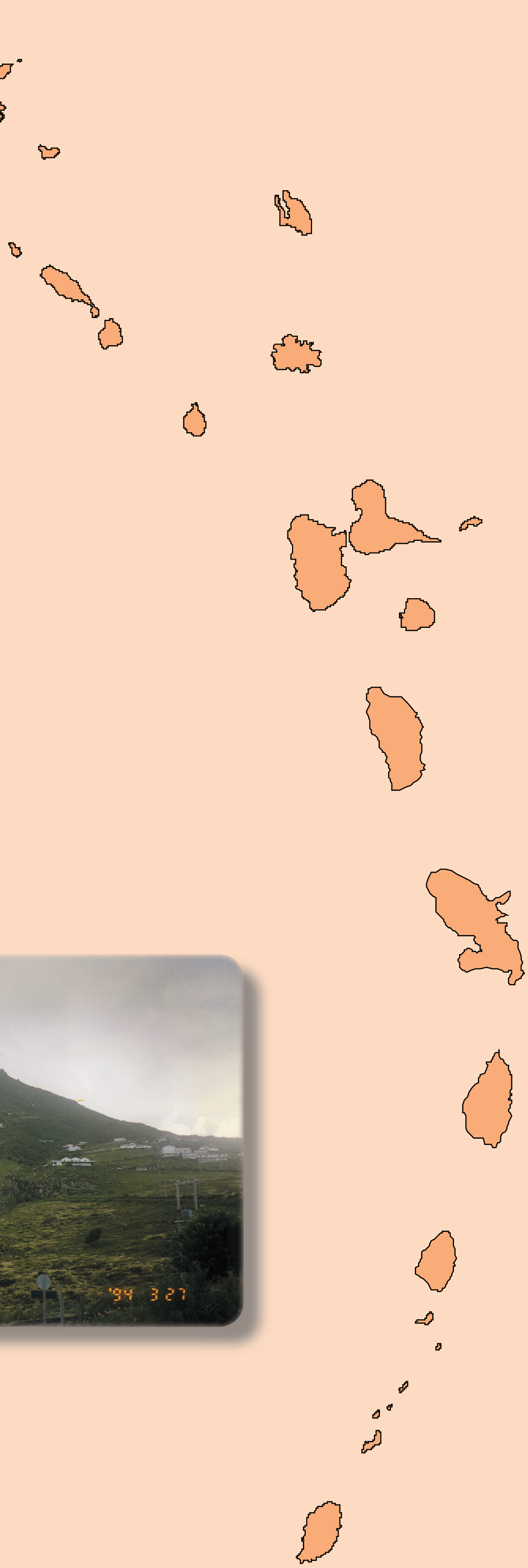
Saba



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Abstract

The island of Saba is a complex stratovolcano composed of over 20 andesitic domes produced by Pelean-style eruptions. Other eruptive styles have occurred in the past, but these are represented by only a small percentage of the island's stratigraphy. The last identified eruption was a small Pelean eruption from Great Hill that has been dated at 280 years BP, just prior to European settlement of the island. The most likely scenario for renewed magmatic activity would be an explosive Pelean-style eruption from a vent somewhere within the NE-SW fault zone that crosses the island. The eruption would produce a dome and associated pyroclastic deposits. Such activity could be preceded by increased seismicity and/or phreatic or phreatomagmatic eruptions that could occur tens, or in some cases hundreds, of years before an actual magmatic eruption. Because of its small size, the entire island falls within the zone of very high hazard so that in the event of any type of precursor activity the whole island would need to be evacuated.

Introduction

The information in this contribution has been compiled by the authors from past studies on Saba, the results of which are presented in greater detail in Roobol et al. (1997) and Roobol and Smith (2004). Funding for these studies was provided by the Netherlands Geological Survey, together with grants from NASA and the National Science Foundation of the USA.

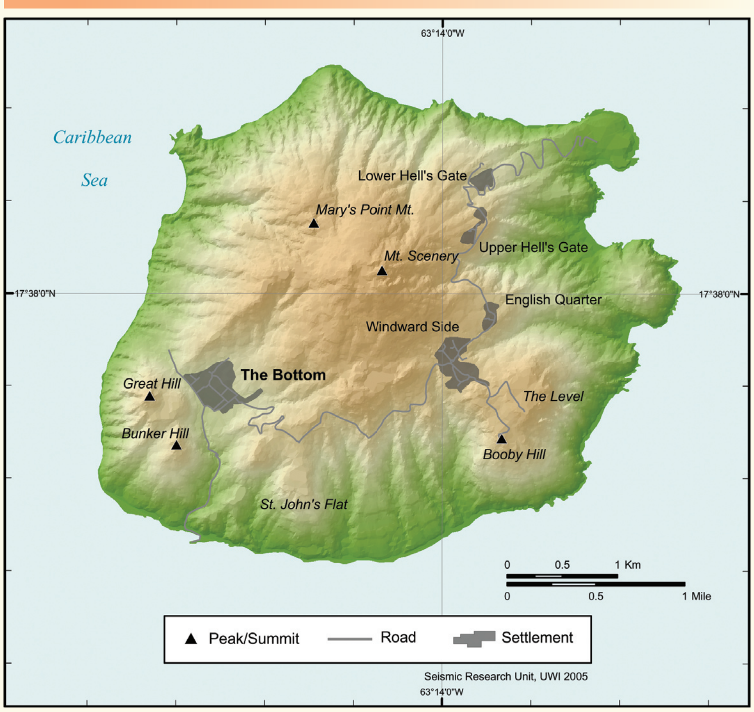
Geographical Setting

Saba is the northernmost of the islands that make up the active arc of the Lesser Antilles. The island has an approximate area of 13 km^2 with a population of around 1,400. The administrative capital of the island is The Bottom, located on the southwest side of the island. The two points of entry to the island are its harbour, located at Fort Bay on the southwest coast and the airport located at the island's northeast corner. Although the island is dominated by Mt. Scenery (until recently called The Mountain), which rises to 887 m above sea level, it is also characterised by the presence of numerous hills, e.g. Booby Hill, Bunker Hill and Great Hill, giving the island a very irregular topography. Much of Saba is covered by relatively dense vegetation, especially on the upper slopes of Mt. Scenery which supports a tropical rainforest.

Previous work

The geology and petrology of Saba were described by Westermann and Keil (1961), who also summarised the earlier geological literature of the island (Cleve 1871, 1882; Molengraff 1931; LaCroix 1890, 1893; Hovey 1905; Sapper 1903, 1904; Boldingh 1909 and Perret 1942). More recent studies include Smith et al. (1978); Baker et al. (1980); Roobol and Smith (1980a,b); Smith et al. (1980); and Defant et al. (2001), this last publication being based on an unpublished MS thesis by Sherman (1992). Sapper (1903), Kruythoff (1939), Gunlaugsson (1981) and Roobol et al. (1981, 1997) have reported the temperatures of the hot springs. Initial GPS measurements on the island were reported by Mattioli et al. (1999). Ambeh and Lynch (1995) gave an account of the 1992 earthquake sequence. The first assessment of the island's volcanic hazard was made by Roobol and Smith (1978-1981), the results of which were submitted to the Netherlands Geological Survey (Roobol et al. 1981). This report was made confidential by the Netherlands Antilles Government but was finally published in 1997 (Roobol et al. 1997). Extensive additional work on Saba was conducted by Roobol and Smith during the period 1981 to 1997. A comprehensive memoir of this work has been published by the Royal Netherlands Academy of Arts and Sciences (Roobol and Smith 2004).

Relief Map of Saba

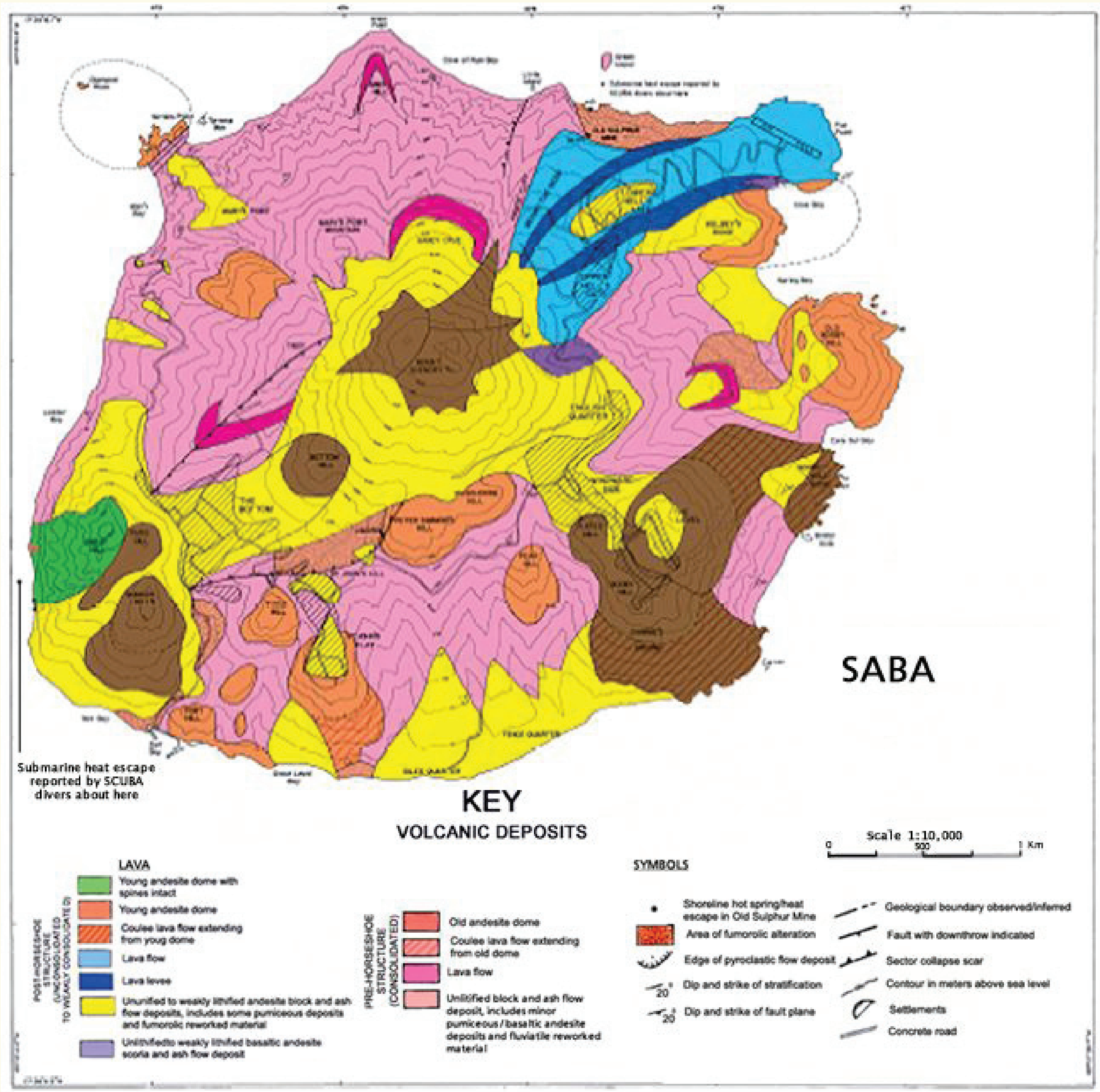


The Bottom village

Geology

In general terms, the island of Saba can be regarded as a single stratovolcano. However it is not a simple structure, as its flanks are dominated by the presence of about twenty andesitic domes, most of which are associated with near-vent, coarse block and ash flow deposits. However four of these domes (Bunker Hill, St. John's Flat, Booby Hill, The Level) do not appear to have associated aprons of pyroclastic material, but instead pass into thick, steeply-dipping andesitic lava flow extensions orientated down slope (seaward) or radially outwards from the dome. The stratovolcano-like appearance of Saba results from the fact that Mt. Scenery is composed of a complex of Pelean domes and their surrounding pyroclastic aprons that sit somewhat eccentrically

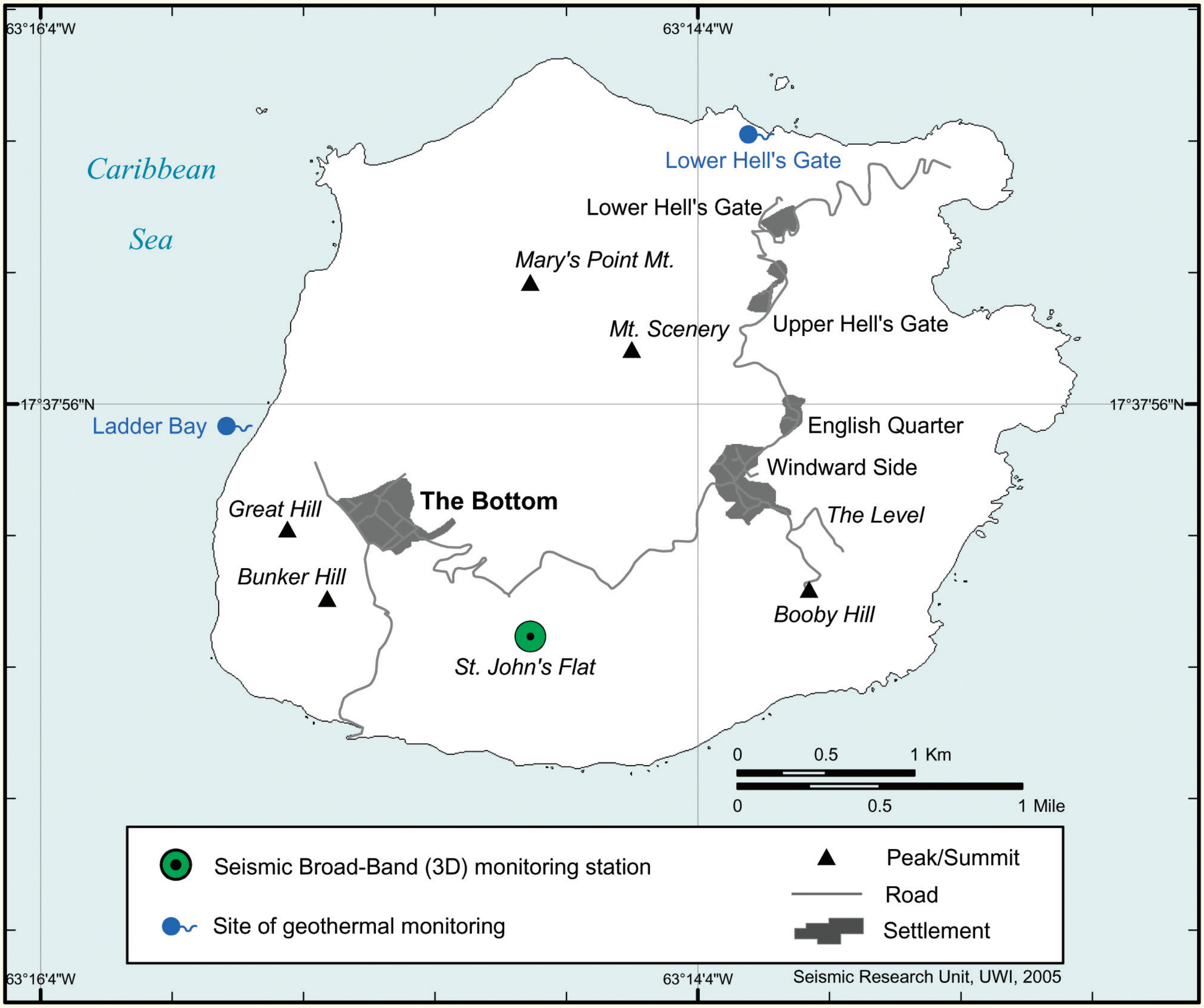
Geological map of Saba



on top of the juxtaposed older Pelean-dome complexes. Andesite and basaltic andesite lava flows are a minor component on Saba, and there is only one well-preserved basaltic andesite flow forming the northeast corner of the island. This flow has pronounced levées and the island's airstrip is built on its flat terminus.

The geology of Saba can be subdivided into two major geological divisions: an older division composed of lithified rocks of dominantly andesitic composition that pre-date the formation of a major sector collapse, and a younger division of weakly lithified to unlithified rocks also of andesitic composition that post-date this event. The sector collapse scar has an elongate horseshoe shape that opens to the southwest with a maximum width below Mt. Scenery of 1.2 km and is partially exposed for a length of 2.5 km. The structure has now been largely infilled by the Mt. Scenery dome/pyroclastic complex, however its rim is preserved as a series of flats or levels around the island. The age of the structure is not known but can be approximately estimated at around 100,000 years because it cuts across the oldest parts of the island where the pyroclastic deposits are lithified and it is largely infilled by weakly lithified to unlithified deposits (Roobol and Smith 2004).

Block and ash flow deposits and associated surge deposits dominate the stratigraphy of Saba indicating that the dominant pyroclastic volcanism that built up both stratigraphic divisions of the subaerial superstructure of the island was Pelean-style.



Deposits representing other volcanic styles (St. Vincent, Asama and Plinian) are relatively minor (Roobol and Smith 2004).

Although the volcanic rocks from Saba range from basalt to dacite (SiO_2 from 49 to 65%) approximately 75% of the rocks are andesites. Rocks from both stratigraphic divisions (pre- and post-sector collapse) are indistinguishable on geochemical variation diagrams suggesting a single magmatic suite.

Mt. Scenery

Volcano monitoring

During the late 1970s and early 1980s Lamont Doherty Geological Observatory (LDGO) operated a single one-component seismometer in Saba as part of their northeastern Caribbean network. After that, the island remained without local geophysical monitoring until 1992, when, in response to an unusual number of earthquakes being felt in Saba, the Government of the Netherlands Antilles invited the Seismic Research Unit to install monitoring instruments locally to increase the detection capability to include the smallest earthquakes occurring close to Saba. At that time, the nearest station in the permanent regional network was located in St. Kitts some 55 km away from Saba. As a result, a seismometer was installed on Mt. Scenery on 14 June 1992, as well as an additional seismometer on both St. Eustatius and St. Martin. This seismometer is still in operation as of 2004. Other monitoring methods include measurement of hot spring temperatures, which has been carried out sporadically since these springs were first described by Sapper (1903), and campaign-style GPS surveys, using a network of five stations, that have been carried out on a regular basis since 1997 by Mattioli (Mattioli et al. 1999; Mattioli unpub. data).

West coast cliffs, showing sequence of block and ash flows deposits

Potentially active volcanic centres

Saba volcanic centre

The island of Saba represents the subaerial part of a single volcanic complex formed dominantly of multiple Pelean-style eruptions resulting in domes and associated pyroclastic fans.

Past eruptive activity

The subaerial evolution of Saba can be divided into four stages. During Stage 1, at about 500,000 years BP, the island developed a complex of andesitic Pelean domes and dome flows surrounded by aprons of pyroclastic material. During Stage 2, between approximately 400,000 and 100,000 years BP, Plinian-style activity produced andesitic-dacitic pumiceous fall and flow deposits along with the more ubiquitous Pelean activity. Some andesitic lava flows were also produced at this time. During Stage 3, at about 100,000 years, the horseshoe-shaped structure formed, probably by gravitational sector collapse of a zone of hydrothermally altered rocks (Reid et al. 2001) triggered perhaps by inflation of the volcanic edifice and/or earthquakes. The exposed walls of the structure reveal the hydrothermally-altered core of the volcano in the area of the present-day village of The Bottom. During Stage 4, from approximately 100,000 years BP to the present, the horseshoe-shaped structure was progressively infilled by andesitic domes and pyroclastic material. In addition, a number of parasitic flank Pelean domes, with aprons of unconsolidated andesitic block and ash flow deposits, as well as dome flows were extruded. The basaltic andesite lava flows outcropping between Upper Hell's Gate and the airport probably also belong to this stage, as do the pyroclastic deposits representing St. Vincent and Asama-styles of activity. The most recent eruption of Saba is thought to be represented by a dense andesite surge deposit containing accretionary lapilli described from a pit dug in The Bottom (Roobol et al. 1997; Roobol and Smith 2004). This deposit which has been dated at 280±80 years BP, occurs below layers of fluviatile sands and mudflow/lahar deposits containing European style pottery fragments, and above two Amerindian occupation levels, the upper one of which has been dated at 525±66 years BP.

Booby Hill dome

Age determinations

Only four radiocarbon ages were obtained from Saba, all are from the younger stratigraphic division that post-dates the horseshoe-shaped structure. The youngest age of 280 years BP was obtained from dispersed small charcoal fragments contained in a thin ash surge with accretionary lapilli believed to represent the most recent eruption on Saba. Two of the other dates are from charcoal associated with human activity. One is from an Amerindian cooking fire (525 years BP), and the other from a conch shell hand-axe (3,155 years BP) buried in a fine-grained ash showing a weakly developed soil (Roobol and Smith 1980b). The association of pyroclastic deposits with evidence of Amerindian occupation of Saba suggests that volcanism was contemporaneous with an Amerindian population who occupied the island at least for brief intervals for almost 2,500 years before European settlement. The fourth date (34,750 years BP) was obtained from a semi-vesicular clast from a block and ash flow deposit exposed in a cistern pit in The Level. In addition, three $^{39}Ar/^{40}Ar$ ages ranging from 0.21 to 0.42 Ma have been reported by Sherman (1992) and Defant et al. (2001) which support the suggestion that the age of the horseshoe-shaped structure is around 100,000 years.

Radiometric age dates for Saba (Roobol and Smith 2004[1]; Defant et al. 2001[2])

Type of deposit	Location	Age ± 1 std. deviation
Dense andesite surge	Pit in The Bottom	280 ± 80 years BP[1]
Paleosol	Pit in The Bottom	525 ± 60 years BP[1]
Conch shell handaxe	Alongside road between The Bottom and Fort Bay	3,155 ± 65 years BP[1]
Semi-vesicular andesite block and ash flow	Pit in The Level	34,750 ± 850 years BP[1]
Lava flow	Immediately north of The Bottom within wall of horseshoe-shaped structure	0.21 ± 0.09 Ma[2] 0.13 ± 0.09 Ma[2]
Lava flow	Below Hell's Gate	0.36 ± 0.15 Ma[2]
Dome	Torrens Point	0.42 ± 0.07 Ma[2]

South coast of Saba, showing The Bottom and Windward Side villages; peak is Mt. Scenery

Historical eruptions

There have been no reports of volcanic eruptions on Saba in historical time, although the youngest radiocarbon age indicates that an eruption probably occurred just prior to European settlement of the island.

Geothermal activity

Hot springs have long been known on the island of Saba and were first described by Sapper (1903). Today three hot springs are known at sea level around the coast of the island, and heat is escaping from a sulphur mine adit high in the sea cliffs near Lower Hell's Gate and at two shallow submarine sites.

Hot springs at Well Bay.

Hot springs at Well Bay were reported by Sapper (1903), however by 1939 they had been overwhelmed by the sea and had disappeared (Kruythoff 1939). Recent searches for these springs have failed to locate them, so we have no record of their present-day temperature.

Hot springs between Ladder Bay and Tent Bay.

These are the most accessible of the hot springs on Saba. They are located 900 m south of the Ladder (the stone steps leading down the sea cliff to Ladder Bay), below the steep, high cliffs that truncate the Great Hill dome. Two closely-spaced springs occur at sea level and are just covered by seawater at high tide. Temperature measurements of these springs indicate that from 1903 to the mid-1990s the temperature appears to have been constant at or around 55 °C, however in January 1997, it was found to have increased to 62 °C. A further measurement in August 1997 indicated that the temperature was still at an elevated level. More recent measurements by representatives of the Saba Marine Park indicate that the temperature has subsequently decreased to its more normal values.

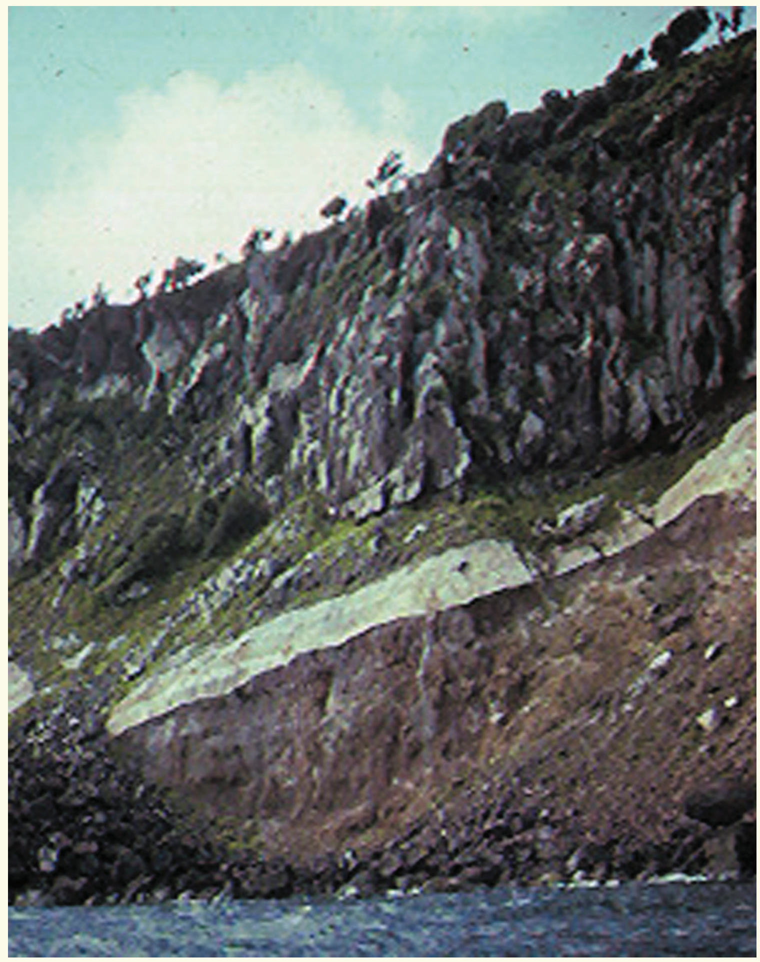
Measurements of volcanic heat emission on Saba

Date	Hot spring, 900m south of Ladder	Hot Spring opposite Green Island
1903[1]	54.2 °C	
1950[2]	55-57 °C	
1979[3]	51-55 °C	72 °C
1981[4]	55 °C	66.5 °C*
1994[3]	54.2 °C	54 °C*
1996[3]		80 °C, 82 °C
1997[3]	62 °C 62 °C	
1998[3]		79 °C

References: [1]Sapper (1903); [2]Westermann and Keil (1961); [3]Roobol and Smith (2004); [4]Gunnlaugsson (1981)
**Submerged, probably minimum temperature*

A hot spring opposite Green Island

This hot spring is situated on the northern shoreline immediately below the abandoned sulphur mine and opposite Green Island. Access both from the sea due to the high surf, and from land, down a vertical cliff below Lower Hell's Gate is difficult. The spring occurs at sea level and is often covered by surf, boulders and gravel. It was not recorded by Sapper (1903) nor Westermann and Kiel (1961), but was known to the islanders who reported that sometimes in winter, steam could be seen rising from the shore at this point.



Exposure on the northeast coast of a lava flow overlying a sulphur layer which was mined about 100 years ago

The temperature of this hot spring was measured on July 27, 1979 and found to be 72 °C. It was next visited by Gunlaugsson (1981), who found it buried in sand, but was able to measure a temperature of 66.5 °C. This indirect measurement of the temperature of the spring water is probably lower than the emission temperature. When revisited on March 9, 1994, it was again deeply buried in sand, and the spring was hidden. Direct measurement was not possible, but a maximum temperature of 54 °C was obtained. This measurement also does not reflect the true temperature of the spring, which was not determined. In April, and again in September 1996, residents of the island measured the spring and its temperature was found to have increased to 80 and 82 °C respectively. It appears that the temperature of this spring and the Ladder Bay spring both increased between 7 to 12 °C sometime between March, 1994 and April, 1996.

Entrance to Sulphur mine

Heat escape from the sulphur mine adit

On the north coast, near Lower Hells Gate a pyroclastic layer immediately beneath a prominent andesitic lava flow has been extensively altered. Native sulphur concentrated in this layer was commercially mined during the late 19th and early 20th centuries. The abandoned sulphur mine adit, situated at the top of the sea cliffs directly above the shoreline hot spring opposite Green Island, is also the site of heat escape. In 1994, a maximum air temperature of 32.5˚ C, was found at the deepest point at the back of the mine in a short vertical shaft leading up from the adit.

Submarine hot springs

The formation of the Saba Marine Park around the island in 1987, and resulting tourist SCUBA activity, has resulted in the identification of two areas of heat escape on the seabed. One of these locations is in 10 m of seawater about 150 m offshore of the Ladder Bay hot spring in Ladder Bay. No temperature measurements have yet been made at this site. A second site of underwater heat escape was located in 1994. It lies on the seabed between Green Island and the hot spring on the shoreline below the sulphur mine; again there are no temperature measurements for this location.

Other reported areas of heat escape on Saba Island

There exist other reports of heat escape on Saba island, only one of these is regarded as reliable. A newspaper report in 1995 noted that a cave on the upper northeast side of Great Hill had rocks at depth of at least 200 m that were too hot to touch. This report is considered reliable, as the position of the hot rocks inside the Great Hill dome is approximately 400 m horizontally from the hot springs at Ladder Bay.

At the present time heat is escaping from the island of Saba and immediately off its shores at six locations. These occur in two clusters of three on opposite sides of the island along a line orientated southwest-northeast. In the northeast, the three occurrences of the sulphur mine adit, the shoreline opposite Green Island and the seabed near Green Island occupy a horizontal length of 300 m. In the southwest, the hot springs dive site, the Ladder Bay springs, and the cave with hot rocks in Great Hill occupy a horizontal distance of 600 m. The northeast-southwest direction outlined by the hot springs may well mark a fault through the submarine banks beneath the island of Saba. Such a fault may also control the location of the main Saba vent. The existence of this possible fault is further supported by the location of recent earthquake epicentres in the area and also by the orientation of the horseshoe-shaped sector collapse scar.

Seismicity

Since the settlement of Saba in 1640, and up to and including the publication of the work of Westermann and Kiel in 1961, there appear to be no records in Saba of felt seismic activity. Neither are there any records of local micro-seismic activity during the period of operation of the LDGO station. During the past 10 years, however, there have been reports of felt earthquakes of magnitude greater than 4.0 located in the northern Leeward Islands. Saba has also been affected by small tectonic earthquake sequences consisting of foreshocks, a main shock and some aftershocks.

The 1992 felt seismic sequence

In June 1992, a minor earthquake sequence occurred near Saba, some of the events of which were felt and heard by the populations of Saba, St. Kitts and St. Martin. The initial period of seismic activity was recorded at the permanent eastern Caribbean seismic stations, and from 1992/06/14 the smallest events were recorded by the local station. According to Ambeh and Lynch (1995), 60 events were detected, of which only 15 were located. The main shock of the sequence that occurred on 1992/06/11 was of duration magnitude, Mt, 4.5 and was felt at Modified Mercalli Intensities of IV-V in Saba, and III in St. Kitts. A plot of epicentres for the period June 5-16 indicated that they all lie on a southwest-northeast trend (Ambeh and Lynch 1995). The focal depths for these events clustered in the range of 10-16 km (Ambeh and Lynch 1995). This orientation, when compared to the faults and lineaments of the submarine banks (Roobol and Smith 2004), suggests that the earthquakes originated on a northeast-southwest fault crossing the submarine banks. The seismic events of 1992 are regarded as wholly tectonic in origin and unrelated to any magmatic activity under the volcano.

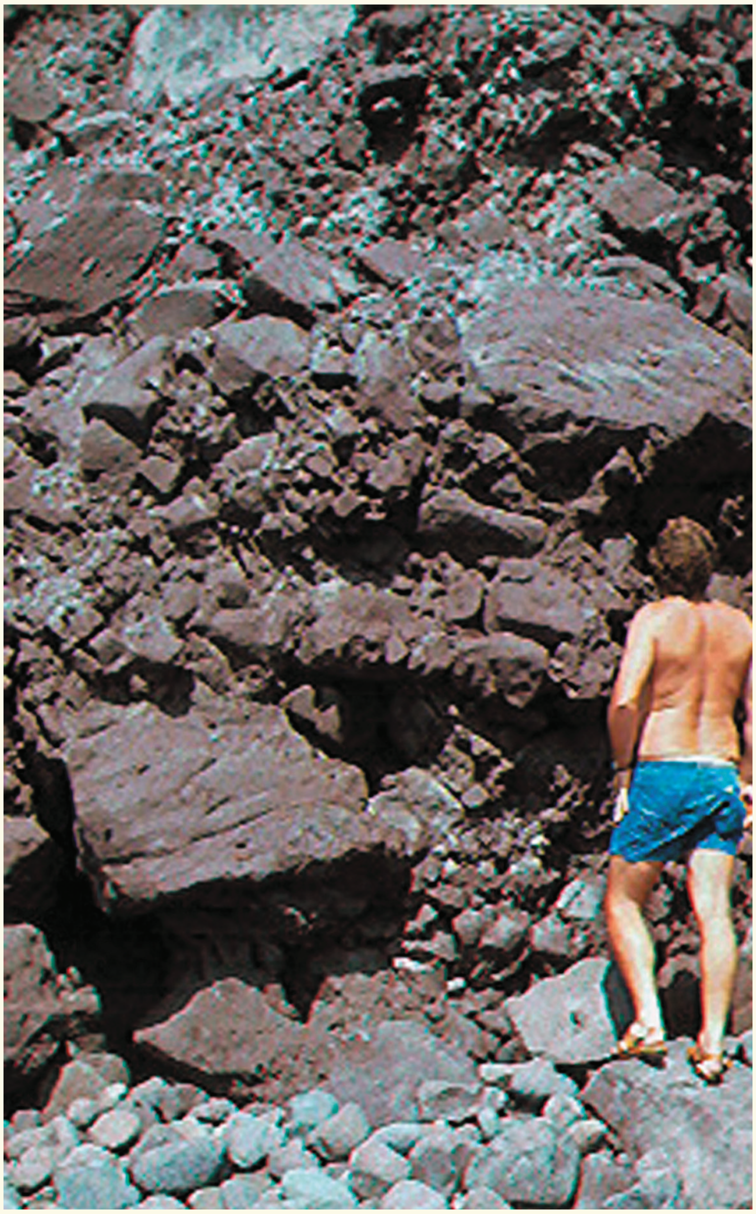
The April 1994 felt earthquakes

An earthquake and six aftershocks occurred on April 21-25, 1994. The main shock had a magnitude of 4.9 and a hypocentre at a depth of 14 km, and was felt with a Modified Mercalli Intensity of V in Saba, St. Kitts and St. Martin (Seismic Research Unit and University of Puerto Rico at Mayaguez unpub. data). The position of the epicentre of the main shock is seen to lie near to Anguilla and St. Martin, on the direct extension of the southwest-northeast alignment of the 1992 swarm. The 1992 and 1994 hypocentre plots provide the first evidence that Saba may have formed astride one of the many faults cutting directly through the arc. Again the 1994 earthquakes are regarded as purely tectonic, related to faulting, and having no relationship to magma movement.

The microseismic activity of 1995 to 1997

Since 1992 and before May 1995, the single seismometer installed in Saba recorded very few small local earthquakes believed to be associated with the volcano. Between May 1995 and April 1997 there was a noticeable increase in the number of such small local earthquakes with a peak in December 1996 when there was a burst with a total of 64 events being recorded during that month. The 1995-1997 microseismic activity is believed to be associated with the 7-12˚ C temperature increase of the hot springs recorded on the island between 1994 and 1996.

These events can be considered a mild volcano-seismic crisis, and the increased heat flow may have resulted from the opening of new fissures beneath the island permitting deeper circulation of groundwater. The possibility of renewed magma movement beneath the island, however, cannot be eliminated.



Deposits from Great Hill Dome

Future eruptions

Past activity on Saba indicates that the most likely style of future magmatic activity will be a Pelean–type eruption involving the growth of a lava dome accompanied by the development of block and ash flows and associated surges. Deposits from past eruptions suggest that the most likely mechanism for the generation of these pyroclastic flows would be by gravitational dome collapse, rather than explosive dome collapse. However, since Saba has not erupted for over 300 years, the initial activity would most probably not be magmatic but rather phreatic or phreatomagmatic in style, and it is highly possible that the renewed activity may not progress any further. Volcano-seismic activity without any associated eruptive activity is also a possible scenario. Both of these types of activity could occur more than once before a magmatic eruption and could precede one by tens or even hundreds of years. Although not as common, Saba has experienced other styles of activity, including St. Vincent-, Asama- and Plinian-style explosive eruptions, as well as effusive eruptions that have produced lava flows and dome flows, suggesting that these styles of activity also need to be taken into account in any hazard assessment.

Volcanic Hazards

Based on past activity the dominant volcanic hazard on Saba would be the growth of a dome and associated pyroclastic activity (ash and dust falls, block and ash flows, dense andesite surges). The area affected would depend on the location of the new vent which, based on the geological evolution of Saba, is not possible to predict. Three scenarios are likely: 1) renewed activity at Mt. Scenery; 2) the opening of a new subaerial vent somewhere within the possible NE-SW fault zone cutting the island; 3) the opening of a submarine vent within this fault zone.

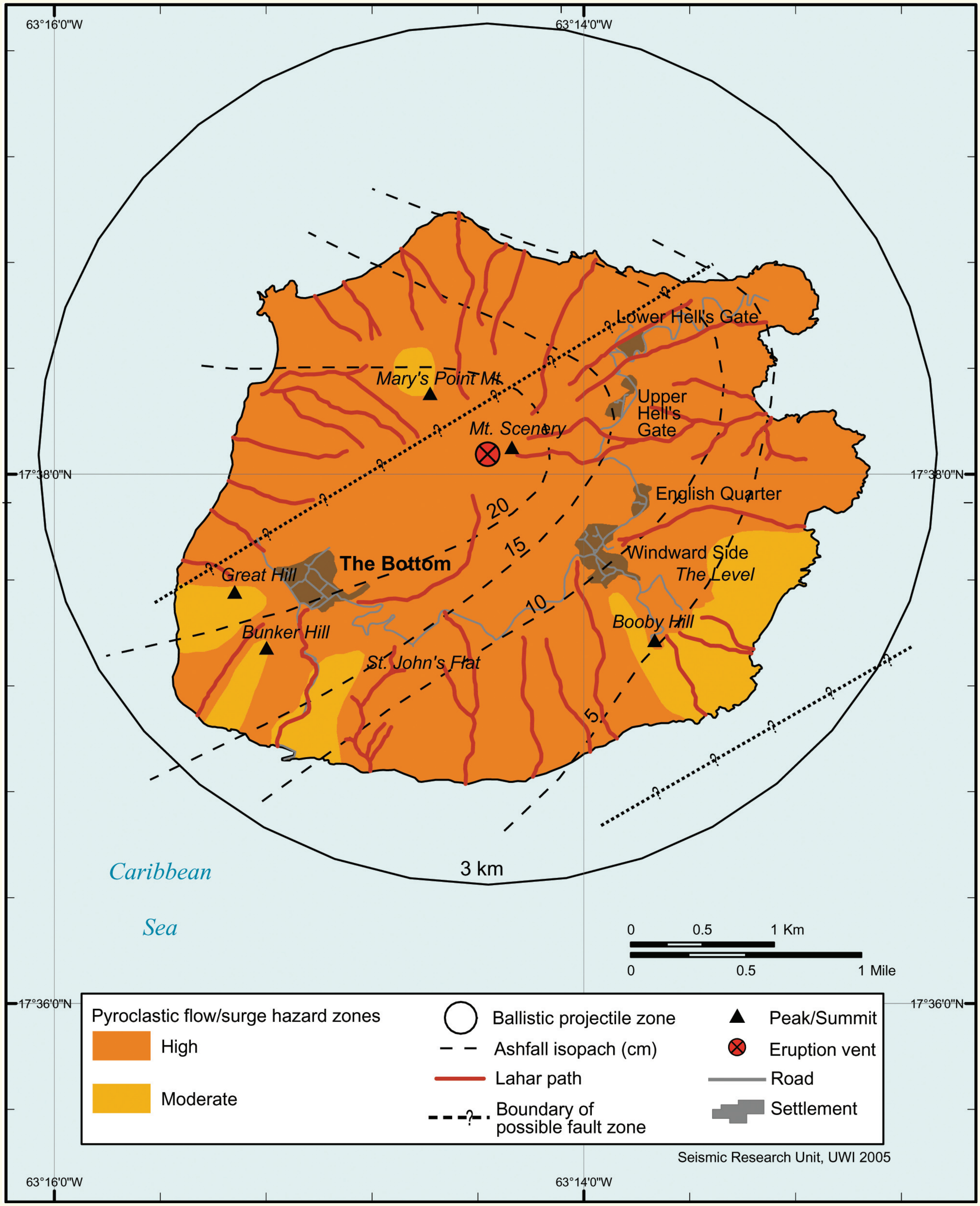
A submarine eruption would probably initially only affect the immediate coast near the vent and thus not directly endanger the island's population. Ash produced by explosions from a vent off the NE coast could affect the island's airport as well as the villages of Upper and Lower Hell's Gate, whereas a vent off the south coast within the SW extension of this probable fault zone (e.g. offshore of Great Hill), could affect access to the island's only harbour. Ash from explosions at such a vent would most probably be directed out to sea as a consequence of the prevailing surface winds. If any submarine vent, as a consequence of repeated eruptions, became joined to Saba, then the danger would be significantly increased as flows and surges would now have an opportunity to reach the island's shores. The steep cliffs along the NE coast and the domes of Great, Paris and Bunker Hills would afford protection to Upper and Lower Hell's Gate and The Bottom respectively.

For renewed subaerial activity, given the small size of Saba, the opening of any vent in the southern half of the island would place the entire population in a high-risk area. In such a scenario, the northern half of the island would be at a slightly lesser risk, as it would be somewhat shielded by Mt. Scenery. However, if Mt. Scenery should be the site of renewed activity, then the whole of the island would form an extremely high-risk area. For both subaerial scenarios heavy rainfall on steep, ash-covered slopes would, undoubtedly, produce lahars and debris flows. Landslides and rock falls could also be generated by local earthquakes without rain. In the event of any renewed subaerial activity, the island's only main road would probably become impassible, thus potentially isolating various communities from either the harbour and/or the airport. Ash from any explosive activity would be dispersed mainly to the west of the vent in the direction of the dominant trade winds and would blanket most of the island. The distribution and thickness of ash from prehistoric eruptions and from eruptions on nearby islands (e.g. Montserrat, St. Kitts) have been used to define the probable ash fall pattern for future eruptions of Mt. Scenery. Ballistic projectiles may also be generated by explosive eruptions and would affect all parts of the island. For the hazard map, Mt. Scenery has been arbitrarily chosen as the site of renewed activity.

Integrated Volcanic Hazard Zones

The hazard map has been used to create integrated volcanic hazard zones for the island of Saba. Because of its small size, most of the island falls within the area of high pyroclastic flow hazard, and the entire island falls within the 3 km ballistic

Volcanic hazard map for a dome-forming eruption from Mt. Scenery, Saba



Integrated volcanic hazard zones for a dome-forming eruption from Mt. Scenery, Saba

projectile zone. For this reason, the entire island is considered to have a very high integrated hazard. In the event of signs of renewed activity the entire island would have to be evacuated in order to avoid loss of life. The most likely method of evacuation would be by sea. Any type of eruptive activity would most probably damage or destroy a high percentage of the buildings on the island, and completely disrupt its infrastructure.

Conclusion

The island of Saba is a live volcano and has the potential to undergo volcanic activity in the future. The most likely style of activity would be Pelean, with the extrusion of a lava dome and the generation of pyroclastic flows and surges, although other styles of activity are also possible. Precursor activity could include periods of increased local seismicity, as well as phreatic/phreatomagmatic explosive activity. Both of these precursors could precede a magmatic eruption by a considerable time period. The similarities in eruptive style and magmatic processes between Saba and the Soufrière Hills volcano on Montserrat makes the Montserrat example a very good analogue for future activity on Saba.

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