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Volcanic Hazard Assessment for Saint Lucia, Lesser Antilles

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September 2002

Sulphur Springs geothermal field, southern Saint Lucia.

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EXECUTIVE SUMMARY

In July 2000 the Seismic Research Unit began recording an increase in daily number of shallow earthquakes in southern St Lucia. This led to a campaign of reinforced volcano monitoring involving an upgrade of the seismic network, the installation of a ground deformation network and sampling of volcanic gases. Geological fieldwork was also carried out. This hazard assessment is a summary of this work, which was carried out between January and April 2001.

By early 2001 seismic activity in southern Saint Lucia had returned to pre-swarm background levels, and there are at present (September 2002), no signs of increased volcanic activity. However, the occurrence of such occasional swarms of shallow earthquakes together with the vigorous hot spring activity in southern Saint Lucia indicate that this area is still potentially active and the island can therefore expect 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 at this centre; in order of decreasing probability these are: 1) a phreatic (steam) or hydrothermal[1] 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 magmatic eruption from either the Central Highlands or from within the Qualibou Caldera.

The most likely activity is a phreatic (steam) or hydrothermal eruption from the Sulphur Springs geothermal field. Such an eruption would be relatively small, and would only affect the area directly surrounding Sulphur Springs. Phreatic and hydrothermal eruptions do not erupt fresh magma, and tend to be short lived (a few hours or days). A prolonged series of large phreatic eruptions may, however, herald the onset of an actual magmatic eruption. 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. Such an eruption is likely to be relatively short lived, lasting only a few weeks to months. It will only affect the area within the Qualibou depression, although some ash fall may occur outside the depression. The second most likely scenario for a magmatic eruption is a dome-forming eruption from within the Qualibou Caldera. Such an eruption would be similar to the ongoing eruption of the Soufrière Hills volcano in Montserrat and may generate dome-collapse pyroclastic flows,

[1] All scientific terms used in this report are defined in a glossary at the back of the report.

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 scenario for a future eruption in Saint Lucia is a large explosive magmatic eruption from the Soufrière Volcanic Centre. This is also considered the "worst-case" scenario. Such an eruption may generate column-collapse pyroclastic flows, surges and associated airfall. As with a dome-forming eruption, 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.

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 scenarios for the three most-likely eruptions have been used to develop volcanic hazard zones for southern Saint Lucia. These zones show which areas are most vulnerable in the event of an eruption, and should be used by government authorities to prepare for such a volcanic emergency. Authorities should also be aware that Saint Lucia may also be affected by volcanic eruptions on neighbouring islands. The information contained in this report should be used to update the National Volcanic Plan and to guide long-term land use planning. In addition, the population of Saint Lucia should be educated about volcanic hazards before a crisis occurs.

INTRODUCTION

Volcanic eruptions have killed over 30,000 people in the Lesser Antilles during the last century and at present more than a quarter of a million people live on the flanks of live volcanoes in the region. Ongoing monitoring of the volcanoes and assessment of volcanic hazards are therefore essential to reduce the risk to lives and property.

Volcanic hazard assessment is based on the principle that the past is the key to the future. By determining how a volcano behaved in the past, scientists can better predict the style and frequency of future eruptions and the areas likely to be affected. In practice, this involves extensive geologic fieldwork to describe and interpret past eruptive deposits associated with a particular volcano. The type of deposit tells us whether previous eruptions were explosive or effusive, the number of deposits and their ages tell us how frequently the volcano erupted in the past, and the extent and thickness of the deposits tells us how large previous eruptions were. A hazard assessment should subsequently be used to plan and prepare for such a volcanic event. The assessment should also be used to educate the general population and for long-term land use planning.

Considerable work has been done in the past on the youngest volcanic centres in the southwest of Saint Lucia, much of which has been concentrated on the Sulphur Springs geothermal field. Despite this previous work, confusion still remains regarding the nature and vent locations of the youngest centres, and the only hazard assessment that exists was prepared by Ephraim (2000) as an undergraduate project at the University of Bristol. While that report is well researched and provides some useful recommendations, it was recognised that a more detailed hazard assessment should be produced for Saint Lucia, incorporating the results of seismic and other monitoring efforts and including the production of high-quality hazard maps.

This Volcanic Hazard Assessment is based on a total of three months fieldwork carried out in Saint Lucia by staff of the Seismic Research Unit between January and April 2001 together with an extensive literature search of past research on the geology and seismicity of the island. It is part of an ongoing regional project at the Seismic Research Unit to assess the volcanic hazards for the English-speaking islands of the Eastern Caribbean. Significant funding for the Saint Lucia hazard assessment was provided by the Government of Saint Lucia.

This report is based on a considerable amount of scientific data. In order to avoid the report becoming too technical and cumbersome, scientific details are provided in the "Scientific Supplement" to this report. Any scientific terms mentioned in the hazard assessment are explained in the glossary.

REGIONAL SETTING

The islands of the Lesser Antilles form an arc along the eastern margin of the Caribbean sea that stretches ~700 km from Grenada in the south to Sombrero in the north (Figure 1). There have been at least 33 historical eruptions of volcanoes in the Lesser Antilles and 19 volcanoes are considered to be active or potentially active (Figure 1). Only one active submarine volcano (Kick'em Jenny) has been identified in the region. It is located ~9 km north of Grenada. The Soufrière Hills volcano on Montserrat has been in a continuous phase of eruption since 1995 and is the only volcano currently erupting in the Lesser Antilles. Many of the islands in the Lesser Antilles have no live volcanoes. On these islands, volcanism died out many millions of years ago and the old volcanic landscape has since been eroded and is covered by coral and limestone. These islands are referred to as the 'Limestone Caribbees' and are shown in brown on Figure 1. The islands of the Lesser Antilles with live volcanoes are referred to as the 'Volcanic Caribbees', and these are shown in red on Figure 1.

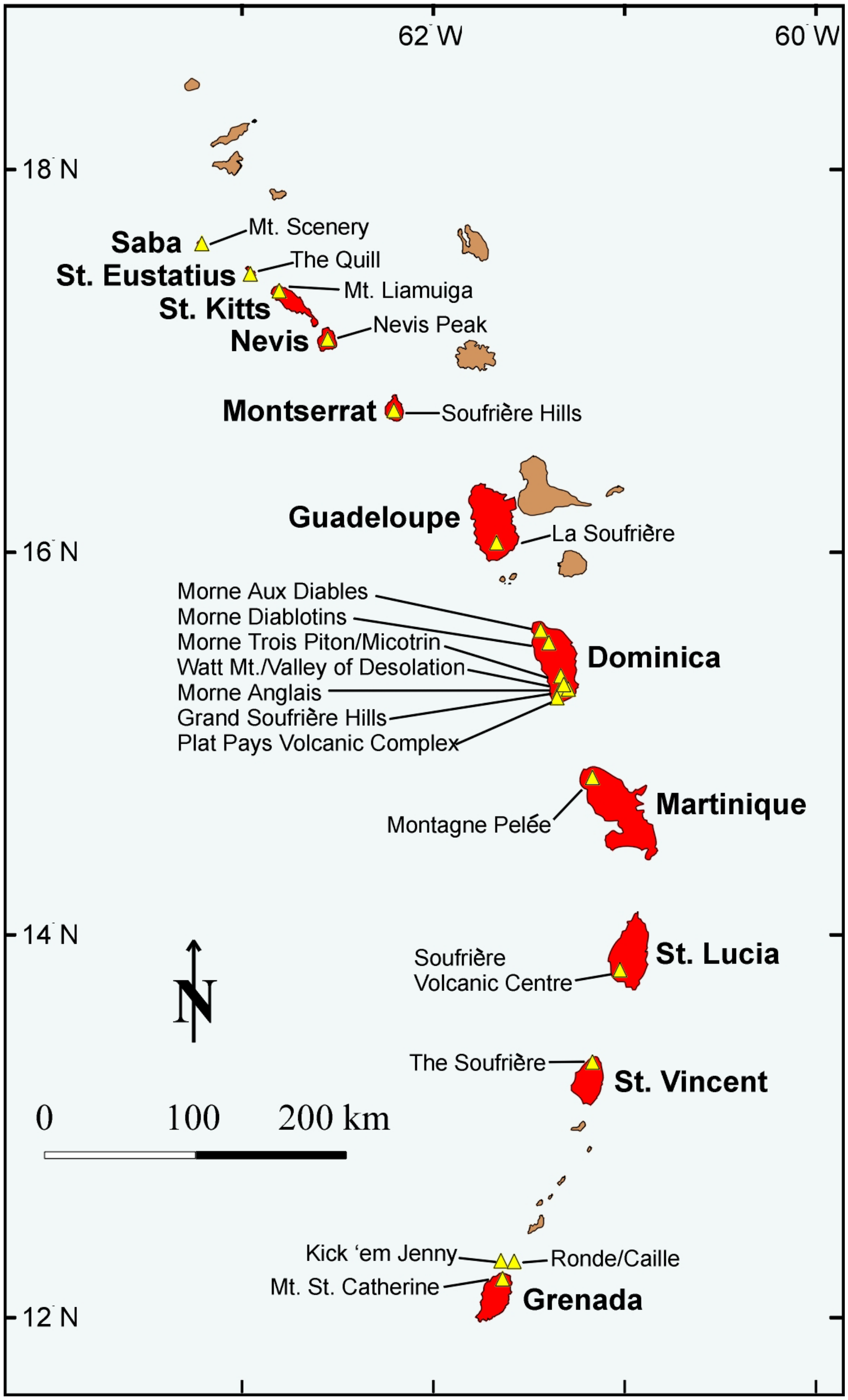

Figure 1: Distribution of the islands of the Lesser Antilles. The islands of the 'Volcanic Caribbees' are shown in red and the islands of the 'Limestone Caribbees' are shown in brown. The locations of the 19 active or potentially active volcanoes are indicated by yellow triangles.

VOLCANIC CENTRES IN SAINT LUCIA

Saint Lucia is made up almost entirely of volcanic rocks. Like all of the islands of the Lesser Antilles, Saint Lucia began its life as a series of submarine volcanoes. After many eruptions over millions of years these volcanoes built large topographic features that slowly rose above the surface of the water, joined with neighbouring volcanic islands, and grew to the island we see today. Newman (1965) divided the volcanic centres in Saint Lucia into 3 broad groups based on age and geographic distribution. From oldest to youngest these groups are 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. We prefer to use a slightly revised version of the original subdivision, grouping the volcanic rocks of Saint Lucia as follows:

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

The eroded basalt and andesite centres are the oldest rocks on Saint Lucia and are located in the northern and southernmost parts of the island. Age dates for the centres in the north range from 18 – 5 Ma[2] (Briden *et al.*, 1979; Le Guen de Kerneizon *et al.*, 1983). The centres in the south, including Mt. Gomier, Morne Caillandre/Victorin, Moule a Chique/Maria islands, Savannes, Beauséjour, St. Urbain and Mt. Tourney, have published ages ranging from 10.1 Ma (lava near De Mailly) to 5.2 Ma (lava from Savannes). The age of these eroded centres indicates that they are unlikely to erupt again. However, there is some shallow seismicity and cold fumarolic activity associated with some of the southern centres (discussed further below), and these centres should be monitored closely for any signs of reactivation.

The dissected andesite centres comprise the central and eastern part of Saint Lucia and are somewhat younger than the eroded dominantly basaltic centres to the north and south. Age dates for these centres range from 10.4 Ma (lavas west of Dennery) to 2.8 Ma (lavas from Derriere Dos). These old ages indicate that these centres are unlikely to be the site of future volcanic activity. More detail on the older centres of Saint Lucia is provided in the scientific supplement.

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[2] Ma = Millions of years

The youngest volcanic activity in Saint Lucia produced the rocks of the Soufrière Volcanic Centre. The rest of this report will focus on the Soufrière Volcanic Centre, as this is the most likely location for future eruptions in Saint Lucia.

SOUFRIÈRE VOLCANIC CENTRE

The Soufrière Volcanic Centre is the focus of the most recent volcanic activity in Saint Lucia. It comprises a series of different volcanic vents and a vigorous high-temperature geothermal field manifested at the Sulphur Springs area. It is located within the Qualibou depression, an arcuate structure that formed about 300 thousand years ago due to an extremely large gravity slide (Figure 2). The oldest dated rocks of the Soufrière Volcanic Centre are 5 – 6 million year old basaltic lava exposed near the coast at Jalousie and Malgretoute. This probably correlates with the basaltic activity of similar age further to the southeast. About 2 million years ago a major phase of volcanism led to the formation of Mt. Gimie and its neighbouring mountains. The spectacular Pitons are the remnants of two large dacitic lava domes that formed about 200 – 300 thousand years ago.

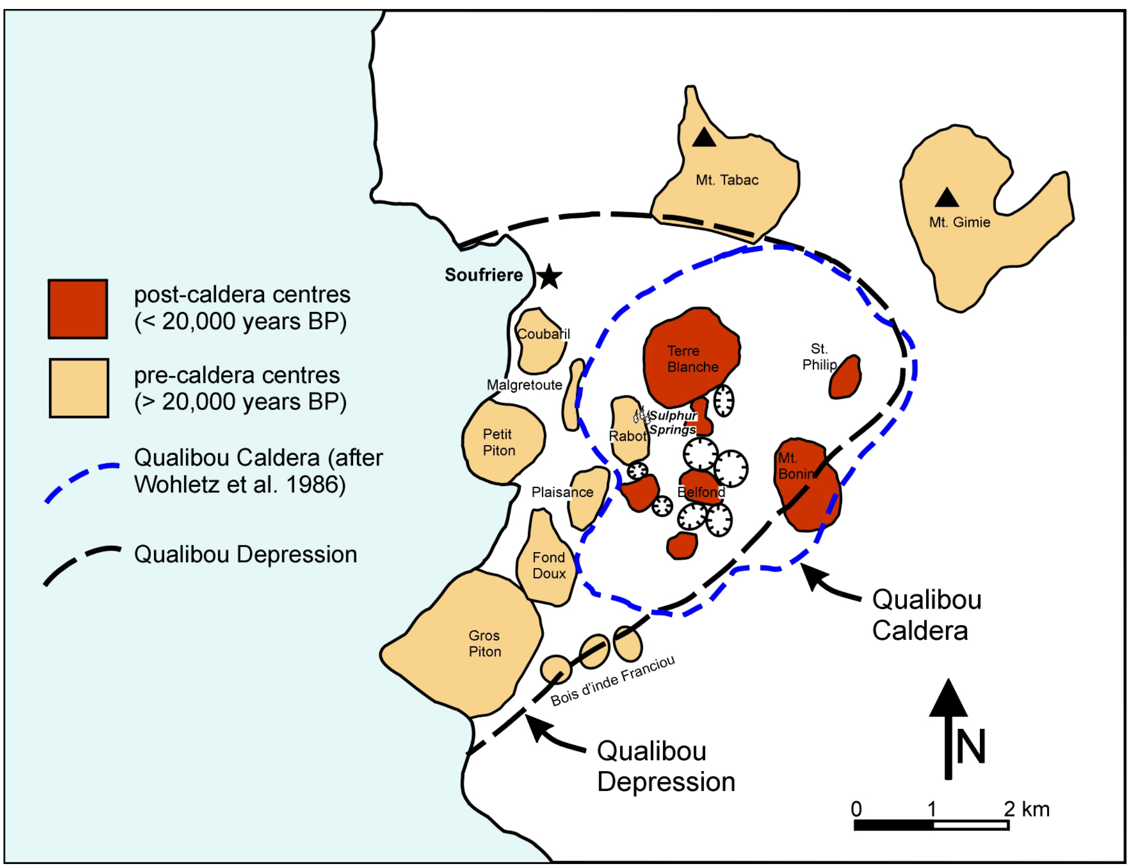


Figure 2: Sketch map of the Soufrière Volcanic Centre showing the volcanic features discussed in the text.

An intense and violent phase of volcanic activity occurred at the Soufrière Volcanic Centre between 40 and 20 thousand years ago when a series of major 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. The deposits formed during these explosive eruptions have been divided into two main groups: the Choiseul and the Belfond pumice deposits (Wright *et al.* 1984). It has been proposed that these explosive 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; see Figure 2). Other workers claim that the radial distribution of the numerous pyroclastic flow deposits in southern Saint Lucia suggests that they did not come from within the Qualibou depression at all, rather from small vents in the Central Highlands (e.g. Mt. Grand Magazine and Piton St. Esprit) (Roobol *et al.* 1983 and Wright *et al.* 1984). The nature of the Choiseul and Belfond pyroclastic flow deposits indicate a particular style of eruption. They were formed by explosive eruptions that generated a buoyant eruption column which subsequently collapsed to produce pyroclastic flows. Such eruptions are particularly devastating, because the pyroclastic flows that are generated can travel out from the vent in all directions.

After the phase of explosive activity that formed the Choiseul and Belfond pyroclastic deposits a series of small lava domes (e.g. Terre Blanche, Belfond) and explosion craters (e.g. La Dauphine estate) formed near the centre of the depression. 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 events. Field relations indicate that the explosion craters are younger than the adjacent Belfond lava dome. Unfortunately none of these domes or craters has been dated and it is therefore impossible to say with certainty when the last magmatic eruption occurred in Saint Lucia.

The presence of the relatively young (< 20,000 years) 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.

A Note on Terminology

There is some confusion surrounding the actual nature of the "volcano" in southern Saint Lucia, and some of this stems from the variety of names that are often used for its volcanic features. Thus the low-lying area (depression) near the town of Soufrière (Figure 2) has been referred to in the past as the 'Soufrière depression', the 'Qualibou structure' and the 'Qualibou depression'. The caldera that has been proposed to lie within this structure (Figure 2) has been referred to as the 'Qualibou caldera', the 'Soufrière volcano' and the 'Soufrière caldera'. The scientific literature tends to favour the terms 'Qualibou depression' and 'Qualibou caldera', whereas the local populace tends to use the term 'Soufrière volcano', which to them usually means the steaming ground at Sulphur Springs.

Another terminology problem arises when discussing the volcanic features in general. In southwestern Saint Lucia there are numerous volcanic 'pitons' (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, we prefer to refer to these as different vents of the same volcano, which we call the Soufrière Volcanic Centre.

Because of the general misuse of the term 'Soufrière volcano' in Saint Lucia to refer to the steaming ground at Sulphur Springs, we prefer not to use this term in our report lest it generate more confusion. We will refer to the steaming ground at Sulphur Springs as the Sulphur Springs geothermal field, and the overall volcanic field in which it is located as the Soufrière Volcanic Centre. We refer to the structural depression as the Qualibou depression, and the caldera as the Qualibou caldera.

HISTORICAL ERUPTIONS

Historical eruptions in the Caribbean are generally regarded as those that have occurred since European settlement and the introduction of written records of the region. In Saint Lucia European settlement began in the early 1600s but was intermittent for most of the 17th century, changing hands several times between the French and English. 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 historic 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

Volcanic earthquakes

Volcanic earthquakes are common in the islands of the Lesser Antilles. They occur when molten rock (magma) ruptures the lithosphere as it tries to force its way to the surface. Such earthquakes are typically shallow and often occur in swarms, i.e. groups of many earthquakes of similar size occurring closely clustered in space and time with no dominant main shock. They are often a precursory sign that a volcano is getting ready to erupt. Not all volcanic earthquakes in the Lesser Antilles culminate in an eruption, but all eruptions are preceded by volcanic earthquakes. This is why seismic monitoring is so important at potentially active volcanoes.

Shallow earthquake swarms in Saint Lucia

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, and at least three of these seem to have been triggered by a larger tectonic earthquake (1906, 1990 and 2000). A fifth burst may have occurred in early 1998 when a number of earthquakes were reported felt. Unfortunately the equipment and personnel of the Seismic Research Unit were heavily committed in Montserrat at the time and there were no seismograph recordings (Figure 3).

In February 1906 Saint Lucia was rocked by a large tectonic earthquake which was also felt as far south as Grenada and as far north as Dominica. Newspaper reports indicate that Saint Lucia experienced 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 the cumulative number of shallow earthquakes has increased irregularly in a series of bursts (Figure 3). 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. The second burst occurred between May and June 1990, peaking on May 19th when 29 earthquakes occurred in a single day. Most of these 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 1999 105 volcanic earthquakes were recorded in southern Saint Lucia. These earthquakes were only strong enough to record on one station, and none were reported felt.

The most recent swarm occurred between July 2000 and January 2001. Figure 3 shows daily numbers of earthquakes in Saint Lucia up until June 2002, and clearly shows that the burst of recent seismic activity was largely over by early 2001.

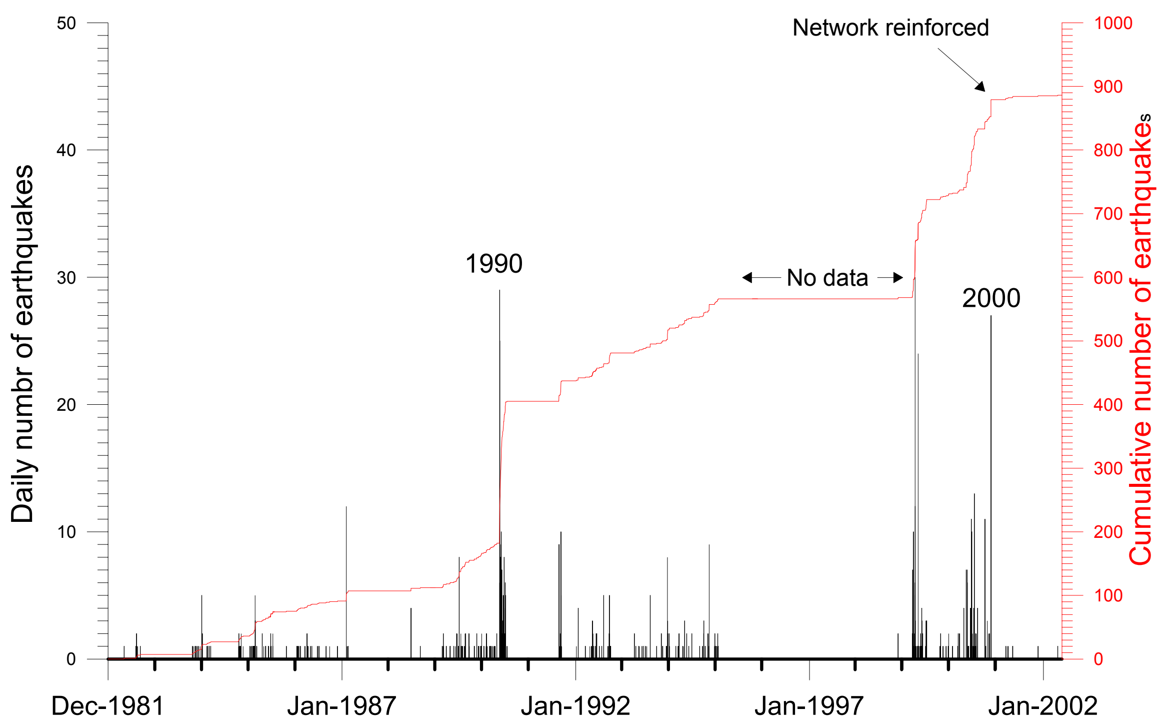


Figure 3: Earthquake numbers for Saint Lucia from January 1982 to June 2002.

Interpretation of recent earthquake swarms

As the volcanic earthquakes of the 1999 swarm were only recorded on one station, they could not be reliably located although we can say that they definitely occurred in southern Saint Lucia. Neither of the recent shallow earthquake swarms in Saint Lucia for which we have good seismograph data (1990 and 2000) were directly related to the area of most recent volcanic activity, the Soufrière Volcanic Centre (Figure 4). In fact, some of the earthquakes of these swarms are located beneath 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.

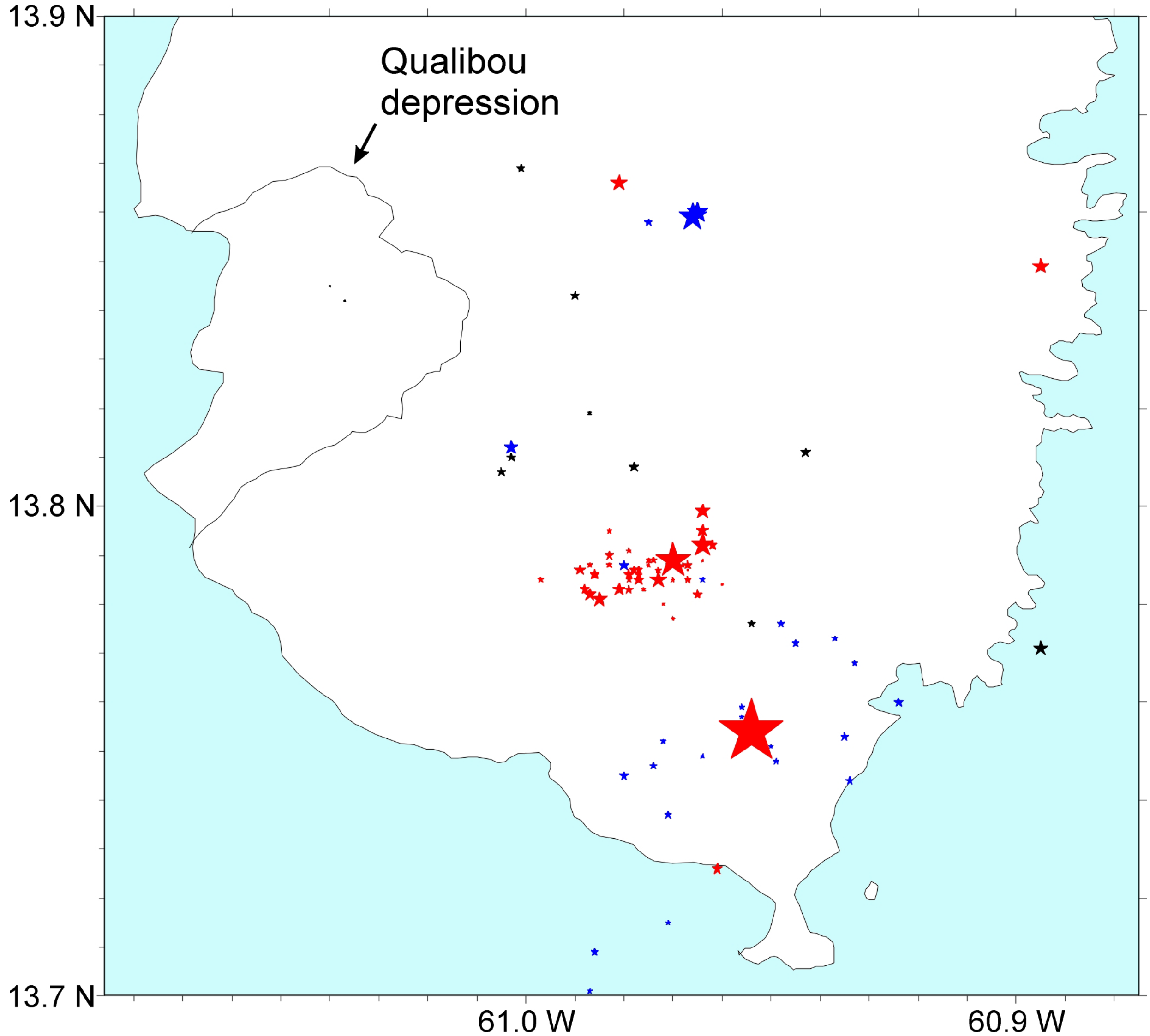


Figure 4: Epicenters of earthquakes in St. Lucia: red stars indicate the earthquakes of the 1990 swarm; blue stars those of the 2000 swarm, and black stars are all other located earthquakes that have occurred since the monitoring network was installed. The size of the stars increases with magnitude.

The two main swarms of shallow earthquakes in 1990 and 2000 displayed a similar pattern: a single large shock was followed by a sequence of gradually diminishing smaller shocks. This pattern is in fact typical of tectonic earthquake sequences – that is, 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 kilometres. 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 therefore have characteristics of both volcanic and tectonic earthquakes which make them difficult to interpret. In fact, these earthquakes have features that are consistent with a special class of tectonic earthquakes called Near Plate Boundary Intraplate Earthquakes. These are common in the northern Lesser Antilles but less so in the islands to the south.

The most likely interpretation of the recent swarms is that several Near Plate Boundary Intraplate earthquakes of magnitude > ~3 occurred, triggering seismic activity on nearby near-surface faults. 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 (Figure 4). In fact this is a dominant structural trend of southern St Lucia, with numerous faults and volcanic vent alignments trending in this direction. 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. There is, therefore, a slight possibility that the swarms of 1990 and 2000 may reflect new periods of magma migration along shallow NE-SW trending faults. Some of the earthquakes of the 1990 and 2000 swarms occurred near or beneath existing volcanic centres (Gomier and Caillandre/Victorin, respectively). Although available age dates for these centres indicate they are old and probably dead, their associated seismicity indicates that they should be closely monitored for any signs of reactivation.

GEOTHERMAL ACTIVITY

Sulphur Springs

Introduction and description

The well-known Sulphur Springs of Saint Lucia is the hottest and most active geothermal area in the Lesser Antilles. It consists of a main area of thermal manifestations on the southwestern side of the Sulphur Springs road, and some smaller features near the "Volcanic Restaurant" on the western flanks of Terre Blanche. It is located within the Qualibou caldera on the northeastern flank of Rabot ridge, a precaldera dome that was truncated during collapse of the caldera (Wohletz *et al.* 1986). The main area of Sulphur Springs 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. Many fumaroles have temperatures 100°C or hotter, and temperatures of up to 172°C have been recorded. 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.

Geothermal systems such as Sulphur Springs form when rainwater seeps into the ground where it is heated by hot rock. The hot water becomes buoyant, and rises back to the surface along cracks. In some places the water is heated so much that it rises as steam. 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.

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. It is possible that, over time, activity at Sulphur Springs might continue migrating to the south and west. Such migration of activity in geothermal systems such as Sulphur Springs is quite normal. The area should, however, be watched closely for signs of further migration, as this may have a significant long-term impact on nearby residences and structures, such as the viewing platform. Migrating geothermal activity into areas of steep slopes may also increase the likelihood of landslides triggered by extensive hydrothermal alteration. Any significant changes in the geothermal features at Sulphur Springs should be reported to the National Emergency Management Organisation (NEMO) and/or the Seismic Research Unit.

Myths associated with the Sulphur Springs

Unfortunately, several myths about the Sulphur Springs geothermal field exist in Saint Lucia. The first myth is that the hot springs and fumaroles of Sulphur Springs act as a safety valve, thus reducing the likelihood of an eruption. This is not true. The Sulphur Springs geothermal field is a relatively surficial feature, with water circulating to depths of about 1 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. It is practically impossible for a blockage of steam or water vents at Sulphur Springs to affect the magma chamber. Changes in the magmatic system, however, *may* be reflected in the chemistry and temperature of the gases at Sulphur Springs, hence the importance of monitoring fumarolic activity. It is also 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. By the same token, 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.

Another popular myth is that Sulphur Springs represents the vent of a volcano. This is not true. 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. Hot springs and fumaroles are *not* volcanoes. They represent small cracks in the ground where hot water and steam escape at the surface. They are common in volcanic areas because magma bodies at depth provide a heat source, but can in fact occur anywhere that the cracks in the rock allow heated water to reach the surface. This may be in the vent or on the slopes of a volcano, or in the surrounding countryside, miles away from the volcano. Sulphur Springs itself is therefore not a volcano; rather it is a geothermal field located within the much larger Soufrière Volcanic Centre.

Other geothermal areas in southern Saint Lucia

In addition to Sulphur Springs, there are several other occurrences of geothermal activity located in southern Saint Lucia, outside the Qualibou caldera. There are warm springs present at Jalousie and Choiseul and residents have reported underwater gas vents at Black Bay and offshore between Anse Mamin and Soufrière Bay. In addition, 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, on the Pierre residence. These fumaroles are approximately 28°C, acidic, and are located in areas of highly altered rock. There have also been reports of a cold soufrière near the summit of Morne Caillandre/Victorin, although this was not observed during our study.

Newman (1965) reports that there is an area of intensely hydrothermally altered clayey ground about a mile to the south of Piton Canarie. This is probably an area of fossil hydrothermal activity.

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 ever present, i.e. are totally independent of an increase in volcanic activity in Saint Lucia. Many people in Saint Lucia do not appreciate these dangers, and each is discussed in detail below.

Volcanic gases

Hot geothermal systems 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). Some of these gases, when released into the atmosphere, can produce acid rain and mist which affect human and animal eyes and respiratory systems and corrode metal building materials.

CO_2 is extremely dangerous. Inhalation of CO_2 at low concentrations may cause rapid breathing, increased heart rate, headaches, sweating, dizziness, muscular weakness and drowsiness. Breathing air with greater than about 11% CO_2 results in unconsciousness in a minute or less, and concentrations greater than about 20% CO_2 can cause almost instantaneous death. As it is heavier than air, CO_2 tends to accumulate in hollows in the ground, displacing the breathable air. Since it is invisible and has no taste or smell, people and animals are unable to notice that it is there and may suffocate. 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. People have also died in this way at the Boiling Lake in the Valley of Desolation in Dominica.

SO_2 has a characteristic pungent odour and can cause inflammation and burning of the eyes and respiratory tract, and difficulty in breathing. When SO_2 is released into the atmosphere, it reacts with air and water particles to form sulfuric acid (H_2SO_4), a constituent of acid rain which can corrode metal. This causes destruction of vegetation and severe irritation of the eyes, nose and throat. When SO_2 is inhaled directly, sulfuric acid is formed in the upper respiratory tract. Repeated or prolonged exposure to H_2SO_4 vapour may cause erosion of the teeth, and chronic irritation of the eyes, nose, throat and lungs.

H_2S is an extremely toxic gas that has a very strong and unpleasant smell, like rotten eggs. Breathing low concentrations causes headaches, fatigue, dizziness, excitement, diarrhoea and irritation of the eyes and upper respiratory tract. Inhalation of H_2S is extremely detrimental to the sinus and respiratory systems, and can cause bronchitis and bronchopneumonia. Very large amounts result in paralysis of the respiratory system and death. Prolonged exposure to even low concentrations of H_2S can cause pharyngitis and bronchitis. Like CO_2, H_2S is denser than air and can accumulate in low-lying areas.

Extreme care should be taken when visiting Sulphur Springs and other areas of fumarolic activity in Saint Lucia, including the cold soufrière. In these areas, people should not enter low-lying hollows to remove dead animals in case there is a build-up of CO_2. Anyone intending to get close to the vigorous fumaroles at Sulphur Springs should wear a gas mask.

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. These may be triggered by earthquakes. There are reports of such a landslide occurring on the Terre Blanche flank of Sulphur Springs 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.

Boiling pools

The ground is very soft at Sulphur Springs and in places it is very easy to break through the thin crust into hot water below. In the 1980s one of the guides at Sulphur Springs was severely burnt after falling into a hole. Since then, guides no longer take tourists through the field, instead they describe the features of Sulphur Springs from the safety of a viewing platform close to the road. Where possible, people should avoid walking through the area, particularly without proper footwear.

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-like material which coats leaves of nearby plants. 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). Such eruptions are not true volcanic eruptions in that they do not eject any new magma. The ash-like material ejected during a phreatic eruption is usually made up of mud and old altered rock and mineral fragments. 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. It is not unusual for small amounts of mud and debris to be ejected by boiling mud pools or fumaroles from time to time in intense geothermal systems such as Sulphur Springs. This phenomenon probably represents local adjustments in the geothermal system that lead to a minor, 'throat-clearing' phreatic eruption. Phreatic and hydrothermal eruptions are discussed in more detail below.

FUTURE ACTIVITY IN SOUTHERN SAINT LUCIA AND ASSOCIATED HAZARDS

How do we predict future activity?

Predictions of future activity in southern Saint Lucia are based on an analysis of past eruptive history and seismicity together with comparisons of behaviour at similar volcanoes that are better understood. 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.

Where and when will future activity occur?

For the last 20 thousand 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 1766 phreatic eruption together with the vigorous and changing nature of the Sulphur Springs geothermal field suggests that phreatic and hydrothermal eruptions have occurred regularly at Sulphur

Springs in the past. This history indicates that the Soufrière Volcanic Centre is the most likely location for future eruptions in Saint Lucia.

In order to determine when a future eruption may occur it is often useful to look at the past eruption frequency at a given volcano. Eruption frequency can be estimated from carbon dating charcoal found in pyroclastic deposits or by dating lava flows or domes. Analyses of both charcoal and lava samples of the Soufrière Volcanic Centre have yielded ages ranging from about 5 million years 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, the explosion craters within the caldera, or the domes of Bois d'inde Francou, 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, and minor explosive activity leading to the formation of small explosion craters. The only historic activity in the Soufrière Volcanic Centre has been minor phreatic eruptions from Sulphur Springs, the most recent in 1766. The lack of age data makes it impossible to develop an eruption frequency for Saint Lucia, and therefore difficult to determine when the next eruption might occur.

It is important to note here that not all erupted products are preserved in the geologic record and only those pyroclastic deposits in which charcoal is found can be dated. Pyroclastic deposits are unconsolidated and easily eroded. For example, the 1902 eruption of the Soufrière of St. Vincent killed ~1600 people but the deposits from this major eruption have been almost completely eroded away and there is very little geologic record of the eruption (R. Robertson, pers. comm.). It is therefore possible that more eruptions have occurred in Saint Lucia over the last 20 thousand years and that their products have not been preserved.

Precursory signs and expected hazards

Prior to the onset of a volcanic eruption at the Soufrière Volcanic Centre there will be precursor signs of activity, such as an increase in the number and intensity of shallow earthquakes and a measurable deformation (swelling) of the ground. Once these signs start to appear they can be used to better forecast when and where the next eruption is likely to occur. Changes in the chemistry, temperature, vigour or location of geothermal activity may also occur, although, as mentioned above, these changes can also occur independent of volcanic activity due to fluctuations in groundwater supply and changes in the plumbing system.

There are a number of hazardous phenomena that can be expected in the event of an eruption at the Soufrière Volcanic Centre. They are divided into two broad categories. **Primary volcanic hazards** result from direct eruptive activity and the immediate effects of such activity. They include pyroclastic flows, surges and falls, lava flows and lava domes, debris avalanches, directed blasts, volcanic gases and lightning strikes. **Secondary volcanic hazards** result indirectly from volcanic activity, and can occur during the eruption but may also continue long after the eruption has ceased. These include lahars or debris flows (mudflows), volcanic earthquakes and tsunamis. Detailed descriptions of these hazards are given in the glossary.

ERUPTION SCENARIOS

Four different scenarios for future activity have been developed for the Soufrière Volcanic Centre. These can be divided into two groups based on eruption size and probability (see Table 1) and are discussed in detail below.

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 eruption from either the Central Highlands or from within the Qualibou Caldera

Table 1: Possible scenarios for future activity from the Soufrière Volcanic Centre. The scenarios decrease in likelihood from Scenario 1 (most likely) to Scenario 4 (least likely). Scenarios 2-4 are magmatic eruptions, i.e. involve the effusive or explosive ejection of magma at the surface of the Earth. In Scenario 1 there is no eruption of fresh magma at the surface.

It should be emphasized 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 eruptions styles may occur simultaneously. Intense phreatic eruptions may or may not culminate in magmatic eruptions. The eruption of La Soufrière in Guadeloupe in 1976-1977, for example, was entirely phreatic and did not culminate in a magmatic eruption. At the Soufrière Hills volcano in Montserrat the current eruption sequence began with a series of phreatic explosions before switching to effusive dome-forming activity, which itself is occasionally interrupted by small explosive eruptions.

Scenario 1: Phreatic or hydrothermal eruption from the Sulphur Springs geothermal field

The most likely type of volcanic activity to occur in southern Saint Lucia is a phreatic or hydrothermal eruption from the Sulphur Springs geothermal field. Phreatic and hydrothermal eruptions are minor steam-driven eruptions that eject fragments of old rock and ash into the air and are very common in geothermal areas. They are not true volcanic eruptions in that they do not erupt fresh magma, although both types of eruptions can emit dangerous gases.

Hydrothermal eruptions usually form when local depressurization (e.g. due to earthquakes or the release of overburden from landsliding) permits water to boil and flash to steam, which has enough energy to break up (brecciate) and eject surrounding rocks. The energy for such eruptions derives solely from the internal dynamics of a geothermal system, i.e. no magma is involved. Hydrothermal eruptions have been known to eject clasts up to 2-3 m in diameter several hundred meters from the vent. They can be locally very destructive, causing loss of life and damage to structures. A hydrothermal eruption may last for several days, and continue until the steam forms too slowly to provide sufficient lifting power to eject rocks from the crater. Steam may continue to be discharged for up to several years after the hydrothermal eruption has ended. There are several small crater areas in the Sulphur Springs field that may have sourced small hydrothermal eruptions in the past, and it is very likely that such eruptions will occur again in the future. For this reason people living or working in the Sulphur Springs area should be made aware of the possibility that earthquakes or landslides could trigger a hydrothermal eruption. If a hydrothermal eruption occurred at Sulphur Springs, it could eject boulders up to 200m from the vent. In this scenario it would be wise to instigate a safety zone ≥ 200 m in diameter for the duration of the eruption.

Phreatic eruptions are similar to hydrothermal eruptions in that they are also driven by steam generated by heated sub-surface geothermal water under pressure. However, they tend to eject more ash than rock fragments, and are usually more short lived. Unlike hydrothermal eruptions whose energy derives solely from the internal dynamics of a geothermal system, the heat needed to flash water to steam and thus generate a phreatic eruption is often provided by an underlying magma body. Phreatic eruptions may be accompanied by volcanic earthquakes. Phreatic eruptions have occurred in Saint Lucia in the past, the most recent in about 1766. Generally, phreatic eruptions only represent a localised hazard, and people should keep a safe distance until the eruption is over. Individual phreatic explosions may last up to an hour or more, and a series of blasts may continue intermittently for several months. In some instances, particularly if they occur in a sequence, phreatic eruptions may herald the arrival of an actual magmatic eruption.

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. The Sulphur Springs road will likely become 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 forming an explosion crater in the Belfond area

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 (see Figure 2) 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 3 km from the vent. They are unlikely to produce pyroclastic flows and lahars. Such an eruption is likely to 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 from the Soufrière Volcanic Centre

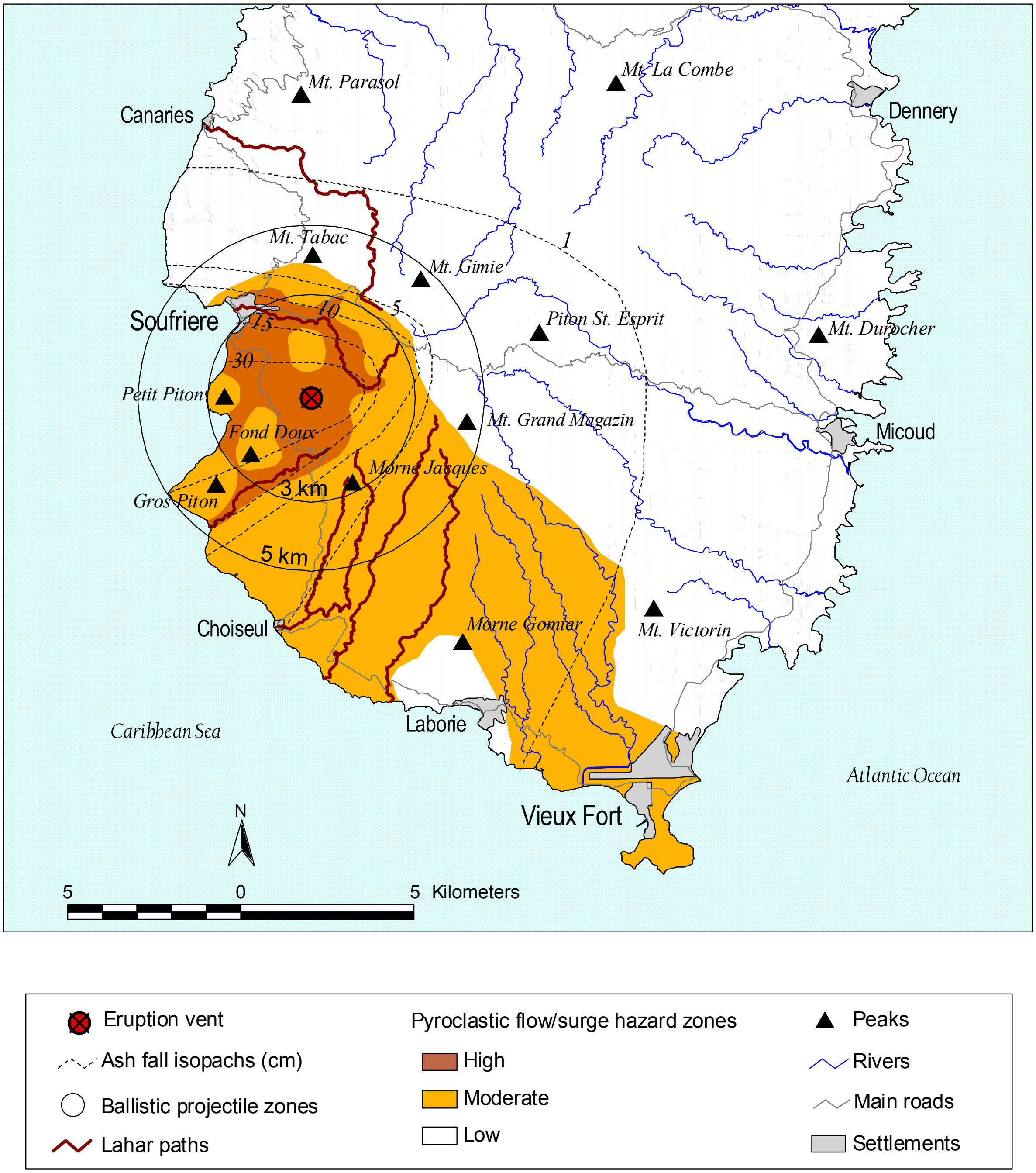
The second most likely scenario for a *magmatic* eruption is an effusive dome-forming eruption from within the Qualibou Caldera. Several dome-forming eruptions have occurred from the Soufrière Volcanic Centre over the last 20,000 years (e.g. Terre Blanche and Belfond), and as such this is considered the most-likely scenario for a *major* volcanic eruption in Saint Lucia. Such an eruption would be similar to the ongoing eruption of the Soufrière Hills volcano in Montserrat. It may continue for many years and would affect large areas of southern Saint Lucia. In order to prepare for such an eruption a hazard map has been compiled to visually display the areas that are likely to be affected and the types of hazards that can be expected (Figure 5).

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 give us an idea of vent location, we cannot 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 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.

In this scenario, the initial phases of dome-growth would involve non-explosive, passive eruption of lava to form a mound or hill, similar to but possibly bigger than Terre Blanche. This phase of activity may or may not be preceded by a series of phreatic eruptions. As the lava dome grows, it may become oversteepened and unstable, causing it to periodically collapse. This dome collapse results in a type of pyroclastic flow known as a block and ash flow. Block and ash flow deposits have been found near Terre Blanche and Belfond, indicating periods of past dome-collapse at these centres. In addition, explosive activity may occur during dome-forming eruptions and will generate abundant ash as well as ballistic projectiles. This style of eruption involving dome growth and periodic collapse interspersed with small explosions is typical for the ongoing eruption on Montserrat.

The greatest hazard in the event of a dome-forming eruption within the Qualibou Caldera would be from lava dome collapse 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 Soufrière and Belfond (Figure 5). 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.

Figure 5: Volcanic Hazard map for Saint Lucia based on Scenario 3: A dome forming eruption from within the Soufrière Volcanic Centre.



The steep-sided walls of the Qualibou depression should prevent pyroclastic flows travelling outside the depression, although vigorous flows and surges may be energetic enough to cross this barrier and spread to the south. Such energetic flows are likely to follow the paths of major river valleys, e.g. those leading to Anse John, Choiseul and even Vieux Fort (Figure 5).

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 dominant wind direction. In the case of Saint Lucia the dominant wind direction is from the east (easterlies) at lower elevations (< ~5km), and from the west (westerlies) at higher elevations (> 5-8 km). Ash may travel for kilometres and affect neighbouring islands and at times severely disrupt air traffic. The ash fall will be thickest close to the vent and will decrease in thickness away from the vent. The pattern of accumulated ashfall 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 ashfall pattern for this scenario (Figure 5). 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. Unconsolidated pyroclastic deposits are easily mixed with water to form a dense slurry which travels down valleys at high velocities. Lahars will bury anything in their path and can occur with little or no warning. On the island of Montserrat lahar and pyroclastic flow formation occur simultaneously when dome collapse events occur during heavy rainfall, and lahars have been a significant factor in burying and destroying the town of Plymouth in Montserrat. Lahars remain a threat for months to years after volcanic activity has ceased since abundant loose deposits are produced by an eruption. These are easily transported downslope during heavy rainfall. In Saint Lucia lahars 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 Figure 5.

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.

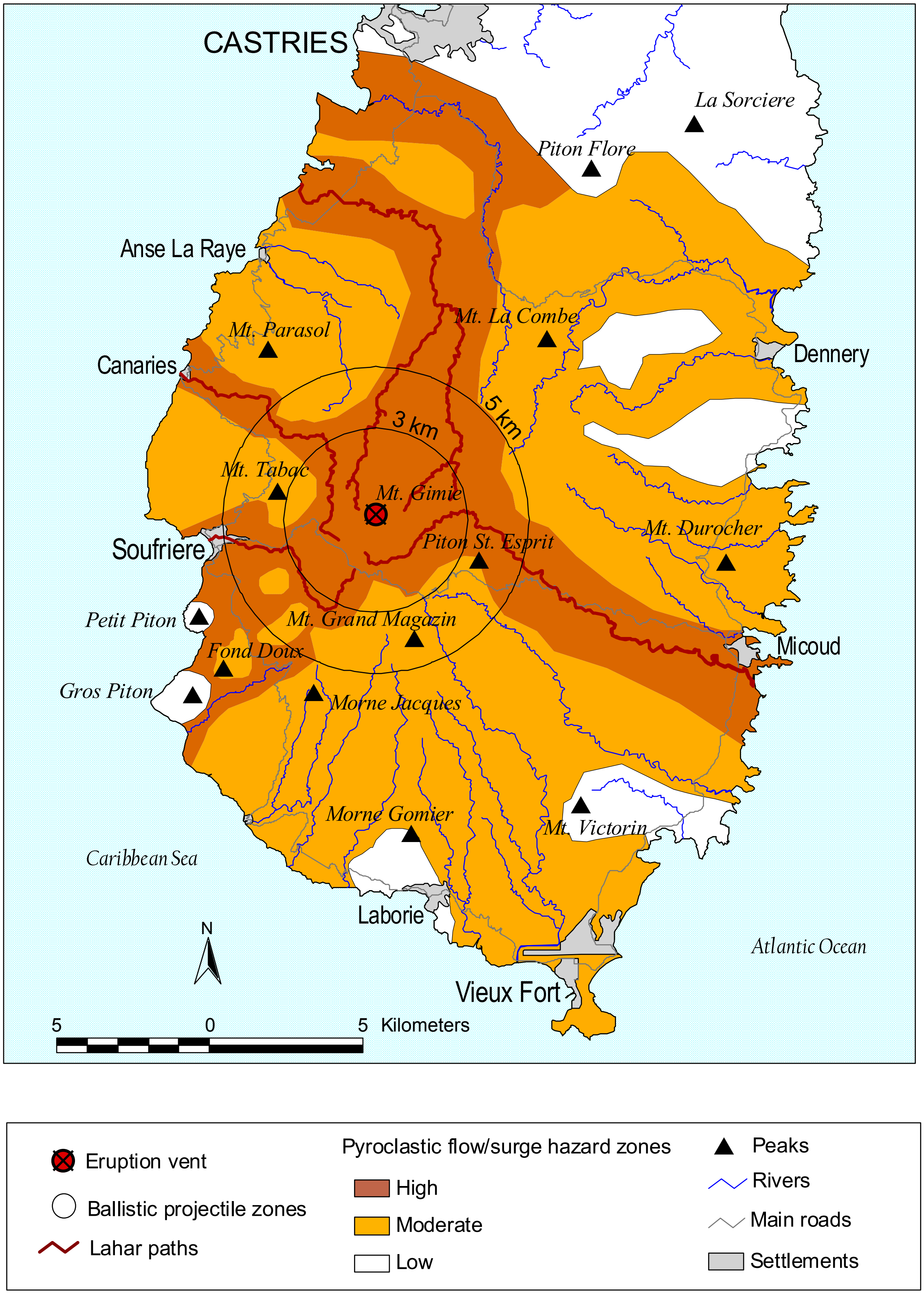
Scenario 4: Explosive Eruption from the Soufrière Volcanic Centre

Since the Soufrière Volcanic Centre has produced violent explosive eruptions in the past, it is possible that similar eruptions may occur in the future. The geologic record suggests, however, that no such eruption has occurred in the last 20,000 years. For this reason, a large explosive magmatic eruption from the Soufrière Volcanic Centre can be considered the least-likely or *worst-case* scenario. 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 in Figure 6 gives an indication of the areas that would be affected during an explosive magmatic eruption at the Soufrière Volcanic Centre.

Such an eruption would generate a buoyant eruption cloud of ash and larger rock fragments. Subsequent collapse of this eruption column would generate pyroclastic flows and surges radially around the vent, down the major valleys in southern Saint Lucia (see the brown area on Figure 6). Infrequent but extremely energetic pyroclastic flows and surges would be less restricted by topography and would have the potential to cover most areas of southern Saint Lucia (yellow area on Figure 6). No pattern of ash distribution is shown on Figure 6 as no suitable ash isopachs are available for this scenario; however, copious amounts of ash would fall downwind from the volcano. 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 and volcanic earthquakes would also occur, and 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.

The vent area in Figure 6 is arbitrarily located at Mt. Gimie. In this scenario, 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 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 Caldera then some areas to the north and northwest may be somewhat protected by the Qualibou depression margin and the peaks of the Central Highlands.

Figure 6: Volcanic Hazard map for Saint Lucia based on Scenario 4: An explosive magmatic eruption from within the Soufrière Volcanic Centre.



Integrated Volcanic Hazard Zones

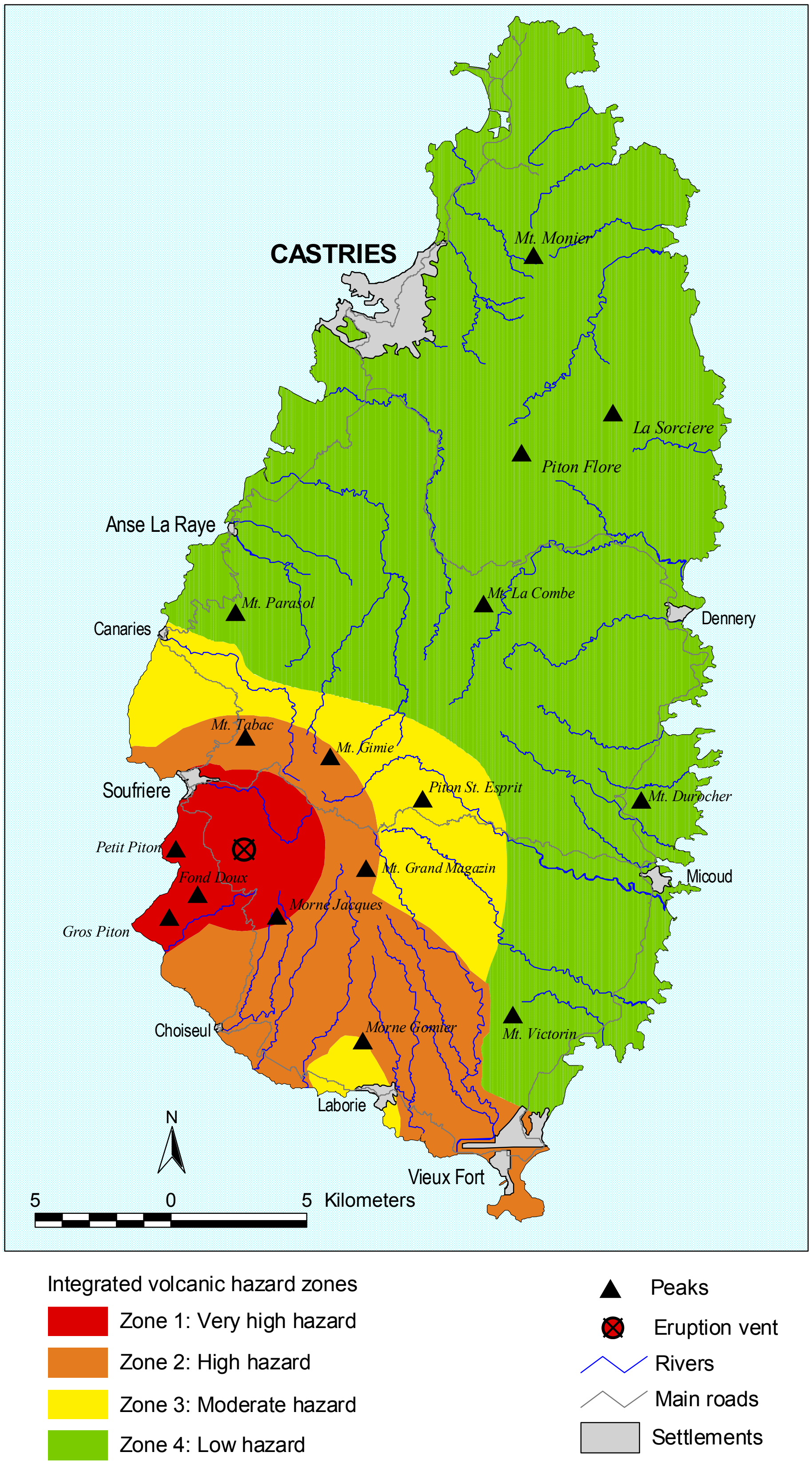
The areas most likely to be affected in the three most likely scenarios have been used to define overall areas of high and low hazard on Saint Lucia and to produce hazard zones for the island (Figure 7). The worst-case scenario involving a major explosive eruption has not been taken into consideration in the production of this map as this is considered the least-likely scenario. These integrated hazard zones should be used for planning evacuation scenarios and in long-term land-use planning in Saint Lucia.

Zone 1 (red) is the area of very high hazard. In the event of a dome-forming eruption (scenario 3) this is the area most likely to be affected by the dome itself, dome-collapse pyroclastic flows and surges, heavy ash fall and ballistic ejecta. It was determined by combining the following from scenario 3: the area with a high pyroclastic flow hazard, the 3km radius ballistic projectile zone and the area likely to receive > 15 cm of ash. In the event of such a dome-forming eruption from the Soufrière Volcanic Centre 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-moderate ash fall. It was determined by combining the following from scenario 3: the area with a moderate pyroclastic flow hazard, the 5km radius ballistic projectile zone and the area likely to receive > 5cm 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 >1cm 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 airfall.

Zone 1 (red) 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 either of these scenarios, 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.

The boundaries of the zones in Figure 7 must never be considered sharp, narrow lines as shown on the map. The boundaries will vary slightly depending on exact eruption location, and eruption and weather conditions. In the event of a volcanic eruption, this hazard map will be revised regularly by scientists.

Figure 7: Integrated Volcanic Hazard Zones for Saint Lucia based on a combination of the three most-likely scenarios.



Furthermore, the map in Figure 7 only shows hazard zones on land. An eruption in Saint Lucia may present hazardous effects that can also be felt at sea. In the event of a magmatic eruption in Saint Lucia a maritime exclusion zone around the southwestern part of the island should be enforced. 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.

VOLCANO MONITORING IN SAINT LUCIA

A future eruption on Saint Lucia should be preceded by characteristic warning signs, and monitoring of the volcanic features for these warning signs is extremely important. More detailed information regarding the monitoring program is provided in the scientific supplement.

Volcanic eruptions are usually preceded by shallow earthquake swarms, and seismic monitoring is the single most useful monitoring technique at an active volcano. The Seismic Research Unit monitors earthquake activity in Saint Lucia via seismometers installed near the volcano. Recently, the seismic network in Saint Lucia was upgraded from 4 to 7 stations (Figure 8), and a base station installed at Moule-a-Chique.

Prior to erupting at the surface, magma often causes updoming within the crust which is detectable using sophisticated equipment for measuring ground deformation. In January 2001 a base network for measurement of ground deformation was set up in southern Saint Lucia. This involved the installation of a number of metal pins whose precise location will be measured periodically using GPS equipment. This will allow scientists to check for minute displacements of the ground in volcanic areas that might indicate magma movement towards the surface. This is a powerful tool that will be used to identify precursor activity prior to the onset of a volcanic eruption and to identify any post-eruption activity.

Sometimes changes in the chemistry, temperature, energy and location of fumaroles and hot-springs may precede a volcanic eruption. In the event of a future eruption from the Soufrière Volcanic Centre the fumaroles and hot springs of Sulphur Springs *may* show signs of increased activity in the months prior to the onset of an eruption. 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. In April 2001 the Seismic Research Unit established a programme to regularly sample and analyse gas and water samples from Sulphur Springs. Any changes in fumarolic or hot/cold spring activity on Saint Lucia should be reported to the National Emergency Management Organisation (NEMO) and/or the Seismic Research Unit as soon as possible.

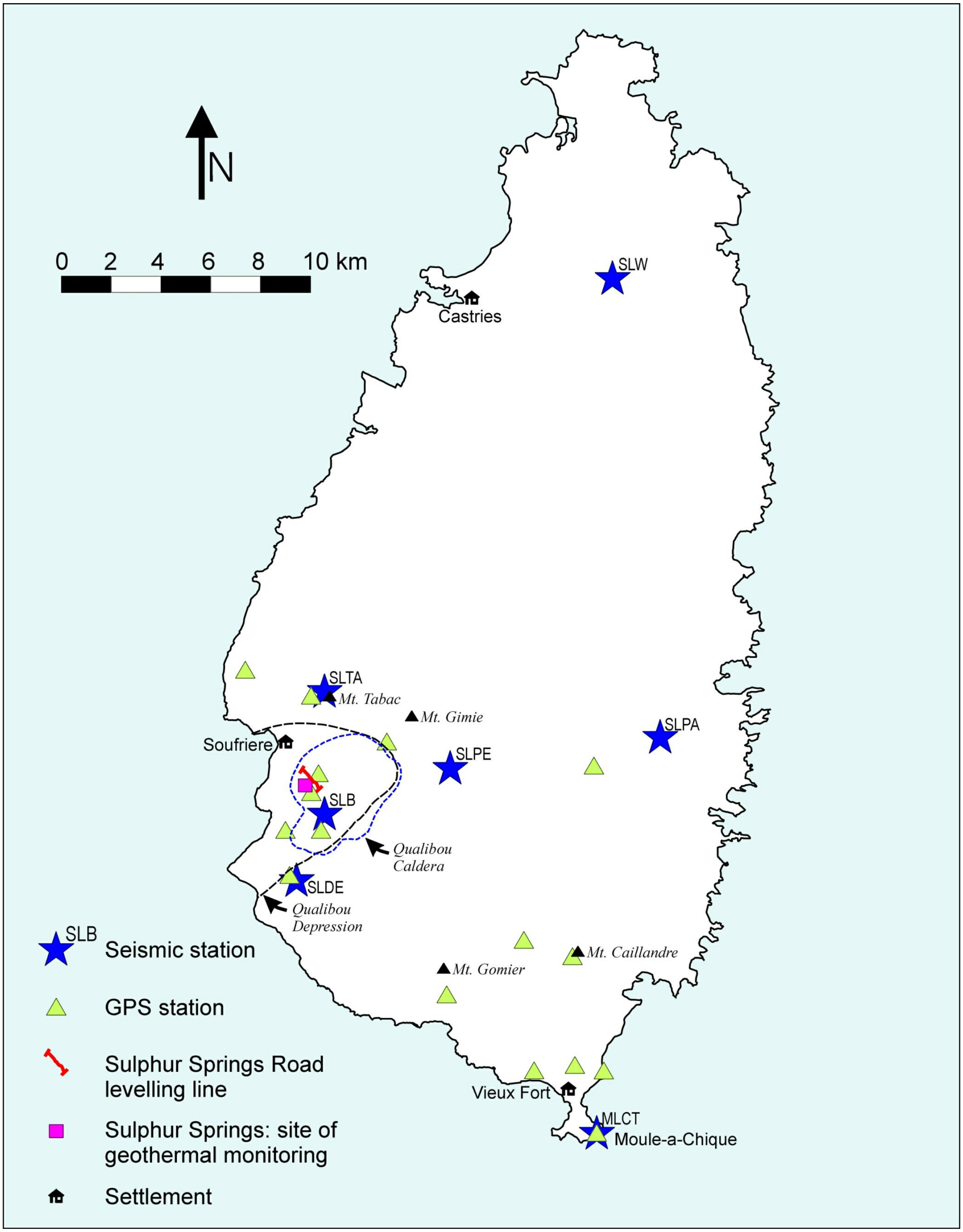


Figure 8: Volcano monitoring network in St Lucia. The base stations for both seismic and GPS sub networks are located at Moule-a-Chique.

HAZARD MITIGATION

Although the youngest age dates available for volcanic rocks on Saint Lucia are 20,000 years BP[3], we know that several domes and explosion craters have formed since then. The Government of Saint Lucia needs to seriously consider the possibility of future volcanic eruptions and to plan in advance for such a crisis. A volcanic eruption from the Soufrière Volcanic Centre is a realistic possibility, and needs to be addressed immediately. The hazards associated with volcanic eruptions generally necessitate evacuation of high-risk areas prior to the onset of activity in order to avoid any loss of life. In addition, as is the case with the ongoing eruption of Soufrière Hills on Montserrat, volcanic eruptions can continue for years. Even after an eruption has ceased the land may not be habitable for tens of years afterward. A volcanic eruption can displace a large proportion of the population for decades. It is the responsibility of the Government to ensure the safety of its citizens, and to be educated and prepared for such a crisis. An eruption from the Soufrière Volcanic Centre would necessitate the evacuation of Soufrière and surrounding villages. The Government needs to have an emergency plan to house these people in safe areas in the north of the island. Furthermore, in the event of a volcanic emergency the major sources of income on the island, tourism and agriculture, would be severely impacted.

In addition to possible future activity from the Soufrière Volcanic Centre, Saint Lucia may also be affected by volcanic eruptions elsewhere in the region. Depending on the wind direction, explosive eruptions on neighbouring islands may result in significant ashfall in Saint Lucia. The 1979 eruption from the Soufrière in Saint Vincent, for example, led to some light ashfall in the south of the island. Furthermore, a large eruption from the submarine volcano Kick 'em Jenny could generate a small tsunami that may reach the western and southern coasts of Saint Lucia. Such an eruption is, however, at present considered very unlikely.

The Seismic Research Unit provides an indication of the status of any given volcano in the Eastern Caribbean using Volcanic Alert Levels. The colour coded alert level table for onshore volcanoes of the Eastern Caribbean is shown in Table 2. The alert level reflects the status of each volcano at any given time, and may change according to level of activity. In Saint Lucia's case, the alert level reflects the general status of volcanic activity in southern Saint Lucia. This is because we cannot say with certainty where a future eruption may occur. Once precursory symptoms begin to appear it will be possible to be more specific about which volcanic vent may become activated, and from that point on the alert level will apply to that vent area.

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[3] Before Present

Alert Level	Symptoms	Action by scientists	Recommended action: civil authorities
Green	Volcano is quiescent; seismic and fumarolic (steam vent) activity are at or below the historical level at this volcano. No other unusual activity has been observed.	Normal monitoring.	Undertake on-going public awareness campaigns and work on volcanic emergency plans.
Yellow	Volcano is restless; seismicity or fumarolic activity or both are above the historical level at this volcano or other unusual activity has been observed (this activity will be specified at the time that the alert level is raised).	Monitoring system will be brought up to full capability. Civil authorities alerted. Communication system tested.	Undertake on-going public awareness campaigns and work on volcanic emergency plans. Advise vulnerable communities of evacuation procedures in the event of an emergency.
Orange	Highly elevated level of seismicity or fumarolic activity or both, or other highly unusual symptoms. Eruption may occur with less than twenty-four hours' notice.	Monitoring system continuously manned. Regular visual inspection of potential vent areas. Continuous ground deformation and hydrothermal monitoring. Daily assessment reports to civil authorities.	Coordinate evacuation (if necessary) based on hazard zones. Entry to the restricted-access zone by scientists will be permitted after evaluation on a case by case basis. Organise regular radio and television announcements.
Red	Eruption is in progress or may occur without further warning.	Measurements as permitted by safety conditions. Civil authorities advised continuously.	Coordinate continued evacuation as necessary. Organise regular radio and television announcements.

Table 2: Alert Level Table for the onshore volcanoes of the Eastern Caribbean

Currently (September 2002), southern Saint Lucia is at alert level GREEN. Should there be a significant increase in volcanic activity in Saint Lucia, the Seismic Research Unit will issue a change in volcanic alert status. A series of actions that should be undertaken by the civil authorities at each alert level is recommended in the table. These should be integrated into the National Volcanic Plan for Saint Lucia.

Public education is a very important part of hazard mitigation. Many governments avoid public education because they do not want to cause unnecessarily panic among the population in times of no increased volcanic activity. Consequently, in times of crisis the public are not adequately prepared or educated about the risks of living on the flanks of a potentially active volcano. This can lead to misunderstandings, misinterpretations, confusion and panic during a crisis. The population of southern Saint Lucia should be educated about the risks of living near a potentially active volcano BEFORE an increase in volcanic activity occurs. In addition, earthquakes are an everyday threat to the populations of Saint Lucia regardless of the volcanic activity. There are procedures that should be followed to minimise damage caused by earthquakes. The general population should be familiar with these procedures. The Seismic Research Unit is willing to help organize and sustain a public education program for Saint Lucia on volcanic and seismic hazards. One of the most effective ways of sustaining awareness is to introduce a volcanic and seismic hazards component into the school curriculum thus ensuring that the information is passed on from generation to generation.

RECOMMENDATIONS

The following is a brief list of recommendations for government authorities and citizens of Saint Lucia based on the results of this study.

1. The 'National Volcanic Plan' for Saint Lucia should be updated as soon as possible to include the volcanic alert level table in Table 2 and the map of integrated hazard zones in Figure 7.

2. The 'National Volcanic Plan' should include a comprehensive plan for the evacuation of Soufrière and nearby towns. In addition to evacuation by road, evacuation by sea should also be planned for in the event that roads are blocked off during a crisis. Refuge points should be identified and the public made aware of their location. Be aware that volcanic eruptions may continue for years, and it may not be possible to resettle on the evacuated areas.

3. Simulation exercises based on the most likely scenario for a major eruption (scenario 3) could be undertaken to test and update the 'National Volcanic Plan'. This would include co-ordinating the complete evacuation of the population of all towns within the Qualibou Depression, including Soufrière, and their temporary accommodation in safe areas to the north. If required, the Seismic Research Unit could assist in such a simulation exercise by providing real time simulated scientific advisories.

4. The map of integrated volcanic hazard zones (Figure 7) for Saint Lucia should be used in long-term land-use planning.

5. Continued support should be given to the Seismic Research Unit. This unit maintains a volcano monitoring program that is essential in order to recognize precursor signs to volcanic activity.

6. The staff of the Soufrière Foundation should be vigilant at all times when working in or near the Sulphur Springs geothermal field, and should report any changes in geothermal activity immediately to the local Disaster Coordinator or the Seismic Research Unit (contact information is given at the end of the report).

7. Copies of this hazard report should be given to staff of the Soufrière Foundation in order for them to better understand the relationship between the Sulphur Springs geothermal field and the Soufrière Volcanic Centre, and to familiarise themselves with the hazards (e.g. gases and hydrothermal eruptions) specific to the Sulphur Springs geothermal field.

8. Ongoing public awareness campaigns should be undertaken for both volcanic eruptions and earthquakes. This needs to be done BEFORE a crisis occurs.

9. Volcanic and seismic hazards should be taught as part of the regular school curriculum to ensure ongoing awareness. A volcanic and seismic hazard awareness week every couple of years would also be an effective way to educate the larger population and could involve simulation exercises for both volcanic and seismic hazards.

10. This report should be made available to the general public so that the citizens can judge for themselves whether they want to risk living or working in areas of highest hazard, as well as be aware of the areas that may offer refuge in the event of a volcanic eruption.

11. The relevant authorities from Saint Lucia would benefit greatly from a field trip to Montserrat to see first hand the devastating effects of a volcanic eruption and the different effects of the various eruption styles. This would also be an opportunity to discuss with the disaster co-ordinator on Montserrat the importance of being prepared and educating the public before the crisis begins.

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GLOSSARY OF TERMS USED IN THIS REPORT

Active volcano
A volcano that is currently erupting (e.g. Montserrat) or in an ongoing eruptive phase (e.g. Kick 'em Jenny).

Airfall (see **pyroclastic fall**)

Aftershocks
A series of smaller earthquakes which may follow a large earthquake.

Andesite
A type of volcanic rock with 55–63 wt.% SiO_2. (see also **magma**)

Ash fall
Explosive volcanic eruptions produce fine material called volcanic ash, which is carried upwards in a buoyant eruption column before it settles out downwind to form ash fall. Ash falls can blanket the entire landscape for kilometres around a volcano, and may even reach nearby islands. Close to the eruption vent, ash may be thick enough to collapse buildings and destroy vegetation. Ash can cause aircraft, ship and car engines to malfunction. Ash can also be very dangerous to the health of people and animals since ash may cause serious respiratory problems if inhaled. Ash falls can be particularly damaging to livestock as small amounts of ash can lead to fluorosis if ingested. This hazard from ash fall may persist long after the eruption itself has ended.

Ballistic projectile
A ballistic projectile is a rock fragment that is ejected from a volcanic vent at high velocity and follows a ballistic trajectory (i.e. travels like a cannonball from a cannon). These rocks are called *blocks* if they were solid at the time they were fragmented and *bombs* if they were liquid. They usually land within 2 km of the vent but can travel as far as 5 km, or even further if the eruption is very explosive.

Basalt
A type of volcanic rock with 45–55 wt.% SiO_2. (see also **magma**)

Block and Ash flow
A type of pyroclastic flow that forms when a lava dome collapses.

Caldera
A caldera is a large, more or less circular-shaped volcanic collapse feature which forms when magma is either withdrawn or erupted from a shallow underground magma reservoir.

Carbon or ^{14}C dating
A method of determining the dates at which volcanic rocks were erupted based on the analysis of material that was previously alive (e.g. charcoal)

Dacite
A type of volcanic rock with 63–70% SiO_2. (see also **magma**)

Dead volcano
A volcano that scientists believe no longer has the ability to erupt again is sometimes referred to as 'dead'.

Debris avalanche
A debris avalanche is a sudden and rapid movement of rock and other debris (e.g. vegetation) driven by gravity. It may result from the collapse of the side of an oversteepened volcano or gravitational collapse of unconsolidated sediments. Depending on their scale, debris avalanches may destroy everything in their path. They can occur during volcanic eruptions or when a volcano is not actively erupting. They are one of the most hazardous but least common volcanic events.

Earthquake swarm
A group of many shallow earthquakes of similar size occurring closely clustered in space and time with no dominant main shock. Earthquake swarms may indicate that magma is moving beneath a volcano, and almost always precede volcanic eruptions in the Lesser Antilles. (see also **volcanic earthquake**)

Effusive eruption
Eruptions can be explosive or effusive, depending on the physical properties of the magma. Effusive eruptions occur when molten rock (lava) reaches the Earth's surface and erupts passively. The products of these eruptions are lava flows and lava domes. They generally occur when the gas content of the magma is low. Basalts tend to erupt effusively and produce lava flows. The dominant style of the ongoing eruption of the Soufrière Hills Volcano in Montserrat has been the effusive eruption of lava leading to the formation of a lava dome.

Epicentre
The point on the surface of the Earth directly above the hypocentre (or focus) of an earthquake.

Eruption column
Explosive eruptions generate abundant ash and other volcanic particles which are carried up into the atmosphere by expanding hot gases to produce a buoyant eruption column.

Eruption column collapse
The collapse of an eruption column occurs when the density of the volcanic particles entrained in the column exceeds the upward buoyancy of the column. The volcanic particles fall back down to the ground under the influence of gravity and can form pyroclastic flow, surge and fall deposits.

Explosive eruption – 3 types
Eruptions can be explosive or effusive, depending on the physical properties of the magma. An Explosive eruption involves the rapid expansion of gas causing the surrounding rock or magma to fragment explosively. There are 3 types of explosive eruptions:

Magmatic eruptions
Explosive magmatic eruptions occur when dissolved gases in a rising magma expand to form gas bubbles which then burst as the magma nears the Earth's surface, leading to explosive fragmentation of the magma. The bigger fragments are ejected (ballistically) like cannonballs while the smaller fragments are transported vertically at great velocities into the atmosphere to form a vertical eruption column. Under certain circumstances eruption columns can collapse, resulting in the formation of energetic pyroclastic flows and surges as well as associated ash fall. Pyroclastic flows and surges resulting from column collapse are very dangerous as they are not always confined to valleys and may travel radially down all flanks of the volcano, burying and destroying everything in their path. On the lower flanks of the volcano they may become confined to valleys. Several magmatic explosions have occurred during the ongoing eruption of the Soufrière Hills in Montserrat, and this is the type of eruption that produced the Choiseul and Belfond pumice deposits.

Phreatomagmatic eruptions

Phreatomagmatic eruptions occur when magma comes into contact with water causing the water to flash to steam. The expanding steam disrupts not only the pre-existing solid rock but also the magma itself so that the fragments thrown out are a mixture of broken-up old rocks and new rocks. The products of a phreatomagmatic eruption include pyroclastic fall, flow and surge deposits. The 1979 eruption of the Soufrière of St. Vincent began as a phreatomagmatic eruption and this is also the predominant eruption style of the Kick 'em Jenny submarine volcano.

Phreatic eruptions

Phreatic eruptions occur when confined, sub-surface geothermal waters are heated to temperatures above their boiling point and flash to steam, thereby expanding to form an explosion. Such eruptions eject abundant hot steam, hot water, mud and old rock debris in to the air. In some cases the mud and water ejected may be acidic. No new magma is involved in a phreatic eruption, although the heat needed to flash water to steam and thus generate a phreatic eruption is often provided by an underlying magma body. In some instances, particularly if they occur in a sequence, phreatic eruptions may herald the arrival of an actual magmatic eruption. In the Eastern Caribbean, there have been numerous phreatic eruptions, e.g. the 1976-1977 eruption of La Soufrière in Guadeloupe, the 1880 and 1997 eruptions in the Valley of Desolation in Dominica and the 1766 eruption at Sulphur Springs in Saint Lucia.

Fumaroles (steam vents)

Fumaroles are cracks or openings in the ground through which volcanic gases from beneath the Earth's surface escape. Monitoring of fumaroles by analysing the gases and measuring temperatures may be useful in predicting volcanic eruptions. Volcanic gases may be hazardous to humans and animals and have in some cases caused death. Condensation of the gases into groundwater can result in alteration and dissolution of rock near the surface, making areas surrounding fumaroles prone to collapse or subsidence.

Geothermal activity

Geothermal activity results from elevated heat flow in the Earth's crust. One of the ways heat flow becomes elevated is by intrusion of magma to shallow levels in the crust, such as below a volcano. Typical features of geothermal activity are hot springs, geysers, fumaroles and bubbling mud pools. These features form when rainwater seeps into the ground where it is heated by hot rock. The hot water becomes buoyant, and rises back to the surface along cracks in the Earth's surface. The water heated by geothermal activity is called hydrothermal water.

Geothermal system

A concentrated zone of geothermal activity.

GPS

GPS stands for **G**lobal **P**ositioning **S**ystem. This is a geophysical technique used to accurately determine the locations of specific points in three dimensions. Very small (mm scale) changes in the locations of these points can be recorded over time.

Hazard maps

Volcanic Hazard maps are important tools in planning mitigation of the harmful effects of volcanic eruptions. They take several forms and most often show the areas around a volcano which are likely to be affected by different types of hazardous phenomena related to the volcano. They should be used in advance of a volcanic eruption to avoid extensive construction in areas of high hazard, and to plan evacuation routes and shelters in the event of an emergency.

Hydrothermal alteration
When hydrothermal water (hot water) moves through rocks beneath the surface, chemical reactions between the water and the rocks occur. These chemical reactions change (or alter) the rocks by destroying original minerals and depositing new minerals. Hydrothermally altered rocks commonly have white, yellow, orange or red colouration and may be softer than unaltered rocks.

Hydrothermal eruption
A Hydrothermal eruption is an eruption of steam and rocks whose energy derives solely from the internal dynamics of a geothermal system, i.e. no magma is involved. Such eruptions are common in active geothermal fields and can be locally very destructive, causing loss of life and damage to structures. They have been known to eject clasts up to 2-3 m in diameter up to several hundred meters from the vent, and may produce craters and deposits known as hydrothermal eruption breccias. They form when water flashes to steam which erupts, cracking (brecciating) rocks and ejecting them at the surface. Such eruptions are usually triggered by local depressurization, e.g. due to earthquakes or the sudden release of overburden from landsliding. They can also be triggered if the system becomes sealed or covered, allowing internal pressures to increase and become greater than that of the surrounding rock. This sealing can occur naturally (e.g. if silica precipitates from geothermal waters to form an impermeable deposit) or by man (e.g. if asphalt or concrete slabs are placed over geothermal features). A hydrothermal eruption may last for several days, and continue until the steam forms too slowly to provide sufficient lifting power to eject rocks from the crater, although steam may continue to be discharged for up to several years after the hydrothermal eruption has ended. Hydrothermal eruptions may cause major changes to the hydrology of the geothermal field.

Hypocenter (focus)
Most earthquakes result from sudden breakage of rock within the Earth. The point at which the breakage starts is called the hypocentre or focus of the earthquake.

Lahars
Lahars are mudflows formed when volcanic particles mix with water. The source of the water may be a crater lake, heavy rain or snow. The loose ash and volcanic fragments are transformed into a dense fluid-rock mixture that rushes down the slopes of a volcano and into surrounding valleys. Lahars are destructive to everything in their path, and the threat from lahars may last for years after an eruption has ended.

Lateral blasts
A lateral blast is a laterally directed volcanic explosion of rock fragments and gas that explodes outwards at high velocity from the side of a volcano. It can affect a 180° sector and extend up to 30 km outward from the volcano. Lateral blasts are not affected by topography and can develop without warning. These types of eruptions are rare but can be triggered by failure of newly erupted lava domes or by the collapse of a large portion of the volcanic edifice.

Lava
Magma that erupts passively at the Earth's surface.

Lava flows and lava domes
Lava flows are hot streams of molten rock that travel down valleys on the slopes of volcanoes. The distance lava flows travel depends on the viscosity ('stickiness') of the lava. If the lava is viscous (sticky) it cannot flow easily so it tends to form short thick lava flows or pile up around the vent to form a hill, or lava dome. Lava flows generally move slowly and therefore usually pose little hazard to humans, although they destroy everything in their path and can cause forest fires. However, viscous (sticky) lava flows and domes can be hazardous as their steep sides often become unstable and can collapse, causing a type of

small pyroclastic flow known as a block and ash flow. Lava flows are uncommon on the volcanoes of the Lesser Antilles but lava domes are abundant and their collapse has caused significant loss of life.

Lightning strikes
Powerful displays of lightning can occur during volcanic eruptions. Such lightning results from friction between ash, rock fragments, steam and gases in the eruption cloud. Lightning strikes can pose a threat to life and property and disrupt communication systems.

Lithosphere
The rigid outermost part of the Earth.

Live volcano
A volcano that is currently erupting or that scientists believe has the capacity to erupt again is sometimes referred to as 'live'.

Magma
Magma is a mixture of molten rock, crystals and gases present beneath the Earth's surface. It usually accumulates in magma chambers before erupting at the surface. Magma is divided into types according to silica (SiO_2) content, which controls viscosity (ease of flowing) and hence influences eruptive styles. The most silica-poor (45–55 wt.% SiO_2) fluid magmas are called **basaltic** magmas. **Andesitic** and **dacitic** magmas have intermediate compositions (55–63 wt.% and 63–70% SiO_2, respectively). The most silica-rich, viscous magmas (> 70 wt.% SiO_2) are called **rhyolitic** magmas.

Phreatic Eruption (see **explosive eruption**)

Pumice
A lightweight volcanic rock that contains many vesicles (holes where gas bubbles used to be). Pumice is a quenched sample of gas-rich magma that has erupted explosively.

Pyroclastic
The word pyroclastic is derived from two Greek words meaning "fire" and "broken". It refers to volcanic particles formed by the fragmentation of magma. The smallest fragments (less then 2 mm in diameter) are called *ash*. Fragments between 1mm and 1cm in diameter are called *lapilli*. Larger fragments are called *blocks* if they were solid at the time they were fragmented and *bombs* if they were liquid.

Pyroclastic fall (airfall)
Pyroclastic fall refers to the ash, lapilli, blocks or bombs produced during an explosive magmatic eruption that fall to Earth, usually from an eruption column.

Pyroclastic flow
A pyroclastic flow is a hot (100-600^{O}C), fast-moving (>100 km/hr) mixture of ash, rock fragments and gas. Such flows form when an eruption column or a lava dome collapses. They usually travel down valleys and cause total devastation of the area over which they flow. People in the path of a hot pyroclastic flow can be killed by asphyxiation, heat and noxious gases. Pyroclastic flows have been the main cause of destruction and loss of life in Montserrat since 1995.

Pyroclastic surge
A pyroclastic surge is a dilute, turbulent cloud of gases and rock debris that moves above the ground surface at great speeds. Pyroclastic surges form in a similar way to pyroclastic flows, but their effects are more widespread as they are less confined by topography and may therefore sweep across ridges and hills

as well as down valleys. Pyroclastic surges can be either hot (several hundred °C) or cold (< 100 °C). Cold pyroclastic surges are generally known as base surges, and are commonly generated by phreatic and phreatomagmatic explosions. The hazardous aspects of both types of surges include the destruction of vegetation and structures, impact damage by rock fragments, and burial by ash and rock debris. People in the path of a hot pyroclastic surge can also be killed by asphyxiation, heat and noxious gases. Pyroclastic flows and surges from Mt. Pelèe completely destroyed the town of St. Pierre in Martinique in 1902, killing about 30,000 people.

Seismograph
A group of instruments used to record earthquakes. A seismograph includes a seismometer as well as all equipment used to convert, transmit and display the signals generated by the seismometer.

Seismometer
A sensitive instrument installed on or in the ground to detect earthquakes.

Tectonic Earthquake
A rupture in the stiff, outermost part of the Earth called the lithosphere. Tectonic earthquakes are triggered by the movement of tectonic plates relative to one another.

Tsunamis
Tsunamis are large waves generated by the sudden displacement of water resulting from underwater disturbances such as a large earthquake or submarine volcanic eruption. Tsunamis travel extremely fast, reaching ~800 km/hr in the deep oceans. When tsunamis reach land they inundate low-lying coastal areas. In Saint Lucia the threat of tsunamis is an indirect one. The entrance of pyroclastic flows into the sea in southern Saint Lucia could generate minor tsunamis that could affect coastal areas in northern Saint Lucia.

Volcanic Ash
The fine material (< 2 mm in diameter) that is ejected from a volcano.

Volcanic earthquake
An earthquake characterised by high-frequency seismic signals thought to be generated by the fracturing of rock in response to the intrusion and migration of magma. Volcanic earthquakes always precede the onset of volcanic activity, although they do not always culminate in a volcanic eruption. They often occur in swarms. Volcanic earthquakes are the most effective monitoring tool for predicting a volcanic eruption. In some cases they may in themselves be severe enough to cause significant damage. A sequence of volcanic earthquakes in Montserrat between 1931 and 1938 destroyed a large number of buildings, and volcanic earthquakes in Dominica between 1998 and 2000 triggered numerous rock falls and landslides. (see **earthquake swarm**).

Volcanic gases
Magma contains dissolved gases that are released into the atmosphere during eruptions. In addition, geothermal systems such as Sulphur Springs also emit large amounts of 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) and sulphur dioxide (SO_2) with smaller amounts of hydrogen sulphide (H_2S), carbon monoxide (CO), hydrogen chloride (HCl) and hydrogen fluoride (HF). SO_2, CO, CO_2 and H_2S are present in toxic amounts close to the vent of an erupting volcano and may be emitted from fumaroles. Further away from the vent these gases can become dissolved in atmospheric clouds to produce acid rain and mist which affect human and animal eyes and respiratory systems and corrode metal building materials. One of the most common volcanic gases, carbon dioxide (CO_2) is extremely dangerous as breathing air with greater than about 20% CO_2 can cause almost instantaneous death. As it is heavier

than air, CO_2 tends to accumulate in hollows in the ground, displacing the breathable air. Since it is invisible and has no taste or smell, people and animals are unable to notice that it is there and may suffocate. People have died in this way at the Boiling Lake in the Valley of Desolation in Dominica and livestock have been found dead in low-lying areas near cold soufrière in Saint Lucia.

Volcaniclastic deposit
The term volcaniclastic deposit is a general term describing any deposit that contains volcanic fragments. It is often used when the process by which a particular deposit formed is unclear. All pyroclastic deposits, lahar deposits and debris avalanche deposits are types of volcaniclastic deposits.

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ACKNOWLEDGEMENTS

We would like to thank the Government of Saint Lucia for providing logistic and financial support for this hazard assessment; we are particularly grateful to Mr Bishnu Tulsie and his staff in the Sustainable Development and Environment section of the Ministry of Planning. We are also grateful to the staff of the Forestry Department, especially Rhikkie Alexander, for valuable assistance in the field. We thank the whole staff of the Seismic Research Unit for their assistance in all aspects of this project, in particular Chan Ramsingh and Wilke Balgobin for the successful extension of the seismic network, Uche Osuji for his assistance with the GPS and levelling work, Nolan Ali for preparation of the GPS benchmarks and Shahiba Ali for preparation of the hazard maps. We also thank Daniel Goode of Cardiff University and Linda Brown of the University of New Mexico for their assistance in the field. The Lands and Survey Department of Saint Lucia provided critical maps, and we thank the Soufrière Foundation for assisting us with our work at Sulphur Springs. We are grateful to the Airport Authority at Vieux-Fort for granting us permission to access GPS points close to the tarmac. Similarly, the Port and Sea Authority of Castries was helpful in allowing us access to the GPS point at the Moule-a-Chique lighthouse. We thank the Water Authority of St. Lucia, WASCO, for allowing us to install seismic equipment on one of their reservoir properties, and we are grateful to Bruno William of WASCO for his assistance in the installation of both seismic and GPS equipment.