Grenada

Richard Robertson
Seismic Research Unit, The University of the West Indies, Trinidad and Tobago

Abstract

The island of Grenada is composed of a mixture of monogenetic and polygenetic volcanic centres, none of which has erupted during the historical period. The abundance of reworked volcaniclastic deposits throughout the island limits the reconstruction of the island's volcanic history and hampers hazard assessment. Monogenetic explosion craters define a NE-SW trend across the island, and it is possible that similar craters may develop along this line in the future. Mt. St. Catherine is considered to be the only live polygenetic volcano on Grenada based on its well-preserved morphology, the presence of associated fumaroles on its flanks and the occurrence of volcanic earthquakes in the past. Its volcanic deposits indicate that both effusive (dome-building) and explosive eruptions are possible. The types of volcanic activity expected in the future are steam venting, phreatic explosions and lava dome-building eruptions from a vent located within the breached crater at the summit. Such activity may result in pyroclastic flows and surges, lahars and ash fall which will likely affect villages located to the east and west of the volcano. Explosive eruptions would impact a much wider area but are considered to be less likely to occur in the near future.

Introduction

In assessing the volcanic hazard likely to be posed by future eruptions on Grenada, this chapter takes an empirical approach utilising both published reports on the geology of the island and fieldwork conducted by the author. In attempting to define the most likely styles of eruption possible on the island, consideration is given to the historical seismicity and geothermal activity along with the geologic record of past eruptions. The style of activity exhibited by volcanoes elsewhere in the region is also considered.

Geographical Setting

Grenada is an oval shaped island, elongate in a north-east to south-west direction. It is approximately 34 km long and 19 km wide with a total area of 312 km^2. It has a rugged topography reaching a maximum height of 910 m at the Mt. St. Catherine volcanic centre. Central peaks stretch along the length of the island. Apart from Mt. St. Catherine, the principal peaks from north to south are Mt. Granby (683 m), Mt. Qua Qua (640 m), South East Mt. (703 m), Mt. Lebanon (700 m), Mt. Sinai (703 m) and Mt. Maitland (522 m). The island is asymmetric, with the western side of the island being well dissected with deep, sharply cut valleys forming a well-indented coastline, while the east coast slopes gently to the sea. The population is 97,000, with the majority located in and around the capital of St. George's. The economy is based largely on agriculture and tourism.

Relief map of Grenada

Seismic Research Unit, UWI 2005

Previous work

Prior to an extensive study carried out by Arculus (1973), no detailed work had been done on the geology of Grenada. Harrison (1896) gave the first account of the geology of the island. Earle (1924) commented on the folded lower Tertiary basement and noted the presence of gypsum in some horizons. He recognised the occurrence of clinopyroxene-rich basalt and cumulate plutonic blocks. Martin-Kaye (1969) did further work on the lower Tertiary basement and was able to determine the stratigraphic relationships and ages of units using the fossil faunal content. He also noted the approximate north-east trend of the explosion craters, suggesting that these may be related to a possible fault zone. Robson and Tomblin (1966) gave a brief account of the overlying volcanics and noted the unusually mafic nature of the volcanic products. Andrew et al. (1970) conducted a gravity survey of the entire island.

Arculus and Curran (1972) presented evidence from lavas in Grenada which suggested a source area in the Upper Mantle for the genesis of the calc-alkaline suite. They noted that there was a complete petrographic and chemical continuity between the undersaturated magmas of basanite and alkali-olivine basaltic affinities and the typical calc-alkaline lavas found elsewhere in Grenada and the other islands of the Lesser Antillean Arc. Arculus (1973) conducted an extensive study of the Miocene-Recent rocks of the island as part of a programme of research into the problems of island arc volcanology, petrology and geochemistry initiated in the 1960s.

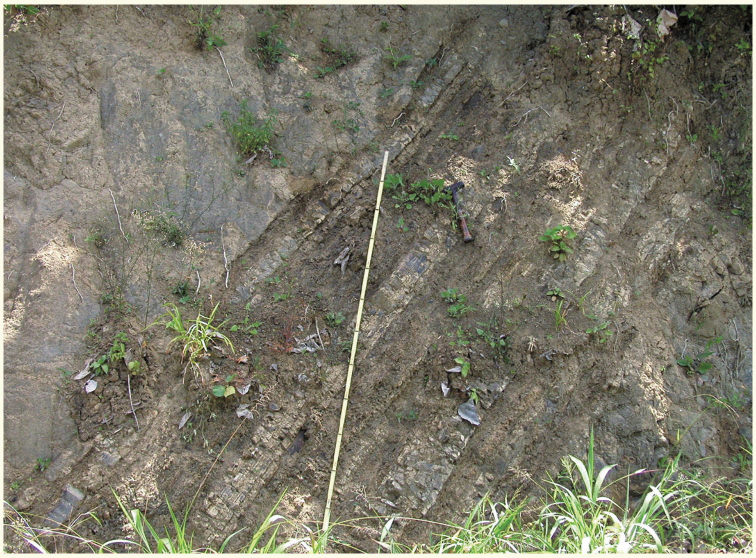
Cawthorn et al. (1973) used experimental and chemical data to conclude that the unusual differentiation trend of Grenadian rocks (from Ne-normative through hypersthene-normative to quartz-normative) is a result of amphibole fractionation under intermediate pressures in the presence of water. Sigurdsson et al. (1973) examined the evidence for undersaturated magmas derived from partial melting of the Upper Mantle on the island of Grenada.

Shimizu and Arculus (1975) presented Rare Earth Element (REE) data in support of partial melting of a garnet lherzolite source to produce the range of basanitoid and alkalic basalt rocks observed on Grenada. Arculus (1976) discussed the field occurrence and major and trace element geochemistry of the Grenada suite of rocks. He indicated that there was an intimate field relationship of silica-undersaturated lava rocks with silica-saturated calc-alkaline andesite and dacite.

Brown et al. (1977) described the results of a regional geochemical survey based on new rock analyses. They felt that partial melting of upper mantle peridotite above the subducted slab was responsible for the generation of the basanitoids. Arculus (1978) described the petrology and mineralogy of the lavas on Grenada and made some estimates of the physical conditions prevailing during the genesis and evolution of the suite. Major and trace element analyses were reported by Arculus (1973, 1976) and Hawkesworth et al. (1979) presented Sr-Nd isotope and REE analyses of Grenada.

Graham (1980) examined the genesis of the igneous rock suite of Grenada. Two distinct basaltic series were identified (Thirlwall and Graham 1984) corresponding to ankaramites and microphyric basalts distinguished by Hawkesworth et al. (1979). These were renamed the C- and M-series, respectively, which could not be related to each other by a one stage process (Thirlwall and Graham 1984). Thirlwall and Graham (1984) examined the evolution of the high Ca, high-Sr, C-series basalts from Grenada, looking particularly at the effects of intra-crustal contamination. They concluded that the major element variation in Grenada C-series basalts was controlled by high-level fractional crystallisation of an augite-plagioclase-olivine-magnetite assemblage.

Arculus and Wills (1980) described the petrology of plutonic blocks from the Lesser Antilles including Grenada. They noted that the strong trace element (Arculus 1976) and ^{87}Sr/^{86}Sr-^{143}Nd/^{144}Nd (Hawkesworth et al. 1979) characteristics of different volcanic series in the same centres on Grenada suggested that the inclusions were related to their host lava sequence.



Sand and shale beds of the Tufton Hall Formation at Malagon Estate north-north-west of Mt. St. Catherine

Devine (1995) presented a comprehensive revision of the petrogenesis of the basalt-andesite-dacite association of Grenada. He restored the data bases of Brown et al. (1977) and Arculus (1973), which had been shown to contain analytical errors (Graham 1980; Thirlwall and Graham 1984) and supported the inference that the Grenada M-series basalt-andesite-dacite suite was largely the product of fractional crystallisation of high-MgO basalt (Arculus 1973, 1976; Devine 1987). Devine (1995) indicated that there was little evidence to suggest that assimilation of crustal material or magma mixing plays an important role in the evolution of M-series magmas.

Geotermica Italiana (1991) undertook an investigation of the geothermal resources on Grenada and yielded additional information on the island with new geological sketch maps and age determinations being completed. Van Soest et al. (1998) presented data on helium and carbon relationships from Grenada as part of a regional survey of geothermal fluids from the Lesser Antilles island arc.

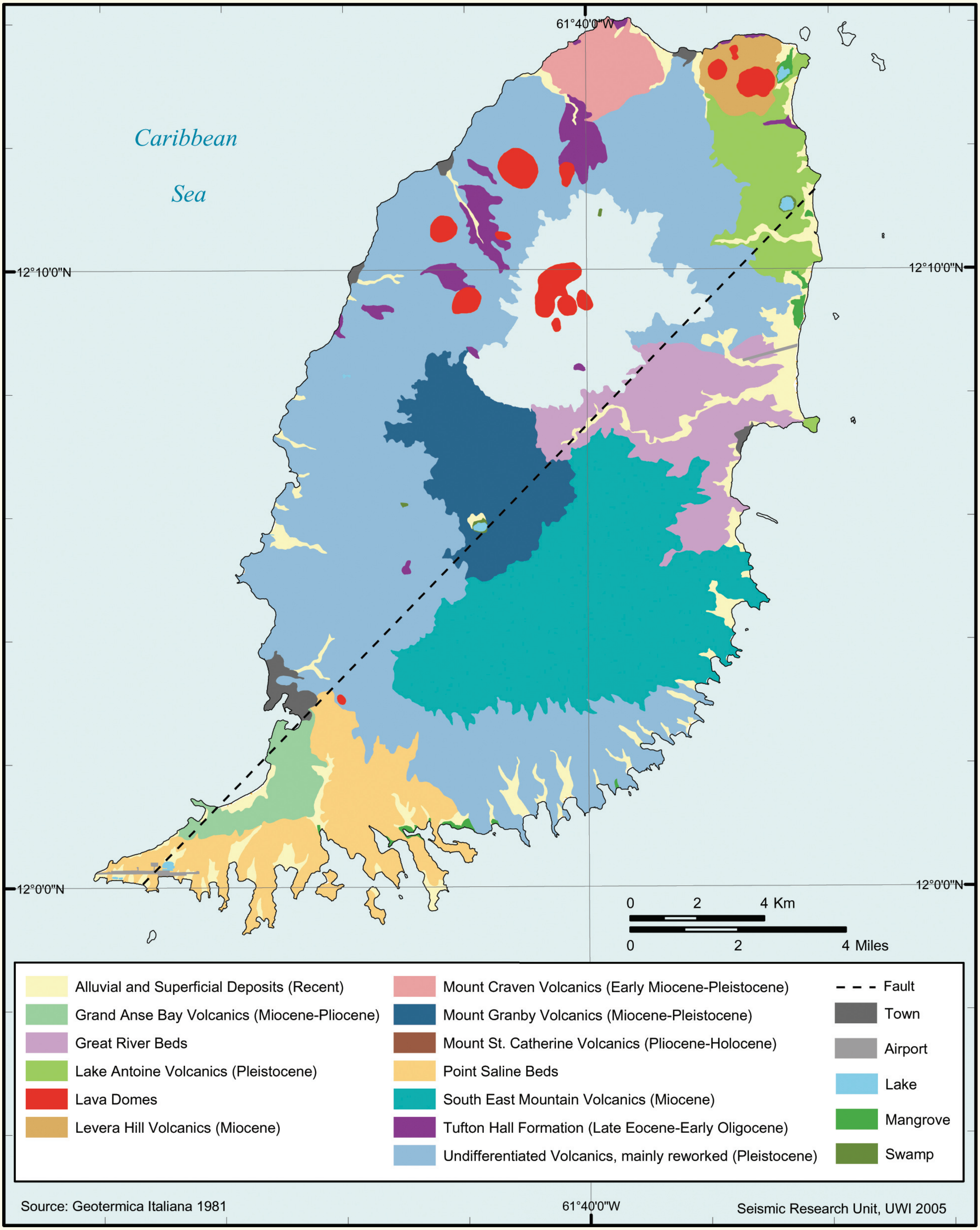
Andesite domes of Levera Island and Green Island (background), part of the Northern Domes Volcanic Centre.

Geology

A characteristic feature of the geology of Grenada is the large surface area of secondary or reworked volcanic material (Arculus 1973) caused by erosion of primary volcanic deposits. This has made it difficult to determine the lateral extent and evolution of volcanic centres. Past efforts at reconstructing the volcanic geology of the island (e.g. Arculus 1976; Geotermica Italiana 1991) have been based on geological observations, the degree of dissection of the topography, radiometric ages and photogeological interpretation.

Grenada is unusual in the Caribbean in its abundance of monogenetic basaltic explosion craters and is unusual among arc volcanoes in general in its abundance of highly magnesian and silica-undersaturated basalts. It consists of a folded lower Tertiary volcaniclastic and sedimentary basement (the Tufton Hall formation) overlain by an approximately 900 m (2500 ft) thick sequence of eroded but tectonically undisturbed Miocene to Recent volcanic rocks (Arculus 1976). Arculus (1973, 1976) divided the Miocene to Recent volcaniclastic rocks into a number of volcanic centres including: the Northern Domes, Southwest Grenada, Southeast Grenada, Mt. Sinai, Mt. Moritz, Mt. Maitland; Mt. Granby-Fedon's Camp, Mt. St. Catherine and the Explosion Craters. Geotermica Italiana (1991) also subdivided the volcanic formations but used slightly different boundaries. The description used in this chapter follows that of Arculus (1973, 1976) with the incorporation of information provided by Geotermica Italiana (1991).

Geological map of Grenada



Source: Geotermica Italiana 1981

Seismic Research Unit, UWI 2005

Tufton Hall Formation

The oldest rocks on Grenada belong to the Tufton Hall Formation and comprise a well-bedded sequence of Eocene to Miocene calcareous shales, siltstones and sandstones that contain foraminiferal fauna dated as Upper Eocene to Lower Oligocene in age (Martin-Kaye 1961). The formation contains tuffaceous horizons and thin limestone and generally surrounds the northern dome centres. The presence of allochthonous volcanic minerals and tuffaceous horizons indicate that igneous activity was already taking place in the Eocene and probably continued into the Oligocene (Arculus 1973).

Levera Hill dome as seen from Grenada Bay on the east coast

The Northern Domes Centre

Mt. William, Mt. Rodney, Mt. Alexander, Mt. Craven

This area is referred to as the Mt. Craven-Prospect area by Geotermica Italiana (1991). K-Ar dating of whole rocks by Briden et al. (1979) suggested that this area contained the oldest volcanic rocks on the island (21.2 Ma at Mt Craven) but ^{39}Ar/^{40}Ar dates of 1.3-1.8 Ma obtained for similar samples by Speed et al. (1993) have cast doubt on this age. Although prominent above the surrounding terrain, the domes reach a maximum height of only 280 m. No summit craters remain, but Arculus (1973) suggests that the generally circular distribution of the andesite domes at Mt. William, Mt. Rodney and Mt. Alexander may be attributed to the massive infilling of a pre-existing crater. Geotermica Italiana (1991) identified two concentric structures to the west of Mt. Craven based on photogeologic interpretation. These structures were interpreted to have originated from volcano-tectonic collapse. The rock types exposed in the area range from basalt to dacite and are mostly weathered. The volcanic history of this area appears to be one in which local eruptions of basalt and andesite lavas were initially interspersed with periods of explosive activity that culminated in the intrusion of domes (Arculus 1973).

Levera Hill centre

The composition and state of weathering of the deposits at this centre suggest that it was probably formed during the same general period of activity described for the domes above. Radiometric dating by Geotermica Italiana (1991) gave an age of 7.1 Ma (upper Miocene) for a rock sample from Levera Hill (848 ft), a hornblende andesite dome surrounded by the remnants of a pyroxene-phyric basalt flow. On the northern flanks of Levera Hill are two smaller dome structures exposed at Helvellyn and Dead Man’s Hill. The Helvellyn dome intrudes brecciated fragments of the Tufton Hall Formation. The volcanic history of this centre appears to have included the initial extrusion of a variety of ***M-series basalt and andesite lavas*** that were intruded by the domes of Helvellyn and Dead Man’s Hill, causing local brecciation of the lavas. Renewed activity with the extrusion of pyroxene-phyric ***C-series basalt flows*** culminated in the extrusion of Levera Hill dome, which caused brecciation around the flanks, and intermixing of the previously erupted rock units (Arculus 1973).

Southwest Grenada

This area is generally low-lying (maximum height 200 m) and is composed of reworked volcanic deposits interlayered with basalt lava flows. Many of the lavas are deeply weathered, but some were originally columnar jointed. Fresh samples have been dated at 3.7-3.5 Ma (Briden et al. 1979). Lava flows and reworked

K-Ar Radiometric age determinations of rocks from Grenada

Sample Number	Description	Location (°N, °)	Rock Type	Age±error (Ma)
GG6	N. of Gouyave	12° 10.2’; 61° 43.7’	Dacite	1.6±0.14[1]
GG20	Block from Lake Antoine	12° 10.9’; 61° 35.8’	Olivine basalt	1.65±0.19[1]
GG24	From the top of Levera Hill	12° 13.0’; 61° 37.3’	Andesite dome	7.13±0.1[1]
GG31	Mt. Hope	12° 09.5’; 61° 40.2’	Dacite dome	1.0±0.11[1]
6928084	Grand Mal	12° 04.6’; 61° 45.2’	Olivine basalt lava	1.47±0.12[2]
6928159	La Borie	12° 02.5’; 61° 43.6’	Olivine basalt lava	1.45±0.08[2]
6928162	St. Paulus	12° 02.9’; 61° 43.7’	Olivine basalt lava	1.43±0.08[2]
6928196	N. of Mt. Royal	12° 03.4’; 61° 44.7’	Olivine basalt lava	0.98±0.10[2]
6928240	Marigot	12° 07.7’; 61° 45.0’	Olivine basalt lava	0.94±0.11[2]
6928286	Richmond Hill	12° 03.0’; 61° 44.3’	Olivine basalt lava	1.68±0.07[2]
6928371	S of Ross Point	12° 02.2’; 61° 45.3’	Olivine basalt lava	3.77±0.11[2]
6928380	Goat Point	12° 01.4’; 61° 46.6’	Olivine basalt lava	3.56±0.10[2]
RJA267	Near Belvedere	12° 07.7’; 61° 41.1’	Olivine basalt lava	3.31±0.16[2]
RJA344	Mt Ellington	12° 11.3’; 61° 40.5’	Olivine basalt lava	2.36±0.11[2]
RJA507	Annandale Falls	12° 05.2’; 61° 43.1’	Olivine basalt lava	14.0±0.4[2]
RJA528	Morne Delice	12° 02.2’; 61° 43.0’	Olivine basalt lava	10.3±0.3[2]
RJA531	South East Mtn	12° 05.9’; 61° 40.2	Olivine basalt lava	10.9±0.3[2]
RJA341	Diego Piece Crayfish	12° 12.1’; 61° 41.0’	Basalt	1.89±0.09[2]
RJA354	Mt. Craven	12° 12.9’; 61° 39.2’	Andesite dome	21.2±1.0[2]

Source of data: [1]Geotermica Italiana (1981); [2]Briden et al. (1979)

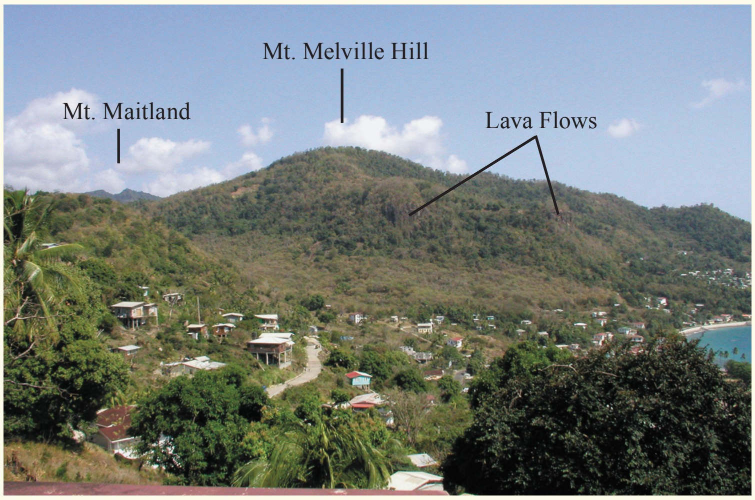
deposits of the younger (1.6 to 1.4 Ma) Mt. Sinai-Mt. Maitland-Mt. Moritz centre overlie much of the area, particularly in the north, and so have obscured possible interpretation of the origin of the older deposits in the southwest.

At Prickly Point, the southernmost tip of Grenada, a resistant dacite plug, mantled by a sequence of reworked volcanic deposits, is exposed. Arculus (1973) suggested that the area might have been submerged on occasions and that some marine deposition had occurred. The indentation of the coastline in this region was noted as evidence of slight oscillations in sea level.

The South East Mountain Volcanic Centre

The topography of this centre is dominated by a ridge extending southwards from South East Mountain (780 m) towards Mt. Lebanon (700 m). The area is composed of andesite and basalt lava flows and pyroclastic flow deposits that radiate from the South East Mountain. The lava flows are so closely intermixed and weathered that it is difficult to distinguish between the different compositions on a map. These flows range in composition from basalt to dacite, although there is a predominance of basalt compositions at the surface. The distal ends of the lava flows overlie and appear to pass through reworked volcaniclastic deposits that form a coastal sheet extending around the southern and eastern coasts of Grenada. Evidence of the contact between the lava flows and the reworked deposits is the presence of a red lateritic soil which contrasts with the grey weathered appearance of the reworked volcaniclastic deposits.

The northern and northeastern ridges of this centre contain mainly pyroxene-phyric basalt flows, some of which extend for 2 km towards Richmond. The summit of Mt. Lebanon and surrounding slopes appear to comprise a weathered andesite dome. The southern ridge of Mt. Lebanon consists of a lava flow that extends for 1 km. At Munich, angular andesite bounders suggest the presence of an old lava flow.



Lava flows at Mt. Melville Hill, part of Mt. Moritz Volcanic Centre in southwestern Grenada

Mt. Sinai-Mt. Maitland-Mt. Moritz Volcanic Centre

This centre is characterised by subdued topography and discontinuous units. It can be divided into two main areas by the St. John's River, which flows from NE to SW and divides Mt. Maitland from Mt. Moritz. Mt. Sinai is the highest of these centres (~ 703 m), and elevation decreases westwards. This also appears to have been the dominant direction of lava flows whose path may have been blocked by the South East Mountain. The oldest rock analysed from this centre is a 14 Ma basalt (Briden et al. 1979) from Annandale Falls, but Speed et al. (1993) have suggested that this date is suspect.

Basaltic lava flows dominate surface outcrops. Andesitic and dacitic material is found only as fragments in reworked volcanics interlayered with some of the lava flows. A rare ultrabasic lava flow is exposed at Mt. Gay (1 km north of St. George's). The flow has baked the underlying pyroclastic deposit, and both the massive and fragmental material exhibits columnar jointing. Generally there appears to be a gradual transition from silica-undersaturated to silica-saturated compositions with elevation. For example, the ultrabasic flow at Mt. Gay is succeeded at greater elevations on Mt. Maitland by pyroxene-phyric lava flows of greater silica content (Arculus 1973).

The centre of activity appears to have been located somewhere in the vicinity of Mt. Maitland and Mt. Sinai. The sequence of activity appears to have involved emission of a series of mainly basaltic lava flows and pyroclastic deposits during the Upper Pliocene to Lower Pleistocene.

The path of the St. John's River may be fault controlled, and the steep northern faces of Mt. Maitland and Mt. Sinai may represent eroded fault scarps.

Reworked volcaniclastic deposits at Morne Docteur on the flank of Mt. Granby.

Mt. Granby-Fedon's Camp Volcanic Centre

This forms the high ground in the middle of the island and is probably a composite centre whose eruptive vents are no longer recognisable. Radiometric dating and morphological evidence indicate that this area was affected by volcanic activity in the Pliocene to Pleistocene (Briden et al. 1979). Lava flows radiate from Mt. Granby (720 m), Fedon's Camp (820 m) and Mt. Qua Qua (760 m) and may be all part of a single composite volcanic centre (Arculus 1973). The dominant direction of lava flows is westwards. At sea cliffs and in deep river valleys exposures show a repeated alternation of basalt and andesite deposits suggesting a cyclical pattern of transition from silica under-saturated to over-saturated compositions. Generally the source of lava flows appears to shift southwards suggesting a migration of volcanism in this direction (Arculus 1973).

Reworked pyroclastic deposits form a large part of the area, particularly along the west coastal strip from St. George's to Gouyave. These deposits are widespread and appear to be the remnants of the earliest period of volcanism at this centre. They consist of graded and ungraded beds that contain a wide variety of clasts of different sizes and compositions. Some deposits exhibit current bedding and others display sufficient homogeneity in composition and lateral extent to suggest that they are primary tephra fall deposits.

The area exhibits inverted topography in some areas with younger valley filling lavas now capping ridges. The basaltic lava flows are in cases up to 5 km long. They have massive and often columnar jointed interiors with vesicular and platy flow tops overlain by rubble. They often have steep (25°) dips and are interleaved with basaltic ashes which are sometimes baked and reddened by the overlying flow. The lengths of andesite lava flows are comparable with basaltic flows but they may reach up to 70 m in thickness.

Mt. St. Catherine Volcanic Centre viewed from Morne Longue

Mt. St. Catherine Centre

This is the youngest polygenetic volcanic centre on Grenada and the only one considered to be live. Although no age dates have been obtained for this centre, it is considered to be of Pleistocene to Holocene age (Arculus 1973). The summit rises to 910 m (the highest point on the island) and is formed of deeply weathered massive andesitic lava. It consists of a 1.7 km wide, horseshoe-shaped crater that is breached to the southeast. Within the crater lies a central andesite dome (213 m wide and 122 m high) surrounded by lava flows and pyroclastic flows that are mantled with scree deposits. Several domes (andesite to dacite) have grown in the summit area and some appear to be younger than the collapse of the summit crater (Geotermica Italiana 1991).

Below 350 m the terrain is generally covered by a mantle of secondary fragmental deposits (maximum ~70 m at Waltham and Victoria cliffs). These deposits include fine-grained, reworked ash and pumice, some of which are clay-sized and display current bedding. Andesitic and basaltic fragments found in these deposits are similar in composition to material found at higher altitude on Mt. St. Catherine. Good exposures of these deposits are found at Belmont, 5 km northeast of the centre. Mudflow deposits are exposed in areas to the west of the summit.

Primary airfall deposits of mainly andesitic composition are exposed on the northern and eastern slopes of the volcano near Plaisance and Montreuil. These are thinly bedded and contain bomb impact structures. Their genesis is uncertain since they may have originated from one of the explosion craters. However, the explosion crater deposits are dominantly basaltic, so it is more likely that these airfall deposits originated from Mt. St. Catherine.

Rock types of this centre vary from basanitoid to dacite but are predominantly of andesite to dacite. The range of compositions from silica-undersaturated to oversaturated is similar to that of Mt. Granby-Fedon's Camp Volcanic Centre, but without as many repetitions of the sequence.

Ash fall deposits with bomb sag at Plaisance Estate in northern Grenada.

Explosion Craters

The most recent activity on the island consisted of the formation of several small craters. They are morphologically well-preserved centres of basanitoid, basaltic and andesitic scoria fall and flows, which were formed during the most recent period of volcanic activity on the island. The craters have a maar to tuff ring type morphology, generally 0.5 km in diameter, their size likely depending on the amount of groundwater present during eruptions. Most are composed of silica-undersaturated alkali basalt scoria and ash along with a variety of basement and wall rock fragments. There are no lava flows associated with these craters. Devine (1995) noted that the most recent eruption produced a scoria cone near Radix valley that may be less than 1000 years old.

Grenada is characterised tectonically by two conjugate fault trends (Martin-Kaye 1969; Arculus 1976). The main one runs NNE-SSW and corresponds to the elongation of the island; the other is approximately normal to the main trend. Martin-Kaye (1967) and Arculus (1976) have suggested that the orientation of the explosion craters may be controlled by the main NNE-SSW fault trend.

Lake Antoine explosion crater

Lake Antoine

Lake Antoine is the best preserved of the craters. A lake 500 m in diameter occupies the crater floor, which is surrounded by a 60 m high tuff ring composed of ejected blocks, scoria and ash. Arculus (1973) noted that the overall morphology is that of maars, which are structures associated with explosive activity of hydrous magma or contact between magma and local groundwater.

In general the ash fall sequence surrounding Lake Antoine thickens towards Grenada Bay. The maximum size of the ejected blocks also increases to 50 cm in diameter in this direction. The sequence contains evidence of several pulses of activity represented by repetitions of graded layers of ash, interspersed with layers of larger scoria and bombs. The earliest deposits, which are exposed at the southern end of the High Cliff Point, are predominantly of alkali basalt scoria and ash. They also contain fragments of andesitic composition and blocks of previously consolidated ash. Some layers contain bomb impact structures with distortion of bedding.

Tephra deposits from Lake Antoine explosion crater exposed at High Cliff Point along the east coast of Grenada

The Punchbowl crater

Located 3 km northwest of Lake Antoine, this is of smaller diameter (100 m) and steep-sided. The crater walls reach up to 30 m high and slope at angles up to 60°. The ejecta that comprises the crater walls is dominated by wall-rock fragments, although weathered basaltic ash is also present.

Grand Etang

Grand Etang consists of two explosion craters, one of which is filled by a lake. It is located at an altitude of 500 m near to Mt. Qua Qua and Mt. Sinai. Most of the ash associated with these craters has been deeply weathered to form a red lateritic soil (Arculus 1973).

Grand Etang explosion crater viewed from the east

St. George's

A series of coalescing explosion craters, including the basin that is outlined by the Carenage, are located in this area.

Queens Park

This is a well-preserved crater that erupted alkali basalt scoria and ash. The crater deposits are currently being quarried. The ejecta from this centre is found as far north as Mt. Moritz.

In addition to the well-preserved craters outlined above, there are localised deposits of coarse scoria and ash of relatively young appearance that cannot be associated with any recognisable crater. Their composition (alkali basalt) and unweathered state suggest that they are associated with the same type and period of activity as the craters described above. These deposits are found at Grand Anse Bay, Plaisance Estate and Grenville. It is also possible that Levera Pond located in the northeast of the island occupies the floor of another explosion crater.

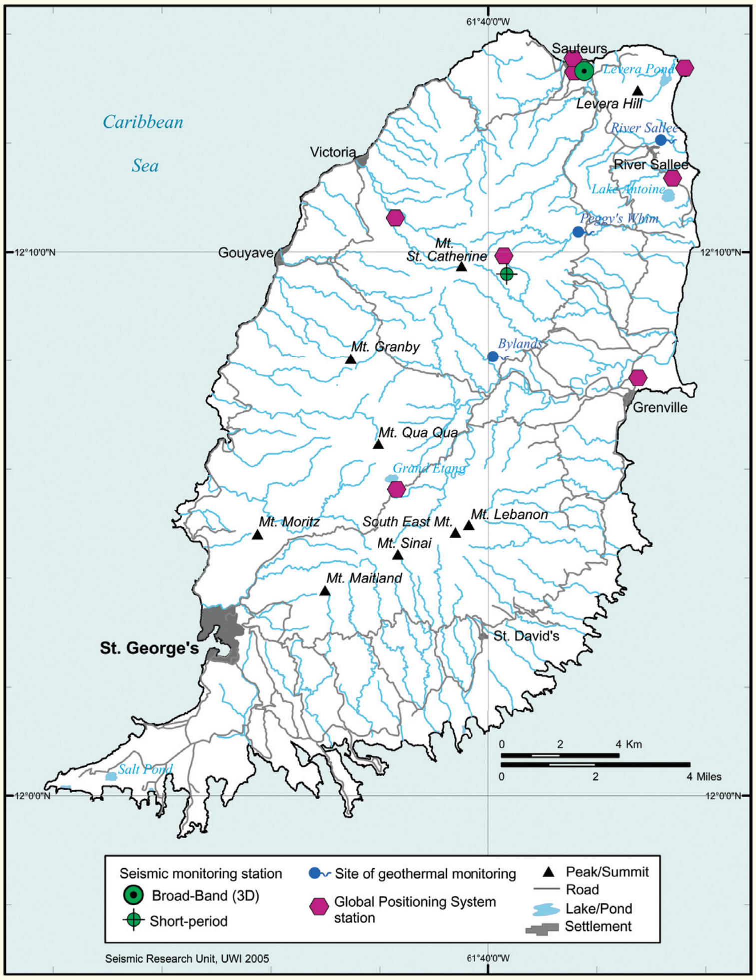
Volcano monitoring

Mount St. Catherine is monitored by the Seismic Research Unit of the University of the West Indies using a network of stations that study ground deformation, seismicity, and geochemistry of hot springs and fumaroles. The monitoring network consists of two seismic and eight GPS stations (Robertson and David 2002) and also involves the collection of gas, water and condensate from fumaroles located on the flanks of Mount St. Catherine. The GPS network was mainly designed to monitor possible ground deformation associated with Mount St. Catherine. In choosing the sites, however, consideration was given to detection of possible activity associated with the explosion craters at Levera Pond, Lake Antoine and Grand Etang. A small volcano observatory located at Sauteurs in the north of the island serves as the collection point for signals from the seismic network on Grenada. The data are accessed from Trinidad via the Internet.

MONOGENETIC AND POLYGENETIC VOLCANISM

Volcanoes formed during single episodes of volcanic activity, without subsequent eruptions, are referred to as monogenetic. Monogenetic volcanoes are commonly clustered within volcanic fields or may constitute linear chains that follow tectonic structures, such as faults. Over long periods of time, monogenetic volcanic activity can result in extensive volcanic fields consisting of hundreds to thousands of individual volcanoes and cumulative volumes approaching those of individual composite volcanoes. Monogenetic volcanism usually occurs because the magma supply for the volcano is so small or episodic that any pathways to the surface have cooled down and are no longer favoured routes for the next magma batch. In contrast, polygenetic volcanoes have a sufficiently large and persistent magma supply rate that an ascending magma is able to follow the still-hot pathway of the preceding batch. Polygenetic volcanoes therefore erupt repeatedly from the same vent and lead to the formation of large composite structures. Grenada is unusual in the Caribbean region in the abundance of monogenetic volcanic centres. These centres define a NNE to SSW trend and often contain lakes.

Volcano monitoring network on Grenada



Potentially active volcanic centres

Mt. St. Catherine volcanic centre

Mt. St. Catherine is the only polygenetic volcanic centre on Grenada that is considered to have the potential to erupt in the future.

Past eruptive activity

The only evidence of volcanic activity is the presence of numerous hot springs and periodic earthquake swarms. Based largely on field evidence, Arculus (1973) proposed that the first eruptions from Mt. St. Catherine probably occurred from a region near Plaisance and Malagon. Exposures of these early basalt flows can be found at River Sallee and Mt. Ellington. The lava flows were probably widespread but were overrun by more acidic lavas ranging from andesite to dacite in composition. As the volcanic edifice built up, basalts were again erupted along with some pyroxene-rich lavas. The latter deposits are found in the Crayfish area and around Peggy's Whim.

The eruptive centre then probably migrated southwards towards the present location of Mt. St. Catherine. A thick sequence of andesitic and dacitic lava flows and pyroclastic flows were directed towards the northwest, forming the St. Marks Mountain and the local bedrock found in the rivers. Pyroclastic flows towards the west reached Gouyave and formed the western ridge of Mt. St. Catherine. They represent the best preserved and most voluminous of the pyroclastic flow deposits on Grenada. Andesitic and dacitic lava flows were extruded contemporaneously toward the east, forming the eastern ridges above St. James and Paraclete.

Volcanic activity climaxed with the partial infilling of the crater by an andesitic dome. Subsequent erosion and weathering has so altered the deposits of Mt. St. Catherine that it is difficult to correlate the pyroclastic flow deposits with any of the various stages in the evolution of the volcano.

Historical eruptions

There are no historical records of eruptions on Grenada. Anderson and Flett (1903) dismissed reports of an eruption of sulphurous vapours within the harbour of St. George's in 1867 and 1902. They suggested that these were over-dramatised reports associated with eruptions elsewhere in the Lesser Antilles.

Seismicity

Grenada is located within a region that has a moderate seismic risk. There have been few earthquakes associated with volcanic activity on the island and most felt earthquakes have been a result of activity at the offshore Kick 'em Jenny volcano located just 9 km to the north of the island (see chapter on Kick 'em Jenny and Île de Caille in this volume).

Geothermal activity

Hot springs associated with Mt. St. Catherine are present at Hapsack Hall, Tufton Hall (St. Mark's), Mt. Ellington, Peggy's Whim, River Sallee, and Lavez Chaud. Most are sulphurous, and they emit hot water at temperatures $<50^{o}$ C. Since the first records were made of these hot springs the temperatures appear to have decreased. Most of the springs issue from massively jointed igneous rock. At River Sallee the bedrock is obscured by sulphur deposits, while at Peggy's Whim the basement rock is indurated mudflow deposits.

In 1985 a field visit to Mt. St. Catherine confirmed areas of geothermal activity in the upper tributaries of the St. Mark's River in the Tufton Hall Estate (Shepherd 1985). This site is located on the northeastern side of the Mt. St. Catherine volcano and is characterised by alteration of the bedrock that is most extensive in the northern tributary. Here the rocks have been transformed into yellowish-white material by the actions of hot geothermal water and sulphurous gases. A visit to the area in April 2002 revealed that the region is still hydrothermally active with small fumarolic vents with yellow-brown sulphur deposits (Robertson and David 2002). Temperatures of the ground in the area ranged from 35.7 ^{o}C – 41.0 ^{o}C at the time.

Fumarolic vent at Upper Tufton Hall on the northwestern flank of Mt. St. Catherine.

Recorded temperatures of hot springs in Grenada

Locality	Feature	Date	Temp. (^{o}C)	pH
Bellevue Mt.	Hot spring	1971[3]	50.0	
	Hot spring	1972[3]	50.4	
Lavez Chaud	Hot spring	1965[2]	34.7	
		1971[3]	36.5	
		1972[3]	35.6	
Tufton Hall	Hot spring	1903[4]	48.9	
Upper Tufton Hall	Hot spring	1965[2]	37.4	
	Hot spring	1971[3]	36.4	
	Hot spring	1972[3]	36.0	
Lower Tufton Hall	Hot spring	1971[3]	36.5	
	Hot spring	1972[3]	36.1	
St. Mark's River (Upper tributary area)	Bubbling pools	1985[5]	40.0-50.0	
	Small vents	1985[5]	55.0-70.0	
	Small vents	2002[6]	35.7-41.0	7
	Bubbling pool	2002[6]	72.4	2
	Bubbling pool	2002[6]	50.3	2
Mt. Ellington	Hot spring	1971[3]	37.5	
	Hot spring	1971[3]	41.0	
	Hot spring	1972[3]	37.5	
	Hot spring	1972[3]	39.7	
Peggy's whim	Hot spring	1896[1]	44.4	
	Hot spring	1965[2]	38.8	
	Hot spring	1971[3]	39.5	
	Hot spring	1972[3]	39.4	
	Water spring	1998[7]	35	
	Cold pool	2003[8]	25.0	5
River Sallee	Hot spring	1965[2]	31.9	
	Hot spring	1971[3]	32.0	
	Hot spring	1972[3]	31.9	
	Hot spring	1998[7]	32	
	Ditch Vent	2003[8]	33.0	

Source of data: [1]Harrison (1896), [2]Robson and Tomblin (1966), [3]Arculus (1973), [4]Sapper (1903), [5]Shepherd (1985), [6]Robertson (unpubl. data), [7]van Soest (1998); [8]Joseph (2003).

Future eruptions

Based on the geologic record, future eruptions on Grenada may involve activity at Mt. St. Catherine or single explosive eruptions from monogenetic volcanic centres similar to those found at Grand Etang and Lake Antoine. There appears to be a roughly linear trend in the location of the existing explosion craters and it is most likely that future activity of this type will follow this trend. It should be noted that the potential distribution of future explosion craters extends from Sauteurs in the north to St. George's in the south of Grenada. Specific hazard maps for these types of eruptions cannot be drafted before the actual onset of eruptive activity since the future vent location of a monogenetic explosion crater cannot be predicted prior to the onset of precursory activity.

The evolution of Mt. St. Catherine has involved both explosive and effusive types of activity with the latter being the most recent type of activity exhibited. However, extensive erosion and lack of exposure has hindered attempts at determining the impact of eruptive activity in the past. Despite this it is possible to derive a number of eruptive scenarios for future activity and to use these to derive volcanic hazard maps. The presence of a dome within the breached crater of Mt. St. Catherine suggests that future magmatic activity will be initiated by steam emissions and possibly phreatic explosions prior to the actual effusion of magma at the surface.

Eruption Scenarios

Three scenarios have been inferred for Mt. St. Catherine. It is possible that these may occur as single independent events or they may simply be different stages in the evolution of a given crisis.

Scenario 1: Steam venting and phreatic explosions

The existence of several fumaroles and hot springs on the flanks of Mt. St. Catherine suggests the possibility of steam explosions, considered the most likely scenario for future activity at this volcano. This activity may take the form of simple steam venting or a more intense phreatic explosion from one of the existing soufrières located on Mt. St. Catherine or in the vicinity of Mt. Hope. Steam venting and/or phreatic explosions may be triggered by the heating of groundwater due to the upward movement of magma, or it may be a localised event due to blockage of a pre-existing fumarole. Blockage of steam vents may be caused by mass movement (landslides) following heavy rainfall, which may result in the build-up of sufficient pressure to cause minor explosions as the vents are cleared. Such explosions can cause localised dispersal of fine ash in the vicinity of the fumarole.

Upward movement of magma associated with an impending magmatic eruption could heat ground water and lead to vigorous steam venting and explosions on a much larger scale than those associated with blockage of fumaroles. The impact of this type of activity (mainly ash fall) is not expected to extend beyond 2 km of the source vent, and such explosions are more important as precursors to dome growth and explosive magmatic activity. Given their minor impact, the effects of steam venting and phreatic explosions are catered for in the hazard maps created for scenario 2.

Scenario 2: Effusive dome growth

The production of domes characterised the latest stage in the evolution of Mt. St. Catherine, and an effusive dome-building eruption is therefore considered to be the most likely scenario for a future magmatic eruption from Mt. St. Catherine. The type of activity exhibited by the ongoing eruption of the Soufrière Hills Volcano on Montserrat is a good model for what may occur in the event of this type of activity on Grenada. The distribution of ash fall and pattern of accumulated ash fall thickness experienced between 1995 and 2001 at this volcano (Norton et al. 2001) has been used to define a possible ash fall pattern for this type of eruption at Mt. St. Catherine. Dome collapse pyroclastic flows and surges are largely determined by the configuration of the summit area and the surrounding topography.

The first stage in the evolution of this type of activity is likely to be quite similar to that described in scenario 1. The movement of magma towards the surface and its eventual extrusion is likely to be accompanied by steam venting and phreatic explosions. Upon eventual extrusion dome growth will begin, leading to the formation of a rounded and potentially unstable pile of rock. With oversteepening of the sides of the dome, collapse will occur leading to the formation of dome collapse pyroclastic flows and surges and their accompanying ash clouds. Gravitational collapse of the steep sides of a growing volcanic dome may be caused by relatively minor disturbances such as a swarm of small earthquakes or heavy rainfall. It is not possible to determine exactly where the vent or source for extrusion will be, but it is likely to be in the vicinity of the breached summit crater, possibly near the youngest dome at Mt. Hood. Continued growth of the dome may lead to collapse of dome rocks into the Grand Bras River, sending pyroclastic flows towards Mt. Horne Estate. Collapse could also occur into the Grand River and so may affect areas such as Bylands and Mirabeau Estate. These early-formed dome collapse pyroclastic flows are unlikely to reach Pearls or Grenville but this may change with continued dome growth and gravitational collapse and potential infilling of the river valleys leading from the volcano. If dome growth continues, the edifice might become sufficiently large to enable collapse of material into an increasing number of surrounding valleys.

The pattern of pyroclastic flow and surge distribution is therefore likely to be one in which the flows will begin within the open end of the breached crater and then fan out into the surrounding valleys. Given the topography, it is expected that dome collapse will occur into the St. Marks River, then into Charlotte and later into Balthazar and Great River.

Scenario 3: Explosive eruption

The early stages in the evolution of Mt. St. Catherine involved explosive eruptions, which produced pyroclastic deposits that are presently exposed along the west coast from Gouyave to Victoria. Explosive eruptions do not appear to have occurred within the more recent period of the volcano's evolution and so are considered to be the least likely future scenario. This is also considered to be the worse case scenario for eruptions at Mt. St. Catherine.

An explosive eruption is likely to be preceded by significant precursory activity including earthquake swarms and ground deformation. It may not be the first phase of an eruptive sequence and could follow an ongoing effusive dome-forming eruption. Whatever its origin, an explosive eruption will involve the explosive fragmentation of magma and generation of pyroclastic flows and surges by eruption column collapse. Pyroclastic flows and surges produced by column collapse will be much less confined by topography than those produced by dome collapse as described in scenario 2. They will therefore have an equal chance of entering any of the many valleys that drain the summit of the volcano. However, the open eastern end of the summit crater will remain the easiest and therefore most favoured pathway for pyroclastic flow and surges. It is possible that flows may go into the St. Patrick and Duquesne rivers to the north, but they are more likely to be confined to the upper parts of these valleys.

Pyroclastic flows and surges and mudflows will affect all areas surrounding Mt. St. Catherine, with the towns of Grenville, Victoria and Gouyave being possibly affected. Given the distance from the summit, it is likely these hazards will affect Victoria and Gouyave before they affect Grenville. It is unlikely that flows will reach Sauteurs early on, but this may change if the eruption continues and pyroclastic flow deposits fill the upper

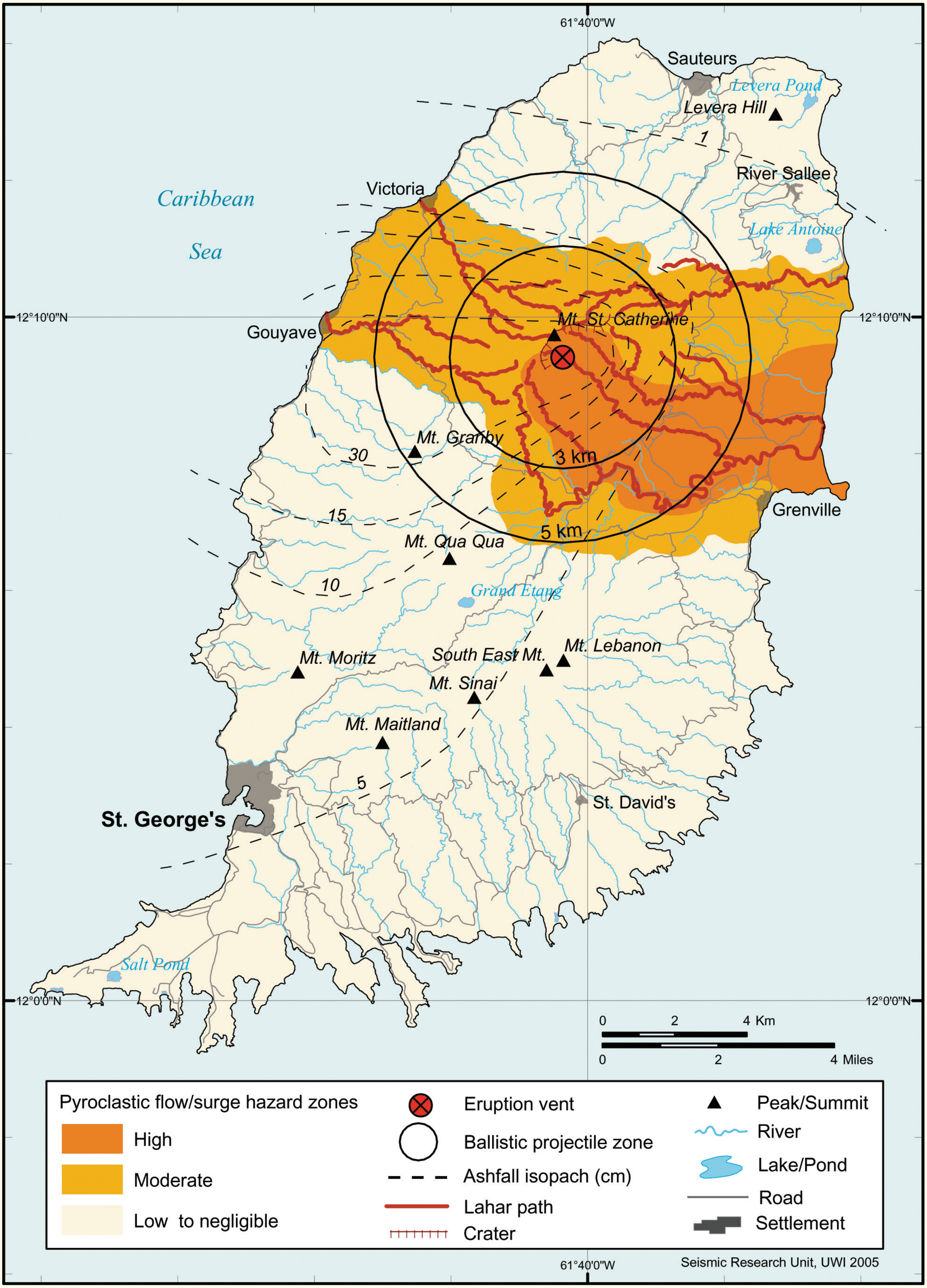
Explosion craters on Grenada

Although Mt. St. Catherine is the only live volcano on Grenada, the presence of a number of explosion craters on the island suggests the possibility that such craters can develop. Given our present understanding of the island's geology it is not possible to determine exactly where on the island such explosion craters will develop in the future. However, the existing craters define a NNE-SSW trend which may be controlled by NE-SW faulting. It is possible that the development of such craters may be tectonically controlled and, as such, future activity of this type may follow a similar trend. It is therefore possible to define a region where explosion craters are most likely to develop. Future activity at explosion craters is likely to involve the explosive ejection of ash and rock fragments. The main hazards from such activity will be ash falls and ballistic projectiles. Based on the distribution of deposits from existing craters it is unlikely that the hazardous impact will extend beyond a 3 km region around the vent.

Queens Park explosion crater, the site of the National Stadium and a well populated area in Grenada

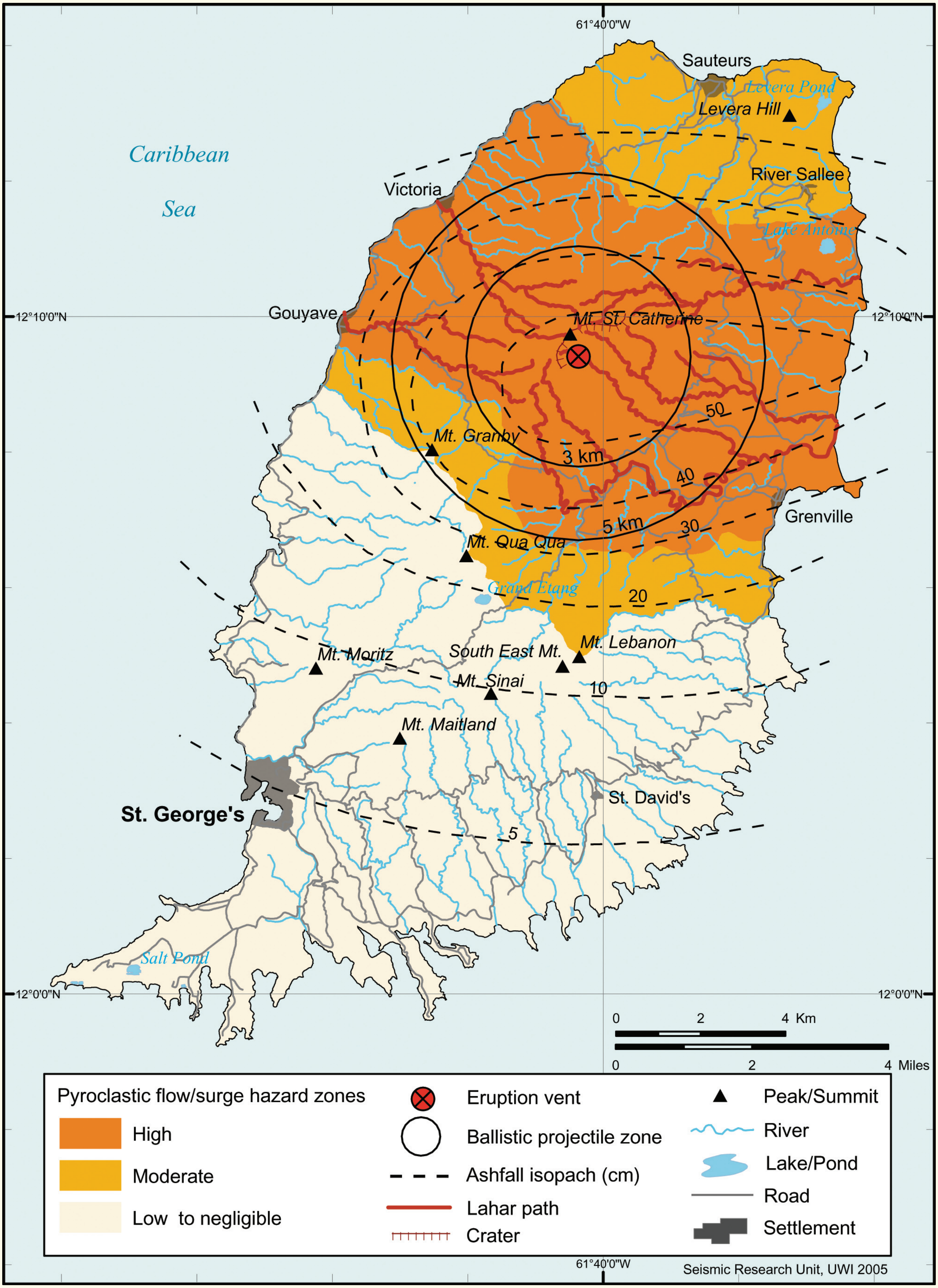
Most likely region within which explosion craters may develop on Grenada

Volcanic hazard map for eruption Scenario 2: Effusive dome growth from Mt. St. Catherine



Seismic Research Unit, UWI 2005

Volcanic hazard map for eruption Scenario 3: Explosive eruption from Mt. St. Catherine



reaches of the St. Patrick river. The closer proximity of major population centres to the east and west of the volcano means that these areas will be most adversely affected.

The pattern of ash fall thickness and distribution exhibited during the 1902 eruption of the Soufrière in St. Vincent (Robertson 1992) has been used to define a possible ash fall pattern for this scenario.

Integrated Volcanic Hazard Zones

The hazard maps have been used to derive integrated volcanic hazard zones for future volcanic eruptions from Mt. St. Catherine. These zones attempt to give an indication of the overall hazard in different parts of the island so as to enable disaster officials to better prepare for future activity (including the assessment of volcanic risk).

The effects of each hazard have been combined for each scenario to produce maps that show zones of relative hazard from future volcanic eruptions on the island. These zones range from 1 to 4 with Zone 1 representing an area of highest hazard. The derivation of these zones are described below.

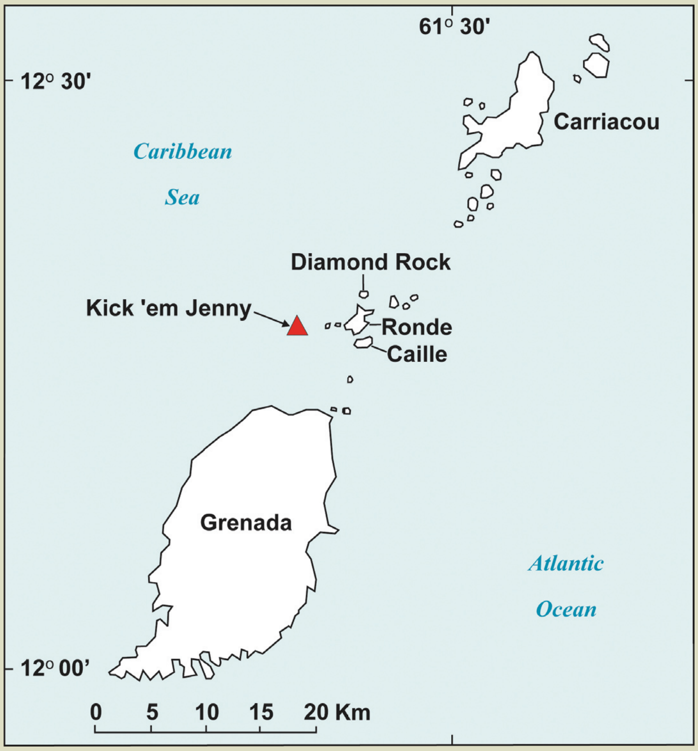
Zone 1 (red) includes all the areas of high pyroclastic flow and surge hazard, all lahar paths and the area within the 3 km radius ballistic projectile zone. This zone is also expected to experience >30 cm of ash fall and numerous lahars. It is probable that there will be total destruction of buildings and property in Zone 1. This zone will need to be evacuated prior to the onset of eruptive activity. Zone 2 (orange) includes all the areas of moderate pyroclastic flow and surge hazard and the area within the 5 km ballistic projectile zone. Ash fall thickness is expected to range from 10-30 cm within this zone. Zone 3 (yellow) is an area of moderate hazard whose boundary with Zone 4 is defined by the 5 cm ash isopach. This area is not expected to be affected by pyroclastic flows and surges, lahars or ballistic projectiles. In two areas the potential lahar paths extended north of this zone, and a 250 m buffer was applied to the river valleys in question so as to define the extension of Zone 3 into the area of low hazard. Zone 4 (green) is an area of low hazard in which little or no direct effect of the volcano will be felt. The area may experience periodic light ash fall, mainly in the event of the worse case explosive eruptive scenario. Ash fall thickness is expected to be <5 cm in this zone. Both zones 3 and 4 are not expected to be affected by pyroclastic flows and surges, lahars or ballistic projectiles.

St. George's capital of Grenada showing the harbour that now occupies the explosion crater located at this site

HAZARDS FROM KICK 'EM JENNY

Eruptions of Kick 'em Jenny submarine volcano to the north of the island could produce ash fall that may affect the northern parts of the Grenada including offshore islands. The effects of tsunamis may extend further south although these events are presently considered to be unlikely from Kick 'em Jenny. Full details of the potential effects of this volcano on Grenada can be found in the Kick 'em Jenny and Île de Caille chapter in this volume.

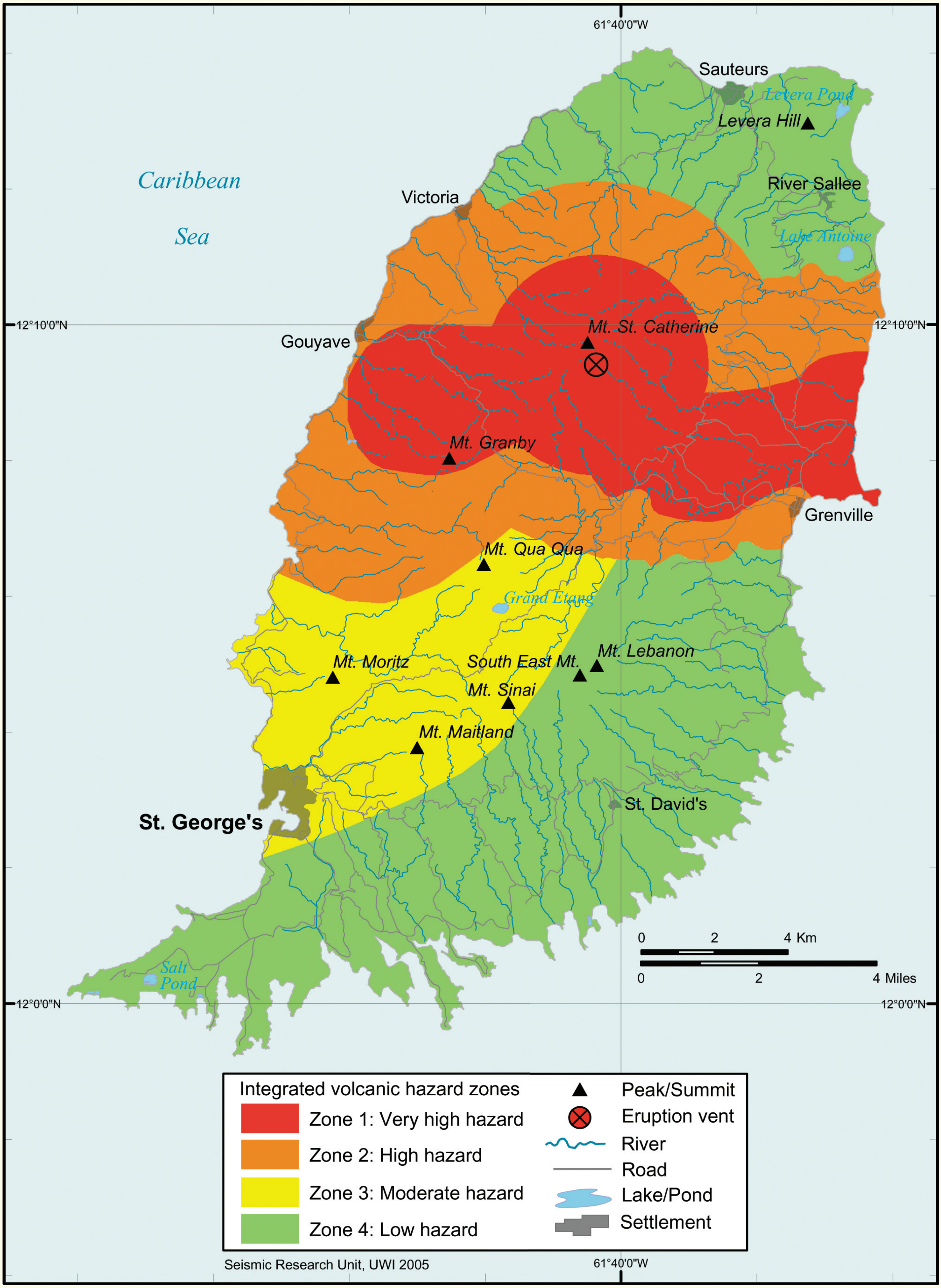
Location of Kick 'em Jenny and Île de Caille in the Grenada Grenadines, showing their close proximity to Grenada



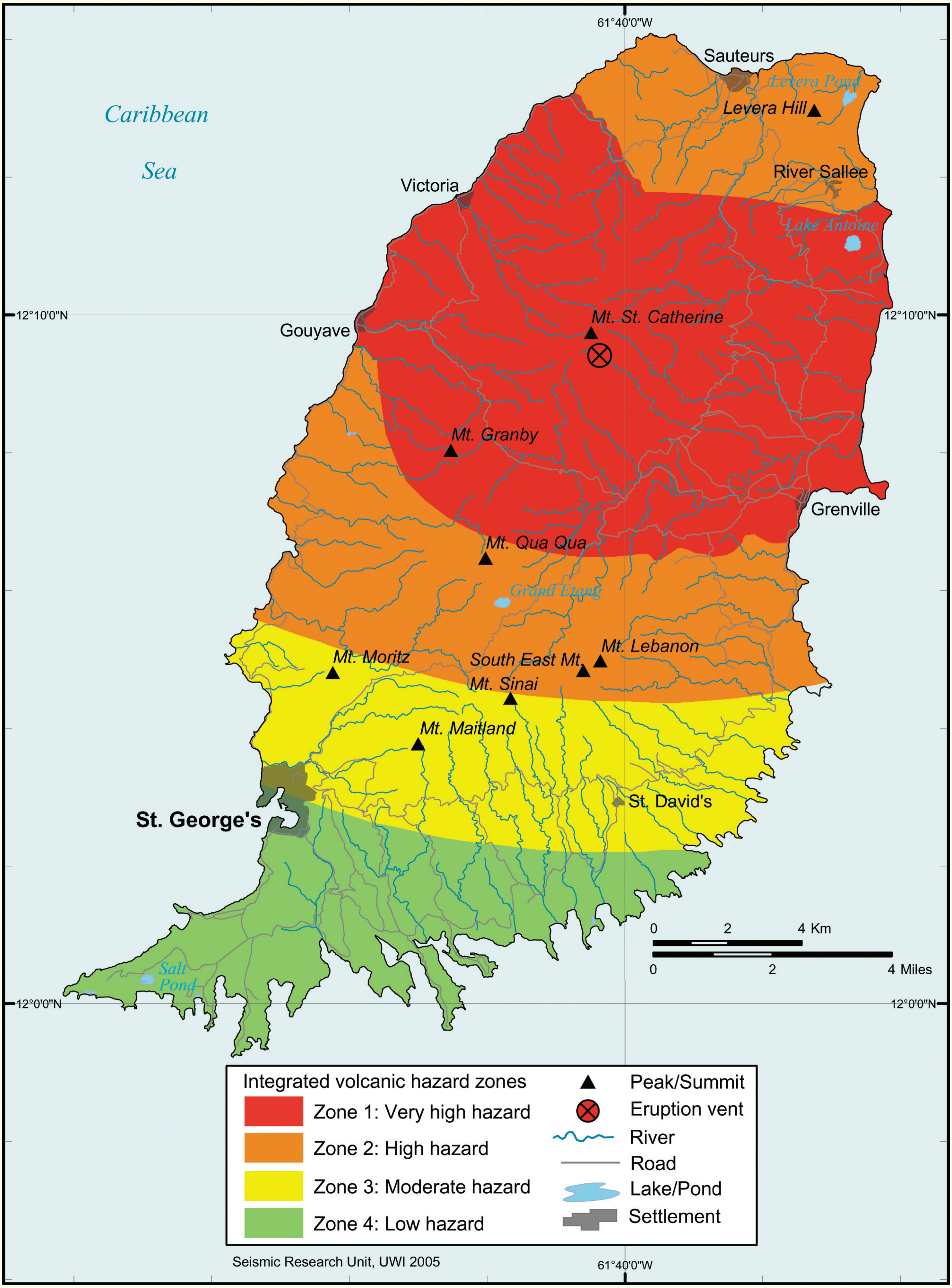
Conclusion

Future volcanic activity in Grenada is most likely to involve phreatic outbursts from fumaroles associated with Mt. St. Catherine volcano. However, plans should be made for the possibility of monogenetic craters developing anywhere along a northeast-southwest trending zone that extends the length of the country. In terms of magmatic eruptions, the most likely event will be an effusive dome-building eruption from Mt. St. Catherine, the only live volcano on the island. This eruption is likely to develop in a very similar manner to the 1995 eruption of the Soufrière Hills Volcano on Montserrat. The potential impact of hazardous volcanic activity on the island may necessitate evacuation of vulnerable communities on the eastern flank of the volcano and provision for further evacuation should the eruption continue. A much less likely but potentially more devastating eruption would involve explosive magmatic activity at the volcano.

Integrated volcanic hazard map for eruption Scenario 2: Effusive dome growth from Mt. St. Catherine



Integrated volcanic hazard map for eruption Scenario 3: Explosive eruption from Mt. St. Catherine



The integrated hazard maps presented in this chapter should be used by emergency management officials to draft contingency plans for the various scenarios that have been described. One of the key elements in future preparedness must be continuation of the volcano monitoring program. This will allow authorities to be forewarned of an impending crisis, and provide them with sufficient time to fine-tune response plans which should now be drafted.

Bibliography

Anderson T, Flett JS (1903) Report on the Eruption of the Soufrière of St. Vincent in 1902 and on a Visit to Montagne Pelée in Martinique. Part I. Philos Trans R Soc London A(200):353-553

Andrew EM, Masson-Smith D, Robson GR (1970) Gravity anomalies in the Lesser Antilles. NERC Inst Geol Sci Geophysical Paper 5

Arculus RJ (1973) The Alkali Basalt, Andesite Association of Grenada, Lesser Antilles. PhD Thesis, University of Durham, pp 1-312

Arculus RJ (1976) Geology and Geochemistry of the Alkali Basalt-Andesite Association of Grenada, Lesser Antilles Island Arc. Geol Soc Am Bull 87:612-24

Arculus RJ (1978) Mineralogy and Petrology of Grenada, Lesser Antilles Island Arc. Contrib Mineral Petrol 65:413-24

Arculus RJ, Curran EB (1972) The Genesis of the Calc-Alkaline Rock Suite. Earth Planet Sci Lett 15:255-62

Arculus RJ, Shimizu N (1974) Rare Earth Elements in a Suite of Basanitoids and Alkali Olivine Basalts from Grenada, Lesser Antilles. Carnegie Institute Washington Year Book, Vol 73

Arculus RJ, Wills KJ (1980) The petrology of plutonic blocks and inclusions from the Lesser Antilles Island Arc. J Petrol 21(4):743-799

Boynton CH, Westbrook GK, Bott MHP and Long RE (1979) A seismic refraction investigation of crustal structure beneath the Lesser Antilles island arc. Geophys J R Astron Soc 58:371-393

Briden JC, Rex DC, Faller AM, Tomblin JF (1979) K-Ar Geochronology and Palaeomagnetism of Volcanic Rocks in the Lesser Antilles Island Arc. Philos Trans R Soc London A(291):485-528

Brown GM, Holland JG, Sigurdsson H, Tomblin JF, Arculus RJ (1977) Geochemistry of the Lesser Antilles Volcanic Island Arc. Geochim Cosmochim Acta 41:785-801

Cawthorn RG, Curran EB, Arculus RJ (1973) A petrogenetic model for the origin of the calc-alkaline suite of Grenada, Lesser Antilles. J Petrol 14(2):327-38

Devine J (1987) Roles of Volatiles in Lesser Antilles Island Arc Magmas. PhD Thesis, University of Rhode Island, pp 1-612

Devine J (1995) Petrogenesis of the basalt-andesite-dacite association of Grenada, Lesser Antilles island arc, revisited. J Volcanol Geotherm Res 69:1-33

Earle KW (1924) Geological Survey of Grenada and the (Grenada) Grenadines. St. George's, Grenada, Government Printing Office

Geotermica Italiana S.r.l. (1991) Reconnaissance Study of the Geothermal Resources of the Republic of Grenada - Final Report. 126: Latin American Energy Organization

Graham AM (1980) Genesis of the Igneous Rock Suites of Grenada. PhD Thesis, Edinburgh University, pp 1-339

Graham AM (1981) Melting relations of island arc lavas from Grenada, Lesser Antilles. Progr Exp Petrol 5:126-132. (NERC Publications, Series D, 18, London)

Harrison JB (1896) The Rocks and Soils of Grenada and Carriacou. Waterlow & Sons, London

Hawkesworth CJ, O'Nions RK, Arculus RJ (1979) Nd and Sr Isotope Geochemistry of Island Arc Volcanics, Grenada, Lesser Antilles. Earth Planet Sci Lett 45:237-48

Hawkesworth CJ, Powell M (1980) Magma Genesis in the Lesser Antilles Island Arc. Earth Planet Sci Lett 51:297-308

Hofmann AW, Feigenson MD (1983) Case studies on the origin of basalt. I. Theory and reassessment of Grenada basalts. Contrib Mineral Petrol 84:382-389

Joseph EP (2003) Sampling of geothermal features in Grenada and St. Vincent 18th-21st June 2003. Internal Report, Seismic Research Unit, St. Augustine, Trinidad

Martin-Kaye PHA (1961) Progress Report No 12. Geological Survey, Windward Islands

Martin-Kaye PHA (1969) A Summary of the Geology of the Lesser Antilles. Overseas Geology and Mineral Resources 10(2):172-206

Norton G, Harford C, Young S (2001) Volcanic Geology of Montserrat, West Indies. Field Guide

Olade (1981) Reconnaissance study of the geothermal resources of the republic of Grenada

Robertson REA (1992) Volcanic Hazard and Risk Assessment of the Soufrière Volcano, St. Vincent, West Indies. MPhil Thesis, The University of Leeds

Robertson R, David J (2002) Ground deformation network on Grenada. Internal Report, Seismic Research Unit, St. Augustine, Trinidad

Robson GR, Tomblin JF (1966) Catalogue of the active volcanoes of the world including solfatara fields, part 20, the West Indies. International Association of Volcanologists, pp 1-56

Sapper K (1903) Ein Besuch Der Insel Grenada. Zentralblatt für Mineralogie, Geologie, Paleontologie 182-186

Shepherd JB (1985) Internal Report on the Geological Activities in the Mt. St. Catherine Area. Internal Report, Seismic Research Unit, St. Augustine, Trinidad

Shimizu N, Arculus RJ (1975) Rare earth element concentrations in a suite of basanitoids and alkali olivine basalts from Grenada, Lesser Antilles. Contrib Mineral Petrol 50:231-240

Sigurdsson H, Tomblin JF, Brown GM, Holland JG, Arculus RJ (1973) Strongly Undersaturated Magmas in the Lesser Antilles Island Arc. Earth Planet Sci Lett 18:285-95

Speed RC, Smith-Horowitz PL, Perch-Nielsen KvS, Saunders JB, Sanfilippo AB (1993) Southern Lesser Antilles arc platform: Pre-Late Miocene stratigraphy, structure, and tectonic evolution. Geol Soc Am Special Paper 277, pp 1-98

Thirlwall MF, Graham AM (1984) Evolution of High-Ca, high-Sr C-series basalts from Grenada, Lesser Antilles - the effects of intra-crustal contamination. J Geol Soc London 141:427-45

Thirlwall MF, Graham AM, Arculus RJ, Harmon RS and Macpherson CG (1996) Resolution of the effects of crustal assimilation, sediment subduction, and fluid transport in island arc magmas: Pb-Sr-Nd-O isotope geochemistry of Grenada, Lesser Antilles. Geochim Cosmochim Acta 60(23):4785-4810

van Soest MC, Hilton DR, Kreulen R (1998) Tracing crustal and slab contributions to arc magmatism in the Lesser Antilles island arc using helium and carbon relationships in geothermal fluids. Geochim Cosmochim Acta 62:3323-3335

Acknowledgements

This chapter represents work specifically commissioned for the *Atlas* project. The hospitality of the people of Sauteurs during one month of field work on Grenada is greatly appreciated. Funding for fieldwork on Grenada was obtained from the Caribbean Development Bank (CDB) through its Disaster Mitigation Facility for the Caribbean (a partnership between CDB and USAID Office of Foreign Disaster Assistance). The author would like to thank all the staff of the Seismic Research Unit for their help, in particular Patricia Joseph for geothermal data and Shahiba Ali for preparation of most of the maps. The chapter greatly benefited from detailed reviews provided by Joe Devine, Jan Lindsay and Lee Siebert.

Photograph Credits

All photographs were taken by the author.