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FIELD GUIDES

FIELD TRIP #4

Field Guide to St. Vincent

by

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Front cover: Photograph of the raised coastal platform along the eastern seaboard of St. Vincent.The coastal road runs along steep bluffs that are composed of thick ash and pumice beds of the Yellow Tuff formation.

INTRODUCTION

St. Vincent is located between latitude 13° and 13°30' N and longitude 61° and 61°30' S, about 100 miles west of Barbados, 68 miles north of Grenada and about 190 miles north of Trinidad (Figure 1). The island is roughly oval and has an area of 344 sq. km. It is approximately 29 km long and 17.5 km wide and is located within the Lesser Antilles island arc, a region of active volcanism caused by subduction of the North American and/or South American Plate beneath the Caribbean Plate. Plate convergence rates in the Lesser Antilles is lower than in most arc systems and have been estimated at 2.2-3.8 cm/yr (Minster 1978; Sykes 1982).

The island consists of a central axial range of mountains starting from La Soufrière (1,178 m), in the north, to Mount St. Andrew (736 m) to the south. This range of volcanic mountains divides the island almost equally between a gently sloping eastern or windward side and a deeply dissected and rugged western or leeward side. Volcanic materials have been severely affected by extensive erosion and deeply weathered due to the tropical climate. With an extensive vegetation cover good outcrops are limited and often confined to the steep coastline, road cuttings, quarries and landslides in the mountainous areas. These limitations combined with the inherent difficulties of mapping pyroclastic deposits have restricted the ability to determine detailed stratigraphy for each volcanic centre.

STRATIGRAPHY

GENERAL RELATIONSHIPS

St. Vincent is entirely volcanic and Rowley (1978a) observed that there is "roughly an even distribution of lava flows and pyroclastics". It is unclear from Rowley's statement whether this refers to similar proportions of these deposits everywhere or roughly that the proportions of the two types of deposits are similar. This ambiguity along with the limitation of good exposures to sea cliffs and road cuttings prevents this assertion from being rigorously validated. However, recent field mapping (Robertson 2002) suggest that there is much variation in this distribution, so that at some centres (e.g. SE Volcanics) lavas are dominant while at others (e.g. Grand Bonhomme Volcanic Centre), volcaniclastics predominate. Approximately 55% of the island is mantled by well-bedded, pyroclastic fall deposits (the Yellow Tuff Formation), produced by eruptions of the Soufrière volcano during the late Pleistocene (Rowley 1974). The volume of these deposits was estimated to be 48 km^3.

St. Vincent has several springs, both inland and close to or directly on the seashore. These are usually related to the presence of paleaovalleys that have been filled in by lava flows and then covered with thick pyroclastic deposits. Two areas of mineral springs located at Belair and Montreal (locally know as Spa springs), are caused mainly by gas lift effect. Fumarolic activity on the island is confined to the interior crater of Soufrière volcano where two groups of fumaroles are active on the 1979 dome. The only other area of thermal activity is a lukewarm spring (37 °C) that occurs in the upper parts of the Wallibou River.

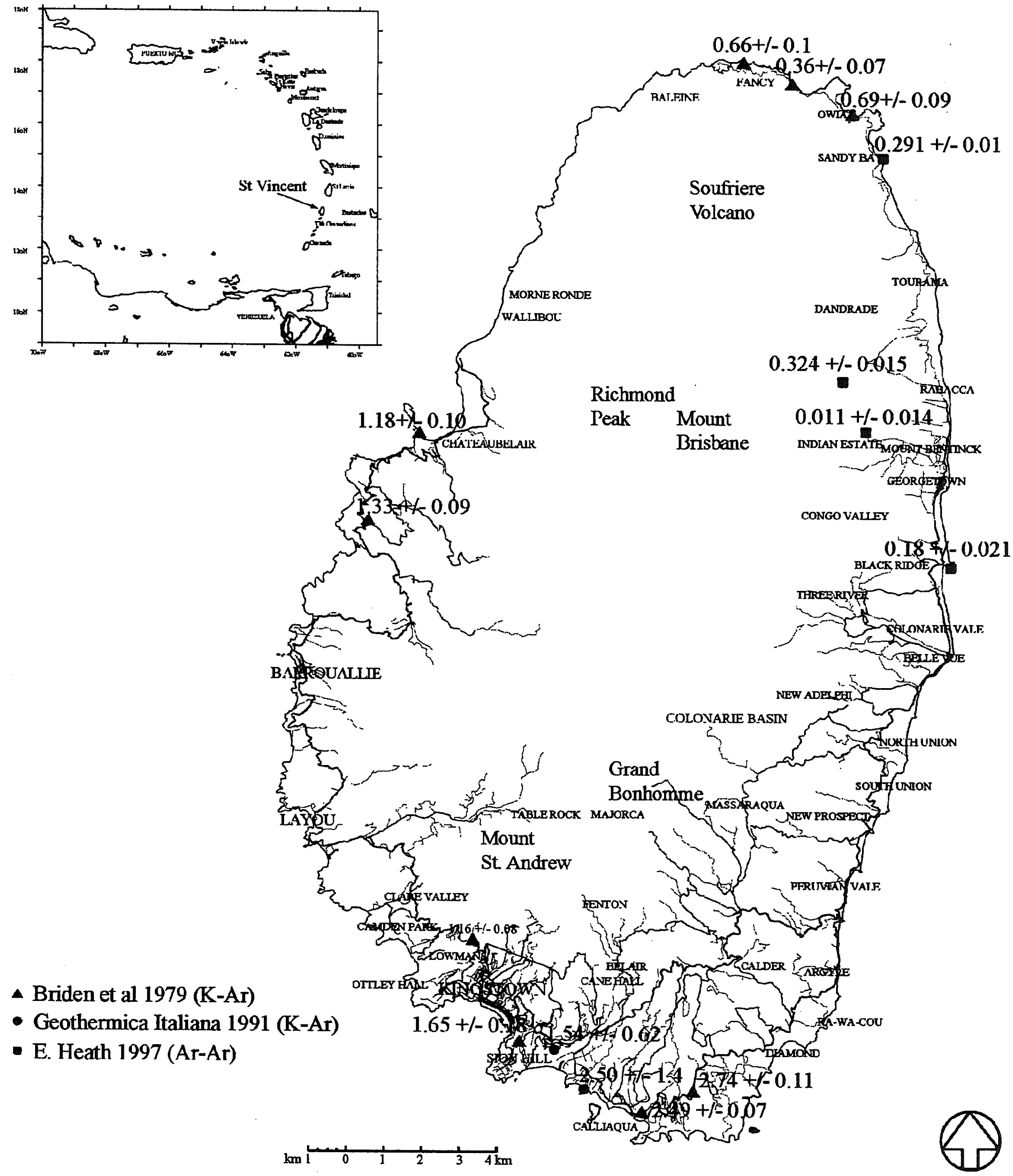

Figure 1: Map of St. Vincent showing its location within the Eastern Caribbean, radiometric dates obtained from rock formations and the main place names used in the text.

DESCRIPTION OF ROCK FORMATIONS

The island has been divided into four geologic regions (Figures 2 & 3) based on the observed rock units their apparent genetic relations, geochemistry and structural relations (Robertson 2002).

The Southeast Volcanics

The most southerly region is the SE Volcanics, which is bordered on the west by the Warrawarrow River and to the east by the extensive Yambou lava flow. The area extends from Argyle to Arnos Vale and consists of a dissected landscape of rounded hills with generally low topography (< 210 m). It contains the oldest rocks found on the island (2.74 ± 0.11 Ma) and is dominated by red scoriaceous basaltic spatter interbedded with and often overlying, massive to well jointed basaltic lava flows which are intruded by dykes. The entire area is overlain by a fine-grained yellow tephra, which is correlated with the late Pleistocene Yellow Tuffs (Hay 1959a; Rowley 1978b) erupted by the Soufrière volcano. Alluvial deposits found in the river valleys are the youngest deposits exposed in the area.

Grand Bonhomme Volcanic Centre

The Grand Bonhomme Volcanic Centre is a composite of several smaller centres including Grand Bonhomme (970m and incl. Petit Bonhomme), Mount St. Andrews (735m) and an unnamed peak (1021m). It is separated from Morne Garu by a saddle that extends to the Cumberland River in the west and the Colonaire River to the east. This is the largest volcanic centre on the island and is a stratovolcano with interbedded sequences of block and ash pyroclastic flows, tephra, lava flows and subordinate domes. The landscape is heavily forested and the interior inaccessible and composed of deeply weathered lavas and volcaniclastic deposits.

The western flanks of the Grand Bonhomme stratovolcano have steep gradients and consist of pyroclastic flow and fall units with subordinate lavas. In some areas, these form discrete successions, which extend, as ridges from the eruptive centre but are not laterally continuous. Dykes occur in the Mt. Wynne to Chalmers Hill area and at Belleisle Hill, where red scoria bombs composed of olivine, micro-phyric basalts form a localised spatter cone. As is common in most of the island, the entire area is overlain by mantle bedded yellow tephra.

The eastern flank of the volcano is gentler and contains an extensive raised shelf. The main deposits are weathered volcanic agglomerate overlain by mantle bedded yellow ash. The agglomerate is poorly exposed but appears to be quite extensive throughout the area. Distal outcrops (e.g. along Colonaire to Peruvian Vale), consists of spheroidally weathered, coarse-grained lithic clasts (maximum size 8 m) in a fine to coarse-grained matrix. This deposit is laterally contiguous with clast supported breccia beds (max clast size 1.5 m), which occur in the Marriaqua valley. The extent of the deposit (>15 km^2) along with the occurrence of an arcuate depression in Marriaqua valley suggests that it is a debris avalanche deposit related to large-scale edifice collapse that occurred at some time during the evolution of the volcano. No radiometric dates are available for the Grand Bonhomme volcanic centre but its geomorphology suggests that it is older than the Marne Garu Volcanic Centre.

Various types of alluvial and reworked deposits are exposed throughout the area. The Marriaqua valley contains a fines-depleted deposit consisting of rounded boulders. In Arnos Vale a fluvial deposits abuts a basaltic-andesite dome lava mined locally for aggregate. At Ottley Hall a bedded alluvial deposit lies unconformably beside autoclastite. In the Buccament Valley, reworked yellow boulders and clays are exposed.

Morne Garu Volcanic Centre

The Morne Garu Volcanic Centre occurs immediately to the north of Grand Bonhomme and consists of Mount Brisbane (932 m) to the east and Richmond Peak (1074 m) to the west.

These two peaks are the remnants of an eroded Morne Garu crater or caldera that is estimated to have been 3 km in diameter (Sigurdsson *et al.* in press). Morne Garu is largely inaccessible and the underlying volcanics are extensively covered with fine-grained yellow tephra. Previous dating of lavas from Richmond Peak suggested that volcanism must have been in the million-year range (Briden *et al.* 1979), but recent ages obtained by Heath *et al.*. (1998b) suggests that volcanism may have been much younger and possibly overlapped with the Soufrière Volcano to the north (i.e. < 0.7 Ma). The major formations exposed are lava flows, undifferentiated volcaniclastics, red scoria deposits and yellow tephra fall. Reworked alluvial deposits occur in the major river valleys.

- ***The Soufrière Volcanic Centre***

The youngest volcanic centre on St. Vincent is the Soufrière volcano (Figure 4), which occupies the northernmost third of the island and rises to 1178 m. No detailed geological map exists of the volcano although the principal formations have been identified (Robertson 1992; Robson 1966; Rowley 1978a; Sigurdsson 1981). The volcanic edifice consists of an older strato-cone or Somma, which forms a steep arcuate ridge to the north, and a younger pyroclastic cone, which has been the source of recent eruptions and is nestled within the Somma. An unresolved problem regarding the stratigraphy of the volcano has been the correlation of the succession exposed on the flank of the volcano with the rocks exposed in the crater walls. The lack of dated samples from the crater wall succession allows only a lithological correlation of crater wall formations with the radiocarbon and Ar-Ar dated deposits on the lower flanks.

Four principal rock formations have been identified in the crater (Sigurdsson 1981; Sigurdsson and Carey 1990; Sigurdsson *et al.* in press). The *Debris Flow formation* is the lowest exposed formation and is a massive deposit consisting of angular, matrix supported, basaltic blocks (max. 3m diameter) in a poorly sorted sandy matrix. Overlying this is the *Brown Tuff* a 20 m thick, well-bedded succession of tephra falls and minor surge layers, which contain angular basaltic lithic fragments. Thick basaltic andesite and andesite lava flows, which form the lower half of the vertical eastern and northern crater walls, are called the *Crater Lavas formation*. The topmost deposit exposed in the crater consists of thick units of pyroclastic flows and tephra fall beds, which are called the *Pyroclastic Formation*.

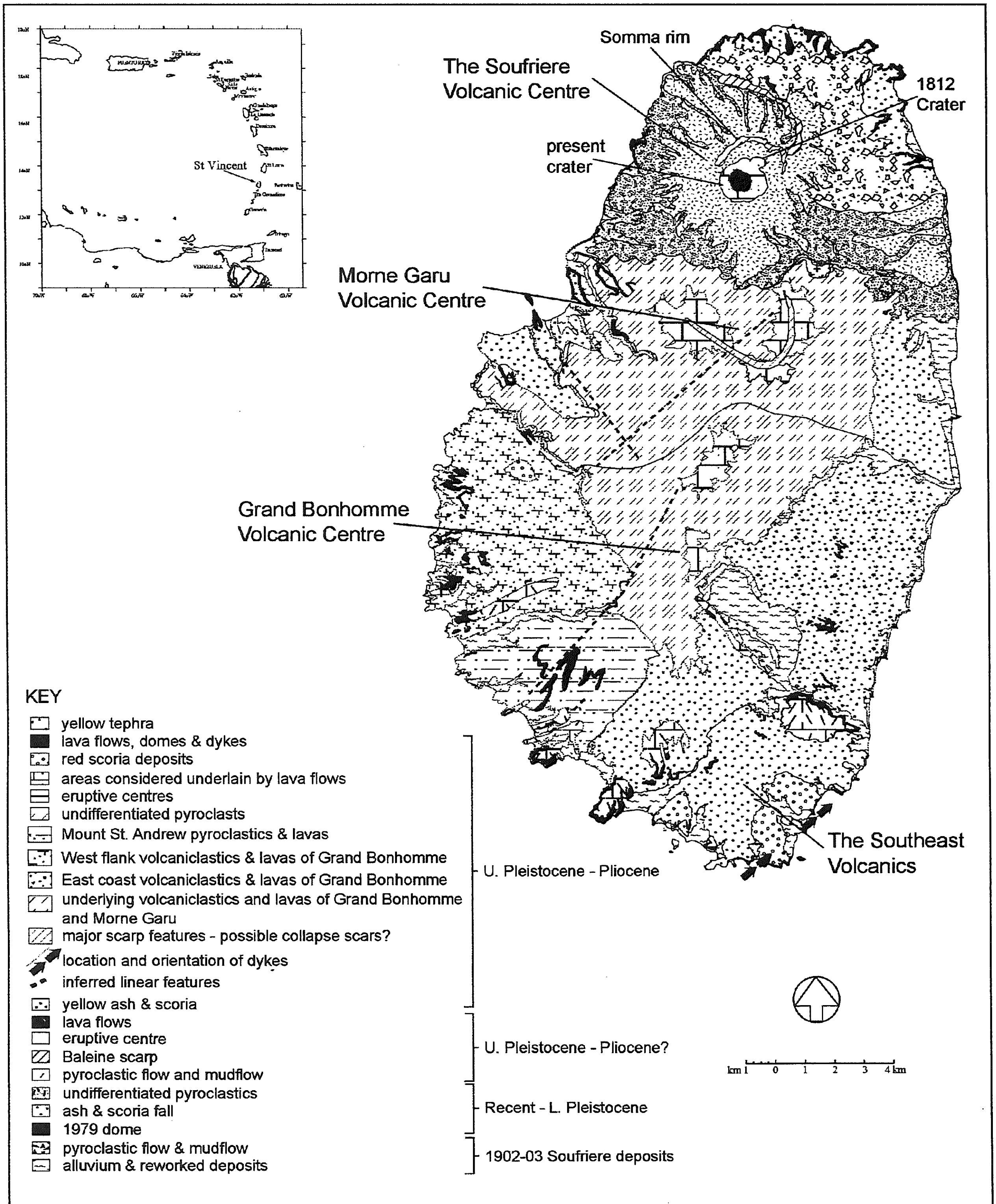

Figure 2: Geological map of St. Vincent

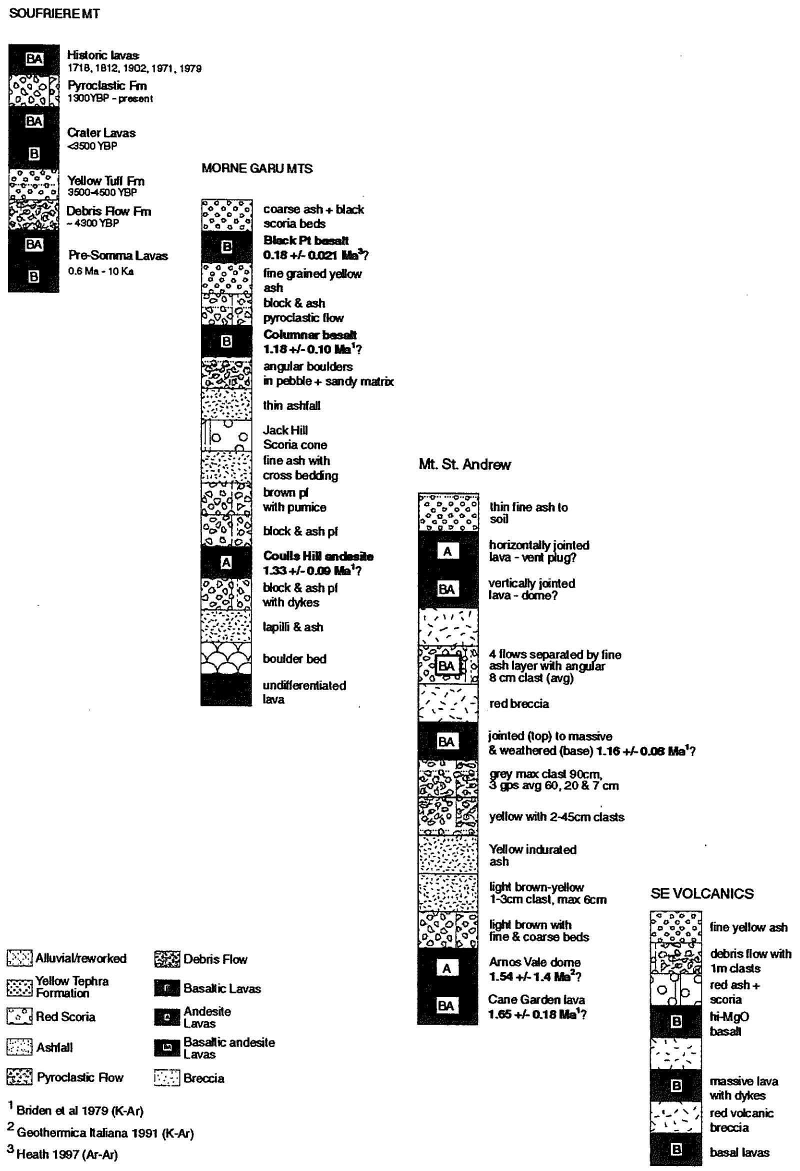

Figure 3: Generalized stratigraphic sections of the main volcanic centres

The oldest formations exposed on the flanks of the volcano are basaltic lavas, which form the remnants of the pre-historic Somma crater. These are overlain by beds of pumiceous yellow tephra (the *Yellow Tuff formation*), which have been correlated with yellow pyroclastic fall deposits that mantle the island (Hay 1959a; Rowley 1978a). The units are often reversely graded and contain beds of black scoria to yellow lapilli and pumiceous tuff that range in composition from basalt to andesite. In the river valleys, alluvial deposits, basaltic andesite pyroclastic flows and breccia layers or mudflows unconformably overlie the Yellow Tuffs. The mudflows are massive, thick (up to 25 m) deposits with angular blocks of basalt and basaltic andesite. On the lower flanks of the volcano, the mudflows are overlain and interbedded with basaltic andesite pyroclastic flow deposits, thin tephra falls and minor alluvial beds. The pyroclastic units are discontinuous, channel-fill deposits that show little variation in lithology.

STRUCTURAL FRAMEWORK

The island of St. Vincent is aligned along a north-south axis. Slope gradients along the west of the central axis of the island are significantly greater than those on the east. No field evidence has been found of faulting but some of the rivers (e.g. Colonaire River) follow courses that exhibit features expected from structurally controlled topography (e.g. abrupt change in flow orientation). An emergent coastline found along the east coast has been suggested by Rowley (1978a) to be due to Plio-Pleistocene uplift. Erosion has severely dissected the southern volcanic centres and original structures cannot be readily identified. Arcuate scarp features located at Grand Bonhomme, Morne Garu and the Soufrière volcano have been attributed to relict caldera or collapse structures (Geotermica Italiana 1992; Rowley 1978a; Sigurdsson and Carey 1990).

The island is affected by three major tectonic patterns. Two of these trends are observed throughout the island: a N45W and N45E trend, which probably represents a conjugate system. These are best defined by the orientation of the major river valleys (e.g. Warrawarrow, Buccament, Cumberland, Three Rivers), which appear to be structurally controlled. Geotermica Italiana (1992) also identified the presence of a NNW-SSE trend in the northern parts of the island that was not observed in this study.

A few dykes and small plugs or domes intrude the basaltic lavas and red scoria of the SE Volcanics. Wadge (1986) found the dominant trend to be NNE, which concurs with the general northerly trend obtained from dykes mapped during this study. At the Soufrière volcano, the Debris Flow formation is cut by three north to northeast trending dykes (Rowley 1978a; Sigurdsson 1981).

The structural framework of the Soufrière volcano is more complex than the southern centres since it is affected by a number of features not present in the rest of the island. The arcuate Baleine scarp is the dominant feature (~3.5 km long) and probably represents the results of large-scale flank failure. In addition, the summit areas consists of three craters; the pre-historic Somma, the 1812 crater and the currently active crater. The remnants of the pre-historic Somma crater (~2.2 km in diameter) is the largest feature and is made up of massive lava flows which forms a prominent ridge to the north of the active crater. Nestled within the Somma caldera is the dominantly pyroclastic sequences that make up the 1812 crater (300 m diameter) and the present crater (1.4 km in diameter).

The Mesopotamia valley is a large elongated depression (1.5 km x 4 km), which extends from the foothills of Grand Bonhomme to Hopewell. The origin of this feature is still unclear but the presence of extensive, poorly sorted, coarse breccia and agglomerate units along its eastern margins suggest that structural collapse may have been involved. The basaltic lava flow, which extends for over 2.5 km along the Yambou River, may represent a late stage effusive event associated with this collapse.

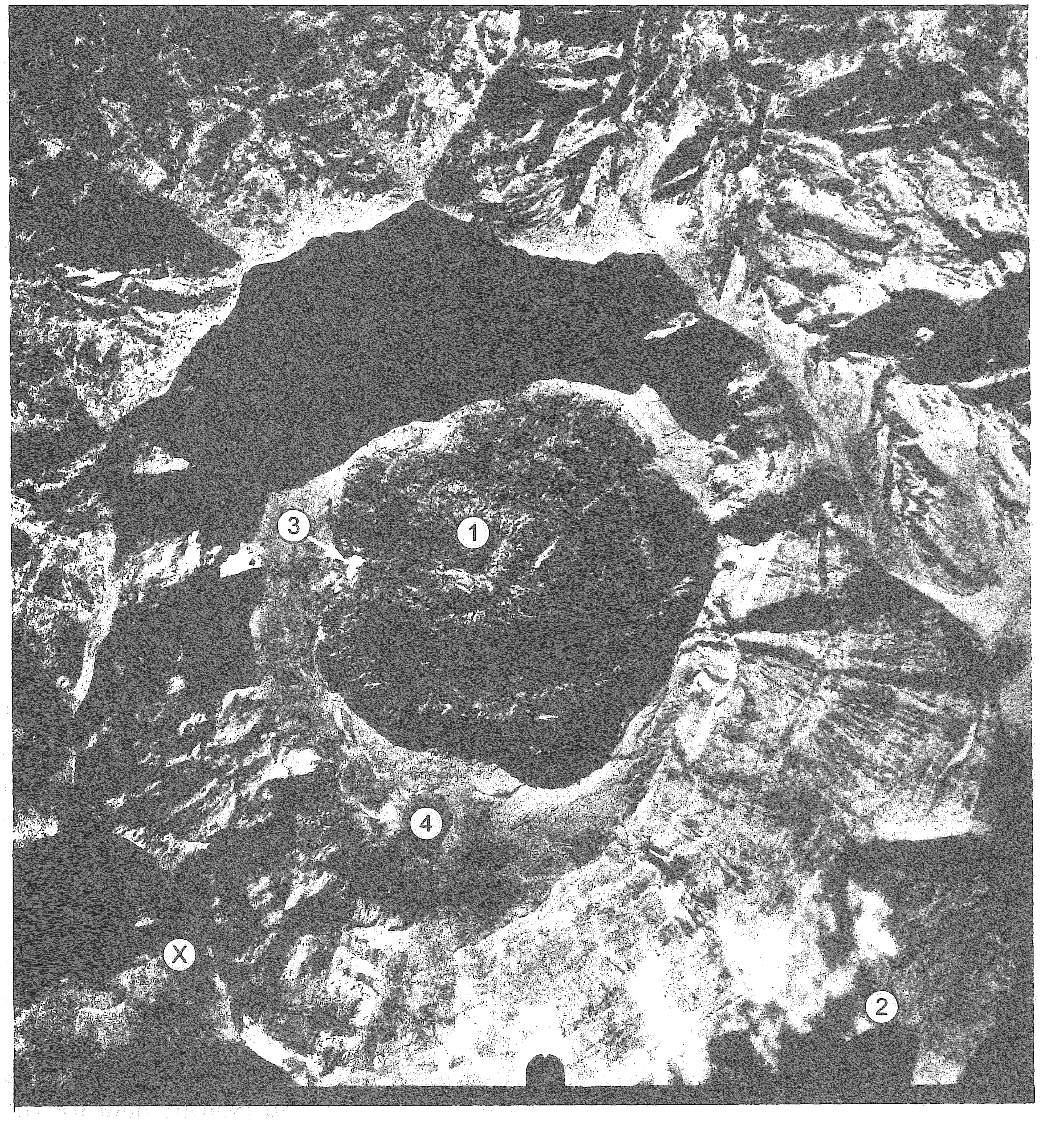

Figure 4: Aerial photography of the Soufriere volcano taken in 1999. Some of the features of the crater are visible in this photography including (1) the 1979 dome; (2) parts of the 1812 crater; (3) fumaroles and (4) temporary lake. 'X' marks the spot where the trail to the summit ends.

GEOCHEMISTRY

Rowley (1978a) observed that the rock types exposed on the island were calc-alkaline basalts and low-silica andesites with little chemical or mineralogical variation between the various volcanic centres and within the products of a single centre. However, Geotermica Italiana (1992) found a narrow but notable variation in the nature of rock types present on the island. They listed four compositional groups: basalts; basaltic andesites; andesites and xenoliths of coarse-grained plutonic and metamorphic character. This interpretation is supported by geochemical data obtained recently (Robertson 2002) although plutonic and metamorphic xenoliths are less common in the southern parts of the island.

St. Vincent rocks are classified as basalt, basaltic andesites and andesites, using the chemical classification scheme of Le Bas *et al.* (1986). Basalts are present in relatively greater amounts than basaltic andesites and andesites. Basaltic magmas are most common during the early stages in the evolution of individual volcanic centres and andesites are most common as dykes and as the last stage dome or central plugs, which occupy the vent at some centres.

The basalts can be further subdivided into two groups based on geochemical and petrological criteria. The High-MgO basalts (*HMBs*) contain 9-16 wt. % MgO, and are enriched in Ni (179-434ppm), Cr (484-1295ppm), Co (37-55ppm) and Fe (9.25-11.67 wt. %). The Low-MgO basalts (*LMBs*) have <10 wt. % MgO, low Ni and Cr and higher contents of incompatible elements (e.g. K, Rb, Sr,). Graham and Thirlwall (1981) observed that magnesian basalts from the Soufrière volcano were microphyric and contained olivines up to Fo_{88}, Cr-Al spinels and magnesian clinopyroxenes. They felt that these basalts possibly represented the primitive magmas, which were present beneath the Soufrière volcano.

St. Vincent rocks are easily classified as sub-alkaline (Figure 5). However, a clear distinction cannot be so easily made with regards to the tholeiitic *vs.* calc-alkaline character of the rocks. Thirlwall *et al.* (1994) referred to the high-MgO basalts of St. Vincent as transitional between tholeiitic and calc-alkaline. Smith *et al.*. (1996) referred to St. Vincent rocks as tholeiitic and noted that they were petrographically and chemically similar to the basalts of Bequia. Heath *et al.*. (1998a) suggested that trace and isotope data for rocks from the Soufrière volcano provided a rationale for the selection of a calc-alkaline affinity for these rocks.

On a $FeO^*/MgO-SiO_2$ plot (Figure 6) the St. Vincent rocks scatter across the boundary between tholeiitic and calc-alkaline fields. However most samples plot outside the area in which this classification scheme is most successful ($2.0<FeO^*/MgO<5.$) and as such the results are inconclusive. Similarly on the K2O vs. SiO2 diagram (Figure 7), the rocks appear to be mostly low-K or tholeiitic although all rock types have members which plot in the medium-K or calc- alkaline field. On an AFM diagram (Irvine and Baragar 1971; Kuno 1968), the St. Vincent rocks define an ambiguous pattern (Figure 8). The conclusion of Thirlwall *et al.* (1994) that the St. Vincent rocks are transitional is therefore considered to be the most accurate classification of St. Vincent rocks.

With the data available it is difficult to distinguish between the various volcanic centres based on the patterns exhibited by REE, trace and major elements. They are treatment as a single co-genetic group, representative of the entire suite, which characterise the island. The rocks do not display any systematic variation with age, deposit type or formation. However, there are a few notable regularities in the distribution of volcanic deposits versus composition. The dykes are andesitic in composition and are only found in the southern parts of the island, mainly in the southeast. High MgO basalts are most abundant amongst the South-east Volcanics where they occur as lavas and pyroclastic deposits closely associated with cinder cones. Pyroclastic flows, which occur at all volcanic centres apart from the SE Volcanics, are most often basaltic andesite in composition.

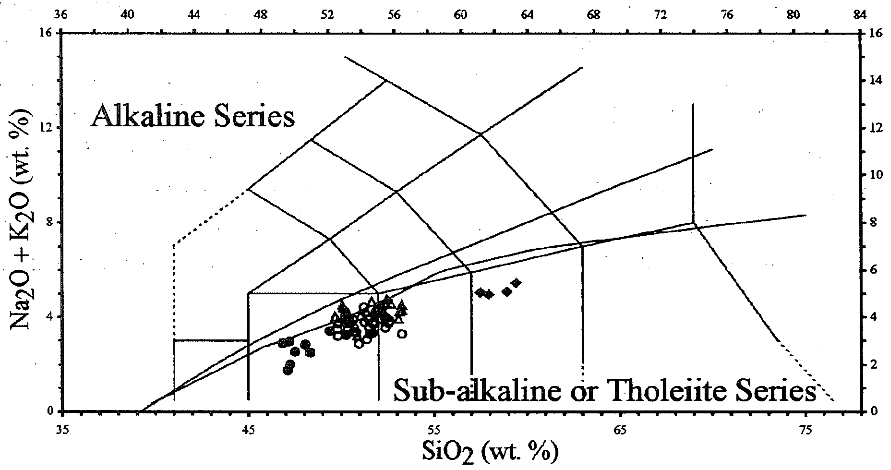

Figure 5: St. Vincent rocks plotted on a Total Alkali (Na2O + K2O) vs. Silica (SiO2) diagram showing the boundaries to IUGS volcanic rock names as specified in Le Bas et al. (1986). Plot symbols represent High-MgO basalts (solid circles), Low-MgO basalts (open circle), basaltic andesites (open triangles) and andesites (solid diamonds). The two curved lines shown represent the high and low ranges of the alkaline and subalkaline boundary lines used by various workers and compiled by Rickwood (1989).

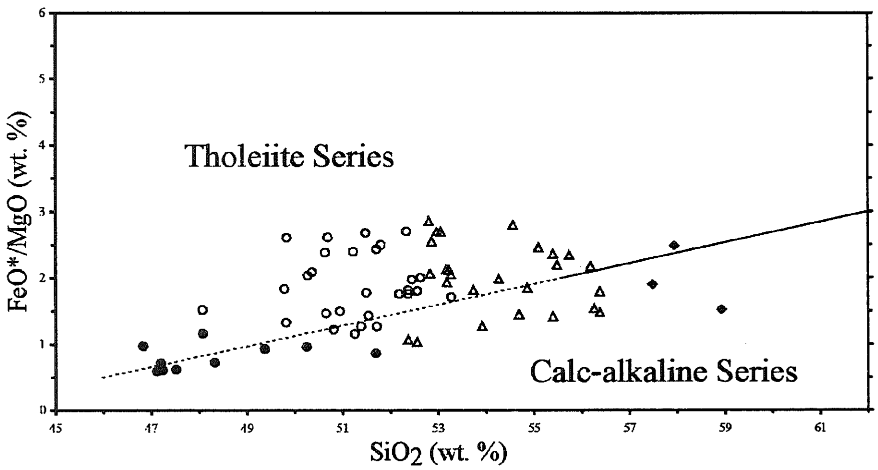

Figure 6: FMS (wt. % FeO*/MgO vs. SiO2) discrimination diagram after Miyashiro (1974) and Rickwood (1989) for St. Vincent rocks. FeO* is total Fe expressed as FeO. Most of the St. Vincent samples plot outside the recommended range (shown as a solid line), over which the classification should be used (2.0<FeO*/MgO<5). Plot symbols are the same as for Figure 5.

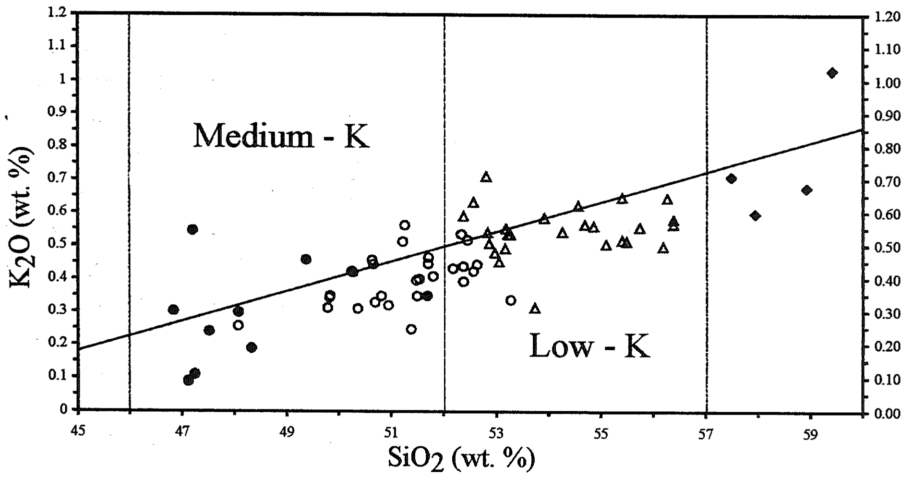

Figure 7: St. Vincent rocks plotted with weight % K2O vs. SiO2 after Peccerillo and Taylor (1976). Vertical lines indicate the boundaries for basalts, basaltic andesites and andesites. Most rocks plot in the Low-K or tholeiitic field. Plot symbols are the same as those given in Figure 5.

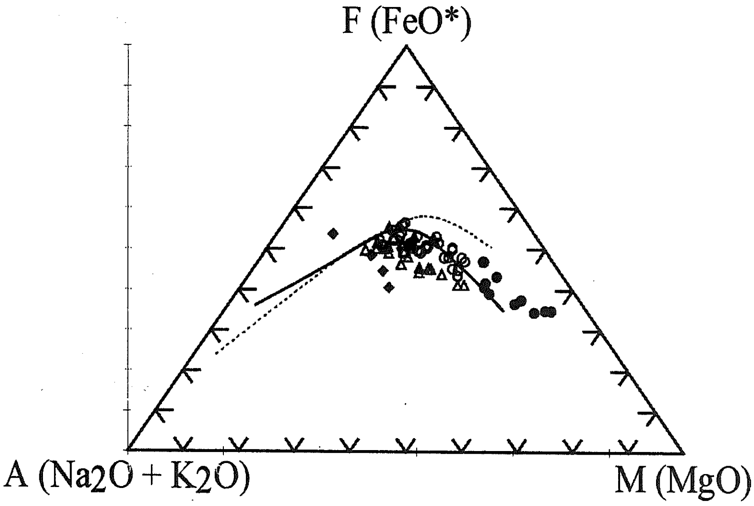

Figure 8: AFM plot with weight % [Na2O + K2O]-[total Fe as FeOT]-[MgO] and used to subdivide sub-alkaline rocks into tholeiite and calc-alkaline series. Field boundaries are defined according to Irvine and Baragar (1971) and Kuno (1968). Plot symbols are the same as for Figure 5.

EVOLUTION OF VOLCANISM

Considerably more geochronological dating is required before an accurate picture can be deduced of the evolution of volcanism on St. Vincent. The island is composed of four north-south trending stratovolcano centres which show a northward migration in age from 3 Ma, near the south of the island, to 0.6 Ma at the Soufrière volcano (Briden *et al.* 1979; Heath *et al.* 1998b; Rowley 1978a). It is unclear from the radiometric dates available whether this migration has been progressive and the extent to which volcanism at each centre may have overlapped. Rowley (1978a) suggested that after the main eruptive centres had migrated to the Morne Garu and Soufrière volcanoes to the north, minor eruptions might have occurred at Belleisle Hill and Kings Hill-Brighton to the south. The young-looking morphology of spatter cones at Belleisle Hill and Brighton-Kings Hill support this conclusion. However, Wadge (1986), concluded that the migration of volcanism on St. Vincent resulted from the movement of a single source of magma, or plume trace. Although this allows for some overlap in eruptive activity at adjacent centres (e.g. Morne Garu and Soufrière), it would be difficult to reconcile with a switch back of activity to centres located >14 km to the south. Relatively young dates obtained recently (Heath *et al.* 1998b), for lava flows at Black Point (180 ± 21 ka), Rabacca (324 ± 15 ka) and Indian Estate (11 ± 14 ka) indicate the early activity of the Soufrière volcano overlapped with that of Morne Garu to the south. An alternate explanation is that these lavas originated from the Pre-Somma period of the Soufrière's evolution when laterally extensive lava flows were more common.

The physical evolution of the southern volcanic centres may have followed a similar pattern to the Soufrière volcano to the north (Figure 9). The basement formation at each centre consists of basalt and basaltic andesite lavas flows, which suggest that sub-aerial eruptions were initially effusive. These eruptions were followed by a period of alternating effusive and explosive activity during which the main volcanic edifice was constructed. Explosions may have culminated in large scale sector collapse and/or caldera forming eruptions, the evidence of which remain as arcuate scarps at the summit of some centres (e.g. Morne Garu). The waning stages of activity consisted of the emplacement of andesite plugs or domes at summit craters which now remain as steep sided hills. The formation of spatter cones at Belleisle, Brighton and Diamond must have occurred after this evolutionary sequence had been completed at Grand Bonhomme since it is unlikely that eruptive activity would have been reactivated at these centres after volcanism had migrated further north. The absence of these spatter cones at Morne Garu and Soufrière suggest that this may have been late stage activity associated with evolution of the two southernmost volcanic centres.

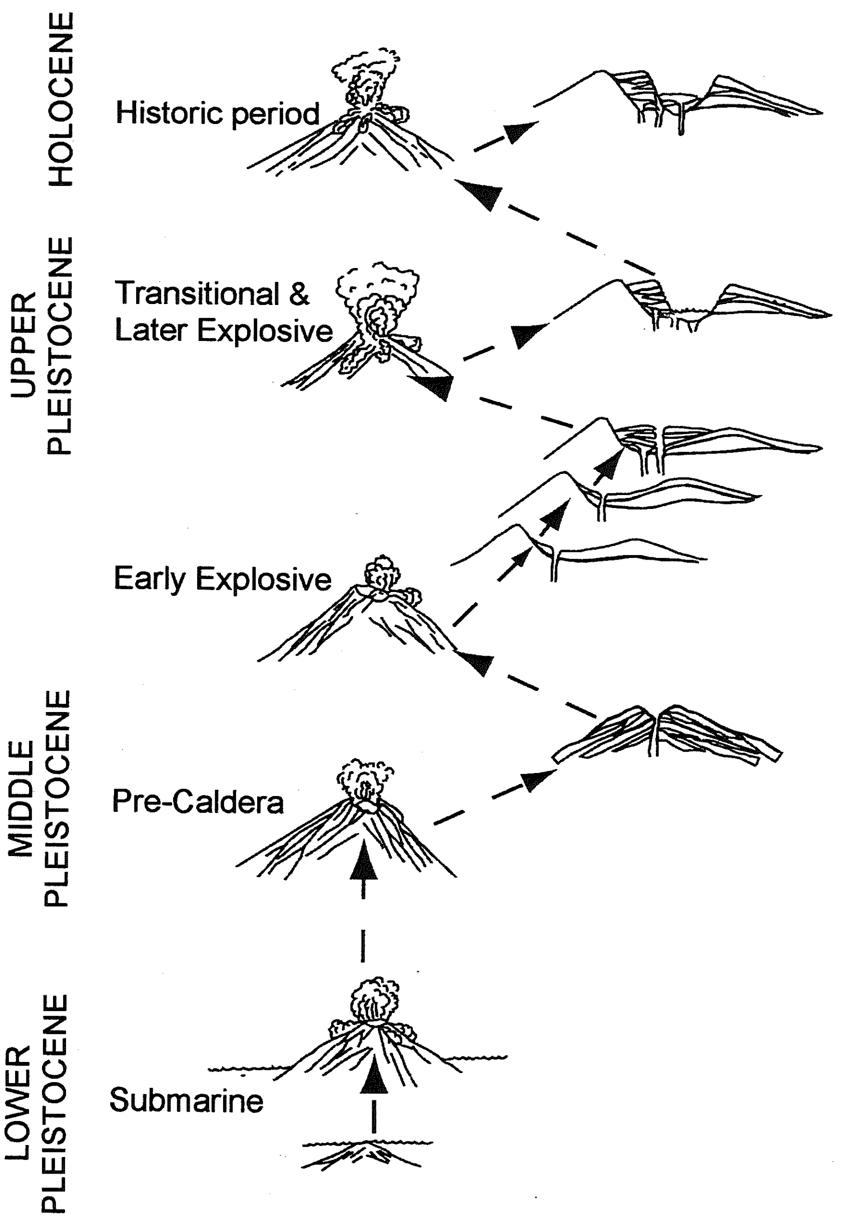

Figure 9: Schematic perspective of the evolution of the Soufriere Volcano (after Rowley, 1978a, Sigurdsson 1990)

Itinerary in St. Vincent

Day 1: Arrival (late evening/night)

Arrive in Kingstown by air from Barbados; check into Villa Lodge Hotel, located between Greathead Bay and Indian Bay, south of Kingstown. Discussion (~15 minutes) on the geology of St. Vincent and briefing on the logistical arrangements for the next day's fieldtrip.

Day 2: Windward coast and the Soufrière volcano (start at 8:00 am)

Drive from Villa Lodge going eastward along the windward coast of the island. We will obtain views of Fort Duvernette (an old volcanic plug) and Young Island (composed of proximal pyroclastic deposits), offshore towards the south. Good views will be obtained of the northern Grenadine islands of Baliceaux, Battowia, Bequia and Mustique, all of which have similar geology to the South East Volcanic centre whose geology is exposed for the first part of our journey.

The journey from Villa to Argyle takes us through the South-East Volcanics and allows views of the main rock units that make up this area. The lavas are olivine microphyric basalts, which are interbedded with red scoria beds. The flows are massive but exhibit jointing and rare platy textures in some localities. Individual lava flows are separated by massive red scoriaceous autobreccia and are frequently <10 m thick. Several dykes intrude the basal lavas and red scoria deposits and are well exposed along the coast at Kings Hill. Dykes exhibit distinctive vertical jointing, large variation in grain size and have vertically oriented contacts. Fine-grained yellow tephra, which have been correlated with late-Pleistocene pyroclastic fall deposits (Hay 1959a; Rowley 1974), cover the entire area. The tephra deposit is massive and individual beds are not easily distinguished.

Stop 1: Red scoria deposits of Milikin Bay (~ 8:15-8:45am)

About 3.5 km from Villa Lodge and after a 10-minute drive, we turn off the road at Belvedere and take the secondary road past Brighton Village towards the coast at Milikin Bay. A good outcrop of ash and scoria beds is exposed along the road from Brighton Village to Milikin Bay. Red pumice and scoria beds are unconformably overlain by yellow tephra and recent yellow soil. The beds vary in thickness from 18-260 cm and dip 21-23° towards 215-225°. These beds are clast-supported (max. clast size 2.5 cm in diameter) and are separated by coarse-grained sand that exhibit normal and reverse grading. At the coastline the deposits thicken and become more agglutinated. High MgO basalts intrude the red spatter deposits and are exposed as about 100 metres along the coast east of the parking lot (Figure 10).

As we leave Milikin Bay we return to the main coastal road which takes us past the Kings Hill Forest Reserve which forms a prominent hill to the west of the road. This hill is one of the best preserved spatter cones that exist on the island. The topography changes after Argyle as we leave the South East Volcanics and travel on the raised platform, which forms the eastern seaboard of the island. Yellow Tuffs become the most prominent geologic deposit exposed from this point onwards to the Soufrière volcano.

The Yellow Tuffs are a succession of ash deposits that covers the entire island with about 2 to 20 m thick deposit (Figure 2). The deposits thicken towards the north and are generally considered to have been derived from late Pleistocene eruptions of the Soufrière volcano. Some beds are clearly fall deposits, while others have internal structures suggestive of surge or pyroclastic flow activity. Their origin is therefore still unclear and it is possible that some elements of the deposits may have been formed from late stage eruptions of one or more of the southern volcanic centres. The tuffs are extensively altered in some outcrops, weathering to yellowish-brown clay, chiefly halloysit.$4H_20$ (Hay 1959a, 1959b).

Stop 2: Bellevue road section (9:00 - 9:30am)

About 12 km from Stop 1 at Milikin Bay we will stop about 200 metres from the coastal village of Belle Vue where there is an excellent exposure of the Yellow Tuffs. The > 20 m thick outcrop exposes at least two major sections in the Yellow Tuff succession: an upper brown mantle-bedded ash deposit and a lower yellow-brown tuff formation. These are separated by an unconformity and a deep paleosol. The lower tuffs are poorly bedded and contain units that generally range from 0.5 to 1 m but reach a maximum of 2 m thick. These include a 30 cm thick yellowish grey coarse pumice fall layer and a 1.5 m fine-grained pyroclastic flow. Cross-bedded surge layers are present, with dune-like structures. The overlying brown and less weathered tuffs contain a 30 cm fall of dense scoria, dark grey and relatively fresh and unconsolidated. The upper succession is dominantly composed of 20 to 30 cm fall layers, some of which contain yellowish crystal-rich pumice, but some massive pyroclastic flow-like units are also present. Each layer grades upward into a soil, which generally equals or exceeds the thickness of underlying tephra fall. The upper succession appears to represent a series of fall deposits, with a prolonged break between fall events for soil development to occur. Erosion within the succession is minor or absent. At the base of the outcrop is a highly weathered and consolidated conglomerate that possibly represents a debris flow deposit from the Grand Bonhomme volcanic centre in the interior. (Description of outcrop mainly taken from Sigurdsson and Carey 1990).

From Belle Vue, we continue on the coastal road towards Georgetown and the Rabacca Dry River. From Colonaire we travel over a raised beachfront with truncated cliffs of Yellow Tuff immediately inland. We will go past Black Point, a relatively young (0.18 Ma) lava flow from Mount Brisbane volcanic centre, which is composed of some of the most primitive looking rocks on the island

Figure 10: Milikin Bay outcrop of thin fine grained High MgO basalt interbedded with red ash and scoria beds of the Brighton spatter cone

Climb of Soufrière Volcano (9:45am - 12:00 noon)

After passing the Rabacca Dry River we will turn inland along the secondary road and drive for about 2.5 km until we come to 'Bamboo Range' a small clearing at the end of the motorable road. The secondary road takes us over the extensive pyroclastic fan built up by historic eruptions of the Soufrière volcano. We will pass through Lot 14, an area where several persons were killed as they became stranded on the banks of the Rabacca River during the 1902 eruption. The sequence of events is described below.

During the early hours of May 7th 1902, the Crater Lake was partly ejected causing flooding of the Wallibou River. Solid material was ejected first at 6:00 am, with the emission of steam accompanied by a black cloud that subsided rapidly. At 7:40 am, another steam cloud was emitted; estimated to have reached over 9 km in only one minute. There were ashfalls at Wallibou (9:00 am), Fancy (11:00am), and Kingstown (11:15 am) and explosions were heard at Fancy. A column of whitish vapour ascended to over 9 km. At 12:25 pm dense black upheavals from the crater accompanied flooding of the Rabacca River, as more of the lake water was ejected. At 1:00 pm there was an eruption and mudflow streamed down the Rabacca River. Stones were projected in great number and more eruption columns formed as activity intensified. At 2:00 pm, the climax of the eruption occurred with the formation of a pyroclastic flow in the Wallibou, Larikai, Baleine and Rabacca rivers. Extensive destruction and death was caused in the areas of Lot 14, Langley Park, Rabacca, Waterloo, Orange Hill, Tourama and Overland. All who were not in well sealed rooms were killed.

We will leave the vehicles at Bamboo Range point and continue on foot along the minor footpath that leads to the Soufrière volcano. The climb to the summit, is a moderately tough climb starting with a gentle gradient and increasing rapidly about 1/3 the way up along the trail. The trail is in good condition and with a moderate pace the crater rim (3027 ft) can be reached in about 2.5 hours. Local farmers cultivate the pyroclastic fan built up at the base of the volcano with bananas and coconut palm. The fertile volcanic soils and high rainfall on the volcano has produced lush vegetation that consists of secondary rain forest at the base and changing rapidly to tree ferns then palm brake, elfin woodland and later grasses and ferns. At the summit tundra-like moss and lichen are dominant (Beard 1945).

The first part of our hike up the volcano will take us upon Lower Pleistocene to Holocene pyroclastic flows and mudflows. At the 'river bed', about 1 km along the route, we will cross a massive basaltic andesite lava flow that belongs to the Somma Lava formation. Closer to the summit the deposits are mainly ash and scoria from historic eruptions. Localised gullies along the path allow inspection of some of the recent pyroclastic deposits of the volcano.

Stop 3: The Soufrière Crater (12:00 noon – 1:00pm)

The main crater of the Soufrière volcano is 1.6 km in diameter at the top and about 1100 m wide at the floor level. Its floor is largely covered by the 1979 basaltic andesite lava dome, which has a diameter of 870 m and 130 m high. Emplacement of the lava dome followed the period of explosive activity (12-26 April 1979) and occurred between May to October 1979. The growth rate was initially 0.5 x $10^6 m^3$/day and when growth stopped in October 1979, the dome had grown to $37x10^6 m^3$. This contrasts with extrusion of the 1971 lava dome that attained a volume of over 80 x $10^6 m^3$. The surrounding crater floor consists of a yellowish grey pyroclastic flow deposit from the explosive stage of the 1979 eruption and later alluvial deposits. The current crater floor level is about 28 m higher than the former level of the Crater Lake. There is minor fumarolic activity in the southern part of the lava dome. Far to the north of the crater is the Somma rim: an amphitheatre-like wall that was formed as the head scarp of the sector collapse of the old Soufrière volcano. Beneath this wall is the 1812 crater formed by an explosive eruption that occurred between 27 April and 9 June 1812. This eruption was preceded by > 200 earthquakes and resulted in the death of about 56 persons. . Pyroclastic flows and mudflows descended the Wallibou, Rabacca, Baleine and Tourama Rivers and ashfall was widespread. The 1812 crater is a bowl-shaped depression (310 x 250 m) with a tuff ring that reached up to 30 m. It was reported to be very deep, with steep inner walls, immediately after the 1812 eruption and must have been filled with deposits from subsequent eruptions.

Weather permitting we will go west around the crater rim for about 400m to a prominent ridge which provides excellent views of the main crater formations, the fumarolic field located on the 1979 dome and the pyroclastic fan on the west and east coast. The ridge is short lava flow that forms part of the Crater Lava formation.

Return from the summit.

<u>Note</u>: Depending on time availability after we return from the summit, we will attempt to visit the two localities below.

Stop 4: Orange Hill Estate (3:15 – 3:30 pm)

The Orange Hill estate, which was at the time cultivated with sugar cane, was severely affected by the 1902 eruption. At Orange Hill we will a large stone-built rum cellar that, at the onset of the 1902 eruption, was made available by the manager to provide refuge for the estate workers, who fled from their huts in the village on the afternoon on May 7th. About seventy people fled to the cellar. Forty were in the main room and all survived. Thirty were in the passage leading to the cellar and they were all killed. None survived in the huts or other buildings on the estate. The manager, Mr Fraser, and his wife first fled to the rum cellar, but found the crowd unbearable and were returning to their house when the glowing avalanche struck. The manager was found dead on the veranda of his house and his wife on the steps leading up to it.

Stop 5: Rabacca River (3:45 – 4:45 pm)

Hike up the Rabacca valley from the road crossing for about 500 m to an outcrop of pyroclastic flow deposit. The dark grey deposit contains large lithic blocks and scoria of basaltic andesite. There are a number of gas escape pipes in the deposit, probably due to the passage of the flow over water. Note the abundant charcoal near the base of the flow. Further upstream the flow is overlain by mudflows.

Stop 6: Rabacca Dry River

Just north of Georgetown the road travels on top of 1902 mudflow, fluvial outwash and pyroclastic flow deposits. The original Rabacca river bed was buried by the 1902 pyroclastic deposit and the new Rabacca Dry River which enters the sea to the north of the original channels has cut into this deposit. Surges from these flows reached the northern outskirts of Georgetown and are now exposed in isolated areas between Langley Park and the new Rabacca Dry River. Between Langley Park and the Rabacca air strip the inland road provides access to an outcrop of massive, lithic-rich, dark grey and sandy 1902 flow deposit that has been incised by the new Rabacca Dry River. Several units in the 1902 pyroclastic flow deposit are exposed at this outcrop that is underlain by the Yellow Tuff.

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Table 2.1: Radiometric ages of rocks from St. Vincent.

Sample No.	Locality	Latitude °N	Longitude °W	Age/Ma	Method
683762	Calliaqua	13° 07'	61° 11'	2.49 ± 0.07	K-Ar[1]
683761	Prospect corner	13° 08'	61° 11'	2.74 ± 0.07	K-Ar[1]
683763	Cane Garden road	13° 09'	61° 14'	1.65 ± 0.18	K-Ar[1]
683741	Lowmans Leeward	13° 10'	61° 14'	1.16 ± 0.08	K-Ar[1]
683749	Coulls Hill	13° 16'	61° 16'	1.33 ± 0.09	K-Ar[1]
683747	Richmond Vale	13° 18'	61° 15'	1.18 ± 0.10	K-Ar[1]
683756	Rouges Hill, Owia	13° 22'	61° 08'	0.69 ± 0.09	K-Ar[1]
683755	Commantawana Bay	13° 22'	61° 09'	0.36 ± 0.07	K-Ar[1]
683740	Porter Point	13° 23'	61° 10'	0.66 ± 0.10	K-Ar[1]
SV-18	Arnos Vale	13o 09'	61° 13'	1.54 ± 0.62	K-Ar[2]
SV-29	Villa Dyke	13° 08'	61° 12'	2.50 ± 1.4	K-Ar[2]
STV 301	Black Point	13° 15'	61° 07'	0.18 ± 0.02	Ar-Ar[3]
STV323	Sandy Bay	13° 21'	61° 07'	0.291 ± 0.01	Ar-Ar[3]
STV 345	Indian Estate	13° 17	61° 08'	0.011 ± 0.014	Ar-Ar[3]
STV 358	Rabacca River	13° 18'	61° 08'	0.324 ± 0.015	Ar-Ar[3]

1Briden *et al.* 1979

2Geotermica Italiana 1992

3Heath 1997

Table 2.2: Summary of the geological history of St. Vincent (adapted from Tomblin 1970).

Age	Volcanic Centres			
	Soufrière Volcano	Morne Garu	Grand Bonhomme	SE Volcanics
Holocene	Historic Period: historic eruptions of 1718, 1812, 1902, 1971 & 1979 - formation of pyroclastic flows and lava domes			
Upper Pleistocene	Transitional & Late explosive stage: Prehistoric tephra falls and pyroclastic flows – formation of the Pyroclastic & Yellow Tuff Fm (<14,000 ybp)	Late stage flank eruptions – emission of Indian Estate lava (11 ± 14 ka)		
Middle Pleistocene	Early Explosive stage: explosive and effusive eruptions as the collapsed Somma crater is filled - formation of Crater Lavas and Brown Tuff formation			
	Sector collapse - formation of Baleine scarp			
Lower Pleistocene	Pre-Caldera stage: growth of the main Somma crater by alternating lava flow and pyroclastic eruptions – Somma Lava Fm	Effusive activity at Mt Brisbane: Black Point and Rabacca basalts		
	Submarine stage: Volcanism initiated as submarine eruptions which overlapped with continuing activity at Morne Garu	Effusive activity at Richmond Peak: Chateaubelair basalts & Coulls Hill basaltic andesite dyke		
Upper Pliocene		Construction of the main volcanic edifice with alternating explosive and effusive eruptions	Formation of lavas and domes of Mount St. Andrew >2 Ma	
Lower Pliocene		Lava flow and pyroclastic eruptions begin >2 Ma	Activity begin with explosive and effusive activity at least 3 Ma	Lavas and dykes at Calliaqua, Prospect & Indian Bay >3 Ma

REFERENCES

Beard, J.S., 1945, the progress of plant succession on the Soufrière of St. Vincent: Journal of Ecology, v. 33, p. 1-8.

Briden, J.C., Rex, D.C., Faller, A.M., and 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, v. A291, p. 485-528.

Geotermica Italiana, srl, 1992, Exploration for geothermal resources in the Eastern Caribbean. Island Report: St. Vincent, Pisa, United Nations - DTCD, CARICOM - Secretariat, p. 192.

Graham, A. M., and Thirlwall, M. F., 1981, Petrology of the 1979 Eruption of Soufrière Volcano, St. Vincent, Lesser Antilles: Contributions to Mineralogy and Petrology, v. 76, p. 336-342.

Hay, R.L., 1959a, Origin and weathering of late Pleistocene ash deposits on St. Vincent, B.W.I.: Journal of Geology, v. 67, p. 65-87.

Heath, E., 1997, Genesis and evolution of calc-alkaline magmas at Soufrière volcano, Lesser Antilles arc: Unpub. PhD thesis, Lancaster University 257 p.

Heath, E., MacDonald, R., Belkin, H., Hawkesworth, C., and Sigurdsson, H., 1998a, Magmagenesis at Soufrière Volcano, St Vincent, Lesser Antilles arc: Journal of Petrology, v. 39, p. 1721-1764.

Heath, E., Turner, S. P., Macdonald, R., Hawkesworth, C. J. & , and van Calsteren, P., 1998b, Long magma residence times at an island are volcano (Soufrière, St. Vincent) in the Lesser Antilles: evidence from U-238-Th-230 isochron dating: Earth and Planetary Science Letters, v. 160, p. 49-63.

Irvine, T.N., and Baragar, W.R.A., 1971, A Guide to the Chemical Classification of the Common Volcanic Rocks: Canadian Journal of Earth Sciences, v. 8, p. 523-548.

Kuno, H., 1968, Differentiation of basalt magmas, *in* Hess, H. H. a. P., A., ed., Basalts: The Poldervaart Treatise on Rocks of Basaltic Composition, New York, Interscience, p. 623-688.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

Minster, J.F. & Jordan, T.H., 1978, Present-day plate motions: Journal of Geophysical Research, v. 83, p. 5331-5354.

Miyashiro, A., 1974, Volcanic rock series in island arcs and active continental margins: American Journal of Science, v. 274, p. 321-355.

Peccerillo, A., and Taylor, S.R., 1976, Geochemistry of Eocene Calc-Alkaline Volcanic Rocks from Kastamonu Area, Northern Turkey: Contributions to Mineralogy and Petrology, v. 58, p. 63-81.

Rickwood, P. C., 1989, Boundary Lines Within Petrologic Diagrams Which Use Oxides of Major and Minor Elements: Lithos, v. 22, p. 247-263.

Robertson, R. E. A., 1992, Volcanic Hazard and Risk Assessment of the Soufrière Volcano, St. Vincent, West Indies: Unpub. MPhil thesis, The University of Leeds 219 p.

Robertson, R.E.A., 2002, An investigation of the genesis and evolution of volcanism on the island of St. Vincent, W. I.: Unpub. PhD thesis, University of the West Indies, Mona Jamaica. (UNDER EXAMINATION)

Robson, C.R. and Tomblin, J.F., 1966, Catalogue of the active volcanoes of the world. Part 20, West Indies, Rome, International Association of Volcanology, p. 56.

Rowley, K., 1978b, Late Pleistocene pyroclastic deposits of Soufrière Volcano, St. Vincent, W.I.: Geological Society of America Bulletin, v. 89, p. 825-835.

Rowley, K.C., 1974, The Late-Pleistocene pyroclastic fall deposits of Soufrière, St. Vincent: Unpub. MSc thesis, University of the West Indies 78 p.

Rowley, K.C., 1978a, Stratigraphic and geochemical studies of Soufrière volcano, St. Vincent, West Indies, University of the West Indies.

Sigurdsson, H., 1981, Geological observations in the crater of Soufrière volcano, St. Vincent, University of the West Indies, p. 25.

Sigurdsson, H., and Carey, S., 1990, Caribbean volcanoes, a field guide, Geological Association of Canada, p. 101.

Sigurdsson, H., Macdonald, R., Harkness, D.D., Pringle, M., Robertson, R., and Heath, E., in press, Volcanic History of the Soufrière of St. Vincent.

Smith, T. E., Thirlwall, M. F., and Macpherson, C., 1996, Trace element and isotope geochemistry of the volcanic rocks of Bequia, Grenadine Islands, Lesser Antilles arc: A study of subduction enrichment and intra-crustal contamination: Journal of Petrology, v. 37, p. 117-143.

Sykes, L.R., McCann, W.R., & Kafka, A.L., 1982, Motion of Caribbean Plate during the last 7 million years and implications for earlier Cenozoic movements: Journal of Geophysical Research, v. 87, p. 10656-10676.

Thirlwall, M. F., Smith, T. E., Graham, A. M., Theodorou, N., Hollings, P., Davidson, J. P., and Arculus, R. J., 1994, High-Field Strength Element Anomalies in Arc Lavas - Source or Process: Journal of Petrology, v. 35, p. 819-838.

Tomblin, J.F., 1970, Geological Field Guide to St. Vincent, West Indies, International Field Institute Guidebook to the Caribbean Island Arc System, Washington, D.C., American Geological Institute.

Wadge, G., 1986, The dykes and structural setting of the volcanic front in the Lesser Antilles island arc: Bulletin of Volcanology, v. 48, p. 349-372.