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Scientific Supplement
to the Volcanic Hazard Assessment for Saint Lucia, Lesser Antilles

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GPS reference point at Moule a Chique lighthouse

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INTRODUCTION

This Scientific Supplement provides the scientific background to the Volcanic Hazard Assessment prepared by Lindsay *et al.* (2002). It incorporates the results of recent field work, literature reviews as well as the results of seismic and other monitoring efforts. It was our aim to make the accompanying Hazard Assessment as succinct as possible, and we therefore deliberately chose to include most of the scientific information in this separate report. For most purposes, the Hazard Assessment will provide sufficient information to be used without readers having to refer to the Scientific Supplement. The supplementary report can be referred to if more detail on a particular aspect of the Hazard Assessment is required.

In this Scientific Supplement the regional setting of Saint Lucia is explained in detail, and a comprehensive discussion of previous work is included. A thorough description of the various volcanic centres of Saint Lucia is provided, as is a discussion of the controversial Qualibou caldera. This report also provides details of the Seismic Research Unit's monitoring program, including the location and description of seismic and GPS stations, and initial results of gas analyses from Sulphur Springs.

REGIONAL SETTING

Saint Lucia lies in the Lesser Antilles between the islands of Martinique in the north and St. Vincent in the south (Figure 1). The islands of the Lesser Antilles form an arcuate line along the eastern margin of the Caribbean sea that stretches ~700 km from Sombrero in the north to Grenada in the south and that marks the boundary between the North American and Caribbean plates.

The islands have formed over millions of years by volcanic processes related to the westward subduction (underthrusting) of the North American plate beneath the Caribbean plate. These processes are still going on today. When the North American plate reaches depths of about 100 km, certain hydrous minerals start to break down and release water into the mantle beneath the overriding Caribbean plate. This water has the affect of lowering the melting point of the mantle, which melts to form magma. This magma is less dense than the surrounding rock, and rises up to the surface where it erupts to form volcanoes. This process happens all the way along the plate boundary, and the line of volcanoes that is produced is called an arc.

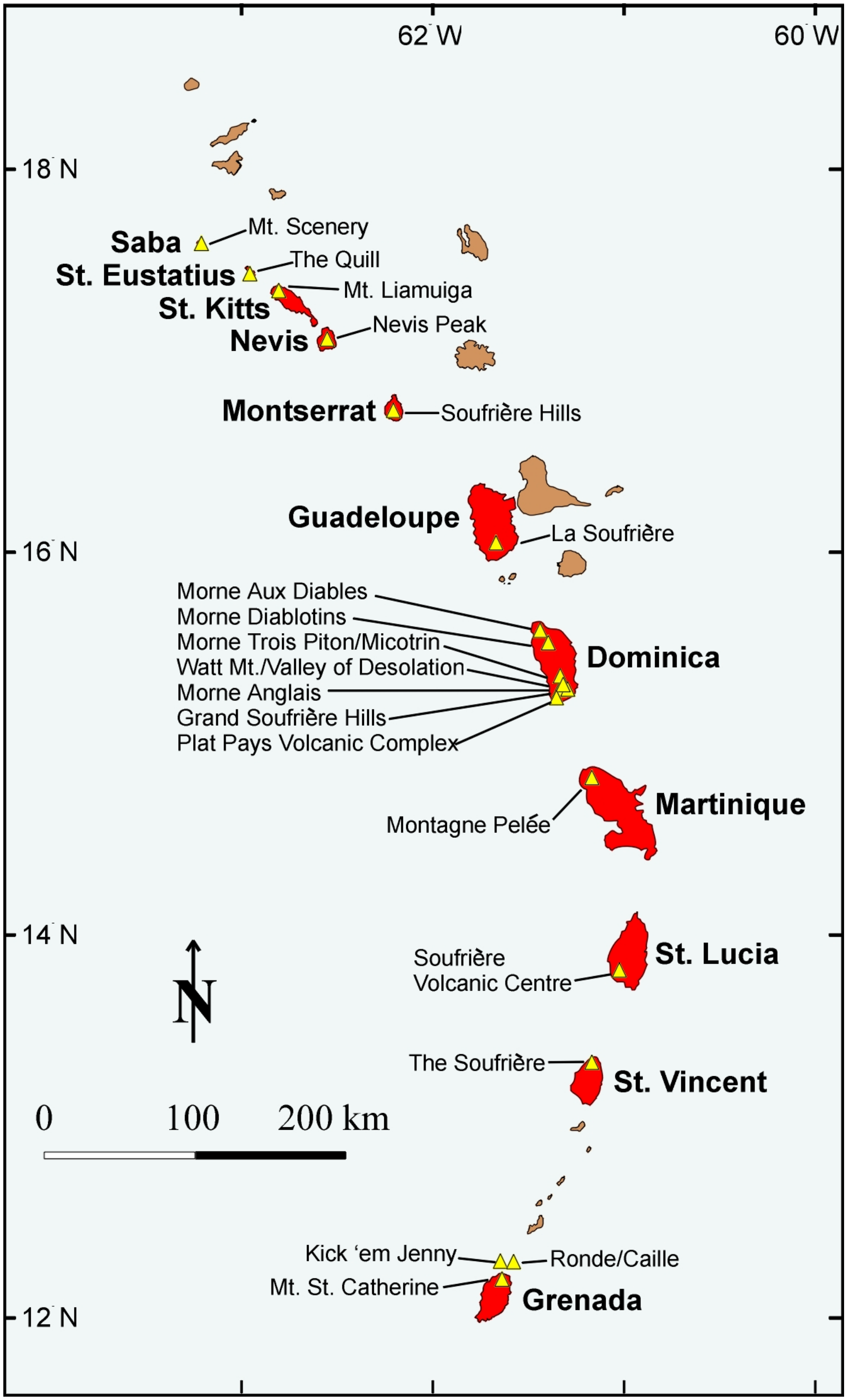


Figure 1: Distribution of the islands of the Lesser Antilles. The islands of the 'Volcanic Caribbees' are shown in red and the islands of the 'Limestone Caribbees' are shown in brown. The locations of the 19 active or potentially active volcanoes are indicated by yellow triangles.

North of Dominica the arc is split into two. The islands of the eastern arc (shown in brown on Figure 1) are made up of old (50-20 million year old) eroded volcanoes overlain by limestone and are often referred to as the 'Limestone Caribbees'. The islands of the western arc (shown in red on Figure 1) consist almost entirely of younger (< 2 million year old) volcanic rocks and are often referred to as the 'Volcanic Caribbees'. The reason for the double arc in this area is that subduction geometry has changed over time causing the axis of volcanism to move westward. The volcanoes that make up the foundations of the 'Limestone Caribbees' are considered 'dead', i.e. no longer have the ability to erupt again. South of Dominica the axis of volcanism has stayed in more or less the same place over the last 50 million years, and so the islands contain components of both the northern arcs, i.e. old volcanic rocks overlain in places by limestone, and a covering of young (Pleistocene) volcanic rocks.

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).

GEOGRAPHICAL SETTING

The island of Saint Lucia has an area of approximately 610 km^2. It has a youthful topography, being rugged and mountainous with narrow valleys. Only in the southeast corner is there a small coastal plain. The most pronounced topographic feature is the axial range extending centrally down the length of the island. The highest mountain, Mount Gimie (950 m), is located in the southwestern part of the range. On both the eastern and western sides of the axial range, heavily forested ridges descend to the coast, some interrupted by spectacular isolated pitons (cone shaped pinnacles of solid lava from residual volcanic plugs). The northern part of the island has smaller more rounded hills and gentler valleys and is the oldest part of the island. The extreme southwestern part of the island is characterised by fan-shaped slopes that dip gently seaward and are cut by narrow and deep river valleys. Saint Lucia has a population of about 163,267, with a large number (64,344) living in the capital city, Castries (2001 census).

PREVIOUS WORK

Previous studies on the geology of Saint Lucia all recognised that the youngest volcanoes lie in the southwest, near the town of Soufrière. Numerous studies have been carried out in this area, both on the volcanic geology and on the geothermal system at Sulphur Springs (all previous work is listed in the bibliography). Despite these studies, there is considerable confusion amongst the public of Saint Lucia as to the nature and actual location of the 'volcano' at Soufrière, and opinions are even divided in the scientific literature. Below an attempt is made to explain how the ideas on volcanism in southwest Saint Lucia have evolved over the years.

The most detailed and comprehensive geological study of the Soufrière area was carried out by Tomblin (1964). He interpreted the cirque-shaped depression in this area as a caldera that formed more than 40,000 years ago at the end of a period of extremely violent volcanic activity (Tomblin 1964, 1965; Robson and Tomblin 1966; Westercamp and Tomblin 1979). Figure 2(a) shows Tomblin's (1965) interpretation of the Soufrière depression. Tomblin and coworkers defined calderas as 'large volcanic depressions, more or less circular or cirque-like in form, the diameters of which are many times greater than those of the included vent or vents, no matter what the steepness of the walls or form of the floor'. Their interpretation of the Soufrière depression as a caldera was based on several lines of evidence:

1. the depression has a distinct cirque-like, steep-walled topography,
2. the depression is partially infilled by younger lava domes and craters, and
3. the landscape surrounding the depression is coated by a great thickness of pyroclastic deposits, estimated by Tomblin (1964) to be about 40,000 years old, which could have been produced during a caldera-forming event.

Studies carried out in the early 1980s led to a redefinition of the Qualibou depression based primarily on new age dates. Basalts at Malgretoute and Jalousie located within the depression south of the town of Soufrière were dated as being 5 - 6 million years old (Table 1). The nearby Gros and Petit Piton, also located within the structure, were dated at 230 - 290 thousand and 260 thousand years, respectively. These dates constrain the age of the depression. The 5-6 Ma old basalts are associated with the arcuate ridge of Malgretoute which was interpreted by Roobol *et al.* (1983) as a block of material that slumped into the depression after its formation. This interpretation implies that the depression formed sometime after 5-6 million years ago. This provides an *upper* age constraint for the age of the depression. Alternatively, the basalts at Malgretoute and Jalousie may be in situ deposits that became exposed during formation of the depression, which is also consistent with formation of the depression after eruption of the lavas. The Pitons, on the other hand, lie undisturbed on the floor of the structure, which indicates the depression must have formed before them, i.e. earlier than 290 thousand years ago. This provides a *lower* age constraint for the age of the depression. The depression therefore formed sometime between 5-6 million and 290 thousand years ago.

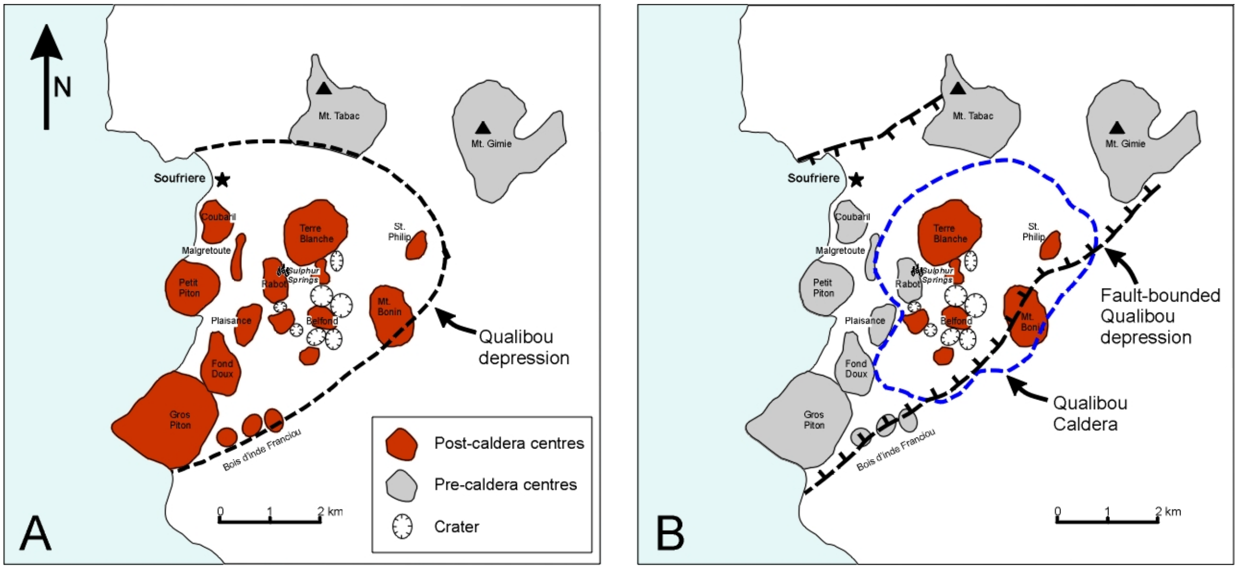


Figure 2: Contrasting interpretations of the Soufrière area by A) Tomblin (1964); and B) Wohletz *et al.* (1986). Tomblin (1964) believed the Qualibou depression formed by caldera collapse, whereas Wohletz et al (1986) believed only a portion of the depression is occupied by a caldera.

A recent study of the seafloor off Saint Lucia revealed a series of large-scale debris avalanche deposits off the southwestern coast of the island that may be related to the formation of the Qualibou depression (Deplus *et al.* 2001). An estimated age of <100–200 thousand years based on the thickness of overlying sediments was given for these deposits, which further constrains the age of the depression. This age estimate itself is probably too young, as it implies flank collapse *following* the formation of the Gros and Petit Pitons, which lie undisturbed on the floor of the depression. It does, however, suggest that the collapse probably occurred much closer to 290 thousand years ago than the upper age constraint of 5 – 6 million years. Based on this data, we estimate that the Qualibou depression formed about 300 thousand years ago. This categorically rules out early suggestions by Tomblin and co-workers that the depression formed by caldera collapse associated with the eruption of the thick sequence of pyroclastic rocks found surrounding the depression, as these were deposited much later, between 20 and 40 thousand years ago.

Based on age data obtained in the 1980s together with some new geologic mapping, Roobol *et al.* (1983) and Wright *et al.* (1984) reinterpreted the large, arcuate Soufrière depression as a head scarp of a rotational gravity slide. They believed the numerous pyroclastic flow deposits in southern Saint Lucia did not come from the Soufrière area at all, rather from small vents in the Central Highlands (e.g. Mt. Grand Magazine and Piton St. Esprit). They based this interpretation primarily on the distribution of the pyroclastic deposits which they describe as being radially oriented around the central highlands. This interpretation was supported by Mattioli *et al.* (1995), who concluded that digital elevation models of the onshore and offshore portions of the Qualibou depression were consistent with a sector collapse origin.

Extensive geothermal exploration drilling and geophysical surveys were carried out in the Soufrière region between 1974 and 1984, and these led Wohletz *et al.* (1986) to yet another interpretation of the depression. They did not dispute the interpretation of the large, Soufrière depression as some sort of structural depression, but they believed there was convincing structural and stratigraphic evidence that a little over half (about 12 km^2) of the area within the Soufrière depression is occupied by a caldera, which they termed the Qualibou caldera. They believed that the extensive pyroclastic deposits in southwest Saint Lucia were indeed sourced from the caldera during a series of violent eruptions between 20 and 40 thousand years ago, and not from the volcanoes in the Central Highlands as proposed by Wright *et al.* (1984). Their reinterpretation of the Soufrière depression is shown in Fig. 2(b).

In addition to the geologic studies related to the Qualibou depression, much work has been carried out over the past 20 years in the Sulphur Springs area for the purpose of evaluating its potential as a geothermal power source (e.g. Williams and Wright 1978; Aquater SpA 1982; LANL 1984; UNRFNRE 1989; Geothermica Italiana 1992; GENZL 1992). Most structural, hydrogeologic and geophysical data obtained by these workers are consistent with the Wohletz *et al.* (1986) model of a small caldera restricted to the central part of the Qualibou depression, although there are some inconsistencies (discussed in a separate section below). These geothermal investigations reached the following similar conclusions:

1. The Sulphur Springs is the surface manifestation of a high-temperature, sub-surface geothermal field with good energy-producing potential.

2. The geothermal field is related to young volcanic activity within the NE-SW trending Qualibou depression. Geophysical surveys have revealed a possible magma body beneath the Belfond/Terre Blanche area (Gandino *et al.* 1985) which probably represents the heat source for the Sulphur Springs geothermal field.

3. The Qualibou depression formed by a combination of down-faulting along NE-SW trending regional faults and possible caldera subsidence related to volcanic activity (note that the subsequent results of Deplus *et al.* 2001 show that there was probably also a major gravity slide component).

The only detailed volcanic hazard and risk assessment that existed for Saint Lucia prior to this study was carried out by Ephraim (2000). She identified the following two possible eruption scenarios for which she produced hazard maps: 1) a dome-forming eruption from within the Qualibou caldera; and 2) a dome-forming eruption from the central highlands near Mt. Gimie.

VOLCANIC CENTRES

Saint Lucia is made up almost entirely of volcanic rocks (Figure 3). 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 different volcanic centres in Saint Lucia into 3 broad groups based on age and geographic distribution, from oldest to youngest: the Northern, Central and Southern series. This subdivision is somewhat confusing, as several of the centres within the Northern Series are actually located in the south of the island. Furthermore, subsequent age dates obtained for the volcanic rocks of Saint Lucia show that several centres that were originally classed as part of the youngest Southern Series more likely correlate with the older centres of the Northern Series. We prefer to use a slightly revised version of the original subdivision, grouping the volcanic rocks of Saint Lucia as follows (Figure 3):

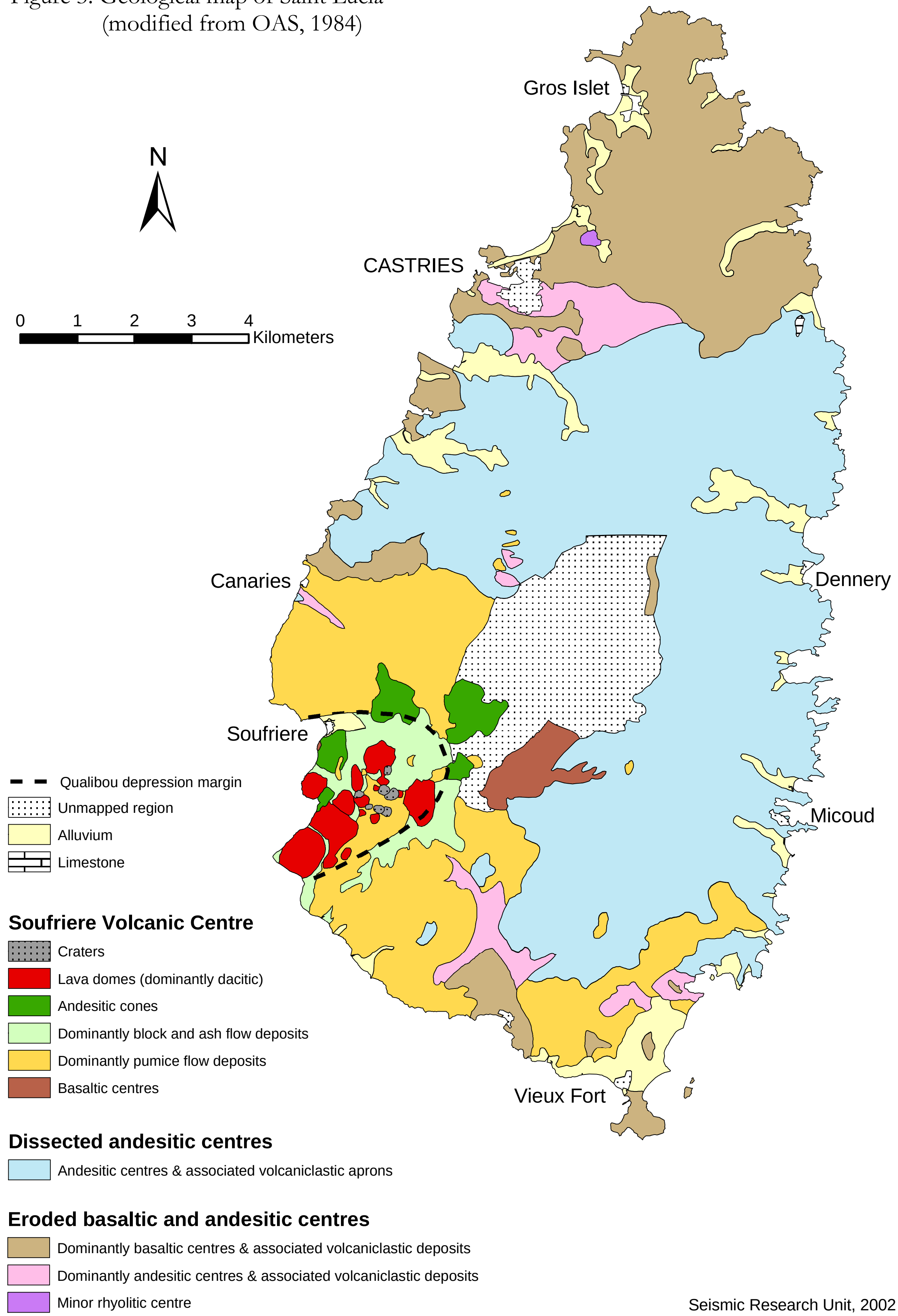
1) Eroded basalt and andesite centres (a revision of the 'Northern Series' of Newman, 1965)
2) Dissected andesite centres (called the 'Central Series' by Newman, 1965)
3) The Soufrière Volcanic Centre (a revision of the Southern Series of Newman, 1965)

All age determinations available for volcanic rocks on Saint Lucia are presented in Table 1.

Eroded Basalt and Andesite Centres

The eroded basalt and andesite centres are the oldest rocks on Saint Lucia. They crop out in the northern and southern-most parts of the island, and for this reason we have divided them into the *northern* and *southern* series. Rocks of similar age and composition probably underlie most of the younger rocks found elsewhere on Saint Lucia.

Figure 3: Geological map of Saint Lucia
(modified from OAS, 1984)



Northern Series

The centres in the north are characterised by highly deformed basaltic and andesitic lavas and pyroclastic deposits. The oldest of these represent the earliest volcanic activity in Saint Lucia. Based on comparisons with similar rocks in Martinique, Newman (1965) suggested that these oldest rocks, which were deposited in shallow sea water, are Eocene in age (i.e. 50 to 40 million years old), although no rocks from Saint Lucia this old have yet been dated. The oldest age obtained from basalts in this northern series is 18 Ma (Briden *et al.* 1979) and Le Guen de Kerneizon *et al.* (1983) obtained ages of between 15 and 5 Ma for the rocks of this series (Table 1). The youngest centres of the northern series are those of Mt. Pimard and Vigie, and have been dated at 5 - 6 million years old (Briden *et al.* 1979); a sample of lava from Mt. Monier also yielded an age of 5 Ma (Le Guen de Kerniezon *et al.*, 1983; Table 1). There are no known hot fumaroles in this area, although there is a relatively large (50 m x 30 m) area of warm spring activity and weak diffuse fumarolic activity in Ravine Raisinard on the south flank of Mount Monier. The temperatures of the springs in January 2001 were 30°C. Despite this weak geothermal activity, its old age and lack of seismicity suggests that northern Saint Lucia is unlikely to be the site of future volcanic activity.

Southern Series

There are numerous small basaltic andesite centres in the south of Saint Lucia, including Mt. Gomier, Morne Caillandre, Moule a Chique/Maria islands, Savannes, Beauséjour, St. Urbain and Mt. Tourney. Age dates for these centres range from 10.1 Ma (lava near De Mailly) to 5.2 Ma (lava from Savannes) (Table 1). These ages are consistent with the subdued topography of these centres which suggests an older age.

Two recent (1990 and 2000) shallow earthquake swarms were associated with these centres (these swarms are discussed in detail in the Hazard Assessment). There are no hot fumaroles associated with these centres. There are, however, 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 underwater gas vents at Black Bay to the west of Vieux Fort as well as a cold soufrière near the summit of Morne Caillandre, although these were not observed during our study. Some of these centres appear to aligned (e.g. Morne Caillandre – Beausejour - Mt. Tourney) forming semi-continuous elongate ridges, suggesting that there may be some structural control on their distribution. If this is the case then the presence of faults may explain the shallow seismicity and presence of cold fumaroles. The age of these centres suggests that they probably correlate with basaltic activity of the same age to the north, and are unlikely to erupt again. However, the shallow seismicity and cold fumarolic activity in this area suggests that they should be monitored closely for any signs of reactivation.

Dissected Andesite Centres

In the central part of the island and extending down the southeast coast are many andesitic lavas and volcaniclastic deposits that appear younger than the deformed basaltic rocks to the north, yet are dissected enough not to appear recent. These were referred to as the 'Central Series' by Newman. The rocks of this series were deposited following a period of increased sea level across the entire region of the Lesser Antilles that occurred approximately 25 million years ago. They form a series of heavily forested and largely inaccessible volcanic centres in the centre of the island including La Sorciere and Piton Flore to the north and the entire central highlands between Millet and Piton St. Esprit. Le Guen de Kerneizon *et al.* (1983) obtained 6 ages ranging from 10.4 Ma (lavas west of Dennery) to 2.8 Ma (lavas from Derriere Dos) for volcanic rocks in this group (Table 1).

The paucity of age dates for the andesite centres of central Saint Lucia make it difficult to say with certainty when they were last active. There are no known active fumaroles associated with these centres, although warm springs have been reported in the forest west of Dennery and in the Cul-de-Sac river. A large landslide on the northwest flank of La Sorciere has exposed an area of hydrothermally altered ground. This represents an area of fossil hydrothermal activity. Despite this evidence for past volcanic activity, the only age determination obtained from lava of La Sorciere (from Barre Coulon) yielded an old age of 8.9 Ma (Le Guen de Kerneizon *et al.*, 1983; Table 1). Further evidence of fossil hydrothermal activity in central Saint Lucia is indicated by two significant geochemical anomalies defined by elevated concentrations of As, Au, Sb, Se and Pb: one in the upper reaches of the Roseau, Grande Riviere du Mabouya and Troumassee river drainages and the other within the Ravine Souffre drainage near Marc Marc (Maassen and Bolivar, 1987).

The lack of active fumaroles associated with the dissected andesite centres together with their age and lack of seismicity suggest it is unlikely that they will erupt again, although more work is needed in this area to elucidate its volcanic history.

Table 1: Age determinations from volcanic rocks on Saint Lucia.

	Description	Location	Age ± error	Method	Ref.
Soufrière Volcanic Centre					
Historical activity					
	Phreatic blast	Sulphur Springs	1766 AD	historic reports	1
Young dacitic dome lavas					
	Belfond dome	Belfond	3.30 ± 0.24 Ma*	K-Ar	3
	Belfond dome	Etangs	5.30 ± 0.39 Ma*	K-Ar	3
	St. Phillip dacite(?) lava		no date	-	-
	Terre Blanche dome		no date	-	-
	Morne Bonin dome		0.91± 0.08 Ma*	K-Ar	3
Dacitic pyroclastic flow deposits					
Belfond Pumice deposit					
	'ash flow deposit'	Upper deposit, Saltibus	20,000 ± 1,120	C14	2
	'pumice flow deposit'	near Choiseul	20,980 500	C14	2
	'pumice flow deposit'	Anse Noir	22,380 ± 420	C14	2
	'pumice flow deposit'	near Choiseul	23,080 ± 280	C14	2
	pyroclastic flow deposit	east of Laborie, opposite Riverside bar	23,170 ± 180	C14	8
	pyroclastic flow deposit	north of Millet	24,210 ± 150	C14	8
	'ash flow deposit'	Durandeau-Millet	25,300 ± 700 24,900 ± 700	C14	2
Choiseul Tuff					
	'youngest Belfond dacite pumice flow'	Choiseul	39,050 ± 1500	C14	4
	'pumice flow'	south of Saltibus	>32,840	C14	2
	base of pyroclastic flow deposit	east end of Choiseul beach	34,500 ± 350	C14	8
	'ash flow deposit'	Lower deposit, Saltibus	34,200 ± 1670	C14	2
	'nappe' of dacite pumice	near Micoud	0.87 ± 0.07Ma*	K-Ar	3
Dacitic plugs and ridges					
	andesite domes	Fond Doux complex	no date	-	-
	dacite lavas similar to that of the pitons	Rabot, Plaisance and Malgretoute ridges	no date	-	-
	andesite domes	Bois d'inde Francou	no date	-	-

Table 1 continued:

dacite lava	Gros Piton	0.23 ± 0.1 Ma	K-Ar	5
dacite lava	Gros Piton	0.29 ± 0.1 Ma	K-Ar	5
dacite lava	NW flank of Petit Piton	0.26 ± 0.04 Ma	K-Ar	6
Andesitic stratovolcanoes				
andesite lava	Mt. Gimie	0.9 ± 0.8 Ma	K-Ar	5
andesite lava	Mt. Gimie	1.7 ± 0.2 Ma	K-Ar	7
andesite lava	near Migny (Gimie?)	3.3 ± 0.16 Ma	K-Ar	3
andesite lava	Mt. Tabac	no date	-	-
Basaltic lava				
aphyric basalt lava	Malgretoute	5.61 ± 0.25 Ma	K-Ar	6
basalt lava	Jalousie	6.1 ± 0.6 Ma	K-Ar	5
basalt lava	Jalousie	6.5 ± 0.6 Ma	K-Ar	5
Dissected Andesite Centers				
basalt lava	Anse Galet	2.02 ± 0.08	K-Ar	6
andesite lava	Derriere Dos	2.80 ± 0.14	K-Ar	3
andesite lava flow	Migny	3.13 ± 0.16	K-Ar	3
basaltic andesite lava flow	Dennery	5.52 ± 0.27	K-Ar	3
altered andesite pumice	Dennery	5.70 ± 0.28	K-Ar	3
basalt lava flow	Barre Coulon	8.87 ± 0.44	K-Ar	3
rhyolitic tuff	Dennery	10.40 ± 0.52	K-Ar	3
Eroded basalt & andesite centres				
Northern Series				
andesite lava flow	Mt. Monier	4.66 ± 0.23 Ma	K-Ar	3
andesite plug	Mt. Pimard	5.62 ± 0.21 Ma	K-Ar	6
andesite plug	Vigie	5.94 ± 0.23 Ma	K-Ar	6
basalt lava flow	Labrelotte Point	7.68 ± 0.57 Ma	K-Ar	3
andesite lava	Pigeon Island	8.28 ± 0.41 Ma	K-Ar	3
andesite sill	Pigeon Island	9.12 ± 0.46 Ma	K-Ar	3
basaltic block in tuff	Sth of Point Hardy	9.39 ± 0.55 Ma	K-Ar	6
basalt lava	Sth of Point Hardy	9.63 ± 0.56 Ma	K-Ar	6
basalt lava flow	Esperance Hb	9.68 ± 0.48 Ma	K-Ar	3
andesite lava flow	Careffe	9.90 ± 0.74 Ma	K-Ar	3
basalt dike	Mt. Jambe	10.00 ± 0.75 Ma	K-Ar	3

Table 1 continued:

	lava	Nth of Gros Islet	10.3 ± 0.6 Ma	K-Ar	6
	basalt dike	Esperance Hb	10.80 ± 0.54 Ma	K-Ar	3
	basalt intrusion	Anse Lavoutte	10.94 ± 0.82 Ma	K-Ar	3
	submarine basalt lava flow	Pt. Hardy	11.30 ± 0.84 Ma	K-Ar	3
	basalt intrusion	Anse Galet	11.40 ± 0.85 Ma	K-Ar	3
	basalt dike	Cap Point	15.01 ± 0.75 Ma	K-Ar	3
	hornblende andesite in conglomerate	Cap Point	18.3 ± 0.9 Ma	K-Ar	6
Southern Series					
	basalt centre	Morne Caillandre	no date	-	-
	basalt lava	Savannes	5.21 ± 0.15 Ma	K-Ar	6
	andesite lava flow	Laborie (Gomier?)	7.10 ± 0.36 Ma	K-Ar	3
	andesite dome	Beausejour	7.30 ± 0.36 Ma	K-Ar	3
	andesite dike	Moule a Chique	8.15 ± 0.40 Ma	K-Ar	3
	andesite dome	St. Urbain	8.66 ± 0.43 Ma	K-Ar	3
	andesite lava flow	de Mailly	10.12 ± 0.50	K-Ar	3

Age is given in 'years before present' unless otherwise stated. Ma = million years. References: 1= Lefort de Latour (1787); 2= Wright *et al.* 1984; 3= Le Guen de Kerneizon *et al.* (1983); 4= Tomblin (1964); 5= Aquater SpA (1982); 6= Bridon *et al.* (1979); 7= Westercamp and Tomblin (1979); 8= this study. Major centres/units that are as yet undated are also included in the table in their estimated stratigraphic position. *age may be wrong due to excess Ar.

The Soufrière Volcanic Centre

The Soufrière Volcanic Centre is the focus of the most recent volcanic activity in Saint Lucia. It comprises a series of volcanic vents and a vigorous high-temperature geothermal field and is associated with the Qualibou depression, a large arcuate structure that formed in southwest Saint Lucia about 300 thousand years ago as a result of a giant landslide or structural collapse (Figure 3). The various volcanic features of this center are discussed below.

Basaltic lava

The oldest dated rocks of the Soufrière Volcanic Centre are 5 – 6 million year old, weathered aphyric basaltic lavas exposed near the coast at Malgretoute and Jalousie (Table 1). This lava probably correlates with other ~5Ma basalts in Saint Lucia (e.g. Savannes in the south and Mt. Pimard and Vigie in the north) and may have become exposed following the removal of overlying volcanic debris during the formation of the Qualibou depression.

Andesitic stratovolcanoes

About 2 million years ago a major phase of volcanism led to the formation of Mt. Gimie and its neighbouring mountains. It is unlikely that each of these mountains represents a separate volcanic centre. It is more likely that Mt. Gimie, Mt. Tabac and Piton Canarie represent the remnants of one centre, and Piton St. Esprit and Grand Magazin the remnants of another. Alternatively, all these mountains may represent the remnants of a single large stratovolcano. This stratovolcano(es) erupted many times to form thick accumulations of andesitic volcaniclastic deposits in the southwestern part of the island (the 'caldera wall andesite agglomerate' and 'vulcanian andesite agglomerate' of Tomblin, 1964). These deposits are particularly well exposed around Colombette, where a stack of at least 30 different block and ash flow deposits indicates a long history of summit dome growth and collapse. Very few dates are available for this phase of activity. Those that are available range from 3 million years (an andesitic lava from near Migny; Le Guen de Kerneizon *et al.* 1983) to 1 million years (an andesite lava from Mt. Gimie; Aquater SpA, 1982) (Table 1). Block and ash flow deposits from these centres are truncated at the northern margin of the Qualibou Depression, indicating that these centres were active prior to the formation of the depression.

Dacitic plugs and ridges

There are numerous predominantly dacitic dome-remnants and ridges located within the Qualibou depression but outside the proposed caldera. These centres represent a period of volcanic activity that occurred after the formation of the depression yet before the major period of explosive volcanic activity that led to the deposition of the Choiseul and Belfond pyroclastic flow deposits.

The spectacular Gros and Petit Piton are the remnants of two large dacitic lava domes that formed about 200 – 300 thousand years ago (Table 1). More specifically, they represent the steep inner core of two lava domes after almost all the loose rubbly material that normally aprons lava domes (dome talus) has been removed by efficient erosion due to the wind and the sea. The Pitons lie undisturbed on the floor of the Qualibou depression, which indicates the depression must have formed before them, i.e. earlier than ~ 300 thousand years ago. The Malgretoute and Plaisance ridges are made up of similar lava to the Pitons (Wohletz *et al.* 1983), and have been interpreted by Roobol *et al.* (1983) as slump blocks that slided into the Qualibou depression after its formation. Wohletz *et al.* (1986) noted that Belfond tephra completely blankets Rabot ridge, making it difficult to ascertain the nature of the underlying block, although they conclude it probably also comprises similar lava to the Pitons. Wohletz *et al.* (1986) suggested that the

Malgretoute, Rabot and Plaisance ridges are domes that were truncated to develop their ridge shape by faults during the formation of the Qualibou Caldera (see below).

The Coubaril ridge between Soufrière and Plaisance was interperted by Tomblin (1964) as an andesitic cone remnant, contemporaneous with Mt. Gimie and Mt. Tabac. Wohletz *et al.* (1986) found the ridge to be primarily composed of highly altered dacitic lavas and breccias. It is possible that this ridge represents remnants of the larger Gimie/Tabac stratovolcano, however its location within the depression is more consistent with it being dome-related material deposited after the formation of the Qualibou depression. An alternative explanation for the Coubaril ridge was recently proposed by Boudon *et al.* (2002). They suggest that this ridge represents a 'megablock', i.e. a remnant of a debris avalanche deposit associated with the large sector collapse that formed the depression.

The Fond Doux ridge, located south of Plaisance, comprises predominanlty andesitic lavas (Tomblin, 1964). Wohletz *et al.* (1986) claim that Belfond tephra (pyroclastic flow and surge deposits) are present on the summit of the Fond Doux ridge. Very little else is known about this centre, other than it probably represents a lava dome similar in age but probably somewhat younger than the Pitons and related domes. To the south of Fond Doux lie the three domes of Bois d'inde Franciou. These domes are similar in composition to Fond Doux, and appear to have erupted along a NE-trending fault near the southern margin of the Qualibou depression.

Dacitic pyroclastic flow deposits

An extremely violent phase of volcanic activity occurred at the Soufrière Volcanic Centre between 40 and 20 thousand years ago when a series of major 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. It has been proposed that these extremely 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). 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 Magazin and Piton St. Esprit) (Roobol *et al.* 1983 and Wright *et al.* 1984).

The deposits that formed during these explosive eruptions have been divided into two main groups: the Choiseul and the Belfond pumice deposits (Wright *et al.* 1984). Each of these deposits is made up of a series of different units which probably represent different eruptions or phases of an eruption. The Choiseul pumice deposit is a crystal-poor non-welded pyroclastic flow deposit containing pumices that are compositionally low-silica dacites. It is named after its type locality at Choiseul, where it forms the thick cliffs at the beach and in road cuts. Only one age date was available for this deposit prior to this study, this was a radiocarbon age of 39,000 ± 1,500 years obtained by Tomblin (1964) (Table 1). The unit from which this date was obtained was described by Tomblin (1964) as the 'youngest Belfond dacite pumice flow' at Choiseul, but was later assumed to be the Choiseul pumice flow by subsequent workers (e.g. Wright *et al.* 1984).

One sample of charred remains from the base of the Choiseul pyroclastic flow deposit at Choiseul beach was analysed in this study, and yielded an age of 34,500 ± 350 years (Table 1). This suggests that at least some of the Choiseul eruptions occurred ~6,000 years more recently than previously thought. This age is within error of the age determined for the lower "Belfond" unit at Saltibus (34,200 ± 1670, Wright *et al.* 1984) indicating that this unit probably belongs to the Choiseul deposit (see Table 1).

The Belfond pumice deposit lies above the Choiseul pumice deposit. It is a crystal-rich, non-welded pyroclastic flow deposit with pumices that are compositionally high-silica dacites. This deposit was formed by a series of up to 10 pyroclastic flows that occurred between 25,000 and 20,000 years ago (Wright *et al.* 1984). These ages were confirmed in this study: two charcoal samples from previously undated outcrops of Belfond pyroclastic units yielded ages of 23,000 and 24,000 years (Table 1).

The nature of the Choiseul and Belfond pyroclastic flow deposits indicate a particular style of eruption. They were formed by large explosive eruptions that generated column-collapse pyroclastic flows. Such eruptions are particularly devastating, because the pyroclastic flows that are generated can travel out from the vent in all directions.

Young dacitic lava domes and explosion craters

After the phase of explosive activity that formed the Choiseul and Belfond pyroclastic deposits a series of lava domes (e.g. Terre Blanche, Belfond) and explosion craters (e.g. La Dauphine estate) formed near the centre of the proposed Qualibou caldera. Some minor dome-collapse pyroclastic flow deposits (block and ash flow deposits) are associated with the lava domes, indicating a history of dome growth and collapse. Thin deposits of pyroclastic material surround the explosion craters, and these probably formed during minor short-lived, explosive events. Field relations indicate that the explosion craters are younger than the adjacent Belfond lava dome. Two K-Ar ages of samples from the southern part of the Belfond dome yield stratigraphically inconsistent old ages: 5.3 and 3.3 Ma (Le Guen de Kerneizon *et al.* 1983; Table 1). Wohletz *et al.* (1986) suggest a syn- or post-crystallisation enhancement in magmatic Ar to explain these old ages. Unfortunately no other dates are available from these domes or craters and it is therefore impossible to say with certainty when the last magmatic eruption occurred in Saint Lucia.

The presence of these 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.

Is there a caldera in Saint Lucia?

Wohletz *et al.* (1986) proposed that the Belfond and Choiseul pyroclastic flow deposits were sourced from a caldera within the Qualibou depression (Figure 2b). 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 Magazin and Piton St. Esprit) (Roobol *et al.* 1983 and Wright *et al.* 1984). In our study we could find no unequivocal evidence for a caldera in Saint Lucia. We also could not find unequivocal evidence that the Belfond and Choiseul pyroclastic deposits were sourced from within the Central Highlands. Despite this lack of conclusive data, we feel it is worthwhile to discuss this issue here in some detail.

Wohletz *et al.* (1986) proposed that intermittent, explosive eruption of 6 km^3 (dense rock equivalent) of andesitic tephra (the Choiseul pumice) led to the collapse of a semi-circular feature referred to as the Qualibou caldera between 32,000 and 39,000 years ago. The location of the proposed caldera is shown in Figure 2b. They also proposed that magmatic resurgence following caldera collapse led to the subsequent eruption of the Belfond pumice flows leading to further collapse of the caldera. There are numerous problems with this interpretation, these are itemised below.

1. Wohletz *et al.* (1986) estimated a volume for caldera collapse of 5 – 10 km^3 which they say is accounted for by the 6 km^3 of Choiseul pumice. In order to calculate the latter figure, however,

they included the 'vulcanian andesite agglomerate' of Tomblin (1964) which they believed to be part of the Choiseul pumice but which actually represents a series of block and ash flow deposits originating from Morne Gimie and Tabac. It is unclear whether or not Wohletz *et al.* (1986) included the proposed 'intracaldera fill' in their volume estimate. Point 2 below shows that there is, in fact, no evidence for 'intracaldera' fill, so if it was in fact included in the volume estimate it would also lead to erroneously high values. The volume of the Choiseul pumice remaining after the removal of the 'vulcanian andesitic agglomerate' and the 'intracaldera fill' must therefore be much smaller than that estimated by Wohletz *et al.* (1986).

2. When a caldera forms, some of the material ejected into the air is deposited outside the caldera to form what is called an 'outflow' deposit. It has been estimated that at least half and sometimes more of the erupted material collapses back into the caldera to form a thick pile of intracaldera deposits as the caldera subsides. These intracaldera deposits have a distinctive character (they are usually indurated and welded), and in young calderas are usually not exposed unless there has been magma resurgence from below leading to an updoming of the intracaldera deposits. This means that 1) any non-indurated, non-welded, non-consolidated pyroclastic flow deposits located *within* a caldera must have flowed into the caldera from an outside source. They cannot represent the caldera-forming eruptions, and 2) bore-hole data from within a caldera should show a thick sequence of indurated and welded tuff that can be correlated with the outflow deposits. This has the following two implications for the Saint Lucia caldera discussion: 1) as non-indurated Belfond pyroclastic flow deposits outcrop in several places *within* the proposed caldera these cannot have formed during caldera collapse, rather must have flowed into the caldera after its formation, and 2) borehole data from within the proposed caldera do not reveal a thick sequence of welded tuff. The hole drilled by Merz and McLellan (1977) near Terre Blanche penetrated dacite dome lava for the first 130 ft where a transition to 'piton-type dacite' occurred. This was tentatively identified down to ~1,300 ft. For the last 400 ft of this 1738 ft hole aphyric basalt was encountered. A hole drilled ~400 m northwest of Terre Blanche initially encountered Belfond ash deposits then 'caldera wall agglomerate'. The hole was abandoned at 390 feet in dark andesite similar to surface exposures on Coubaril and Mt. Gimie. Neither of these holes encountered any indurated or welded Belfond or Choiseul pyroclastic flow deposits. The two wells drilled by UNRFNRE (1989), SL-1 and SL-2, also did not encounter any pyroclastic deposits within the proposed caldera.

3. The northern and eastern walls of the Qualibou depression would have acted as a topographic barrier to some of the activity within the caldera, strengthening the argument that there should be a significant thickness of intra-caldera deposits.

4. A gravimetric survey carried out by Aquater SpA (1982) indicated the presence of a positive gravity anomaly beneath the proposed caldera. If the caldera was filled with pyroclastic material associated with the Choiseul eruption, then this should have resulted in a *negative* gravity anomaly.

5. Thick deposits of the Belfond pumice flow to the north of the Central Highlands (at Durandeau-Millet) also speak against a source from within the proposed caldera, as the Central Highlands would have acted as a considerable topographic barrier for any flow originating near the proposed caldera.

6. The caldera as proposed by Wohletz *et al.* (1986) only occupies a portion of the Qualibou depression. This implies that outflow deposits should outcrop in those areas that are outside the caldera yet still inside the depression (for example to the west of the caldera at Jalousie and around the Pitons). There are, however, no such deposits.

7. The Choiseul pumice does not represent one large caldera-forming eruption. Rather, it comprises a series of pyroclastic flow deposits that represent a series of eruptions. Most caldera-forming events produce a distinctive and correlatable deposit of considerable thickness.

Roobol *et al.* (1983) and Wright *et al.* (1984) propose that the Choiseul and Belfond pyroclastic deposits originated from an as yet unidentified vent (or vents) within the Central Highlands. They claim that this would better explain the radial distribution of these deposits about the central highlands. As with the caldera theory discussed above, there are several problems with this suggestion:

1. The only age dates available for the rocks of the Central Highlands (3 – 1 Ma; Table 1) suggest that these centers are much older than the Choiseul and Belfond deposits.

2. There are few outcrops of the Choiseul pumice to the north and east of the Central Highlands, i.e. in their topographic shadow. This suggests that either these deposits originated from the south of

the Central Highlands (for example in the Qualibou depression) or they originated from one of the western centres of the Central Highlands (e.g. Mt. Gimie or Mt. Grand Magazin).

3. If the pyroclastic flows originated from Mt. Gimie or Mt. Grand Magazin, then it would seem logical for these to have flowed into the low-lying Qualibou depression, yet there is not a single outcrop of the Choiseul pumice within the depression.

Clearly more work needs to be done in southern Saint Lucia to determine the source region of the Belfond and Choiseul pyroclastic flow deposits. This is beyond the scope of this study. For the purposes of hazard assessment the lack of consensus in the source of these deposits does not make a great deal of difference; both proposed source areas lie close together within the Soufrière Volcanic Centre, and should there be a similar eruption in the future, eruptions from either proposed vent area would affect a similar region.

VOLCANO MONITORING

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. The Seismic Research Unit of the University of the West Indies (UWI) is responsible for monitoring the volcanic activity in the islands of the English-speaking Caribbean. Seismic, ground deformation and geothermal monitoring techniques are all employed. The monitoring network in Saint Lucia is presented in Figure 4, and each technique is discussed in detail below.

SEISMICITY

Volcanic eruptions are usually preceded by recognizable symptoms, such as 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. Prior to 2001, the seismic network in Saint Lucia comprised 4 stations which transmitted their signals by UHF radio to the St. Vincent Volcano Observatory in Belmont, St. Vincent, where they were recorded on a computer connected via internet to the Seismic Research Unit computers in Trinidad. In early 2001 the seismic network in Saint Lucia was upgraded, and now comprises 7 stations, including a complete seismograph network base-station at Moule-a-Chique (Figure 5).

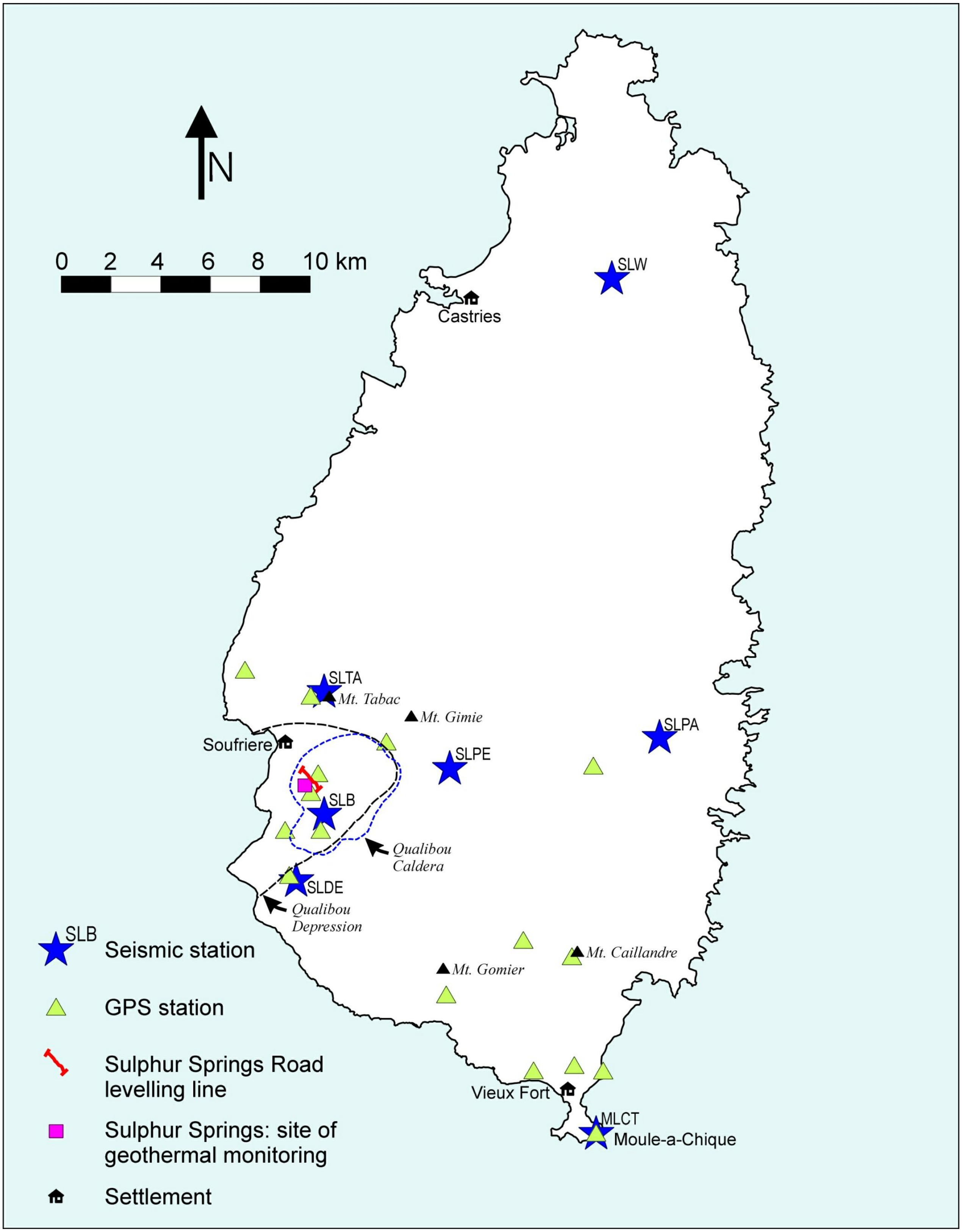


Figure 4: Volcano monitoring network in St Lucia. The base stations for both seismic and GPS sub networks are located at Moule-a-Chique.

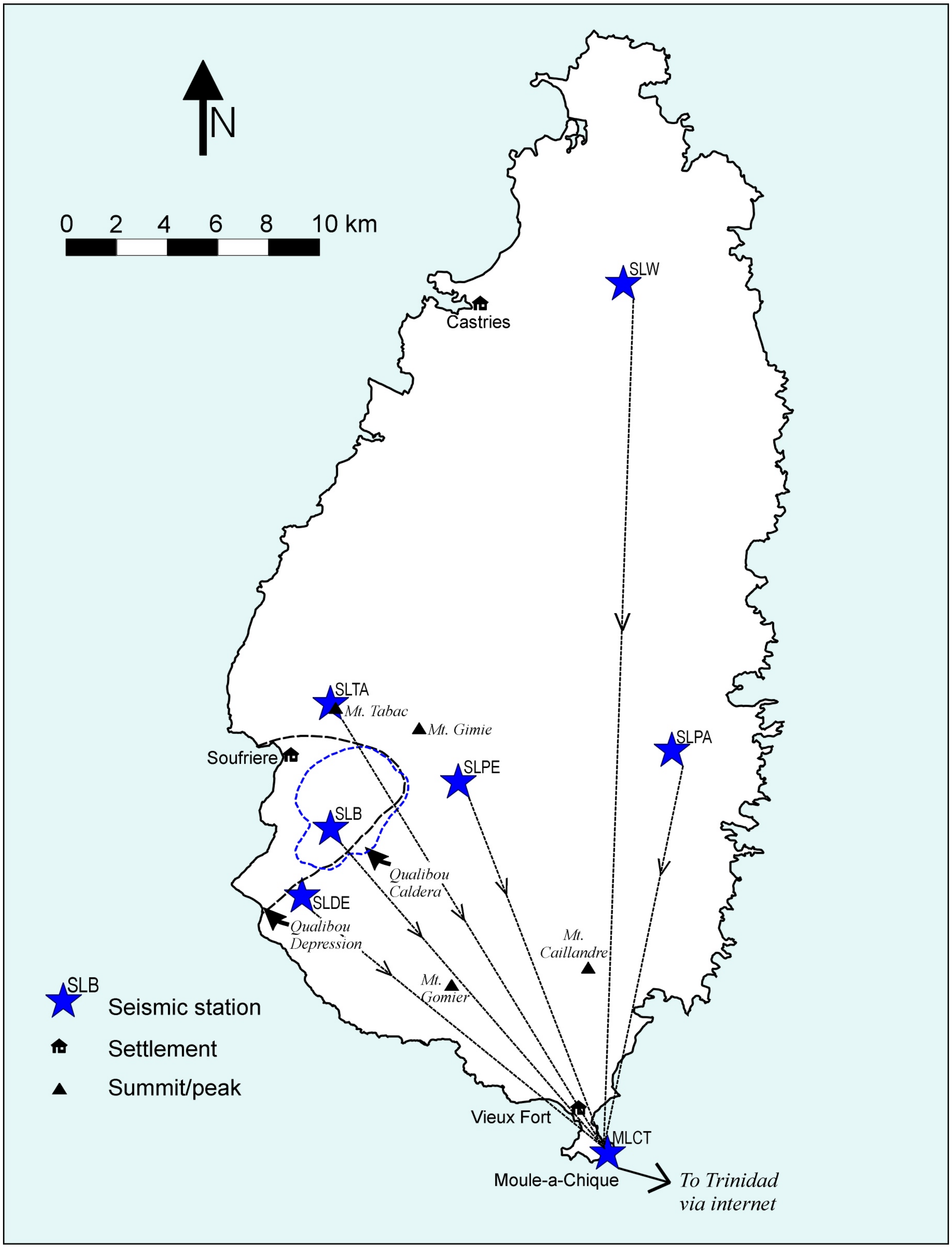


Figure 5: Seismograph network in St Lucia. The network base station is located at Moule-a-Chique.

Seismograph Network Upgrade

The upgrade of the seismograph network was carried out in early 2001. In the first stage a new computer-equipped seismograph base station was added at Moule-a-Chique lighthouse. This station is equipped with a state-of-the art three-component broadband seismometer recording digitally on a local computer. The computer records data from nine channels of seismograph data (seven vertical and two horizontal components). Timing is provided by a GPS satellite receiver which records time with an absolute accuracy of better than one tenth of a microsecond. The computer automatically transmits data to Trinidad twice daily through an internet link and data can be retrieved on demand through the telephone system (Figure 5). If an emergency arises the station can be manned continuously and data examined in real time.

In addition to this, the existing single-component short-period stations at Belfond (SLB), Delcer (SLD) and Petit Monier (SLW) which previously transmitted their signals by UHF radio to the St. Vincent volcano observatory were re-equipped and the signals were re-directed to Moule-a-Chique. New single component stations were added at Patience (SLPA), Morne Tabac (SLTA) and Piton St. Esprit (SLPE). The characteristics of the base station as well as the short period stations are shown in Table 2.

Table 2: Characteristics of Moule-a-Chique base station (MLCT) and the short period stations.

	Moule-a-Chique base station	**Short period stations**
Seismometer	Guralp CMG 40-T (3 components)	Mark Products L4C (Single vertical component)
Pass Band (-3db points)	0.033 – 50 Hz	0.5 – 30 Hz
Recorder	PC	PC
Sampling rate	100 s/s	100 s/s
Digitization	16 bits	16 bits
Gain ranges	1x and 100x	100x
Maximum dynamic range	96 + 40 = 136db	96 db (but limited to about 40db by analogue telemetry)
Timing	From GPS satellite	From GPS satellite

Since the seismograph network in Saint Lucia has been upgraded it has had the capacity to provide accurate locations for any earthquakes down to about magnitude 1.0 which happen anywhere within or close to the island.

GROUND DEFORMATION

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 (Figure 4). 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.

Global Positioning System (GPS) stations.

The main component of the ground deformation network in Saint Lucia is the GPS network in the southern part of the island. The GPS network is based on a constellation of earth satellites maintained by the United States Department of Defense primarily for military purposes. It provides a means whereby the position of points on the surface of the Earth can be determined to a high degree of accuracy. With the equipment used in Saint Lucia the position of points can be determined to an accuracy of about five millimeters (5 mm) in lateral position and one centimeter (1 cm) in height. GPS stations are extremely simple; they consist of nothing more than metal (usually stainless steel) pins firmly fixed into the ground. The best GPS sites are on solid rock with a clear view to the open sky. We have used three types in Saint Lucia:

(i) Existing survey points established by other agencies. We used four of these. Three (TLPL A, TLPL B and TLPL C) were established by the United States Geodetic Survey at Hewanorra airport (Vieux-Fort) and last occupied in 1997. These points consist of standard US Geodetic Survey Markers set in concrete monuments. The fourth is a standard surveying marker at Moule-a-Chique lighthouse. We occupied these points by setting up a standard surveying tripod at a known height above the point and mounting a Leica System 500 geodetic GPS receiver directly above the point.

(ii) Points similar to the above but established by us.

(iii) Points established by us to which the GPS receivers could be attached directly.

Installation of the GPS network

Two different regions were selected for detailed survey: 1) the Qualibou depression and 2) the zone of the 1990 and 2000 seismic swarms. A sub-network was installed for each region, one in the Southwest with 8 stations, and one in the Southeast with 4 stations (Figure 4).

In the first stage a reference GPS station for use in the entire network was established using the DOS point at Moule-a-Chique lighthouse. In order to obtain the exact coordinates of this site we made measurements to the three principal stations installed in 1996 by the United States Geological Survey National Geodetic Survey (USGS_NGS) at the Hewanorra International Airport in Vieux-Fort. After the reference point was installed, the two sub-networks were established.

Methodology

The duration of observations for the network depended on the distances involved between the points. The critical distance in GPS is 20 km. This means that when the distance between points is less than 20 km, the geometry of the satellite configuration above the two points being measured is not sufficiently different. In order to obtain a position we need to register a sufficient quantity of data. The **rapid-static** operating mode was used during the campaign. The time required to obtain a position is related to the distance between 2 points in the following manner:

Time of occupation = (5-10 min[1] + 1-2 min) x (distance between the points)

Past experience of such measurements led us to increase the time deduced from the equation above for the Saint Lucia campaign in order to improve on the quality of data. Typically we used a duration of observations of 30 min for baselines <10 km and 1 hour for baselines between 10 and 20 km, except in a few special cases where we encountered logistical problems. In rapid-static, we used an observation rate of one second. This gives the largest quantity of data possible and is compatible with the storage capacity of the PC-Cards used (4 and 10 MB).

[1] The lower figure (i.e. 5 min & 1 min) is for the occupations done during the night or during periods of low ionospheric activity. The higher figure is for day and high ionospheric activity measurements. During the campaign the second case applied since all measurements were done during the day

When the distance between points is larger than 20 km, the geometry of the satellite configuration above the 2 points is sufficiently different. It is therefore necessary to make the measurements over a certain time period to obtain this geometry. For distances between 20 and 30 km, the duration of the observation is commonly 2 hours and the observation rate between 10 and 30 seconds. In St Lucia, we did not follow this rule, even if some distances were close to the 20 km limit.

The equipment used for the campaign consisted of 3, Type 530, Leica GPS receivers. Processing of the data was done with the Leica SKIPro v1.1 software, using broadcast ephemeris. We obtained accuracy in the measurements of better than 10 mm in the horizontal and 20 mm in the vertical direction. The good accuracy of the measurements is linked to the good redundancy of the measurements and the good geometry of the network. Full details of the GPS network including the coordinates and location of the stations used are presented in Appendix 1.

Levelling

The second component of the ground deformation network in St Lucia comprises a levelling network inside the Qualibou depression. Established close to the Sulphur Springs geothermal field, this network will enable determination of any vertical displacement associated with volcanic activity. Twenty-three pins were used in a levelling profile along the road to the Sulphur Springs. The pins were installed either on the shoulders of the road or on the road itself.

The measurements were done with a Leica NA3003 level and two 2-meter Leica invar staffs. No additional processing of the data was required since the instrument provides the results directly in the field. The results of the levelling measurements as well as a summary of the station locations are contained in Appendix 2.

Distance Measurements

A further objective of the ground deformation campaign was to compliment the GPS results with distance measurements wherever this was possible. In the Southeast, the lighthouse point was used as the main station. Three GPS stations were measured: TLPL B, TLPL C and CAI1. The other points were too distant or invisible to make measurements. Some distance measurements were also made at the Sulphur Springs. A specific EDM point was installed and the distances between this point and 5 of the levelling benchmarks were measured. The measurements were made using a Leica distancemeter DI3000S and a Leica reflector GPR1. The results are presented in Appendix 3.

GEOTHERMAL ACTIVITY

Volcanic Gas Chemistry

Although there is almost no *direct* interaction between a magma chamber and an overlying geothermal field, 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. For this reason it is useful to monitor gas and hot-spring activity in geothermal areas associated with volcanoes.

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. Since April 2001 the Seismic Research Unit has been involved in a collaborate effort with Dr. Tobias Fischer of the University of New Mexico to collect and analyse gas and water samples from Sulphur Springs. The aim of the initial phase of this work is to establish baseline data for a volcanic gas monitoring programme. The first campaign to sample the features of Sulphur Springs took place in April 2001. A map showing the locations of the features sampled is shown in Figure 6 and some characteristics of these features are given in Table 3.

Analyses of gases collected in April 2001 are presented in Appendix 4. These first results indicate that the Sulphur Springs gases are quite typical for subduction-related geothermal fields. Despite considerable differences in temperature (see Table 3), the four gas samples analysed have similar chemical characteristics, and any future deviations from this composition will be immediately obvious. The next sampling trip is planned for October 2002 and the data collected then will allow us to make the first comparisons between samples collected during the wet season and those collected during the dry season. Recent analyses of samples from the Valley of Desolation in Dominica show that there is a considerable compositional difference between the wet and dry seasons. One major implication of this compositional difference is that the probability of phreatic eruptions increases considerably in the wet season (Brown, 2002). Once we have more data from Saint Lucia it will be possible to see whether the same applies to Sulphur Springs.

There are also several areas of 'cold Soufrière' on Saint Lucia with minor fumaroles. In future visits to Saint Lucia we will attempt to sample these features for comparison with those of Sulphur Springs.

Table 3. Geothermal features of Sulphur Springs, Saint Lucia, sampled on 15th April 2001

Specific location	Feature	Temperature	pH	Sample (#)
Northern Valley area	Painted pool	84.9 °C	6	water
Sulphur Slope	Fracture fumarole	96.6 °C	5	gas (C8)
Southern Valley area	Dan's bubbling pool	83.9 °C	6	water
Southern Valley area	Dasheen Devil fumarole	137.6 °C	7	gas (C2)
Gabriel's crater area	Fizzy pool	70.0 °C	6.5	gas (C11), water
Calalloo Creek	Small green gasser	93.3 °C	7	gas (C3), water
Gabriel's crater area	Lake Placid	77 °C	7	water

Physical Characteristics of Geothermal Features

The fumaroles and hot springs of Sulphur Springs should also be monitored for changes in character and location. Often such changes simply represent local adjustments in the geothermal system, but occasionally can reflect changes in the magma chamber below. Any significant changes in the Sulphur Springs geothermal system should be reported to the National Emergency Management Organisation (NEMO) and/or the Seismic Research Unit.

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 also used to be 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 and probably reflects local adjustments in the geothermal system. 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.

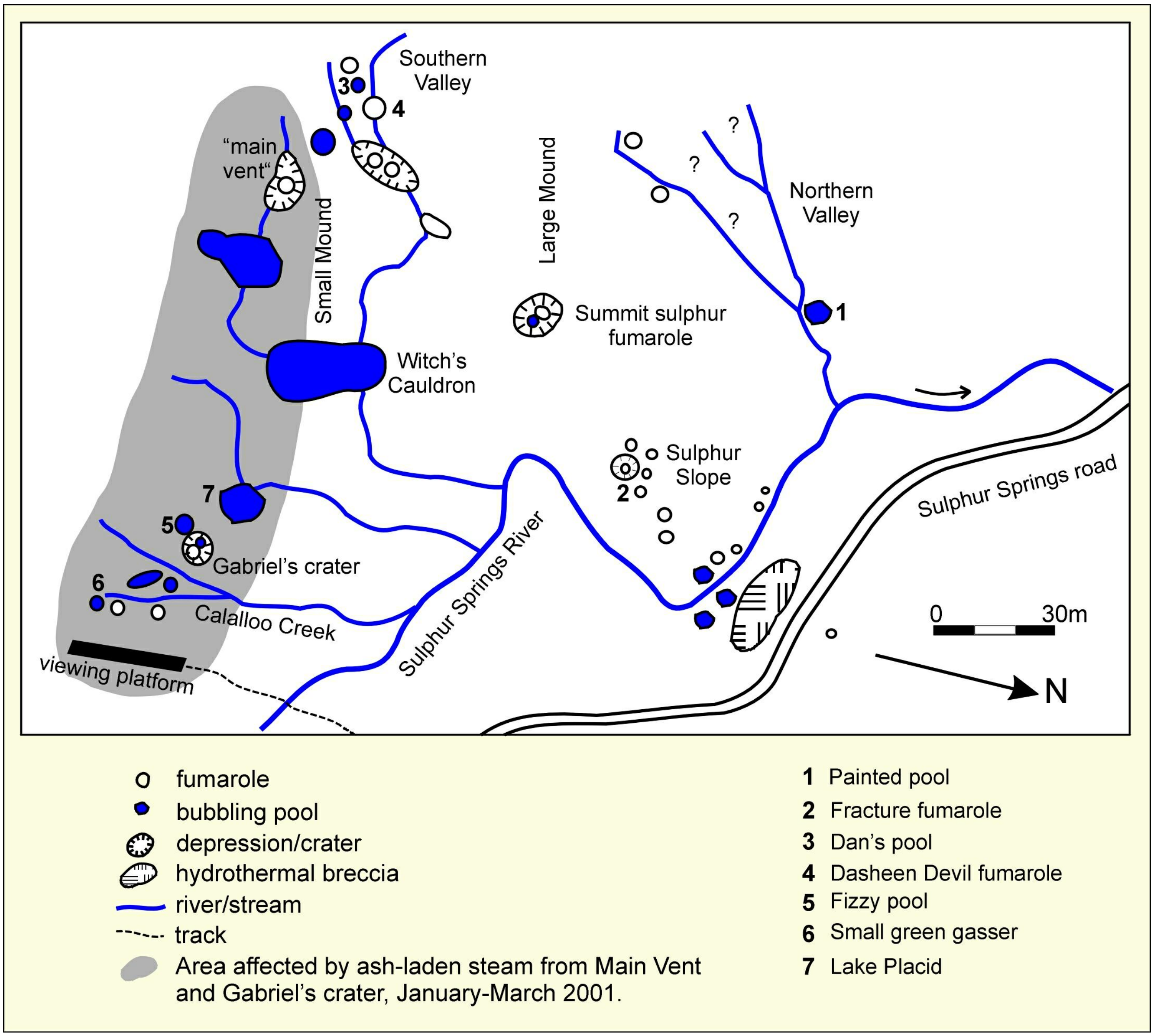


Figure 6: Map of Sulphur Springs geothermal field.

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 (Figure 6). The ash-like material ejected from Gabriel’s crater in January 2001 comprises mainly mud, old rock fragments, numerous wisps of organic material and the minerals quartz, feldspar and pyrite. It contains no juvenile (fresh magmatic) material, rather is typical of material found in regions of intense hydrothermal alteration of dacitic and rhyolitic rocks. 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. Large phreatic eruptions or a prolonged series of phreatic eruptions may herald the onset of an actual magmatic eruption, and should therefore be taken very seriously.

SUMMARY

This document presents the results of an intensive campaign carried out in early 2001 to upgrade the volcano monitoring network in Saint Lucia. It also provides a summary of previous work carried out on the geology of Saint Lucia, and describes in detail the various volcanic centres on the island. It is intended to be used in conjunction with the Volcanic Hazard Assessment for St Lucia prepared by Lindsay *et al.* (2002). Much of the scientific data upon which the Volcanic Hazard Assessment is based is contained in this scientific supplement.

Clearly more work needs to be done to elucidate the volcanic history of the Soufrière Volcanic Center, and future geological studies should focus on this area. The monitoring network in Saint Lucia is considered one of the best in the Lesser Antilles, and continued support should be given to monitoring efforts to ensure timely recognition of any precursory signs of volcanic activity. Staff of the Seismic Research Unit will continue to carry out campaigns, at regular intervals, to occupy the GPS and levelling stations and to sample geothermal features at Sulphur Springs.

BIBLIOGRAPHY

Aquater SpA (1982): Exploration of St. Lucia's Geothermal Resources, Annex A – Geological Survey. Unpublished general report to the Government of St. Lucia Ministry of Finance and Planning 40pp.

Aspinall W. P., Michael M.O., Tomblin J. F. (1976): Evidence for fluid bodies beneath the sulphur springs geothermal region, Saint Lucia, West Indies. Geophysical Research Letters 3(2): 87-90.

Aspinall W. P., Shepherd J.B, Woo G, Wightmann A., Rowley K.C., Lynch L.L. and Ambeh W.B. (1994): Seismic Ground Motion Hazard Assessment at a Site near a Segmented Subduction Zone: the Roseau Dam, Saint Lucia, West Indies. Earthquake Spectra 10(2): 259-292.

Battaglia S., Gianelli G., Rossi R. and Cavarretta G. (1991): The Sulphur Springs Geothermal field, St. Lucia, Lesser Antilles; hydrothermal mineralogy of wells SL-1 and SL-2. Journal of South American Earth Sciences 4 (1-2):1-12.

Boudon G., Le Friant A., Deplus C., Komorowski J-C. and Semet M.P. (2002): Volcano flanks of the Lesser Antilles arc collapse, sometimes repeatedly: how and why. International Colloquium 'Montagne Pelee 1902 – 2002. Explosive volcanism in subduction zones'. Saint Pierre, Martinique.

Briden J.C., Rex D.C., Faller A.M., Tomblin J.F. (1979): K-Ar geochronology and palaeomagnetism of volcanic rocks in the Lesser Antilles island arc. Philosophical Transactions of the Royal Society of London A291: 485-528.

Brown L.K. (2002): Geochemistry of the volcanic hydrothermal systems of Dominica and St. Lucia, Lesser Antilles: implications for volcanic monitoring. Unpublished undergraduate thesis; University of New Mexico.

Deplus C., Le Friant A., Boudon G., Komorowski J-C., Villemant B., Harford C., Ségoufin J and Cheminée J-L. (2001): Submarine evidence for large-scale debris avalanches in the Lesser Antilles Arc. Earth and Planetary Science Letters 192 : 145-157.

Earle K.W. (1923): The Geology of St. Lucia. The Government Printing Office, Castries, St Lucia

Ephraim J. (2000): A Hazard and Risk Appraisal of the Soufrière Volcano, St. Lucia. Unpublished Honours thesis, University of Bristol.

Gandino A., Piovesana F., Rossi R. and Zan L. (1985): Preliminary evaluation of Soufrière Geothermal Field, St. Lucia (Lesser Antilles): Geothermics 14(4): 577 - 590

GENZL (1992): St. Lucia Geothermal Project. Well-2 discharge testing, well safety evaluation and resources assessment. Unpublished report for St. Lucia Electricity Services Ltd. (LUCELEC)

GEOTHERMICA ITALIANA (1992): Exploration for geothermal resources in the Eastern Caribbean. United Nations – Dept. for Technical Cooperation and Development and CARICOM, final report, TCD CON 15/90 – RLA/87/037

Goff F. and Vuataz F. D. (1984): Hydrogeochemistry of the Qualibou Caldera geothermal system, St. Lucia, West Indies. Transactions - Geothermal Resources Council 8: 377-382.

Greenwood P.G. and Lee M.K. (1975): Geophysical Surveys in St. Lucia for geothermal resources. Applied Geophysical Unit, Institute of Geological Sciences Geophysics Division. London, 1-25.

Hovey E.O. (1904): Soufriere de Sainte Lucie. Bulletin of the Geological Society of America 16.

ITALIANA G. (1992): Exploration for geothermal resources in the Eastern Caribbean., United Nations - Department for Technical Cooperation and Development and CARICOM.

LANL (Los Alamos National Laboratory) (1984): Report of St. Lucia Geothermal Resources. Los Alamos Report LA – 10234-MS.

Lee M. K. and Greenwood P. G (1976): The Interpretation of Resistivity Surveys for Geothermal Resources in St. Lucia., Applied Geophysics Unit, Institute of Geological Sciences, Geophysical Division: 1-9.

Lefort de Latour (1787): Description génerale et particulière de L'Ile de Sainte Lucie.

Le-Guen de Kerneizon M., Carron J. P., Bellon H. and Maury R.C.. (1981): Enclaves metamorphiques et plutoniques, provenant du substratum des Petites Antilles, dans les formations volcaniques de I'ile de Sainte-Lucie. C.R. Acad. Sci., Paris 292 (2): 899-902.

Le-Guen de Kerneizon M., Carron J. P., Maury R.C., Bellon H., and Dupuy C. (1982): Les rhyolites a fayalite et ferroaugite de Sainte-Lucie (arc insulaire des Petites Antilles). Bull. Mineral. 105: 203-211.

Le-Guen de Kerneizon M., Bellon H., Carron J. P. and Maury R.C (1983): L'Ile de Sainte-Lucie (Petites Antilles); distinction des principales series magmatiques a partir des donnees petrochimiques et geochronologiques. Translated Title: "Saint Lucia (Lesser Antilles); distinction of principal magmatic series from petrochemical and geochronologic data." Bulletin de la Societe Geologique de France 25(6): 845-853.

Lindsay J., David J., Shepherd J. and Ephraim J. (2002): Volcanic Hazard Assessment for St. Lucia, Lesser Antilles. Unpublished report presented to the Government of St. Lucia, September 2002.

Maassen L.W. and Bolivar S.L. (1987): A geochemical Survey of St. Lucia, West Indies. Journal of Geochemical Exploration 28. p451-466.

Martin-Kaye P.H.A. (1956 – 1961): Progress reports 1-12 Geological Survey, Windward islands.

Martin-Kaye, P. H. A. (1959): Reports on the geology of the Leeward and British Virgin Islands: Castries, St. Lucia., Voice Publication Company Limited.

Mattioli G.S, Jansma P.E., Jaramillo L. and Smith A. (1995): Sector collapse in island arc volcanoes: a digital topographic and bathymetric investigation of the Qualibou Depression, St. Lucia, Lesser Antilles. Caribbean Journal of Science 31(3-4): 163-173.

Merz and Mclellan (1977): Report on exploration and drilling at Soufrière. Ministry of overseas development , London and government of St. Lucia 48pp.

Newman W.R. (1965): A Report on General and Economic Geological Studies St. Lucia, West Indies. United Nations report prepared for the Government of St. Lucia.

OAS (1984): St. Lucia Development Atlas.

Robson G.R and Tomblin J. F. (1966): Catalogue of the Active Volcanoes of the World; Part XX. West Indies.

Robson G.R. and Willmore P.L. (1955): Some heat measurements in West Indian soufrières. Bulletin of Volcanology: 13-39

Roobol M.J., Wright J.V., Smith A.L. (1983) Calderas or gravity-slide structures in the Lesser Antilles island arc? Journal of Volcanology and Geothermal Research 19: 121 – 134

Sapper K. (1903): Zur Kenntniss der Inseln St. Lucia, Montserrat, Nevis und St. Kitts. Zentralblatt für Mineralogie, Geologie und Palaeontologie. 273-278.

Tomblin J. (1964): The Volcanic History and Petrology of the Soufrière region, St. Lucia. Unpublished PhD thesis, University of Oxford. 213pp.

Tomblin J. (1965): The Geology of the Soufrière Volcanic Centre, St. Lucia. Fourth Caribbean Geological Conference, Trinidad.

Tomblin J. F. (1968): Field Trip Guide St. Lucia. Transactions of the Fourth Caribbean Geological Conference, 28th March-12th April 1965, Port-of-Spain, Trinidad & Tobago. J. B. Saunders. Port-of-Spain, Trinidad and Tobago, Queens College Press. Flushing, NY, United States: 451-455.

Tomblin J. F. (1968): The geology of the Soufrière volcanic centre, Saint Lucia. Caribbean Geological Conference, 4th, Port-of-Spain, Trinidad and Tobago, 1965, Transactions.: 367-376.

UNRFNRE (United Nations Revolving Fund for Natural Resources) (1989): St. Lucia geothermal exploration project, Final Report Volume II, Wells SL-1 and SL-2. Report STL/GT/84/001

Vidal P., Le-Guen de Kerneizon M., Maury R.C., Dupre B. and White W.M. (1991): Large role of sediments in the genesis of some Lesser Antilles andesites and dacites (Soufriere, St. Lucia); isotopic constraints. *Bulletin de la Societe Geologique de France.* 162 (6):993-1002.

Westercamp D. and Tomblin J.F. (1979): Le volcanisme récent et les éruptions historiques dans la partie centrale de l'arc insulaire des Petites Antilles. Bulletin du B.R.G.M. section 4, no. 3/4: 293-319.

Williamson K. (1979): A model for the Sulphur Springs Geothermal Field St. Lucia. Geothermics 8: 75-83.

Williamson K. and Wright E. (1978): St. Lucia geothermal project. Transactions of the Geothermal Resources Council 2: 731-733.

Wohletz K., Heiken G., Ander M., Goff F., Vuataz F-D. and Wadge G. (1986): The Qualibou Caldera, St. Lucia, West Indies. Journal of Volcanology and Geothermal Research 27: 77-115

Wright J.V., Roobol M.J., Smith A.L., Sparks R.S.J., Brazier S.A., Rose W.I. and Sigurdsson H. (1984): Late Quaternary explosive silicic volcanism on St Lucia, West Indies. Geological Magazine 121(1): 1-15.

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Appendix 1: GPS

Appendix 1.1 Summary of existing GPS points measured by international agencies:

University of Colorado (archived at the UNAVCO, 1994 campaign), NGS (1996 and 1997 campaigns) and CPACC (1998 campaign) networks.

Websites:
PI: Roger Bilham, University of Colorado, http://www.colorado.edu/;
UNAVCO, University NAVSTAR Consortium, www.unavco.ucar.edu/unavco.html;
NGS, National Geodetic Survey, www.ngs.noaa.gov;
CPACC, Caribbean: Planning for Adaptation to Climate Change, www.cpaccrac.org.

Name	Place	Latitude N Deg min sec	Longitude W Deg min sec	Ellipsoidal height (m) Tidal height (m)	Order H=Horizontal. V=Vertical, if any E=Ellipsoidal.
001A 1998	Castries, Marine Police Base	?	?	?	?
001B 1998	Castries, Marine Police Base	?	?	?	?
001C 1998	Castries, Marine Police Base	?	?	?	?
LUCI	?	14d 05’ 38.04”	60d 57’ 53.27”	87.00 ?	?
T 1	Vieux-Fort, port	13d 43’ 14.59552”	60d 57’ 11.22070”	-31.91 2.61	H=First V=Third? E=First, class I
TLPL A	Vieux-Fort, airport	13d 44’ 05.31872”	60d 56’ 59.32622”	-30.33 4.4	H=A E=First, class I
TLPL B	Vieux-Fort, airport	13d 43’ 58.35906”	60d 56’ 23.90239”	-32.38 2.4	H=First E=Fourth, class I
TLPL C	Vieux-Fort, airport	13d 43’ 58.59842”	60d 57, 55.75325”	-32.29 2.5	H=First E=Fourth, class I
DCS 33	Mons Fortune	13d 59’ 47.12265”	60d 59’ 34.77603”	224.54 259.59	H=First V=Third? E=First, class I
LS 61 G		14d 00’ 51.04600”	61d 00’ 24.56538”	-20.75 15.	H=First E=First, class I
TLPC A	Castries, airport	14d 01’ 12.86456”	60d 59’ 36.70994”	-32.65 2.8	H=A E=First, class I
TLPC B	Castries, airport	14d 01’ 18.57475”	60d 59’ 14.20712”	-32.79 2.6	H=First E=Fourth, class II
TLPC C	Castries, airport	14d 01’ 04.43771”	60d 59’ 58.60362”	-29.72 5.7	H=First E=Fourth, class II
DCS 31	Castries, Vigie Lighthouse	14d 01’ 20.51990”	61d 00’ 04.27060”	55.35 90.64	H=First V=Third? E=First, class I
DCS 28	Pointe du Cap	14d 06’ 22.21548”	60d 56’ 36.94488”	113.72 149.14	H=First V=Third? E=First, class I

Appendix 1.2: Historical record of GPS measurements on St Lucia

(M for measured, blank for no existing measurements)

Code	19-22 May 1994	Dec 1996- Jan 1997	7 Aug 1998	Feb-Mar 2001	Installation (year if known)
LUCI	M				
TLPC A		M			NGS (1996)
TLPC B		M			NGS (1996)
TLPC C		M			NGS (1996)
DCS 28		M			SLDS (1954)
DCS 31		M			SLDS (1954)
DCS 33		M			SLDS (1954)
LS 61 G		M			Paul Bolan, private surveyor (1994)
TLPL A		M		M	NGS (1996)
TLPL B		M		M	NGS (1996)
TLPL C		M		M	NGS (1996
T1		M			CGS (1949)
001A 1998			M		CPACC (1998)
001B 1998			M		CPACC (1998)
001C 1998			M		CPACC (1998)
LIG0				M	SLDS
CAI1				M	Seismic (2001)
MIC1				M	Seismic (2001)
GRA1				M	Seismic (2001)
BLA1				M	Seismic (2001)
DEL1				M	Seismic (2001)
BEL1				M	Seismic (2001)
FON1				M	Seismic (2001)
RAB1				M	Seismic (2001)
TER1				M	Seismic (2001)
COL1				M	Seismic (2001)
JIM1				M	Seismic (2001)
BOU1				M	Seismic (2001)

Appendix 1.3: Coordinates of the GPS benchmarks established during the Seismic Research Unit's campaign of February-March 2001.

Point Id	Latitude °’”	Longitude °’”	Ellipsoidal Height m
TLPL A	13°44’05.31871”N	60°56’59.32623” W	-30.3305
TLPL B	13°43’58.35877”N	60°56’23.90235” W	-32.3793
TLPL C	13°43’58.59841”N	60°57’55.75332” W	-32.2929
T1 (1996)	13°43’14.59552”N	60°57’11.22070” W	-31.91
LIG0	13°42’39.64970”N	60°56’30.13155” W	187.9251
MIC1	13°50’37.94480”N	60°56’35.39549” W	301.7457
CAI1	13°46’23.12407”N	60°57’04.94503” W	222.5884
GRA1	13°46’46.40670”N	60°58’06.90238” W	131.4780
BLA1	13°45’35.19943”N	60°59’49.94536” W	243.1553
BEL1	13°49’12.86819”N	61°03’19.66542” W	445.8053
DEL1	13°48’14.02685”N	61°03’15.81968” W	174.9672
FON1	13°49’42.68897”N	61°02’35.58158” W	417.9238
RAB1	13°50’03.94187”N	61°02’48.91110” W	297.1209
TER1	13°50’27.69086”N	61°02’37.52312” W	431.4669
COL1	13°52’10.25317”N	61°02’48.89439” W	355.3061
JIM1	13°51’09.38698”N	61°01’07.88146” W	572.0994
BOU1	13°52’46.29420”N	61°04’14.79766” W	193.1719

Appendix 1.4: Chronology of GPS measurements, February-March 2001.

Date, Day of the year,GPS week	Points measured	Personnel
9 February, 40, 11005	TLPL A – LIG0	Jerome David
12 February, 43, 11011	TLPL A – LIG0 TLPL C – LIG0 TLPL A – TLPL C	Jerome David Rhikkie Alexander
14 February, 45, 11013	LIG0 – CAI1 LIG0 – MIC1 CAI1 – MIC1	Jerome David Uche Osuji Rhikkie Alexander
15 February, 46, 11014	TLPL A – TLPL C TLPL A – TLPL B TLPL A – LIG0 TLPL B – LIG0 TLPL C – LIG0	Jerome David Uche Osuji Rhikkie Alexander
19 February, 50, 11021	LIG0 – CAI1 LIG0 – GRA1 LIG0 – BLA1 CAI1 – GRA1 CAI1 – BLA1	Jerome David Rhikkie Alexander
24 February, 55, 11026	LIG0 – CAI1 LIG0 – BLA1 LIG0 – BEL1 CAI1 – BEL1 BLA1 – BEL1	Jerome David Rhikkie Alexander
27 February, 58, 11032	LIG0 – BEL1 LIG0 – DEL1 LIG0 – FON1 LIG0 – RAB1 BEL1 – RAB1 BEL1 – FON1 BEL1 – DEL1	Jerome David Rhikkie Alexander
28 February, 59, 11033	LIG0 – BEL1 LIG0 – JIM1 BEL1 – JIM1	Jerome David Rhikkie Alexander
01 March, 60, 11034	LIG0 – BEL1 LIG0 – BOU1 LIG0 – COL1 BEL1 – BOU1 BEL1 – COL1	Jerome David Rhikkie Alexander
11 March, 70, 11050	LIG0 – BEL1 LIG0 – TER1 BEL1 – TER1	Jerome David Rhikkie Alexander Vincent Louis

Appendix 1.5: Pictures and descriptions of GPS station localities.

TLPL A: The point is located at the airport of Vieux-Fort. It is in the ground close to the control tower. Some small posts are protecting the zone. You need a tripod to measure the point.

TLPL B: This point located at the airport of Vieux-Fort, at the eastern end of the landing tarmac. It is on the ground and is protected by small posts. You need a tripod to measure this point.

TLPL C: The point is at the western end of the landing tarmac. Small posts protect it. You need a tripod to measure the point.

T1 (no photo): This point was installed by the US army in 1949 and measured by the NGS in 1996. The point is on the jetty of the port at Vieux-Fort. You need a special tripod to make the measurement because the point is on the edge of the jetty.

LIG0: The point is inside the property of the lighthouse of Moule a Chique, in Vieux-Fort. You need a tripod to measure it.

MIC1: This point is near to Micoud. On the main road from Vieux-Fort to Castries, you take the Des Cartiers trace, after Micoud. Drive for 2.5 miles on the trace and then take the 4th trace on the right at the place named Ti Riviere. Drive another 0.7 miles and take a right turn into a place called Despointes (a banana hangar). Continue along this trail for 0.2 miles. The point is on the left of the road, at the top of a small hill. If you continue, you will reach the hangar of M Descates. You need a 4-wheel vehicle to reach the point. A tripod is not needed to make the measurement.

CAI1: On the main road between Vieux-Fort and Castries, take the road on the left after the new stadium to Pierrot. Continue along this road until you reach the end. There is a trace on the right to go to the top of the hill (you should see the HOT FM mast). The reservoir is just at the beginning of the trail on the left. The point is at the top of the reservoir of water. A tripod is not needed to make the measurement.

GRA1: On the main road between Vieux-Fort and Castries, take the road on the left before the new stadium. Take the road on the right to Beausejour and Grace. Continue along this road until you reach the school. The point is on the car park of the health centre after the school on the right. You will need a tripod for this point.

BLA1: On the main road between Vieux-Fort and Soufrière, in Laborie, take the road on the right to Mount Monier. On this road, take the road on the left to Mount Le Blanc. The point is at the end of this road, before the ruins. It is at the base of a cement structure. You will need a tripod to make the measurement and a 4-wheel vehicle to reach the point.

BEL1: On the main road between Vieux-Fort and Soufrière (in the caldera), take the road on the left to the Fond Doux estate. Take the road on the left to Chateau Belair. Continue along this road until its abrupt end. There is a house on the right. You must enter to the right and go into their plantation to the top of the hill. The point is close to a reservoir of water. You do not need a tripod to make the measurement. You need a 4-wheel vehicle to reach the point.

DEL1: When you take the main road between Vieux-Fort and Soufrière (in the caldera), follow the trail of the Gros Piton. Continue past St Remy estate and cross the L'Ivrogne River. In Delcer, after the fish basins, and before the school, take the road on the left. This goes to a water tank where the seismic station SLD is located. Continue along this road for 200 m.. The point is on a rock to the right side of the road. You will need a tripod to make the measurement and a 4-wheel vehicle to reach the point.

FON1 (no photo): On the main road between Vieux-Fort and Soufrière (in the caldera), take the road on the right to Belfond. You will reach a large open area with a bar on the right. Continue straight on and on the right, just after the place, you should see 2 houses. The first one is a wooden house. Turn to the right after this house. The point is on the edge of the deep exploratory well SL-1, close to the house of M Vincent Louis (Bousquet). You need a tripod to make the installation and a 4-wheel car to reach the point.

TER1: On the main road between Vieux-Fort and Soufrière (in the caldera), take the road on the right to Sulphur Springs (at the bus stop). After the fumarolic field, stop at the turning point and climb the Terre Blanche dome until the flat part of it on the west. The best way is to climb in the forest until you reach a high altitude. Our guide to the point is M Vincent Louis (Bousquet, on the photo). You will not need a tripod to make the measurement.

RAB1: On the main road between Vieux-Fort and Soufrière (in the caldera), take the road on the right to Hermitage. Continue until a crossroad with the road to the top of Rabot. The point is on the right side in the cement. You need a tripod to make the measurement.

JIM1: In Soufrière, take the road to St Philip. Turn towards the left to Fond St Jacques. Continue after Migny until you reach the crossroad of Edmond Forest trail. Turn on the left and continue until a banana hangar on the right.. After this go to the East towards the wooden house. Leave the house on the right and continue into the field. The point is behind a dasheen field. The owner of the property is M Son. You will need a tripod to measure the site and a 4-wheel car to reach the point.

COL1: Take the main road between Soufrière and Castries, on the northern caldera rim and stop in the turning point before Mount Tabac. The point is on the right side of the road. You will need a tripod to make the installation.

BOU1 (no photo): Take the main road between Soufrière and Castries. After the caldera rim, there is a crossroad named Quatre Chemins. Turn towards the left to Bouton. Go to the end of the road and you will find the point on the ground near the school. You will need a tripod to make the measurement and a 4-wheel vehicle to reach the point.

Appendix 2: Levelling

Appendix 2.1: Chronological record of levelling measurements done along the road between Sulphur Springs and Rabot

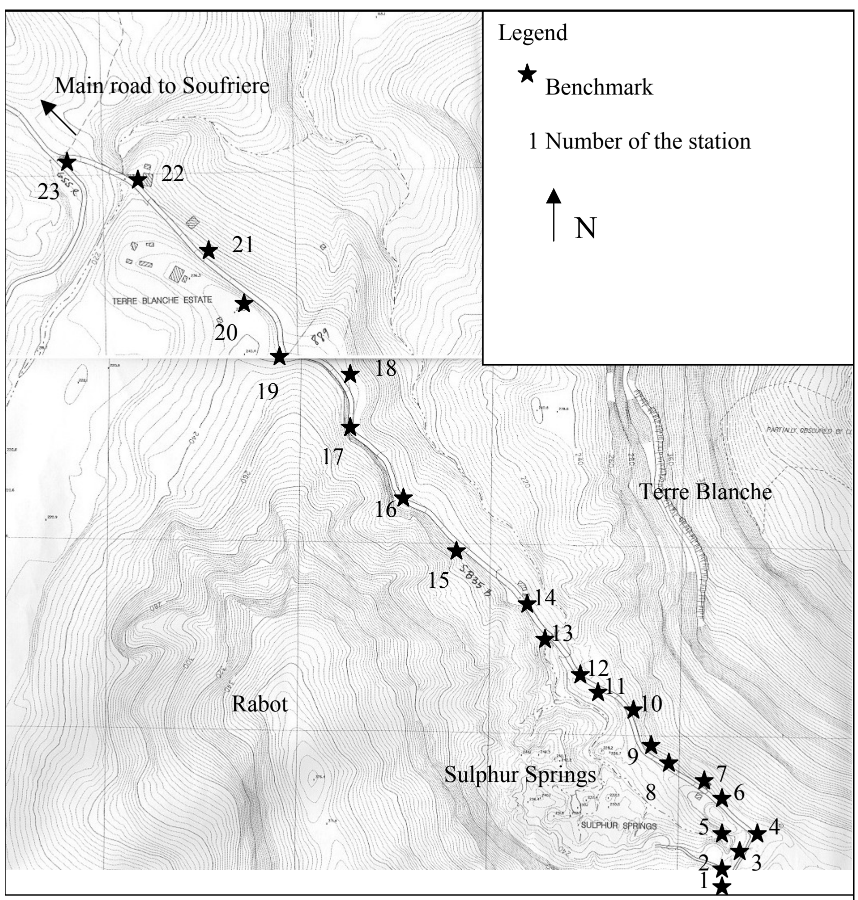
Date	Heights measured	Value (m)	MisClosure (mm)	Operators
16 February	1-2	-1.4171	0.5	Level: J.D Staff: U.O
16 February	2-3	-1.4509	0.2	Level: J.D Staff: U.O
16 February	2-3	-1.4472	0.1	Level: U.O Staff: J.D
16 February	3-4	0.5311	0.1	Level: U.O Staff: J.D
16 February	4-5	-2.6800	1.8	Level: U.O Staff: J.D
1 March	3-2	1.4476	0.9	Level: J.D Staff: R.A
5 March	5-6	-0.3587	0.6	Level: J.D Staff: R.A
5 March	6-7	-2.8481	-0.1	Level: J.D Staff: R.A
5 March	7-8	-3.5811	0.7	Level: J.D Staff: R.A
5 March	8-9	-2.6376	0.6	Level: J.D Staff: R.A
5 March	9-10	-2.4749	1.8	Level: J.D Staff: R.A
9 March	10-11	-2.9321	0.2	Level: J.D Staff: R.A
9 March	11-12	-2.9082	1.4	Level: J.D Staff: R.A
9 March	12-13	-7.0341	1.4	Level: J.D Staff: R.A
9 March	13-14	1.0978	2.8	Level: J.D Staff: R.A
9 March	14-15	2.9882	0.4	Level: J.D Staff: R.A
9 March	15-16	6.1367	0.3	Level: J.D Staff: R.A
9 March	16-17	2.8871	0.1	Level: J.D Staff: R.A
13 March	17-18	7.4090	-0.4	Level: J.D Staff: R.A
14 March	18-19	-4.1257	0.2	Level: J.D Staff: R.A

14 March	19-20	-2.9744	13.1	Level: J.D Staff: R.A
14 March	19-20	-2.9748	0.2	Level: J.D Staff: R.A
14 March	20-21	-6.6947	0	Level: J.D Staff: R.A
14 March	21-22	-5.4620	-0.7	Level: J.D Staff: R.A
14 March	22-23	6.0918	0.5	Level: J.D Staff: R.A
J.D is Jerome David R.A is Rhikkie Alexander U.O is Uche Osuji				

Appendix 2.2: Description and location of the levelling stations.

The network is situated on the road crossing Sulphur Springs. It starts at the turning point of the road above the fumarolic field on Rabot flank. It ends at the crossroad with the main road. All the benchmarks are screws put in the ground with epoxy glue.

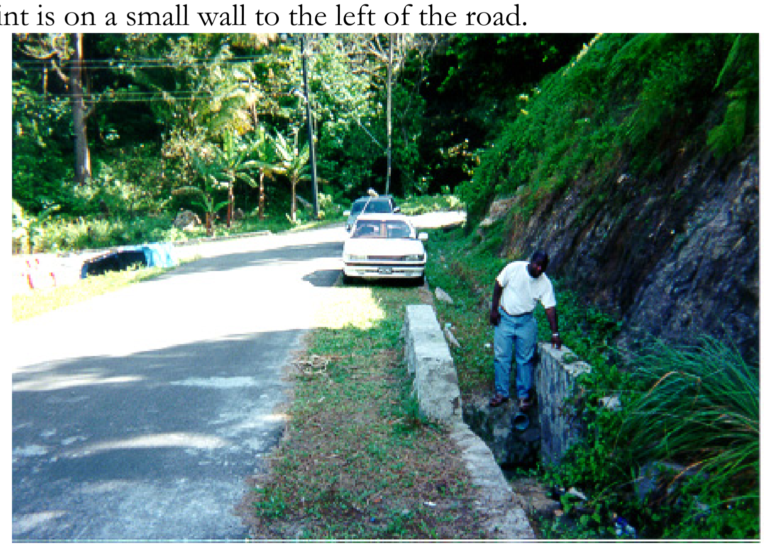
Map of the position of the benchmarks used for the levelling line.



Appendix 2.3: Pictures and descriptions of the levelling station localities

Benchmark 1: The point is situated on a small wall to the left of the road.

Benchmark 2:This point is on a small wall to the left of the road.



Benchmark 3: The point is situated on the wall close to a small bridge. A hot spring is at the base. The photograph is taken from the right side of the road.

Benchmark 4: The point is at the crossroad between the Sulphur Springs road and the trace that goes to the area where deep drilling was carried out in the 1980s.

Benchmark 5: The benchmark is on the left side of the road, behind some bricks, on the fence of a canal.

Benchmark 6: The point is close to a drain on the right side of the road.

Benchmark 7: The point is on the right side, close to the toilets.

Benchmark 8: The point is on the road, on the right side. It is approximately in front of the trace , which goes to the viewing point for the Soufrière.

Benchmark 9: The point is on the right side of the road, close to a post.

Benchmark 10: The point is on the right side of the road where it curves.

Benchmark 11: The point is on a big stone beside the left side of the road.

Benchmark 12: The point is on a big stone on the left side of the road.

Benchmark 13 :The point is situated on the left side of the bridge above the river.

Benchmark 14: The point is situated close to the guide house.

Benchmark 15: The point is on a shoulder of the drain.

Benchmark 16 (no photo): The point is situated on a small wall that is part of a drain. It is on the left side of the road.

Benchmark 17: The point is on an old part of the road.

Benchmark 18: The point is at the top of a big stone.

Benchmark 19: The point is in a curve, on an old part of the road.

Benchmark 20: The point is on a big stone.

Benchmark 21: The point is on a big stone.

Benchmark 22: The point is on the ground, beside the volcanic restaurant.

Benchmark 23: The point is just at the crossroad between the main road and the road to Sulphur Springs

Appendix 3: Distance Measurements

Appendix 3.1: Results of distance measurements

19 March

Points measured I=instr	Slope distance (m)	T (° F)	P (Inches Hg)	%H	Altitude Instrument (Feet)	Height above point (Inst, m)	Height above point (Ref, m)
S(I)-N8	93.676	74	29.85	70	800	1.122 Hm 0.251 Hh 0.196 Hy 1.569 Hi	1.012 Hm 0.351 Hh+c 1.363 Hr
S(I)-N9	108.987	71		77			0.872 Hm 0.351 Hh+c 1.223 Hr

21 March

Points measured I=instr	Slope distance (m)	T (° F)	P (Inches Hg)	%H	Altitude Instrument (Feet)	Height above point (Inst, m)	Height above point (Ref, m)
LIG0(I)-TLPL B	2,436.103	91	30.05	63	730	1.084 Hm 0.251 Hh 0.196 Hy 1.531 Hi	1.065 Hm 0.351 Hh+c 1.416 Hr
LIG0(I)-TLPL C	3,542.954	89	30.1	60			1.152 Hm 0.351 Hh+c 1.503 Hr
LIG0(I)-BLA1	No contact	84	29.9	65			0.960 Hm 0.351 Hh+c a 1.311 Hr b 0 Hr
LIG0(I)-CAI1	6,947.132	82		66			0.899 Hm 0.351 Hh+c 1.250 Hr

22 March

<table>
<tr><th>Points measured I=instr</th><th>Slope distance (m)</th><th>T (° F)</th><th>P (Inches Hg)</th><th>%H</th><th>Altitude Instrument (Feet)</th><th>Height above point (Inst, m) *</th><th>Height above point (Ref, m) **</th></tr>
<tr><td>S(I)-N8</td><td>93.671</td><td>75</td><td rowspan="2">29.85</td><td>77</td><td rowspan="5">800</td><td rowspan="5">1.209 Hm
0.251 Hh
0.196 Hy
1.656 Hi</td><td>1.260 Hm
0.351 Hh+c
1.611 Hr</td></tr>
<tr><td>S(I)-N9</td><td>108.975</td><td>77</td><td>71</td><td>1.074 Hm
0.351 Hh+c
1.425 Hr</td></tr>
<tr><td>S(I)-N10</td><td>142.593</td><td>83</td><td rowspan="3">29.8</td><td>60</td><td>1.084 Hm
0.351 Hh+c
1.435 Hr</td></tr>
<tr><td>S(I)-N12</td><td>185.699</td><td rowspan="2">79</td><td rowspan="2">66</td><td>1.001 Hm
0.351 Hh+c
1.352 Hr</td></tr>
<tr><td>S(I)-N14</td><td>307.144</td><td>1.162 Hm
0.351 Hh+c
1.513 Hr</td></tr>
</table>

<u>NB:</u>

Jerome DAVID is the operator and installed some of the reflector stations.
Rhikkie ALEXANDER installed some of the reflector stations.

- Height *Hi,* of the distancemeter above the point was determined by combining the following measurements:
  - *Hm,* is the height measured by the height hook
  - *Hh,* is the height of the height hook
  - *Hy,* is the height of the support of the distancemeter (i.e. the yoke)

- Height *Hr,* of the reflector above the point was determined by combining the following measurements:
  - *Hm,* is the height measured by the height hook
  - *Hh + c,* is the height of the height hook plus the height of the carrier

Appendix 3.2: Pictures and descriptions of the distance measurement localities

LIG0: A picture and description of this point has already been given in Appendix I.5. It was the location of the distancemeter for the measurements done to the airport and Morne Caillandre.

S: The point is the reference for the distance measurements at Sulphur Springs.

TLPL B: A picture and description of this point has already been given in Appendix I.5.

TLPL C: A picture and description of this point has already been given in Appendix 1.5

CAI1: A picture and description of this point has already been given in Appendix 1.5.

Benchmark 8: A picture and description of this point has already been given in Appendix 2.2.

Benchmark 9: A picture and description of this point has already been given in Appendix 2.2.

Benchmark 10: A picture and description of this point has already been given in Appendix 2.2.

Benchmark 12: A picture and description of this point has already been given in Appendix 2.2.

Benchmark 14: A picture and description of this point has already been given in Appendix 2.2.

Appendix 4: Geothermal Monitoring

Appendix 4.1: Gas chemistry of Sulphur Springs fumaroles, sampled on 15th April 2001.

Feature	**T °C**	**pH**	**ref.**	**CO_2**	**$S_{tot.}$**	**H_2S**	**H_2**	**CH_4**	**N_2**	**O_2**	**CO**	**N_2/Ar**	**N_2/ He**
Fracture fumarole	96.6	5	C8	993	3.54	3.54	4.99	0.86	1.41	0.00	0.01	192	5419
Dasheen Devil fumarole	137.6	7	C2	992	6.75	6.75	5.46	1.03	1.57	0.00	0.01	220	4487
Fizzy pool	70.0	6.5	C11	993	2.91	2.91	4.52	0.80	1.43	0.00	0.00	269	4340
Small green gasser	93.3	7	C3	992	4.11	4.11	5.79	0.99	1.64	0.02	0.00	552	4794

analyses in mmol/mol dry gas.