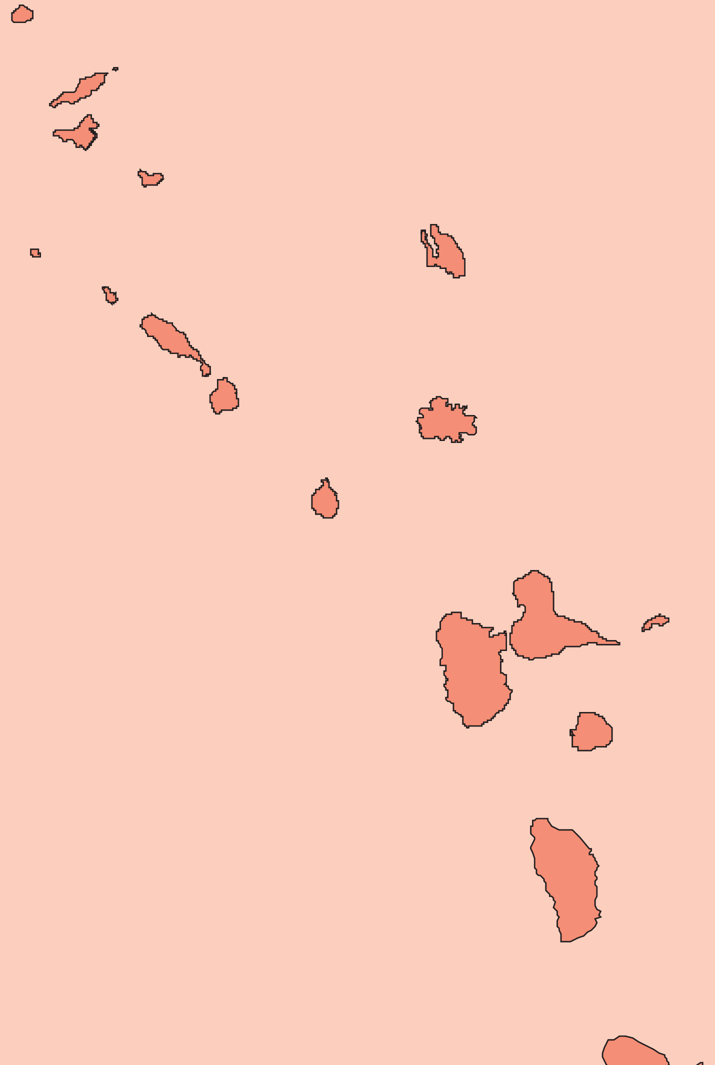
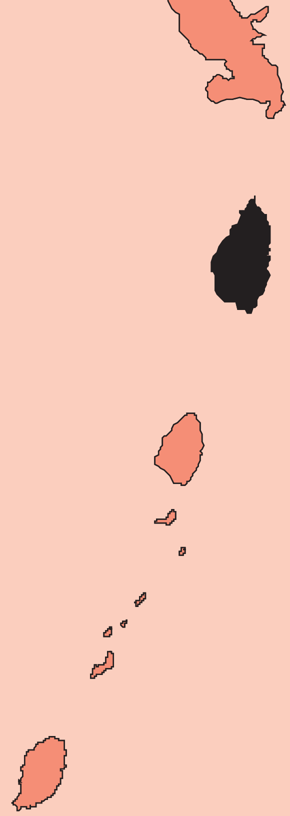
Saint Lucia





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Abstract

Saint Lucia is made up almost entirely of volcanic rocks, but only one volcano, the Soufrière Volcanic Centre in the southwest of the island, is considered to be potentially active. The youngest age dates available for activity at the Soufrière Volcanic Centre are 20,000 years BP. Several lava domes and explosion craters have, however, formed since then, which, together with the occurrence of occasional swarms of shallow earthquakes and vigorous hot spring activity in southern Saint Lucia, indicates that this area is still potentially active and can generate volcanic eruptions in the future. Four different scenarios for future activity are presented in order of decreasing probability. The most likely activity is a phreatic eruption from the Sulphur Springs geothermal field. Such an eruption would be relatively small and would only affect the area directly surrounding Sulphur Springs. The most likely scenario for a magmatic eruption is the formation of an explosion crater within the Qualibou Caldera, probably adjacent to Belfond. Eruptions that generate explosion craters can produce large amounts of ash and ballistic projectiles, but are unlikely to produce pyroclastic flows and lahars. The second most likely scenario for a magmatic eruption is a dome-forming eruption from within the Qualibou Caldera. Such an eruption may generate dome-collapse pyroclastic flows, pyroclastic surges and airfall. Lahars may also be generated at times of heavy rainfall during and after the eruption. A dome-forming eruption may continue for many years and would affect large areas of southern Saint Lucia. The least-likely or "worst-case" scenario is a large explosive magmatic eruption from either the Central Highlands or from within the Qualibou Caldera. Such an eruption may generate column-collapse pyroclastic flows, surges and associated airfall. Lahars may be generated at times of heavy rainfall during and after the eruption. Such an explosive eruption may last for years but could also be short-lived (weeks to months). Whatever the duration, areas affected by the eruption will remain uninhabitable for many years. Hazard maps, indicating areas most likely to be affected, have been generated for the two scenarios involving major magmatic eruptions from within the Soufrière Volcanic Centre.

Introduction

The information in this contribution is largely based on a recent Volcanic Hazard Assessment prepared for the Government of Saint Lucia by the Seismic Research Unit together with an extensive literature search of past research on the geology and seismicity of the island. Assessment of volcanic hazard was based on a thorough review of past volcanic activity, as evidenced by the distribution and type of existing deposits, comparison with other volcanoes in the Lesser Antilles (e.g. Montserrat) and an evaluation of historical volcanic seismicity and geothermal activity (Lindsay et al. 2002).

Relief Map of Saint Lucia

Geographical setting

The island of Saint Lucia, located in the southern region of the Lesser Antilles, is one of the larger islands of the arc, with an area of approximately 610 km^2. It has a youthful topography, being rugged and mountainous with narrow valleys. Only in the southeast corner is there a small coastal plain. The most pronounced topographic feature is the N-S trending axial range with the highest mountain, Mount Gimie (950 m; 3117 ft), located in the southwestern part of the range. On both the eastern and western sides of the axial range, heavily forested ridges descend to the coast, some interrupted by spectacular isolated pitons (volcanic necks/plugs). The northern part of the island has smaller, more rounded hills and gentler valleys and is the oldest part of the island. The southern part of the island is characterised by fan-shaped slopes that dip gently seaward and are cut by narrow and deep river valleys. Saint Lucia has a population of 163,267, with a large number (64,344) living in the capital city, Castries (2001 census).

Previous work

Although there are a few studies on the general geology of Saint Lucia (Sapper 1903; Earle 1923; Martin Kaye 1956 - 1961; Newman 1965), most previous work has concentrated on the volcanic geology and geothermal activity in the young southwestern part of the island around the town of Soufrière. The most detailed and comprehensive geological study of the Soufrière area was carried out by Tomblin and coworkers (Tomblin 1964, 1965; Robson and Tomblin 1966; Westercamp and Tomblin 1979).

More recent geological studies of the Soufrière area have been carried out by Roobol et al. (1983); Wright et al. (1984); Wohletz et al. (1986) and Mattioli et al. (1995). Early descriptions of activity at Sulphur Springs were given by Lafort de Latour (1787) and Hovey (1905), and the first detailed study of the area was made by Robson and Willmore (1955). More recent studies of the Sulphur Springs area have been directed towards evaluating its potential as a geothermal power source (e.g. Greenwood and Lee 1975; Lee and Greenwood 1976; Merz and Mclellan 1977; Williamson and Wright 1978; Williamson 1979; Aquater 1982; LANL 1984; Gandino et al. 1985; UNRFNRE 1989; Battaglia et al. 1991; GENZL 1992). Geochemical studies on the volcanic rocks have been published by Le Guen de Kerneizon et al. (1981; 1982; 1983) and Vidal et al. (1991), and several ages for rocks of Saint Lucia were presented in Briden et al. (1979) and Le Guen de Kerneizon et al. (1983). A reconnaissance-scale geochemical study of stream sediment and beach sand was carried out by Los Alamos National Laboratory and summarised in Maassen and Bolivar (1987). The earliest geological map of Saint Lucia was prepared by Newman (1965). This was updated by LANL (1984), OAS (1984), and most recently by Lindsay et al. (2002). Studies of Saint Lucia's seismicity were presented in Aspinall et al. (1976; 1994). Recently, detailed volcanic hazard assessments have been prepared for Saint Lucia by Ephraim (2000) and Lindsay et al. (2002).

Geology

With the exception of some minor sedimentary rocks of lower Miocene age cropping out on the east coast, Saint Lucia is made up entirely of volcanic rocks. Newman (1965) divided the different volcanic centres in Saint Lucia into three broad groups based on age and geographic distribution. These are, from oldest to youngest: the Northern, Central and Southern series. This subdivision is somewhat confusing, as several of the centres within the Northern Series are actually located in the south of the island. Furthermore, subsequent age dates obtained for the volcanic rocks of Saint Lucia show that several centres that were originally classed as part of the youngest Southern Series more likely correlate with the older centres of the Northern Series. Lindsay et al. (2002) suggested a slightly revised version of the original subdivision, grouping the volcanic rocks of Saint Lucia as follows:

1. *Eroded basalt and andesite centres (a revision of the 'Northern Series' of Newman 1965)*
2. *Dissected andesite centres (called the 'Central Series' by Newman 1965)*
3. *The Soufrière Volcanic Centre (a revision of the Southern Series of Newman 1965)*

Eroded basalt and andesite centres

The eroded basalt and andesite centres are the oldest rocks on Saint Lucia. They crop out in the northern and southern-most parts of the island, and rocks of similar age and composition probably underlie most of the younger rocks found elsewhere on Saint Lucia.

Northern Series

The centres in the north are characterised by highly deformed basaltic and andesitic lavas and pyroclastic deposits and represent some of the earliest volcanic activity in Saint Lucia. The oldest radiometric age obtained from rocks in this northern series is 18 Ma (Briden et al. 1979), and the youngest centres (Mt. Pimard, Vigie and Mt. Monier) have been dated at 5 - 6 Ma (Briden et al. 1979; Le Guen de Kerneizon et al. 1983). There are no known hot fumaroles in this area, although there is a relatively large (50 m x 30 m) area of warm spring activity and weak diffuse fumarolic activity in Ravine Raisinard on the south flank of Mount Monier. The temperatures of the springs in January 2001 were 30^{o} C (Lindsay et al. 2002). Despite this weak geothermal activity, its old age and lack of seismicity suggest that northern Saint Lucia is unlikely to be the site of future volcanic activity.

Southern Series

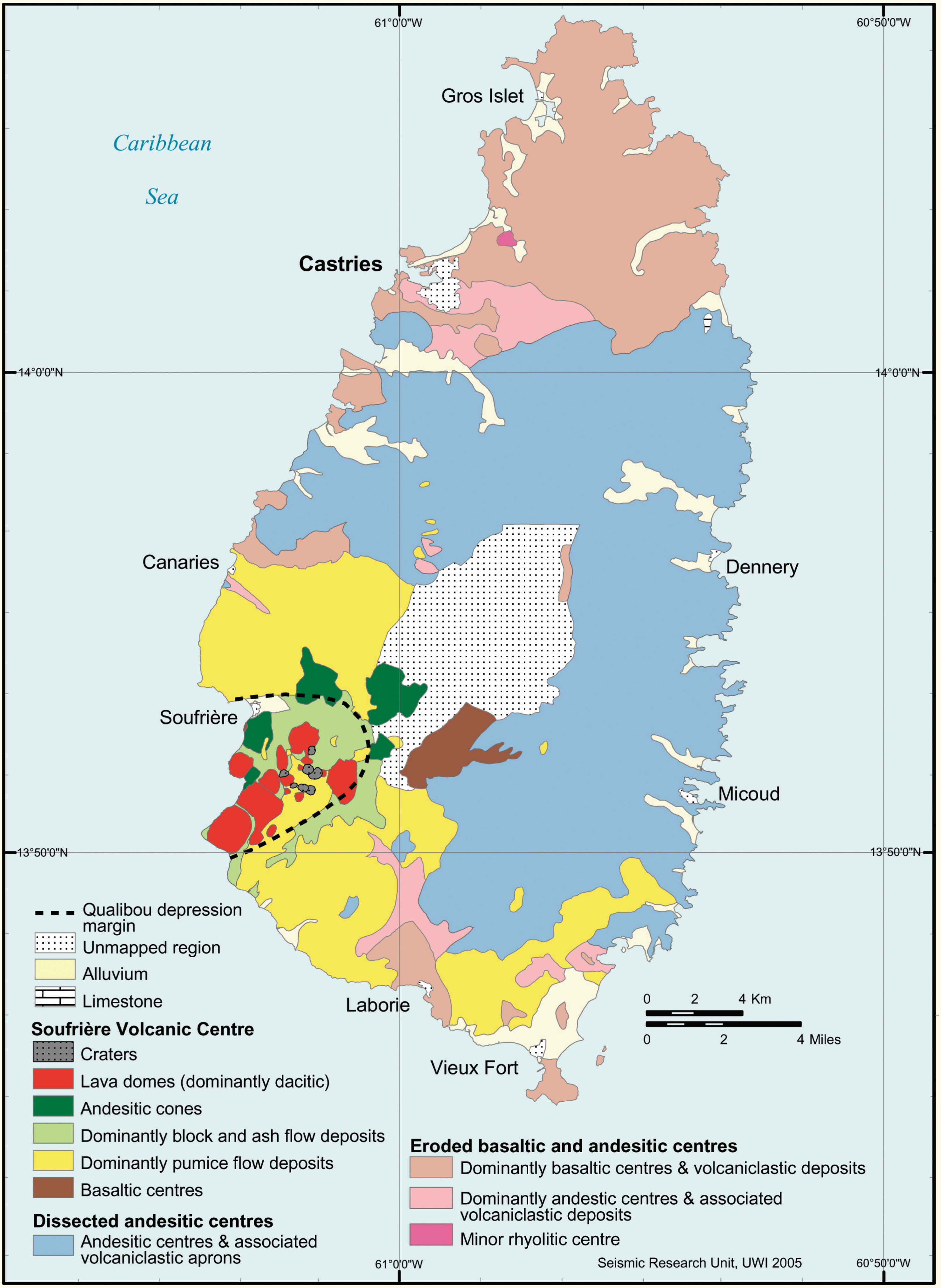
There are numerous small basaltic andesite centres in the south of Saint Lucia, including Mt. Gomier, Morne Caillandre, Moule a Chique/Maria islands, Savannes, Beauséjour, St. Urbain and Mt. Tourney. Age dates for these centres range from 10.1 Ma (lava near De Mailly) to 5.2 Ma (lava from Savannes). These ages are consistent with the subdued topography of these centres which suggests an older age. Some of these southern centres appear to be aligned (e.g. Morne Caillandre - Beauséjour - Mt. Tourney) forming semi-continuous elongate ridges, suggesting that there may be some structural control on their distribution. Two recent (1990 and 2000) shallow earthquake swarms were associated with these centres (Lindsay et al. 2002). There are no hot fumaroles associated with these centres, although there are several instances of 'cold soufrière' (i.e. areas of cold fumarolic activity); e.g. near Bois Demanje north of Grace, and in the village of De Mailly. These fumaroles are approximately 28^{o} C, acidic, and are located in areas of highly altered rock (Lindsay et al. 2002). There have also been reports of warm springs at Choiseul, a cold soufrière near the summit of Morne Caillandre/Victorin and underwater gas vents at Black Bay to the west of Vieux Fort. The age of the centres of the southern series suggests that they probably correlate with basaltic activity of the same age to the north and are unlikely to erupt again. However, the shallow seismicity and cold fumarolic activity in this area suggests that they should be monitored closely for any signs of reactivation.

Southern basaltic centres: Moule a Chique (right) and Maria islands and small quarried hill at airport (left)

Dissected andesite centres

In the central part of the island and extending down the southeast coast are many andesitic lavas and volcaniclastic deposits that appear younger than the deformed basaltic rocks to the north, yet are dissected enough not to appear recent. These were referred to as the 'Central Series' by Newman (1965). The rocks

Geological map of Saint Lucia (from Lindsay et al. 2002)



Age determinations of volcanic rocks from Saint Lucia

Description	Location	Age ± error	Method	Ref.
Soufrière Volcanic Centre				
Late-stage lava domes and explosion craters				
Belfond dome	Belfond	3.30 ± 0.24 Ma*	K-Ar	3
Belfond dome	Etangs	5.30 ± 0.39 Ma*	K-Ar	3
Morne Bonin dome		0.91± 0.08 Ma*	K-Ar	3
Dacitic pyroclastic flow deposits				
Belfond Pyroclastic flow deposit	Saltibus	20,000 ± 1,120	C14	2
Belfond Pyroclastic flow deposit	near Choiseul	20,980 ± 500	C14	2
Belfond Pyroclastic flow deposit	Quiesse Reserve	21,440 ± 640	C14	9
Belfond Pyroclastic flow deposit	Anse Noir	22,380 ± 420	C14	2
Belfond Pyroclastic flow deposit	near Choiseul	23,080 ± 280	C14	2
Belfond Pyroclastic flow deposit	east of Laborie	23,170 ± 180	C14	8
Belfond Pyroclastic flow deposit	Durandeau	23,500 ±140	C14	1
Belfond Pyroclastic flow deposit	north of Millet	24,210 ± 150	C14	8
Belfond Pyroclastic flow deposit	Venus Estate	24,520 ± 340	C14	1
Belfond Pyroclastic flow deposit	Durandeau-Millet	25,300 ± 700 24,900 ± 700	C14	2
Belfond Pyroclastic flow deposit	Ravine Poisson	29,100 ± 1,100	C14	2
Belfond Pyroclastic flow deposit (probably Choiseul Tuff)	Saltibus	34,200 ± 1670	C14	2
Choiseul Tuff	Choiseul	39,050 ± 1500	C14	4
Choiseul Tuff	south of Saltibus	>32,840	C14	2
Choiseul Tuff	east end of Choiseul beach	34,500 ± 350	C14	8
Choiseul Tuff	near Micoud	0.87 ± 0.07Ma*	K-Ar	3
Early dome-forming activity				
Gros Piton		0.23 ± 0.1 Ma	K-Ar	5
Gros Piton		0.29 ± 0.1 Ma	K-Ar	5
Petit Piton	NW flank	0.26 ± 0.04 Ma	K-Ar	6
Andesitic stratovolcanoes				
Mt. Gimie		0.9 ± 0.8 Ma	K-Ar	5
Mt. Gimie		1.7 ± 0.2 Ma	K-Ar	7
Mt. Gimie?	near Migny	3.3 ± 0.16 Ma	K-Ar	3
Early effusive activity				
basalt lava	Malgretoute	5.61 ± 0.25 Ma	K-Ar	6
basalt lava	Jalousie	6.1 ± 0.6 Ma	K-Ar	5
basalt lava	Jalousie	6.5 ± 0.6 Ma	K-Ar	5
Dissected Andesite Centres				
basalt lava	Anse Galet	2.02 ± 0.08 Ma	K-Ar	6
andesite lava	Derriere Dos	2.80 ± 0.14 Ma	K-Ar	3
andesite lava flow	Migny	3.13 ± 0.16 Ma	K-Ar	3
basaltic andesite lava flow	Dennery	5.52 ± 0.27 Ma	K-Ar	3
altered andesite pumice	Dennery	5.70 ± 0.28 Ma	K-Ar	3
basalt lava flow	Barre Coulon	8.87 ± 0.44 Ma	K-Ar	3
rhyolitic tuff	Dennery	10.40 ± 0.52 Ma	K-Ar	3
Eroded Basalt & Andesite Centres				
Northern Series				
andesite lava flow	Mt. Monier	4.66 ± 0.23 Ma	K-Ar	3
andesite plug	Mt. Pimard	5.62 ± 0.21 Ma	K-Ar	6
andesite plug	Vigie	5.94 ± 0.23 Ma	K-Ar	6
basalt lava flow	Labrelotte Point	7.68 ± 0.57 Ma	K-Ar	3
andesite lava	Pigeon Island	8.28 ± 0.41 Ma	K-Ar	3
andesite sill	Pigeon Island	9.12 ± 0.46 Ma	K-Ar	3
basaltic block in tuff	South of Point Hardy	9.39 ± 0.55 Ma	K-Ar	6
basalt lava	South of Point Hardy	9.63 ± 0.56 Ma	K-Ar	6
basalt lava flow	Esperance Hb	9.68 ± 0.48 Ma	K-Ar	3
andesite lava flow	Careffe	9.90 ± 0.74 Ma	K-Ar	3
basalt dike	Mt. Jambe	10.00 ± 0.75 Ma	K-Ar	3
lava	North of Gros Islet	10.3 ± 0.6 Ma	K-Ar	6
basalt dike	Esperance Hb	10.80 ± 0.54 Ma	K-Ar	3

Description	Location	Age ± error	Method	Ref.
basalt intrusion	Anse Lavoutte	10.94 ± 0.82 Ma	K-Ar	3
submarine basalt lava flow	Pt. Hardy	11.30 ± 0.84 Ma	K-Ar	3
basalt intrusion	Anse Galet	11.40 ± 0.85 Ma	K-Ar	3
basalt dike	Cap Point	15.01 ± 0.75 Ma	K-Ar	3
hornblende andesite in conglomerate	Cap Point	18.3 ± 0.9 Ma	K-Ar	6
Southern Series				
basalt lava	Savannes	5.21 ± 0.15 Ma	K-Ar	6
andesite lava flow	Laborie (Gomier?)	7.10 ± 0.36 Ma	K-Ar	3
andesite dome	Beauséjour	7.30 ± 0.36 Ma	K-Ar	3
andesite dike	Moule a Chique	8.15 ± 0.40 Ma	K-Ar	3
andesite dome	St. Urbain	8.66 ± 0.43 Ma	K-Ar	3
andesite lava flow	de Mailly	10.12 ± 0.50 Ma	K-Ar	3

*Age is given in 'years before present' unless otherwise stated. Ma = million years. References: 1= Smith and Roobol, unpublished data; 2= Wright et al. (1984); 3= Le Guen de Kerneizon et al. (1983); 4= Tomblin (1964); 5= Aquater (1982); 6= Briden et al. (1979); 7= Westercamp and Tomblin (1979); 8= Lindsay et al. (2002); 9= Roobol et al. (1983). *Age may be wrong due to excess Ar.*

of this series were deposited following a period of increased sea level across the entire region of the Lesser Antilles that occurred approximately 25 million years ago. They form a series of heavily forested and largely inaccessible volcanic centres in the centre of the island, including La Sorciere and Piton Flore to the north and the entire central highlands between Millet and Piton St. Esprit. Le Guen de Kerneizon et al. (1983) obtained 6 ages ranging from 10.4 Ma (lavas west of Dennery) to 2.8 Ma (lavas from Derriere Dos) for volcanic rocks in this group. The paucity of age dates for the andesite centres of central Saint Lucia make it difficult to say with certainty when they were last active. There are no known active fumaroles associated with these centres, although warm springs have been reported in the forest west of Dennery as well as in the Cul-de-Sac river. A large landslide on the northwest flank of La Sorciere has exposed an area of hydrothermally altered ground, which represents an area of fossil hydrothermal activity. Despite this evidence for past volcanic activity, the only age determination obtained from lava of La Sorciere (from Barre Coulon) yielded an old age of 8.9 Ma (Le Guen de Kerneizon et al. 1983). Further evidence of fossil hydrothermal activity in central Saint Lucia is indicated by two significant geochemical anomalies defined by elevated concentrations of arsenic, gold, antimony, selenium and lead: one in the upper reaches of the Roseau, Grande Riviere du Mabouya and Troumassee river drainage systems and the other within the Ravine Souffre drainage system near Marc Marc (Maassen and Bolivar 1987). The lack of active fumaroles associated with the dissected andesite centres, together with their age and lack of seismicity, suggest it is unlikely that they will erupt again, although more work is needed in this area to elucidate its volcanic history.

Soufrière Volcanic Centre

The Soufrière Volcanic Centre is the focus of the most recent volcanic activity in Saint Lucia (Lindsay et al. 2002). It comprises a series of volcanic vents and a vigorous high-temperature geothermal field and is associated with the Qualibou depression, a large arcuate structure that formed about 300,000 years ago as a result of an extremely large gravity slide. Published ages for volcanic activity at the Soufrière Volcanic Centre range from 5 Ma to 20 ka, although the youngest volcanic activity, a series of lava domes and small explosion craters, has not been dated. The presence of relatively young (<20 ka old) lava domes and craters together with the active geothermal field at Sulphur Springs indicates that the Soufrière Volcanic Centre is potentially active and may erupt again. This centre will be discussed in more detail under 'Potentially active centres' below.

A note on terminology

In southwestern Saint Lucia there are several volcanic necks/plugs (e.g. Gros and Petit Piton), volcanic domes (Terre Blanche, Belfond, Bonin), craters (e.g. those near Belfond), some larger structures that are probably the remains of a large stratovolcano (Mt. Gimie, Mt. Tabac), and possibly one caldera (the Qualibou caldera). Depending on the definition of 'volcano' that is used, these may be referred to as separate volcanoes, or as separate vents of the same volcano. Given their close proximity to each other, Lindsay et al. (2002) suggested these were best referred to as different vents of the same volcano, which they referred to as the Soufrière Volcanic Centre. They also recommended that the term 'Soufrière volcano' be avoided, due to the widespread misconception amongst the local populace that the active 'Soufrière volcano' in Saint Lucia is the steaming ground at Sulphur Springs.

Volcano monitoring

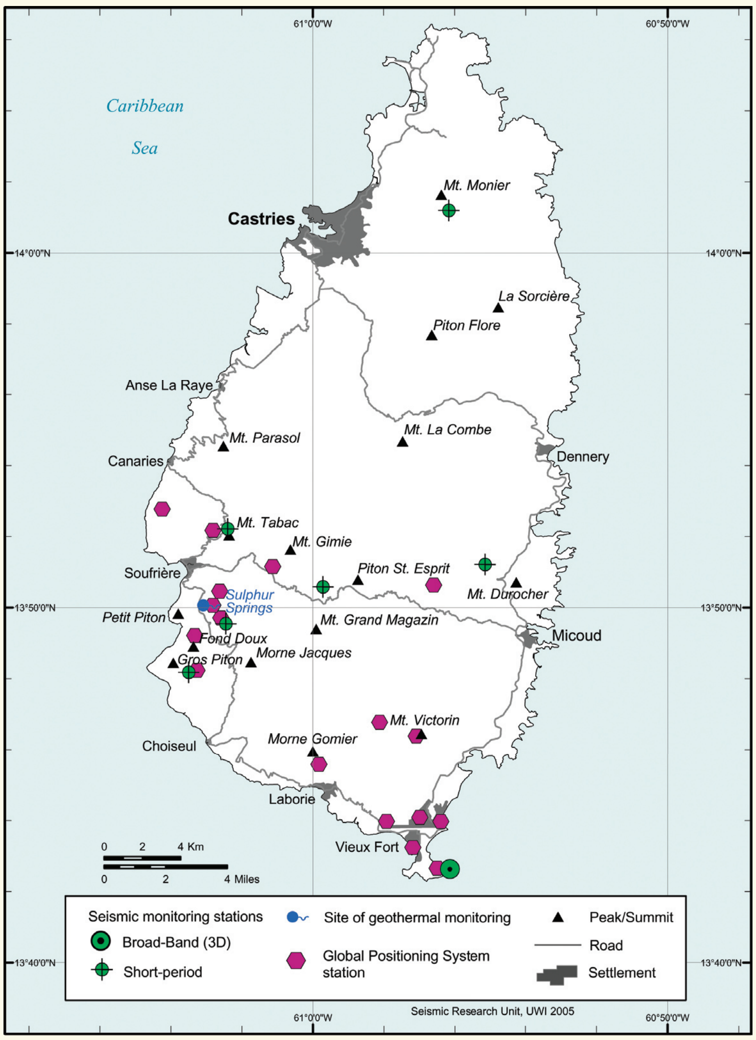
Volcanic and seismic activity in Saint Lucia is monitored by the Seismic Research Unit of the University of the West Indies, St. Augustine, Trinidad. In early 2001, the seismic network in Saint Lucia was upgraded, and now comprises 7 stations that transmit their data to a complete seismograph network base station at Moule a Chique. The computer at Moule a Chique automatically transmits data to Trinidad twice daily through an internet link and data can be retrieved on demand through the telephone system.

In January 2001 a 12-station GPS network was set up in southern Saint Lucia and a 23-pin levelling profile established close to the Sulphur Springs geothermal field. GPS results were complemented with distance measurements (EDM) wherever this was possible. The ground deformation network will be re-measured annually. To date there have been many investigations into the potential geothermal energy resource at Sulphur Springs, but no programme of regular monitoring of geothermal activity existed until April 2001, when the Seismic Research Unit established a programme to regularly sample and analyse gas and water samples from Sulphur Springs.

Ground deformation monitoring, near Terre Blanche, Soufrière Volcanic Centre

Steep slopes behind the northern end of the town of Soufrière represent the northern margin of the Qualibou depression

Volcano monitoring network, Saint Lucia



The Qualibou depression

The Qualibou depression is a large, cirque-shaped feature that dominates the topography of southwestern Saint Lucia. It was initially interpreted as a caldera that formed c. 40,000 years ago during the eruption of the thick sequence of pyroclastic rocks found surrounding the depression (Tomblin 1964, 1965; Robson and Tomblin 1966; Westercamp and Tomblin 1979). Subsequent age determinations showed that in situ features within the depression, such as the Gros and Petit pitons, were much older than the young pyroclastic deposits on the island, implying an older age for the depression. These age dates together with recently published evidence for offshore debris avalanche deposits (Deplus et al. 2001) constrain the age of the depression to ~300,000 years (Lindsay et al. 2002). Although the depression probably formed as a result of flank collapse (Roobol et al. 1983; Wright et al. 1984; Mattioli et al. 1995) some workers believe that part of the depression is occupied by a caldera (Wohletz et al. 1986).

Potentially active volcanic centres

Soufrière Volcanic Centre

The Soufrière Volcanic Centre is currently considered to be the only live volcanic centre in Saint Lucia.

Past eruptive activity

Early effusive activity

Earliest activity associated with this centre dates back to about 5 to 6 million years ago and is represented by weathered aphyric basaltic lavas exposed near the coast at Malgretoute and Jalousie. These lavas probably correlate with basalts of similar age at Savannes in the south and Mt. Pimard and Vigie in the north, and may have become exposed following the removal of overlying volcanic debris during the formation of the Qualibou depression.

Formation of andesitic stratovolcanoes

About 2 million years ago a major phase of volcanism led to the formation of Mt. Gimie and its neighbouring mountains, which may represent the remnants of a single large stratovolcano. This stratovolcano erupted many times to form thick accumulations of andesitic volcaniclastic deposits in the southwestern part of the island (including the 'caldera wall andesite agglomerate' and 'vulcanian andesite agglomerate' of Tomblin 1964). The few dates that are available for this phase of activity range from 3 Ma (an andesitic lava from near Migny; Le Guen de Kerneizon et al. 1983) to 1 Ma (an andesite lava from Mt. Gimie; Aquater 1982). Block and ash flow deposits from these centres are truncated at the northern margin of the Qualibou depression, indicating that these centres were active prior to the formation of the depression.

Early dome-forming activity

Between ~300 and ~40 ka ago there was a period of dome-forming activity within the Qualibou depression. This activity produced numerous predominantly dacitic lava domes and thick lava flows, which are preserved today as a series of dome-remnants and ridges (such as the Malgretoute, Plaissance, Coubaril and Rabot ridges) scattered within the depression. The spectacular Gros and Petit Piton are the remnants of two large dacitic lava domes that formed about 200 - 300 thousand years ago. They represent the steep inner core of two lava domes after almost all the loose rubbly material that normally aprons lava domes (dome talus) has been removed by efficient erosion due to the wind and the sea. The Fond Doux ridge and the three domes of Bois d'inde Franciou probably represent lava domes similar in age but probably somewhat younger than the Pitons and related domes.

Petit Piton, Soufrière Volcanic Centre

Explosive phase generating dacitic pyroclastic flows

An extremely violent phase of volcanic activity occurred at the Soufrière Volcanic Centre between 40 and 20 thousand years ago when a series of major explosive eruptions produced numerous dacitic pyroclastic flows and surges that flowed down all major valleys in the southern half of Saint Lucia and produced the deposits that now make up the southern slopes of the island. Two contrasting theories have been proposed for the source regions of this volcanic activity: 1. The eruptions occurred from within the Qualibou depression and led to the formation of a semi-circular volcanic collapse feature known as the Qualibou caldera (Wohletz et al. 1986). 2. The eruptions occurred from small vents in the Central Highlands, such as Mt. Grand Magazin and Piton St. Esprit (Roobol et al. 1983 and Wright et al. 1984).

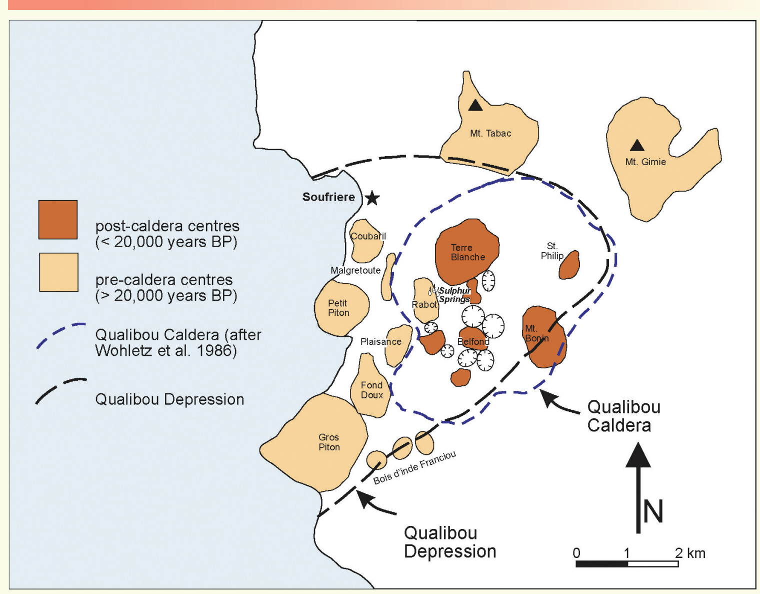
The nature of these pyroclastic flow deposits indicates that they formed by large explosive (Plinian) eruptions that generated column-collapse pyroclastic flows. The deposits that formed during these explosive eruptions have been divided into two main groups: the Choiseul and the Belfond pumice deposits (Wright et al. 1984). Each of these groups is made up of a series of different units which probably represent different eruptions or phases of an eruption. The Choiseul pumice deposit is a crystal-poor non-welded pyroclastic flow deposit containing pumices that are compositionally low-silica dacites. It is named after its type locality at Choiseul, where it forms the thick cliffs at the beach and in road cuts. To date only two samples from this deposit have been dated; these yielded radiocarbon ages of 39,000±1,500 years BP (Tomblin 1964) and 34,500±350 years BP (Lindsay et al. 2002). These ages suggest that the explosive eruptions that produced the Choiseul deposits may have spanned a period of several thousand years. The Belfond pumice deposit lies above the Choiseul pumice deposit. It is crystal-rich, non-welded and contains pumices that are compositionally high-silica dacites. This deposit was formed by a series of at least 10 pyroclastic flows that occurred between 25,000 and 20,000 years ago (Wright et al. 1984; Lindsay et al. 2002).

A 20 m thick sequence of dacitic pyroclastic deposits (probably Choiseul Tuff) produced during a Plinian eruption is exposed at the beach at Canaries

Late-stage generation of lava domes and small explosion craters

After the phase of explosive activity that formed the Choiseul and Belfond pyroclastic deposits a series of lava domes (e.g. Terre Blanche, Belfond) and explosion craters (e.g. La Dauphine estate) formed near the centre of the proposed Qualibou caldera. Some minor dome-collapse pyroclastic flow deposits (block and ash flow deposits) are associated with the lava domes, indicating a history of dome growth and collapse. Thin deposits of pyroclastic material surround the explosion craters, and these probably formed during minor short-lived, explosive

Sketch map of the main vents of the Soufrière Volcanic Centre



events. Field relations indicate that the explosion craters are younger than the adjacent Belfond lava dome. Two K-Ar ages of samples from the southern part of the Belfond dome yield stratigraphically inconsistent old ages of 5.3 and 3.3 Ma (Le Guen de Kerneizon et al. 1983). Wohletz et al. (1986) suggest a syn- or post-crystallisation enhancement in magmatic Ar to explain these old ages. Unfortunately no other dates are available from these domes or craters, and the date of the last magmatic eruption in Saint Lucia is therefore uncertain.

Historical eruptions

There have been no historical magmatic eruptions in Saint Lucia, i.e. eruptions involving the effusive or explosive ejection of magma at the surface of the Earth. There have, however, been several minor phreatic (steam) explosions from the Sulphur Springs area in historical times. The last one occurred in about 1766 and was described by Lefort de Latour (1787) as a 'minor explosion…… which spread a thin layer of cinders far and wide'. These 'cinders' (ash) probably represented fragments of old rock blasted apart by expanding steam rather than fragments of new magma.

Seismicity

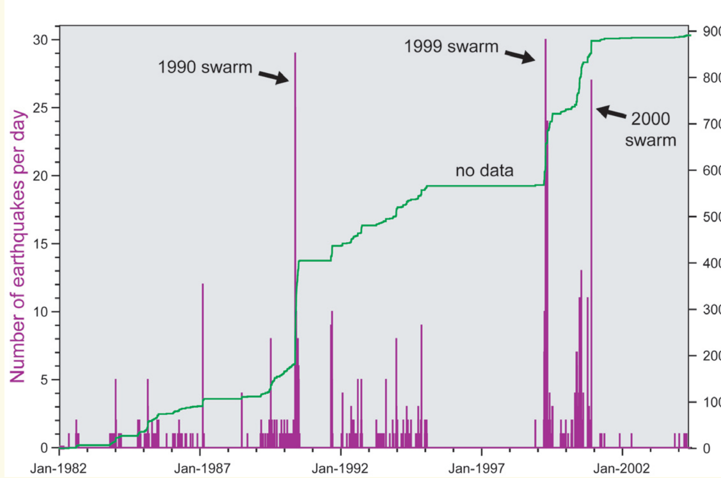
There have been at least five swarms of shallow earthquakes in Saint Lucia in the last 100 years. These occurred in 1906, 1986, 1990, 1999 and 2000. A sixth burst may have occurred in early 1998 when a number of earthquakes were reported felt but for which there were no seismograph recordings. At least three of these swarms, those of 1906, 1990 and 2000, seem to have been triggered by a larger tectonic earthquake.

1906 and 1986 swarms

In February 1906 Saint Lucia was shaken by a large tectonic earthquake which was also felt as far south as Grenada and as far north as Dominica, with the island experiencing numerous sharp shocks and tremors in the months that followed. Some of these were also noticed in nearby islands and may have been aftershocks following the larger earthquake. A great number, however, were only reported felt in Saint Lucia and probably comprised a tectonically triggered volcanic earthquake swarm.

A continuous seismic monitoring programme was established in Saint Lucia in 1982, and since then there have been periods of relatively low seismicity interrupted periodically by bursts of shallow earthquakes. The first burst culminated in early 1986, when 12 earthquakes happened in a single day, of which four were reported widely felt in southern Saint Lucia.

Earthquake numbers for Saint Lucia from 1982 to June 2002



1990, 1999 and 2000 swarms

Another burst of shallow earthquakes occurred between May and June 1990, with activity peaking on May 19, when 29 earthquakes occurred in a single day. Most of these earthquakes were felt, and the largest was of magnitude 4.5 which was sufficient to cause significant damage close to the epicentre. Fortunately the epicentre was in one of the most sparsely-populated parts of Saint Lucia, to the north of Mt. Gomier in the south of the island, so little damage was in fact caused. Between April and June of 1999, 105 volcanic earthquakes were recorded in southern Saint

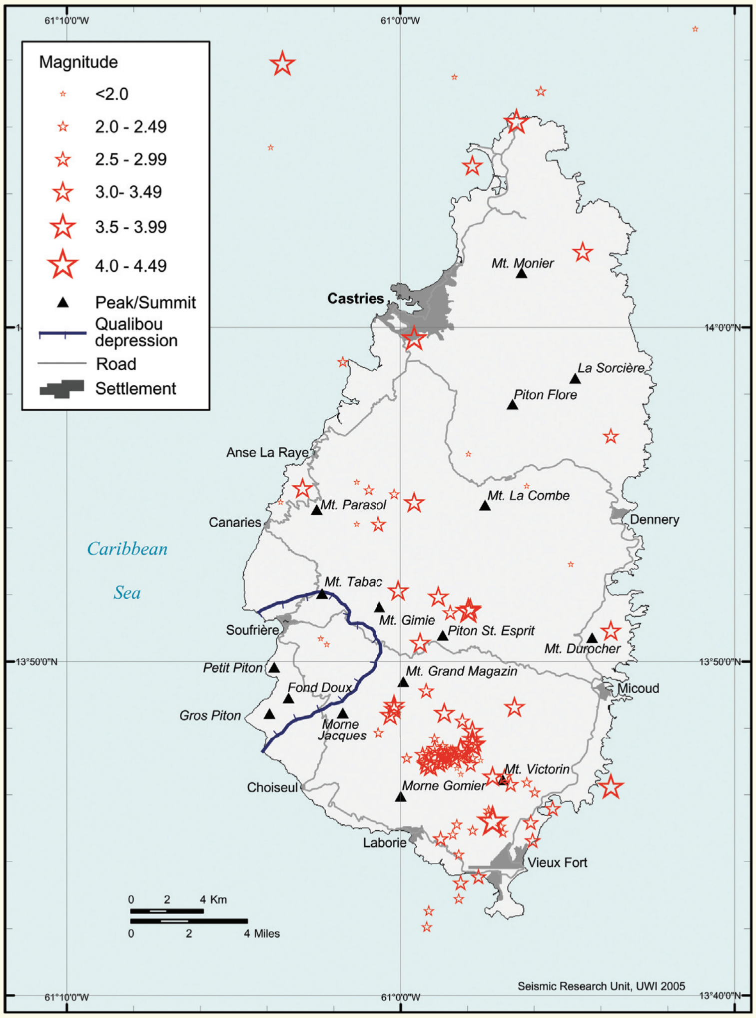
Interpretation of recent earthquake swarms

None of the recent shallow earthquake swarms in Saint Lucia for which epicentre locations were determined were directly related to the area of most recent volcanic activity, the Soufrière Volcanic Centre. Some of the earthquakes of the 1990 and 2000 swarms are associated with older basaltic centres that have previously been considered 'dead' (e.g. Mt. Gomier and Morne Caillandre/Victorin). This is in strong contrast to the situation in other islands such as St. Vincent, Dominica, Montserrat and St. Kitts where the majority of local earthquakes are strongly associated with individual young volcanoes.

The two main swarms of shallow earthquakes in 1990 and 2000 were characterised by a single large shock followed by a sequence of gradually diminishing smaller shocks (Lindsay et al. 2002). This pattern is typical of tectonic earthquake sequences, i.e. sequences of earthquakes which are not connected with volcanic activity. This is quite puzzling, given that the shallow depths of the earthquakes are more consistent with a volcanic origin. Also puzzling is the fact that tectonic earthquakes in the Lesser Antilles typically do not occur close to Saint Lucia, and those that do generally have depths greater than 70 km. Furthermore, the epicentres of the "aftershocks" do not cluster around the epicentre of the main shock, which is not typical of tectonic earthquakes. The earthquakes that occurred in St Lucia in 1990 and 2000 have characteristics of both volcanic and tectonic earthquakes which make them difficult to interpret. These earthquakes have features that are consistent with a special class of tectonic earthquakes called Near Plate Boundary Intraplate Earthquakes, which are more common in the northern rather than southern Lesser Antilles.

The most likely interpretation of the recent swarms is that several Near Plate Boundary Intraplate earthquakes of magnitude greater than about 3 occurred, triggering seismic activity on nearby near-surface faults (Lindsay et al. 2002). This would explain the shallow depth of the earthquakes and the fact that the "aftershocks" do not cluster around the epicentre of the main shock. A similar scenario on a larger scale may have occurred in the swarm of 1906. The earthquakes of the two most recent swarms appear to have a NE-SW trend paralleling a dominant structural trend of faults and volcanic vents in southern St Lucia. It is likely that shallow NE-trending faults have, in the past, acted as paths of weakness in the crust of southern St Lucia along which magma has migrated to the surface. It is, therefore, possible that the swarms of 1990 and 2000 may reflect new periods of magma migration along shallow NE-SW trending faults.

Epicentres of earthquakes in Saint Lucia since 1982



Lucia. These earthquakes were only strong enough to record on one station, and none were reported felt. The most recent swarm began in July 2000 and culminated on November 24 with 27 earthquakes occurring in a single day. Activity was largely over by January 2001.

Geothermal activity

There are numerous areas of fumarolic and hot spring activity associated with the Soufrière Volcanic Centre. Most of these occur in and around the well-known Sulphur Springs area, with warm springs also present at Jalousie and underwater gas vents offshore between Anse Mamin and Soufrière Bay. Newman (1965) reports an area of intensely hydrothermally altered clayey ground about a mile to the south of Piton Canarie, which is probably an area of fossil hydrothermal activity.

Sulphur Springs geothermal field, Soufrière Volcanic Centre

Characteristics of selected geothermal features of Sulphur Springs, from Joseph and Robertson (2003)

Specific location	GPS reading	Feature	Date	Temperature (°C)	pH
Northern Valley area	13° 50.328' N ; 061° 02.811' W	Painted pool	15.04.01 14.11.02 26.05.03 03.11.03	84.0 89.0 81.4 84.8	6 6 7 6
Sulphur Slope	13° 50.312' N; 061° 02.789' W	Fracture fumarole	15.04.01 15.11.02 27.05.03 03.11.03	96.6 94.5 35.1? 92.6	5 4.5 5 5
Gabriel's crater area	13° 50.254' N; 061° 02.765' W	Fizzy pool	15.04.01 15.11.02 26.05.03 04.11.03	70.0 73.2 41.5 43.8	6.5 3 3 3
Calalloo Creek	13° 50.251' N; 061° 02.760' W	Small green gasser	15.04.01 15.11.02 26.05.03 04.11.03	93.3 95.2 89.4 89.5	7 7 7 7
Gabriel's crater area	13° 50.265' N; 061° 02.772' W	Lake Placid	15.04.01 15.11.02 26.05.03 04.11.03	77.0 83.5 71.6 74.4	7 6 6 6
Sulphur Springs river	13° 50.406' N; 061° 02.814' W	Office bath stream	15.11.02	39.5	6
Sulphur Springs river	13° 50.245' N; 061° 02.676' W	Platform pool	15.11.02	33.8	7

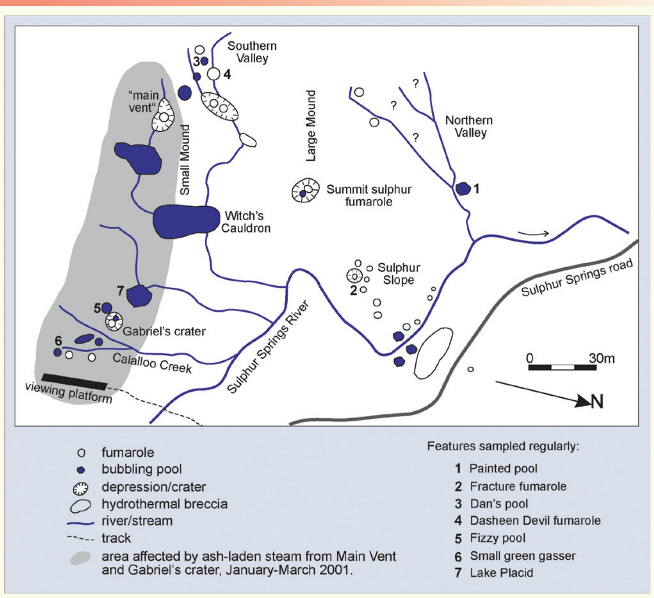
Sulphur Springs

The well-known Sulphur Springs of Saint Lucia is one of the hottest and most active geothermal areas in the Lesser Antilles. It comprises numerous hot springs, bubbling mud pools and fumaroles in an area of strongly hydrothermally altered clay-rich rock approximately 200 m x 100 m in size on the northeastern flank of Rabot ridge. Some smaller features are also present on the western flanks of Terre Blanche. Many fumaroles have temperatures 100 ^{o}C or hotter, and temperatures of up to 172 ^{o}C have been recorded. The heat source for the Sulphur Springs geothermal system is probably the cooling magma body responsible for the young volcanism of the Soufrière Volcanic Centre. Numerous studies have been carried out over the past 50 years to investigate the geothermal energy potential of Sulphur Springs. To date, however, no attempt at exploitation has been made.

Currently, activity at Sulphur Springs is concentrated on the western side of the Sulphur Springs Road. However, extensive areas of hydrothermally altered ground together with stunted vegetation on the eastern side of the road (i.e. on the flanks of Terre Blanche) clearly show that this area was once active. Furthermore, the area beneath the viewing platform, including Gabriel's crater, does not appear on a map of Sulphur Springs from the 1950s (Robson and Willmore 1955), indicating that this area of activity is relatively recent.

Gases collected from fumaroles at Sulphur Springs have similar chemical characteristics despite considerable differences in temperature, and are quite typical for subduction-related geothermal fields (Brown 2002).

Sulphur Springs geothermal field, Soufrière Volcanic Centre



Misunderstood facts about Sulphur Springs

1. Contrary to popular belief, the hot springs and fumaroles of Sulphur Springs do not act as a safety valve reducing the likelihood of an eruption. The Sulphur Springs geothermal field is a relatively surficial feature, with water probably only circulating to depths of up to a few km below the surface. In contrast, the magma chamber beneath the Soufrière Volcanic Centre is a very deep feature, and is probably located about 6 - 8 km beneath the surface. Changes in the magmatic system may be reflected in the chemistry and temperature of the gases at Sulphur Springs, hence the importance of monitoring fumarolic activity. The reverse, however, is not true: changes in Sulphur Springs (such as blocked vents) do not affect the magma chamber below. It is possible to get small, localised, steam-driven eruptions of old rocks and ash (known as hydrothermal eruptions) from time to time in geothermal fields such as Sulphur Springs, and these can be triggered by blockages of thermal vents. However, if a steam vent is blocked the more common response is that steam simply finds a new pathway along a new crack to the surface. If steam stops coming out of a particular vent, this does not necessarily mean that there is a blockage in the vent. It may mean that the internal plumbing has changed and the steam now has an alternative route to the surface, or it may mean that a period of lowered rainfall has led to a decrease in activity.

2. Sulphur Springs itself is not a volcano. It is a geothermal field located within the much larger Soufrière Volcanic Centre. Although some small hydrothermal and phreatic eruptions may be produced at Sulphur Springs from time to time, a future magmatic eruption could occur from anywhere within the Soufrière Volcanic Centre.

Dangers associated with geothermal activity in Saint Lucia

There are numerous dangerous phenomena associated with the Sulphur Springs geothermal field and other geothermal areas in Saint Lucia that are totally independent of an increase in volcanic activity in Saint Lucia.

Volcanic gases

Fumarolic areas such as Sulphur Springs emit large amounts of harmful gases. Areas of cold spring activity also release dangerous gases into the atmosphere. The most common gases in volcanic areas are water vapour (H_2O), carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen (H_2), hydrogen sulphide (H_2S) and carbon monoxide (CO). Inhalation of SO_2 and H_2S can cause chronic inflammation and burning of the eyes and respiratory tract. Residents that live close to the "cold soufrière" in Saint Lucia report sometimes finding dead animals in low-lying areas near the gas vents. These animals probably asphyxiated due to the inhalation of CO_2.

Chemistry[1] of selected Sulphur Springs fumaroles sampled in April 2001 (Brown 2002)

Feature	T ^{o}C	pH	CO_2	S_{tot}	H_2S	H_2	CH_4	N_2	O_2	CO	N_2/Ar	N_2/He
Fracture fumarole	96.6	5	993	3.54	3.54	4.99	0.86	1.41	0.00	0.01	192	5419
Dasheen Devil fumarole	137.6	7	992	6.75	6.75	5.46	1.03	1.57	0.00	0.01	220	4487
Fizzy pool	70.0	6.5	993	2.91	2.91	4.52	0.80	1.43	0.00	0.00	269	4340
Small green gasser	93.3	7	992	4.11	4.11	5.79	0.99	1.64	0.02	0.00	552	4794

[1]*Gas analyses in mmol/mol dry gas*

Scientists collecting gas samples at Sulphur Springs

Landslides
The circulation of acidic water beneath geothermal areas leads to intense rock alteration, resulting in soft clay-rich ground. Such ground is unstable, and from time to time slumps or landslides may occur, particularly in those geothermal areas located on steep slopes devoid of vegetation. Landslides may be triggered by earthquakes. There are reports of such a landslide occurring on the Sulphur Springs flank of Terre Blanche in 1990, and landslides can occur at any time in the active portion of Sulphur Springs. There is evidence for recent landslide activity on the upper slopes of the Sulphur Springs geothermal area near Rabot. This area must be considered very unstable. Landslides in geothermal areas can change the internal plumbing of the system, leading to the blocking off of some vents and opening of others. If large amounts of material are removed, a hydrothermal eruption may be triggered. There is evidence that geothermal activity at Sulphur Springs has migrated in the past, and it is possible that, over time, activity might continue migrating to the south and west. Such migration of activity in geothermal systems is quite normal. However, migration of geothermal activity into areas of steep slopes may increase the likelihood of landslides triggered by extensive hydrothermal alteration.

Terre Blanche dome, with landslides and hydrothermal alteration

Phreatic and hydrothermal eruptions
Although dominated by fairly constant hot spring and fumarolic activity, from time to time the craters of Sulphur Springs may be the source of small phreatic and hydrothermal (steam-driven) eruptions that eject fine ash which coats leaves of nearby plants. Phreatic eruptions do not eject new magma. The ash-like material ejected during a phreatic eruption is usually made up of mud and old altered rock and mineral fragments. These phenomena probably represent local adjustments in the geothermal system that lead to minor, 'throat-clearing' events, although occasionally they can herald the onset of an actual magmatic eruption. The most recent historic phreatic eruption occurred in about 1766, and led to a thin layer of "cinders" being deposited "far and wide" (Lefort de Latour, 1787). In early 2001 the fumaroles in Gabriel's crater and the main vent ejected enough ash-like material to reach people at the viewing platform and to coat nearby trees.

Future eruptions
Unlike most other islands in the Lesser Antilles where there is a single, potentially-active volcano with a long history of past activity (e.g. Mt. Liamuiga on St. Kitts or The Soufrière of St. Vincent), there is no one obvious volcanic vent in Saint Lucia from which future eruptions can be expected. In fact, given the complicated volcanic history of southern Saint Lucia and lack of age data, it is impossible to predict with certainty when and where the next magmatic eruption will occur. Despite this, some constraints do exist, making it possible to develop a series of possible scenarios.

For the last 20,000 years, volcanic activity in Saint Lucia has taken the form of effusive lava dome-forming eruptions and minor explosive eruptions forming explosion craters within the Soufrière Volcanic Centre. The only historical activity in the Soufrière Volcanic Centre has been minor phreatic eruptions from Sulphur Springs, the most recent in 1766. This history indicates that the Soufrière Volcanic Centre is the most likely location for future eruptions in Saint Lucia. Analyses of both charcoal and lava samples of the Soufrière Volcanic Centre have yielded ages ranging from about 5 million to 20 thousand years. The oldest ages were obtained from the basalts at Jalousie and Malgretoute, and the youngest ages from the Belfond pyroclastic flow deposit. There are, unfortunately, many gaps in the data. For example, we do not know the age of Mt. Tabac, or the explosion craters within the caldera, or the domes of Bois d'inde Franciou, Rabot, Fond Doux, Terre Blanche, Morne Bonin or Belfond. The best we can say is that Saint Lucia does not appear to have a long recent history of explosive eruptions, rather, major explosive activity seems to have been concentrated in the time period between about 35 and 20 thousand years ago. Since then there have been several effusive lava-dome forming eruptions from a number of different centres as well as minor explosive activity leading to the formation of small explosion craters.

Eruption Scenarios
Four different scenarios for future activity were developed for the Soufrière Volcanic Centre by Lindsay et al. (2002). These can be divided into two groups based on eruption size and probability: Minor/most-likely activity (scenarios 1 and 2) and major/least-likely activity (scenarios 3 and 4). It should be emphasised here that explosive and effusive eruptions are not mutually exclusive and they can both occur during a single eruption. An eruption may switch from being dominantly effusive to dominantly explosive or vice versa, or the two eruption styles may occur simultaneously.

Possible scenarios for future activity from the Soufrière Volcanic Centre

Minor activity/Most likely	Major activity/Least likely
Scenario 1: Phreatic or hydrothermal eruption from the Sulphur Springs geothermal field	Scenario 3: Moderate effusive dome-forming eruption within the Qualibou Caldera
Scenario 2: Small explosive eruption forming an explosion crater in the Belfond area	Scenario 4: Large explosive Plinian eruption from either the Central Highlands or from within the Qualibou Caldera

Scenario 1: Phreatic eruption

The most likely type of volcanic activity to occur in southern Saint Lucia is a phreatic eruption from the Sulphur Springs geothermal field. Phreatic eruptions are steam-driven eruptions that eject fragments of old rock and ash into the air and are very common in geothermal areas. They do not erupt fresh magma, although they can emit dangerous gases. Individual phreatic explosions may last up to an hour or more, and a series of blasts may continue intermittently for several months or even years. In some instances, particularly if they occur in a sequence, phreatic eruptions may herald the arrival of an actual magmatic eruption and may be accompanied by volcanic earthquakes.

The craters of Sulphur Springs may also produce hydrothermal eruptions. These are similar to phreatic eruptions, but eject more rock than phreatic eruptions do. Hydrothermal eruptions have been known to eject clasts up to 2-3 m in diameter several hundred meters from the vent and they can be locally very destructive, causing loss of life and damage to structures. A hydrothermal eruption may last for several days, and steam may continue to be discharged for up to several years after the hydrothermal eruption has ended.

Scientists taking measurements at Sulphur Springs

In the event of a phreatic or hydrothermal eruption from Sulphur Springs, the direct effects will probably only be felt over a small area of a few 10s to 100s of metres from the vent. However, the potential impact on life in the area surrounding Soufrière is great, largely due to the indirect effects of an eruption. The water, ash and steam ejected during a phreatic or hydrothermal eruption is likely to be acidic and would contaminate nearby streams and rain-water collection tanks. Both types of eruptions may eject enough water to generate small floods in the Soufrière stream and make the Sulphur Springs road impassable. In general, however, the area affected by a phreatic or hydrothermal eruption will be very small compared with that affected by a magmatic eruption.

Scenario 2: Small explosive eruption

The most likely scenario for a magmatic eruption is the formation of an explosion crater within the Qualibou Caldera. It is difficult to say with certainty where such an eruption will occur. However, existing explosion craters are predominantly associated with the Belfond dome and this seems the most likely location for the site of a future eruption. Swarms of shallow earthquakes should precede such an eruption which will allow more precise estimates of the location of the eruption before it begins. Small phreatic eruptions may also occur prior to the onset of a magmatic eruption. Eruptions that generate explosion craters can produce large amounts of ash and ballistic projectiles which may be thrown up to about 3 km from the vent. They are unlikely to produce pyroclastic flows and lahars and may be relatively short lived, lasting only a few weeks to months. It is likely only to affect the area within the Qualibou depression although some ash may fall outside the depression, depending on wind direction.

Scenario 3: Effusive dome-forming eruption

Several dome-forming eruptions have occurred from within the Soufrière Volcanic Centre over the last 20,000 years (e.g. Terre Blanche and Belfond), and this is considered the most-likely scenario for a major volcanic eruption in Saint Lucia. Based on past activity, a future dome-forming eruption is likely to occur from within the Qualibou Caldera. Until precursory signs (such as earthquake swarms) appear which will provide an idea of vent location, it is difficult to say with certainty whether this activity will lead to the development of a new dome or reactivate an existing one such as Belfond or Terre Blanche. For the purposes of the hazard map prepared for this scenario the vent has been placed between Belfond and Terre Blanche, near some of the young explosion craters and not far from Sulphur Springs. It must be stressed, however, that future dome-forming activity could occur elsewhere within the caldera.

The initial phases of the eruption may involve either non-explosive, passive eruption of lava to form a mound or hill (similar to, but possibly bigger than Terre Blanche) or a period of vigorous 'vent-clearing' explosive magmatic activity followed by passive extrusion of lava. Either scenario for this initial phase is likely to be preceded by a series of phreatic eruptions, and the latter scenario may even generate sizable pyroclastic flows and surges. Once the lava dome is established and begins to grow, it may become oversteepened and unstable, causing it to periodically collapse and generate pyroclastic flows. In addition, explosive activity may occur periodically during dome-formation, possibly triggering explosive dome-collapse events as well as abundant ash and ballistic projectiles. A style of eruption involving dome growth and periodic collapse interspersed with small explosions is typified by the ongoing eruption on Montserrat. The likely duration of an eruption of this sort is between one and ten years.

Terre Blanche dome (left) and Rabot Ridge (right), with Sulphur Springs in between. The town of Soufrière is in the foreground

The greatest hazard in the event of a dome-forming eruption within the Qualibou Caldera is from lava dome collapse (either gravitational or explosive) producing pyroclastic flows and surges with accompanying ash fall. Depending on the height and exact location of the dome that is formed, dome-collapse pyroclastic flows could affect a large area surrounding and including Soufrière and Belfond. Pyroclastic flows and surges will likely reach the sea between Soufrière and Malgretoute, and at Jalousie and Anse l'Ivrogne, where they will create new land. The steep-sided walls of the Qualibou depression should prevent pyroclastic flows generated by gravitational dome-collapse from travelling outside of the depression. However, vigorous flows and surges may be energetic enough to cross this barrier, in particular to the south, where the walls are not as steep. The least-frequent but arguably most-devastating type of activity that could occur in this eruption scenario is typified by the December 26, 1997 ("Boxing Day") activity at the Soufrière Hills Volcano in Montserrat, in which part of the upper flanks of the dome collapsed, producing a debris avalanche, and triggering an energetic volcanic blast. The associated pyroclastic surge devastated an area of 10 km^2 to the southwest of the volcano. If such a lateral blast is directed to the south or southeast of the vent in Scenario 3 for Saint Lucia, then much of the area in the southwest of the island would be devastated, largely irrespective of topography (see tan area on hazard map).

Volcanic explosions and pyroclastic flows and surges generate large amounts of volcanic ash, and ash fall is the most widespread of any volcanic hazard. The walls of the Qualibou depression will have no effect on the distribution of ash fall, which will instead be controlled by the height of the ash cloud together with the dominant wind direction. Ash clouds above pyroclastic flows will be restricted to lower elevations (less than about 5 km) whereas those generated by explosive eruptions will reach much higher elevations. In the case of Saint Lucia, the dominant wind direction is from the east (easterlies) at lower elevations (< about 4-12 km, depending on time of year), and from the west (westerlies) at higher elevations (up to 17-18 km, above which are the stratospheric easterlies). Ash may travel for kilometres and affect neighbouring islands and at times severely disrupt air traffic. Atmospheric effects in ash clouds would generate frequent lightning strikes near and downwind of the vent.

Ash fall will be thickest close to the vent and will decrease in thickness away from the vent. The pattern of accumulated ash fall thickness and distribution exhibited between 1995 and 2001 by the ongoing eruption of the Soufrière Hills volcano in Montserrat (Norton et al. 2001) has been used to define the probable ash fall pattern on the hazard map for this scenario. Ballistic projectiles may also be generated during small explosions or the explosive collapse of a volcanic dome and would mainly affect an area within 5 km of the vent. Lighter fragments (such as pumice) may be kept buoyant in the eruption plume for much greater distances before falling back to Earth.

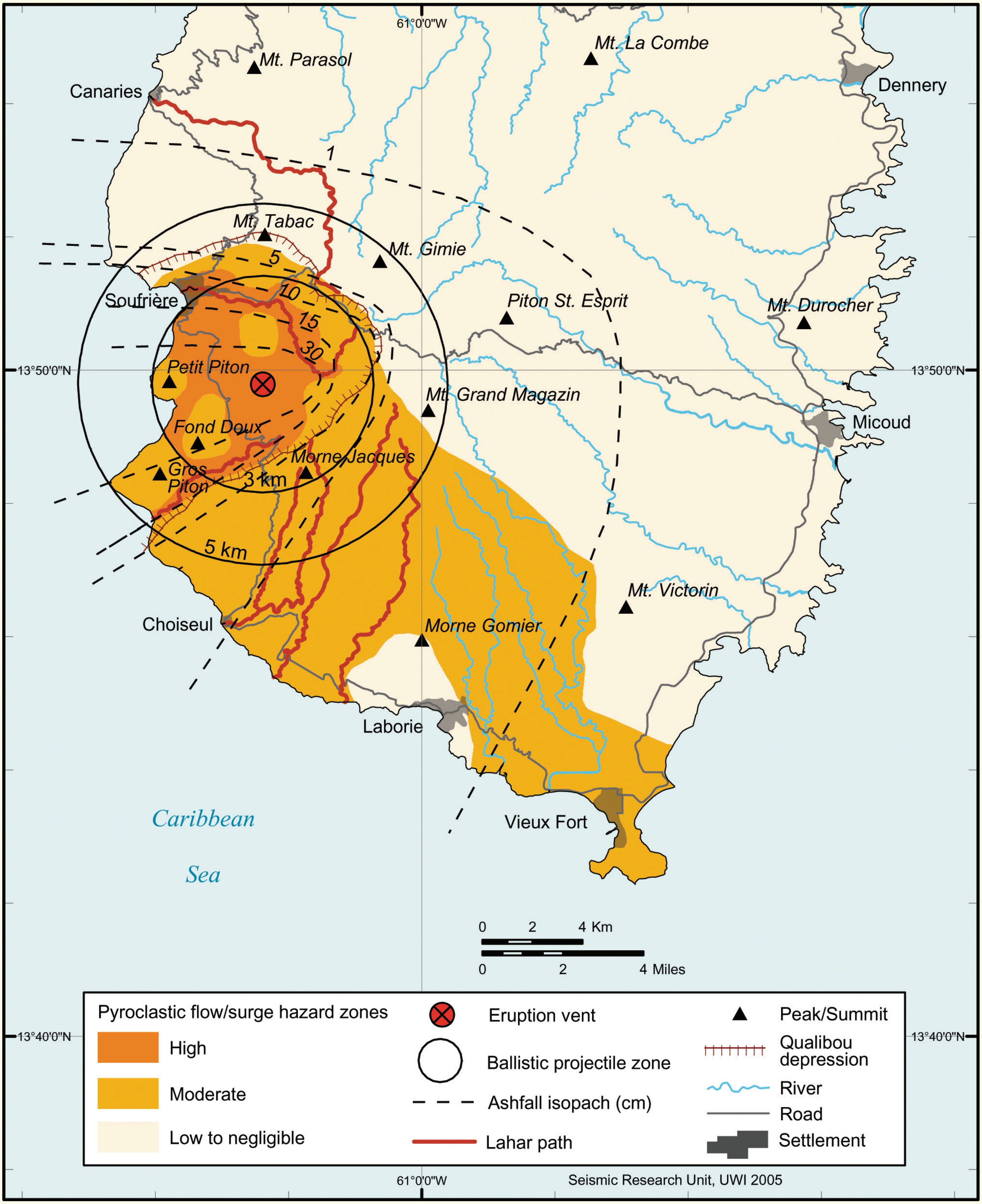
A serious secondary hazard is the formation of lahars or mudflows, which may occur in any of the valleys whose headwaters have been covered in loose pyroclastic material. The most likely valleys to be affected by lahars are shown in the hazard map. Volcanic earthquakes always accompany volcanic eruptions and in themselves may be severe enough to cause damage. Volcanic earthquakes are not predictable and will occur without warning. They may also occur when the volcano is not active and thus are a serious hazard at all times.

Scenario 4: Large explosive eruption

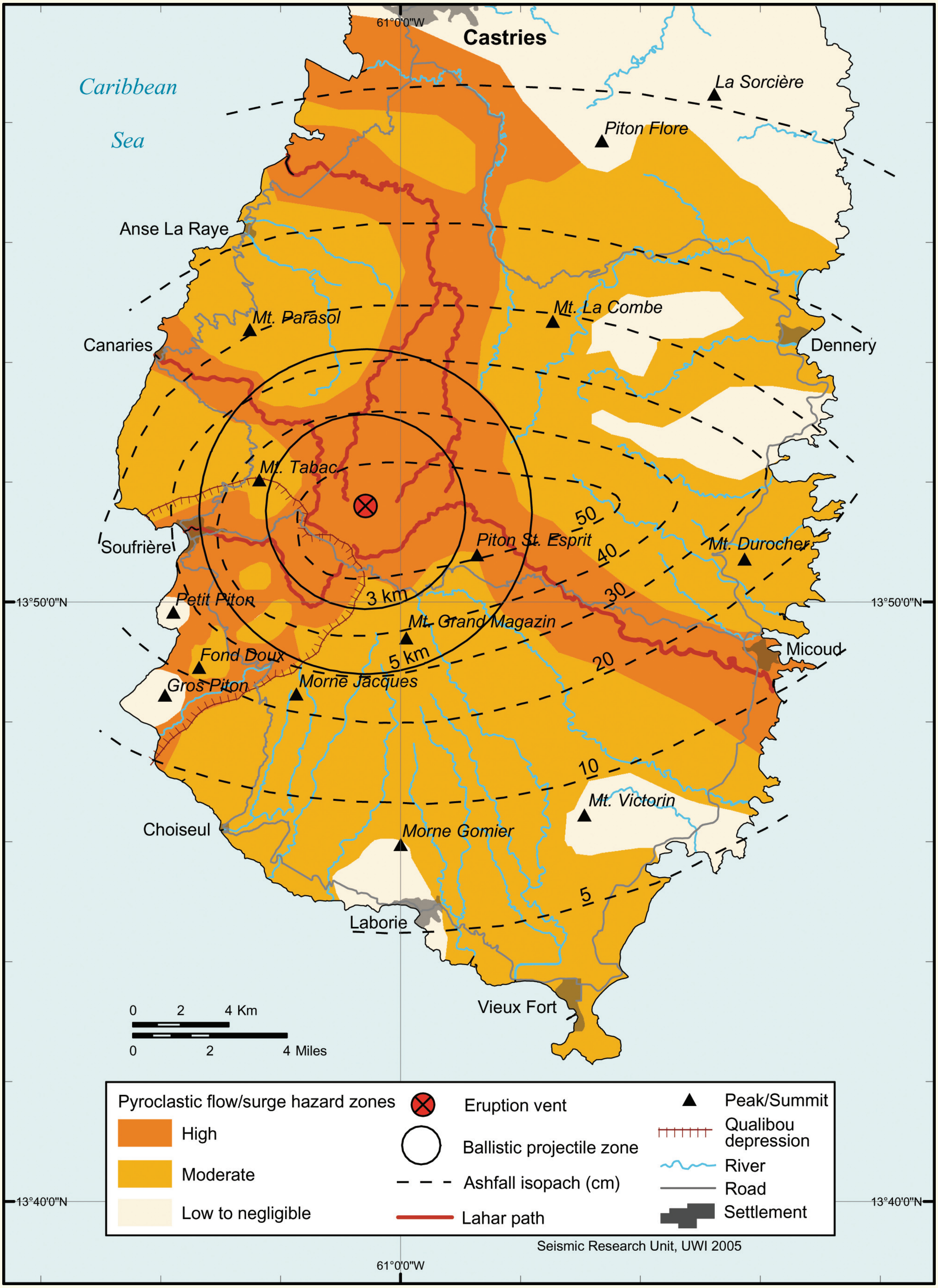
Since the Soufrière Volcanic Centre has produced violent explosive Plinian eruptions in the past, it is possible that similar eruptions may occur from here in the future. The geologic record suggests, however, that no such eruption has occurred in the last 20,000 years. Plinian activity is the most explosive type and results from gas-rich felsic magma that has differentiated in a high-level magma chamber. Such an eruption from the Soufrière Volcanic Centre can be considered as both the least-likely and the worst-case scenario for Saint Lucia. The vent for such an eruption would either be located within the Qualibou Caldera or in the Central Highlands (e.g. from a centre such as Mt. Gimie or Mt. Grand Magazin). Only after the onset of precursory signs such as shallow earthquake swarms will it be possible to determine a more specific vent location. The hazard map for this scenario gives an indication of the areas that would be affected during an explosive magmatic eruption at the Soufrière Volcanic Centre, with the vent area arbitrarily located at Mt. Gimie.

Plinian eruption columns can reach altitudes of 50 km, although most are lower, generally in the 10-20 km range, so that the material is dispersed by both upper and lower tropospheric winds (Trades and Anti-Trades) as well as by the stratospheric easterlies. The pattern of ash fall thickness and distribution exhibited during the 1902 eruption of the Soufrière in St. Vincent (Robertson 1992) has been used to define a possible ash fall pattern. The collapse of a high Plinian eruption column rich in ash would result not only in ash fall over a wide area, but also extensive valley-fill ignimbrites and associated ash-rich surges radially around the vent, down the major valleys in southern Saint Lucia (brown area on the hazard map). Infrequent but extremely energetic pyroclastic flows and surges would be less

Volcanic hazard map for Scenario 3: Dome-forming eruption from within the Soufrière Volcanic Centre



Volcanic hazard map for Scenario 4: Explosive Plinian eruption from within the Soufrière Volcanic Centre



restricted by topography and would have the potential to cover most areas of southern Saint Lucia (yellow area on the hazard map). Ballistic projectiles would be common and would mainly affect an area within 5 km of the vent; lighter fragments (such as pumice) may be kept buoyant in the eruption plume for much greater distances before falling back to earth. Lahars, volcanic earthquakes and lightning strikes would also occur, and lahars may continue long after the eruption itself has ended. Such an explosive eruption may last for years but could also be short-lived (weeks to months). Whatever the duration, areas affected by the eruption will remain uninhabitable for many years.

View of Mount Gimie taken from the southwest

In the scenario illustrated in the hazard map with a vent at Mt. Gimie, the valleys leading to Vieux Fort and Canelles would be somewhat protected by the topographic highs of Piton St. Esprit and Mt. Grand Magazin. However, should the vent for an explosive eruption occur south of Mt. Gimie in the region of Petit St. Esprit, then Vieux Fort would lie well within the high pyroclastic flow hazard zone, and the rivers to the north of the vent (e.g. Roseau and Canaries) may be shielded by Mt. Gimie. Should the vent be located within the Qualibou depression then some areas to the north and northwest may be somewhat protected by both the depression margin and the peaks of the Central Highlands.

A thick sequence of at least nine block and ash flow deposits from the andesitic stratovolcanoes of the Central Highlands overlain by a 4 m thick surge deposit. On main road, west of Mount Tabac

Integrated Volcanic Hazards Zones

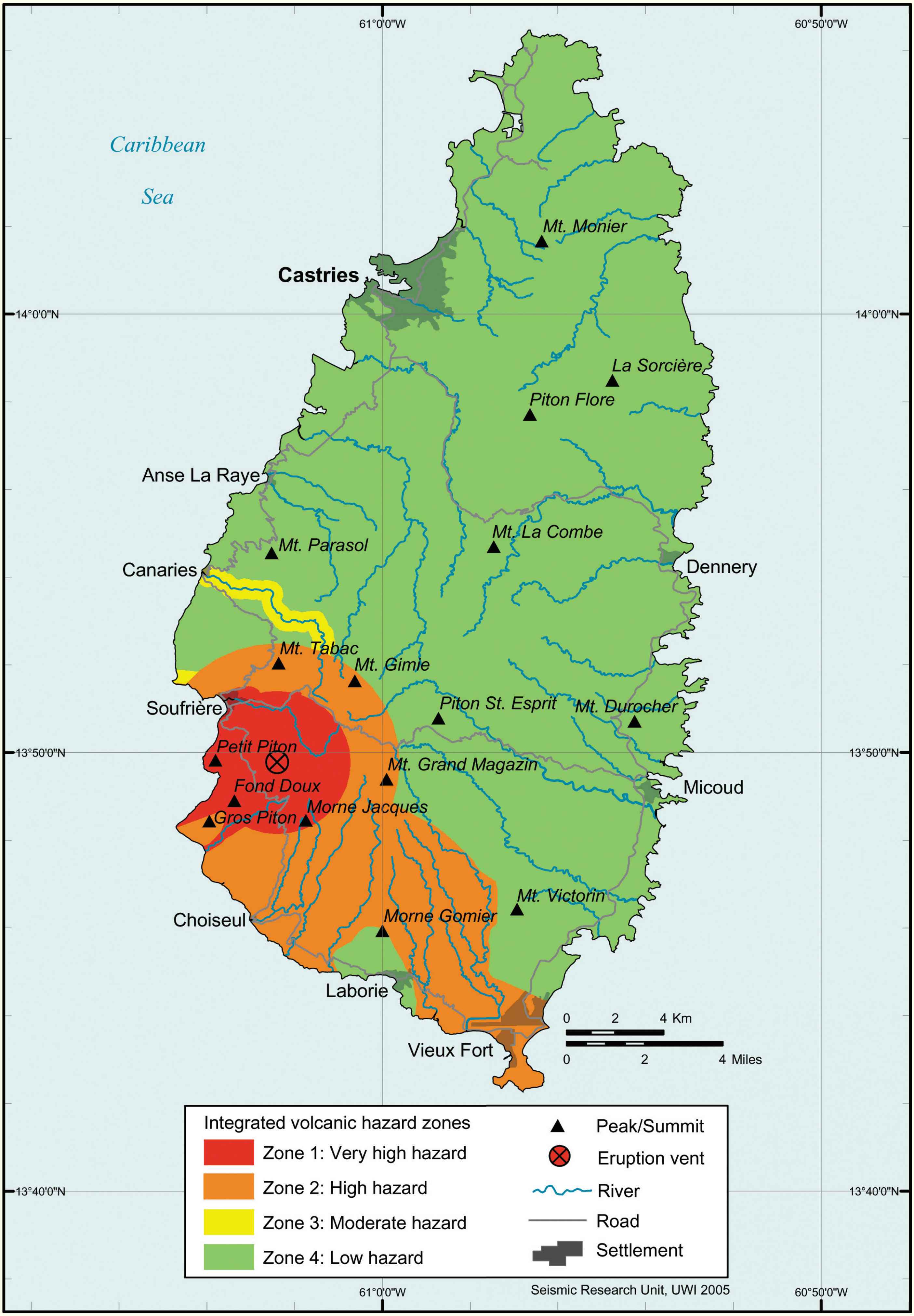
The areas most likely to be affected by specific hazards in the two scenarios for major magmatic eruptions in Saint Lucia have been used to define integrated hazard zones for each scenario which provide an indication of overall hazard in the island in the event that the eruption in that particular scenario occurs. These zones, and the parameters used to define them, are described below. Note that the boundaries of the integrated hazard zones must never be considered sharp, narrow lines as shown on these maps, rather as zones of transition. The boundaries will vary slightly depending on exact eruption location, and eruption and weather conditions. In the event of a volcanic eruption, the relevant hazard map will be revised regularly by scientists. Furthermore, the integrated hazard maps only show hazard zones on land. An eruption in Saint Lucia will, however, likely generate hazardous phenomena that will also impact on the marine environment to varying degrees. Pyroclastic flows and surges can travel over water and thus are a potential hazard to ocean vessels. Airfall can also be expected to be significant at sea, particularly on the western side of the island. For this reason, the integrated hazard zones in these maps must be envisaged as extending some distance offshore, and in the event of a magmatic eruption from the Soufrière Volcanic Centre in Saint Lucia, a maritime exclusion zone around the southwestern part of the island should be enforced.

For Scenario 3 (dome-forming eruption)

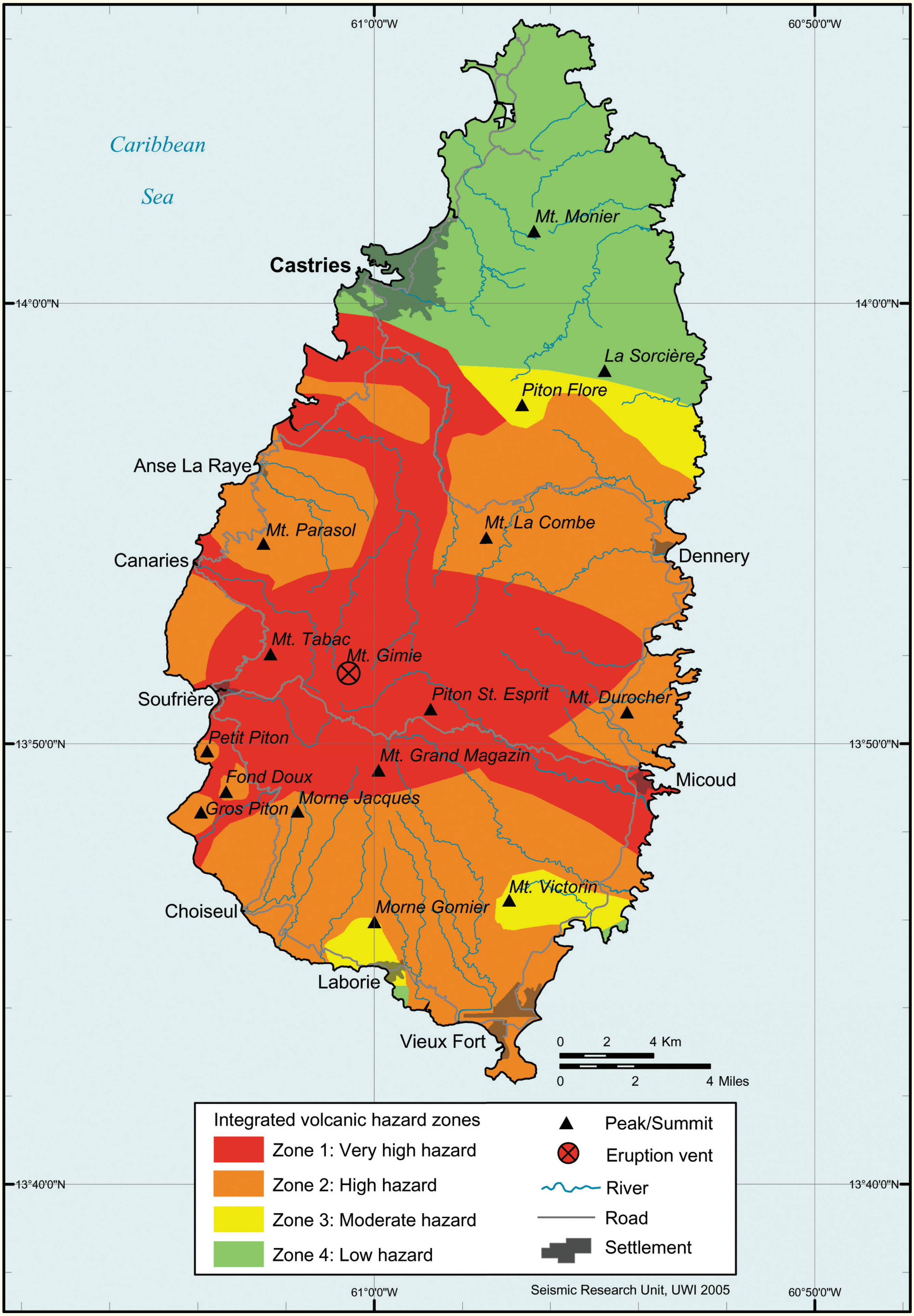
Zone 1 (red) is the area of very high hazard. This is the area most likely to be affected by the dome itself, dome-collapse pyroclastic flows and surges, heavy ash fall, lahars and ballistic ejecta. It was determined by combining the following from scenario 3: the area with a high pyroclastic flow hazard, the 3 km radius ballistic projectile zone and the area likely to receive >30 cm of ash. Total destruction of buildings and property in zone 1 is probable. This zone will need to be evacuated before the eruption begins. Zone 2 (orange) is the area of high hazard. It is the area likely to be affected by energetic dome-collapse pyroclastic flows, surges and ballistic ejecta, lahars, and high to moderate ash fall. It was determined by combining the following from scenario 3: the area with a moderate pyroclastic flow hazard, the 5 km radius ballistic projectile zone and the area likely to receive 10-30 cm of ash. Zone 3 (yellow) is the area of moderate hazard. This zone may be affected by airfall and occasional lahars but should be free from the effects of pyroclastic flows, surges and ballistic ejecta. It was determined by combining the area likely to receive 5-10 cm of ash with lahar paths that do not fall within zones 1 and 2. Zone 4 (green) is regarded as the area of low hazard in which little to no direct effect of the volcano will be felt with the exception of some minor (<5 cm) airfall.

Note that Zone 1 on this map also includes the area likely to be affected by a phreatic or hydrothermal eruption from Sulphur Springs (scenario 1), as well as the area likely to be affected in the event of an eruption from an explosion crater (scenario 2). In the event of scenarios 1 and 2, various areas within the red zone may have to be evacuated. Scenario 2 will have wider and longer-lasting effects than scenario 1, although activity for both scenarios should be largely confined to within the red zone.

Integrated volcanic hazard zones for Scenario 3: Dome-forming eruption from within the Soufrière Volcanic Centre



Integrated volcanic hazard zones for Scenario 4: Explosive Plinian eruption from within the Soufrière Volcanic Centre



For Scenario 4 (explosive Plinian eruption)
Zone 1 (red) is the area of very high hazard. This is the area most likely to be affected by column-collapse pyroclastic flows and surges, heavy ash fall, lahars and ballistic ejecta. It was determined by combining the following from the hazard map of scenario 4: the area with a high pyroclastic flow hazard, the 3 km radius ballistic projectile zone and the area likely to receive >30 cm of ash fall. In the event of an explosive magmatic eruption total destruction of buildings and property in zone 1 is probable. This zone will need to be evacuated before the eruption begins. Zone 2 (orange) is the area of high hazard. It is the area likely to be affected by energetic pyroclastic flows, surges and ballistic ejecta, lahars, and high to moderate ash fall. It was determined by combining the following from scenario 4: the area with a moderate pyroclastic flow hazard, the 5 km radius ballistic projectile zone and the area likely to receive 10-30 cm of ash fall. Zone 3 (yellow) is the area of moderate hazard. This zone may be affected by ash fall but should be free from the effects of pyroclastic flows, surges, lahars and ballistic ejecta. It outlines the area likely to receive 5-10 cm of ash. Zone 4 (green) is regarded as the area of low hazard in which little to no direct effect of the volcano will be felt with the exception of some minor (<5 cm) airfall.

Conclusion

Although the youngest age dates available for volcanic rocks on Saint Lucia are 20,000 years BP, several domes and explosion craters have formed since then. This, together with the occurrence of occasional swarms of shallow earthquakes and vigorous hot spring activity in southern Saint Lucia, indicates that this area is still potentially active and can generate volcanic eruptions in the future.

The Soufrière Volcanic Centre is the most likely location for future eruptions in Saint Lucia. There are four different scenarios for future activity; in order of decreasing probability these are: 1) a phreatic (steam) or hydrothermal eruption from the Sulphur Springs area; 2) a small explosive magmatic eruption forming an explosion crater in the Belfond area; 3) an effusive magmatic dome-forming eruption within the Qualibou Caldera and 4) a large explosive Plinian eruption from either the Central Highlands or from within the Qualibou Caldera.

The hazard maps for the two scenarios involving major magmatic eruptions (scenarios 3 and 4) have been used to develop integrated volcanic hazard zone maps that show the areas of Saint Lucia most vulnerable to future volcanic activity. Scenario 3 is considered the most-likely scenario for a major magmatic eruption in Saint Lucia, and the integrated hazard zones for this scenario should be used by government authorities to prepare for a future volcanic emergency. In the event of a magmatic eruption from the Soufrière Volcanic Centre large parts of southern Saint Lucia will probably have to be evacuated and some communities may have to be permanently resettled. The authorities should also be aware that Saint Lucia may be affected by volcanic eruptions on neighbouring islands.

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