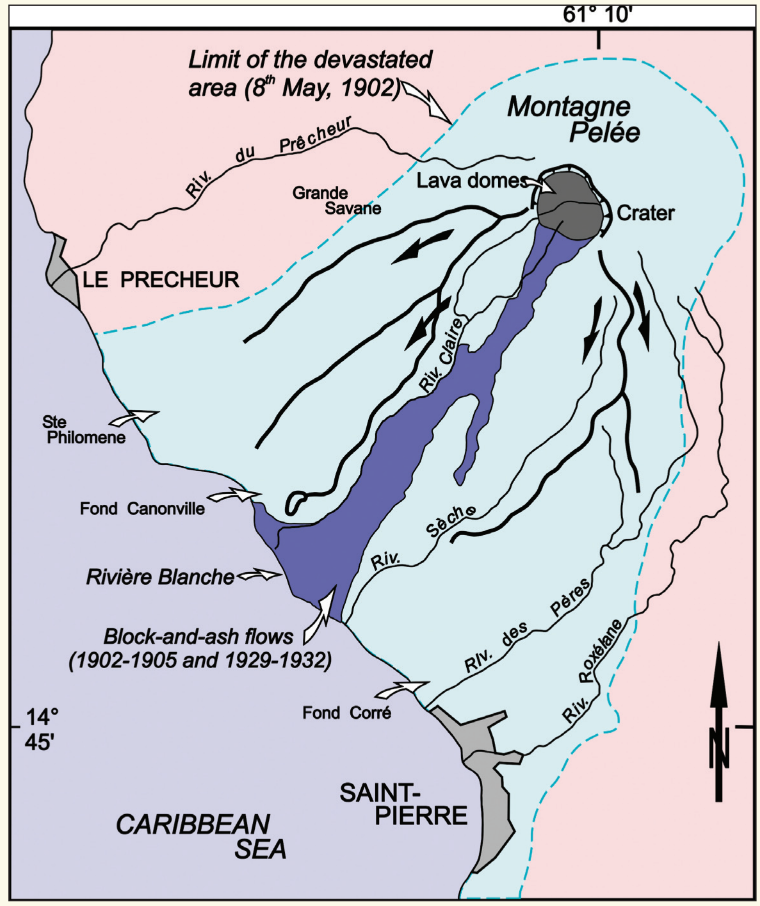
Block-and-ash flow from the 1902-1905 eruption (from Lacroix 1904)

Large spine that grew at the top of the lava dome during the eruption of 1902-1905 (from Lacroix 1904)

* The post climactic stage: from August 30, 1902 to the beginning of 1905, the lava dome continued to grow and numerous block-and-ash flows partly filled the Rivière Blanche valley. This period of magmatic activity was marked by the growth of a large spine at the top of the lava dome from September 1902 to March 1903. It reached a maximum height of 350 m above the summit of the lava dome, and its diameter of ~50 m gives an indication of the upper width of the feeding conduit. This spine was completely destroyed before the end of the eruption.

Summit area of Montagne Pelée showing the two lava domes of 1902-1905 and 1929-1932 inside the "Etang Sec" crater

Distribution of the May 8, 1902 "pelean nuée ardente" and of the block-and-ash flow deposits of the 1902-1905 and 1929-1932 eruptions



The 1929-1932 dome-forming eruption

After 24 years of fumarolic activity, a new eruption occurred in November 1929. As in 1902, it began with a series of phreatic explosions whose ashes covered a large part of the western flank of the volcano. A new lava dome grew inside the Etang Sec crater, and on the western part of the 1902-1905 lava dome, from December 1929 to 1932. The unstable areas of this lava dome collapsed creating numerous block-and-ash flows which completely filled the Rivière Blanche valley. The accumulation of block-and-ash flow deposits from the 1902-1905 and 1929-1932 eruptions may be greater than 50 - 60 m in some places in the Rivière Blanche valley. During the 1929-1932 eruption (described in detailed by F. Perret 1937) there was no highly explosive activity like that which was seen in the 1902-1905 eruption.

View, from the summit, of the Rivière Blanche valley filled by the 1902-1905 and 1929-1932 block-and-ash flow deposits

Seismicity

Since the last magmatic eruption of 1929 to 1932, the volcanic seismicity beneath the active volcano has been very low. Two small crises were recorded. The first one occurred in October-November 1980, where 55 events were recorded in six days. This small crisis was correlated with the occurrence of an important landslide and associated mud-flows; traces of this landslide were observed later in the upper part of the Rivière du Prêcheur, near the summit area. The second seismic crisis occurred between December 1985 and June 1986. Beneath the southern rim of the Etang Sec crater, 40 local events of very low magnitude and shallow depth were recorded (Hirn et al. 1987). In spite of the very low energy of these signals, these events were interpreted as very local and shallow variations in the effective stress of the hydrothermal system below the summit. Since this period, only a few tens of events have been recorded per year beneath the volcano. They are of very low magnitude and always generated at shallow depth.

Geothermal activity

Geothermal activity in Martinique is present in five distinct places: Montagne Pelée, Lamentin plain, Pitons du Carbet and the eastern and southern coasts, the first two fields being the most important. The other places, which correspond to the circulation of meteoric water through relatively superficial fault systems, display low temperatures (~35-40 ^oC) and little or no CO_2 degassing. The thermal activity in Lamentin plain is represented by numerous springs of almost constant composition and temperature (~60 ^oC), with a very low flow rate. It is characterised by low to high CO_2 fluxes. These thermal waters have both a meteoric and a sea water component and are transported from deep aquifers (of ~120 ^oC and possibly even ~200 ^oC) through the active fault system. On Montagne Pelée, the present thermal activity is restricted to its western flank with springs located in the high valley of Rivière Claire, in the Rivière Mitan and Rivière Picodo (north of Rivière Claire) and also along the coast between the mouths of Rivière Claire and Rivière Sèche (Barat 1984). Their temperatures range from ~ 30 ^oC, to a maximum of ~70 ^oC for Rivière Claire. At Puy Chaud (near the coast) a well ~6 m in depth is being monitored by the Observatory for temperature, composition and water table level. This water (mean temperature: ~45 ^oC) is thought to result from hydrothermal circulation along the floor of the flank-collapse structures. Its chemistry corresponds to a mixture of cold superficial meteoric water and meteoric water heated through conductive transfer at depth (temperature of equilibrium: ~200-240 ^oC). At present, there is no fumarolic activity at Montagne Pelée.

Future eruptions

In the last 16,000 years, all eruptions have occurred in the central part of the volcano, usually in or around the summit craters. In the future it is probable that three main types of eruption will occur: phreatic events, dome-forming eruptions and open-vent pumiceous eruptions.

Past phreatic events have been poorly documented, with only four being recorded in historical time: the single events of 1792 and 1851, and those preceding the magmatic activity of 1902-1905 and 1929-1932. A thin layer of phreatic ash is often visible overlying paleosols at the base of prehistoric eruption deposits, attesting to the occurrence of phreatic activity before a magmatic event. Thus the probability of a phreatic event in a future eruption is said to be 100%. One of the challenges will be, as for most volcanoes, to clearly identify the possible evolution of eruptive styles and to anticipate a possible transition from a phreatic to a magmatic event.

The second most probable type of activity that could occur on Montagne Pelée is a dome-forming eruption. Of the 28 magmatic eruptions identified in the last 16,000 years, 19 were dome-forming events, giving a probability of ~ 68%. The growth of the lava dome is generally accompanied by the collapse of its unstable parts or by small explosions that lead to block-and-ash flows channelled down one or two of the valleys radiating from the base of the lava dome. In rare cases, like in 1902-1905, violent and destructive explosions may occur. Unfortunately, the thin layers deposited by these explosions are rapidly eroded so the frequency of this type of event is unknown. In the last 16,000 years, however, 6 layers have been recognised in the last thousand years.

Open-vent pumiceous eruptions are the third type of event which could occur and have a probability of ~35%. They produce ash-and-pumice fall deposits that can completely cover all flanks of the volcano and, in some cases, the northern part of the island. They also produce ash-and-pumice flows which are channelled by the main valleys surrounding the volcano.

Finally, a fourth type of event that may occur is the collapse of the southwestern flank of the volcano. In spite of its low probability (one event in the last 16,000 years), it should be considered because of its devastating effects. These are produced by: the debris avalanche itself; the possible laterally directed blast induced by decompression of magmatic gases and/or hydrothermal system; and by the tsunami created when a significant mass of material suddenly enters the sea.

Most likely scenarios

Scenario 1: Phreatic eruption

This is the most likely scenario that could occur on Montagne Pelée in the future. The position of the vents will probably be located inside the Etang Sec summit crater (where the two recent lava domes were built) or, on the upper western flank of the volcano just below the 1929-1932 lava dome (the location of phreatic activity before the 1902-1905 magmatic eruption). This type of eruption results from the sudden vaporisation of ground-water on interaction with ascending hot gases or magma batches that will not reach the surface. On the basis of historical events, phreatic eruptions are short, usually taking several weeks to months. Successive explosions eject fragments of old rocks and ash. Some of the blocks and lapilli reach a maximum distance of 1 to 2 km from the vent but will not affect the nearest human settlements, which are located at least 4 km from the summit. A plume several kilometres high would produce ash which may cover most of the volcano, in particular the western flank. The coastal villages located in the west would be affected by these ash falls and, to a lesser extent, the town of St. Pierre in the south-west. As few explosions normally occur, however, the thickness of ash fall in inhabited areas will be low. Mudflows produced by the remobilisation of fine ash deposited on the flanks of the volcano can occur in all the main radial valleys of the volcano, but principally on the western flank where the ash covering will probably be the thickest.

Scenario 2. Dome-forming eruption

The second most likely scenario for Montagne Pelée is a dome-forming eruption. This will be preceded by phreatic activity probably shorter but more intense than for a solely phreatic eruption because of the progressive ascent of magma to the surface. In order to build a lava dome, the magma must be partially degassed when it reaches the surface. This degassing generally occurs through the permeable conduit walls during the last kilometre of ascent. Degassing leads to the progressive microcrystallisation of the melt and an increase in magma viscosity. When it reaches the surface, the magma is too degassed to explode and much too viscous to flow. It therefore results in the growth of a lava dome that progressively fills up the crater that was created by the phreatic explosions. As the lava dome grows it becomes unstable: partial dome collapses generate block-and-ash flows that are channelled into the valleys at the base of the lava dome (probably western flank valleys that channelled the pyroclastic flows from the last eruptions: Rivière Claire, Rivière Blanche, Rivière Sèche and Rivière des Pères). This scenario, similar to the last dome-forming eruption of 1929-1932, could be repeated several times depending on the growth rate and the duration of the eruption. Block-and-ash flows would progressively fill up the valley(s). Similar to the on-going eruption of the Soufrière Hills on Montserrat, ash-cloud surges could be produced from the top of the pyroclastic flows. These may overflow the valley sides and are therefore much more destructive. Spines can extrude from the top of the lava dome and may reach several tens of meters before collapsing. In exceptional cases, as in the 1902-1905 eruption, spines can have a long life-time (several months) and may reach several hundreds of metres high. Pyroclastic flows and surges generate ash clouds that may reach a few kilometres in height. The resulting ash falls would cover a large area, principally on the western flank, because of the dominant wind direction (Easterlies) at lower elevations. There would be great thicknesses of deposits close to the vent and in the valleys where the pyroclastic flows were channelled, with thickness decreasing progressively with distance. All these ash-fall deposits could be remobilised triggering mudflows in the main valleys.

Scenario 3: Dome-forming eruption with associated violent explosions

This scenario differs from Scenario 2 at the beginning of the magmatic phase by the occurrence of violent and superficial explosions at the base of the growing lava dome. The eruption would begin, as for Scenario 2, with a series of phreatic explosions that precede the arrival of magma to the surface. In contrast to Scenario 2, however, magma degassing in the feeding conduits is probably lower, therefore maintaining the explosive potential of the dome-forming magma that reaches the surface. The superficial depressurisation of gases at the base of the growing lava dome produces explosions with a dominantly lateral component, increasing their devastating effect. The resulting highly turbulent and dilute ground-hugging pyroclastic flows (pelean nuées ardentes) have a very high velocity, thus allowing their progression to be independent of the topography. Reconstruction of historical and prehistorical eruptions shows that the western and southern flanks of the volcano are most likely to be affected by these pyroclastic flows. Le Prêcheur, St. Pierre and Morne Rouge are the towns most exposed to this type of event. After this violent explosive phase, the course of the eruption is similar to that of Scenario 2: lava dome growth and its associated block-and-ash flows which are channelled by one or two valleys.

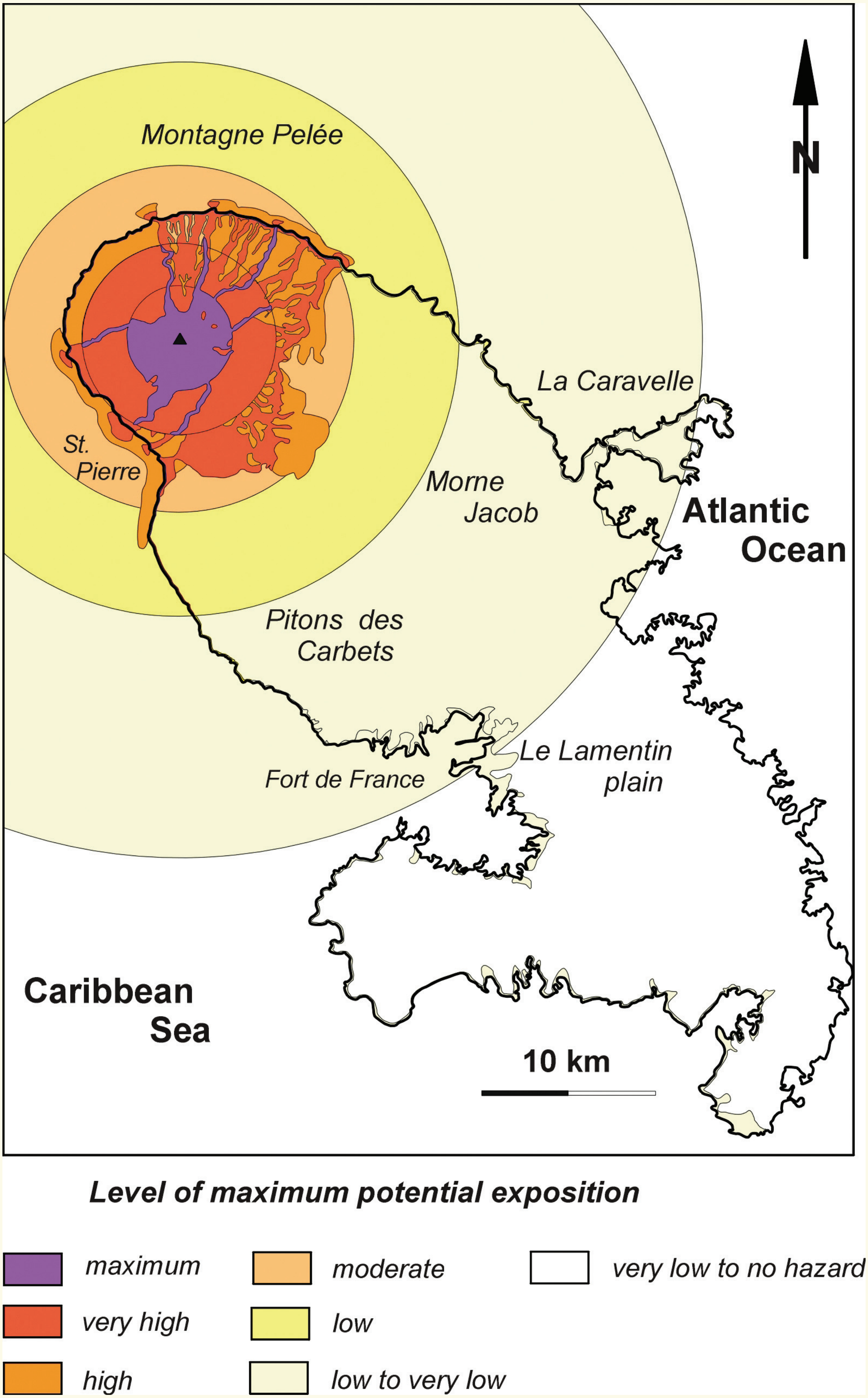
Scenario 4: Open-vent pumiceous eruption

Records of prehistoric activity show that, when the volcano reactivates, pumiceous eruptions are also one of the most probable scenarios. The vent of such an eruption would be located inside the Etang Sec crater at the site of the 1902-1905 and 1929-1932 lava domes. As for the preceding scenario, the eruption would begin with phreatic activity. In this case, the magma would not lose its gases during ascent and would therefore reach maximum possible vesicularity on its way to the surface. Once reaching a few hundred metres below the surface, the magma fragments, producing an ascending convective column. This column attains several tens of kilometres in height, producing a plume where ash and pumice are dispersed. Pumice and ash would fall on all of the volcano's flanks and even on parts of the old volcanoes of Mont Conil and Pitons du Carbet. In the case of large eruptions, they would also fall across the entire northern part of the island. The thickness of pumice falls close to the vent is expected to be large (>10 metres) and then to progressively decrease with distance. In the town of St. Pierre, 5 km from the summit, pumice-fall deposits from the last plinian eruptions range in thickness from 50 cm to 1 m. Partial collapse of the eruptive column would generate ash-and-pumice flows radially around the vent and down to the main valleys of the volcano. The distribution of pumiceous eruption deposits from the last 16,000 years shows that all of the volcano's radial valleys could be affected by ash-and-pumice flows and by secondary mud-flows. In exceptional circumstances, surges could be generated at the vent that would affect all of the volcano's flanks and, for large eruptions, the northern part of the island (e.g. P3 eruption, ~2000 years BP). Such eruptions require large magma production rates.

Scenario 5: Multi-phase eruption

The P1 eruption of 650 years BP is a very good example of a multi-phase eruption that could occur on Montagne Pelée. As with all past events, this eruption began with a phreatic phase followed by the construction of a lava dome in the crater. The lava dome was destroyed by two lateral explosions which generated high-velocity pyroclastic flows of similar extent to those of the 1902-1905 eruption. Although this eruption started in the same way as the 1902-1905 event, the eruptive style then changed by the continuation of explosive activity. The depressurisation of magma in the feeding conduit caused its fragmentation and the transition to a plinian phase producing a convective column several tens of kilometres high. A pumice-fall layer covered all flanks of the volcano, with thicknesses >10 m close to the vent and ~50 cm at 5 km distance. Partial collapse of the column produced ash-and-pumice flows that were channelled by two western flank valleys. This type of transition, from a pelean to a pumiceous eruption, has also been observed in other older deposits on Montagne Pelée. Although the probability is low, a similarly evolving scenario may be possible in the future at

Quantitative assessment of volcanic hazard for Martinique (simplified from Stieljes et al. 2001): hazard zones for Martinique



Montagne Pelée. The problem posed by this scenario is that critical parameters, which may result in dramatic changes of eruptive style, would need to be identified during the course of an eruption.

Scenario 6: Flank-collapse event

During its evolution Montagne Pelée has been subject to repetitive, large volume (several to tens of cubic kilometres), flank-collapse events, two of which occurred during the last 25,000 years. Since the last flank-collapse event, dated at ~9 ka, a new cone has been built on the inclined collapse surface that almost fills the entire horseshoe-shaped structure. Field data indicate that flank collapses occur after such a new cone has been constructed. Consequently, the debris avalanche resulting from a new flank-collapse event could have catastrophic effects both in the immediate region and also in a more widespread area, from the creation of a devastating tsunami. In fact, all of Martinique's coastal areas, as well as those of neighbouring islands, would be threatened by such a tsunami.

Integrated Volcanic Hazard Zones

Stieljes et al. (2001) proposed a complex quantitative methodology for the hazard assessment and zoning of Montagne Pelée. Numerous parameters were taken into account for a reference period of activity (the last 16,000 years), including an inventory of past eruptions and a frequency-intensity scale for dangerous volcanic phenomenon. The events identified as dangerous are: (i) lava flows, lava domes, and intrusions; (ii) pyroclastic flows (block-and-ash flows, surges, and ash-and-pumice flows); (iii) air fall (ash fall, pumice fall and block projectiles); (iv) mudflows (flow thickness >1 m); (v) different-sized landslides (landslides and debris avalanches); (vi) tsunami (run up >2 m); and (vii) emitted gases. The frequency scale has 5 levels, and is established by the frequency of the different types of recorded eruptions. The intensity scale has 5 levels and is based on possible destructive effects on buildings (<5% to >80% damage incurred). GIS maps for each major hazard type have been produced for all exposed areas (a total of 49 maps), and a complex integrated volcanic hazard zoning of seven levels was proposed. We propose here a simplified hazard map based on five levels

The first zone maps the area of maximum hazard. It covers the summit area, the upper flanks of the volcano (≤3 km from the summit), and summital radiating valleys. This zone could be affected by most phenomenon occurring during the previously proposed scenarios: phreatic events, lava dome growth, and open-vent pumiceous eruptions. It is also the most exposed to heavy air-falls and ballistic ejecta, pyroclastics flows and surges, and debris-avalanches and mud-flows in the valleys. Proximal coastlines can also be affected by tsunamis. Both the frequency and the level of destructive intensity would be at a maximum here.

The second zone is a circular area (radius ~5.5 km) of very high hazard which encompasses a large part of the volcano: it covers the entire south-western flank and all valleys radiating from the summit. This area could be affected by ash-and-pumice falls several metres thick, pyroclastic flows (block-and-ash flows and pumice flows), high-velocity pyroclastic flows, and also debris-avalanches and mud-flows.

Zone 2b is a high hazard area which extends outwards from Zone 2 almost entirely covering the volcano. It can be affected by large high-velocity pyroclastic flows (similar to those of 1902) and by ash-cloud surges (which develop at the top of channelled pyroclastic flows and can overflow the valley walls).

Zone 3 represents a circular area of moderate hazard (16 km in diameter). It would mainly be affected by ash-and-pumice falls leaving a maximum deposit thickness of several centimetres to tens of centimetres and by occasional large surges associated with pumiceous eruptions. All flanks of the volcano would be concerned and, in addition, the northern flank of Pitons du Carbet.

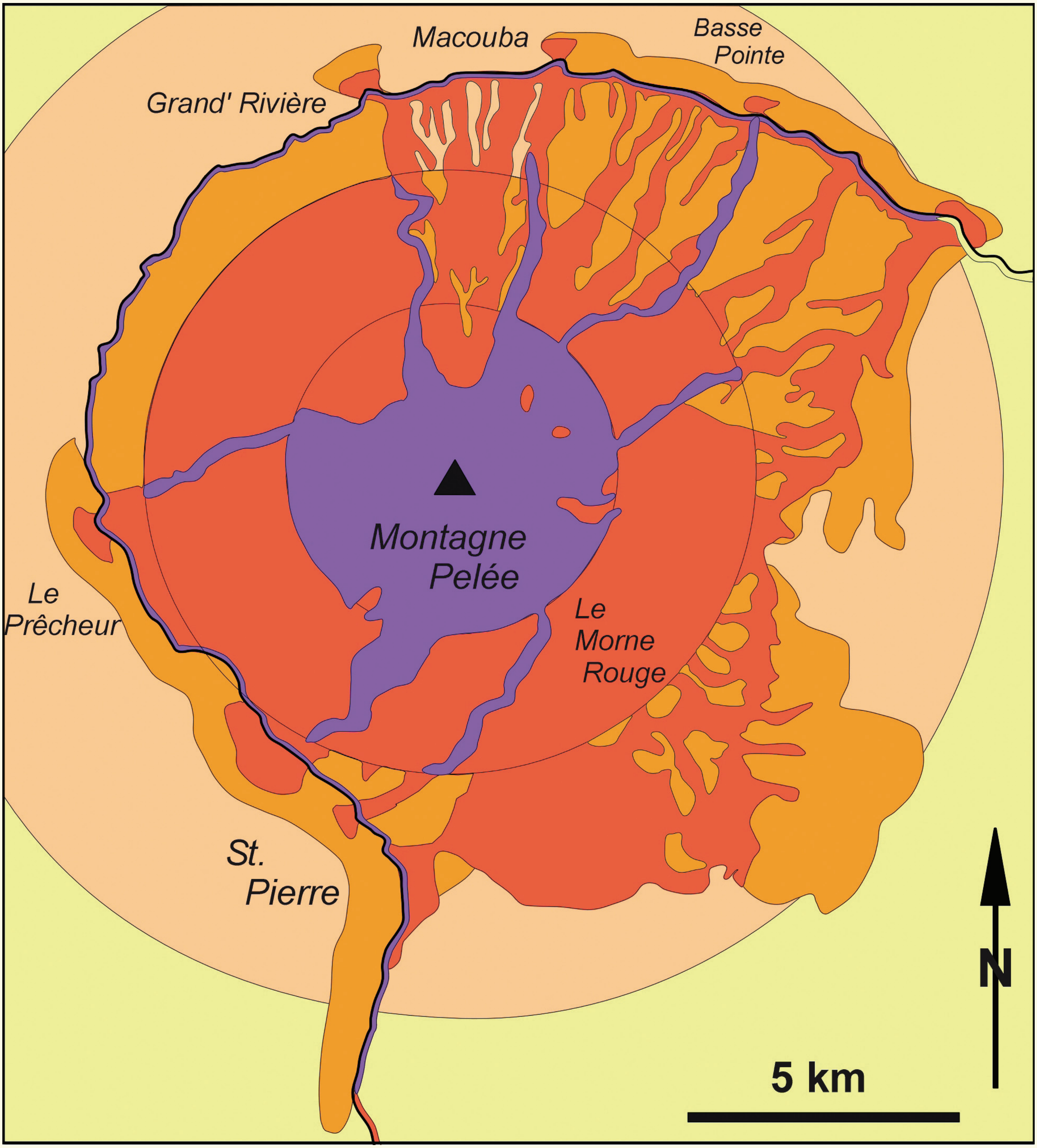
Zone 4 constitutes an area of low hazard, that could be affected by ash-falls resulting in low deposit thicknesses (circular area). This zone also includes the coastal areas that would be destroyed by tsunami in case of large flank-collapse events.

Two other types of hazards must also be taken into account even though their probability is low: (i) the hazard produced when a flank-collapse event occurs on a proximal island (e.g. St. Lucia or Dominica) generating a tsunami that could reach the coasts of Martinique, and (ii) the hazard resulting from a large pumiceous eruption occurring on one of the two neighbouring islands producing a thin ash-fall layer that could cover the whole of Martinique.

Conclusion

Montagne Pelée, one of the most active volcanoes of the Lesser Antilles arc, is the only active volcano of Martinique. Numerous destructive explosive eruptions have occurred in the past. Some of these were undoubtedly witnessed by the pre-Columbian Indians (Roobol et al. 1976), and accounts of the recent eruptions (since 1635) were recorded by the present people. The 1902-1905 dome-forming eruption, with ~30,000 casualties, was one of the world's most tragic events resulting from a primary volcanic event. Since the end of the last eruption in 1932 (more than 70 years ago), no eruptive activity has occurred. With respect to the historical period of activity, the probability of a new eruptive event increases with time. It is probable that a future event will begin with phreatic activity, as this has been systematically observed for all historical events. If the magma does not reach the surface, as happened in the 1792 and 1851 eruptions, the eruption can end at this stage. If however magma reaches the surface, the most likely type of activity will be a dome-forming eruption with associated block-and-ash flows, ash falls and lahars. The probability that violent laterally directed explosions producing highly turbulent and dilute ground-hugging pyroclastic flows occur during a dome-forming event is much lower. The structure of the volcanic edifice indicates that, in the case of a dome-forming eruption, the south-western flank would be the most exposed (all known flank-collapse structures open to the west). The probability of an open-vent pumiceous eruption is also high but lower than that for dome-forming events (the last plinian eruption occurred 650 years ago). In such an eruption all of the volcano's flanks would be affected by ash-and-pumice falls, the main valleys by ash-and-pumice flows and, in the case of a large amplitude event, the northern part of the island would also be covered by ash-and-pumice fall. Mudflows could be produced by the remobilisation of these ash-and-pumice deposits. A large flank collapse may also occur in the future, but the probability is

Quantitative assessment of volcanic hazard for Montagne Pelée (simplified from Stieljes et al. 2001): hazard zones around Montagne Pelée. See previous map for key to colours



low, considering the low number of events recorded in the past. The collapse of the voluminous new cone constructed inside the last horseshoe-shaped structure (km^3 to several km^3) would cause a catastrophic tsunami when the large amount of debris entered the sea. It would affect not only the population located around Montagne Pelée but in fact the entire population living along the coastline of all nearby islands.

The Volcanological and Seismological Observatory of Martinique (Institut de Physique du Globe de Paris) has developed different geophysical networks to monitor the volcano; namely seismic, ground deformation and magnetic networks. Even if Montagne Pelée's activity is very low at present, the Observatory will be ready to detect any precursors of a future eruption.

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