

VOLCANOLOGY OF SABA AND ST. EUSTATIUS,
NORTHERN LESSER ANTILLES

Volcanology of Saba and St. Eustatius, Northern Lesser Antilles

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Abstract

The two small islands of Saba and St. Eustatius (Netherlands Antilles) lie on the northernmost subaerial end of the active arc of the Lesser Antilles. They are separated by the 28 km wide St. Eustatius Passage, and 20 km further along the arc the submarine Lumeyes Bank represents the northernmost volcanic center of the arc. Saba with an area of 13 sq. km rises to the single peak of Mt. Scenery at 877 m above sea level. The island is essentially a complex of andesitic Pelean domes with surrounding aprons of pyroclastic material. Rocks of basaltic andesite composition are sparse, as are the products of St. Vincent-type activity. Also present in small amounts are the semi-vesicular products of Asama-style activity, and the pumiceous products of Plinian-style activity. Areas of hydrothermal alteration including sulfur mineralization, which has been commercially mined in the past, are extensive. The island appears to overlie a northeast-southwest fault zone as indicated by recent seismic activity; the distribution of hot springs including submarine springs off the northeast and southwest shores, and a major sector collapse structure which is directed towards the southwest. The oldest dated rocks on the island are around 400,000 years. Stratigraphic studies have shown that the youngest pyroclastic deposit is a thin ash surge with accretionary lapilli (dated at 280 years B.P.) which overlies Amerindian remains but underlies those of European settlers which arrived on the island in 1640. European settlers may have been particularly attracted to the island because of the presence of meadows of grassland instead of tropical rainforest caused by an eruption shortly before European settlement. Between 1995 and 1997 an increase in the number of local earthquakes was associated with

a 7-12°C increase in the temperature of the hot springs. This recent earthquake activity is thought to represent a mild volcano-seismic crisis, with the increased heat flow resulting from either deeper circulation of groundwater or possibly renewed magma movement.

In contrast, the island of St. Eustatius lies at the north end of a continuous submarine bank that also contains the islands of St. Kitts and Nevis. The island has an area of 21 sq. km and is morphologically dominated by two volcanic centers. At the northern end the extinct Northern Centers rise 289 m a.s.l. and were once a separate island surrounded by sea cliffs. Two and a half kilometers to the southeast the morphologically youthful Quill volcano, with an 800 m diameter open crater, rises to 600 m a.s.l. A third volcanic succession is exposed in the White Wall-Sugar Loaf tilted limestone succession, which forms the southern shoreline of the Quill. The Northern Centers comprise five morphologically distinct coalesced volcanoes, the most youthful of which is the Pisgah Hill-Little Mountain-Bergje Dome complex with a crater 880 m in diameter which contains the youthful Bergje dome. The Northern Centers comprises intercalated pyroclastic deposits (derived from Pelean activity) and lava flows. The Quill is almost entirely composed of pyroclastic deposits mainly representing Pelean-, St. Vincent-, and pumiceous Plinian-style activity including both fall and ignimbrite deposits. The White Wall-Sugar Loaf succession is exposed by the uptilting of marine bank sediments to angles of 40° and contains intercalated with the limestones abundant pumiceous subaqueous pyroclastic deposits. Six recently drilled water wells in the flanks of the Quill have revealed heated groundwater suggesting that the Quill is dormant. The last eruption of the Quill was prehistoric and occurred before settlement of the island by Salidoid Indians probably between 1550 and 1205 years B.P. Our interpretation of the radiocarbon ages suggests that the last erupted bedset probably formed between 1755 and 1635 years B.P. This is considerably younger than the published age for the last activity of the Quill of around 8000 years. The products of the last eruption are a very well preserved and exposed bedset of five Marker units named from oldest, K, to youngest, O. Their preservation has permitted one of the most detailed studies of a prehistoric pyroclastic eruption in the Lesser Antilles. The deposits are essentially pyroclastic flows and show a systematic change in chemistry from andesite at 58% silica up

the stratigraphy to basalt at 51% silica. Early formed mixed-magma deposits (basaltic andesite and andesite in single clast) suggest that the eruption was triggered by the introduction of basalt into an andesite chamber followed by mixing and hybridization and the subsequent emptying of the chamber. The Northern Centers are believed to be the oldest centers on St. Eustatius and although not precisely dated are thought to be less than 1 million years. U/Th dating of limestones in the younger Sugar Loaf succession reveals a range in ages from 68,000 to 320,000 years B.P. The Quill, which overlies the White Wall-Sugar Loaf succession and which is chemically distinct from it, is believed to have started forming around 50,000 years B.P.

Saba and the Quill, St. Eustatius although only 35 km apart have, at least for the past 50,000 years, simultaneously produced two chemically distinct magma series: Saba, medium-K calc-alkaline, and the Quill, low-K calc-alkaline. Such differences may be explained by the primary Saba magmas being produced by lower amounts of partial melting of the mantle wedge than those of St. Eustatius. Saba magmas also appear to have been affected by the assimilation of upper crustal sedimentary material. Variations within the two suites suggest that processes of crystal fractionation and magma mixing/co-mingling relate lavas for both islands. The volcanic rocks of the Northern Centers-White Wall-Sugar Loaf form a distinct trend that crosses from basaltic andesite and andesite of low-K suite to dacite and rhyolite of the medium-K suite. St. Eustatius is unique in the Lesser Antilles in that rhyolite evolved twice in its history, first in the Sugar Loaf, and then later in the Quill pyroclastic succession. An estimate of the time required to form these rhyolites is around 30,000 years.

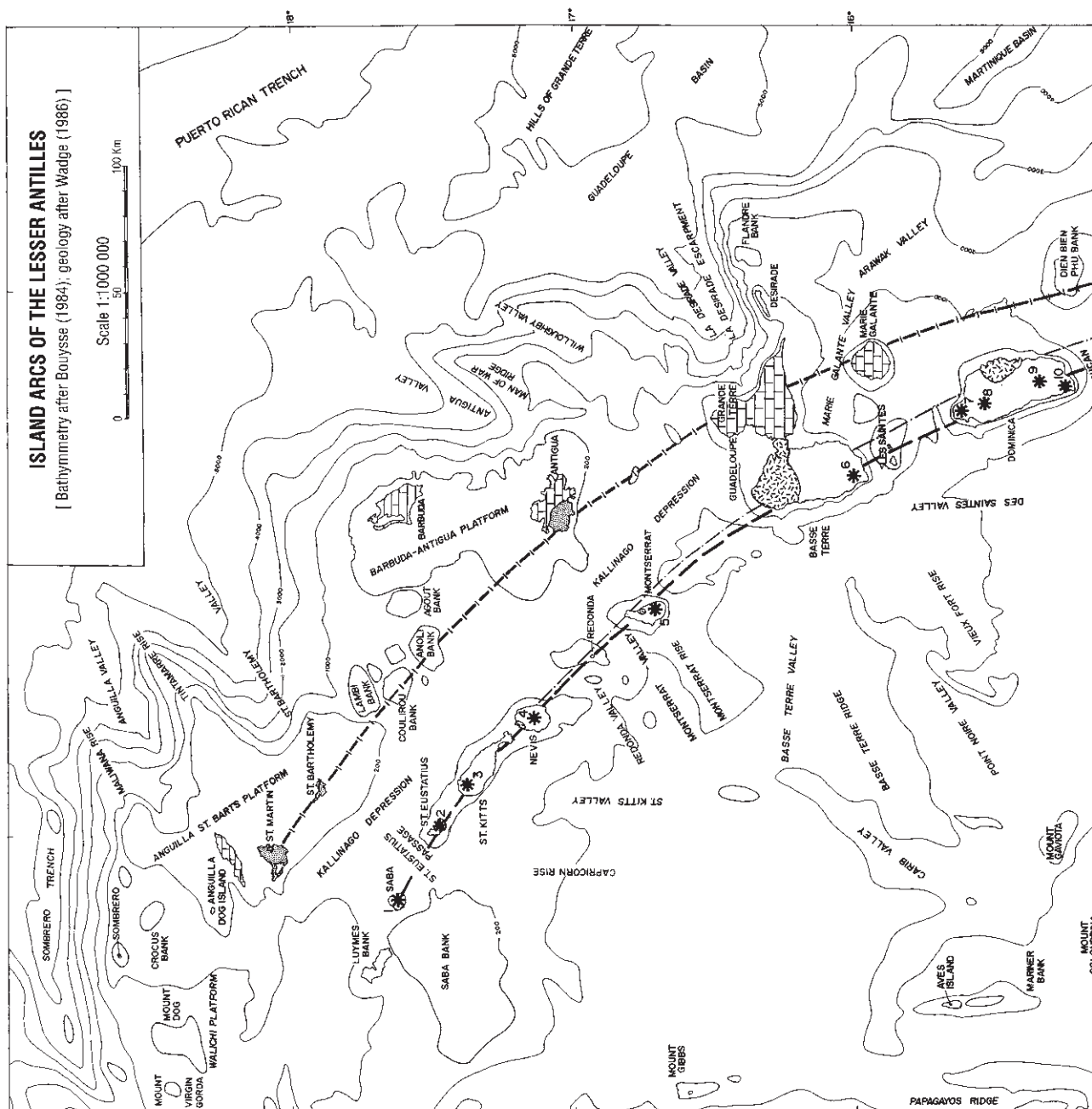
Saba and the Quill are thought to represent different types of volcanoes. The rocks of Saba are commonly filled with rounded hypabyssal inclusions and lack cumulate blocks whereas the lavas of the Quill show the reverse in that they contain cumulate blocks but lack hypabyssal inclusions. Saba is believed to be underlain by a complex of composite dikes, intruded into the underlying northeast-southwest fault zone, where the hypabyssal inclusions form. The Quill is believed to be underlain by a lower crustal magma chamber with a simple conduit linking it to the volcanic edifice. The lavas of the Soufriere Hills, Montserrat show similarities to Saba, and Mt. Pelée, Martinique, and Soufriere, St. Vincent appear to be similar to the Quill.

The northeast end of the Lesser Antilles arc is underlain by extensive submarine banks of low grade metamorphic, volcanic, volcanoclastic and sedimentary rocks capped by Cenozoic limestones. The Saba bank measuring 70 km east-west by 50 km north-south and with water depths of between 20 and 40 m has been drilled for oil so that its stratigraphy is known. On the island of Saba pyroclastic deposits contain sparse blocks of granofels, hornfels and unmetamorphosed late Tertiary fossiliferous limestone. The pyroclastic deposits of the Quill contain an abundance of ejected blocks of green metavolcanic and meta-volcanoclastic rock as well as fossiliferous limestone blocks and those of igneous cumulate material.

It is concluded that Saba and the Quill, St. Eustatius are both active volcanoes and that the island of Saba, like Mt. Pelée, Martinique, is likely to produce Pelean style activity whereas the Quill, like St. Vincent, remains in an open crater stage St. Vincent-style activity. An independent geohazard report on the islands has been completed and published by the Netherlands Geological Survey with recommendations to initiate routine monitoring of both islands because of their small areas and relatively dense populations.

ISLAND ARCS OF THE LESSER ANTILLES

[Bathymetry after Bouysse (1984); geology after Wadge (1986)]



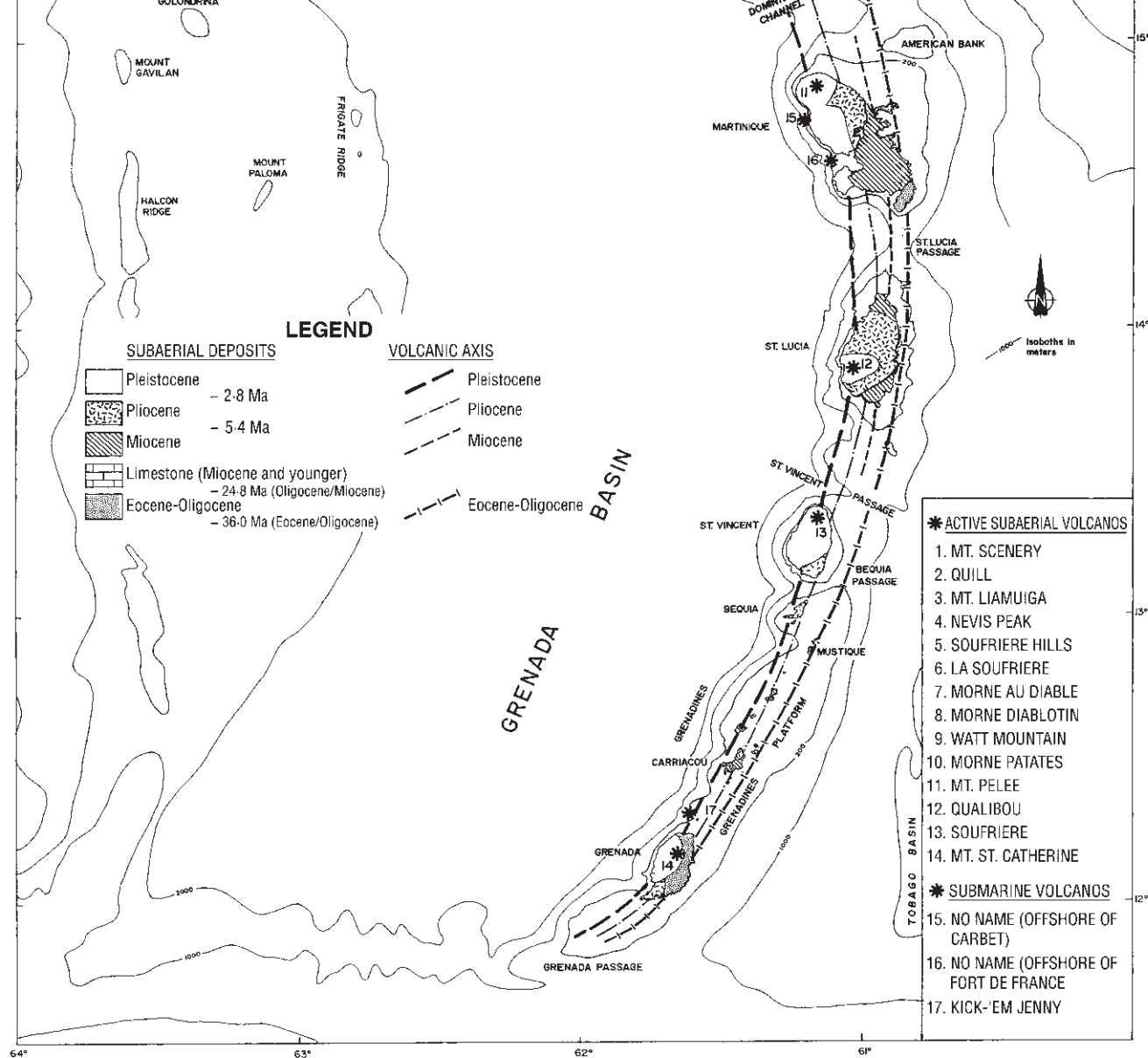


FIGURE 1. Bathymetry of the Eastern Caribbean showing the ages of the exposed rocks of the Lesser Antilles and axes of component arcs.

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Work on Saba and St. Eustatius has extended over a period of 25 years during which many individuals and organizations helped us. Our interest in both Saba and St. Eustatius began in 1975 when we sailed to the islands in the company of B. Gunn aboard his fifty-foot ketch *Pelorus Jack* as part of his sabbatical leave voyage from Canada. His help included the setting up of the X-ray analytical laboratory at the University of Puerto Rico, and the first modern chemical analyses from Saba and St. Eustatius. It was administrator G. Sleeswick of Saba who brought to our attention the lack of monitoring and awareness of volcanic hazard on these islands. J. Tomblin and E.M. Fournier d'Albe of UNESCO supported our letters to G.C. Brouwer of the Rijks Geologische Dienst (RGD), that modern volcanological work should be conducted on these islands. Research presented here was supported by NSF Grants EAR 73-00194, EAR 77-17064, RII 88-02961, HRD 93-53549, and GEO 0119934, NASA-TCESS (Tropical Center for Earth and Space Sciences) grant, and funding from the University of Puerto Rico, and California State University San Bernardino. Production of the 1981 geohazard report was funded by a grant from RGD, administered by G.C. Brouwer and A. van Adrichem Boogaert. We would also like to thank the following for participation in the fieldwork, P. Jansma, J. Joyce, G. Mattioli, K. Rowley, J.H. Schellekens, and J. Tomblin. Mr. George Seaman of Windwardside, Saba collected and brought to Puerto Rico one of the only four charcoal samples dated from that island. We should also like to thank W. Rose Jr. (Michigan Tech.), F. Frey (MIT), J. Stipp (U. Miami), and D. Blatter (UC Berkeley) for undertaking geochemical analyses,

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Introduction

The volcanic islands of the northern Lesser Antilles, including Saba and St. Eustatius have been formed on top of extensive, shallow-water submarine banks. These banks lie between the Virgin Islands in the north and Dominica in the south, and occupy an area measuring around 300 km northeast-southwest by 400 km northwest-southeast (Plate 1). These small islands, which make up only three percent of this 120,000 sq. km area, show a surprisingly varied geology, and provide a window into the dominant complex submarine banks and basins. The islands are divided into the Leeward and Windward Islands. The former are part of the active volcanic arc and extend from Saba, through St. Eustatius, St. Kitts, Nevis, Redonda, Montserrat to Basse Terre of Guadeloupe. Geologically these islands are composed of Pliocene and younger volcanic rocks and their reworked equivalents with small amounts of uplifted platform limestones (Maury et al., 1990). The latter belong to an older extinct volcanic arc known as the Limestone Caribbees and are composed of the islands of Sombrero, Anguilla, St. Martin, St. Barthélémy, Antigua, and Grande Terre of Guadeloupe. These islands are composed of Eocene to Oligocene igneous rocks with a capping of Miocene and younger limestones (Maury et al., 1990).

Geologically distinct from the volcanic islands described above are the islands of St. Croix and La Desirade. The former, lying to the southeast of the Anegada Passage is composed of Upper Cretaceous deformed low-grade metamorphosed volcanoclastic sediments overlain by Upper Oligocene to Lower Miocene mudstones and limestones. The only igneous rocks on the island are two lava flows and two intrusions (Whetten, 1966; Lidiak and Jolly, 1998; Smith et al., 1998). The geology of St. Croix appears to be

more similar to that of the Greater Antilles than to the volcanic islands of the Lesser Antilles to the south (Mattson et al., 1990). The island of La Desirade, to the east of the double island of Guadeloupe, is composed of a Jurassic trondjhemitic intrusion unconformably overlain by Jurassic to Cretaceous submarine volcanic rocks and cherts, capped by Lower Pliocene limestones (Maury et al., 1990).

The many small islands stand on a vast area of shallow submarine banks well defined by the 1000 m submarine contour (Plate 1). Submarine dredging on the steep sides of the banks has yielded igneous and sedimentary rocks of Mesozoic age (Andrieiff et al., 1979; Bouysse et al., 1985b; Maury et al., 1990). One of the banks — Saba Bank — immediately west of Saba island has been drilled during oil exploration to reveal Eocene and younger sedimentary rocks overlying Upper Cretaceous igneous rocks (Warner, 1990).

Samples of the underlying banks occur as blocks in the lavas and pyroclastic deposits of the islands. These blocks, which are not common, provide the only direct evidence of the nature of the older submarine banks underlying the volcanoes. They include limestones which range in age from Eocene (Hutton, 1978) to Plio-Pleistocene, together with more common metavolcanic/volcaniclastic rocks colored green by epidote and chlorite. A few of the latter also contain green amphibole suggesting that they were subjected to conditions of green schist facies metamorphism. Partially granulated, tectonized felsic plutonic rocks have been found on Saba island only. The most exotic ejected block collected so far, is a potassic lamprophyre composed essentially of hornblende and biotite that was also collected from Saba island.

To better understand this complex but poorly-exposed area, the different components are next described separately.

ISLAND ARCS OF THE EASTERN CARIBBEAN

The bathymetry of the eastern Caribbean is described by Bouysse and Martin, (1979) and shows the area to be composed essentially of four components (Plate 1). First is the Lesser Antilles, comprising multiple superimposed island arcs all of Cenozoic age (Fig. 1). Second is the Aves

Ridge, an extinct island arc of Upper Cretaceous to Paleocene age. Third are the Venezuela and Grenada ocean basins with water depths in excess of 3,000 m. Fourth are the extensive shallow-water submarine banks of the northern Lesser Antilles.

The composite arc of the Lesser Antilles

The Lesser Antilles is a chain of volcanic islands with an arc length of 740 km that stretches from the Anegada Passage in the north to the South American continental margin. The Lesser Antilles was regarded as a double arc by Martin-Kaye (1969), and as a multiple arc by Westercamp (1979), who subdivided it into arcs of pre-Miocene, Miocene and post-Miocene to Recent ages. The multiple nature of the arc was also noted by Wadge (1986), who plotted the arc axes of Eo-Oligocene, Pliocene and Pleistocene-Recent ages. In Figure 1 (see p. xvi/xvii) the axes of four arcs ranging in age from Eo-Oligocene in the east systematically through Miocene, and Pliocene to Pleistocene-Recent in the west are shown. For the southern Lesser Antilles (Grenada to St. Lucia) the arcs appear tightly superimposed. In Martinique and northwards the arcs bifurcate, as is best seen in Basse Terre and Grande Terre of Guadeloupe. In the north, the axis of the Eo-Oligocene arc in St. Martin is 50 km northeast of the Pleistocene-Recent arc on Saba.

The Active Arc

The chain of islands from Grenada in the south through the Grenadines, St. Vincent, St. Lucia, Martinique, Dominica, Les Saintes, Basse Terre of Guadeloupe, Montserrat, Redonda, Nevis, St. Kitts, St. Eustatius and Saba comprises the Active Arc or Volcanic Caribbees. The Active Arc, which equates with the Pliocene and Pleistocene-Recent arcs of Wadge (1986), is characterized by hot springs, fumeroles, historic volcanic activity (including the on-going eruption on Montserrat), as well as pre-historic activity which affected the Amerindian populations. A summary of this activity, after Roobol and Smith (1989) and Shepherd (1989), is shown in Figure 2.

Although Saba is the northernmost island of the Active Arc, a possible submarine extension for a further 40 km northwest has been proposed (Bouysse et al., 1981) to include the submarine volcanic center of the

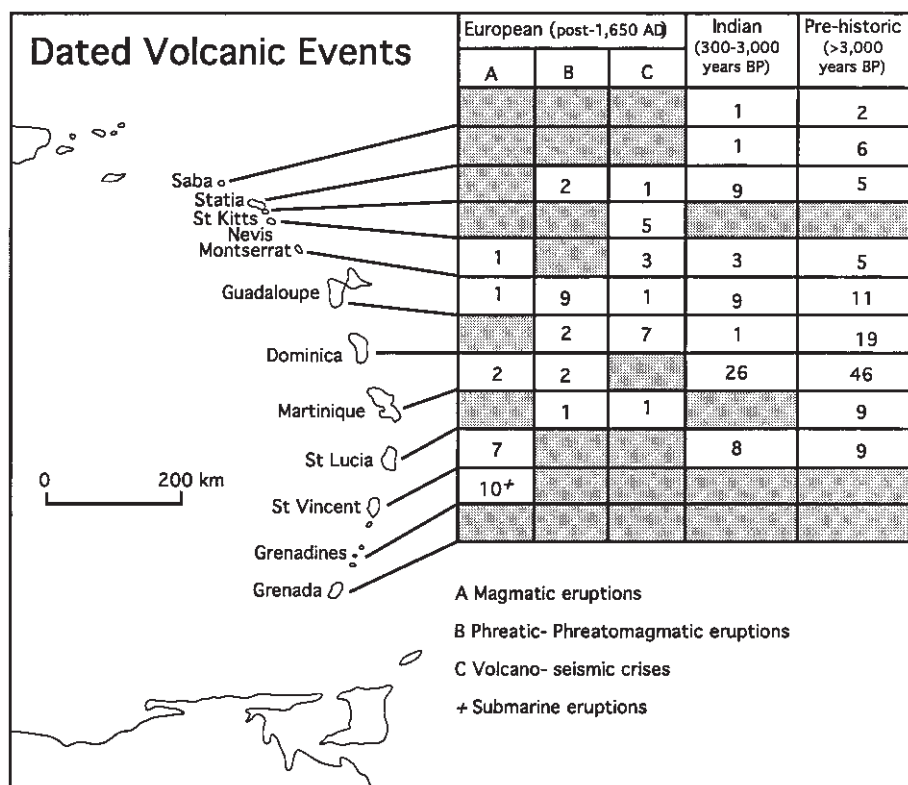


FIGURE 2. Volcanic activity as determined from historic eruptions and dated deposits (at present state of knowledge), grouped according to European, Amerindian, and pre-historic periods, for the Active Arc of the Lesser Antilles (modified from Roobol and Smith, 1989).

Banc de Luymes. Dredge samples from the Banc de Luymes described as andesites (Table 1) containing phenocrysts of plagioclase, amphibole, and titanomagnetite, have yielded a whole rock K/Ar age of 3.6 Ma (Bouysse et al., 1981). An additional four dredge samples identified as hornblende-bearing calc-alkaline andesites, and dated at 4 Ma, were recovered from Mt. du Noroit on the edge of the Anegada Passage (Bouysse et al., 1985c), and it was suggested that this center was the actual northern termination of the Lesser Antilles. However when these rock compositions are compared with those from the Luymes Bank and the active submarine volcano of Kick'em Jenny (Table 1) the lavas appear to be alkali basalts rather than calc-alkaline andesites. Mt. du Noroit (Plate 1), which lies off the axis of

TABLE I. Chemical composition of volcanic rocks dredged from Mt. du Noroit seamount, the Luymes Bank and Kick 'em Jenny Volcano

	Mt. du Noroit seamount ¹				Luymes Bank ²	Kick'em Jenny ³
	A	B	C	D		
SiO ₂	50.39	51.03	51.17	53.61	60.20	51.84
TiO ₂	0.88	0.98	0.93	0.79	0.47	0.93
Al ₂ O ₃	19.22	22.51	20.42	21.14	17.95	19.06
Fe ₂ O ₃ *	10.67	7.26	8.28	7.15	5.57	8.80
MnO	0.25	0.35	0.66	0.31	0.09	0.13
MgO	4.26	2.61	3.46	2.49	3.28	5.50
CaO	9.58	8.62	9.46	8.05	8.29	10.14
Na ₂ O	4.08	5.00	4.34	4.76	3.46	2.78
K ₂ O	0.51	1.47	1.15	1.61	0.55	0.83
P ₂ O ₅	0.14	0.16	0.11	0.08	0.14	N.D.
Cr	14	10	11	9	N.D.	N.D.
Ni	25	40	40	20	N.D.	34
Sr	348	427	348	353	N.D.	305

Major element analyses recalculated to 100% volatile free.

* Total iron as Fe₂O₃

N.D. Not determined.

1 Bouysse et al. (1985c).

2 Bouysse et al. (1981).

3 Devine and Sigurdsson (1995).

the Active Arc, is therefore regarded as an alkali basalt seamount associated with the northeast-southwest rift zone of the Anegada Passage. Such an origin has also been proposed by Jany et al. (1990) on tectonic grounds.

The Extinct Arc of the Limestone Caribbees

The northern part of the extinct arc is well preserved in the Windward Islands of Sombrero in the north, through Dog, Anguilla, St. Martin, St. Barthélemy, Barbuda, Antigua, and Grande Terre of Guadeloupe to Marie Galante in the south (Fig. 1). These islands are all relatively low-lying with older volcano-sedimentary and igneous rocks of mid-Eocene to Oligocene age (Christman, 1972; Gunn and Roobol, 1976; Westercamp, 1979; Andreieff et al., 1981; Wadge, 1986; Davidson et al., 1993; Smith et al., 1998). These older rocks of the Limestone Caribbee arc

have been peneplaned and are partially or completely capped by mid-Miocene to Pleistocene limestones (Andreieff, 1982; Andreieff and Cottez, 1976; Andreieff et al., 1984). From Martinique southwards, the younger arcs are partially superimposed on volcanic and sedimentary rocks of Eocene to Oligocene age. The older rocks are exposed on the eastern or windward side of these islands (Fig. 1).

The systematic shift of the axis of volcanism for the northern Lesser Antilles from the Eo-Oligocene Limestone Caribbee arc through the Miocene, and Pliocene to the Pleistocene-Recent arc has been explained by the attempted subduction of aseismic ridges which exist on the North American plate from St. Lucia northwards (McCann and Sykes, 1984; Westbrook and McCann, 1986; Bouysse and Westercamp, 1990). Bouysse and Westercamp (1990) have proposed that the attempted subduction of such buoyant aseismic ridges beneath the Lesser Antilles arc blocks the subduction process by underplating the ridge beneath the forearc. Continued motion of the North American plate results in the initiation of a new subducting slab with the resulting westward migration of the focus of volcanism. An alternative explanation is that the eastward movement of the Caribbean plate has been impeded in the south by interaction with the South American continental margin, so that continued eastward movement of the plate has resulted in a progressively larger displacement of the focus of volcanism from south to north.

Aves Ridge

The Aves Ridge lies to the west of the Lesser Antilles and is separated from it by the Grenada Basin. It has similar dimensions and form to the Lesser Antilles composite arc, but is almost entirely submarine. The ridge extends north-south from the Anegada Passage for 600 km to the South American continental margin. It rises 1,000-2,000 m above the flanking Venezuela and Grenada basins, and has an east-west width of over 100 km. These dimensions suggest a complex evolution through multiple arcs as has been suggested for the Lesser Antilles. Drilling and dredging on the Ridge indicate the presence of Miocene to Recent pelagic limestones, middle Eocene to early Miocene shallow-water limestones, and upper Cretaceous (Turonian to late Senonian) to Paleocene volcanic, plutonic and volcanoclastic rocks. The latter indicate that the Aves Ridge was an

active volcanic arc during the late Mesozoic and early Tertiary, however the polarity of subduction for this arc is at present unknown (Nagle, 1972; Donnelly, 1975; Fox and Heezen, 1975; Westbrook, 1975; Keary, 1976; Clark et al., 1978; Bouysse et al., 1985a and b).

VENEZUELA AND GRENADA BASINS

The Venezuela and Grenada Basins are both underlain by oceanic crust (Officer et al., 1959; Edgar et al., 1971; Ludwig et al., 1975; Boynton et al., 1979; Diebold et al., 1981; Bouysse, 1988). The eastern part of the Venezuela Basin has a normal oceanic crustal thickness of around 5 km. In contrast, Boynton et al. (1979) have proposed that the Grenada Basin is composed of approximately 10 km of oceanic crust, which in the southern part of the basin is buried beneath a thick sedimentary cover. The Mayreau Basalt of probable Eocene age is thought to have formed in a back-arc setting and may represent an on-land exposure of this oceanic material (Speed and Walker, 1991; Speed et al., 1993). Magnetic stripes on the floor of the Venezuela Basin have been dated at 136-130 Ma, i.e. Jurassic (Ghosh et al., 1994), whereas the Grenada Basin is thought to have formed in the early Paleogene (Speed et al., 1984).

SUBMARINE BANKS OF THE NORTHERN LESSER ANTILLES

The platform on which the islands of the Lesser Antilles stand is readily delineated by the 1000 m submarine contour (Fig. 1). The platform increases steadily in width from 20 km near Dominica to 250 km in the vicinity of Saba and St. Eustatius. Rising above this broad platform are shallow water banks defined by the 200 m submarine contour (Bouysse et al., 1985a). These banks are separated into eastern and western groups by the Kallinago Depression. Perhaps the most remarkable feature of the submarine banks is their highly irregular morphology, particularly along the Atlantic margin, where seven wedge-shaped submarine ridges extending into the Atlantic are bounded by steep slopes (Plate 1). The margins of the banks extending into the northern Grenada Basin are similarly highly

irregular, showing steps and indentations. One of the steepest of these submarine scarps is parallel to, and falls away from, the north shore of La Desirade island, with its exposed Jurassic to Cretaceous rocks (Fink, 1970; Mattinson et al., 1973; 1980; Montgomery et al., 1992). A case for these steep and planar submarine scarps to be fault planes can be demonstrated not only from their morphology, but also from measured historic seismic activity, geophysical studies, and dredging of the scarps. Some of the lineations indicated by these steep submarine scarps parallel geological faults mapped on the adjacent small islands, however for many of these features there is little structural data. From the review of the structural data presented in Plate 1, we prefer to regard the submarine banks as composed of Mesozoic to Tertiary basement which was broken into blocks, now represented by the submarine banks, by several major prominent fault systems of different orientations and displacements. Some of the major submarine escarpments can be traced towards the young Plio-Pleistocene islands of the Active Arc where such major fault escarpments are absent, suggesting that most of the faulting occurred before the Plio-Pleistocene and mainly affects the Eocene rocks and to a lesser extent the Miocene rocks. The occasional occurrence of parallel faults on the islands suggests that there must have been some reactivation during the Plio-Pleistocene. Some of the major features are described in more detail in the following sections.

Anegada Passage

The Anegada passage is a steep-sided submarine trough with a width of about 30 km. It is bounded by steep submarine slopes along the south-east margin of the Virgin Islands bank, and by an irregular south-east margin along the submarine banks of the northern Lesser Antilles. Bouysse et al. (1985a and b) have identified two arcuate faults corresponding to the Anegada passage. A more complex pattern of lineations, and possible faults is shown in Plate 1 based, in part, on the work of Jany et al. (1990). These authors interpreted the Anegada Passage as being formed of two right-lateral pull-apart basins, the Virgin Islands and St. Croix basins, with the Tortola Ridge forming a restraining bend between right-lateral strike-slip faults. Within this complex rift zone two ENE-WSW volcanic lineaments have been identified, the more northerly of which contains the Mt. du Noroit seamount.

Kallinago Depression

The Kallinago depression (Plate 1) runs along the crest and long axis of the submarine banks and separates them into two groups supporting the Windward and Leeward islands. From Anguilla to Guadeloupe it has a length of 250 km and becomes progressively broader and deeper to the northwest. Adjacent to St. Eustatius it has a bottom width of 20 km. It appears to be truncated by the double island of Guadeloupe, yet there is a continuation south of Grande Terre with similar orientation known as the Arawak Valley. The northernmost part of the Kallinago depression has been shown by deep seismic reflection profiles to be a graben structure (Westbrook et al., 1984a and b). This interpretation can probably be extended to the whole structure and its probable continuation in the Arawak valley. Although its present position is fore-arc relative to the Active Arc, it may have originated in a back-arc position relative to the older, now-extinct arcs.

Seismically Active Faults

The Lesser Antilles arc is the surface manifestation of a subduction zone where the North and South American plates are underthrusting the Caribbean plate. The zone of underthrusting is today located about 150 km east of the Active Arc and is inclined towards the west. The Wadati-Benioff zone, which varies in thickness between 30 and 50 km, appears to systematically change in dip along the length of the arc, becoming steeper towards the south (Tomblin, 1975; Aspinall and Tomblin, 1975; Dorel, 1978; McCann and Sykes, 1984; Wadge and Shepherd, 1984), and shows an inflexion south of Martinique (Wadge and Shepherd, 1984). A series of faults transverse to the arc have been identified by alignments of located epicenters (Fig. 3) (Tomblin, 1972; Westercamp, 1979; Wadge and Shepherd, 1984; Wadge, 1986; Ambeh and Lynch, 1993, 1995). One of these proposed faults runs close to La Desirade island and has an active length of 200 km. Another runs through Montserrat and immediately south of Antigua into the Valley of Antigua with an active length of 140 km. A third lies immediately to the south of Dominica. Epicenters from recent seismic activity felt on Saba, St. Eustatius and St. Martin described later in this report delineate another possible transverse fault.

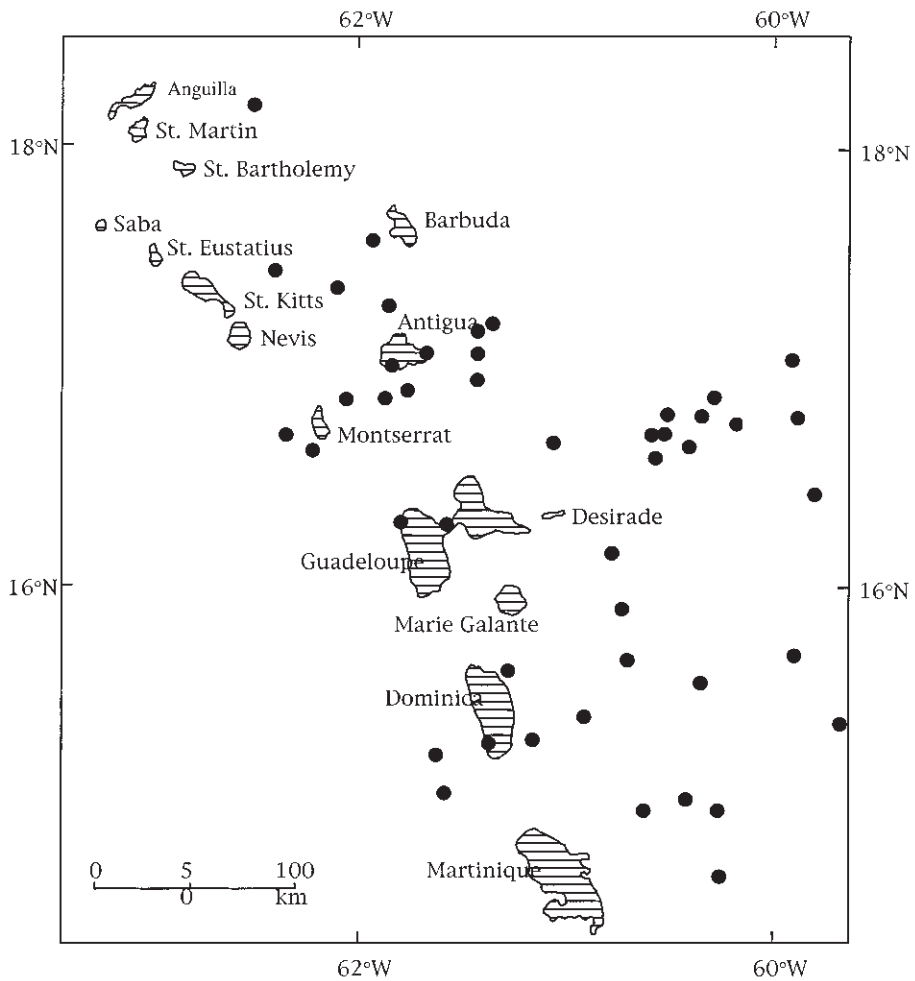


FIGURE 3. Plot of epicenters of selected earthquakes and associated aftershocks for the northeast Caribbean (Data sources: Tomblin, 1972; Aspinall and Tomblin, 1975; Ambeh and Lynch, 1993, 1995; Puerto Rico Seismic Network, unpublished data).

Faults revealed by seismic reflection profiles

Plate 1 also shows the location of faults recognized from seismic reflection profiles (Westbrook et al., 1984a and b). These faults are both parallel to, and transverse to the arc, and indicate a horst and graben structure as the dominant tectonic style in the region. These faults mainly affect the basement, but with an indication in a few seismic lines of reactivation (Speed et al., 1984).

Lineaments

Although no geological proof of faulting is present for many of the steep submarine scarps, a number of lineaments have been drawn which probably correspond to fault scarps. The lineaments shown in Plate 1 are purely interpretative, but without them the observed morphology makes little sense. Some support for the idea that they represent faults is indicated by the parallel orientation of faults on adjacent small islands, by the correspondence of faults recognized from seismic reflection profiles, and from lines of earthquake epicenters that correspond to some of the proposed lineaments.

The general directions shown by the faults and lineaments in Plate 1 are northeast-southwest and northwest-southeast. Similar directions have been obtained from studies of joints (Bonneton and Scheiddegger, 1981), and dikes (Wadge, 1986) on the Lesser Antillean islands. Similar directions are also seen in the distribution of earthquake epicenters related to the initiation of the current eruption of the Soufriere Hills, Montserrat (Aspinall et al., 1998). In addition, GPS ground deformation studies of this eruption suggest that it was caused by the intrusion of a northwest-southeast orientated dike (Mattioli et al., 1998). Such data therefore suggest that the principal tectonic stress directions for the entire length of the Lesser Antilles arc are also orientated in these two general directions.

Drilling and seismic reflection studies on Saba Bank

The Saba Bank, located 13.5 km southwest of the island of Saba, is a completely submerged carbonate platform that stands approximately 1000 m above the surrounding sea floor. It has dimensions of around 50 by 70 km, and water depths of 20 m in the south and 40 m in the north. Hydrocarbon exploration of the bank (Warner, 1990) resulted in seismic reflection profiles and two exploratory wells which revealed that the bank is composed of a western platform facies, and an eastern basin facies (Fig. 4). Four major stratigraphic units were encountered in the two wells drilled into the bank. At the bottom of the drilled section there occurs an andesitic porphyry dated at 64.5 Ma, which has been interpreted as a shallow sub-surface intrusion. Above this in well SB-1, is a thin quartz conglomerate overlain by Eocene reef limestone. Equivalent strata in well SB-2 are thin clay and sandstone beds of turbiditic origin. Overlying these beds in both wells are volcanoclastic rocks consisting of conglomerates (only in SB-1), sandstones and

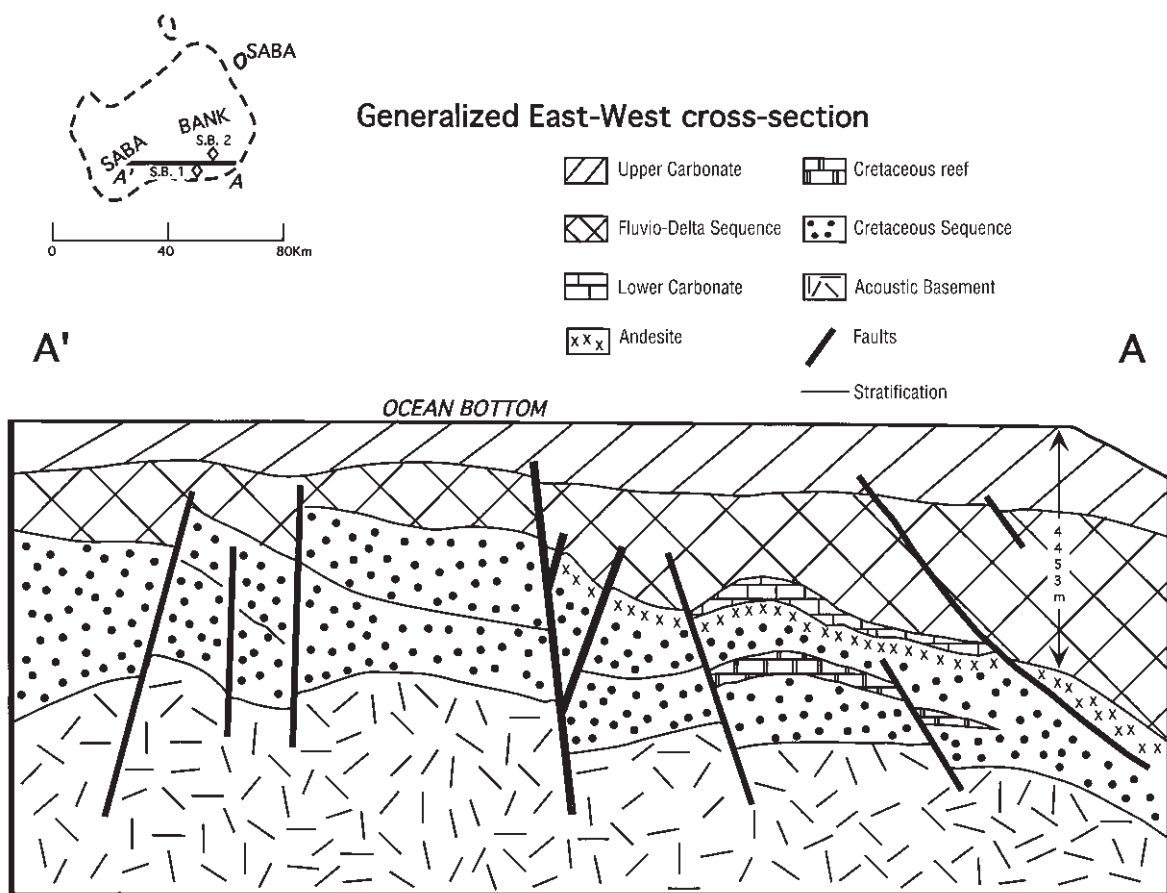


FIGURE 4. East-west cross section through the south part of the Saba Bank showing stratigraphy based on seismic refraction profiles and two exploratory wells (after Warner, 1991). Vertical scale is indicated by depth of well S.B.2 located near right-hand margin of figure.

siltstones of upper Eocene to lower Miocene age. The environment of deposition of this unit is thought to be near-shore deltaic at SB-1, and a neritic to deep-water submarine fan at SB-2. The Bank is capped by middle Miocene to early Pliocene platform limestones (Warner, 1990).

Seismic reflection and magnetic data suggest that underlying the andesite porphyry (dated at 64.5 Ma) is a thick sedimentary sequence that could be as old as early Cretaceous (Warner, 1990). What may be similar rocks of Cretaceous age are exposed on St. Croix, which also

lies on the south side of the Anegada fault on an extension of the submarine banks of the northeastern Caribbean. The seismic reflection profiles also revealed a basement reflector beneath the sedimentary rocks, which could represent either the Caribbean crust or an older sedimentary sequence perhaps equivalent to the Jurassic rocks exposed on Puerto Rico and La Desirade (Montgomery et al., 1992, 1994a and b).

Mesozoic rocks of St. Croix and La Desirade islands

The oldest rocks exposed on St. Croix are epiclastic mudstones and minor turbidites of the Caledonia Formation, which in the west of the island grades into the tuffaceous Allendale Formation. The age of these rocks is Cenomanian to Maastrichtian (Speed, 1989; Speed and Joyce, 1989). Speed et al. (1979), based on isotopic ages of included igneous clasts have suggested that the Lower Caledonia Formation is Santonian or Cenomanian in age. The Fountain Gabbro which intrudes the overlying Judith Fancy Formation gives an $^{39}\text{Ar}/^{40}\text{Ar}$ age of 68 Ma (Smith et al., 1998). Based on lithology, stratigraphy, and paleontological and radiometric age dating, these Cretaceous formations are comparable to the Yauco Formation of Puerto Rico (Joyce, personal communication, 1996).

The oldest proven rocks outcropping in the northern Lesser Antilles occur on the east-west fault-dominated island of La Desirade, which is part of a very steep scarp named the Desirade escarpment by Bouysse et al. (1980). Igneous and sedimentary rocks on La Desirade have been described by Fink (1970), Mattinson et al. (1973,1980), Westercamp (1980), Bouysse et al. (1983), and Le Guen de Kerneizon et al. (1979). Montgomery et al. (1992) have identified Jurassic (upper Tithonian) radiolaria in red ribbon cherts on La Desirade. Similar cherts of equivalent or older age also occur in Puerto Rico (Montgomery et al., 1994a), and the Dominican Republic (Montgomery et al., 1994b), and have been interpreted as originating in a pre-Caribbean Pacific Ocean setting (Montgomery et al., 1994a, b).

Mesozoic rocks dredged from submarine scarps on banks in the northeastern Caribbean

Pre-Tertiary rocks have been dredged from the steep submarine escarpments east of Antigua, Barbuda and Anguilla, and north of Sombrero

(Fox and Heezen, 1975). Those from the north slope of the Anguilla platform are radiolarian-bearing tuffs and marls assigned to the upper Cretaceous (upper Senonian to Santonian) by Bouysse et al. (1985b). Rocks of similar lithology and age have also been described from the Desirade escarpment (Westercamp, 1980).

Discussion

The submarine banks underlying the northern Lesser Antilles may have a Jurassic to Cretaceous stratigraphy similar to that of the Greater Antilles, as hinted at by such exotic materials as the Jurassic ribbon cherts exposed on La Desirade island, quartz conglomerate identified in drilling the Saba Bank, and green metamorphosed magmatic rocks known from dredging the Desirade escarpment (Westercamp, 1980). The ejected green volcanoclastic blocks observed on the islands of Saba, St. Eustatius, St. Kitts and Montserrat are likely to be of Tertiary age. Geophysical evidence has suggested that the entire Lesser Antilles was built on a Mesozoic basement and that the Aves Ridge separated from it by back-arc spreading in the Paleocene (Maury et al., 1990). In contrast, Keary (1976) proposed that the subduction zone jumped eastward from the Aves Ridge to its present position at the beginning of the Eocene suggesting that the present Lesser Antilles arc was built completely on oceanic crust. A similar idea by Bouysse and Martin (1979) proposed that the southern Lesser Antilles was offset from the more northerly arc system by an east-west transform fault, thus in the north the Lesser Antilles arc was built on a Mesozoic basement, whereas in the south the basement was probably oceanic crust, which may be exposed in the Grenadines as the Mayreau Basalt (Speed and Walker, 1991).

The basement underlying the submarine banks of the northeast Caribbean has been broken up by faulting and blanketed by Tertiary limestones. The latter cap the banks only, without extending down the steep submarine scarps, implying that faulting continued after deposition of the limestone caps. However volcanism ceased at different times on the different submarine banks so that the limestones formed after volcanism ceased are of different ages. Thus for St. Croix and the drilled Saba Bank, volcanism ceased in the Upper Cretaceous, and Eocene limestones were deposited. On the Anguilla-St. Martin-St. Barthélemy Bank,

volcanism ceased in the middle Oligocene around 27 Ma, and limestone deposition commenced in the Lower Miocene. On Antigua, volcanism ceased in the Oligocene, and limestone deposition began almost immediately in the Upper Oligocene (Masle and Westercamp, 1983). The southernmost islands of the Limestone Caribbees, Grande Terre of Guadeloupe and Marie Galante are entirely covered by limestones of Pliocene-Quaternary age. The limestone cap of La Desirade was deposited in the Lower Pliocene and the major Desirade escarpment appears to have truncated this cap. Seismic records (Fig. 3) indicate that some of the faults cross-cutting the submarine banks of the northeast Caribbean are still active today.

On both Saba and St. Eustatius blocks and fragments of limestone, up to 10 cm, are not uncommon as lithic ejecta within pyroclastic deposits, and as inclusions in andesitic lava blocks. These fragments provide direct evidence of the stratigraphy of the limestone platforms underlying the volcanoes, and examples are described later.

The Plio-Pleistocene volcanic superstructure of the Lesser Antilles arc lies mainly above the 200 m submarine contour. This of course excludes submarine turbidites and gravity collapse deposits, the former have been shown to extend onto the floor of the Grenada basin (Sigurdsson et al., 1980). There is a particularly interesting structural problem in the case of the double island of Guadeloupe and the Kallinago depression and its possible extension to the south of Guadeloupe as the Arawak Valley (Plate 1). The double island of Guadeloupe appears to be superimposed on, and blankets the Kallinago Depression and its possible extension into the Arawak valley, although the east coast of Grande Terre of Guadeloupe appears to have been shaped by the head-scarp of the submarine La Desirade valley (Plate 1). Such observations, and the relationships of the lineaments and faults of the submarine banks (Plate 1) suggest that faulting occurred throughout the Cenozoic, and based on seismic records appear to be continuing up to the present.

The extensive submarine banks underlying the volcanoes of the northern Lesser Antilles arc are much affected by tectonism. This is well demonstrated by the highly irregular submarine morphology of the fore-arc region between the Limestone Caribbean Arc and the ocean floor trench marking the boundary with the North American plate. Here a

series of ridges separated by valleys extend perpendicular to the arc front. The Malliwana and Tintamarre rises separated by the Anguilla valley extend east-northeast towards the Atlantic, parallel with the elongated island of Anguilla. A similar relationship exists east-northeast of Antigua with the Man of War ridge bounded by the Antigua and Willoughby valleys. The relationship is again repeated in the vicinity of La Desirade island, with the La Desirade valley and the Flandre Bank. A summary of the published data together with an interpretation of submarine lineations based on the bathymmetry of Bouysse et al. (1985a) is shown in Plate 1. The basement faults described by Westbrook et al. (1984a and b) are also identified on Plate 1 and correspond closely with the lineations identified from the bathymmetry of Bouysse et al. (1985a). For example, the Kallinago depression is described by Westbrook et al. (1984a and b) as a graben structure but only for the section from Redonda to St. Eustatius. In the case of the Anegada Passage, the latest interpretation of Jany et al. (1990) has been followed, in which the area of the Anegada Passage has been interpreted as a complex pull-apart structure bounded by strike-slip faults between which the Sombrero Trench, the St. Croix Basin and the Virgin Islands Trough are pull-apart basins.

A review of the pyroclastic deposits of the Lesser Antilles

INTRODUCTION

The most important tool of the volcanologist today in understanding the volcanoes in the Lesser Antilles lies in the preserved stratigraphic record of each volcano. This is because the historic period of the Lesser Antilles during which written records were kept is relatively short, and deposits exist in the stratigraphic record which have never been seen forming since the time of written observations. For both Saba and St. Eustatius islands, where there are no records of eruptive activity since European settlement in 1640 AD and 1636 AD respectively (Hartog, 1975, 1976), the entire pyroclastic history and resulting geohazard interpretations have to be reconstructed from the stratigraphic records (Roobol et al., 1997).

For the Lesser Antilles as a whole, records exist of twenty-seven sub-aerial eruptions and nineteen volcano-seismic crises, including the one which preceded the 1995 eruption of the Soufriere Hills, Montserrat (Table 2). In addition ten submarine eruptions have occurred from Kick'em Jenny in the Grenadines (Robson and Tomblin, 1966; Shepherd, 1989; Simkin and Siebert 1994; McClelland et al., 1989; SEAN, 1986, 1988, 1989; GVN, 1990, 1992, 1995, 1996, 1997, 1998, 1999, 2000). The older part of this record is far from complete as the islands were not settled until the mid-17th century (Cotner, 1975; Hartog, 1975, 1976; Fergus 1994), and the earliest recorded eruption is not until 1680 AD (Robson and Tomblin, 1966). The historic record shows three events in the 17th century, six events in the 18th century, thirteen events

TABLE 2. Historic subaerial volcanic activity and associated volcano-seismic crises of the Lesser Antilles

Date	Volcano	Type of volcanic activity
1680?	La Soufriere, Guadeloupe	Phreatic
1692?	Mt. Liamuiga*, St. Kitts	Phreatic
1696	La Soufriere, Guadeloupe	Phreatic
1718	Soufriere, St. Vincent	St. Vincent-style
1765	Northern/Central Dominica?	Volcano-seismic
1766	Qualibou, St. Lucia	Phreatic/Phreatomagmatic
1784	Soufriere, St. Vincent	Dome
1792	Mt. Pelée, Martinique	Phreatic
1797	La Soufriere, Guadeloupe	Phreatic
1798-99	La Soufriere, Guadeloupe	Pelean-style
1809-12	La Soufriere, Guadeloupe	Phreatic
1812-14 [#]	Soufriere, St. Vincent	St. Vincent-style
1831-35	Nevis Peak, Nevis	Volcano-seismic
1836-7	La Soufriere, Guadeloupe	Phreatic
1841	Morne Diablotins?, Dominica	Volcano-seismic
1843?	Mt. Liamuiga*, St. Kitts	Phreatic
1843	La Soufriere, Guadeloupe	Phreatic/Phreatomagmatic
1849	Morne Plat Pays, Dominica	Volcano-seismic
1851	Mt. Pelée, Martinique	Phreatic/Phreatomagmatic
1880	Valley of Desolation, Dominica	Phreatic
1880?	Soufriere, St. Vincent	Dome
1893	Morne Diablotins?, Dominica	Volcano-seismic
1897-1900	Soufriere Hills, Montserrat	Volcano-seismic
1902-03 [#]	Soufriere, St. Vincent	St. Vincent-style
1902-05 [#]	Mt. Pelée, Martinique	Pelean-style
1903	La Soufriere, Guadeloupe	Phreatic
1926	Nevis Peak, Nevis	Volcano-seismic
1929-32	Mt. Pelée, Martinique	Pelean-style
1933-36	Soufriere Hills, Montserrat	Volcano-seismic
1937-38	Morne Plat Pays, Dominica	Volcano-seismic
1947-48	Nevis Peak, Nevis	Volcano-seismic
1950-51	Nevis Peak, Nevis	Volcano-seismic
1956	La Soufriere, Guadeloupe	Phreatic
1959	Southern Dominica	Volcano-seismic
1961-62	Nevis Peak, Nevis	Volcano-seismic
1962	La Soufriere, Guadeloupe	Volcano-seismic
1966-67	Soufriere Hills, Montserrat	Volcano-seismic

TABLE 2. continued

Date	Volcano	Type of volcanic activity
1967	Southern Dominica	Volcano-seismic
1971	Southern Dominica	Volcano-seismic
1971-72	Soufriere, St. Vincent	Dome
1974	Morne Plat Pays, Dominica	Volcano-seismic
1976	Micotrin, Dominica	Volcano-seismic
1976-77	La Soufriere, Guadeloupe	Phreatic
1979	Soufriere, St. Vincent	Phreatomagmatic/Dome
1985-86	Morne Plat Pays, Dominica	Volcano-seismic
1988	St. Kitts	Volcano-seismic
1990	St. Lucia	Volcano-seismic
1992-95	Soufriere Hills, Montserrat	Volcano-seismic
1995-#	Soufriere Hills, Montserrat	Pelean-style
1994-95	Southern Dominica	Volcano-seismic
1997	Valley of Desolation, Dominica	Phreatic
1997	Southern Dominica	Volcano-seismic
1998-	Morne Plat Pays	Volcano-seismic

Data from Robson and Tomblin (1966), Shepherd (1989), Simkin and Siebert (1994), McClelland et al. (1989), Roobol and Smith, (1989), SEAN (1986-1989), GVN (1990-2002), and Seismic Research Unit, UWI, Trinidad, unpublished data.

* Formerly Mt. Misery.

Denotes loss of life.

in the 19th century, and thirty-three (including the ten submarine eruptions) events in the 20th century, twenty of these occurred since the 1950s when the Seismic Research Unit, Trinidad was established to monitor volcanic activity on the British Caribbean islands. These figures strongly indicate the sparse nature of the early historic record. With over fifteen potentially active volcanoes in the Lesser Antilles, the historic data provide a very poor basis on which to understand the wide variety and frequency of activity for each volcanic center. For example Mt. Pelée, Martinique has only erupted block and ash flows during the historic period, however stratigraphic evidence indicates periods of extensive eruption of ignimbrites prior to the arrival of the Europeans. Ignimbrites overlie archeological occupation levels of the Ameridian populations of Martinique (Roobol et al., 1976; Smith and Roobol, 1990).

DEVELOPMENT OF PYROCLASTIC STUDIES IN
THE LESSER ANTILLES

In the Lesser Antilles, pyroclastic studies were pioneered on Mt. Pelée, Martinique by LaCroix (1904) for the 1902-05 eruption, and Perret (1937) for the 1929-32 eruption, and for the 1902 eruption of Soufriere, St. Vincent, by Anderson and Flett (1903) and Anderson (1908). All of these studies concentrated on the observations of the mechanisms of the eruptions rather than on the deposits, although the publications were well illustrated by photographs of the resulting deposits. The deposits from the 1902 eruption of Soufriere, St. Vincent were subsequently studied by Hay (1959), who developed a model for the generation of this type of deposit by collapse of the eruption column.

The 1960s ushered in the modern era of detailed studies on the volcanic deposits in the Lesser Antilles. The first of these were in the form of general Ph.D. dissertations dealing with specific areas such as Baker's study of Mt. Misery, St. Kitts (Baker, 1963, 1969, 1980), Tomblin's study of the Qualibou structure, St. Lucia (Tomblin, 1964, 1965), Rea's study of Montserrat (Rea, 1970, 1974), Arculus' study of Grenada (1973, 1976) and Rowley's study of Soufriere, St. Vincent (Rowley, 1978a and b). Petrologic and geochemical studies were also undertaken as part of these studies, and their results were summarized by Brown et al. (1977). Recently a large number of publications more specifically dealing with pyroclastic deposits have been undertaken on the different islands and key references are given in Table 3. A number of these publications describe the Roseau Ash of Dominica (Sigurdsson, 1972; Carey and Sigurdsson, 1980; Sparks et al., 1980). This deposit and its submarine extensions in the Atlantic Ocean and Caribbean Sea, with an estimated total erupted volume of 58 cu km of dacitic pumiceous pyroclastic material is believed to be the largest volume eruption in the past 200,000 years in the Lesser Antilles arc. A recent highlight in volcanological research occurred during the present eruption of the Soufriere Hills, Montserrat when in 1996 pyroclastic flows were filmed descending the Tar River valley and advancing across the sea surface before slowing and dropping their hot blocks of lava into the sea with resulting black, ash-rich hydrovolcanic explosions (MVO archives). The activity seen in these

TABLE 3. Selected recent references on pyroclastic deposits of the Lesser Antilles

Island	Publication
Saba	Roobol and Smith, 1980b; Roobol et al., 1981a; Smith et al., 1985; Roobol et al., 1997.
St. Eustatius	Roobol and Smith, 1980b; Roobol et al., 1981a; Smith et al., 1985; Roobol et al., 1997.
St. Kitts	Baker, 1980,1985; Roobol et al., 1981b, 1985,1987; Smith et al., 1985.
Nevis	No Data.
Montserrat	Smith et al., 1985; Wadge and Isaacs, 1988; Roobol and Smith, 1998; Cole et al., 1998; Robertson et al., 1998; Young et al., 1998.
Guadeloupe	Sheridan, 1980; Westercamp, 1981; Boudon et al., 1984, 1987, 1989.
Dominica	Sigurdsson, 1972; Carey and Sigurdsson, 1980; Sparks et al., 1980; Roobol et al., 1983; Wadge, 1985, 1989.
Martinique	Roobol and Smith, 1975a,b,1976a,b; Fisher et al., 1980; Fisher and Heiken, 1982; Walker and McBroome, 1983; Westercamp and Traineau, 1983a,b; Boudon and Gourgaud, 1989; Boudon and Lajoie, 1989; Boudon et al., 1989; Charland and Lajoie, 1989; Chretien and Brousse, 1989; Lajoie et al., 1989; Smith and Roobol, 1990; Smith et al, 1999.
St. Lucia	Tomblin, 1964, 1965; Wright et al., 1984; Wohletz et al., 1986.
St. Vincent	Roobol and Smith, 1975a; Rowley, 1978b; Fisher and Smith, 1980; Sigurdsson, 1981; Shepherd and Sigurdsson, 1982; Brazier et al., 1982.
Grenadines	Devine and Sigurdsson, 1995.
Grenada	Arculus, 1973.

films provides a possible explanation how the fourteen ships anchored in the roadstead of St. Pierre, Martinique were devastated on the morning of May 8, 1902 in the opening phase of the 1902 eruption of Mt. Pelée, Martinique.

CLASSIFICATION OF PYROCLASTIC DEPOSITS OF
THE LESSER ANTILLES

Although a general agreement exists on the classification of modern pyroclastic rocks, regional differences often add significant complications, so that specific classification schemes may not be readily adaptable to all areas. For example, in the Lesser Antilles the explosive and gravitational collapse of domes produce pyroclastic flows characterized by the presence of variable amounts of blocks, up to 6 m in size, enclosed in a matrix of fine-grained, pulverized ash-sized material. Such deposits are termed block and ash flows. In contrast, in the Cenozoic rift lava fields of Saudi Arabia (Camp and Roobol, 1991; Roobol and Camp, 1991a and b) morphologically similar trachyte lava domes are surrounded by aprons of pyroclastic flows and surges. These deposits however are almost entirely lacking in ash (Merle and Smith, 1998), thus making the term block and ash flows inappropriate. Factors that may explain these differences could be entirely environmental, water-logged stratovolcanoes in the Lesser Antilles versus the paucity of groundwater in Saudi Arabia, or inherent in the composition of the magma (andesite/dacite versus trachyte/comendite).

The formation and role of ash in the classification of pyroclastic deposits is an important subject in view of the differences between deposits such as those discussed above. Fine-grained material in pyroclastic rocks is composed of juvenile clasts, lithic clasts (derived from the erosion of the volcanic vent), and crystals. Original vitric-crystal ratios are preserved within large clasts in pyroclastic flow deposits, so that large pumice blocks can be crushed and original vitric-crystal ratios measured. Similar determinations on the ashy matrix of the same deposit will then reveal any depletion in fine-grained vitric ash. Such determinations have shown that Lesser Antillean pyroclastic flows can show vitric losses of up to 44 weight percent (Wright et al., 1984; Roobol et al., 1987; Smith and Roobol, 1990). These losses have been attributed to two mechanisms. The first of these is caused by the occurrence of low-lying oceanic volcanoes having high-level water tables as a consequence of heavy rainfall. These water tables cause hydrovolcanic activity with the production of phreatic/phreatomagmatic eruptions. The second is due to ingestion of lush dense tropical vegetation which fills the valleys draining the West Indian

volcanoes, down which many of the pyroclastic flows travel (Wright et al., 1984; Smith and Roobol, 1990). The resulting water vapor causes expansion of the pyroclastic flows with increasing elutriation of the lightest vesiculated juvenile component which is lost in the rising ash cloud and dispersed to form thin laminated ash falls.

Fisher (1991) has emphasized that to call a deposit 'fines depleted' requires proof that the original eruptive mass contained fines that then became depleted during transportation and deposition. There are two lines of evidence to show that the pyroclastic deposits of Lesser Antillean volcanoes are commonly fines depleted. The first is, as outlined above, that the vitric-crystal ratios of juvenile clasts in the pyroclastic deposits are higher compared to their fine-grained ashy matrices. A second indication that vitric-fines depletion occurs during transportation is demonstrated by the fact that ash hurricane deposits at locations progressively more distal to Mt. Pelée and nearer to the capital of Fort-de-France show a systematic increasing crystal enrichment (Smith et al., 1999).

For the Lesser Antilles a pyroclastic classification developed for the deposits on one island can however be applied to other islands in the same arc, but may be inadequate to address the details of specific deposits from different geological settings. The classification used here was specifically developed to understand the pyroclastic deposits of the Lesser Antilles and should be used in other geological settings with caution. A classification of pyroclastic deposits for the Lesser Antilles developed from that proposed by Smith and Roobol (1990) is presented in Table 4. The classification emphasizes the relationship between eruptive style, the wide variety of deposit types that can result from each style, and the lithological variations found on Lesser Antillean volcanoes.

Pelelean-style eruptions

Pelelean-style eruptions are well documented for the type example of the 1902-05 eruption of Mt. Pelée (LaCroix 1904; Roobol and Smith, 1975a; Fisher et al., 1980; Smith and Roobol, 1990), which was repeated in the 1929-32 eruption (Perret 1937; Roobol and Smith, 1975a; Smith and Roobol, 1990). The juvenile component is andesite, and the activity commences with phreatic/phreatomagmatic explosions followed by dome growth which is continually interrupted by both explosive

TABLE 4. Summary classification of pyroclastic deposits of the Lesser Antilles

Lithology	Pyroclastic flow deposit	Pyroclastic surge deposit	Pyroclastic fall deposit	Eruptive style
Dense andesite juvenile clasts	Block and ash flow	Dense andesite surge	Ash and dust fall*	Pelean
Scoriaceous basalt/basaltic andesite juvenile clasts	Scoria and ash flow; Scoriaceous ash flow	Scoriaceous surge	Scoriaceous lapilli and ash fall	St. Vincent
Pumiceous andesite/ dacite/ rhyolite juvenile clasts	Pumice and ash flow (ignimbrite) Ash hurricane (ignimbrite)	Pumiceous surge	Pumiceous lapilli and ash fall	Plinian
Semi-vesicular andesite juvenile clasts	Semi-vesicular andesite block and ash flow	Semi-vesicular andesite surge	Semi-vesicular andesite lapilli and ash fall	Asama
Dominantly lithic clasts	Lithic block flow*	Lithic surge*	Lithic lapilli and ash fall	Phreatic

* No deposits of this type yet identified on Saba and St. Eustatius

pyroclastic emissions through and around the dome, and gravitational collapse of the dome. The pyroclastic flows of block and ash type typically emerge to expand rapidly into a flow-head rich in dense blocks ripped from the dome, which by air ingestion rapidly expands to form an overriding ash-rich cloud. Following the flow-head is the body of the flow containing smaller blocks in a fine vesicular ash/gas suspension. The final part is the tail of the flow which is ash rich. The most striking deposit produced by Pelean-style eruptions is a *coarse, unsorted block and ash flow deposit* which occurs as valley-fills (high-aspect ratio or HAR deposits). The body and tail of the flow composed of progressively smaller clasts and ash may break away from the main part of the flow by surmounting intervening topographic barriers and cover wider sectors of the volcano's flanks to form an *ash-rich, fine-grained block and ash flow deposit* (low-aspect-ratio or LAR type). The overriding ash cloud can cover even wider sectors of the volcano to form *dense andesite surge deposits (ash cloud surges)* (Sparks and Walker, 1973; Fisher, 1979) with variable thickness and internal dune and anti-dune structures. Such deposits are characteristically rich in carbonized plant remains. The finest ash, which rises to the highest elevations, is deposited as thin laminated *ash and dust fall layers*, composed dominantly of pulverized rock. These are deposited over wide sectors of the volcano's flanks.

St. Vincent-style eruptions

The type St. Vincent-style eruption was that of Soufriere, St. Vincent in 1902, when explosion columns of vesiculated basaltic andesite rose from an open crater. Partial collapse of the columns produced pyroclastic flows which followed the valleys to the coast to produce distinctive *scoria and ash flow deposits*. These are characterized by blue-black basalt/basaltic andesite clasts up to 50 cm diameter showing cauliflower-morphology surfaces. The cores of the clasts and the smaller angular clasts (formed from the break up of larger clasts) are vesicular with large rounded vesicles. They are contained in a matrix of black-purple ash. The pyroclastic flow deposits are associated with *scoriaceous surge deposits* showing variable thickness and internal dune bedding. Also associated with these deposits are well-sorted stratified *scoriaceous lapilli and ash fall beds* with internal layering composed of lapilli and ash of vesiculated scoria. These arise directly from pyroclastic eruptions from an open crater. The pyroclastic flow and fall deposits from the type eruption were first described by Hay (1959). A description of the eruption was given by Anderson and Flett (1903) and was discussed by Roobol and Smith (1975a).

Plinian-style eruptions

Plinian-style eruptions have not occurred during the period of European settlement of the Lesser Antilles. They were experienced by the pre-Columbian Indians however, as locations are known where village sites on the flanks of Mt. Pelée, Martinique are overlain by deposits from this style of activity (Roobol et al., 1976). This type of eruption comprises a series of sustained explosions from an open crater that produces an eruption column up to 50 km high (Walker, 1981). Column collapse generates pumiceous pyroclastic flows and surges (Fisher, 1979). The former, as with other flows, can be divided into a flow-head, flow-body and flow-tail (Wilson and Walker, 1982).

Pumice and ash flow deposits (ignimbrites) occur as valley fills (HARI type). They are composed of white, highly-vesicular blocks (to 1m) and lapilli set in a matrix of white pumiceous ash. Individual deposits may be up to 50 m thick, contain abundant carbonized wood, gas segregation pipes and are rarely welded. *Ash hurricane deposits* are ash-rich pumiceous flow deposits of variable thickness up to 3 m. Individual beds thin over topographic highs and lack dune bedding structures characteristic of

surge deposits. Ash hurricane deposits are widely dispersed and may be termed low aspect ratio ignimbrites or LARIs. *Pumiceous surge deposits* are composed of pumiceous lapilli, crystals and ash with variable thickness and internal dune bedding. They commonly contain carbonized wood. On Mt. Pelée these surge deposits are closely associated with the central vent and are not found at any distance from it, suggesting that they originated from the partial collapse of the primary eruption column (Smith and Roobol, 1990). Plinian-style fall deposits are *pumiceous lapilli and ash fall layers* which are well sorted, internally layered, and mantle topography on all flanks of the volcano. Individual layers are thought to originate from successive explosions.

Asama-style eruptions

This type of activity has also not yet been witnessed in the Lesser Antilles and has only been identified by comparison with deposits described from the 1783 eruption of Mt. Asama in Japan (Aramaki, 1956, 1957). During this eruption, the activity was described as a pyroclastic flow that 'boiled over' the rim of the crater without forming an explosive eruption column. Deposits of this type are not common in the Lesser Antilles, but have been described from Saba (Roobol and Smith, 1980b), the Quill, St. Eustatius (Roobol and Smith, 1980b; Roobol et al., 1997), the Soufriere Hills, Montserrat (Smith et al., 1985; Roobol and Smith, 1998), Dominica (Roobol and Smith, unpub. data), and Mt. Pelée, Martinique (Smith and Roobol, 1990). They are of interest as they may mark transitional intervals between long periods of Pelean activity and long periods of Plinian activity as has been indicated by the stratigraphy of Mt. Pelée.

The deposits are typically unsorted pyroclastic flow type containing subangular clasts up to 30 cm in a fine-grained ash-rich matrix, that are termed *semi-vesicular andesite block and ash flow deposits* (Roobol and Smith, 1980a and b; Wright et al., 1980; Smith and Roobol, 1990), and were first described in the Lesser Antilles from the islands of Martinique and Saba (Roobol and Smith, 1980b). The deposits appear intermediate in character between block and ash flow and pumice and ash flow deposits. The larger clasts show outer vitric selvages devoid of vesicles and the cores contain 30-50 % small round vesicles up to 1.5 mm in diameter. In one example on Mt. Pelée, a semi-vesicular andesite block and ash

flow deposit, has a thickness of 11 m and is welded with columnar joints. Asama-style eruptions can also produce *semi-vesicular andesite surge* and *lapilli and ash fall deposits*, although these are much less common than the flow deposits.

The eruption of the Soufriere Hills volcano on Montserrat, 1995 to present, has drawn attention to a type of block and ash flow deposit which is intermediate in character between block and ash flow deposits produced by Pelean-style activity (dominated by juvenile blocks of dense andesite) and the semi-vesicular andesite block and ash flow deposits produced by Asama-style activity (dominated by juvenile clasts of semi-vesicular andesite). These are block and ash flow deposits with abundant juvenile blocks of both semi-vesicular andesite and dense andesite types. In these, the semi-vesicular clasts are concentrated in the upper one-third of each deposit. Such deposits occur also in stratigraphic sections of the same volcano where they have been dated between 22,000 to 20,000 years B.P. (Roobol and Smith, 1998).

Phreatic/phreatomagmatic-style eruptions

Since European settlement of the Lesser Antilles the most common style of eruptive activity has been phreatic or phreatomagmatic eruptions (Table 2). Historic examples include fine ashes composed entirely of hydrothermally altered dome rocks produced during the 1976-77 eruption of La Soufriere, Guadeloupe (Le Guern et al., 1980), and thin ashes with accretionary lapilli produced during the 1979 eruption of Soufriere, St. Vincent when rising basaltic andesite magma interacted with water in a crater lake (Brazier et al., 1982; Shepherd and Sigurdsson, 1982). Fine-grained ashes with accretionary lapilli and entombed gas cavities were also characteristic of the initial stages of both the 1902 eruption of Mt. Pelée, Martinique (Smith and Roobol, 1990) and the current eruption of the Soufriere Hills, Montserrat. In both of these cases rising magma is thought to have interacted with abundant groundwater, which in the case of Mt. Pelée appears to have been expelled onto the surface (Roobol and Smith 1975a; Smith and Roobol, 1990). Prehistoric deposits of a similar nature have been reported from Martinique (Roobol and Smith 1976b; Smith and Roobol, 1990), Montserrat (Smith et al., 1985), and St. Kitts (Roobol et al., 1985).

In the case of phreatic activity the resulting *lithic lapilli and ash fall deposit* comprises stratified ash composed of rusty altered lithic clasts lacking any juvenile component (Smith and Roobol, 1990). Where fine-grained, the beds may be internally laminated, weakly lithified, contain accretionary lapilli and entrapped air bubbles (Roobol et al., 1985). In the case of phreatomagmatic eruptions, *lapilli and ash fall deposits* are very similar in appearance to the lithic fall deposits but contain, in addition, a juvenile component usually of vitric-crystal material. *Lithic surge deposits (phreatic / phreatomagmatic)* have been described by Baker (1985) from St. Kitts, by Shepherd and Sigurdsson (1982) from the 1979 eruption of Soufriere, St. Vincent, and from the older deposits from the Soufriere Hills volcano on Montserrat (Smith et al., 1985). Clast-supported *lithic block flow deposits* resulted from the 1976 phreatic eruption of La Soufriere, Guadeloupe and were described by Sheridan (1980). A general description of the structures of phreatomagmatic ashes resulting from water-magma interaction can be found in Lorenz (1974).

The above examples all involve the interaction of groundwater or surface water with rising magma, however other forms of water-magma interaction are also possible. For example the interaction of magma and sea water. An excellent example of such interaction is the hornblende-bearing alkali basalt volcano of Kick'em Jenny in the Grenadines. This volcano, which is at a minimum depth of 182 m below sea level, has undergone ten episodes of activity since 1939, several of which have been accompanied by boiling of the sea. Similar reports of boiling of the sea have been reported offshore of Carbet on the west coast of Martinique (Smith and Roobol, 1990).

Volcaniclastic deposits lacking primary pyroclastic structures

The lower subaerial flanks of most of the Lesser Antillean volcanoes contain a significant proportion (up to 50% of the stratigraphic column) of deposits that have been fluvialite reworked and have lost their primary pyroclastic characteristics. For example, in the older stratigraphy of Mt. Pelée, revealed on the Atlantic coast of Martinique, the deposits are dominated by thick successions of yellow pumiceous fluvialite strata with alternations of thick successions of gray, coarse, dense andesite boulder deposits. The younger stratigraphy of Mt. Pelée, well exposed on the

Caribbean coast, comprises thick successions of pumiceous deposits resulting from Plinian activity which alternate with thick successions of dense andesite block and ash flow deposits produced by Pelean eruptions. It is therefore reasonable to conclude that the pattern of alternating Plinian and Pelean activity dominated the entire history of the volcano. Smith and Roobol (1990) have classified these fluviatile reworked deposits to be epiclastic even though their components are entirely pyroclastic. This has been questioned by Fisher (1991) who prefers that the term epiclastic be reserved for particles whose primary formation is due to the erosion of any type of pre-existing rock. In the terminology of Fisher (1991), the fluviatile reworked deposits should be termed fluviatile reworked pyroclastic rocks, such as fluviatile reworked ash, or fluviatile reworked block deposits rather than fluviatile sandstone and conglomerate as used by Smith and Roobol (1990).

Another problem of terminology arises with the definition of mudflows and lahars. Lahars are essentially mudflows generated during the course of an eruption. Their composition may range from entirely reworked pyroclastic material (e.g. when rain falls on unconsolidated ash) to a multilithologic volcanoclastic deposit caused by a volcanic-related earthquake triggering the collapse of a water-saturated slope. Mudflows form in a similar manner but are not directly associated with a volcanic eruption. Both types of deposit contain non-carbonized wood or hollows where the wood once existed but has since rotted away. They also lack gas escape structures. This serves to separate them from pyroclastic flow deposits, but they cannot be confidently distinguished from one another in the stratigraphic record. Lahars can in fact only be confidently identified by direct observation during the course of an eruption. Smith and Roobol (1990) included mudflow/lahar deposits under epiclastic rocks which was also questioned by Fisher (1991). However as we have not yet confidently identified a lahar in the stratigraphic record, we prefer using the combined term mudflow/lahar, and draw attention here to the fact that in general they probably should not be grouped with epiclastic rocks *sensu stricto*, although a detailed study of the lithic components of this type of deposit might establish a range from wholly pyroclastic to wholly epiclastic.

Saba

INTRODUCTION

The island of Saba has an approximate area of 13 sq. km, with a population of around 1,400. The administrative capital of the island is The Bottom, located on the southwest side of the island just above the harbor at Fort Bay. Although the island is dominated by Mt. Scenery, which rises to 887 m above sea level, it is also characterized by the presence of numerous hills e.g. Booby Hill, Bunker Hill, Great Hill etc, giving the island a very irregular topography. Much of the island is covered by relatively dense vegetation, especially on the upper slopes of Mt. Scenery, which supports a tropical rainforest.

MORPHOLOGY AND BATHYMETRY OF SABA

Saba is a rhomb-shaped single volcano rising to a central dome-capped peak. The longest axis of the island (5.1 km) runs northeast-southwest, whereas the shorter northwest-southeast axis is 4.3 km long (Fig. 5). This is unusual for the Lesser Antilles where the long axis of the islands usually runs parallel to the arcuate axis of the island arc. In the case of Saba the long axis is perpendicular to this direction. A possible reason for this difference is that recent seismic data suggest that the island is located above a fault orientated perpendicular to the volcanic arc. Further indications for the presence of such a fault are the occurrence of hot springs on and immediately off-shore of the northeast and southwest corners of

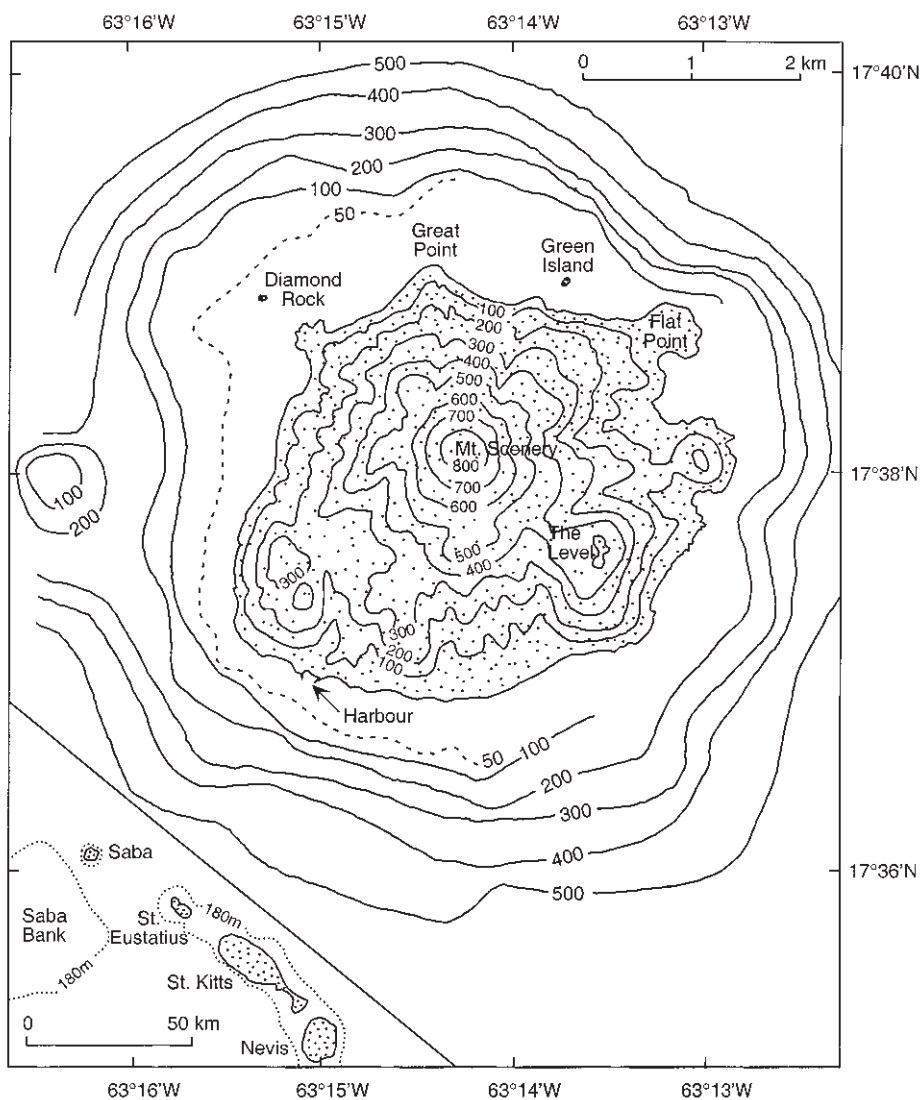


FIGURE 5. Topography and bathymetry of Saba island (after U.S. Coast Guard chart 25607). All contours, above and below sea level are in meters. Inset shows the relative position of Saba, Saba Bank, and the St. Eustatius-St. Kitts-Nevis bank (after Westermann and Kiel, 1961).

the island, and the orientation towards the southwest of a major sector collapse scar on the island. Defant et al. (2001) also propose that the island is cut by a northeast-southwest fault extending from Great Hill to Flat Point.

The bathymetry around the island of Saba to a depth of 500 m is shown in Figure 5, with data taken from U.S. Coast Guard Chart 25607. Generally, the submarine morphology slopes uniformly away from the island in all directions except in the west, suggesting that the island can be regarded as a single volcanic complex, the subaerial part of which has dimensions which measure fifty percent of those defined by the 500 m submarine contour. To the west of the island, approximately 1.3 km immediately offshore of Ladder Bay, is a conical submarine mountain rising, from depths of 300 m to 23 m below sea level. The dimensions and morphology of this feature are similar to any one of the Pelean domes exposed on Saba island. It seems most likely that this feature is a single dome formed parasitically on the western flanks of the volcano. Although it is at present entirely submarine, the possibility exists that it formed at least partially in a subaerial environment probably during the Pleistocene, and was subsequently drowned by the post-Pleistocene rise of sea level.

A seismic reflection line off the southwest coast of Saba (Laban, 1996) reveals the presence opposite Great Hill (approximately 1 km offshore) of a significant positive feature at a depth of approximately 200 m. This 'hill' probably represents a dome, as was suggested above for a similar feature off Ladder Bay. Further to the south is a deeper (~520 m), less pronounced positive feature (2 km off the coast), which may represent older lava flows or possibly debris flows. Further to the southeast, the sea floor is down-dropped to the southeast by two prominent scarps (25 and 40 m relief) and two lesser scarps that appear to have been produced by recent faulting. The approximate orientation of these faults is NE-SW, i.e. parallel both to the long axis of the island and the postulated NE-SW fault zone believed to exist in the underlying bank beneath the island.

The outline of Saba island shows a series of headlands or promontories protruding into the sea separated by arcuate embayments. At the same time the 50 m submarine contour most closely approaches the eastern side of the island and defines a broader shallow-water platform especially on the western and northern flanks. This is the reverse of what is commonly found on most of the other volcanic islands in the Lesser Antilles,

where broad submarine platforms occur on the windward or Atlantic sides of the islands. This morphology probably results from the distribution and spacing of lava domes and lava flows. Protruding headlands consist of lava flows and domes, whereas the bays are formed in the volcanoclastic host rocks. The most prominent headlands are Old Booby Hill, Flat Point and Torrens Point. At the north of the island, Great Point has resulted from the protection of an intercalated lava flow now exposed at a low level in the cliffs. Both Flat Point and Old Booby Hill are the subaerial expressions of submarine ridges on the flanks of the volcano. It is probable that these ridges represent submarine lava flow extensions. If this is so, then the apparent lava flow terminus at Flat Point is an artifact caused by the basaltic andesite flow crossing a shallow wave-cut platform before continuing down the steeper submarine slope. The small sea cliff in the flow at Flat Point would therefore be of erosional origin.

GEOLOGY OF SABA

The geology and petrology of Saba island was described in detail by Westermann and Kiel (1961), who also summarized the earlier geological literature of this island (Molengraff, 1886; LaCroix, 1890, 1893; Hovey, 1905a,b; Sapper, 1904, and Perret, 1942). Their memoir includes geological maps, cross-sections, photographs, mineralogical and petrographic descriptions of the rocks, and some whole rock major element chemical analyses. Since this work was published in 1961, the science of volcanology and especially pyroclastic deposits, both worldwide and in the Lesser Antilles, has been greatly advanced. The pyroclastic deposits of Saba and St. Eustatius today can now be interpreted in terms of styles of volcanic activity (Table 4).

A new geologic map of Saba (Plate 2) was prepared with the aim of better subdividing the stratigraphy of the island and to identify the youngest centers. A major difficulty encountered in this study was a general paucity of carbonized wood within the pyroclastic deposits when compared to other Lesser Antillean volcanoes. The reason for this paucity is that ingested vegetation, including tree trunks and fragments of wood, are carried downslope by pyroclastic flows and surges, and are

deposited most commonly in the nearly flat-lying distal deposits. On Saba island such deposits are submarine and it is only the superstructure of the volcano that is subaerial.

In general terms, the island of Saba can be regarded as a single strato-volcano. However this is not a simple structure as its flanks are dominated by the presence of about twenty andesitic domes. Most of these are Pelean domes with associated near-vent coarse block and ash flow deposits. However four of these domes, Bunker Hill, St. John's Flat, Booby Hill and The Level have short, thick, steeply-dipping lava flow extensions orientated downslope (seaward) or radially outwards from these domes. These four examples do not appear to have associated aprons of pyroclastic material. They cannot therefore be identified as Pelean domes and are here termed *dome flows*.

Other volcanic centers in the Lesser Antilles with comparable structure to Saba are the Pitons du Carbet center on Martinique (Westercamp, 1975; Smith and Roobol, 1990) and the Soufriere Hills center on Montserrat (Rea, 1974; Smith and Roobol, 1990; Roobol and Smith, 1998). The stratovolcano-like appearance of Saba results from the fact that Mt. Scenery (until recently named The Mountain), the highest peak on the island, is composed of a complex of Pelean domes and their surrounding pyroclastic aprons, that sit somewhat eccentrically on top of juxtaposed older Pelean dome complexes.

On Saba the steeply dipping, weakly-consolidated to unconsolidated pyroclastic aprons around the summit domes are being stripped off by erosion to create steep-sided gullies. Lava flows are a minor component on Saba and there is only one well-preserved flow forming the northeast corner of the island. This basaltic andesite flow has well preserved lava levées. The island's airstrip is built on the flat terminus of this flow and the main access road up to Hell's Gate village zigzags up the main flow channel between the lava levées (Fig. 6; Plate 2).

The horseshoe-shaped crater/sector collapse structure of Saba

Two major geological divisions are recognized on the geological map (Plate 2). An older division composed of lithified rocks that pre-date the formation of a major structure combining a crater with a sector collapse scar, and a younger division of weakly lithified to unlithified rocks



FIGURE 6. Oblique aerial view of northeast Saba showing the basaltic andesite lava flow with well developed levées, Mt. Scenery and The Level. The island's airport is constructed on the distal part of the lava flow and the main road zigzags up the surface of the flow between the lava levées.

(including Mt. Scenery) that post-dates this structure. The structure, which has an elongate horseshoe shape that opens to the southwest, has 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 Pelean dome/pyroclastic complex, however its rim is preserved as a series of flats or levels around the island. These give the profile of the island a distinctive shouldered appearance (Fig. 7). The altitude of this distinctive shoulder varies from 540 m on the south rim to 580 m on the northwest rim. Above the village of Hell's Gate, well preserved basaltic andesite lava flows are truncated by the structure at an altitude of 510 m. The interior walls of the structure and the distinctive rims of its southwest extension are well displayed on the northwest and southeast sides of the village of The Bottom (Plate 2). The main concrete road linking The Bottom village with St. John's Hill ascends the southeast wall of this structure in a series of hair-pin bends where hydrothermally altered block and ash



FIGURE 7. View of Saba from the south showing the prominent shoulder from which Mount Scenery rises. The settlements of St. John's and Windwardside occupy the shoulder. The Bottom village can be seen on the left of the photograph above the gut leading down to Fort Bay.

flow deposits can be seen in what is the deepest exposed section into the core of the volcano. The lowest elevation within the largely infilled structure occurs in the village of The Bottom at 200 m above sea level. When it formed the structure had a minimum depth of 380 m.

In the Lesser Antilles arc at least five other horseshoe-shaped structures of similar dimensions have been described. With one exception, English's Crater, Montserrat, which opens to the east, all of these structures open to the southwest. These structures and their dimensions are summarized in Table 5. At the present time there is debate on the mechanism of origin of some of them. The Qualibou morphological depression of St. Lucia, for example, has been identified as a caldera by Tomblin (1964, 1965) and Wohletz et al. (1986). Roobol et al. (1983) noted that these structures, with the exception of Montserrat noted above, exist on the west side of the Lesser Antillean islands, are often adjacent to the steepest submarine slopes, and suggested a mechanism of gravitational sector collapse, perhaps triggered by inflation of the volcano and/or earthquakes, for their formation. Recently Mattioli et al. (1995) have combined submarine and subaerial morphology to model the Qualibou structure of St. Lucia. The resulting digital elevation model (DEM)

TABLE 5. Dimensions and orientations of horseshoe-shaped depressions in the Lesser Antilles Arc compared with the Mt. St. Helens example

Name	Length (km)	Max. width (km)	Max. depth (km)	Orientation of opening	Source
Saba	2.5	1.2	0.38	SW	This publication
English Crater, Montserrat	3.0	0.7	0.15	E	Rea, 1974; Wadge & Isaacs, 1988 Roobol & Smith, 1998
Carmichael Crater, Guadeloupe	1.5	1.2	0.30	SW	Boudon et al., 1987, 1989
Amic Crater, Guadeloupe	1.7	1.3	0.16	SW	Boudon et al., 1984, 1987
Soufriere depression, Dominica	2.0	3.6	0.90	SW	Roobol et al., 1983; Wadge, 1985
Mt. Pelée, Martinique	6.0	2.5	0.30	SW	Vincent & Bourdier, 1989
Qualibou depression, St. Lucia	4.0	5.0	0.50	SW	Roobol et al., 1983; Mattioli et al., 1995
Baleine scarp, Soufriere, St. Vincent	4.8	2.8	0.50	SW	Robson & Tomblin, 1966; Sigurdsson, 1981
Mt. St. Helens, Washington	3.9	2.0	0.75	Not relevant	Lipman & Mullineux, 1981

shows a long submarine extension to the subaerial Qualibou structure, which is interpreted as having the morphology of a submarine sector collapse scar rather than that of a caldera.

The controversy as to the role of volcanism in the formation of these structures was clarified to some extent when one of these structures was seen to form on Mt. St. Helens in 1980 (Lipman and Mullineux, 1981). In the case of Mt. St. Helens, inflation of the northern flank of the superstructure occurred over a period of two months due to the intrusion of a high-level cryptodome. An earthquake at 8:00 am on May 18 1980 triggered the collapse of this northern inflated flank producing an avalanche, which was followed immediately by explosive depressuring of the magmatic/hydrothermal system to generate a lateral blast accompanied by the eruption of a vertical Plinian column. Within a few minutes most of the superstructure of the volcano had been replaced by a horseshoe-shaped morphological depression of similar shape and form to that on Saba. In both the Mt. St. Helens and Saba examples, the structure encloses the central vent zone of the volcano which continues to act as a crater while the elongate extension is preserved as an avalanche scar. Volcanism has

continued within the structure at Mt. St. Helens to produce a dome. In the case of Saba, dome growth and associated pyroclastic products forming Mt. Scenery have largely infilled the crater leaving only the outer part of the sector collapse scar exposed. It is unfortunate that no detailed bathymetric contours are available whereby the avalanche deposits resulting from the sector collapse might be traced on to the sea floor adjacent to Saba, as has been done in the case of Mt. Pelée, Martinique (Le Friant et al., 2002), and for Reunion Island in the Indian Ocean (Lenat et al., 1989). In the case of the Qualibou structure on St. Lucia, Mattioli et al. (1995) were able to trace the sector collapse scar down the submarine flanks of the volcano to the limits of the bathymetric data.

The steep-sided walls of the horseshoe-shaped structure form natural northwest and southeast boundaries to the island's administrative capital of The Bottom. To the northeast are the dome complex of Mt. Scenery and the parasitic dome of Bottom Hill (Plate 2). To the southwest are the domes of Great Hill, Paris Hill and Bunker Hill, which appear to be youthful, and to post-date the horseshoe-shaped structure. The nature of the 'valley' of the Bottom has caused a lengthy debate on the island according to the various opinions of visiting geologists. Cleve (1871, 1882), Boldingh (1909), Perret (1942), and Defant et al. (2001) held the view that the valley of The Bottom is a former crater of Saba's volcano. Sapper (1903), Molengraaff (1931), and Westermann and Kiel (1961) rejected this view. With the recognition and better understanding of horseshoe-shaped structures on stratovolcanoes, it is possible today to say that The Bottom is situated not in a crater, but in the avalanche scar section of a complex structure of combined sector collapse and explosive origin.

The age of the structure is not known but can be approximately estimated 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. Smith and Roobol (1990) estimated that on Mt. Pelée, Martinique the boundary between lithified and non-lithified andesitic block and ash flow deposits was between 50,000 and 70,000 years B.P., i.e. slightly older than the limits of radiocarbon dating. This division does not apply to basaltic andesite scoria and ash flows as these deposits lithify more rapidly, as was found at Grande Riviere, northern Martinique where deposits dated at 25,000-30,000 years showed lithification. In the case of

Saba, andesitic block and ash flow deposits younger than the horseshoe-shaped structure are weakly to non-lithified, whereas those that are older are strongly lithified. The best estimate of the age of this structure is therefore around 100,000 years.

On the new geological map (Plate 2), a single wall of what is probably an earlier sector collapse structure is shown on the north coast adjacent to Little Island. Here a prominent headland and cliff, composed of very ancient yellow, well-lithified block and ash flow deposits, juts out into the sea. The western boundary of this ridge is named Pirate Cliff and forms a vertical geological contact between the yellow, older lithified material and the younger less well-lithified deposits to the immediate west forming the sea cliffs of Cave of Rum Bay (Plate 2). The younger deposits to the west are banked up against the older buried cliff in the manner of a sector collapse scar. The relative ages of the two units is shown by their highly contrasted morphologies. The older deposits form a steep-sided promontory, whereas the younger block and ash flow deposits behind Cave of Rum Bay are very deeply gullied.

The older volcanic division of Saba

The older volcanic division is defined as all the geological deposits that are older than the horseshoe-shaped structure. The oldest exposed rocks on Saba island form Torrens Point on the northwest shore. These are remnants of a Pelean dome that has almost entirely been removed by erosion. Only the southeast margin of the dome remains at Torrens Point, with the overlying pyroclastics dipping at 15° towards the interior of the island. Another remnant of the same dome is present as Diamond Rock outcropping 425 m offshore to the northwest. The seabed between these two is very rugged with irregular outcrops of dome remnants. At Torrens Point the remnant dome margin is separated from the rest of the island by three faults dipping at 70° towards the center of the island with downthrows towards the center of the island of 10 m, 10 m and > 10 m respectively.

The northern and western coasts of Saba are steep and precipitous, and are composed of spectacular successions of lithified, coarse block and ash flow deposits (Figs. 8A and B). These dip at 10°-15° seawards on the west coast, and 15°-20° seawards on the north coast, where valley-infill



FIGURE 8A. The northern coastline immediately west of the old sulfur mine area showing a prominent gully cut into a thick succession of lithified block and ash flow deposits.



FIGURE 8B. The northwest coastline between Great Point and Torrens Point showing a 60 m thick, massive, highly faulted succession of block and ash flow deposits. The geologist standing below the cliffs gives scale.

structures are present. Two andesite lava flows are interbedded within these deposits on the northern flanks to form Grey Hill and Sandy Cruz. In both cases the flat bases of the flows are well exposed. Another andesite flow is exposed within these older deposits in the wall of the horseshoe shaped structure immediately north of The Bottom. On the upper north-west flanks, an andesitic dome forms steep cliffs which are free of the otherwise dense tropical vegetation, that mantles the upper parts of the island. Older lithified block and ash flow deposits are less well exposed on the eastern and southern flanks of the island, where they are partially hidden beneath younger division Pelean domes and their associated block and ash flow deposits. On these flanks the younger division deposits outcrop mainly along the coasts where the island is free of vegetation, whereas the older division block and ash flow deposits occur higher up the slope where rainfall supports a light vegetation cover. Two additional parasitic flank domes similar to the Torrens Point-Diamond Rock example occur. One forms Kelby's Ridge near the airport on the northeast coast where it is marginally eroded by the sea. The other forms Old Booby Hill, which is largely intact and possibly somewhat younger in age. On the south side of the island, older domes contained within the lithified block and ash succession form Peak Hill, Maskehorne Hill, Peter Simmons Hill, Thias Hill, and Fort Hill, with a dome flow forming St. John's Flat.

Locally large areas of the older-division lithified block and ash flow deposits are hydrothermally altered so that the rocks have a bright orange color due to the presence of goethite veins, gypsum and native sulfur. There are six main areas showing this alteration (Plate 2). One is on the north coast, where sulfur was mined commercially from a pyroclastic layer immediately underneath the prominent lava flows that form the northeast corner of the island (Westermann and Kiel, 1961). A second area in the east outcrops at the back of Spring Bay adjacent to Old Booby Hill. A third area lies in the southeast wall of the horseshoe structure along the road linking The Bottom to St. John's Hill. The fourth is exposed along the stream gulley followed by the main road linking Fort Bay to The Bottom and continues in the sea cliffs of the harbor. The fifth area outcrops on the south coast, 1.2 km east of Fort Bay between Great Level Bay and Giles Quarter. The sixth area is located on the west coast at the bottom of Great Hill.

The younger volcanic division of Saba

The younger volcanic division comprises deposits younger than the horseshoe-shaped structure and consists dominantly of Pelean domes and associated aprons of weakly lithified to unconsolidated block and ash flow deposits. The most prominent structure is Mt. Scenery which is composed of a circular dome-like structure with a diameter of 250 m that forms the highest peaks on the eastern side of the summit. This structure is interpreted to be the youngest dome on Mt. Scenery, and two samples collected from its northern and southern sides are both andesites with 60% silica. To the west and north of this dome, the summit of Mt. Scenery consists of two peaks forming an arcuate ridge (Plate 2) that appears to be the remnant of an older dome that has been largely cored-out by the crater-forming event that preceded the extrusion of the younger andesite dome to the southeast. A similar relationship characterizes the summit of Mt. Pelée, Martinique, which is also composed of two domes, one representing the dome formed in 1902-05 that was later cored-out by the early explosions during the 1929-32 eruption. A new dome then grew in this crater until it reached much the same height as the older dome (see cover photograph of Smith and Roobol, 1990). The older remnant dome on Mt. Scenery is basaltic andesite in composition (56% SiO_2), and probably formed in the vent which produced the weakly lithified basaltic andesite scoria and ash flow deposits exposed in the road section between English Quarter and Upper Hell's Gate (Plate 2).

Block and ash flow deposits from the young andesite dome on Mt. Scenery are preserved as remnants all around the volcano except on the north and east coasts. Patches of this cover lie at Lower Hell's Gate on top of the basaltic andesite lava flow there, and partially mantle the andesite domes of the older volcanic succession on Mary's Point Mountain, Kelby's Ridge, Old Booby Hill and the dome flow of St. John's Flat. On the south coast, unconsolidated block and ash flow deposits are absent from the older division domes of Peter Simmons Hill, Maskehorne Hill and Peak Hill. However the younger division pyroclastic flows probably jumped these obstacles for such deposits are well preserved along the coastline beneath them at Giles and Fence Quarters, where they dip seawards at angles of 20° and less. In Giles Quarter the flow front of a block and ash flow deposit is well preserved. Unfortunately repeated searches of

these unconsolidated youthful deposits have failed to locate carbonized wood for age dating.

A single Pelean dome with associated pyroclastic deposits, Bottom Hill, occurs on the lower flanks of Mt. Scenery, within the horseshoe-shaped structure. The southwest termination of this structure is buried beneath the Pelean domes of Great Hill and Paris Hill and the dome flow of Bunker Hill. Great Hill, although eroded on its western, seaward side, appears extremely youthful with a well preserved Pelean spine, and may have been extruded through a crater which cored out most of the older Paris Hill dome. On the southeast flanks of the island, two large dome flows occur at Booby Hill and The Level.

A well preserved 1.8 km long basaltic andesite lava flow outcrops between the village of Upper Hell's Gate and the airport at Flat Point. It has a width of around 400 m and well-preserved lava levées in the upper part. The distal flow terminus is broader, and its flat upper surface has been utilized for the only airstrip on the island. This flow overlies other basaltic andesite lava flows whose form has been modified by erosion on the steep slopes. These eroded flows are probably considerably older than the one with the lava levées. The relative age of these flows to the horseshoe-shaped structure is however unknown. The flows appear to be abruptly truncated immediately above Upper Hell's Gate in an area of talus accumulation. When viewed from the airport there is a possibility that they have been truncated by the horseshoe-shaped structure that may form a morphological shoulder in this area. A visit to the area however reveals only a talus field in the critical area of geology. The youngest morphologically intact Hell's Gate basaltic andesite lava flow has been correlated with basaltic andesite pyroclastic deposits outcropping nearby on the flanks of Mt. Scenery thus making this flow younger than the horseshoe-shaped structure. The ages of the other flows are unknown.

GEOCHRONOLOGY OF SABA

Only four radiocarbon ages were obtained from Saba (Table 6), all are from the younger stratigraphic division which post-dates the horseshoe-shaped structure. The two youngest ages of 280 and 525 years B.P. were

TABLE 6A. Geochronology of Saba: radiocarbon ages

Sample Number	Age $\pm$ 1 std. dev. (years B.P.)	Type of Deposit	Location
SA 114	280 $\pm$ 80	Dense andesite surge	Pit in The Bottom
SA 117	525 $\pm$ 60	Paleosol	Pit in The Bottom
S 85	3,155 $\pm$ 65	Conch shell handaxe	Alongside road between The Bottom and Fort Bay
SA190	34,750 $\pm$ 850	Semi-vesicular andesite block and ash flow	Pit in The Level

TABLE 6B. Geochronology of Saba: argon/argon ages

Sample Number	Age $\pm$ 'error' (Ma)	$^{40}\text{Ar}^*$ 10-8 cc/g	^{36}Ar 10-10 cc/g	($^{40}\text{Ar}^*$) % (^{40}Ar T)	K_2O (Wt. %)
SB 41	0.21 $\pm$ 0.09	0.71	4.22	5.39	1.06
SB 41	0.13 $\pm$ 0.09	0.44	4.41	3.26	1.06
SB 27	0.36 $\pm$ 0.15	1.06	7.55	5.87	0.91
SB 7	0.42 $\pm$ 0.07	1.90	3.95	13.98	1.40
SB 7	0.42 $\pm$ 0.07	1.90	4.43	12.67	1.40

Sherman (1992); Defant et al. (2001).

both obtained from a hand-dug pit in The Bottom. The former, was obtained from dispersed small fragments contained in a thin, yellow-weathering ash surge with accretionary lapilli, and is believed to be from the most recent eruption on Saba. The latter was from an Amerindian occupation level beneath the yellow ash and is believed to have originated from a cooking fire.

Immediately down-gully from The Bottom village is a flat area behind Fort Hill crossed by the concrete road to Fort Bay. There a fine-grained gray ash, with no internal structures and showing a weakly developed soil, overlies a very young, fine-grained block and ash flow deposit about 150 cm thick (stratigraphic section XIII, Plate 3). The upper ash contained Amerindian conch shell (*Strombus*) tools, which were buried with the long axes vertical, and the cutting edges uppermost in a thirty centimeter square at the four compass points, with no associated pottery. In order to establish a minimum age for this ash, one of the axes was

radiocarbon dated at $3,155 \pm 65$ years B.P., which also gives a minimum age for the underlying pyroclastic deposit. A description of this site and its archeological significance is described by Roobol and Smith (1979). This observation suggests that the island of Saba was settled for a very long period before European discovery. In Martinique, contrasting pottery styles of the younger Indian populations showed that they moved on whenever eruptions occurred, and there is no simple evolution of pottery types as would be expected with continual occupation (Roobol et al., 1976; Smith and Roobol, 1990).

The fourth radiocarbon age of $34,750 \pm 850$ years B.P. was obtained from a cistern pit being dug on The Level. These four samples do not reflect the amount of time spent by the authors or the islanders in looking for charcoal, but reflects its genuine paucity in the pyroclastic deposits of the upper flanks of the volcano. Sherman (1992) and Defant et al. (2001) quote a radiocarbon age of 200 years from what they term a 'young pyroclastic flow'. Unfortunately no additional information on this date (exact age, standard deviation or precise location) is provided by the authors.

Two attempts have been made to date the deposits of the older stratigraphic division. In 1981, two samples were submitted by us for K/Ar dating to the Netherlands Geological Survey. One sample was from the eroded Torrens Point dome at Torrens Point, and the other from the lithified block and ash flow deposits on the north coast. The samples were found to be too young for accurate dating but both were thought by the dating laboratory to be less than 1 million years old, indicating the extreme youth of the island. Sherman (Sherman, 1992; Defant et al., 2001) obtained three $^{39}\text{Ar}/^{40}\text{Ar}$ ages (Table 6). One of these, from the oldest dome at Torrens Point yielded an age of 0.42 Ma. A second sample from a lava flow in the sea cliff below Lower Hell's Gate, above the old sulfur mine, yielded an age of 0.36 Ma. A third sample, which yielded ages of 0.21 and 0.13 Ma, was collected from a prominent lava flow remnant exposed within the lithified block and ash flow deposits in the wall of the horseshoe-shaped structure immediately north of The Bottom. Such dates support the suggestion that the age of the horseshoe-shaped structure is around 100,000 years B.P.

The present status of geochronology on Saba island is unsatisfactory, but is sufficient for a broad picture of the evolution of the island to be

determined. This evolution can be divided into: 1) the subaerial part of the island that began forming about 0.5 million years ago; 2) the horse-shoe-shaped structure that formed about 100,000 years ago; and 3) volcanism that occurred up to immediately before the time of European settlement. Some of this volcanism was contemporaneous with an Amerindian population who occupied the island at least for brief intervals for almost 2,500 years before European settlement.

PYROCLASTIC STRATIGRAPHY OF SABA

Twenty-one stratigraphic sections were measured to include both the older and younger stratigraphic divisions of the island. These sections and their locations (arranged in a clockwise manner from the most northeasterly location) are shown in Plate 3, where they have been arranged about a boundary line between the lithified deposits and the weakly-lithified to unlithified deposits corresponding to the formation of the horseshoe-shaped structure. The degree of correlation between the different sections is unusually low owing to the fact that the topography of Saba is dominated by steep slopes, and the pyroclastic deposits, especially the younger unconsolidated ones, are often present only in small patches. Many of the deposits were laid down on steep depositional slopes and the clasts have rolled and slipped on deposition so that the internal structures are somewhat disturbed. Where the stratigraphic sections were measured, care was taken to select the lowest angle of deposition so as to minimize this effect.

The stratigraphic sections are dominated by block and ash flow and associated surge deposits indicating that the dominant pyroclastic volcanism that built up both stratigraphic divisions of the superstructure of the island was Pelean-style. Deposits representing other volcanic styles are relatively minor. St. Vincent-style activity is represented by weakly-lithified basaltic andesite scoria and ash flow deposits particularly in the northeast quadrant (Plate 2); Asama-style activity is represented by a few exposures of unlithified semi-vesicular andesite block and ash flow deposits. Those exposed on The Level are transitional in nature in that the semi-vesicular clasts are concentrated in the upper third of the flow with abundant dense



FIGURE 9. Lithified pumiceous ash and lapilli fall layers in the Fans Quarter, southwest Saba. The layers dip seaward, have an internal unconformity and are disturbed due to deposition on a slope.

andesite clasts in the lower part. Pumiceous deposits, representing Plinian-style activity are present in both the older lithified, and younger unlithified divisions, and include both pumice and ash flow deposits (ignimbrites), pumiceous surge deposits and laminated pyroclastic fall deposits of white andesitic pumice (Fig. 9).

Grain size characteristics

A grain size study was made of representative samples of the main types of pyroclastic deposits on Saba. The only exception was the scoria and ash flow deposits which were too lithified for sieving.

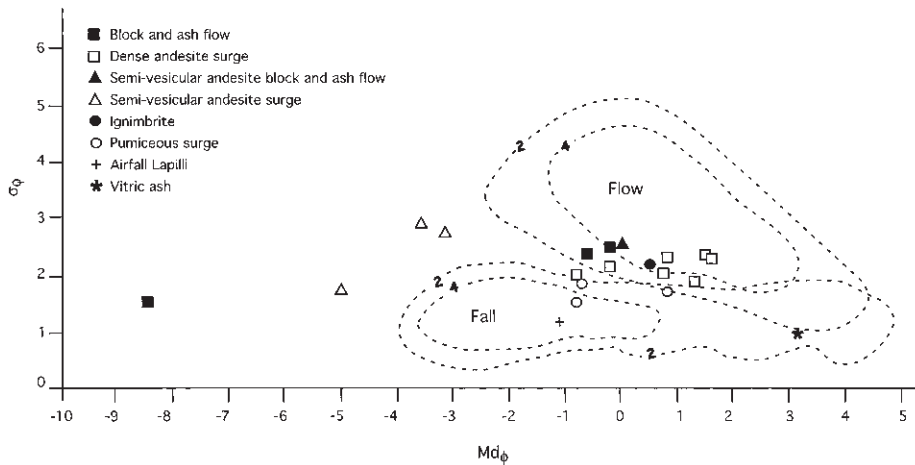


FIGURE 10. $Md\phi$ - $\sigma\phi$ plot of representative deposits from Saba. Pyroclastic flow and fall fields are outlined at the two and four percent contours Walker (1971, 1983) (after Sparks and Wright, 1979). All plots are for bulk samples.

The pyroclastic deposits on Saba show a great range in grain-size distribution. The coarsest deposits are the block and ash flows and the semi-vesicular andesite block and ash flows with $Md\phi$ values of greater than -3.0 (8 mm). In contrast, the ash fall deposit is extremely fine grained with a $Md\phi$ value of +3.0 (125 microns) (Fig. 10).

Histograms showing the distribution of the main components in the various types of pyroclastic deposits are shown in Figure 11. The inset for sample S-95 shows the grain size distribution for the whole sample sieved, whereas the component analysis was conducted on the matrix only. Analysis of the larger grain sizes of such coarse samples were undertaken in the field by measuring and weighing individual large clasts to determine their phi interval and point counting the number of clasts of different size fractions along a number of transects. These data were then combined with sieve data for the finer-grained fraction (Roobol et al., 1987; Smith and Roobol, 1990).

The block and ash flow and dense andesite surge deposits are characterized by an abundance of dense angular juvenile clasts representing disrupted dome material. All flows and surges studied appear to have been produced almost entirely by gravitational collapse, as vesicular material

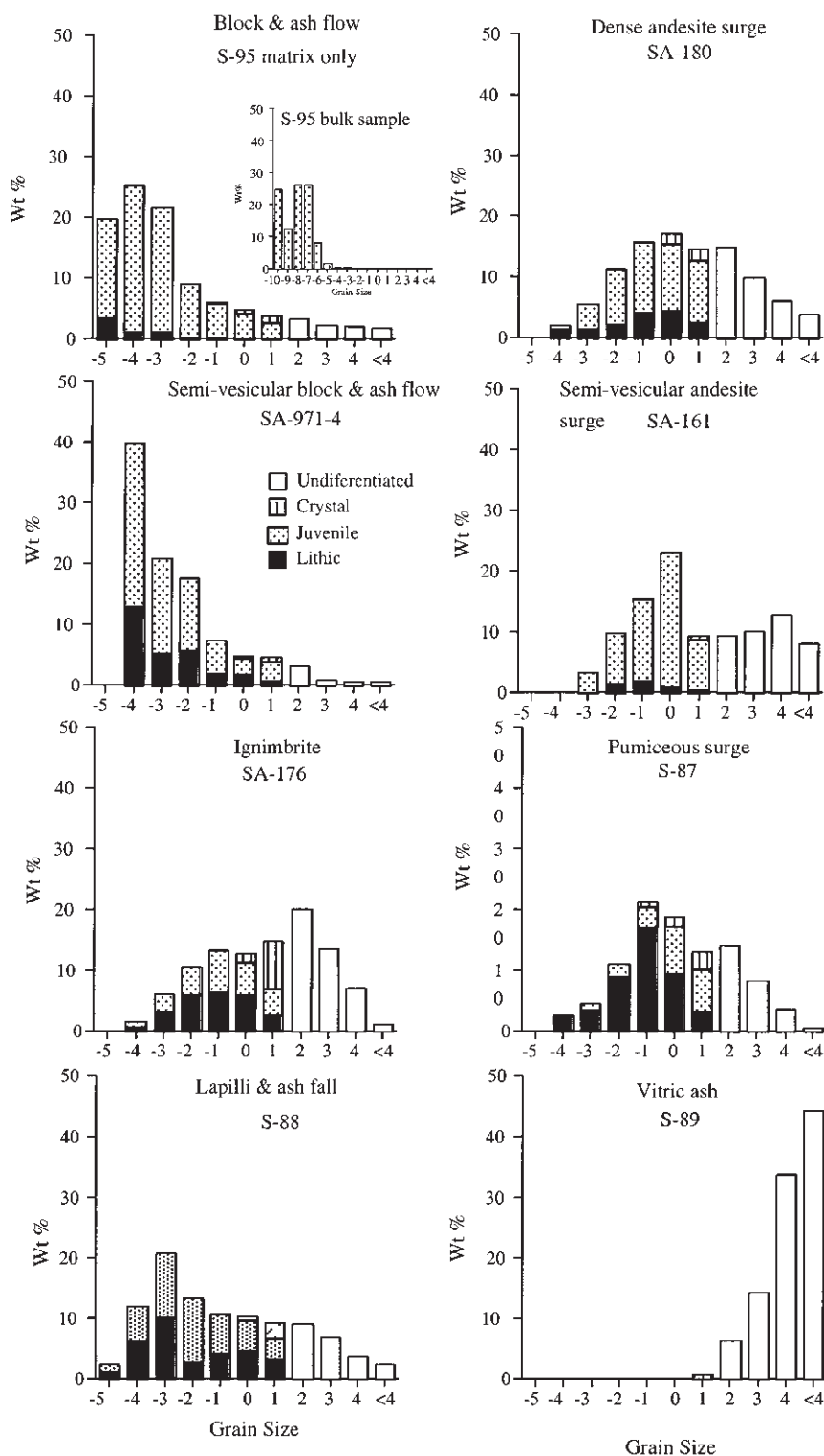


FIGURE II. Size distribution histograms of selected pyroclastic deposits from Saba. The coarser grain sizes are subdivided on their weight proportions of juvenile magmatic material, lithics and juvenile crystals.

makes up <10 % of the juvenile clasts. In contrast, the semi-vesicular andesite block and ash flow and surge deposits studied are dominated by vesicular juvenile clasts with only minor amounts of lithic material. An exception to this is the flow described from The Level which shows an abundance of lithic clasts at its base. These observations suggest that most semi-vesicular andesite block and ash flow deposits were produced by open crater eruptions, whereas the block and ash flow deposits were mainly generated by gravitational collapse of domes. Lithic clasts are also very abundant in the pumiceous flows, surges and lapilli fall deposits. The ignimbrite (SA-176) also shows an enrichment in crystals in the finer grain sizes suggesting a relatively large loss of vitric material as has also been described from other Lesser Antillean volcanoes (Wright et al., 1984; Roobol et al., 1987; Smith and Roobol, 1990). The pyroclastic fall sample (S-89) appears to be entirely composed of juvenile vesicular material and probably represents a co-ignimbrite ash fall deposit.

THE MOST RECENT ERUPTION OF SABA

Since Saba was settled in 1640 AD (Hartog, 1975), there are no records of eruptive activity. The identification of the youngest pyroclastic deposit on the island therefore was a major priority for volcanic hazard assessment. Because the pyroclastic deposits are poorly preserved on the steep slopes and are generally lacking in carbonized wood, a new approach was made to locate the youngest deposits. This involved digging pits into selected flat areas where pyroclastic deposits might have accumulated with included charcoal. Two sites were selected, and pits were hand dug in gardens in Windwardside and The Bottom villages — the main settlements on the island.

In the Windwardside village, a pit was dug to a depth of 3 m (Fig. 12). The resulting stratigraphic section is composed of 37 cm of topsoil containing shards of European pottery which passed down into 50 cm of mudflow/lahar. This deposit overlies 18 cm of hillslip debris with a poorly developed paleosol on top. Beneath this was a young unconsolidated block and ash flow deposit with a thickness exceeding 190 cm. The hole could not be deepened further because of the presence of a large andesite

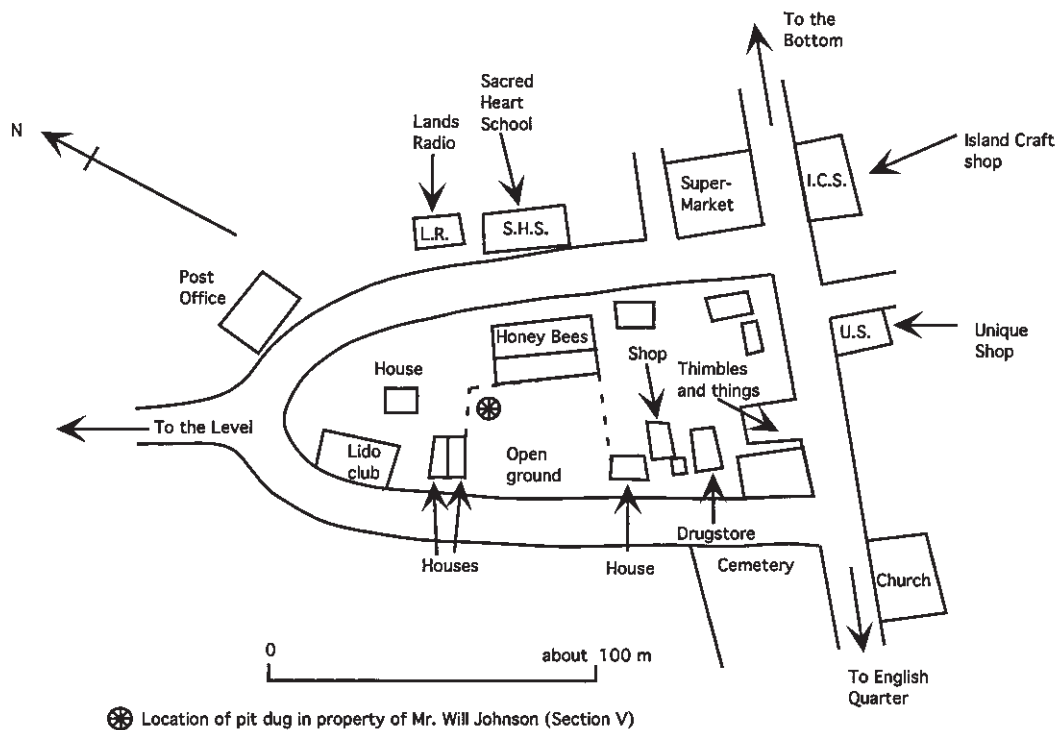


FIGURE 12. Map of part of Windwardside village showing the location of a 4m deep hand-dug pit (stratigraphic section V, Plate 3).

block. Unfortunately no carbonized wood was found and the block and ash flow deposit remains undated (stratigraphic section V, Plate 3).

A pit was also dug in The Bottom village in 1979 in the grounds of a hospital building then under construction. The site was selected because, in an earlier visit in 1976, a shorter section had been measured nearby in a pit dug for the foundations of the Peter Elenor Hassel Home which was under construction at that date. A map showing locations of these two sections is shown in Figure 13. These two stratigraphic sections are labeled as XIV and XV in Plate 3, and the former is shown in more detail in Figure 14.

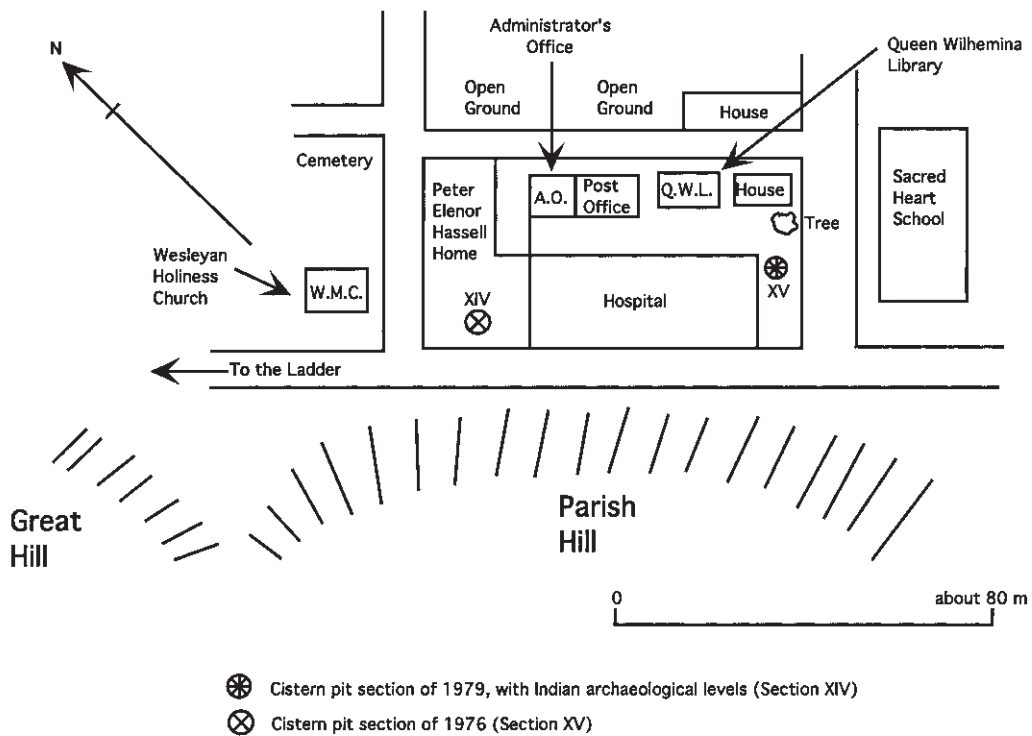


FIGURE 13. Location map for stratigraphic sections XIV and XV (Plate 3) in The Bottom village.

Stratigraphic section XIV was obtained by extending a 2 m deep cistern pit to a depth of almost 4 m (Figs. 14 and 15). Deeper penetration was impossible because large blocks of andesite contained in a block and ash flow deposit were encountered. The results obtained justified the exercise of hand digging in search of stratigraphy, for it yielded not only the youngest pyroclastic deposit on Saba, but an interesting archeological succession, as well as a stratigraphy indicating that the area is prone to flooding and mudflows (Fig. 14). The topsoil is 27 cm thick and rich in European debris, including sherds of glass, glazed earthenware, printed china, rusty nails and clay pipe stems. This is underlain by 20 cm of

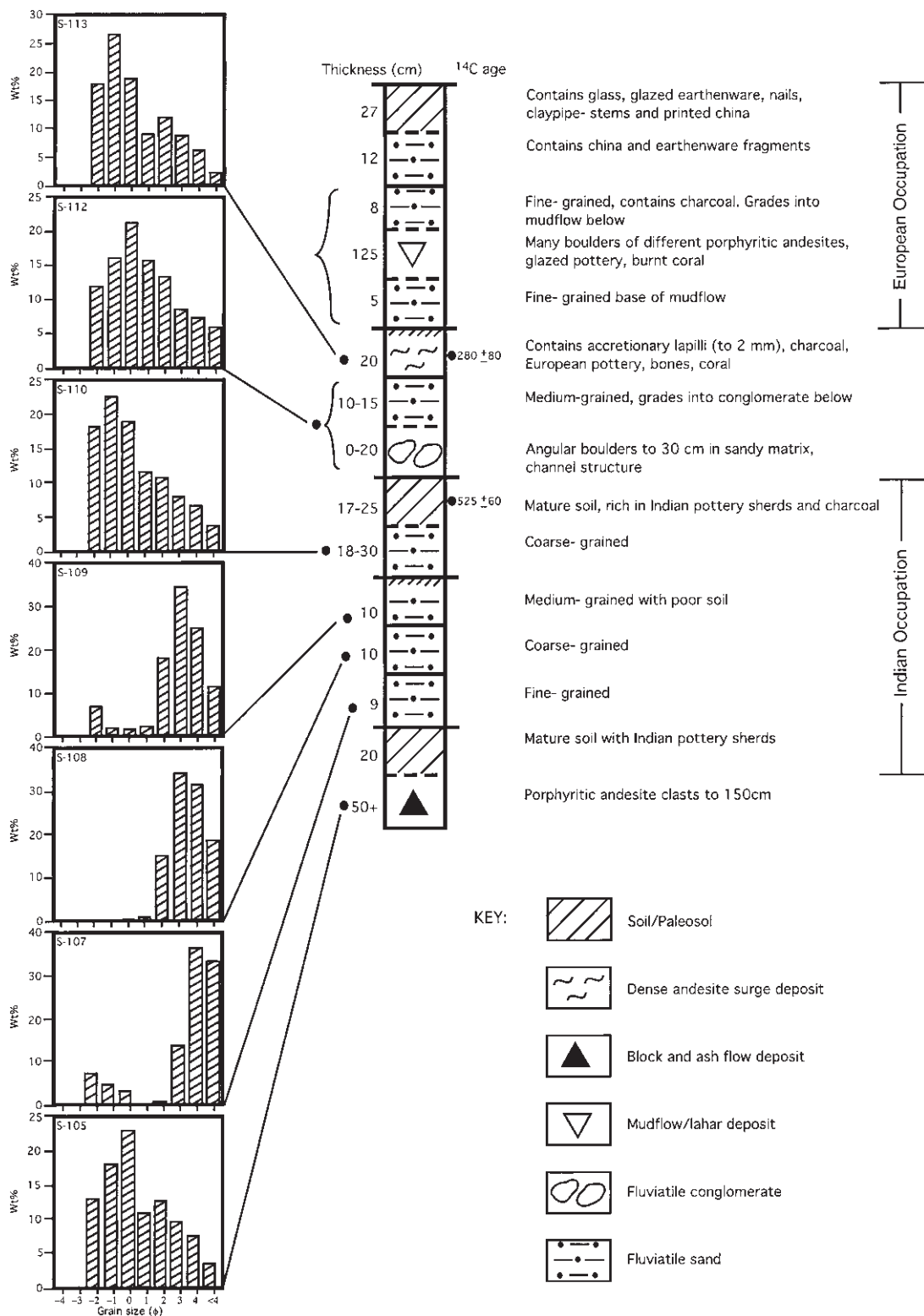


FIGURE 14. Stratigraphy of the pit dug in 1979 in The Bottom village (stratigraphic section XIV, Plate 3).



FIGURE 15. Stratigraphic section XIV measured in a cistern pit in the grounds of a new hospital in The Bottom Village, Saba. The detailed stratigraphy is shown in Figure 14. The mudflow/lahar and the upper fluvial deposits are visible in the photograph.

fluvial sand containing sherds of china and earthenware, as well as fragments of carbonized wood reflecting European settlement. The next deposit encountered, was a mudflow/lahar 125 cm thick containing a polymict assemblage of different types of porphyritic andesite mixed up with sherds of glazed pottery, and burnt coral. This mudflow/lahar was

probably derived from a prominent stream gulley cutting through the wall of the horseshoe-shaped structure immediately to the north of the village. The presence of the burnt coral indicates that farmland was being eroded. This deposit is underlain by 5 cm of fine-grained fluvatile sand, beneath which is 20 cm of a yellow-weathering ash surge containing accretionary lapilli up to 2 mm in diameter, and identified as the youngest pyroclastic deposit found to date on Saba. A poor soil is developed in the top of this deposit, which is disturbed and contains sherds of European pottery, bone fragments, and coral. The undisturbed base of this deposit, which contains the accretionary lapilli, shows a scattering of small carbonized twigs. This charcoal is believed to be part of the pyroclastic surge, and not from the later European occupation level. It yielded an age of 280 ± 80 years B.P. corresponding to a calendar calibrated date of 1640 AD (one sigma calibrated range of 1510 to 1675 AD) which approximates the time of settlement of the island. The deposit is underlain by a thin layer of fluvatile sand which grades down into a thin lens or fluvatile channel structure with angular boulders of andesite up to 30 cm in diameter. Beneath this is a mature paleosol from 17 to 25 cm in thickness which is rich in Amerindian pottery sherds and fragments of carbonized wood presumably from cooking fires. The charcoal was dated at 525 ± 66 years B.P. which corresponds to a calibrated calendar age of 1420 AD. Next comes 60 cm of fluvatile sand containing one paleosol. Beneath this is a 20 cm mature paleosol, again with Amerindian pottery sherds developed on the top of a coarse andesite block and ash flow deposit with blocks up to 150 cm in diameter. The history of the site is one of long-term occupation first by Amerindians then by Europeans. The site has been repeatedly flooded by fluvatile action, and sands and mudflows/lahars deposited. The relative age of the thin surge deposit with accretionary lapilli is readily determined from its position between the layers with European and Amerindian pottery. The radiocarbon age of about the time of settlement merely confirms this observation.

Hartog (1975) describes how the first European settlers established the village of The Bottom in 1640 AD on grassy meadows. Today the gardens of The Bottom village, and the surrounding hill slopes are covered in a dense vegetation including mature trees, whereas on the northern upper flanks of the island and in gullies leading past the Windwardside village

on the east, there is mature tropical rain forest with large trees many centuries old. The Indian pottery found at The Bottom, together with more found at Windwardside (Hartog, 1975) indicate that the island had, prior to European settlement, supported a significant Indian population, which was either absent or reduced to a small number living around the springs at Spring Bay prior to the arrival of the Europeans. It is likely that the first Europeans occupied an area where the mature rain forest had been destroyed by an eruption shortly before and had not re-established itself. Another well-documented instance where Europeans, rather than clear forests established themselves on convenient grassy meadows is St. Pierre, Martinique (Roobol and Smith, 1989). The earliest settlers in northern Martinique named the volcano Mt. Pelée which means 'Bald Mountain'. This was probably because of the lack of vegetation cover on its upper flanks following an eruption at 310 years B.P., that is, shortly before European arrival on the island (Smith and Roobol, 1990).

STRUCTURAL EVOLUTION OF SABA

The subaerial structural evolution of Saba island is illustrated in four stages in Figure 16. In the earliest stage (Stage 1) at about 500,000 years, the island is seen as being formed of a complex of andesitic Pelean domes and dome flows surrounded by aprons of their pyroclastic material. In Stage 2 between approximately 400,000 and 100,000 years B.P., Plinian-style activity producing andesitic-dacitic pumiceous fall and flow deposits occurs with the more ubiquitous Pelean activity. Some andesitic lava flows were also produced at this time. At about 100,000 years (Stage 3) the horseshoe-shaped crater/ sector collapse structure formed exposing the hydrothermally altered core of the volcano in the area of the present-day village of The Bottom. During Stage 4, which extends from approximately 100,000 years B.P. to the present, the horseshoe-shaped structure has been progressively infilled by andesitic domes and pyroclastic material. Also a number of parasitic flank Pelean domes, with aprons of unconsolidated block and ash flow deposits as well as dome flows formed, at this time. The basaltic andesite lava flows outcropping between Upper Hell's Gate and the airport probably also belong to this stage.

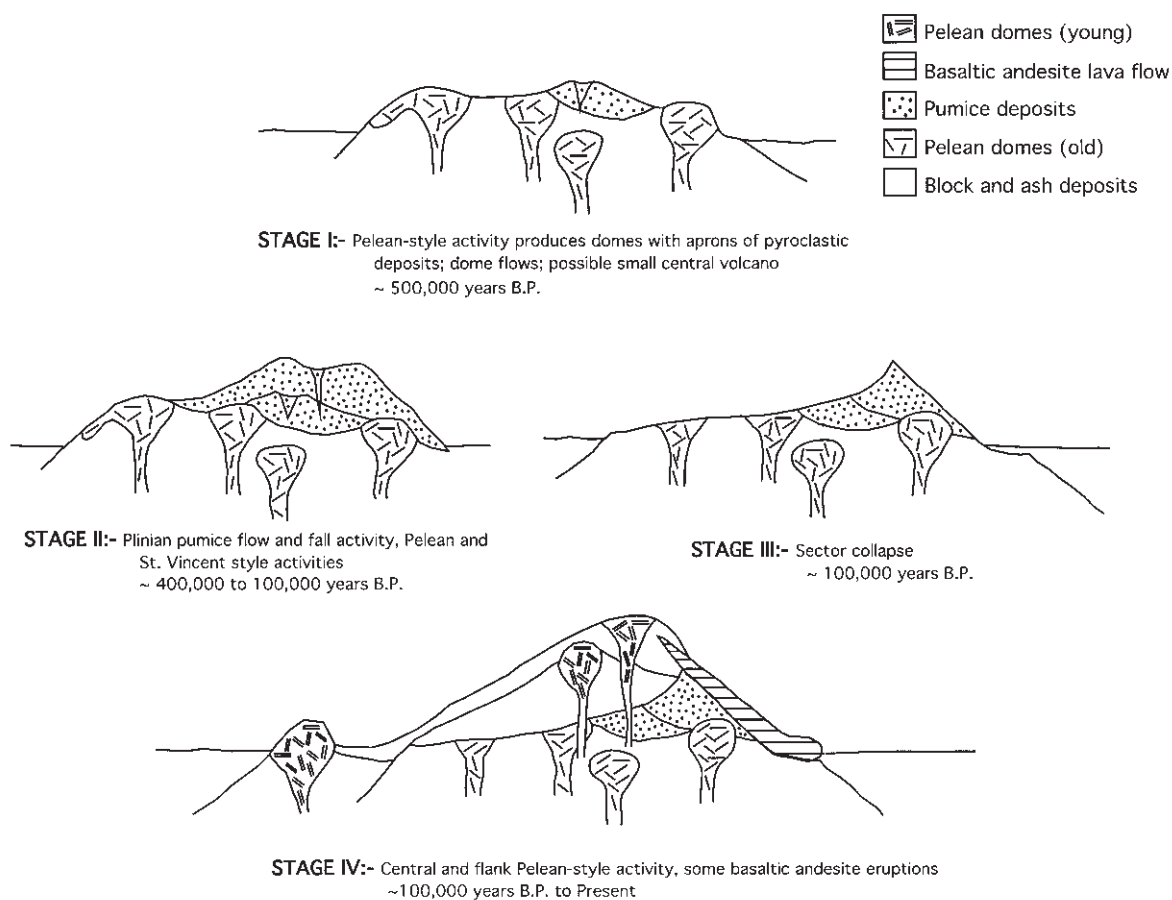


FIGURE 16. Four stages in the structural evolution of Saba volcano. Stage II is characterized by three different types of activity, which were repeated several times.

Petrology and petrogenesis of Saba

INTRODUCTION

The island of Saba is dominantly composed of andesite with relatively small amounts of basalt, basaltic andesite and dacite. The only basaltic volcanic deposit is a scoriaceous lapilli fall overlying an andesite lava flow in the older lithified division at Torrens Point. Also at Torrens Point angular lithic clasts of basaltic composition have been found in an andesitic block and ash flow deposit. Deposits containing clasts showing two compositions flow banded together are also present at various stratigraphic levels. Such clasts provide evidence of co-mingling of magmas as distinct from mixing to produce homogeneous hybrids. For example, on the south coast of the island below Booby Hill, is a block and ash flow deposit with blocks up to 3m in diameter containing white vesicular dacite (64% SiO₂) flow-banded together with a darker andesite (60% SiO₂) (Fig. 17). Other examples of magma co-mingling have been described from Guadeloupe (Vatin-Perignon et al., 1984), Martinique (Smith and Roobol, 1990), Montserrat (Rea, 1974; Roobol and Smith, 1998) and St. Kitts (Roobol et al., 1987). Such magma co-mingling in a high level chamber has been postulated as a possible cause for explosive eruptions (Sparks et al., 1977).

A characteristic feature of the lavas of Saba, which is also present in the deposits of the Soufriere Hills volcano, Montserrat, is an abundance of subrounded to rounded nodules (termed hypabyssal inclusions) 4 to 20 cm in diameter, which stand out on weathered surfaces of the lava (Figs. 17, 18). The rounded inclusions are aphyric, lack fine-grained margins, are coarser grained than their host lavas, but are finer grained than



FIGURE 17. Large co-mingled block in a block and ash flow deposit. White vesicular dacite is flow-banded with darker andesite containing abundant subrounded hypabyssal inclusions. Location is south coast of Saba below Booby Hill. Scale is provided by 65 cm-hammer.

the cumulate blocks found on other Lesser Antillean volcanoes. They usually contain randomly orientated acicular mafic minerals. Their lack of fine-grained margins and absence of deformation when contained in flow-banded rocks (Fig. 17) indicates that they were consolidated when included in the liquid host. The compositional range of these inclusions on Saba is smaller than that of the volcanic rocks, being equivalent in composition to the basaltic andesites. Their origin is more fully discussed in a later section.

An indication of the composition of the submarine bank beneath Saba can be obtained from the sparse population of exotic blocks and micro-inclusions observed in the lavas and pyroclastic deposits. These



FIGURE 18. Porphyritic andesite lava at eastern Fort Bay showing an abundance of subrounded and rounded hypabyssal inclusions. Scale is provided by hammer.

ejected blocks include fossiliferous limestone, hornfels, and tectonized plutonic rocks. Another type of crustal inclusion not observed on Saba but found on St. Eustatius, St. Kitts, and Montserrat are green metavolcanic / volcanoclastic rocks. In addition to these crustal xenoliths, relatively coarse-grained basic plutonic blocks have been observed on St. Eustatius, St. Kitts, and the South Soufriere Hills center on Montserrat (Arculus and Wills, 1980), such plutonic blocks have not been found on Saba.

PETROGRAPHY OF THE VOLCANIC ROCKS AND THEIR INCLUSIONS

Ninety-six samples were collected for petrologic study from the island. Volcanic rock names based on silica content for recalculated volatile-free analyses following Gunn et al. (1980) and Smith and Roobol (1990), are as follows: basalt (<52%), basaltic andesite (52-57%), andesite (57-63%);

dacite (63-68%), and rhyolite (>68%). All of the samples studied are porphyritic with phenocryst minerals typical of the volcanoes of the Lesser Antilles. The dominant phenocrysts are plagioclase + clinopyroxene + amphibole + iron-titanium oxide $\pm$ quartz $\pm$ olivine $\pm$ orthopyroxene. Cristobalite is present in some specimens as a groundmass constituent. Typical groundmass textures range from microcrystalline to partly glassy, with the dominant groundmass minerals in all samples being plagioclase, pyroxene and iron-titanium oxide. Modal analyses of selected Saba volcanic rocks are given in Table 7, and photomicrographs in Figure 19.

Basalt

Only two samples of basalt were found, both at Torrens Point. One of these (SA 141) forms lapilli in a pyroclastic fall bed, and the other (S 25) is found as lithic blocks in a pyroclastic flow. These samples are composed of abundant plagioclase phenocrysts with the great majority free of dusty inclusions. Olive-brown pleochroic hornblende shows partial reaction rims of clinopyroxene. There are a few augite phenocrysts. Sample SA 141 also shows microphenocrysts of iron-titanium oxides. Olivine is absent from both samples (Table 7). The groundmass comprises plagioclase laths, granules of pyroxene, iron-titanium oxide grains, and interstitial brown glass.

Basaltic Andesite

Ten samples of basaltic andesite were studied. These are porphyritic with plagioclase, the most abundant phenocryst, being present as both inclusion-rich and inclusion-free crystals. The dominant mafic minerals are augite, olivine, and hornblende, the first of which is usually the most abundant, hypersthene is relatively rare. Three varieties of brown hornblende are present: in one there is no sign of reaction; a second variety shows reaction rims of clinopyroxene and oxides of variable thickness, and a third variety is entirely replaced by oxides with minor clinopyroxene (opacitized). Bipyramidal quartz crystals, occasionally with reaction rims of clinopyroxene, are found in the majority of samples. Plagioclase, pyroxene and iron-titanium oxides with or without interstitial glass are the main groundmass components. In some samples the groundmass plagioclase shows a preferred orientation due to flow.

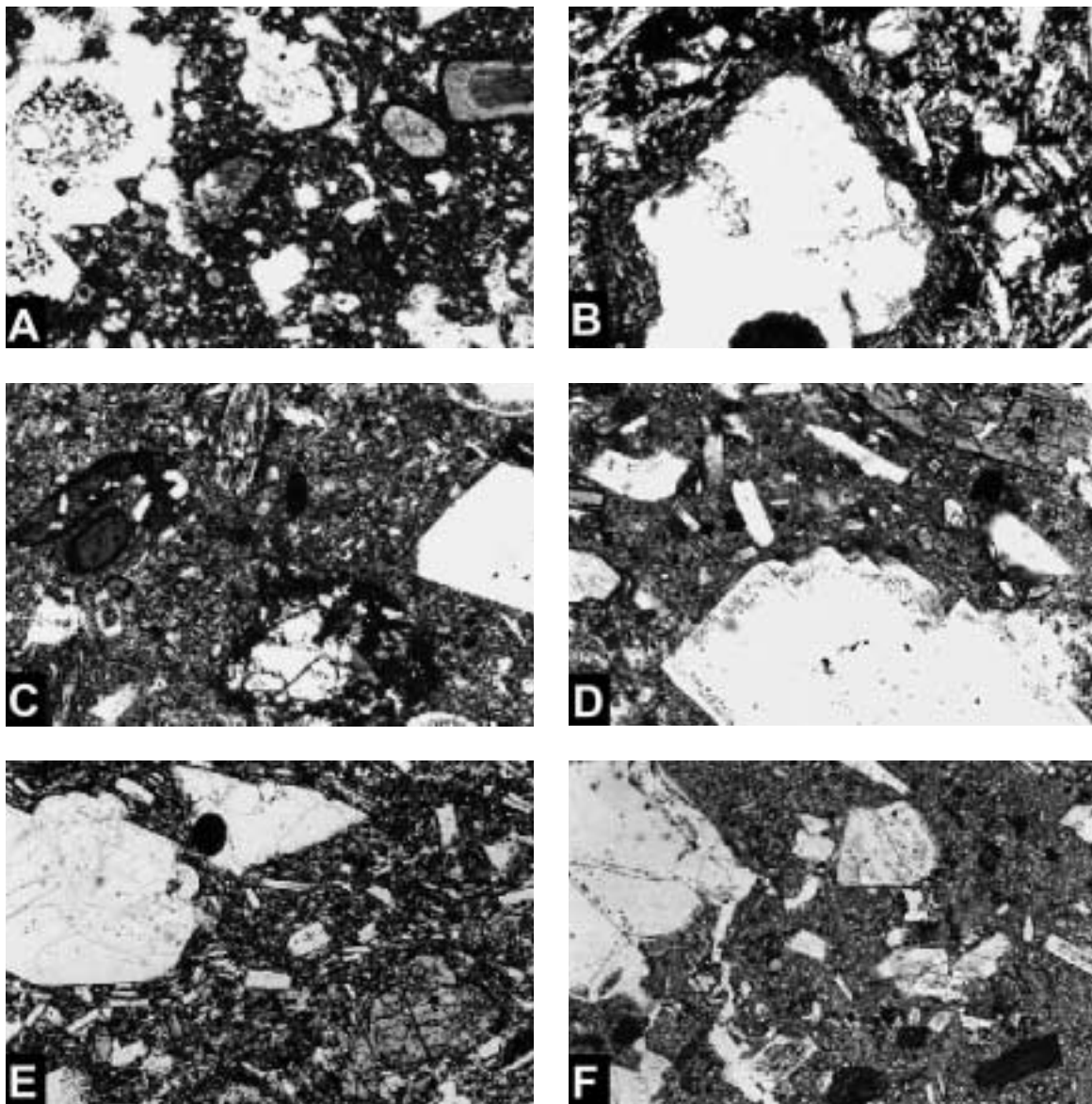


FIGURE 19. Photomicrographs of volcanic rocks from Saba. A) Basalt (S 25) showing plagioclase phenocrysts and microphenocrysts, pleochroic hornblende with reaction rims, and augite. B) Basaltic andesite (SA 163) showing a large crystal of quartz with a well-developed reaction rim of clinopyroxene. C) Andesite (SA 169) showing hornblende crystals with reaction rims, plagioclase, olivine rimmed by hornblende, and augite. D) Andesite (SA 139) showing plagioclase, and augite. E) Andesite (SA 146) showing plagioclase, quartz without a reaction rim, and olivine rimmed by clinopyroxene. F) Dacite (SA 162) showing a large quartz crystal, plagioclase, and hornblende microphenocrysts in a vesicular groundmass. Width of each photograph is 2mm, except B (SA 163) which is 1mm.

TABLE 7. Modal analyses of selected volcanic rocks from Saba

	Basalt		Basaltic Andesite							
	S 25	SA 141	SA 104	SA 152	SA 165	SA 172	SA 173	SA 120	SA 163	SA 154
Plagioclase	17.6	16.1	8.8	21.2	18.3	17.1	18.6	15.4	21.4	10.2
Quartz	0.0	0.0	0.0	0.7	0.3	2.0	0.6	0.4	Tr	0.1
Olivine	0.0	0.0	3.0	3.3	2.7	3.5	5.2	5.2	2.6	6.6
Hypersthene	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0
Augite	0.7	1.1	8.2	7.7	4.1	3.5	6.4	6.0	6.4	6.7
Hornblende	6.8	8.2	0.3	2.4	1.9	6.0	Tr	2.8	2.0	2.7
Iron Oxide	0.7	0.3	0.4	0.7	0.9	0.7	3.2	2.4	1.8	0.9
Groundmass	74.2	74.3	79.3	64.0	71.8	67.1	66.0	67.8	65.6	72.8
SiO ₂	49.66	52.10	54.20	55.64	55.92	56.09	56.17	56.34	56.70	56.78

Andesite													
	SA146	SA142	SA 124	SA103	SA156	SA138	SA150	SA139	SA155	SA153	SA159	SA100	SA169
Plagioclase	16.8	29.4	13.8	25.8	23.4	27.2	22.8	27.2	24.6	25.4	23.0	27.4	26.0
Quartz	0.4	Tr	0.8	0.2	0.8	Tr	1.4	0.0	Tr	1.0	0.0	2.8	0.6
Olivine	5.0	0.0	0.3	1.8	0.0	0.0	1.0	0.0	0.0	0.2	Tr	0.8	2.2
Hypersthene	0.0	0.0	0.0	0.6	0.0	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.0
Augite	9.2	5.0	3.5	5.0	2.0	4.8	4.8	2.0	4.4	3.0	1.4	2.4	1.6
Hornblende	1.8	2.2	4.8	4.4	5.8	1.6	2.6	10.2	3.8	9.2	12.4	9.8	9.2
Iron Oxide	1.2	2.2	1.0	2.4	1.4	2.6	5.2	0.8	2.2	1.6	4.0	0.8	1.2
Groundmass	65.6	61.2	75.8	59.8	66.6	63.8	62.0	59.8	64.8	59.6	59.2	56.0	59.2
SiO ₂	57.43	58.11	58.66	58.97	59.26	59.46	59.66	59.98	60.09	60.85	61.09	61.37	62.93

Dacite				
	SA 162	S 15	SA 167	SA 135
Plagioclase	32.2	36.4	31.6	13.6
Quartz	2.2	1.0	1.0	Tr
Olivine	0.0	0.0	0.0	0.0
Hypersthene	Tr	0.0	0.2	0.0
Augite	0.6	0.6	0.0	1.0
Hornblende	8.2	8.4	11.0	6.0
Iron Oxide	0.8	0.6	1.8	1.4
Groundmass	56.0	53.0	54.4	78.0
SiO ₂	63.17	63.62	64.30	64.65

Tr	Trace amounts

Andesite

This is the dominant rock type on Saba. All samples are highly porphyritic with plagioclase, both clear and containing inclusions, forming the dominant phenocryst phase. Augite is present in all samples, whereas hypersthene is relatively uncommon. Olivine is present in the majority of the samples reaching a maximum modal value of 5% (Table 7), and is generally more abundant in the low-silica andesites. Corroded bipyramidal quartz crystals, sometimes with reaction rims of clinopyroxene are found in approximately two-thirds of the samples, and reach up to 2.8 modal percent. Hornblende is again present in the three varieties described above. The fact that the unaltered variety sometimes rims the other two varieties (only observed in the andesite samples) suggests at least two different periods of hornblende crystallization. In the low-silica andesites the hornblende tends to be sparsely distributed, however in andesites with more than 60% SiO₂, it is usually the dominant ferromagnesian phenocryst. The phenocrysts are contained in a granular groundmass of plagioclase, pyroxene, and iron-titanium oxide.

Dacite

The dacite samples come from two distinct types of deposit. Three samples occur as lapilli in pyroclastic fall deposits, and a further five samples are clasts in pyroclastic flow deposits. The former are characterized by phenocrysts of zoned, clear plagioclase, green pleochroic hornblende, sparse pyroxenes, and iron-titanium oxide microphenocrysts in a vesicular glassy groundmass. In the latter, crystals of hypersthene, and augite are more common, and all phenocrysts are enclosed in a microcrystalline groundmass. Rounded and embayed crystals of bipyramidal quartz were observed in all samples.

Partially resorbed bipyramidal quartz in the volcanic rocks of Saba.

As noted above, many of the volcanic rocks on Saba (but not the hypabyssal inclusions) contain equant bipyramidal quartz crystals, commonly rounded and corroded, with some crystals having reaction rims of clinopyroxene. They are found in about 90% of all rock types, except the basalts, usually in minor quantities up to a maximum modal percentage of 2.8 (Table 7). Their presence as unstrained, single crystals up to 2 mm in size but without evidence of granulation indicates that they have a magmatic

origin. The andesites erupted from the Soufriere Hills, Montserrat contain similar quartz crystals which are thought to have formed at a depth of 5-6 km and at temperatures of $<840^{\circ}\text{C}$ (Barclay et al., 1998). The Saba quartz-bearing lavas are however distinct from those described from the Soufriere Hills in that in approximately 60% of them, the quartz crystals co-exist with olivine phenocrysts. Such a relationship suggests that, unlike the mineral relationships described from the Soufriere Hills (Barclay et al., 1998), the Saba assemblage is a disequilibrium assemblage probably formed by magma mixing.

Hypabyssal inclusions

These are dominantly medium-grained igneous rocks composed of plagioclase, amphibole, clinopyroxene, olivine and iron-titanium oxides. They often show a diktytaxitic texture. Modal analyses of selected inclusions are listed in Table 8, and photomicrographs are shown in Figure 20. Plagioclase is the dominant mineral in all the inclusions and can occur as large phenocrysts, usually with an inclusion-rich core, microphenocrysts, and equant or skeletal groundmass crystals. Amphibole which is present as two varieties, either colored reddish brown (most common) or olive green, occurs as large phenocrysts, skeletal microphenocrysts, and elongated laths. In most samples the margin of the amphibole crystals is partially replaced by elongate clinopyroxene crystals, however in a few samples the entire crystal has been replaced. Amphibole may also rim and/or replace phenocrysts of olivine and pyroxene. Some samples have a microcrystalline groundmass of plagioclase, in others glass is present. In some rocks this forms relatively small interstitial patches, whereas in others, the minerals are entirely enclosed in brown glass. For those samples in which the host lava can be observed, the very glassy samples have very irregular margins with the host lava suggesting that they were only partially crystalline when incorporated. The more crystallized inclusions instead, have somewhat better defined margins. There does not appear to be any change in grain size towards the margins of the inclusions.

An inclusion of a hypabyssal lamprophyre

A single sample of a black fine-grained ultramafic rock (S 34) rich in small visible biotite flakes was collected from one of the many large andesite

TABLE 8. Modal analyses of selected hypabyssal inclusions (including one lamprophyre) from Saba lavas

	S 34*	S 37	SA 175	SA 157	SA 134	S 23	SA 123	S 21	SA 160B	S 36	SA 168	SA 121	SA 158	SA 166	S 11	S 12**
Plagioclase	16.2	26.0	29.7	50.1	39.7	27.2	37.5	43.7	50.7	63.5	49.5	22.5	62.5	45.2	60.7	45.5
Olivine	0	16.0	1.5	0	0	0	8.2	0	3.0	0.5	3.5	0.2	0	0	0	0
Hypersthene	0	0	0	0	0	0	0	Tr	0	0	0	0	2.4	0	0	0
Augite	0	13.7	3.7	15.0	8.5	6.2	10.0	2.0	38.2	9.5	12.5	47.0	15.0	17.0	0	0
Hornblende	30.0	35.5	37.7	29.7	24.5	28.0	36.5	42.7	4.2	19.5	1.0	Tr	5.5	0	14.2	5.4
Biotite	53.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oxide	0	0.5	4.5	5.0	3.5	4.0	2.5	1.0	3.0	2.5	2.2	1.5	2.5	2.7	0.7	0
Glass/ Groundmass	0	8.2	22.7	0	23.7	34.5	5.2	10.0	0.7	4.5	10.0	28.7	12.0	35.0	7.7	49.0
Oxidized mafics	0	0	0	0	0	0	0	0	0	0	21.2	0	0	0	16.5	0
SiO ₂ of Inclusion	46.01	46.69	51.06	51.13	53.02	53.49	53.87	53.94	54.42	54.55	54.89	55.29	55.48	55.72	57.01	66.12
Host Lava	N.C.	S 13	SA 174	SA 156	SA 132	N.C.	SA 122	SA 120	SA 160	S 13	N.C.	SA 120	SA 156	SA 165	S 13	S 13
N.C.	Not collected		*		S 34 - Angular inclusion of lamprophyre											
Tr	Trace amounts		**		S 12 - Angular inclusion of low-K dacite											
	All other inclusions are of rounded hypabyssal type															

boulders that form the beach beneath the sea cliffs of block and ash flow deposits between Wells Bay and Ladder Bay. This inclusion appears to be magmatic, and without any evidence of tectonism or metamorphism, so that it is regarded as contemporaneous with the Saba volcanic complex. The rock consists of interlocking randomly orientated biotite (53.7%) and brown hornblende (30%) up to 1 mm in length. The interstices between the mafic minerals are filled with interlocking equant crystals of zoned orthoclase and minor plagioclase with abundant accessory apatite. Equant iron-titanium oxides with minor alteration to rutile are very sparsely present as inclusions in the mafic minerals (Fig. 21A). The rock is identified as a lamprophyre, and has been termed a minette following the classification of Rock (1991), and is the first lamprophyre to be described from the Lesser Antilles. The occurrence of a distinctly alkaline rock (total alkali content of 5.32% at 46.01% SiO₂) as an inclusion in the medium-

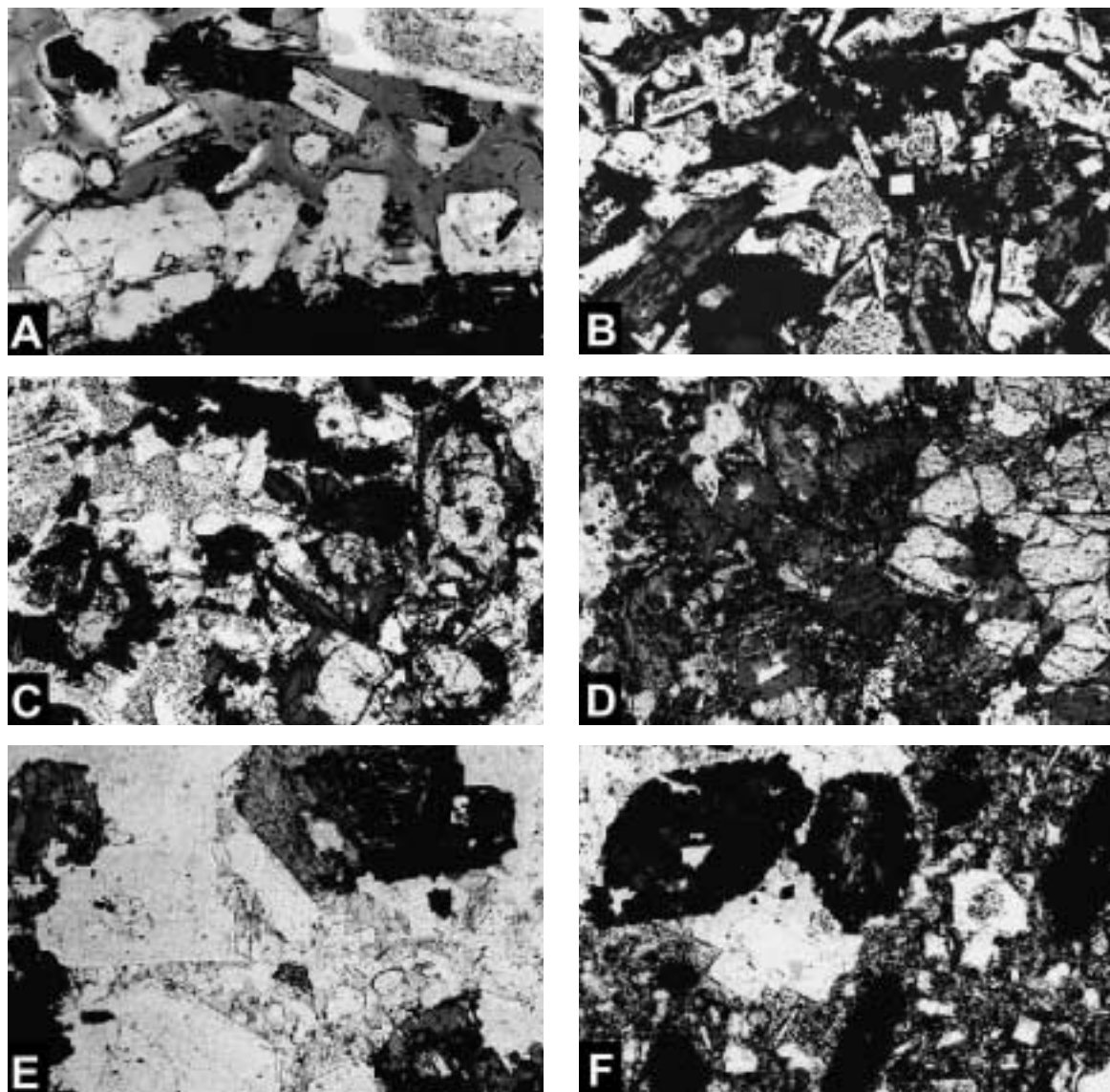


FIGURE 20. Photomicrographs of hypabyssal inclusions from Saba. A) SA 125 showing large crystal of hornblende with a reaction rim of clinopyroxene, plagioclase crystals, acicular crystals of clinopyroxene, and iron oxide in a groundmass of light brown vesicular glass. B) SA 134 showing crystals of green-brown pleochroic hornblende, augite, plagioclase, and iron oxide separated by interstitial dark brown glass and irregular vesicles. C) SA 123 showing small crystals of plagioclase, rounded crystals of olivine rimmed by hornblende, irregular crystals of hornblende in a vesicular groundmass. D) S 37 showing large rounded olivine, smaller clinopyroxene, pleochroic hornblende with a reaction rim of acicular clinopyroxene crystals and interstitial brown glass. E) SA 971-6 showing crystals of plagioclase, hornblende, acicular clinopyroxene, with interstitial light brown vesicular glass. F) S 11 showing sharp boundary between an inclusion composed of plagioclase and hornblende and its host lava composed of plagioclase microphenocrysts, oxidized hornblende in a fine-grained groundmass. Width of each photograph is 2mm.

K calc-alkaline island arc series of Saba requires some explanation. Another example of the occurrence of lamprophyres in an active calc-alkaline volcanic arc is southwestern Mexico (Lange and Carmichael, 1990; Luhr and Carmichael, 1981) where they are associated with the Colima graben (Allan and Carmichael, 1984). These authors suggested that the lamprophyric lavas were related to the rifting process which produced the Colima graben. The Saba minette is interpreted in a similar manner and is regarded as a manifestation of the submarine Kallinago graben which separates the extinct and active arcs of the northern Lesser Antilles. This rock is further discussed in the section on geochemistry.

Exotic crustal inclusions

During the course of sampling the volcanic rocks of Saba and their hypabyssal inclusions, a small suite of exotic nodules derived from the submarine banks beneath the younger stratovolcano was gathered. These samples, although small in number, are highly diverse in type and provide the only direct petrologic data of the crust beneath Saba. The individual types are described next. Representative photomicrographs are shown in Figures 21 B-F.

— *Non-metamorphosed foraminiferal limestone* (Fig. 21B). A single fragment of cream-colored limestone 5 cm in diameter was collected from an andesitic block and ash flow deposit in the lower sequence at Ladder Bay. The fragment is believed to be representative of smaller fragments not uncommonly seen in larger andesitic blocks on the island but difficult to collect because they weather into pits in the surface of the rock. Only the larger clast from Ladder Bay has been thin sectioned and is a fine-grained calcilutite rich in foraminifera. The latter have been identified by Montgomery (pers. comm., 1989) and their species and stratigraphic ranges are given in Table 9, suggesting that the limestone is of late Pliocene to earliest Pleistocene age. In addition, the calcilutite contains a few angular fragments of shells, crystals of plagioclase and quartz, as well as small fragments of volcanic rocks. The oldest known rocks exposed subaerially on Saba island are thought to be around 400,000 years but the presence of this single ejected fragment suggests that the Saba island volcanic complex may have started forming as far back as the late Pliocene or earliest

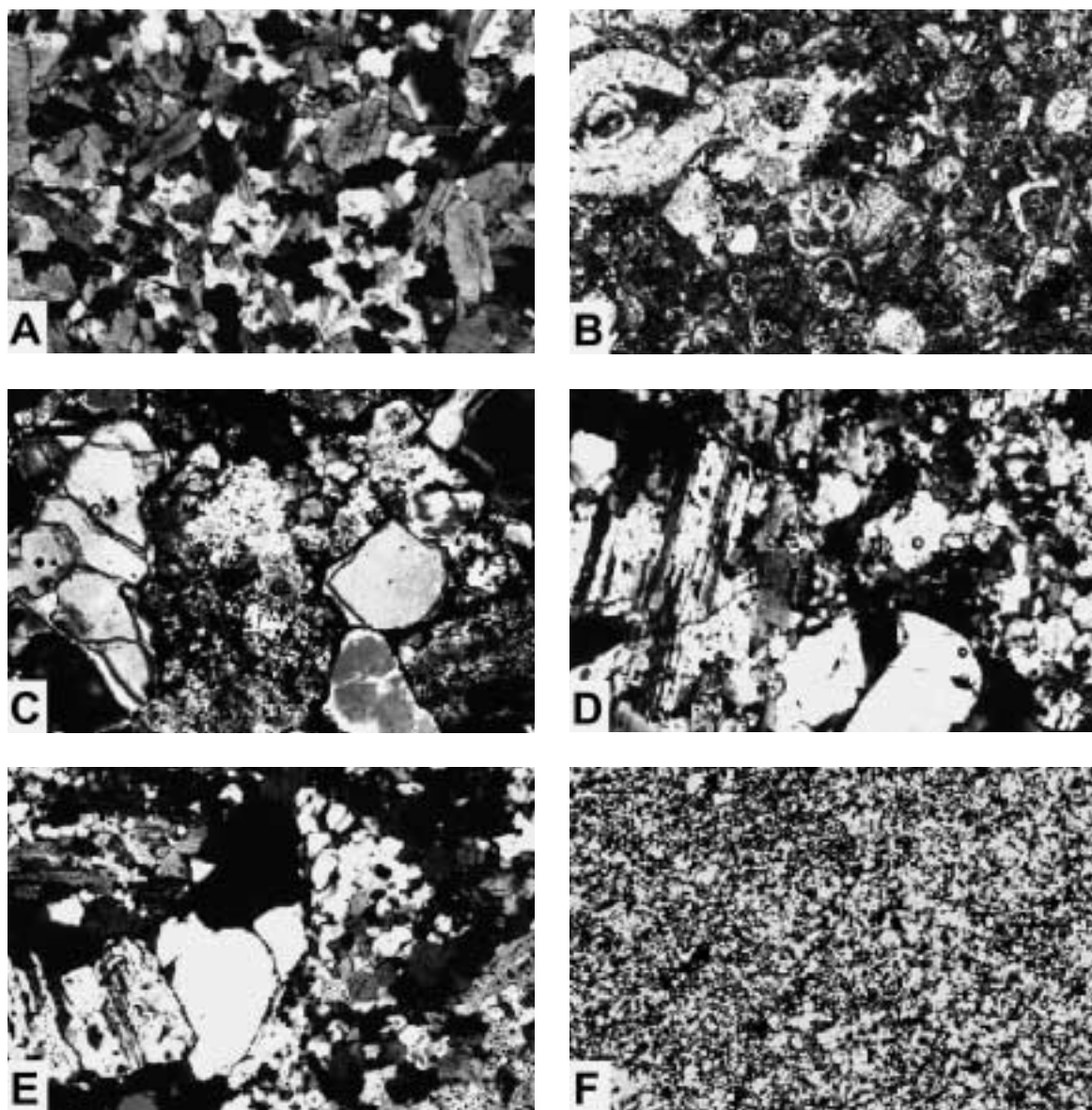


FIGURE 2I. Photomicrographs of exotic inclusions from Saba. A) S 34 is a hornblende-biotite-plagioclase minette. B) S-18 is a foraminiferal limestone. C) S 35 is a plagiogranite showing interlocking equant crystals of quartz (clear) and plagioclase (turbid). D) S 31 is a plagiogranite showing patches of coarse quartz and plagioclase surrounded by granulated quartz and plagioclase. E) S 76 is a biotite-hornblende-clinopyroxene adamellite showing patches of coarse crystals of quartz, plagioclase, and perthite in a granulated matrix. F) S 14 is a fine-grained hornfels. Width of each photograph is 2mm.

TABLE 9. Microfossils from an ejected limestone block within a pyroclastic flow deposit on Saba

Species	Range
<i>Sphaeroidinella dehiscentis</i>	mid-early Pliocene to Holocene
<i>Globorotalia menardii</i>	mid-early Pliocene to Holocene
<i>Globorotalia tosaensis</i>	late Pliocene to earliest Pleistocene

Pleistocene on a carbonate bank developed on an older igneous core similar to that known from the nearby Saba Bank (Fig. 4).

— *Plagiogranite* (Fig. 21 C and D). Two samples were collected of plagiogranite. The first sample (S-35) is a coarse-grained holocrystalline rock composed of interlocking equant crystals of quartz and plagioclase (Fig. 21C). The plagioclase is turbid and filled with many inclusions of iron oxide grains, whereas the quartz remains clear, non-strained, but traversed by healed fractures also rich in opaque oxide granules. The sample is crossed by a one-centimeter wide shear, towards the margin of which the plagiogranite becomes granulated. Within the shear zone the rock is exceptionally fine-grained but contains ragged inclusions of plagiogranite. Towards the margin of the shear, granules of magnetite octahedra are abundant, whereas the center of the shear is rich in granules of a silicate mineral with a high relief, possibly of the clinozoisite-epidote group. Also within the shear are small crystals of green hornblende. The second sample (S 31) is a different plagiogranite as this one contains pale green clinopyroxene, possibly augite-ferroaugite, together with sparse sphene (Fig. 21D). The rock shows patches of coarse plagiogranite which survive in a matrix of granulated material crowded with tiny equant magnetite octahedra. Within the plagioclase crystals accessory apatite can be seen.

The partial granulation of these rocks, the presence of a shear zone in one sample, and the distribution of the tiny magnetite octahedra throughout the sheared and granulated areas suggests that the plagiogranites could be derived from the submarine bank beneath the island of Saba. The age of these rocks is unknown, so that they could either be

of considerable age having undergone tectonism and shearing, or they could be relatively young and have simply been affected by movement on the fault zone that underlies the island.

— *Biotite-hornblende-clinopyroxene adamellite* (Fig. 21E). A single sample of a biotite-hornblende-clinopyroxene adamellite (S 76) was collected. Like the plagiogranites the rock shows 50% granulation with relics of the original rock surviving as patches in the granulated matrix. The granulated areas are crowded with numerous tiny octahedra of magnetite, whereas the surviving relics of adamellite lack these octahedra. The feldspar, of the granulated areas as well as the relict patches of non-granulated material, consists of equal amounts of plagioclase and perthite together with abundant equant quartz. The brown hornblende is marginally replaced by granular iron oxide. The adamellite appears to be of different origin to the plagiogranite but of similar tectonic history as suggested by the intense granulation shown by both petrographic types.

— *Hornfels* (Fig. 21F). A single sample of hornfels (S 14) was collected. This is an exceptionally fine-grained granular rock composed essentially of quartz, K-feldspar, plagioclase, sericite and epidote. Equant crystals of iron oxide with local marginal rutile constitute an accessory phase. The epidote has an extremely heterogeneous distribution usually concentrated along healed fractures in the rock and areas adjacent to them, so that some areas of the rock are free from epidote. The rock is quite distinct from the granulated plutonic rocks because it lacks the abundant magnetite granules. The distribution of the epidote suggests that this mineral is secondary and introduced along fissures, so that the original rock would have been close in composition to the adamellite.

GEOCHEMISTRY OF SABA

Introduction

A suite of fifty-five rock samples from Saba were analyzed at the Centre National de la Recherche Scientifique at Nancy, France using automated optical emission spectrochemical bulk analysis with microwave plasma

excitation for major and nine trace elements. A full description of the latter method, together with its accuracy and precision can be obtained from Govindaraju et al. (1976) and Govindaraju (1979). REE, Hf and Sc analyses on selected samples from this suite were made by F. Frey at Massachusetts Institute of Technology using INAA (see Ila and Frey, 1984, for details of the method). A further suite of twenty-five samples were analyzed at Activation Labs, Canada using INAA, ICP-MS and XRF methods, for major and twenty-five trace elements. The accuracy and precision of the method is given by Schellekens (1993). Five other samples were analyzed by XRF (see Tables 10 and 11 for details). Of the eighty-four analyses, sixty-six are volcanic rocks, two are vitric ashes (Table 10), fifteen are hypabyssal intrusions and one is the lamprophyric intrusion (Table 11). The volcanic rocks have been divided, based on their age relative to the sector collapse feature, into pre- and post-sector collapse suites, and are so designated in Table 10. The types of deposits and locality data for the analyzed samples are listed in Appendix 1.

Many of the samples analyzed are from pyroclastic deposits. In these one or more large juvenile clasts were selected for analysis, so that the ratio of phenocrysts to groundmass is preserved. In no case were mixed samples of ash (crystals, lithics and vitric particles) and larger clasts analyzed, as such bulk samples have undergone mechanical sorting during transportation, and bulk compositions are non-magmatic (Roobol, 1976). Two samples of vitric ash were analyzed (representing high-silica glassy groundmass fragments) and although listed in Table 10 are excluded from the variation diagrams.

Apart from the vitric ashes all analyzed samples of the volcanic rocks have porphyritic textures. Their bulk compositions may not therefore represent true igneous melts due to enrichment or depletion of phenocryst content by mechanical processes.

Geochemistry of volcanic rocks from Saba

The analyzed volcanic rocks from Saba span a silica range from 49 to 65 %. On all geochemical plots (Figs. 22 to 24), samples from the older stratigraphic division (pre-sector collapse) are distinguished from those of the younger stratigraphic division (post-sector collapse). In this manner it can be seen that the rocks of both divisions follow the same geochemical

TABLE 10. Chemical composition of volcanic rocks from Saba

	S 25 ¹	SA 141	SA 104	SA 160	SA 152	S 165	SA 164	SA 172	SA 173	SA 120	S 55 ¹	SA 163	SA 128	S -40 ¹	SA 154
	Pre	Pre	Post	Post	Post	Pre	Pre	Pre	Pre	Pre	Post	Post	Pre	Pre	Pre
SiO ₂	49.66	51.20	54.20	54.99	55.64	55.92	56.03	56.09	56.17	56.34	56.52	56.70	56.74	56.76	56.78
TiO ₂	0.88	0.90	0.99	0.77	0.73	0.78	0.66	0.70	0.72	0.27	0.67	0.76	0.68	0.69	0.76
Al ₂ O ₃	19.69	20.05	17.31	17.40	17.32	17.18	17.09	17.04	17.17	17.32	18.38	17.37	17.20	17.75	16.19
Fe ₂ O ₃ *	9.55	8.09	7.52	7.23	7.46	7.01	7.10	7.02	7.17	6.94	7.04	6.87	7.06	7.81	6.93
MnO	0.14	0.16	0.17	0.20	0.16	0.14	0.17	0.14	0.14	0.17	0.15	0.15	0.16	0.16	0.13
MgO	4.92	4.84	6.85	6.77	5.98	6.27	6.28	6.43	5.97	6.27	3.74	5.52	5.68	3.93	6.86
CaO	11.12	11.04	9.06	8.47	8.54	8.48	8.35	8.33	8.25	8.30	8.42	8.30	8.10	8.12	8.23
Na ₂ O	3.29	3.05	3.06	3.34	3.15	3.18	3.18	3.13	3.18	3.25	3.74	3.30	3.32	3.47	3.16
K ₂ O	0.55	0.64	0.84	0.80	0.88	0.91	0.96	1.07	1.01	1.08	1.16	0.89	1.00	1.12	0.98
P ₂ O ₅	0.20	0.05	N.D.	0.01	0.14	0.12	0.18	0.06	0.21	0.07	0.18	0.15	0.06	0.18	N.D.
S	7825	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	<50	N.D.	N.D.	<50	N.D.
Sc	28	30	27	N.D.	N.D.	N.D.	N.D.	25	N.D.	N.D.	25	N.D.	N.D.	22	N.D.
V	259	254	231	234	192	203	194	206	197	204	161	175	285	168	242
Cr	18	33	239	196	157	205	212	201	194	204	43	162	192	17	312
Co	23	95	93	110	64	257	70	59	82	124	18	95	79	18	97
Ni	24	40	106	124	90	176	177	109	105	188	13	104	100	17	145
Cu	71	70	43	5	14	39	19	37	41	61	47	33	55	65	39
Zn	96	87	73	74	71	70	nd	73	71	68	165	73	80	62	59
Rb	14	12	5	12	5	14	20	18	18	21	21	13	16	23	19
Sr	325	306	287	258	313	312	310	303	304	297	320	332	320	312	251
Y	20	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	14	N.D.	N.D.	20	N.D.
Zr	67	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	93	N.D.	N.D.	81	N.D.
Nb	2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	<2	N.D.	N.D.	3	N.D.
Ba	156	188	269	305	316	296	289	325	333	324	392	320	359	365	299
La	4.50	4.63	6.12	N.D.	N.D.	N.D.	N.D.	6.74	N.D.	N.D.	7.40	N.D.	N.D.	6.40	N.D.
Ce	11	12.5	14.6	N.D.	N.D.	N.D.	N.D.	17.2	N.D.	N.D.	16.0	N.D.	N.D.	14.0	N.D.
Nd	9	7.8	8.7	N.D.	N.D.	N.D.	N.D.	9.1	N.D.	N.D.	8.0	N.D.	N.D.	8.0	N.D.
Sm	2.60	2.37	2.26	N.D.	N.D.	N.D.	N.D.	2.29	N.D.	N.D.	2.2	N.D.	N.D.	2.00	N.D.
Eu	0.91	0.90	0.82	N.D.	N.D.	N.D.	N.D.	0.81	N.D.	N.D.	0.83	N.D.	N.D.	0.76	N.D.
Tb	0.50	0.50	0.33	N.D.	N.D.	N.D.	N.D.	0.46	N.D.	N.D.	0.40	N.D.	N.D.	0.40	N.D.
Yb	2.30	2.14	1.72	N.D.	N.D.	N.D.	N.D.	1.72	N.D.	N.D.	1.90	N.D.	N.D.	1.74	N.D.
Lu	0.33	0.32	0.27	N.D.	N.D.	N.D.	N.D.	0.26	N.D.	N.D.	0.30	N.D.	N.D.	0.28	N.D.
Hf	1.60	1.67	1.82	N.D.	N.D.	N.D.	N.D.	1.97	N.D.	N.D.	2.30	N.D.	N.D.	2.00	N.D.
Th	1.20	0.55	1.10	N.D.	N.D.	N.D.	N.D.	1.40	N.D.	N.D.	1.40	N.D.	N.D.	1.20	N.D.
U	<0.10	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.6	N.D.	N.D.	0.8	N.D.
Ta	0.3	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.9	N.D.	N.D.	0.6	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃ Pre Of pre-sector collapse age
N.D. Not determined Post Of post-sector collapse age

¹ Analyzed at ACTLABS² Analyzed by Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed by XRF at UPRM following method of Gunn et al., 1974; Gunn and Roobol, 1976.
All other analyses by Centre National de la Recherche Scientifique

TABLE 10 (continued). Chemical composition of volcanic rocks from Saba

	SA 146 ²	S 29 ¹	S 45 ¹	SA 142	S 22 ¹	S 16 ¹	SA 101	SA 127	S 28 ¹	S 33 ¹	SA 124	S 19 ¹	SA 170 ²	SA 103	S 56 ¹	SA 119
	Pre	Post	Post	Pre	Pre	Pre	Pre	Pre	Pre	Pre	Post	Pre	Pre	Post	Post	Pre
SiO ₂	57.43	57.59	57.95	58.11	58.14	58.35	58.44	58.44	58.90	58.58	58.66	58.73	58.84	58.97	59.09	59.24
TiO ₂	0.64	0.61	0.58	0.66	0.56	0.65	0.84	0.76	0.61	0.57	0.80	0.57	0.54	0.71	0.62	0.68
Al ₂ O ₃	16.75	17.97	16.56	17.54	18.18	17.43	18.03	17.56	17.84	17.90	17.29	17.93	17.29	17.22	18.06	17.74
Fe ₂ O ₃ *	6.56	7.29	7.57	6.66	7.98	6.64	6.37	6.64	6.42	7.73	6.24	7.76	6.40	6.32	6.44	5.84
MnO	0.15	0.15	0.16	0.15	N.D.	0.14	0.14	0.17	0.15	0.18	0.14	0.18	0.15	0.16	0.14	0.14
MgO	5.85	3.23	4.98	4.08	2.68	4.18	3.56	3.83	3.57	2.72	4.43	2.71	4.29	4.33	3.26	3.81
CaO	8.26	7.67	7.71	8.13	7.54	7.97	7.75	7.94	7.58	7.35	7.80	7.30	7.93	7.58	7.35	7.80
Na ₂ O	3.28	4.07	3.41	3.36	3.77	3.48	3.45	3.53	3.56	3.75	3.27	3.62	3.36	3.52	3.75	3.56
K ₂ O	1.03	1.24	0.92	1.21	0.92	1.02	1.29	1.14	1.17	1.01	1.21	0.99	1.05	1.19	1.13	1.19
P ₂ O ₅	0.05	0.18	0.16	0.11	0.22	0.14	0.13	N.D.	0.18	0.22	0.15	0.22	0.14	N.D.	0.16	N.D.
S	N.D.	7365	<50	N.D.	2850	386	N.D.	N.D.	6250	890	N.D.	<50	N.D.	N.D.	13600	N.D.
Sc	28	20	19	N.D.	11	27	N.D.	N.D.	19	10	N.D.	11	20	N.D.	23	N.D.
V	216	167	149	181	126	211	205	214	161	122	199	131	181	176	180	200
Cr	149	21	126	70	6	70	26	44	48	6	102	6	84	105	25	82
Co	71	17	20	82	15	20	59	58	18	14	107	15	82	164	17	73
Ni	240	10	71	45	9	22	52	33	33	1	140	10	52	144	18	48
Cu	46	41	20	30	34	53	34	40	30	33	36	20	35	29	51	26
Zn	64	69	61	67	92	56	69	82	68	101	64	74	74	78	98	68
Rb	17	20	20	20	15	20	23	24	30	N.D.	5	22	21	24	25	27
Sr	253	405	322	288	449	280	306	334	320	372	263	361	333	321	305	281
Y	N.D.	16	16	N.D.	16	16	N.D.	N.D.	14	16	N.D.	14	N.D.	N.D.	14	N.D.
Zr	N.D.	105	76	N.D.	80	75	N.D.	N.D.	99	89	N.D.	91	N.D.	N.D.	93	N.D.
Nb	N.D.	3	<2	N.D.	4	<2	N.D.	N.D.	<2	5	N.D.	3	N.D.	N.D.	<2	N.D.
Ba	310	451	333	340	357	349	403	412	388	370	321	378	356	390	391	389
La	6.19	7.60	7.00	N.D.	8.10	6.40	N.D.	N.D.	7.1	7.20	N.D.	7.40	6.97	N.D.	7.60	N.D.
Ce	14.0	17.0	16.0	N.D.	18.0	14.0	N.D.	N.D.	16	16.0	N.D.	17.0	16.6	N.D.	17.0	N.D.
Nd	7.0	9	8	N.D.	9	8	N.D.	N.D.	9	8	N.D.	8	9	N.D.	9	N.D.
Sm	1.92	2.10	2.20	N.D.	2.60	2.00	N.D.	N.D.	2.1	2.20	N.D.	2.20	2.23	N.D.	2.10	N.D.
Eu	0.69	0.79	0.80	N.D.	0.91	0.72	N.D.	N.D.	0.81	0.86	N.D.	0.85	0.80	N.D.	0.82	N.D.
Tb	0.35	0.40	0.40	N.D.	0.50	0.40	N.D.	N.D.	0.5	0.40	N.D.	0.40	0.42	N.D.	0.40	N.D.
Yb	1.59	1.77	1.81	N.D.	1.90	1.74	N.D.	N.D.	1.83	1.76	N.D.	1.92	1.84	N.D.	1.94	N.D.
Lu	0.25	0.28	0.28	N.D.	0.30	0.27	N.D.	N.D.	0.29	0.30	N.D.	0.31	0.29	N.D.	0.29	N.D.
Hf	2.02	2.20	2.20	N.D.	1.80	2.20	N.D.	N.D.	2.3	2.00	N.D.	2.20	2.16	N.D.	2.50	N.D.
Th	1.50	1.50	1.20	N.D.	1.90	1.30	N.D.	N.D.	1.3	1.20	N.D.	1.20	1.40	N.D.	1.60	N.D.
U	N.D.	0.7	0.4	N.D.	0.6	0.4	N.D.	N.D.	0.5	0.6	N.D.	0.6	N.D.	N.D.	0.6	N.D.
Ta	N.D.	<0.3	0.8	N.D.	0.8	0.9	N.D.	N.D.	1.0	0.8	N.D.	1.1	N.D.	N.D.	0.9	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃ Pre Of pre-sector collapse age
N.D. Not determined Post Of post-sector collapse age

¹ Analyzed at ACTLABS

² Analyzed by Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed by XRF at UPRM following method of Gunn et al., 1974; Gunn and Roobol, 1976.
All other analyses by Centre National de la Recherche Scientifique

TABLE 10 (continued). Chemical composition of volcanic rocks from Saba

	SA 156 ²	SA 174	S 41 ¹	SA 138	SA 149	S 150	SA 151 ²	S 20 ¹	SA 139	S 24 ¹	SA 155	SA 136	SA 133	S 47 ¹	S 13 ¹
	Pre	Pre	Pre	Pre	Post	Post	Post	Pre	Pre	Pre	Pre	Post	Post	Post	Post
SiO ₂	59.26	59.28	59.43	59.46	59.48	59.66	59.69	59.72	59.98	60.04	60.09	60.09	60.27	60.28	60.33
TiO ₂	0.58	0.62	0.54	0.64	0.55	0.59	0.57	0.58	0.57	0.60	0.59	0.58	0.63	0.50	0.60
Al ₂ O ₃	18.30	16.98	18.15	17.27	16.49	17.35	17.53	16.98	17.59	17.13	17.28	17.65	17.20	17.71	17.49
Fe ₂ O ₃ *	6.12	6.18	7.09	6.78	6.44	6.29	6.35	7.16	5.88	6.59	6.23	6.61	6.23	6.98	6.19
MnO	0.13	0.13	0.14	0.14	0.16	0.15	0.15	0.15	0.12	0.14	0.13	0.17	0.17	0.18	0.14
MgO	3.15	4.60	2.49	3.44	4.91	4.30	4.11	3.12	3.59	3.38	3.27	2.74	3.28	2.43	3.13
CaO	7.44	7.43	7.11	7.43	7.48	7.09	6.97	7.07	7.24	7.05	7.43	7.29	7.33	6.88	6.88
Na ₂ O	3.77	3.49	3.65	3.48	3.29	3.39	3.36	3.84	3.56	3.62	3.60	3.62	3.46	3.74	3.87
K ₂ O	1.22	1.26	1.20	1.30	1.08	1.02	1.01	1.23	1.37	1.29	1.25	1.10	1.37	1.07	1.21
P ₂ O ₅	0.03	0.03	0.20	0.06	0.12	0.15	0.26	0.16	0.10	0.16	0.13	0.14	0.06	0.24	0.16
S	N.D.	N.D.	<50	N.D.	N.D.	N.D.	N.D.	4185	N.D.	870	N.D.	N.D.	N.D.	<50	886
Sc	19	N.D.	12	N.D.	N.D.	N.D.	16	18	N.D.	18	N.D.	N.D.	N.D.	10	20
V	203	150	122	196	162	150	145	178	158	153	204	142	173	58	168
Cr	41	183	11	24	108	88	78	14	76	65	40	17	33	9	20
Co	123	52	14	67	56	97	70	17	178	17	109	73	69	14	17
Ni	54	72	7	30	76	71	58	9	73	20	54	25	28	1	16
Cu	50	24	16	77	91	5	5	32	32	34	61	5	31	14	48
Zn	64	69	63	68	58	70	73	68	62	57	66	78	65	74	66
Rb	22	21	20	21	18	5	5	21	26	33	24	16	23	20	16
Sr	377	316	355	425	300	306	299	428	310	340	379	338	347	376	298
Y	N.D.	N.D.	16	N.D.	N.D.	N.D.	N.D.	12	N.D.	14	N.D.	N.D.	N.D.	12	12
Zr	N.D.	N.D.	100	N.D.	N.D.	N.D.	N.D.	92	N.D.	122	N.D.	N.D.	N.D.	89	112
Nb	N.D.	N.D.	<2	N.D.	N.D.	N.D.	N.D.	<2	N.D.	<2	N.D.	N.D.	N.D.	<2	17
Ba	433	401	432	409	349	397	387	461	415	446	444	377	410	385	411
La	7.67	N.D.	8.20	N.D.	N.D.	N.D.	6.53	7.90	N.D.	8.40	N.D.	N.D.	N.D.	6.80	6.90
Ce	17.8	N.D.	18.0	N.D.	N.D.	N.D.	15.0	17.0	N.D.	19.0	N.D.	N.D.	N.D.	16.0	14.0
Nd	9.1	N.D.	10.0	N.D.	N.D.	N.D.	7.9	9.0	N.D.	9	N.D.	N.D.	N.D.	8	7
Sm	2.22	N.D.	2.20	N.D.	N.D.	N.D.	1.99	2.10	N.D.	2.30	N.D.	N.D.	N.D.	1.96	1.80
Eu	0.78	N.D.	0.84	N.D.	N.D.	N.D.	0.78	0.76	N.D.	0.80	N.D.	N.D.	N.D.	0.82	0.77
Tb	0.36	N.D.	0.40	N.D.	N.D.	N.D.	0.51	0.40	N.D.	0.40	N.D.	N.D.	N.D.	0.40	0.40
Yb	1.73	N.D.	1.92	N.D.	N.D.	N.D.	1.61	1.62	N.D.	1.85	N.D.	N.D.	N.D.	1.66	1.72
Lu	0.28	N.D.	0.30	N.D.	N.D.	N.D.	0.24	0.27	N.D.	0.28	N.D.	N.D.	N.D.	0.26	0.28
Hf	2.30	N.D.	2.60	N.D.	N.D.	N.D.	2.17	2.40	N.D.	2.30	N.D.	N.D.	N.D.	2.60	2.70
Th	1.60	N.D.	1.60	N.D.	N.D.	N.D.	1.60	1.50	N.D.	1.70	N.D.	N.D.	N.D.	1.40	1.40
U	N.D.	N.D.	0.6	N.D.	N.D.	N.D.	N.D.	0.6	N.D.	0.7	N.D.	N.D.	N.D.	0.6	0.8
Ta	N.D.	N.D.	<0.3	N.D.	N.D.	N.D.	N.D.	0.9	N.D.	0.9	N.D.	N.D.	N.D.	1.2	1.1

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃ Pre Of pre-sector collapse age
 N.D. Not determined Post Of post-sector collapse age

¹ Analyzed at ACTLABS² Analyzed by Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed by XRF at UPRM following method of Gunn et al., 1974; Gunn and Roobol, 1976.
 All other analyses by Centre National de la Recherche Scientifique

TABLE 10 (continued). Chemical composition of volcanic rocks from Saba

	SA 102	S 51 ¹	SA 147	SA 116	SA 153	SA 126	SA 159	SA 122	SA 130	SA 113	SA 100 ²	S 50 ¹	S 42 ¹	SA 169 ²	SA 162 ²
	Pre	Pre	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Pre	Post	Post	Post
SiO ₂	60.51	60.60	60.63	60.71	60.85	60.97	61.09	61.10	61.11	61.12	61.37	61.74	61.81	62.93	63.17
TiO ₂	0.78	0.52	0.52	0.58	0.63	0.75	0.60	0.30	0.54	0.57	0.61	0.48	0.52	0.49	0.58
Al ₂ O ₃	17.81	16.90	17.59	18.03	16.87	17.84	17.16	17.34	17.57	18.08	17.11	16.97	16.88	16.22	17.05
Fe ₂ O ₃ *	5.77	6.35	6.60	6.10	6.10	5.58	5.59	5.49	6.09	6.37	5.29	6.69	5.94	5.20	5.39
MnO	0.13	0.15	0.15	0.16	0.15	0.15	0.14	0.12	0.17	N.D.	0.11	0.16	0.14	0.11	0.16
MgO	2.97	3.43	2.69	2.53	3.25	2.62	3.05	3.94	2.48	3.06	3.61	2.33	2.81	3.50	2.37
CaO	7.05	6.93	7.02	6.97	7.14	6.93	6.83	6.74	7.16	6.29	6.73	6.45	6.58	6.45	6.11
Na ₂ O	3.52	3.75	3.60	3.66	3.53	3.62	3.70	3.53	3.65	3.03	3.64	3.85	3.81	3.54	3.79
K ₂ O	1.40	1.19	1.13	1.20	1.38	1.37	1.42	1.35	1.18	1.13	1.45	1.13	1.33	1.47	1.24
P ₂ O ₅	0.05	0.18	0.07	0.07	0.11	0.17	0.41	0.08	0.06	0.26	0.07	0.22	0.18	0.09	0.15
S	N.D.	<50	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	220	<50	N.D.	N.D.
Sc	N.D.	16	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	15	17	9	17	16	10
V	141	129	152	154	172	141	174	162	126	92	154	91	130	160	127
Cr	22	85	21	19	33	19	55	98	16	85	72	8	32	75	36
Co	57	18	55	317	154	43	102	53	45	N.D.	62	13	14	54	105
Ni	34	38	33	221	72	40	33	54	15	44	135	1	12	44	62
Cu	18	28	10	68	14	15	15	5	5	76	19	6	35	5	5
Zn	61	106	77	77	64	69	63	55	76	120	64	75	65	64	67
Rb	16	21	21	25	14	22	25	35	21	25	21	<10	28	26	20
Sr	296	309	343	345	359	330	328	257	357	420	262	359	310	259	333
Y	N.D.	16	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	18	N.D.	12	14	N.D.	N.D.
Zr	N.D.	88	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	107	N.D.	98	106	N.D.	N.D.
Nb	N.D.	2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	2	4	N.D.	N.D.
Ba	454	430	390	424	421	396	448	379	413	N.D.	421	423	464	405	456
La	N.D.	8.10	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	7.51	8.80	8.40	6.89	8.43
Ce	N.D.	18.0	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	17.3	20.0	18.0	14.6	18.5
Nd	N.D.	9.0	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	8.4	10.0	10.0	6.8	9.3
Sm	N.D.	2.10	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	1.86	2.40	2.00	1.71	2.13
Eu	N.D.	0.81	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.67	0.88	0.76	0.65	0.77
Tb	N.D.	0.40	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.32	0.40	0.40	0.34	0.38
Yb	N.D.	1.95	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	1.72	1.82	1.86	1.55	1.72
Lu	N.D.	0.31	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.27	0.28	0.30	0.25	0.26
Hf	N.D.	2.70	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	2.44	2.60	2.60	2.30	2.43
Th	N.D.	1.60	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	2.10	1.40	1.80	1.90	1.60
U	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.6	0.8	N.D.	N.D.
Ta	N.D.	0.1	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	1.0	1.0	N.D.	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃ Pre Of pre-sector collapse age
N.D. Not determined Post Of post-sector collapse age

¹ Analyzed at ACTLABS

² Analyzed by Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed by XRF at UPRM following method of Gunn et al., 1974; Gunn and Roobol, 1976.
All other analyses by Centre National de la Recherche Scientifique

TABLE 10 (continued). Chemical composition of volcanic rocks from Saba

	S 26 ¹	S 15 ¹	SA 131	SA 145	SA 167	SA 132	SA 135 ²	SA** 118#	S 44 ¹ #
	Pre	Post	Post	Pre	Pre	Post	Post	Post	Post
SiO ₂	63.48	63.62	64.19	64.24	64.30	64.55	64.65	65.03	66.31
TiO ₂	0.46	0.45	0.49	0.46	0.42	0.47	0.49	0.30	0.31
Al ₂ O ₃	16.54	16.98	16.64	16.36	16.98	16.77	16.54	14.53	14.57
Fe ₂ O ₃ *	5.74	5.33	4.67	4.88	4.98	4.76	4.94	3.74	4.24
MnO	0.14	0.14	0.13	0.14	0.15	0.16	0.14	0.15	0.15
MgO	2.19	2.22	2.73	2.58	1.93	2.06	2.22	2.87	1.75
CaO	5.79	5.69	5.99	5.91	5.83	5.75	5.78	8.44	7.57
Na ₂ O	4.06	3.98	3.13	3.73	3.86	3.82	3.60	3.98	4.01
K ₂ O	1.44	1.43	2.03	1.69	1.43	1.66	1.58	1.03	0.99
P ₂ O ₅	0.16	0.16	0.01	N.D.	0.12	N.D.	0.06	0.08	0.11
S	340	<50	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	200
Sc	10	11	N.D.	N.D.	N.D.	N.D.	9	9	6
V	100	108	124	137	117	99	105	33	42
Cr	14	17	34	34	17	20	18	<15	5
Co	12	12	50	70	48	63	68	N.D.	5
Ni	12	13	22	40	19	20	17	15	1
Cu	2	23	16	98	5	5	5	34	14
Zn	60	69	61	60	66	59	69	76	49
Rb	25	33	33	29	25	28	24	29	22
Sr	302	313	265	259	334	289	310	406	282
Y	14	12	N.D.	N.D.	N.D.	N.D.	N.D.	25	16
Zr	123	110	N.D.	N.D.	N.D.	N.D.	N.D.	147	105
Nb	<2	3	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	2
Ba	546	533	449	455	486	541	459	57	191
La	9.00	8.3	N.D.	N.D.	N.D.	N.D.	8.67	<10	6.6
Ce	19.0	17	N.D.	N.D.	N.D.	N.D.	19.5	N.D.	18
Nd	9.0	8	N.D.	N.D.	N.D.	N.D.	9.1	N.D.	10
Sm	2.00	1.9	N.D.	N.D.	N.D.	N.D.	2.10	N.D.	2.2
Eu	0.73	0.67	N.D.	N.D.	N.D.	N.D.	0.74	N.D.	0.78
Tb	0.30	0.3	N.D.	N.D.	N.D.	N.D.	0.38	N.D.	0.4
Yb	1.74	1.56	N.D.	N.D.	N.D.	N.D.	1.71	N.D.	2.42
Lu	0.28	0.25	N.D.	N.D.	N.D.	N.D.	0.29	N.D.	0.40
Hf	2.80	2.9	N.D.	N.D.	N.D.	N.D.	2.54	N.D.	2.8
Th	1.90	1.7	N.D.	N.D.	N.D.	N.D.	2.00	N.D.	1.0
U	0.8	0.8	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.6
Ta	1.1	1.0	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	<0.3

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃ Pre Of pre-sector collapse age

N.D. Not determined Post Of post-sector collapse age

¹ Analyzed at ACTLABS vitric airfall ash² Analyzed by Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT³ Analyzed by XRF at UPRM following method of Gunn et al., 1974; Gunn and Roobol, 1976.

All other analyses by Centre National de la Recherche Scientifique

** Analysis by XRF at Michigan Technological University following method of Rose et al. (1986)

TABLE II. Chemical composition of inclusions in volcanic rocks from Saba

	#S 34 ¹	S 37 ¹	SA 175	SA 157 ²	SA 134	S 23 ³	SA 123	S 21 ³	SA 160B	S 36 ¹	SA 168	SA 121	SA 158	SA 166	S 11 ³	##S 12 ³
SiO ₂	46.01	46.69	51.06	51.13	53.02	53.49	53.87	53.94	54.42	54.55	54.89	55.29	55.48	55.72	57.01	66.12
TiO ₂	1.06	0.78	0.87	0.93	0.91	0.90	0.41	0.75	0.86	0.76	0.66	0.33	0.74	0.72	0.66	0.47
Al ₂ O ₃	15.30	13.88	16.35	17.65	18.18	18.61	17.82	18.32	17.52	18.96	17.69	16.91	18.74	18.23	16.88	17.10
Fe ₂ O ₃ *	12.35	10.09	8.78	9.08	8.62	6.44	7.84	7.48	7.29	7.73	7.46	7.94	7.85	7.59	6.65	1.38
MnO	0.37	0.17	0.17	0.15	0.16	0.17	0.17	0.26	0.17	0.19	0.15	0.25	0.22	0.18	0.30	0.03
MgO	12.49	16.67	8.92	6.29	5.33	5.38	6.83	5.14	6.90	4.40	5.93	6.62	3.76	4.71	5.05	1.96
CaO	6.85	9.16	10.51	10.95	9.99	9.79	9.01	8.87	8.74	9.14	9.04	8.38	8.71	8.50	7.47	7.73
Na ₂ O	1.70	2.13	2.70	2.84	2.96	4.17	2.95	4.48	3.33	3.16	3.22	3.17	3.58	3.38	4.88	4.56
K ₂ O	3.62	0.36	0.56	0.85	0.82	0.88	0.98	0.62	0.71	0.96	0.80	0.96	0.82	0.86	0.93	0.45
P ₂ O ₅	0.24	0.08	0.07	0.12	0.01	0.16	0.12	0.14	0.06	0.14	0.16	0.15	0.10	0.11	0.18	0.20
S	90	<50	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	<50	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Sc	48	26	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	24	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
V	308	258	266	317	283	N.D.	246	N.D.	235	251	205	199	207	194	N.D.	N.D.
Cr	640	840	519	83	38	N.D.	206	N.D.	195	19	170	217	22	85	N.D.	N.D.
Co	48	64	71	123	81	N.D.	144	N.D.	82	20	127	66	136	142	N.D.	N.D.
Ni	145	405	165	79	38	16	182	27	110	26	107	97	64	98	80	9
Cu	51	84	77	81	106	153	62	100	<10	89	33	65	71	72	78	160
Zn	231	63	73	68	70	N.D.	67	N.D.	63	80	75	84	79	81	N.D.	N.D.
Rb	100	<10	10	12	14	N.D.	<10	9	14	<10	17	25	15	15	16	4
Sr	144	173	262	521	437	N.D.	275	347	252	313	314	289	385	364	348	401
Y	18	14	N.D.	N.D.	N.D.	N.D.	N.D.	33	N.D.	18	N.D.	N.D.	N.D.	N.D.	35	20
Zr	64	38	N.D.	N.D.	N.D.	N.D.	N.D.	5	N.D.	68	N.D.	N.D.	N.D.	N.D.	43	73
Nb	5	<2	N.D.	N.D.	N.D.	N.D.	N.D.	3	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ba	1226	78	182	225	251	N.D.	238	N.D.	282	339	271	324	318	305	N.D.	N.D.
La	8.4	2.4	N.D.	7.8	N.D.	N.D.	N.D.	N.D.	N.D.	6.6	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ce	20	6	N.D.	18	N.D.	N.D.	N.D.	N.D.	N.D.	16	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Nd	12	4	N.D.	9	N.D.	N.D.	N.D.	N.D.	N.D.	8	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Sm	3.0	1.66	N.D.	2.22	N.D.	N.D.	N.D.	N.D.	N.D.	2.4	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Eu	1.34	0.64	N.D.	0.78	N.D.	N.D.	N.D.	N.D.	N.D.	0.94	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Tb	0.6	0.4	N.D.	0.4	N.D.	N.D.	N.D.	N.D.	N.D.	0.4	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Yb	1.84	1.66	N.D.	1.73	N.D.	N.D.	N.D.	N.D.	N.D.	2.1	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Lu	0.28	0.26	N.D.	0.28	N.D.	N.D.	N.D.	N.D.	N.D.	0.32	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Hf	1.4	1.6	N.D.	2.3	N.D.	N.D.	N.D.	N.D.	N.D.	2.0	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Th	0.6	0.4	N.D.	1.6	N.D.	N.D.	N.D.	N.D.	N.D.	1.2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
U	<0.1	<0.1	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.4	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ta	<0.3	1.0	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	1.2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Major elements recalculated to 100 Wt % volatile-free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

S 34 - Angular inclusion of lamprophyre ## S 12 - Angular inclusion of low-K dacite

All other analyses of rounded hypabyssal inclusions

¹ Analyzed at ACTLABS² Analyzed by Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT³ Analyzed by XRF at UPRM following method of Gunn et al., 1974; Gunn and Roobol, 1976.

All other analyses by Centre National de la Recherche Scientifique

trends showing, as might be expected, that the formation of the horse-shoe-shaped sector-collapse structure is unrelated to any major changes in the plumbing system of the volcano. Its formation is most likely governed by external physical factors such as slope stability due to height increase of the volcano, rock weakness due to development of zones of hydrothermal alteration, and inflation of the cone due to rise of magma.

In the K_2O -silica variation diagram, the volcanic rocks of Saba (Fig. 22A) lie in the medium-K calc-alkaline field of Gill (1981). The Saba volcanic rocks form a single trend from which one sample is clearly different. This sample, which has around 65% SiO_2 and 2% K_2O , is composed of phenocrysts of plagioclase and green hornblende in a vesicular glassy groundmass. Petrographically there is no obvious reason for it to lie off the main trend. A suite of sixteen inclusions is also plotted in Figure 22B. Fourteen of these are rounded nodular calc-alkaline hypabyssal rocks which form a single geochemical trend-line with the volcanic rocks indicating that these inclusions are equivalents of the volcanic suite. Two exceptions can be noted, the first is the least siliceous rock analyzed and represents the lamprophyre inclusion already described. The second is the most siliceous rock analyzed and occurs as an angular inclusion contained within a 40 m thick lava flow at Tent Bay. This rock is a typical porphyritic dacite with fresh well-preserved oscillatory-zoned plagioclase and no appearance of hydrothermal alteration. It is the only rock on the island of Saba that belongs to the low-K calc-alkaline series. Like the lamprophyre its occurrence hints at the presence in the lower submarine parts of the Saba volcanic complex of older rocks with compositions different from those exposed subaerially. Volcanic rocks associated with subduction zones can also be classified into low- and high-Ca suites (Davidson, 1996). The volcanic rocks from Saba would belong to the low-Ca suite, as do volcanic rocks from the islands of Montserrat, Martinique, and St. Vincent (Macdonald et al., 2000).

With the exception of the two analyzed basalts, all other volcanic samples, regardless of whether they belong to the pre- or post-sector collapse subsuites, form a simple single magma series. For the suite as a whole with increasing silica, TiO_2 , Al_2O_3 , Fe_2O_3 , MgO , CaO , Sc , and V decrease, and Na_2O , K_2O , Zr , Ba , Hf , and Th increase (Figs. 22 and 23). One andesite and one basaltic andesite show anomalously low TiO_2 values suggesting

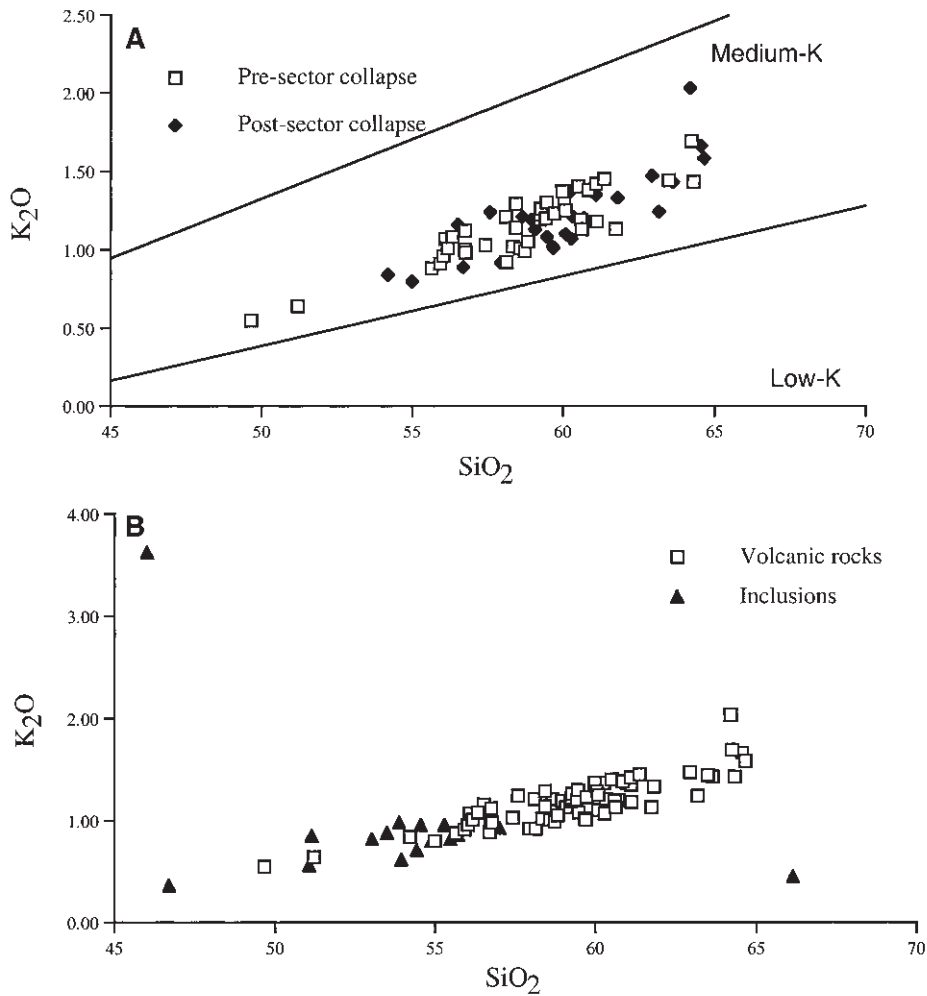


FIGURE 22. K_2O - SiO_2 plot of volcanic rocks and their hypabyssal inclusions from Saba (recalculated to 100% volatile free). The upper diagram (A) shows the volcanic rocks divided into pre- and post-sector collapse subsuites (field boundaries after Gill, 1981). The lower diagram (B) shows all analyzed rocks from Saba divided into volcanic rocks and igneous inclusions contained in the volcanic rocks.

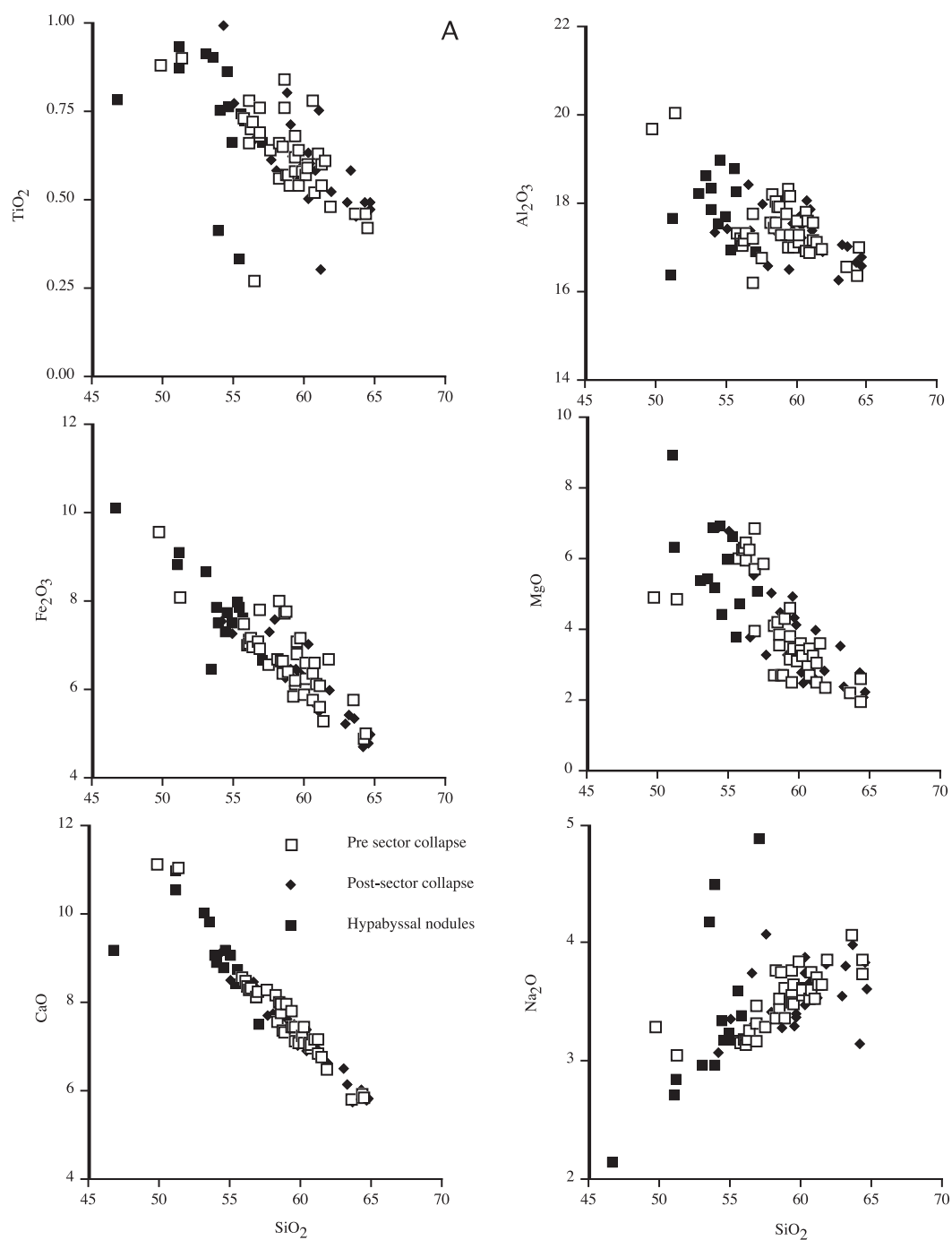


FIGURE 23A. Selected major element analyses of volcanic rocks and hypabyssal inclusions from Saba plotted against SiO_2 . Volcanic rocks are divided into pre- and post-sector collapse subsuites.

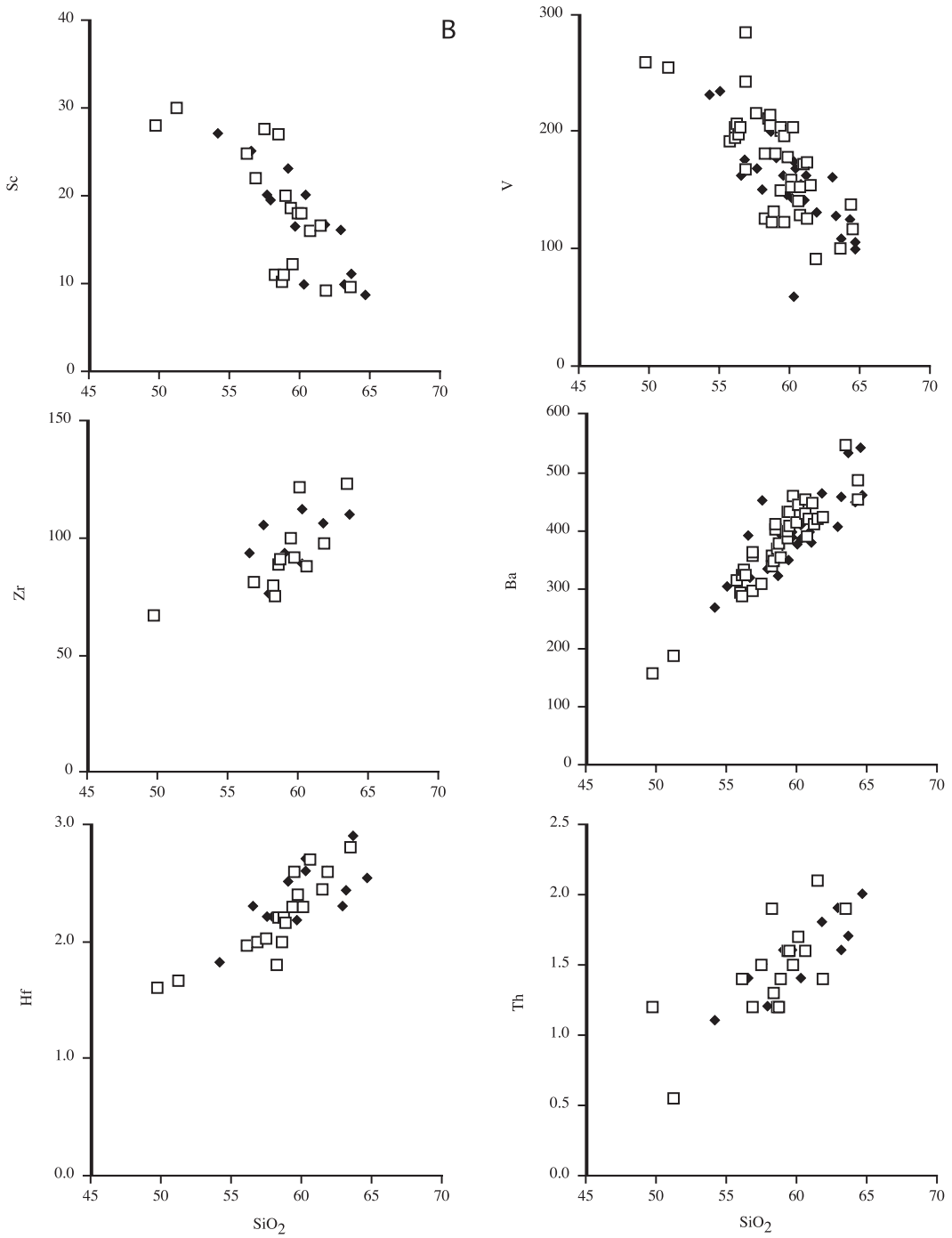


FIGURE 23B. Selected trace element analyses of volcanic rocks and hypabyssal inclusions from Saba plotted against SiO_2 . Volcanic rocks are divided into pre- and post-sector collapse subsuites.

that they underwent titano-magnetite fractionation before eruption. The two basalts are separated from the rest of the samples by around 3% SiO_2 and are especially enriched in Al_2O_3 and depleted in MgO . The enrichment in Al_2O_3 suggests either accumulation of plagioclase in the basalts or the early suppression of plagioclase crystallization, whereas the depletion in MgO may be explained by removal of olivine by crystal fractionation. Cr and Ni values are very variable in the Saba volcanic rocks, with the former ranging from 312 to 8 ppm, and the latter from 240 to 1 ppm. When plotted against SiO_2 no apparent trend can be observed and many intermediate rocks are richer in Cr and Ni than more basic rocks. However when plotted against MgO (Fig. 24), these trace elements show well defined trends suggesting that their abundances are directly related to the olivine content of the rocks — high Cr and Ni samples being olivine enriched and low Cr and Ni samples being olivine depleted.

REE data were obtained for twenty samples of volcanic rocks. Their chondrite-normalized patterns are shown in Figure 25 where the samples have been grouped into petrographic types. The basalts have an almost flat pattern, and $[\text{Ce}/\text{Yb}]_N$ ratios of 1.14 to 1.38, typical of island arc tholeiites. In contrast, the basaltic andesites, andesites and dacites all show similar patterns of moderately enriched light REE and slightly depleted heavy REE which increase slightly with increasing silica content of the rocks. The range in $[\text{Ce}/\text{Yb}]_N$ ratios (1.92 to 2.71) for these more evolved rocks falls within the range determined for the arc as a whole (Macdonald et al., 2000). All samples including the basalts show small to moderate positive Eu anomalies characteristic of plagioclase accumulation. The combination of light REE enrichment, together with an overall concave shape for the middle REEs in all rocks apart from the basalts, suggests that amphibole fractionation was involved in their formation.

Although almost half of the analyzed samples from Saba have sulfur values below the detection limit of 50 ppm (Table 10), the rest have much higher values that reach a maximum in sample S 56 of 13,600 ppm. The new geological map of Saba shows many areas of hydrothermal alteration on the island. In the field many of these areas show evidence of the accumulation of secondary yellow sulfur. The largest of these is in the sea cliffs below Lower Hell's Gate. Here the sulfur was concentrated in mineable quantities in the pyroclastic rocks immediately underlying the

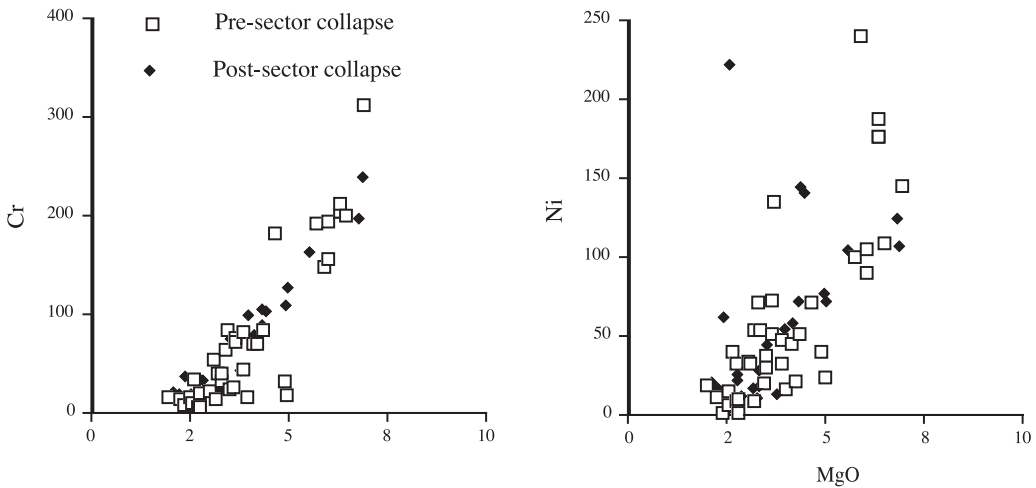
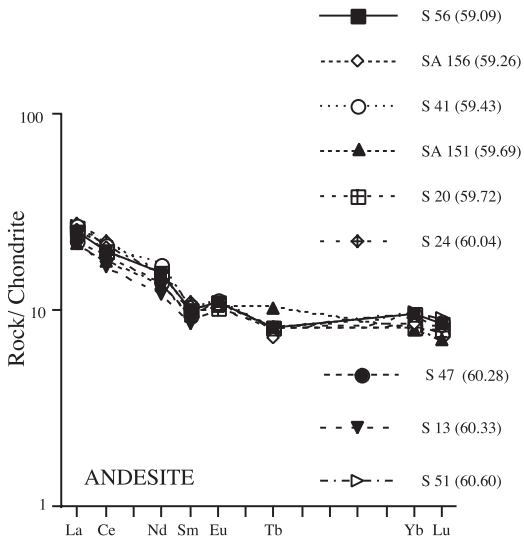
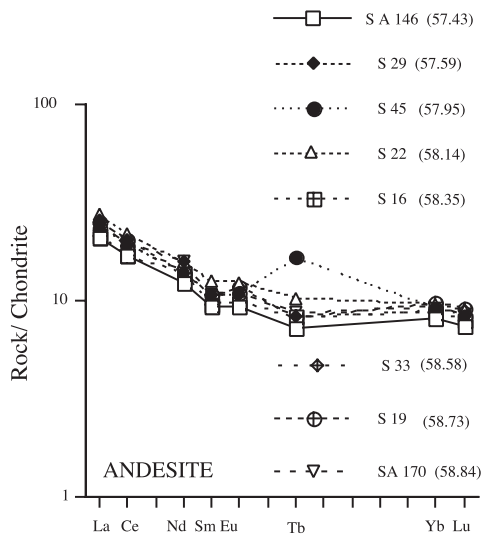
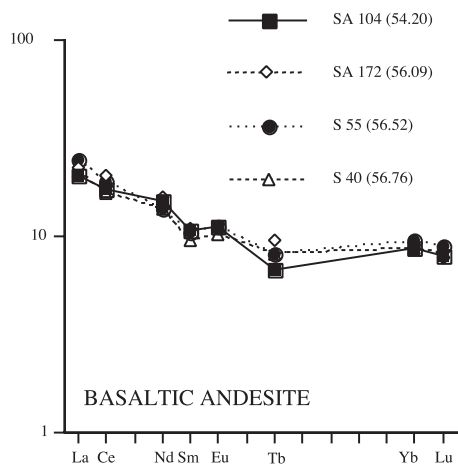
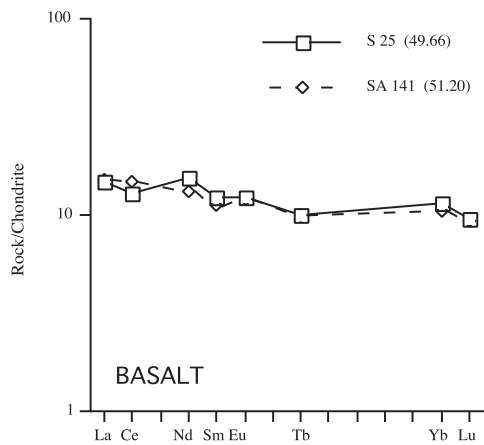


FIGURE 24. Chromium and nickel contents of volcanic rocks from Saba plotted against MgO. Volcanic rocks are divided into pre- and post-sector collapse subsuites.

base of the basaltic andesite lava flows. Clearly hydrothermal activity has played a role in the migration of sulfur in the volcanic complex of Saba. However some lavas collected from areas without obvious hydrothermal alteration also show high sulfur values. This suggests that sulfur contamination of the magma at depth might also have occurred.

Geochemistry of inclusions

Major and trace element analyses of representative inclusions in lavas from Saba are given in Table 11, and plotted in Figures 22 and 23. Ten of the analyzed rounded hypabyssal inclusions together with their host lavas (to which they are joined by tie-lines) as well as the lamprophyre and low-K dacite (the latter also connected to its host lava) are plotted in Figure 26. All ten rounded inclusions are more mafic than their host lavas. For most elements the trends shown by the tie-lines are similar to the trend of the volcanic rocks, for example TiO_2 , MgO, V and Cr all essentially decrease with increasing silica, whereas Na_2O and Ba increase. Two of the rounded inclusions show anomalously high Na_2O values. Both of these are composed almost entirely of plagioclase and hornblende with variable amounts of dark brown glass. The parallelism of the host-inclusion tie-lines with the trend of the volcanic rocks again indicates



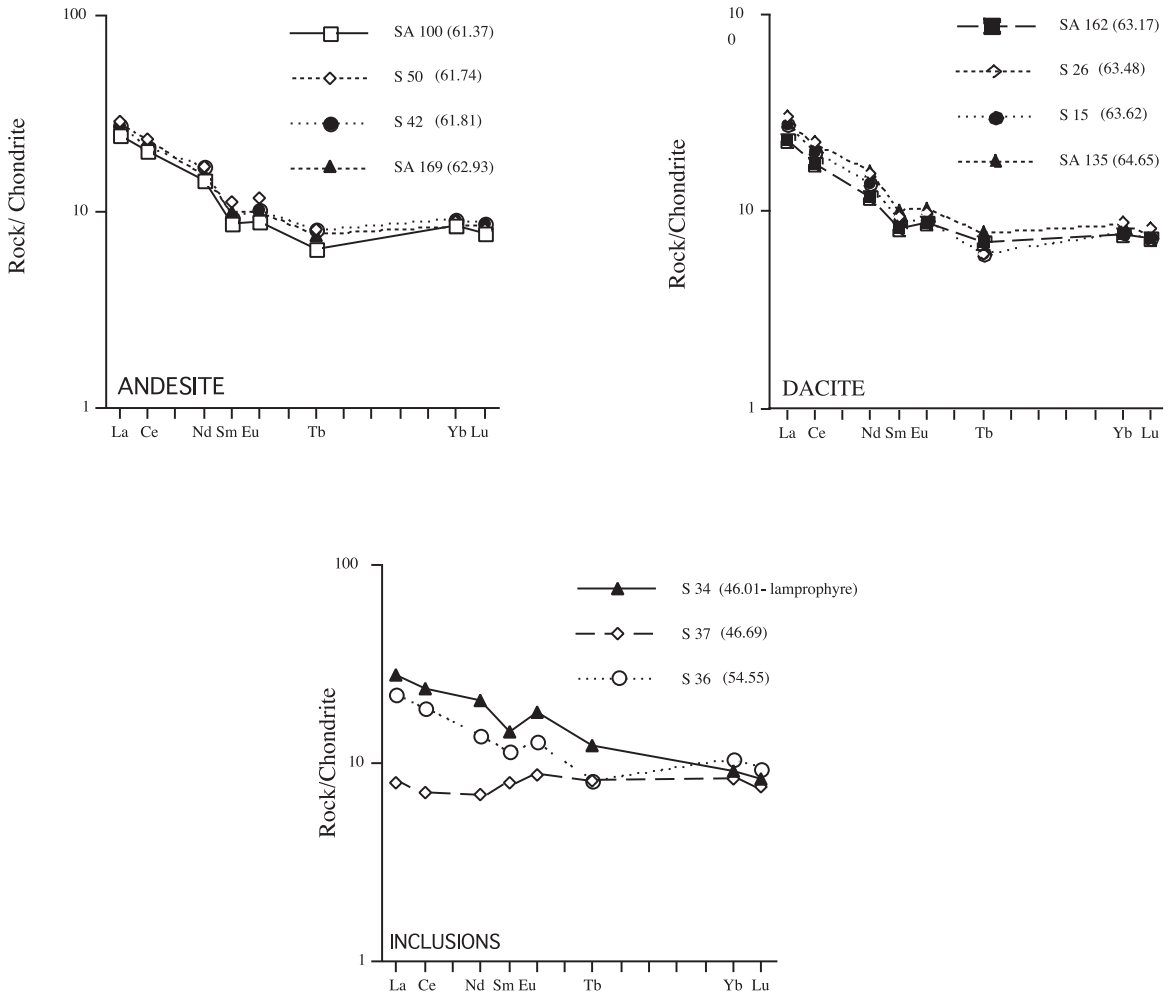


FIGURE 25. Chondrite-normalized REE plots of volcanic rocks and inclusions from Saba (chondrite normalizing factors from Taylor, in Donnelly and Rogers, 1980). Silica percentages of rocks are shown in brackets after sample numbers.

that the inclusions and their host lavas all belong to the same magma series. The angular clast of lamprophyre (S 34) is enriched in K_2O , Rb and Ba and lies off the rounded inclusion-host trend for most major elements suggesting an independent origin (Fig. 26). The angular low-K dacite, although lying on the trend, shows a reverse compositional relationship with its host lava supporting an origin of accidental inclusion with no genetic relationship with its host lava. In conclusion, the rounded hypabyssal inclusions appear to be genetically related to their host lavas, whereas the two angular inclusions (lamprophyre and low-K dacite) are interpreted to be examples of older rocks accidentally incorporated into their host lava.

Two rounded inclusions and the angular lamprophyre inclusion have been analyzed for REE. The rounded augite-hornblende-plagioclase inclusion (S 36) of basaltic andesite composition has a similar pattern to those shown by the basaltic andesites, andesites and dacites, whereas the rounded augite-plagioclase-hornblende inclusion (S 37) of basaltic composition has a similar pattern to the basalt lavas, although with a slightly lower enrichment. The angular lamprophyre (S-34) is distinct from both the other inclusions and the lavas of Saba in showing, apart from a negative Sm anomaly, an almost linear decrease in REE from La to Lu, consistent with its mafic rich composition.

Mineralogy of inclusions

Microprobe analyses of amphibole, plagioclase and orthopyroxene from hypabyssal inclusions of Saba are given by Wills (1974) and are reproduced in Table 12, which also contains analyses of two amphiboles (Baker et al., 1980), one representing a phenocryst in an andesite, and the other from a hypabyssal inclusion. With the exception of the orthopyroxenes which appear to have a relatively constant composition around En_{56} , the other minerals are quite varied in composition. For example, plagioclase varies from An_{83} to An_{45} and there appears to be two varieties of amphibole. Those from the hypabyssal inclusions being richer in Al_2O_3 , TiO_2 , Na_2O and K_2O than those from the volcanic rocks. A similar relationship was also noted from the Soufriere Hills, Montserrat (Murphy et al., 2000). The mineral compositions recorded from the hypabyssal inclusions on Saba are quite distinct from those reported from cumulate blocks such as

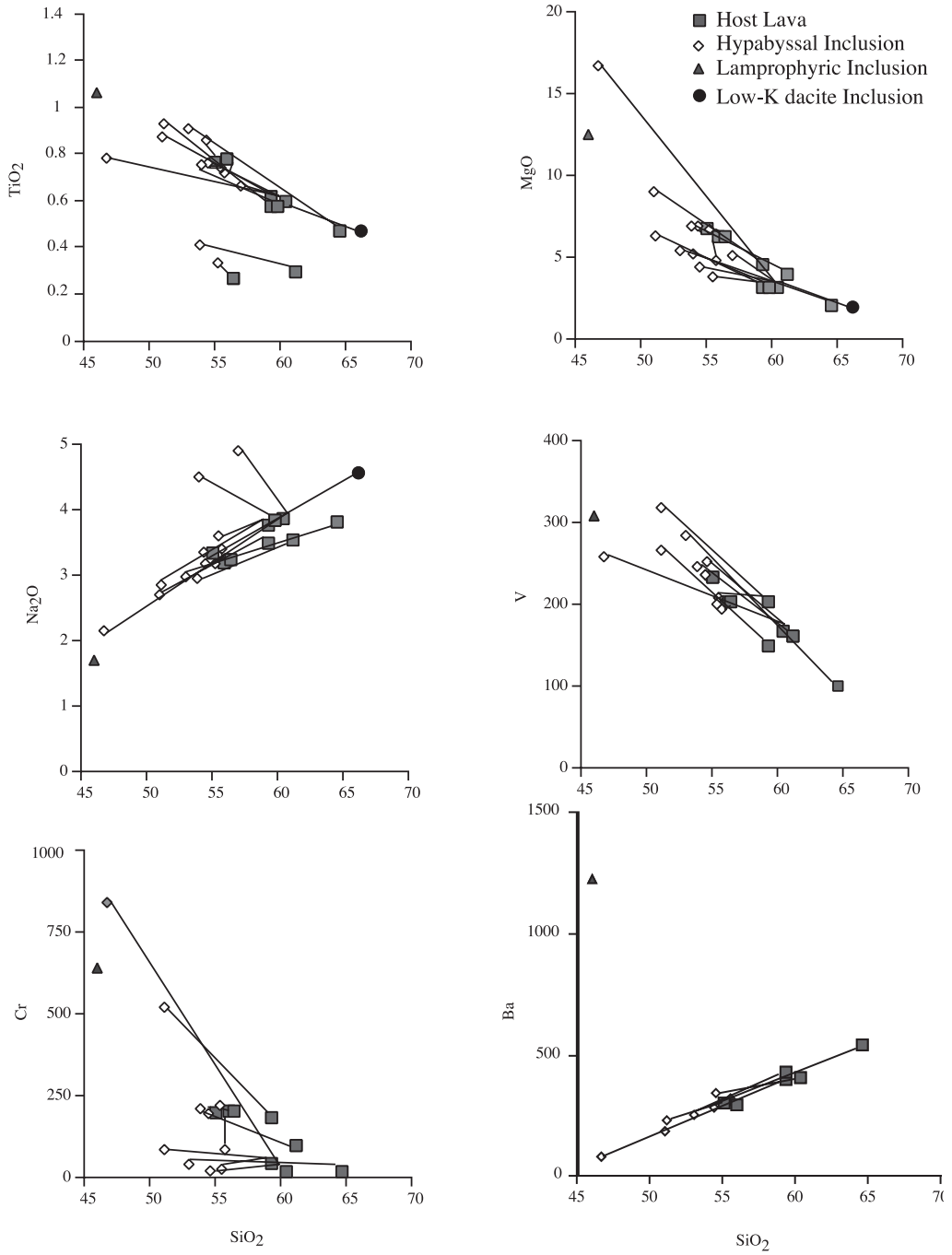


FIGURE 26. Inclusion-host lava plots for selected major and trace elements of samples from Saba plotted against SiO_2 . Inclusions are joined by tie-lines to their host lavas.

TABLE 12. Representative microprobe analyses of minerals from volcanic rocks and hypabyssal inclusions

	Amphibole				Plagioclase			Orthopyroxene	
SiO ₂	48.6*	43.1**	43.55#	45.19#	52.66#	48.14#	57.49#	53.14#	52.00#
TiO ₂	1.0	2.3	1.92	1.78	0.02	0.03	0.04	0.04	0.04
Al ₂ O ₃	6.4	12.8	11.57	9.6	29.72	32.36	26.12	0.44	1.10
FeO	13.2	9.0	15.14	14.17	0.35	0.21	0.23	21.28	22.41
MnO	0.6	0.2	0.52	0.46	N.D.	N.D.	N.D.	1.17	1.45
MgO	15.4	14.6	12.02	13.60	0.08	0.02	0.07	23.03	22.33
CaO	10.5	12.1	10.99	10.82	12.93	16.68	9.11	0.24	0.34
Na ₂ O	1.4	2.3	1.70	1.97	4.41	2.61	6.35	0.03	N.D.
K ₂ O	0.24	0.43	0.42	0.39	0.14	0.04	0.28	N.D.	N.D.
Cr ₂ O ₃	0.05	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.02	0.04
Total	97.39	96.83	97.83	97.98	100.31	100.09	99.69	99.39	99.37

* Hornblende from lava (from Baker et al., 1980).

** Hornblende from hypabyssal inclusion (from Baker et al., 1980).

Minerals from hypabyssal inclusions (from Wills, 1974).

N.D. Not determined

those found in the deposits of the Quill, St. Eustatius (Table 33; Arculus and Wills, 1980) suggesting that the hypabyssal inclusions of Saba crystallized from different magma compositions and under different conditions from those thought to have produced the cumulate blocks (Arculus and Wills, 1980).

ISOTOPIC COMPOSITIONS

Six lava samples have been analyzed for Sr and O isotopes (Table 13A). Both $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ when plotted against SiO₂ (Fig. 27) and MgO show essentially flat trends similar to those obtained from Mt. Pelée, Martinique (Davidson, 1987) suggesting that the volcanic rocks of Saba are related by closed system crystal fractionation. The $\delta^{18}\text{O}$ values for Saba, which are slightly above accepted MORB values even after removing the effects of crystal fractionation (Davidson, 1985), can probably be

TABLE 13. Isotopic analyses of rocks from Saba

A. Whole rock strontium and oxygen isotopic analyses of volcanic rocks

Sample number	SiO ₂ (Wt%)	⁸⁷ Sr/ ⁸⁶ Sr	± 2 std. dev.	δ ¹⁸ O
SA 141	51.20	0.70406	0.00002	+ 8.6
SA 140	54.20	0.70376	0.00002	+ 6.8*
SA 170	58.84	0.70380	0.00005	+ 8.5*
SA 151	59.69	0.70378	0.00002	+ 8.7
SA 169	62.93	0.70394	0.00002	+ 7.9
SA 135	64.65	0.70380	0.00002	+ 8.9

* Average of duplicate analyses on separate aliquots of the sample. Analyses (by Krueger Enterprises Inc.) are normalized to ⁸⁶Sr/⁸⁷Sr = 0.1194. Analyses of NBS-987 run during this period gave ⁸⁷Sr/⁸⁶Sr = 0.71023 (σ₂). Analyses have not been adjusted. ¹⁸O/¹⁶O_{SMOW} = 0.0039948

B. Whole rock strontium and lead isotopic analyses of a lamprophyre inclusion

Sample number	⁸⁷ Sr/ ⁸⁶ Sr	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb
S 34	0.703874	18.761	15.515	38.255

Analyses (by Krueger Enterprises Inc.) are normalized to ⁸⁶Sr/⁸⁷Sr = 0.1194. Ratios are all corrected 0.12%/amu for fractionation and are known to better than 0.05%

most readily explained as a consequence of the hydration of the samples rather than the effects of contamination (Thirwall et al., 1996).

The Saba volcanic rocks are also compared to other volcanic rocks from the Lesser Antilles, to Atlantic Ocean floor sediments and to MORB in terms of Sr, Nd, and Pb isotopic compositions (Fig. 28). On the Sr-Nd isotopic diagram volcanic rocks of the central and southern Lesser Antilles show a large range, with the Miocene volcanic rocks of Martinique overlapping the field of Atlantic sea floor sediments (Fig. 28A). In contrast the Saba volcanic rocks plot within the field of the volcanic rocks of the northern Lesser Antilles (Fig. 28A) and close to but distinct from the field of MORB (Fig. 28B). These results suggest that there has been minor but measurable contamination of the Saba magmas in terms of Sr and Nd. On

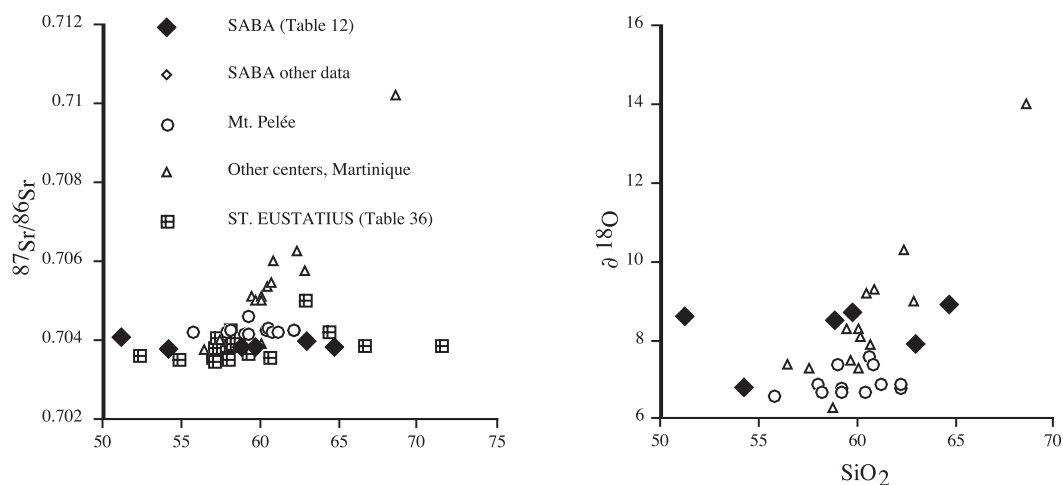


FIGURE 27. $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ values for volcanic rocks from Saba and St. Eustatius (Tables 13 and 39, and Davidson, 1987). Values for volcanic rocks from Mt. Pelée and other centers of Martinique (after Davidson, 1987) are plotted for comparison.

the plots showing variations of the Pb isotopes (Figs. 28C and D), the Saba volcanic rocks lie at the end of the Lesser Antilles volcanic field close to but distinct from the field of MORB, again suggesting limited contamination. From the isotopic data it is not possible to determine if this contamination is related to interaction of magma with subducted or crustal sediments.

The angular lamprophyre inclusion (S 34) was also analyzed for Sr and Pb isotopes (Table 13B). The lamprophyre has similar Sr isotopic values to those of the volcanic rocks of Saba and lies on the extension of the trend shown by the Saba volcanic rocks (Fig. 27). However its Pb isotopic ratios are distinct from those of the volcanic rocks and plot within the field of MORB (Figs. 28C and D). The isotopic evidence strongly suggests a primitive mantle origin for this rock.

PETROGENESIS

Geochemically the lavas of Saba, together with their rounded hypabyssal inclusions, belong to the medium-K (Gill, 1981), and low-Ca (Davidson, 1996; Macdonald et al., 2000) calc-alkaline suites, and form a single magma

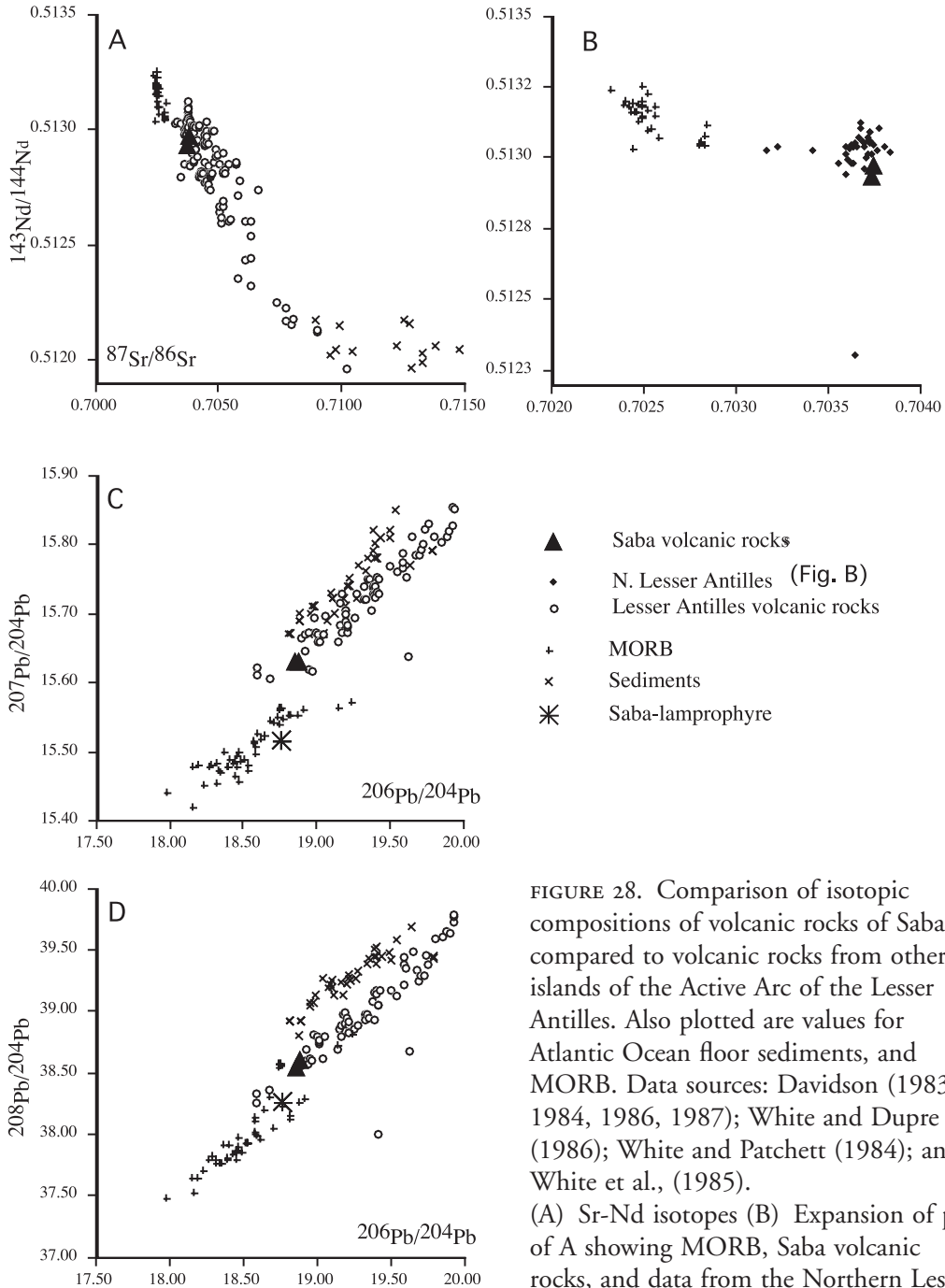


FIGURE 28. Comparison of isotopic compositions of volcanic rocks of Saba compared to volcanic rocks from other islands of the Active Arc of the Lesser Antilles. Also plotted are values for Atlantic Ocean floor sediments, and MORB. Data sources: Davidson (1983, 1984, 1986, 1987); White and Dupre (1986); White and Patchett (1984); and White et al., (1985).

(A) Sr-Nd isotopes (B) Expansion of part of A showing MORB, Saba volcanic rocks, and data from the Northern Lesser Antilles (St. Eustatius, St. Kitts, Nevis, Montserrat) (C) $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ isotopes (D) $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ isotopes

series ranging from basalt to dacite. The rocks of this series appear to be related to each other by fractional crystallization with andesite being the most abundant rock type, although evidence of magma mixing and comingling is also very abundant. The low MgO contents of the two analyzed basalts suggest that they do not represent primary magmas derived by partial melting of the mantle wedge beneath the arc lithosphere, but magma that has been modified by crystal fractionation. It has been proposed that the primary magmas of the Lesser Antilles are Mg-rich picritic basalts derived by partial melting of the mantle wedge that has been variably enriched or depleted relative to average MORB (Macdonald et al., 2000). For Saba, the evidence suggests that the underlying mantle had been enriched by interaction with fluids from the subducted slab. The abundance of andesites on Saba, suggests that little primary basaltic magma has reached the surface and most must have undergone considerable fractionation probably in the upper mantle. Such fractionation would produce large volumes of cumulates which would most likely accumulate at the mantle/crust boundary. Evidence for such accumulations is supported by seismic refraction studies which suggest that the lower arc crust under the northern Lesser Antilles represents oceanic crust that has been subsequently thickened by addition of mafic plutonic rocks (Maury et al., 1990). The apparent restriction of basalt to the rocks of the Torrens Point center, interpreted as the oldest exposed center on the island, suggests that it was only early in the sub-aerial development of Saba that the crust was sufficiently thin to allow basaltic magmas to reach the surface.

The plot of Ba/La versus La/Sm (Fig. 29) has been used to evaluate the roles of hydrous fluid metasomatism (Ba/La) and partial melting (La/Sm) on the petrogenesis of island arc magmas. On such a diagram the majority of the volcanic rocks of the Lesser Antilles show a negative correlation and occupy a relatively flat field, as a consequence of fractional crystallization and/or assimilation of terrigenous sediments (Davidson, 1986; White et al., 1985; White and Dupre, 1986; Defant et al., 2001). In contrast, the Saba volcanic rocks show a positive trend with the majority of the samples plotting in or close to the field of biogenic sediments (Fig. 29). Such a relationship suggests that the composition of the Saba magmas must have been affected by the assimilation of such sediments. Limited sedimentary contamination of Saba magmas is supported by the isotopic data discussed

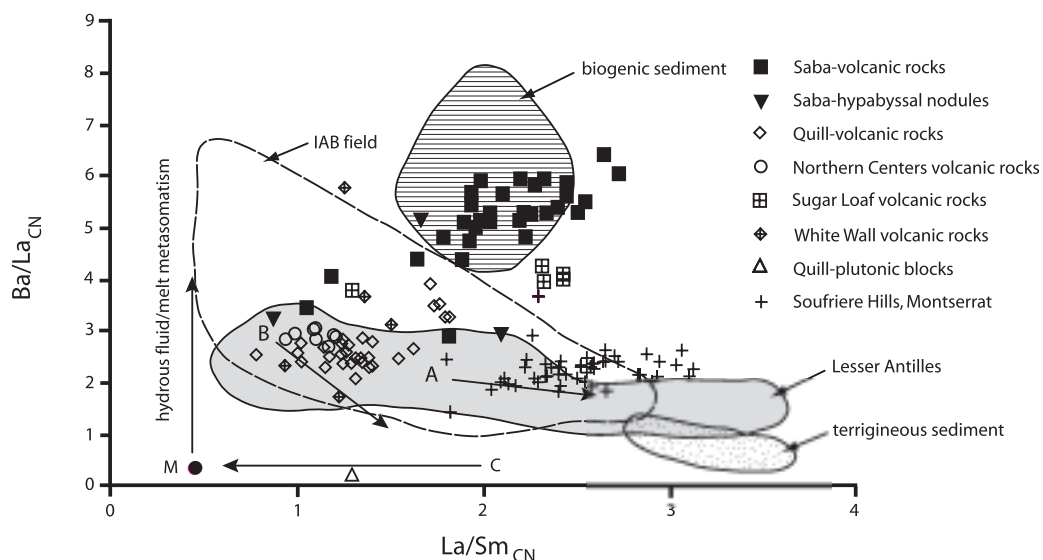


FIGURE 29. Ba/La versus La/Sm (chondrite normalized) (modified from Defant et al., 2001) showing data for the volcanic rocks of Saba (Tables 10 and 11), St. Eustatius (Tables 34, 35, 36 and 38) and Montserrat (Smith and Roobol, unpublished data). IAB (island arc basalt) field after Kay (1980); biogenic field after Ben Othman et al. (1989); terrigenous field after White et al. (1985); Lesser Antilles field after Defant et al. (2001). M – depleted MORB; A – fractionation/crystallization trend of Ol ± Cpx ± Pl ± Opx; B – fractionation/crystallization trend of Am + Pl ± Ol ± Cpx; C – variable degrees of partial melting (after Defant et al., 2001).

above, and by calculations of sediment flux (Plank and Langmuir, 1993), which indicate a greater sediment flux for Saba than previously reported for the other volcanic islands of the northern Lesser Antilles. Some of this sediment contribution could have been in the form of a melt as evidenced by the high Ta/Zr ratios and small Yb concentrations of the Saba volcanic rocks (Turner et al., 1996). However the negative Ce anomalies shown by the Saba lavas do not support contamination by sediments at the source as all possible sediment compositions have positive Ce anomalies (Defant et al., 2001). The most likely source for this sediment would therefore be biogenic sediments within the arc crust. Evidence for the presence of such sediments in the arc crust can be seen from the data collected from the drilling of the Saba Bank, and more importantly by the presence in the pyroclastic deposits and dome lavas of inclusions of crustal rocks including limestones.

The presence of amphibole in all rock types described from Saba suggests that magma crystallization took place under conditions of high $P_{\text{H}_2\text{O}}$, with amphibole formation within the basalts and basaltic andesites being favored by the relatively high Na_2O values characteristic of Saba magmas (Cawthorn, 1976; Cawthorn and O'Hara, 1976; Sisson and Grove, 1993). The high water content required to crystallize hornblende can also be used to explain the general absence of orthopyroxene in the Saba lavas (Sisson and Grove, 1993). The low Ca values characteristic of this suite can also be explained by the fact that high $P_{\text{H}_2\text{O}}$ values are thought to reduce the field of olivine crystallization with respect to that of clinopyroxene (Sisson and Grove, 1993). Recent work on the Soufriere Hills volcano, Montserrat has suggested that amphibole phenocrysts in the andesites of the current eruption were stable magmatic phases at water pressures of >115 MPa, i.e. >5-6 km depth and temperatures of <875°C (Barclay et al., 1998). Similar conditions may also be inferred for the crystallization of amphibole phenocrysts in the Saba lavas.

The high $P_{\text{H}_2\text{O}}$ in the magmas beneath Saba, suggested above, also raises an interesting possibility concerning the high alumina content of the Saba suite (Fig. 23A). High $P_{\text{H}_2\text{O}}$ has been shown to suppress plagioclase crystallization (Yoder, 1965) which would then lead to high Al_2O_3 contents in the derivative magmas. The abundance of plagioclase phenocrysts characteristic of most lavas on Saba may therefore be the result not of crystal accumulation but rather reflect the original high alumina content of the magma due to suppression of plagioclase crystallization at depth.

Disequilibrium relations such as the presence of corroded bipyramidal quartz, often with reaction rims of pyroxene, coexisting with olivine, and complexly zoned plagioclase often showing corroded rims and internal solution slots have been observed in many of the lavas of Saba. Such relationships suggest that the mixing of magmas to produce magma mingling and homogeneous hybrids commonly occur.

The rounded inclusions which abound in the lavas (e.g. Figs. 17 and 18) have a limited compositional range from basalt to basaltic andesite (46 to 57% SiO_2), and are always more mafic than their host lavas, to which they appear to have a genetic relationship, as evidenced for example, by the fact that low- TiO_2 inclusions are contained in low- TiO_2

hosts, and vice versa (Fig. 26). The inclusions also appear to have been largely crystalline when included in their hosts as they generally show relatively well-defined margins with their hosts and are undeformed when included in hosts that are flow-banded (as can be seen from Fig. 17).

Rounded inclusions of similar composition and texture are often found in composite dikes. The latter have been thoroughly described from Iceland (Blake et al., 1965; Gibson and Walker, 1963; Roobol, 1971) where they are much thicker than normal dikes, and are characterized by a mafic margin and a felsic core. These rounded inclusions are believed to form by erosion of the consolidated margins, which because of their more mafic composition have crystallized at a higher temperature than the dike interiors, by the still fluid core (Roobol, 1971). Mixing of mafic and intermediate/felsic magmas have also been described from high level stocks (net-veined complexes), here however mafic magma is chilled against felsic magma to produce pillow-like inclusions with fine-grained margins (Blake et al., 1965; Walker and Skelhorn, 1966; Yoder, 1973).

The abundance of rounded hypabyssal inclusions in the lavas of Saba island and the Soufriere Hills, Montserrat is therefore taken by us to indicate the presence of composite feeder dikes beneath these volcanoes. This interpretation is consistent with the fact that both of these volcanoes are thought to be underlain by major fault zones conducive to the intrusion of such dikes. For Saba the shape of the island, the alignment of the fumeroles, and the locations of epicenters from the recent seismic activity, all suggest that the island overlies a major northeast-southwest crustal fracture. For the Soufriere Hills Montserrat, seismic and GPS studies during the present eruption also suggest that this volcano overlies crustal fractures orientated northeast-southwest and northwest-southeast (Aspinall et al., 1998; Mattioli et al., 1998). Ground deformation studies also suggest that the injection of magma into the upper crust during the present eruption caused expansion mainly on the NW-SE fracture (Mattioli et al., 1998). An alternative explanation for the hypabyssal inclusions in the lavas of the current eruption of the Soufriere Hills, Montserrat has been proposed by Murphy et al. (2000). Similar inclusions are also found in the older deposits from this volcano (Smith et al., 2000). Murphy suggests that the hypabyssal inclusions represent clots of chilled mafic magma that was injected into relatively cool, highly crystalline andesitic magma contained

in a magma chamber at a depth of approximately 6 km. The injection of this basic magma was thought to also remobilize the pre-existing magma triggering the current eruption. We do not favor such an explanation for the hypabyssal inclusions of Saba, as we believe that such an origin cannot account for the observed genetic relationship between the inclusions and their host lavas. Also for the Soufriere Hills volcano, repeated random injections of basic magma (represented by the inclusions) into a high-level magma chamber containing highly crystalline andesite magma (Murphy et al., 2000) is difficult to reconcile with the eruption of andesites of essentially constant composition from the Soufriere Hills for at least the past 300,000 years (Smith et al., 2000, 2002).

A model is developed and more fully described later that emphasizes the distinction between volcanoes such as Saba and the Soufriere Hills, Montserrat which carry only hypabyssal inclusions and lack cumulate blocks, and volcanoes such as the Quill, St. Eustatius, and Mt. Pelée, Martinique, which show the opposite relationship.

In summary, Saba magmas were probably formed by partial melting of the mantle wedge, which had been metasomatized by the interaction of fluids or melts from the slab. These primitive magmas rose to the base of the crust where they probably underwent extensive fractional crystallization, possibly under high P_{H_2O} . The derivative magmas as they rose into the crust, probably in the form of dikes, underwent assimilation of crustal sediments, low pressure fractionation and magma mixing/co-mingling.

St. Eustatius

INTRODUCTION

St. Eustatius is a larger island than Saba with an approximate area of 21 sq. km. The island has a population of around 2,600, with the administrative capital at Oranjestad on the west coast. The dominant morphological feature on the island is the symmetrical stratovolcano of the Quill, which rises to a height of 600 m above sea level. As a consequence of the lower elevations of St. Eustatius, the climate is drier and the island has less of a vegetation cover except on the upper flanks of the Quill volcano. The simple and elegant form of this volcano contrasts greatly with the more rugged and irregular topography of Saba island.

MORPHOLOGY AND BATHYMETRY OF ST. EUSTATIUS

St. Eustatius is elongated northwest to southeast with a length of 7.9 km and a maximum width of 4 km. It is situated at the northeastern end of a shallow elongate submarine bank linking the islands of St. Eustatius, St. Kitts and Nevis. The submarine contours around St. Eustatius reveal that the Northern Centers lie in the middle of a circular submarine bank with the Quill positioned on the southeast margin (Fig. 30). The dominant tectonic trends (NE-SW and NW-SE) characteristic of the Lesser Antilles are also present on St. Eustatius. The northwest-southeast direction is exemplified by the elongation of the island itself, whereas the northeast-southwest direction is well shown by the extension, as defined

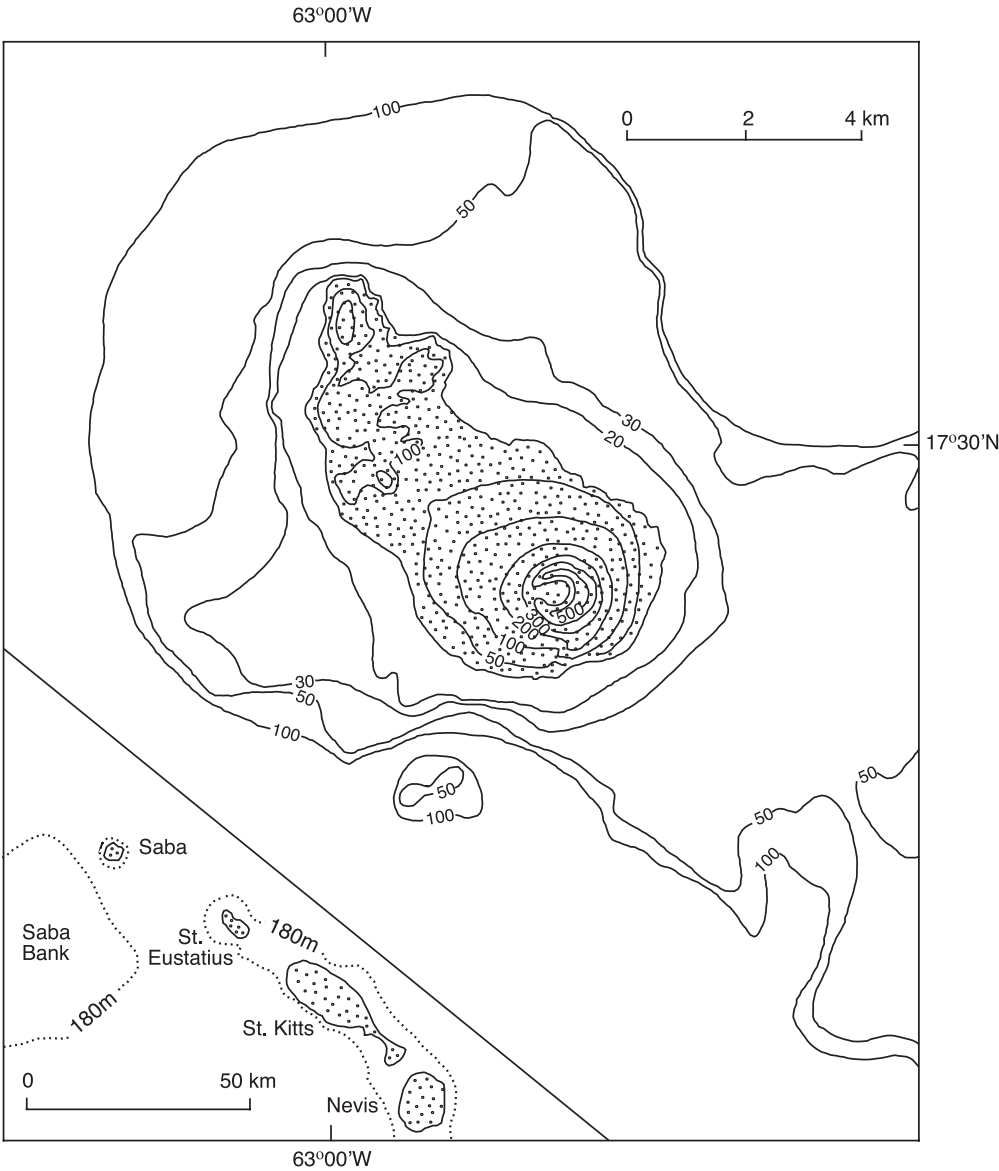


FIGURE 30. Topography and bathymetry of St. Eustatius (after U.S. Coast Guard chart 25607). All contours, above and below sea level are in meters. Inset shows the relative positions of Saba, Saba Bank, and the St. Eustatius-St. Kitts-Nevis bank (after Westermann and Kiel, 1961)

by the 50 m submarine contour, on both sides of the island. The same structural direction is indicated by indentations in the 50 meter submarine contour on opposite sides of the submarine bank suggesting a northeast-southwest fault may cut through the bank between St. Eustatius and St. Kitts. Morphologically it consists of two major components, the Quill stratovolcano and the Northern Centers. The former, which comprises the southern two-thirds of the island, is a young symmetrical, open crater cone built almost entirely by deposition of pyroclastic deposits from numerous eruptions. The latter is an older complex of Pelean domes, lava flows, and explosion craters.

GEOLOGY OF ST. EUSTATIUS

The geology of the island was described in detail by Westermann and Kiel (1961) who also summarized the previous geological work on the island (Maclure, 1817; Cleve, 1871; Molengraff, 1886, 1931; Saper, 1903, 1904; Hardy and Rodrigues, 1947). They recognized three major units which are clearly shown on the new geological map of St. Eustatius (Plate 4). The youngest geological unit is the single volcanic cone of the Quill at the south end of the island. This is a morphologically youthful open-crater stratovolcano with flanks sweeping up to angles of 50° at the crater rim (Fig. 31). The crater has a diameter of 800 m and the eastern rim forms the highest point on the island at 600 m above sea level. The lowest point on the crater floor is 278 m above sea level. A prominent notch/breach/low point exists in the western crater rim which has directed the youngest pyroclastic flows produced by the volcano to the west towards the island capital of Oranjestad (Plate 4). There are no records of historic eruptive activity. The distal deposits of the Quill form the nearly flat-lying central part of the island and terminate against the steep hills of the eroded Northern Centers. The pyroclastic deposits of the Quill are very well exposed in sea cliffs on the northeast and southwest shorelines. Some dome remnants are exposed as rock faces on the highest parts of the Quill and also on the inner walls of the crater.

Of intermediate age to the Quill and the Northern Centers is the geological unit comprising uptilted shallow-water limestones with



FIGURE 31. The Quill from eastern St. Eustatius. In the foreground are pyroclastic flow deposits of the last erupted bedset of the Quill exposed in the cliffs at Schildpadden Baai.

interstratified subaqueous volcanoclastic deposits of the White Wall-Sugar Loaf ridge, forming a part of the Quill on the south shore of the island (Plate 4 and Fig. 32). This succession records shallow-water phreatomagmatic volcanism from an unlocated center on the submarine bank prior to the establishment of the Quill volcano. The uptilting of the interbedded limestone-volcanoclastic succession was probably caused by the intrusion of a dome into the flank of the Quill. Similar uptilted limestone strata surround the Brimstone Hill andesite dome on the west coast of the nearby island of St. Kitts (Baker, 1969). Although the vent for these volcanic rocks is unknown, a possible location lies in the broad twenty to thirty meter deep submarine bank immediately to the west of the Quill volcano (Fig. 30).

The oldest geological unit on the island is the Northern Centers, which is composed of five morphologically distinct volcanic centers with varying degrees of erosion. Lava flows and lithified pyroclastic deposits from these centers are well exposed in the steep sea cliffs around the northern part of the island.

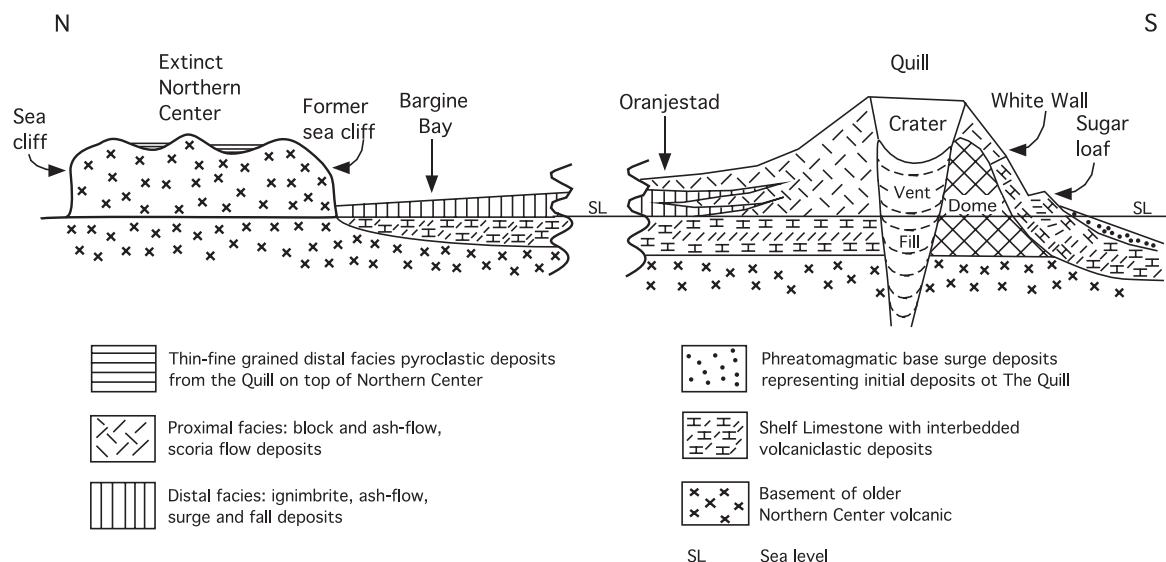


FIGURE 32. The Sugar Loaf ridge viewed east along strike from Fort de Windt, southern St. Eustatius. The prominent bedding plane of the White Wall is on the left.

A schematic longitudinal cross-section of the three main geological units is shown in Figure 33. The section shows the Northern Centers as an extinct former independent volcanic island with surrounding shallow-water carbonate banks containing volcanic deposits which overlap the marine platform. At first, the Quill volcano would have been a separate island from the Northern Centers but was eventually linked to it by the build-up of proximal to distal pyroclastic deposits along the shallow-water top of the bank.

GEOCHRONOLOGY OF ST. EUSTATIUS

Eleven radiocarbon ages have been obtained from St. Eustatius during the study. Four give dates corresponding to the period of European settlement of the island when no volcanic eruptions are known to have



Note: Not to scale

FIGURE 33. Schematic longitudinal cross-section through St. Eustatius from the White Wall-Sugar Loaf ridge to the Northern Centers.

occurred. They are therefore regarded as being caused by human activity such as slash and burn agriculture. The seven remaining ages (Table 14A) range from $22,240 \pm 140$ years B.P. to $1,550 \pm 35$ years B.P. The oldest age comes from an ignimbrite near the exposed base of the stratigraphic succession in the sea cliffs on the east coast (stratigraphic section II, Plate 5). Five dates are from charcoal-rich surge deposits that form a prominent marker unit around most of the island (stratigraphic sections II, XVII, XXX, XXXI, Plate 5). Most of these dated deposits are pumiceous, representing Plinian activity, but the youngest of these dates comes from a surge deposit containing semi-vesicular clasts, and represents Asama-style activity. The youngest age obtained from St. Eustatius is $1,550 \pm 35$ years B.P., and was obtained from charcoal within a pyroclastic deposit (stratigraphic section XXIX, Plate 5). This age (equivalent to 400 AD) corresponds with a period when the island was occupied by Amerindian peoples. Its significance is more fully discussed in a later section.

Although the deposits from the Quill are well exposed in the sea cliffs on both the east and west coasts of St. Eustatius, with the exception of the surge deposits described above, charcoal is not very abundant in the deposits of the Quill, (a total of seven datable volcanic charcoal samples being found during this study). In contrast, during a similar study of Mt. Pelée, Martinique (Smith and Roobol, 1990), fifty radiocarbon dates were obtained. The reason for this paucity in the deposits from the Quill can be attributed to the same reasons as that discussed for Saba, i.e. since St. Eustatius is a relatively small island, for many of the eruptions from the Quill the distal charcoal-bearing deposits would be submarine.

For the intermediate strata of the White Wall-Sugar Loaf ridge, Westermann and Kiel (1961) obtained three radiocarbon ages of $>49,000$, $32,640 \pm 300$, and $21,850 \pm 100$ years B.P. from corals in the limestone (Table 14B). Radiocarbon dating of marine corals is somewhat unreliable owing to diagenetic changes, and care must be taken that the samples dated are composed of original aragonite and not secondary calcite so that these ages have to be viewed with caution. The geochronology of the White Wall-Sugar Loaf succession was re-investigated (Smith et al., 1999) using samples screened for aragonite by X-ray diffraction. An initial group of coral samples from a prominent limestone bed midway within the Sugar Loaf succession (between beds 55a and 55b in the terminology of Westermann and Kiel, 1961), were submitted to the University of North Carolina where they were dated using the U-Th method. The dates obtained range from 218,500 to 236,000 years B.P. (Table 14C), and are considerably older than those obtained by Westermann and Kiel (1961). As a consequence of these older ages, a second group of corals from a number of limestone beds spanning the stratigraphy of the Sugar Loaf were collected and submitted to the University of Florida at Tallahassee for U-Th series analysis. The new data, with dates ranging from 68,000 to $>320,000$ years B.P. (Table 14D) confirm the earlier results and indicate that the limestones of the Sugar Loaf represent approximately 250,000 years of deposition. The White Wall-Sugar Loaf succession is more fully described in a later section.

TABLE 14. Geochronology of St.Eustatius

A. Radiocarbon ages from pyroclastic deposits of the Quill

Sample number	Age $\pm$ 1 std. dev. (years B.P.)	Type of Deposit
E 149	1,550 $\pm$ 35	ash flow
E127	7,810 $\pm$ 70	semi-vesicular andesite surge
E120	7,940 $\pm$ 75	pumiceous surge
EUX 971-1B	8,060 $\pm$ 120	semi-vesicular andesite surge
SE 8208C*	8,250 $\pm$ 60	pumiceous surge
EUX 971-42	8,380 $\pm$ 170	pumiceous surge
E126	22,240 $\pm$ 140	ash hurricane

* J. Davidson, 1984

B. Radiocarbon ages of corals from the White Wall-Sugar Loaf ridge succession (Westermann and Kiel, 1961)

Age $\pm$ 1 std. dev. (years B.P.)	Stratigraphic position
>49,000	Sugar Loaf bed 55a
32,640 $\pm$ 300	White Wall bed 32
21,850 $\pm$ 100	Sugar Loaf bed 31b

C. U-Th ages on corals of the Sugar Loaf succession*

Sample number	Th-230	U-234	$^{230}\text{Th}/^{234}\text{U}$	$^{234}\text{U}/^{238}\text{U}$	Age $\pm$ 1 std. dev. (years)
EUX 88-330	1.936	2.127	0.910	1.12	236,000 $\pm$ 7,458
EUX 88-332	1.942	2.210	0.879	1.06	218,500 $\pm$ 7,866

* Analyzed at the University of South Carolina

D. U-Th series ages on corals of the Sugar Loaf succession**

Sample number	U	Th	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{234}\text{U}$	^{230}Th age $\pm$ 1std dev. (years)
SE 33	2.85 $\pm$ 0.07	<0.005	1.11 $\pm$ 0.01	0.47 $\pm$ 0.02	68,000 $\pm$ 3,400
SE 24	2.68 $\pm$ 0.06	<0.005	1.12 $\pm$ 0.01	0.71 $\pm$ 0.03	130,000 $\pm$ 9,000
SE 29	2.86 $\pm$ 0.08	<0.005	1.09 $\pm$ 0.01	0.88 $\pm$ 0.03	218,000 $\pm$ 29,000
SE 30	2.26 $\pm$ 0.06	<0.005	1.09 $\pm$ 0.01	0.90 $\pm$ 0.03	234,000 $\pm$ 35,000
SE 27	2.91 $\pm$ 0.08	<0.005	1.07 $\pm$ 0.01	0.92 $\pm$ 0.04	251,000 $\pm$ 49,000
SE 28	2.86 $\pm$ 0.08	<0.005	1.04 $\pm$ 0.02	0.95 $\pm$ 0.04	300,000 $\pm$ 103,000
SE 26	2.70 $\pm$ 0.06	0.010 $\pm$ 0.003	1.06 $\pm$ 0.01	0.97 $\pm$ 0.04	>320,000

** Analyzed at Florida State University, Tallahassee, Florida

An attempt was made to date the lavas of the Northern Centers. Four samples were submitted to the Netherlands Geological Survey radiometric dating laboratory for whole rock K/Ar dating. In all cases the amount of radiogenic argon obtained was too small to measure and the rocks were assigned an age of less than 1 million years. The Northern Centers may well be broadly contemporaneous with the older stratigraphic division of Saba including the Diamond Rock-Torrens Point center, i.e. they were formed around 500,000 years ago. At this time the islands of Saba and St. Eustatius were smaller and had different forms to the present day islands.

GEOLOGY OF THE NORTHERN CENTERS

The Northern Centers form a series of hills measuring 2.5 km east-west by 4.0 km north-south. They comprise a youthful complex of five volcanic centers, each of which remains morphologically distinct. The three youngest centers, although eroded, still retain their original volcanic features. The Gilboa Hill center is a circular dome complex 1 km in diameter. Marine erosion along the east side reveals it to be an andesite dome capped by lithified volcanoclastic deposits. Immediately to the west is the Bergje center which comprises a circular dome, Bergje peak, with a diameter of 0.5 km, sitting in a circular erosion-enhanced crater with a diameter of 0.8 km. The southeast part of the dome and part of the crater wall have been destroyed by an elliptical crater measuring 0.3 km east-west by 0.2 km north-south (Plate 4). The southernmost center of Signal Hill is an eroded circular complex with a diameter of 1.2 km, which consists of intercalated lavas and lithified volcanoclastic deposits. The Mary's Glory center immediately adjacent to the airfield, and the Boven center comprising the northernmost part of the island appear to be the two oldest centers as they are considerably destroyed by erosion and are cross-cut by east-west lineations probably representing faults now hidden under the vegetation cover. The rocks comprising the southern slopes of the Boven center are orange colored and mark the site of former fumarolic activity.

SUBMARINE PYROCLASTIC STRATIGRAPHY OF
THE WHITE WALL-SUGAR LOAF RIDGES

These two ridges form an almost continuous stratigraphic section composed of about 200 m of limestones, volcanoclastic rocks and pyroclastic deposits that have been uptilted to 40° (Fig. 34). The limestones are very rich in fossils of Recent shallow water corals, mollusc shells and echinoid fragments. Most of the corals are in upright positions of original growth perpendicular to the stratification, proving that the dip of the limestone is a secondary tilting. A faunal listing from the Sugar Loaf (Table 15) indicates that these organisms lived in water depths of <10 meters. Most diagnostic is the molluscan fauna which suggests very shallow water depths with a back reef to shallow lagoonal paleoenvironment. Further indications of a shallow water origin for the White Wall-Sugar Loaf succession are provided by the presence of coarse boulder beds indicating shallow water to beach paleoenvironments. The depositional environment of the sedimentary rocks is interpreted as representing the flat-lying central part of a submarine bank which from time to time emerged, as indicated by the presence of unconformities within the limestone succession, a gypsum bed representing evaporation of the sea, and a possible subaerial base surge succession. Within the limestones Westermann and Kiel (1961) report the presence of volcanic glass, and crystals of plagioclase, green hornblende, magnetite, augite and hypersthene.

Throughout the stratigraphy of the White Wall-Sugar Loaf ridge there are interstratified volcanoclastic horizons including obvious pyroclastic beds, epiclastic material, and mixed ash and claystone beds (Fig. 34). Stratigraphically the lowest bed (a laminated ashy claystone with a thickness of more than 500 cm) is exposed high on the sides of the cone. The ash in the claystone is fine-grained, giving the bed a gray color. This is overlain by 250 cm of pumice breccia. The clasts in the breccia are angular with a maximum size of 75 cm. These two lithologies are repeated several times throughout the stratigraphy of the White Wall-Sugar Loaf succession and represent pyroclastic material deposited in water and mixed with clays and calcareous muds on the submarine banks. These beds are overlain by 200 cm of limestone containing rounded clasts of water-eroded coral heads and water-rounded boulders of andesite lava. These

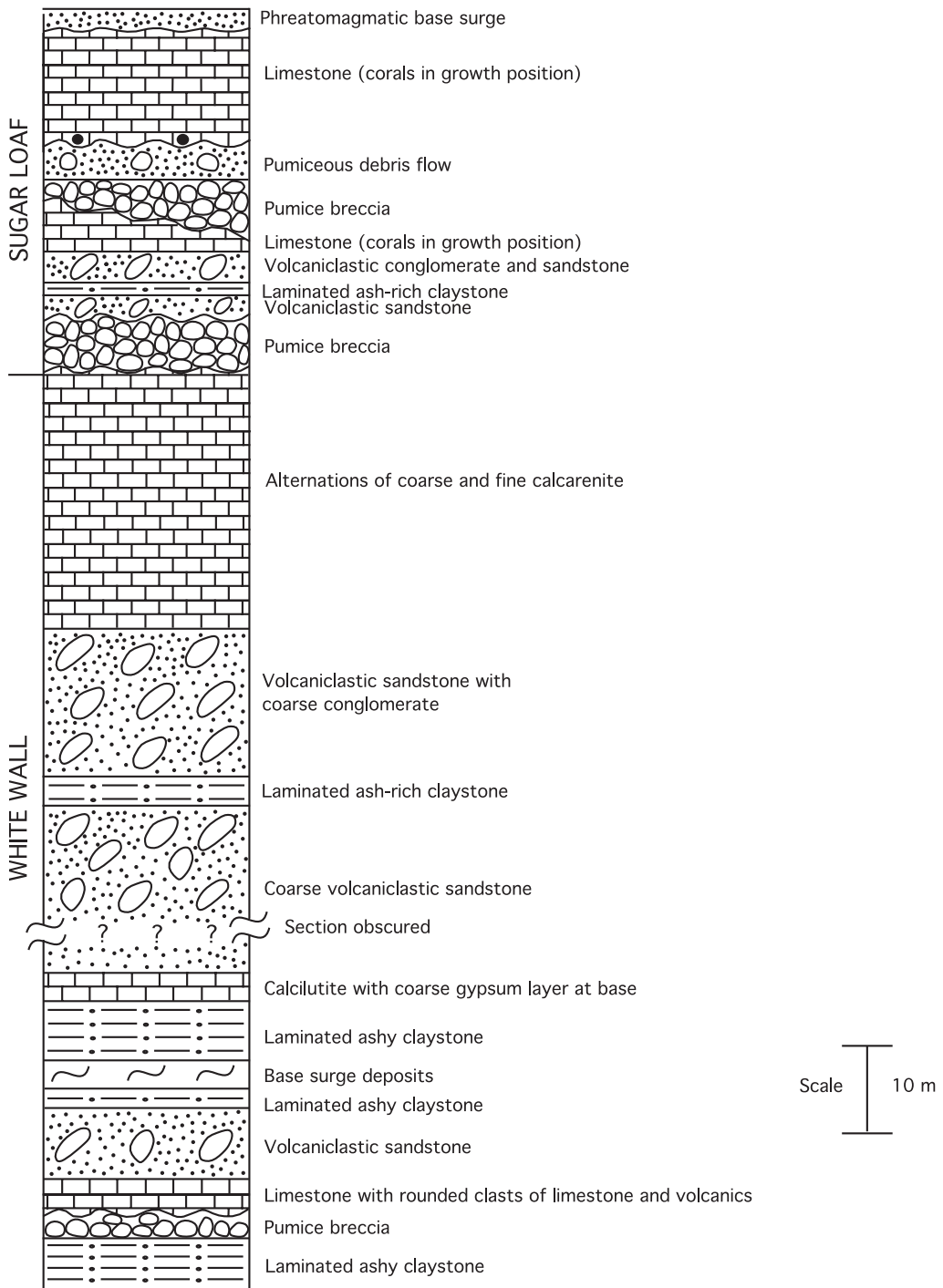


FIGURE 34. Stratigraphy of the White Wall-Sugar Loaf succession.

TABLE 15. Species of corals and molluscs (together with their paleo-environments) from limestone interstratified with pyroclastic deposits of the Sugar Loaf succession

Species	Paleoecology
A. CORALS	
Agaricia, agaricites, var. <i>crassa</i> *	*These living corals are found between water depths of 0.5 and 95m. The growth forms however indicate that the colonies were living in shallow water.
Goniopora sp.	
Montastrea (Orbicella),	
species similar to <i>M. cavernosa</i> *	
Montastrea annularis*	
Latomeardra sp.	
B. MOLLUSCS	
Bivalvia	
Lucina (=Phacides)	All of these molluscs live in shallow water between depths of 0.25 and 10m (<i>Strombus</i> can range to much greater depths 1-100m).
Pectinatus	
Chama macerophylla	
Antigona listeri	Astraea, Petaloconchus and Chama are reef forms.
Codakia orbicularis	
Glycimerus pectinatus	
Glycimerus sericatus	The other species are found in bays and mangrove lagoons.
Gastropoda	
Strombus gigas	
Astrea caelata	
Petalconchus sp.	

deposits appear to be typical of shallow water beach material. This in turn is overlain by volcanic sandstones and more ashy claystones, followed by dark-colored surge deposits. These surge deposits have characteristics similar to the younger deposits of the Quill and probably represent subaerial deposition. More ashy claystones separate the surge

deposits from a 400 cm calcilutite with a 100 cm coarse gypsum evaporite layer at its base. On top of the calcilutite are thick units of volcanic conglomerates containing well-rounded boulders up to 30 cm in diameter, and volcanic sandstones with coarse-grained stream-channel structures. The boulder beds, with rounded pebbles mainly of andesite, and the volcanic sandstones are thought to represent beach ridge material which has migrated along the submarine bank from a source where the material was eroded from block and ash deposits in the sea cliffs of the Northern Centers. The White Wall stratigraphy is capped by a thick succession of coarse and fine calcarenites which, as far as the poor exposure permits, appear to be devoid of volcanoclastic material. In an attempt to age date the limestones of the White Wall succession, X-ray diffraction analyses were made of corals to determine their aragonite content. In all samples collected the original aragonite had been converted to calcite and the samples were unsuitable for radiometric dating. Such was not the case for coral samples from the Sugar Loaf which were successfully dated (Table 14C and D). The stratigraphy of the Sugar Loaf therefore is discussed here in far more detail (Fig. 35) than that of the White Wall.

The Sugar Loaf succession was described by Westermann and Kiel (1961) and their stratigraphic notation (e.g. bed 55b) is cross-referenced in Figure 35. The succession is a series of limestones, some containing coral heads in their position of growth, together with reworked pyroclastic deposits varying from dacite to rhyolite in composition. The stratigraphy commences with 30 cm of an ashy sandstone containing reworked coral heads. This is overlain by 600 cm of white dacite pumice breccia with rounded clasts up to 10 cm. Next comes another ashy sandstone containing rounded clasts of dense andesite, followed by 100 cm of laminated crystal-rich white ash. Between this and the overlying beds is a minor unconformity. Above the unconformity is a sequence of cross-bedded sandstones. These in turn are overlain by 50 cm (bed 31g, Westermann and Kiel, 1961) of white laminated ash layers. These are overlain by an 800 cm bed of fine ash with clasts of pumice, limestone and dense lava, capped by a volcanoclastic conglomerate containing rounded clasts of dense andesite. The latter two beds were designated 31f by Westermann and Kiel (1961). These volcanoclastic beds are followed by a yellow limestone (bed 55a) containing large coral heads, which have yielded ages

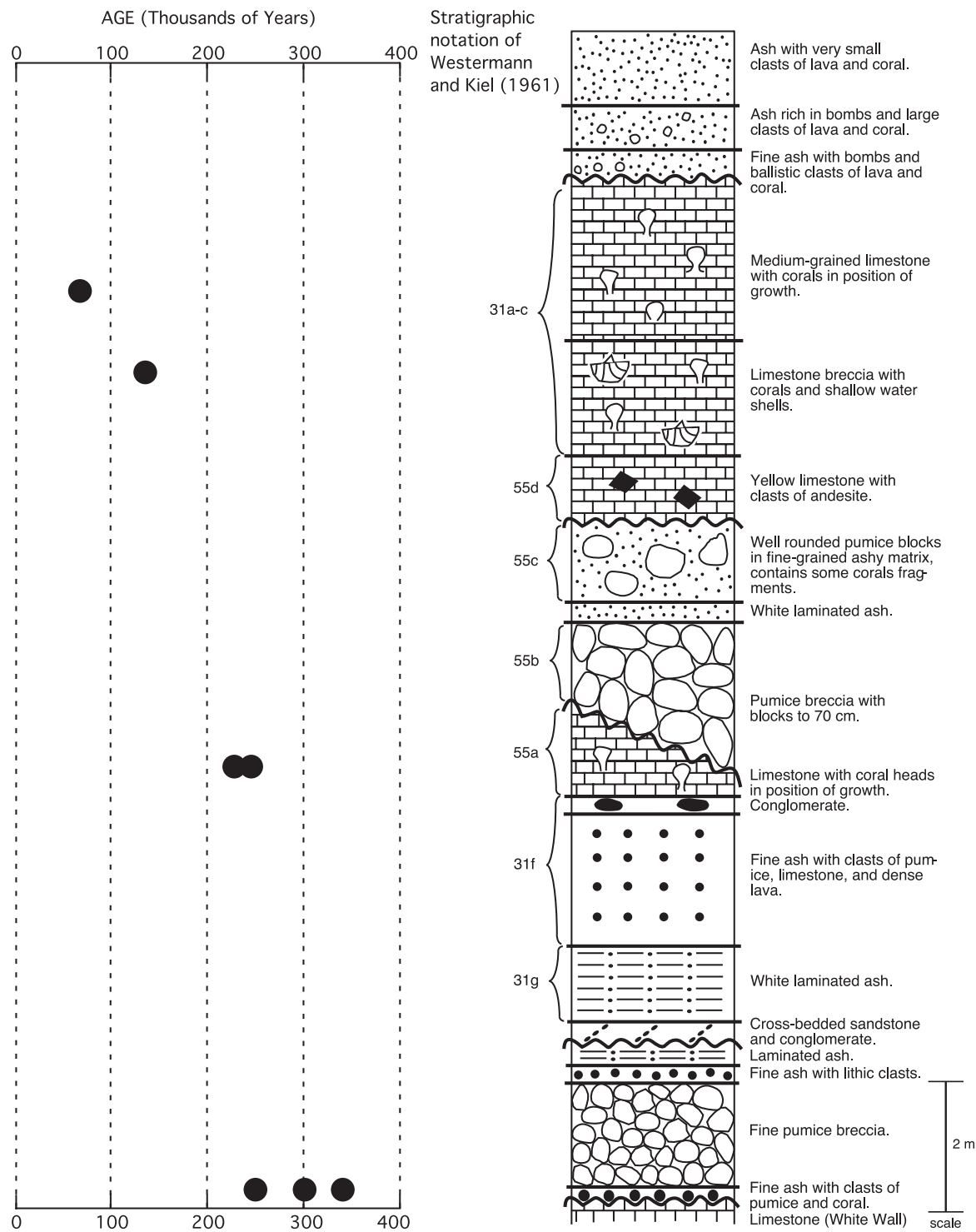


FIGURE 35. Detailed stratigraphy of the Sugar Loaf ridge showing age of limestones based on U-Th and U-Th series dating of corals (Table 14). The stratigraphic notation of Westermann and Kiel (1961) is shown for comparison.

of 236,000 and 218,500 years B.P. (Table 14C). The upper surface of this bed is cut by a well-developed unconformity so that its thickness varies from 300 to 400 cm. The coral heads in this limestone (bed 55a), as well as those higher in the succession (beds 31a-c), are all preserved with the same orientation perpendicular to the tilted stratification (Fig. 35), and are thus in their position of growth.

Immediately above the unconformity separating beds 55a and 55b (Fig. 35) is the most spectacular pyroclastic bed in the whole White Wall-Sugar Loaf succession. This is a 400 to 700 cm thick bed of rhyolitic pumice with blocks of up to 70 cm in diameter. This deposit is extremely bimodal and consists of large clast-supported subangular to subrounded pumice blocks in a very fine-grained ash matrix. The pumice blocks are quite well size-sorted. These characteristics are very similar to a giant pumice bed described from lake deposits in an old caldera of La Primavera rhyolite volcano, Mexico (Clough et al., 1981). A possible model for the formation of this bed might be the extrusion of a rhyolite lava through and onto a carbonate shelf, where the large pumices represent the detached pumiceous carapace of the lava. It is likely that in such highly vesicular pumice the vesicles were linked so that the pumices sank immediately. An alternative origin is that hot pumice blocks explosively erupted, fissured on falling into the seawater to sink immediately. It is unlikely that these giant pumices sank from a floating pumice raft because such large clasts can take months and even years to become waterlogged and would have drifted away from their possible source.

Above the pumice block bed is 50 cm of laminated white rhyolitic ash interpreted as a current reworked deposit. Above this is 400 cm of thickly bedded fine-grained, massive ash with occasional large (up to 1 m in size) well-rounded pumice clasts, and coral fragments, which are thought to represent reworked, matrix-supported pumiceous debris flow deposits. This bed, which was designated 55c by Westermann and Kiel (1960), is interpreted as the final product of rhyolitic Plinian activity from an unlocated center on the submarine bank.

The pumiceous debris flow beds are unconformably overlain by 4,000 cm of shallow water limestones (beds 31a-c), which record the interval of carbonate sedimentation between the extinction of the Sugar Loaf center and the first erupted products of the Quill, which uncon-

formably overlies this unit. The lower part of this sequence is a yellow limestone (bed 55d, Fig. 35) containing sub-angular to sub-rounded porphyritic gray-pink andesite lava fragments up to 5 cm which probably represent reworked older material. Above this is 500 cm of limestone breccia containing coral heads and molluscs dated at 130,000 years B.P. (Table 14D). This is followed by 700 cm of fine calcarenite, typical of a back reef environment, containing isolated corals in their position of growth. U/Th series dating of corals from this bed has yielded an age of 68,000 years B.P. (Table 14D).

Unconformably overlying the limestones of beds 31a-c and well exposed on the present beach platform at the Sugar Loaf is a unit of grey, ash-rich, basaltic andesite base surge deposits more than 2,000 cm thick (the top of the unit is below sea level). These deposits are thought to represent the first erupted deposits of the Quill volcano. However they do not correlate with similar basaltic base surge deposits exposed at the base of the sea cliffs on the northeast coast of St. Eustatius at Compagnie and Bargine Bays. This is because most of the older pyroclastic deposits of the Quill are hidden beneath sea level and cannot be traced to these outcrops.

The base surge deposits at the Sugar Loaf are internally chaotic, and contain abundant angular to sub-angular, matrix-supported volcanic clasts and broken coral heads. Two types of volcanic clasts are found: massive pink to grey andesite blocks up to 30 cm across, and striking black basaltic andesite bombs of about the same size. The latter show thick chilled margins (up to 5 cm) with many radial cooling joints. Such chilled and jointed bombs are well known and described from young submarine vents adjacent to the shores of Oshima volcanic island of Japan, e.g. at Habu-Minato (Oki et al., 1981), and identify the interaction of water with magma during eruption. The large bombs preserved inside their impact craters are shattered (Figs. 36A and B). This relationship is probably due to the fact that the base surge deposits formed in shallow water near the vent where larger bombs were still molten when they landed and shattered. The coral fragments and the pink to grey andesite blocks are interpreted as lithic ballistic ejecta, whereas the basaltic andesite clasts represent juvenile ballistic bombs. The best estimate of the age of these deposits, based on the ages of the corals from the Sugar Loaf (Table 14C and D) and the radiocarbon age from the top of



FIGURE 36.A: 55 cm diameter ballistic lithic block of porphyritic andesite in bomb impact crater in base surge deposits rich in white limestone clasts (Base Surge Division 1) at west end of Sugar Loaf ridge. B: Layer containing ejected fragments of *Monastrea* coral head (C), lithic porphyritic andesite (L), and thick-skinned, chilled basaltic andesite bomb (J). Details as for Figure 36A. Scale is given by knife.

the base surge section on the east coast (22,240 years B.P., Table 14A), is that they formed around 40,000 to 50,000 years ago by a series of phreatomagmatic explosions when basaltic andesite magma was erupted into shallow sea water on a carbonate bank. The Quill at this stage probably emerged as a low tuff ring with a flooded crater.

An interpretation of the stratigraphy of the White Wall-Sugar Loaf ridge provides an unusual and interesting documentation of shallow-water phreatomagmatic activity over a period of several hundred thousand years. In Figure 37, the ages obtained on corals of the Sugar Loaf are plotted against known variations in sea level. The diagram indicates that during the period of limestone deposition sea level fluctuated from plus 6 meters to minus 24 meters relative to present sea level, however all of the limestone beds suggest depths of less than 10 m suggesting that the platform was also subject to tectonic movements. In Figure 38, four sketches illustrate the environments of formation of the different components of the White Wall-Sugar Loaf stratigraphy. During quiescent periods of high sea

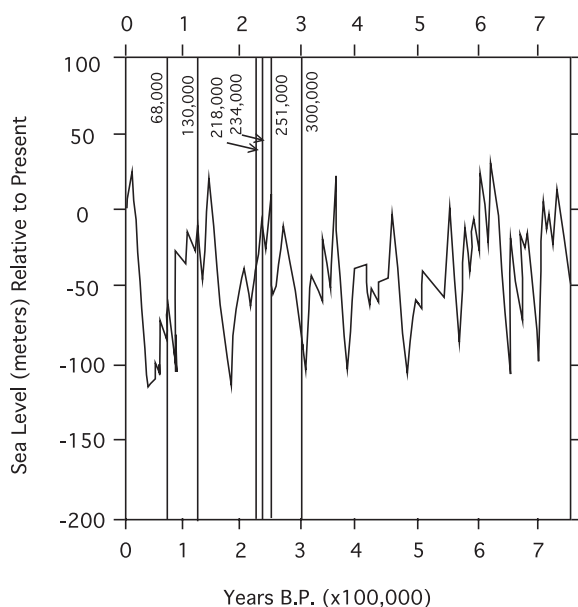


FIGURE 37. U-Th series ages of Sugar Loaf limestones plotted on a Quaternary sea-level curve for the Caribbean region (curve after Emiliani, 1975, and Stienstra, 1982).

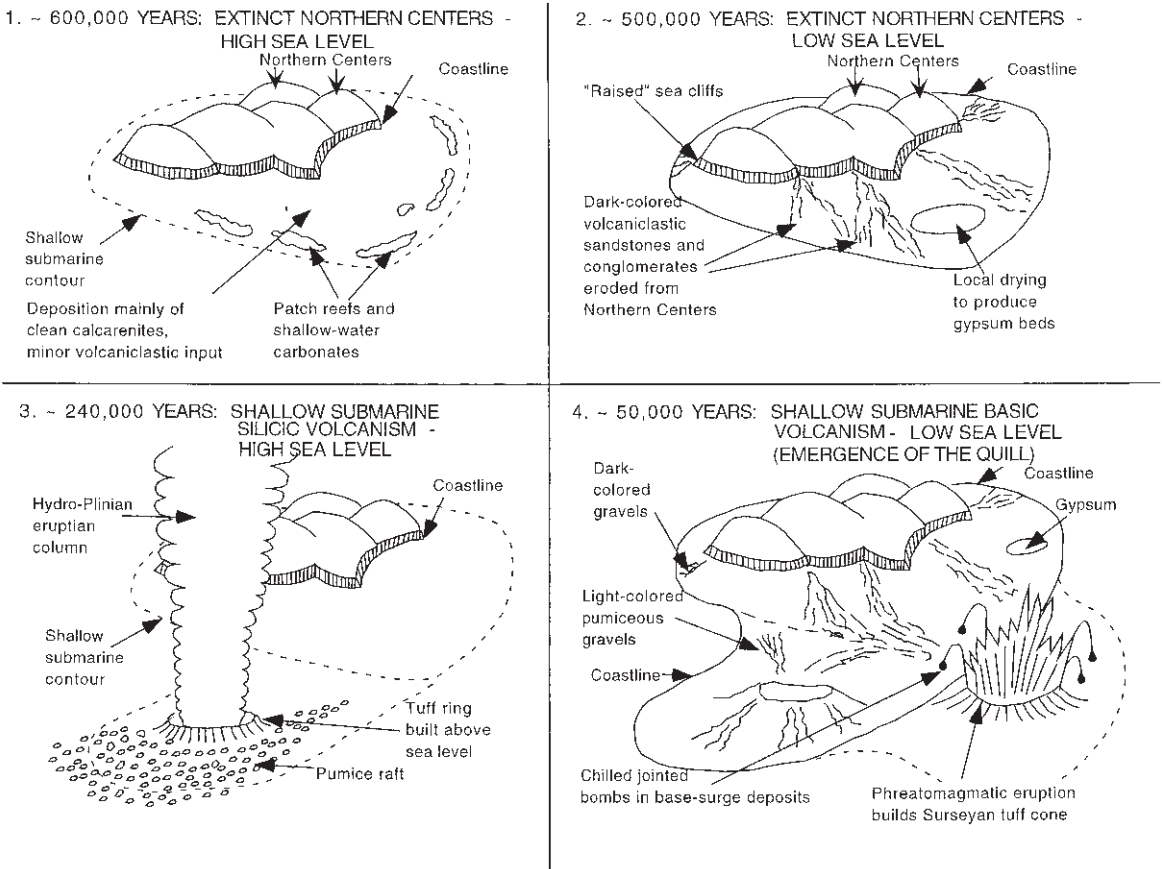


FIGURE 38. Schematic model showing possible manner of formation of main types of deposits that make up the White Wall-Sugar Loaf succession.

level the Northern Centers are seen as a small island complex standing on a shallow marine bank on which clean calcarenites with minor clastic input are deposited in a lagoonal environment with patch reefs behind an offshore coral reef. During dormant stages with low sea levels, volcanic clasts are eroded from the Northern Centers and are transported onto the partially exposed bank as volcanic sandstones and conglomerates along stream channels and beach ridges. The partially dried-out lagoon provided a number of local sites for evaporite formation as witnessed by the occurrence of gypsum. The rhyolitic ashes and giant pumice beds record shallow-water subaqueous rhyolitic eruptions at times of high sea level



FIGURE 39. Seacliffs in Compagnie Baai, northeast St. Eustatius (stratigraphic section V, Plate 5) showing excellent exposures of pyroclastic deposits typical of the seacliffs of St. Eustatius.

when emergent tuff rings were built above sea level and accompanying phreatomagmatic explosions produced very fine-grained ashes, which were often reworked by currents. The exact site of the vent for these deposits remains unknown but may well underlie the shallow-water bank immediately west of the Quill. The beds at the top of the Sugar Loaf succession are seen as forming as submarine eruptions at a time of high sea level, with the vent probably under the present cone of the Quill. Phreatomagmatic eruptions from this vent produced the base surges which may have built up an emergent tuff ring.

PYROCLASTIC STRATIGRAPHY OF THE QUILL

Introduction

Sea cliffs cut into the flank deposits of the Quill provide some of the best exposures of pyroclastic stratigraphy in the Lesser Antilles (Fig. 39). Thirty-five stratigraphic sections have been logged, and their locations numbered in a clockwise direction from the most northeasterly location measured (Plate 5), which permit an unusually high degree of correlation of the pyroclastic deposits. The Quill is composed essentially of pyroclastic deposits amongst which reworked materials are unusually scarce.

The logged stratigraphic sections (Plate 5) demonstrate that the Quill is constructed of deposits produced by five main styles of pyroclastic volcanism (Table 4). Each volcanic style has produced several different types of deposit. These are:

- i. Pelean-style eruptions produced dense andesite deposits of:
 - (a) Block and ash flow (Figs. 40A and B).
 - (b) Dense andesite surge.
 - (c) Ash and dust fall
- ii. St. Vincent-style eruptions produced basaltic/basaltic andesite deposits of:
 - (a) Scoria and ash flow (Fig. 41).
 - (b) Scoriaceous ash flow
 - (c) Scoriaceous surge.
 - (d) Scoriaceous lapilli and ash fall.
- iii. Plinian-style eruptions produced andesite to rhyolite deposits of:
 - (a) Pumice and ash flow (ignimbrite).
 - (b) Ash hurricane (ignimbrite).
 - (c) Pumiceous surge.
 - (d) Pumiceous lapilli and ash fall
- iv. Asama-style eruptions produced semi-vesicular andesite deposits of:
 - (a) Semi-vesicular andesite block and ash flow (Fig. 42)
 - (b) Semi-vesicular andesite surge
 - (c) Semi-vesicular andesite lapilli and ash fall
- v. Phreatic/phreatomagmatic eruptions produced basalt to rhyolite deposits of:
 - (a) Thick units of base surge
 - (b) Khaki-colored laminated ashes

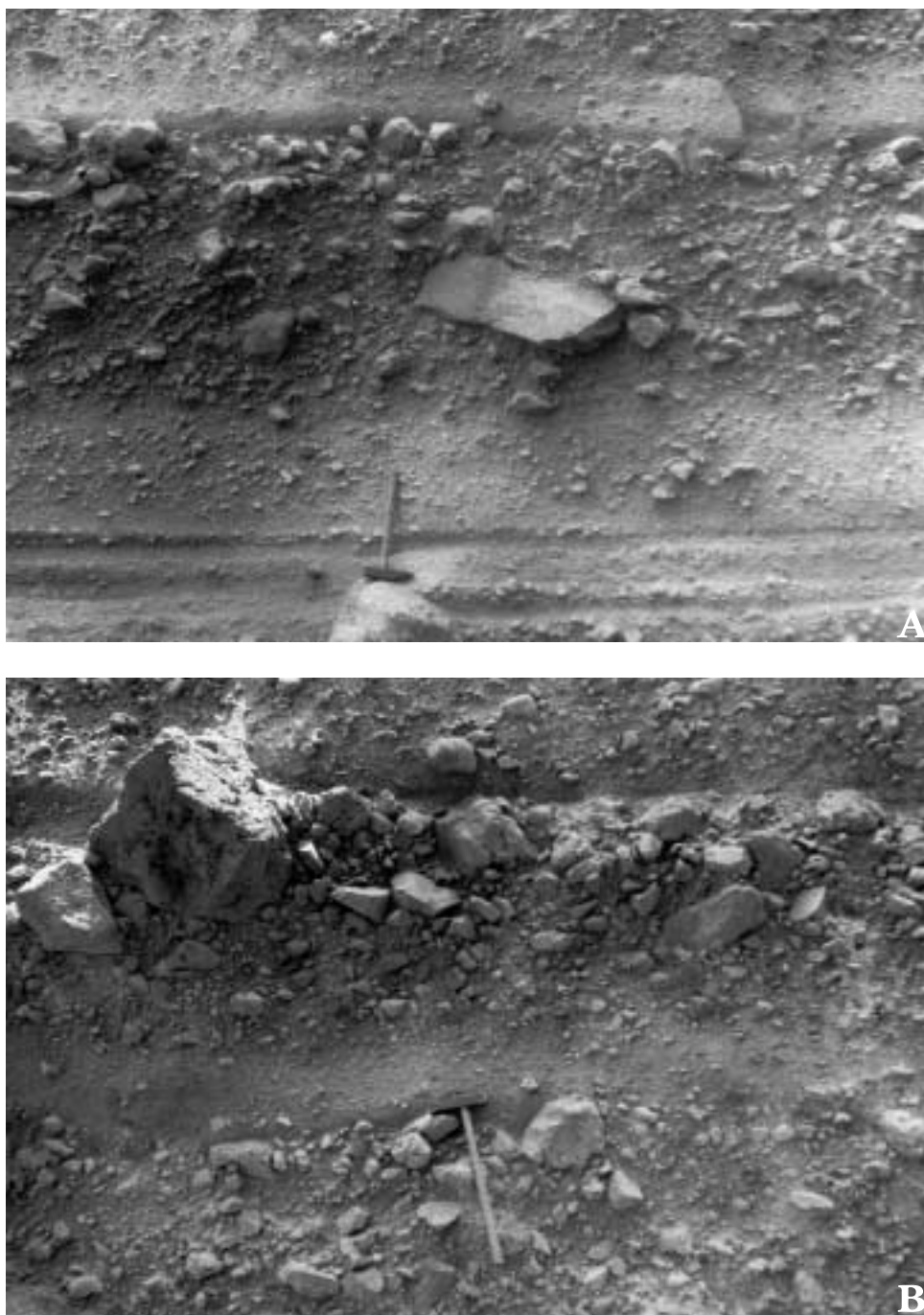


FIGURE 40. Andesitic block and ash flow deposits from the sea cliffs on the east coast near Compagnie Baai.

A. 300 cm deposit (in the center of the photograph) showing a fine-grained base with unsorted, ungraded matrix-supported upper part. 65 cm-hammer provides scale (stratigraphic section V, Plate 5).

B. 100 cm deposit showing fine-grained base with reverse graded clast-supported upper part. 65 cm-hammer provides scale.

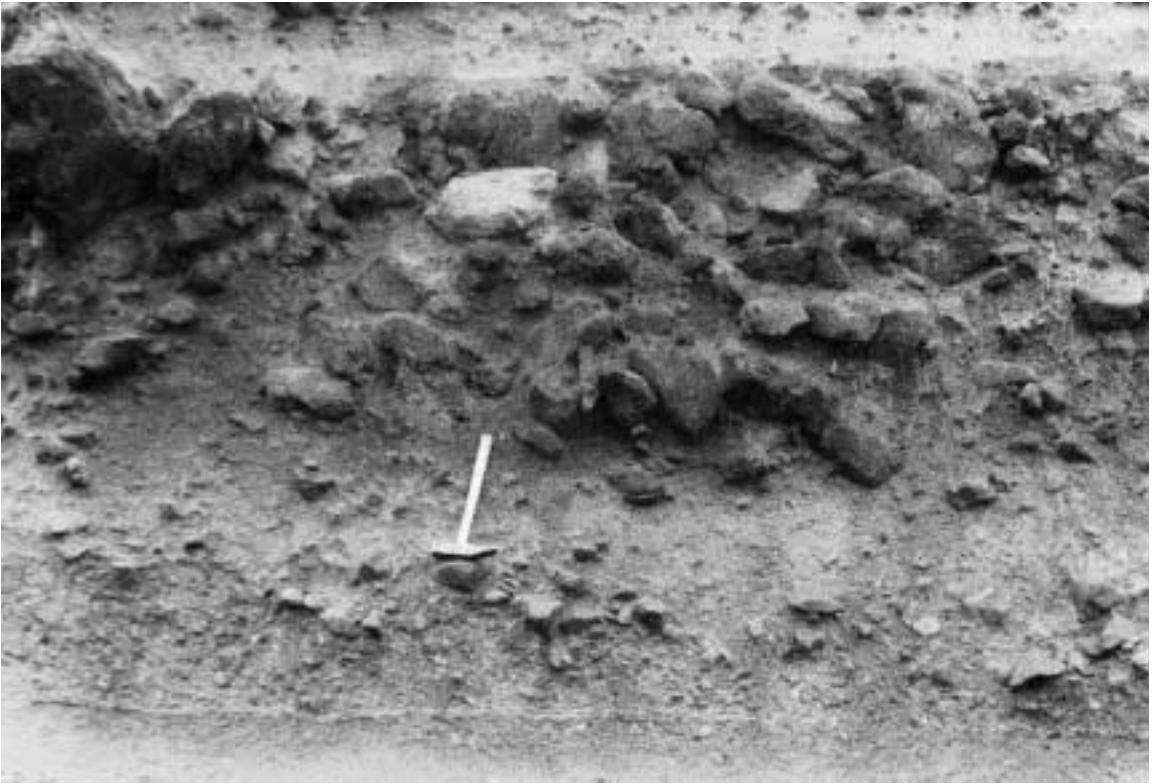


FIGURE 4I. Reverse-graded basaltic andesite scoria and ash flow deposit. The large rounded to subrounded vesicular clasts are concentrated at the top of the deposit. The deposit is 450cm thick. Location is the east coast of St. Eustatius between stratigraphic sections VII and VIII (Plate 5). 65-cm hammer provides scale.

Pyroclastic flow deposits forming the proximal portions of the Quill, are seen to be particularly coarse-grained and thick where the sea cliffs encroach upon the cone as at Kid Sadler (stratigraphic section VIII, Plate 5). Distal to the volcano in the vicinity of the airstrip, and at Pisgah Hill on the Northern Centers the deposits are much finer grained and dominated by phreatomagmatic ashes, pumiceous surges with some ignimbrites. The Quill is therefore a very different type of volcano to Saba, and has close analogies to Mt. Pelée, Martinique. Semi-vesicular andesite block and ash flow and surge deposits are not as abundant as the other types of pyroclastic deposits



FIGURE 42. Reverse-graded semi-vesicular andesite block and ash flow deposit in the seacliffs at Compagnie Baai. Such deposits are thought to have formed by Asama-style volcanic activity. 65-cm long hammer provides scale.

but are more common than was described from Saba. There are also a few fall beds composed of baked and altered lithic fragments indicating the occurrence of phreatic eruptions.

The subaerial stratigraphy of the Quill can be conveniently partitioned into seven Stratigraphic Divisions, subdivided by the presence of four major unconformities, representing long periods of dormancy, and by abrupt stratigraphic changes caused by major alternations in eruption style and composition. Correlation of the Stratigraphic Divisions around the volcano was assisted by the use of thirteen distinctive marker units, described in Table 16, and shown in Plate 5.

TABLE 16. Lithological characteristics of Marker Units used to correlate the stratigraphic sections of the Quill

Stratigraphic Division	Marker Unit	Characteristics
7 Last erupted bedset	O	Fine-grained ash flow rich in small lithic clasts. Upper part of deposit converted to soil and usually stained brown.
	N	Fine-grained scoria and ash flow entirely lacking in co-mingled clasts. Top 50 cm of the deposit is conspicuously colored yellow. Maximum clast size ~20 cm.
	M	A number of scoria and ash flow and surge deposits with a few co-mingled clasts. The lower part of the unit is characterized by an abundance of angular blocks of dense grey andesite.
	L	Ash-rich scoria and ash flow and surge deposits containing a minor amount of co-mingled clasts. Maximum size of ropy-surfaced scoriaceous clasts ~ 50 cm.
	K	A sequence of pyroclastic flow, surge and fall deposits composed of, in decreasing order of abundance, white semi-vesiculated andesite, black basaltic andesite, and co-mingled clasts.
6 Upper Mixed	J	Scoria and ash flow deposit in which both the clasts and matrix have been oxidized to a reddish pink color, which is especially pronounced in the upper part of the deposit. The deposit is non-graded to reversely-graded with a maximum clast size of 500 cm.
5 Upper Pumice	H	White pumiceous bomb and lapilli fall deposit.
	G	Sequence of white to cream colored flow, surge and fall deposits composed of andesite pumice lapilli and ash. At least one deposit contains co-mingled clasts. Some of the finer-grained beds contain accretionary lapilli.
4 Lower Mixed	F	Reversely graded scoria and ash flow and surge deposits which have been oxidized to a reddish color which is especially noticeable in the upper part of the deposit. Maximum size of juvenile clasts ~ 100 cm.
3 Phreatomagmatic	E	Distinctive sequence of surge deposits often rich in charcoal. Juvenile clasts are mainly grey semi-vesicular andesite, although some beds contain andesitic pumice.
	D	White andesitic pumice lapilli fall deposit.
	C	A sequence of rhyolitic ash flow and surge deposits showing dune structures and containing lenses rich in lithic clasts.
2 Lower Pumice	B	Fine-grained rhyolitic surge, with dune structures at base and intercalated layers of ash fall deposits containing accretionary lapilli to 2 cm.
	A	White rhyolitic lapilli fall with lithics of dense andesite.

Stratigraphic Division 1: Base Surge Division (< 40,000 years B.P.)

Stratigraphic Division 1 is composed of basaltic to andesitic base surge deposits (Moore; 1968; Waters and Fisher, 1971; Wohletz and Sheriden, 1983; Fisher and Schminke, 1984), well exposed on the shore at the Sugar Loaf, and at the base of the sea cliffs on the east coast between Concordia Baai and Bargine Bay (stratigraphic sections I and II, Plate 5). The bottom of the Division on the east coast is not seen, but it has a minimum thickness of 6 m (Fig. 43). The deposits are composed of planar-bedded surge deposits with low-angle cross-stratified climbing dunes indicating northerly-directed paleocurrent directions. At 3 km from the crater of the Quill, these dunes show amplitudes and spacings of up to 1 m and 10 m respectively (Fig. 44). The deposits can be divided into several sets, each presumably representing a separate eruptive sequence. The sets are sometimes separated by a mantling ash fall deposit probably representing fall-out from the trailing ash cloud accompanying the surges. The deposits are cream colored with abundant juvenile clasts of chilled dark basalt, and lithic clasts of white limestone and dark hornblende andesite. Ballistic bombs up to 20 cm in diameter and their impact craters, with depths of up to 25 cm, are extremely common (Figs. 45A and B). Unlike similar bombs described from the top of the Sugar Loaf succession, most of these did not shatter on impact. These deposits are unusual in the Caribbean because of their thickness, and the presence of coarse-grained lithic clasts 20 cm in diameter at distances of 3 km from the volcano, suggesting they were formed by extremely powerful hydro-volcanic explosions resulting from a basic magma encountering shallow sea water. Interbedded with these base surge deposits are occasional beds of phreatomagmatic ashes containing accretionary lapilli and entombed gas cavities (Figs. 46A and B).

Stratigraphic Division 2: Lower Pumice Division (~ 23,000 years B.P.)

Stratigraphic Division 2 is composed of pyroclastic deposits of Plinian-style activity that range in composition from andesite to rhyolite. The deposits are best exposed in stratigraphic sections I and II on the north-east coast and in stratigraphic sections XVI, XVII, and XVIII in the lower parts of the sea cliffs below the town of Oranjestad (Plate 5). The succession comprises alternations of ignimbrites, up to 650 cm thick (pumice

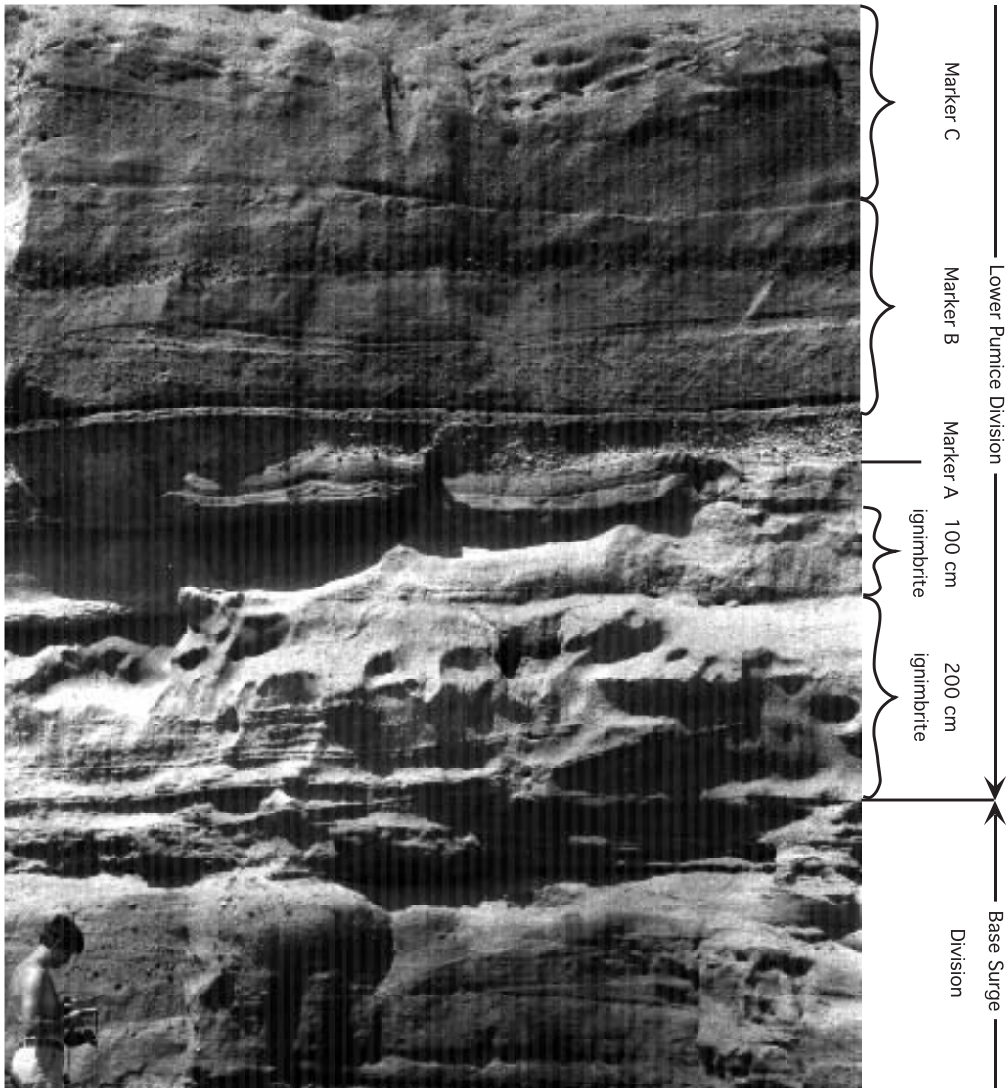


FIGURE 43. Seacliff at Bargine Bay showing the lower part of stratigraphic section II. The lower 4 meters show a series of base surge layers, the uppermost of which has been dated at $22,240 \pm 140$ years B.P. from a carbonized log obtained in the cliff immediately below marked bedding plane. Above this are two fine-grained ignimbrites both with marked paleosols, which are overlain by a thin surge unit, followed by a rhyolitic lapilli fall layer — Marker Unit A. Above this are surge and flow layers of Marker Units B and C.

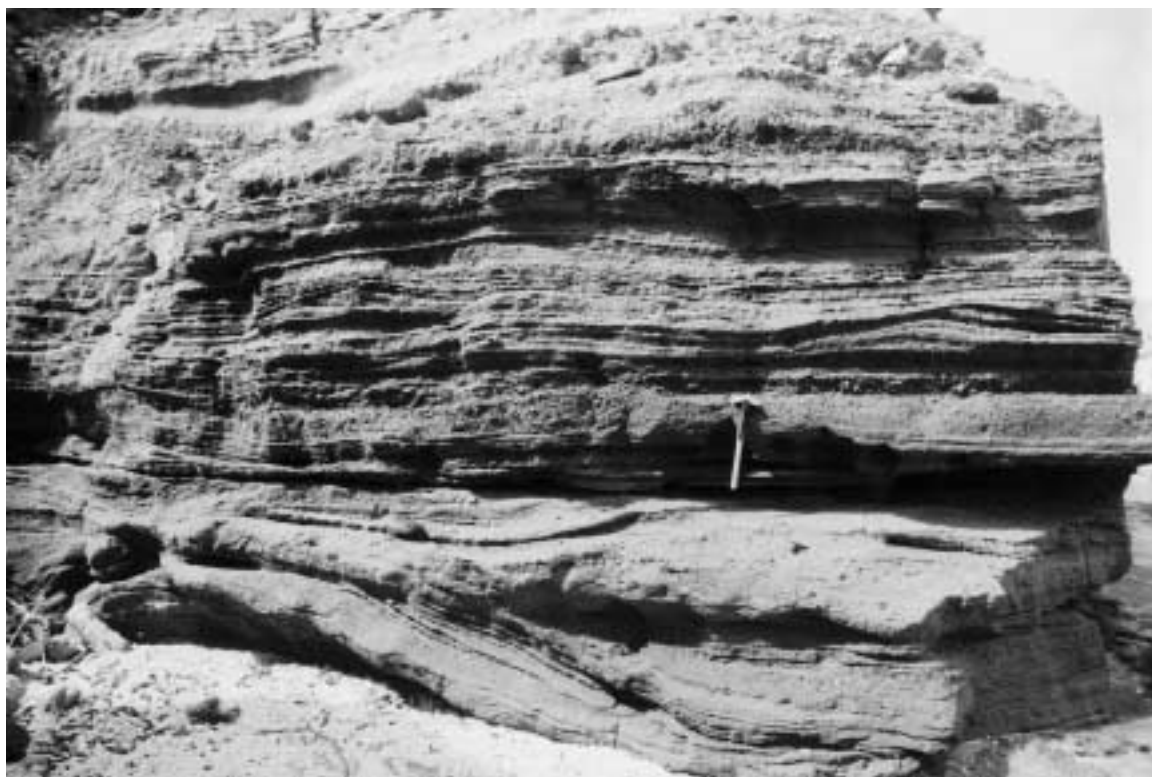


FIGURE 44. Base surge deposits of Stratigraphic Division 1 in seaciffs between Bargine Bay and Schildpadden Bay, northeast St. Eustatius. 43 cm long shovel provides scale.

and ash flow and ash hurricane deposits), pumiceous surge deposits, and lapilli and ash fall beds. Two features suggest a hydrovolcanic component in the mechanism of formation of these deposits. First, the ignimbrites are bounded above and below by thick surge units with major sweeping dune structures of amplitude greater than 1m, similar to the base surge deposits of Division 1. These dune structures are such that the ignimbrite itself is of very variable thickness along its length. Second, is the presence of large white colored accretionary lapilli up to 2 cm diameter which crowd ash layers between flow units of the ignimbrite. These deposits indicate that, whereas Division 1 records shallow-water phreatomagmatic explosions of basic magma, Division 2 represents a rhyolite eruption of Plinian style with a strong hydrovolcanic component suggesting that the vent remained

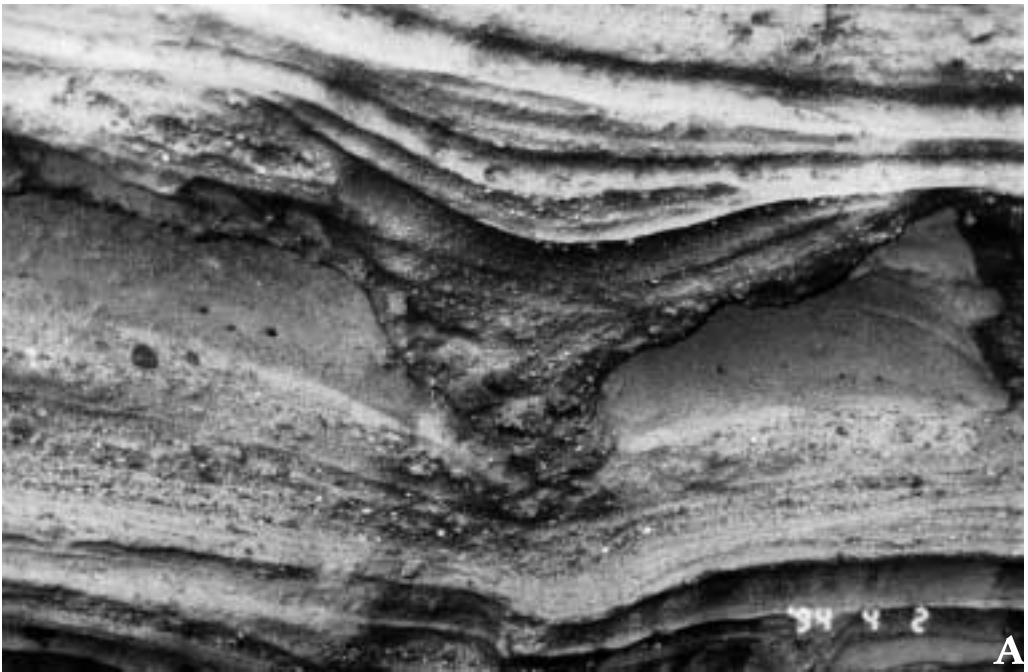


FIGURE 45. Bomb impact structures in Base Surge Division 1 in same location as Figure 44.

- A. Cross-section of bomb impact showing infill with lenses of surge deposit.
- B. Bomb impact structure with thick-skinned, chilled, basaltic bomb in place.

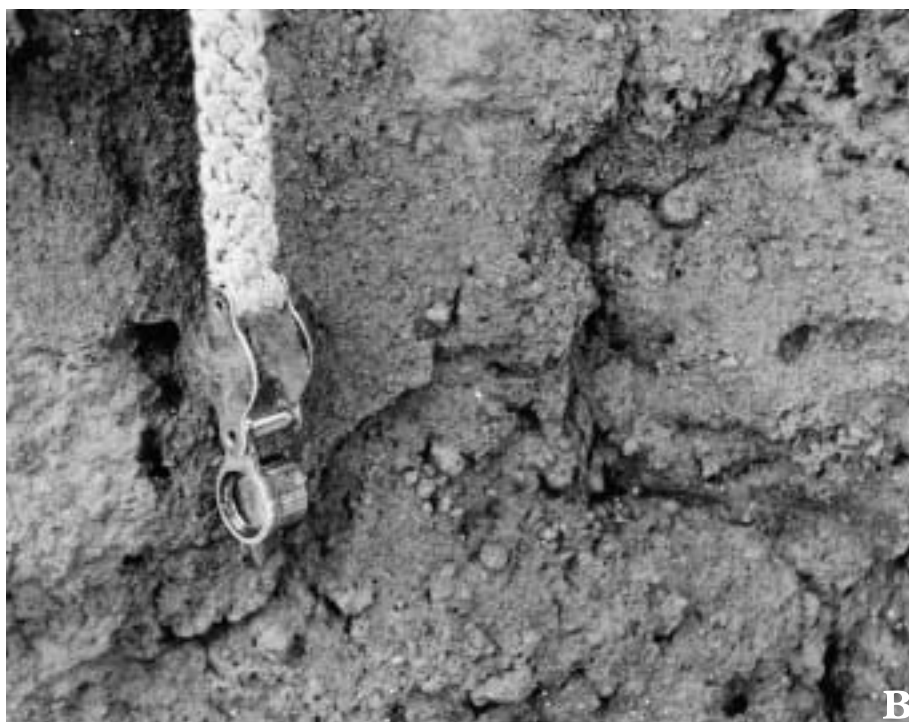


FIGURE 46A. Brown phreatomagmatic ashes with accretionary lapilli in Base Surge Division 1, sea cliffs at Schildpadden Baai.

B. Brown phreatomagmatic ashes rich in entombed gas cavities with some accretionary lapilli. Location the same as Figure 46A.

partially flooded. Deposits of this Division are very distinct, because of their low position in the cliffs and the bright white color of their components. Within the Division there are unconformities and paleosols which divide the deposits into a number of subunits. For example at Concordia Baai (stratigraphic section I, Plate 5) and at Bargine Bay (stratigraphic section II, Plate 5) the deposits can be grouped into the products of at least five eruptions. Marker Unit A is prominent within this division as a fall layer of coarse white rhyolitic pumice lapilli (Fig. 43).

These subaerial deposits, together with the Sugar Loaf submarine deposits, are the only rhyolite pyroclastic deposits described from the Lesser Antilles. The only other known occurrences of rhyolite in the active arc of the Lesser Antilles are the two domes of Les Mamelles of Pliocene age on Guadeloupe, and the Miocene Bise lava flow/plug on St. Lucia.

Stratigraphic Division 2 is also very well exposed on the west coast of St. Eustatius in the base of the sea cliffs at Oranjestad. Three stratigraphic sections have been measured in the cliffs along a distance of 800 meters. Stratigraphic section XVI (Plate 5) was measured immediately behind the petrol station at the harbor entrance; stratigraphic section XVII (Plate 5) was measured along the sides of the rain water cistern adjacent to the Old Gin House hotel, and stratigraphic section XVIII (Plate 5) was measured behind a water well inland from the public bathing beach containing the foundations of old ruined warehouses. The lowest layer exposed is the Plinian fall deposit, Marker Unit A, the base of which was not seen. The stratigraphy closely corresponds to that observed on the northeast coast at Bargine Bay (stratigraphic section II, Plate 5), but the fine-grained pumice and ash flow (ignimbrite) is thicker, and there is a prominent fall deposit of very fine-grained ash with accretionary lapilli. Above the products of this rhyolitic eruption containing Marker Unit A, and separated by an erosion surface, are other rhyolitic deposits representing a separate eruption. At Oranjestad a stratified rhyolitic pumice fall deposit overlain by a thin, fine-grained ash hurricane deposit, is correlated with a thin rhyolitic pumice fall at Bargine Bay (stratigraphic section II, Plate 5).

Stratigraphic Division 2 is bounded both above and below by major unconformities (Plate 5) and has been radiocarbon dated at $22,240 \pm 140$ years B.P. The latter was obtained from a flat lying carbonized tree within a 180 cm thick ignimbrite topped by a paleosol (stratigraphic section II,

Plate 5) at Bargine Bay. The lower unconformity is best seen in the sea cliffs between Schildpadden Baai and Bargine Bay on the northeast coast, where a very weakly-lithified unit of white rhyolite pumice overlaps progressively the older eroded topography.

Stratigraphic Division 3: Phreatomagmatic Ash Division (~ 8,000 years B.P.)
 Stratigraphic Division 3 is composed of phreatomagmatic ash deposits with a compositional range of andesite to dacite. The Division attains a maximum thickness of over 6 m in stratigraphic section XVII (Plate 5) in the cliffs below Oranjestad. In stratigraphic sections I, II and XVI the base of the unit is represented by a single white andesitic pumice fall deposit. In all other sections, the basal unit is composed of khaki-colored phreatomagmatic ashes with interstratified thin layers of dense andesite and semi-vesicular andesite surges. The phreatomagmatic ash layers of Division 3 are internally thinly bedded on a scale of centimeters, and contain layers crowded with accretionary lapilli up to 8 mm in diameter, which alternate with layers rich in entombed gas cavities up to 4 mm in diameter. In the Lesser Antilles such phreatomagmatic ashes are typically weakly lithified and thus resistant to erosion so that they stand out as resistant beds in cliffs of otherwise weakly to unconsolidated pyroclastic deposits. This lithification probably results from the wet nature of the ash on deposition which encourages devitrification. The thin surge units which show small dune structures of amplitude of 2 cm and wave length of 60 cm in some localities, for example stratigraphic section XXX (Plate 5), abruptly thicken within the phreatomagmatic layer. The presence of these widespread phreatomagmatic ashes which are intercalated with semi-vesicular andesite ashes, suggests a major hydrovolcanic influence in the volcanism. In a low-lying, island-arc volcano dominated by volcanoclastic deposits, the structure is likely to be waterlogged, leading to wet-vent hydrovolcanic activity.

This Division is a prominent marker horizon which has been identified in seven of the stratigraphic sections (stratigraphic sections, I, II, XVI, XVII, XVIII, XXX, and XXXI, Plate 5) in all parts of the island. Its identity is readily confirmed by the presence of one or more thin andesite surge beds usually between 10 and 20 cm in thickness which are characterized by an abundance of carbonized twigs which yield radiocarbon ages of between 7,810 and 8,380 years B.P. (Table 14A). This distinctive marker unit has

also been radiocarbon dated at 7,500 years B.P. by van der Valk (1992) who regarded it as the most recent volcanic activity of the Quill. This conclusion is at considerable variance with this work, where Stratigraphic Divisions 4, 5, 6, and 7 are shown to overlie Division 3. The stratigraphic interpretations of van der Valk (1992) are further discussed during a review of archaeological data.

Stratigraphic Division 4: Lower Mixed Division (undated <7,500 years B.P.)

Stratigraphic Division 4 is composed of thick sequences of coarse deposits resulting from Pelean-, St. Vincent-, and Asama-style eruptive activities best seen in the sea cliffs of southeast St. Eustatius at Compagnie Bay (stratigraphic section V, Plate 5), and Corre Corre Bay (stratigraphic section VII, Plate 5). The compositional range is basaltic andesite to andesite. In more distal areas such as Oranjestad (stratigraphic sections XIII, XVI, XVII, and XVIII, Plate 5) coarse pyroclastic deposits are less common, and surge deposits and khaki-colored phreatomagmatic ashes are the norm. No direct dating of this Division was possible, as carbonized wood could not be found.

Prominent amongst the coarse deposits are two distinct and well-exposed semi-vesicular andesite block and ash flow deposits, exposed at beach level at Compagnie Bay (stratigraphic section V, Plate 5, Fig. 47A), at Corre Corre Bay (stratigraphic section VII, Plate 5), and in the sea cliff section at Bargine Bay (stratigraphic section II, Plate 5, Fig. 47B). These two deposits provide some of the best examples of the products of Asama-style activity in the Lesser Antilles. The lower deposit, at Compagnie Bay, is up to 200 cm thick, reversely graded, and composed almost exclusively of semi-vesicular andesite clasts (Fig. 47A). In contrast at Bargine Bay, reversely graded semi-vesicular andesite clasts are confined to the upper third of the deposit, whereas normally graded dense andesite lithic clasts are concentrated at its base (Fig. 47B). Coarse blocks of semi-vesicular andesite, up to 110 cm in diameter, are also locally concentrated at the top of this deposit (Fig. 47C), where they probably mark levées of pyroclastic flow channels. This type of semi-vesicular andesite block and ash flow deposit with an abundance of dense andesite lithics is similar to the transitional type described by Roobol and Smith (1998) from the Soufriere Hills volcano, Montserrat.



FIGURE 47A. Two distinct reversed-graded semi-vesicular andesite block and ash flow deposits. The upper deposit is richer in blocks of dense andesite than the lower. The dense blocks represent dome material (cognate lithics) detached by the explosive ejection of the semi-vesicular andesite. Location is the seacliffs at Compagnie Baai (stratigraphic section V, Plate 5). 65 cm-long hammer for scale.

B. The same two distinctive semi-vesicular andesite block and ash flow deposits as shown in Figure 47A, but here outcropping at Bargine Bay (stratigraphic section II, Plate 5). See text for explanation.

C. Coarse blocks of semi-vesicular andesite (up to 110 cm in diameter) at top of the lower of the two distinctive deposits shown in Figure 47B.

Stratigraphic Division 5: Upper Pumice Division (undated < 7,500 years B.P.)

Stratigraphic Division 5 is composed of andesitic pyroclastic deposits resulting from Plinian-style activity. These are widespread deposits of cream-colored ignimbrite (pumice and ash flow and ash hurricane), pumiceous surge, and lapilli and ash fall layers. Division 5 comprises some of the youngest pyroclastic deposits resulting from Plinian-style activity in the Lesser Antilles. Unfortunately no carbonized wood has yet been found for direct dating. The deposits of Division 5 have been identified in sixteen of the stratigraphic sections, and are undoubtedly present in the northernmost stratigraphic sections of the island, where poor quality charcoal (powder) has prevented the dating of the many similar thin, fine ash layers that occur there (Harkness et al., 1994). The top surface of this division is a prominent and widespread unconformity on which a paleosol is preserved in some sections.

Stratigraphic Division 6: Upper Mixed Division (undated < 7,500 years B.P.)

Stratigraphic Division 6 is composed of deposits resulting from St. Vincent- and Pelean-style activity with a compositional range from basaltic andesite to andesite. The deposits are well exposed in the sea cliffs nearest to the Quill (stratigraphic sections III, II, XVI, and Plate 5). In the upper part of this Division is a distinct crimson-colored coarse scoria and ash flow deposit, identified as Marker Unit J in stratigraphic sections III, V, VII, XI, XII, XIII, XIV, and XV (Plate 5). In distal areas (stratigraphic sections XVII, XVIII, Plate 5) coarse deposits are rarer and surge, fall and phreatomagmatic ash layers are more common. In most sections, the Division is overlain by a widespread unconformity, which forms a prominent step in the sea cliffs where the weakly lithified deposits of Division 6 are overlain by the unconsolidated deposits of Division 7.

Stratigraphic Division 7: The Most Recent Erupted Bedset of the Quill (~1,600 years B.P.)

Stratigraphic Division 7 is particularly well preserved and comprises five distinct lithologic units believed to have resulted from the most recent eruption of the Quill. The compositional range is from basalt to andesite. The distribution of the deposits indicates that this was a major eruption throughout which the notch in the west rim of the crater directed the

pyroclastic flows westwards. Most of the flanks of the Quill were covered by these pyroclastic flows which extend as far north as the former sea cliffs that bound the Northern Centers. The five lithologic units of the most recent erupted bedset have been made the object of a detailed study that will be described later.

DISTAL FACIES PYROCLASTIC DEPOSITS OF THE QUILL PRESERVED ON TOP OF THE NORTHERN CENTERS

A succession of fine-grained ash deposits representing the most distal products of the Quill are preserved on an area of flat ground at elevations around 150 m above sea level on the southern flanks of the Berjge center in an area known as Pisgah Hill. It has not proven possible to correlate any of these ash layers with the stratigraphy of the Quill so they are here described separately. The ashes are exposed in road cuts and excavations that began in 1979 with the construction of an oil storage facility.

Six stratigraphic sections of Quill deposits have been described from this area and three are shown in Plate 5, as stratigraphic sections XXXI-II, XXXIV, XXXV. The deposits reach a maximum thickness of over 4 m (Fig. 48). The layers are thin, and mainly comprise phreatomagmatic ash falls, with or without accretionary lapilli. There are also two types of ash flow deposits — one is a structureless thin pumice and ash flow, and the other a structured ash hurricane. Pumiceous surges are rare, as are pumiceous lapilli falls. There is also a single occurrence of a basaltic lapilli fall deposit, which probably represents St. Vincent-style activity. The Pisgah Hill deposits are thus dominated by Plinian or phreatoplinian activity.

The ash-rich pyroclastic flow deposits, which now occur at heights of up to 290 m above sea level, have traveled distances of 4 to 5 km from the crater of the Quill and surmounted the hills of the Northern Centers. The flow deposits are a condensed succession of thin beds which are rich in charcoal. Unfortunately, this has the form of black powder originating from the low temperature charring of grasses and scrub. There is an absence of good quality charcoal which is most suitable for radiocarbon dating (Harkness et al., 1994). In addition to the remains of carbonized



FIGURE 48. The most distal measured deposits from the Quill at the oil storage facilities on Pisgah Hill (stratigraphic section XXX, Plate 5). The deposits are mainly pyroclastic falls with some interbedded pumiceous flows and surges especially near the base where they overlie a weathered lava flow from the Northern Centers (extreme right).

grasses, the thin flow and surge deposits also contain large gastropod shells up to 20 cm in diameter with the remains of large hermit crabs inside. Such shells containing hermit crabs are commonly found around the island today. Their presence in the ashes at Pisgah Hill indicates that pyroclastic flows and surges from the Quill swept across the island to surmount the Northern Centers and carried along with them much of the animal population as bioclasts in their high-temperature, high-speed passage across the island.

Although the Northern Centers have been overwhelmed by hot pyroclastic flows and surges, the total number of layers in any one section on Pisgah Hill is only around thirteen, and the presence of paleosols suggests that these can be grouped into a smaller number of eruptions. An important conclusion for future geohazard planning on this small island is that the Northern Centers are at risk mainly from pumiceous Plinian-style volcanic activity but they are very infrequently overwhelmed.

GRAIN SIZE CHARACTERISTICS OF THE YOUNGER SUBAERIAL
PYROCLASTIC DEPOSITS OF THE QUILL

Representative samples of the pyroclastic deposits of the Quill were sieved following the methods of Walker (1971) at one phi intervals down to 4 ϕ (0.063 mm). Some selected samples were sieved at 0.5 phi intervals in the <0 ϕ (<1 mm) sizes. Because many of the samples contained >50% ash finer than 4 ϕ (0.063 mm), analyses of these selected samples were completed using a particle counter. From cumulative curves drawn on probability paper distribution parameters of median diameter (Md ϕ =50), and graphical standard deviation ($\sigma\phi$ =[ϕ_{84} - ϕ_{16}]/2)) were calculated (Inman, 1952).

Pelelean-style activity

Block and ash flow deposits have been described from many of the stratigraphic sections on St. Eustatius. All deposits are poorly sorted ($\sigma\phi$ >2.0), and composed essentially of coarse blocks in an ash matrix (Fig. 49A). Depletion in the finest ash/dust fraction (<4 ϕ ; <0.063 mm) is also apparent in the fine-grained ash-rich basal units and in the lateral surge facies (Fig. 49B). These missing fine fractions are thought to produce laminated ash falls such as those described from the 1902-03 deposits of Mt. Pelée (Smith and Roobol, 1990, their Figure 30). Near-vent deposits tend to be much coarser-grained than more distal ones, with the former containing blocks up to 6 m in diameter. As with other pyroclastic deposits, block and ash flows are composed of variable amounts of juvenile and lithic clasts, and crystals (Fig. 50). The juvenile material can be further subdivided into dense angular juvenile clasts representing the disrupted solidified carapace of the dome, and semi-vesicular and vesicular clasts representing the gas-rich interior of the dome or new magma intruded into the dome, as suggested by the model of Sparks (1997). Although some of the proximal block and ash flow deposits are composed mainly of dense angular blocks and represent simple gravitational collapse, most of the block and ash flow deposits on St. Eustatius contain significant proportions of vesicular juvenile clasts, suggesting that they were generated mainly by explosive dome collapse. Such an origin is in contrast to that proposed for the block and ash flows on Saba which are poor in vesicular clasts. Most

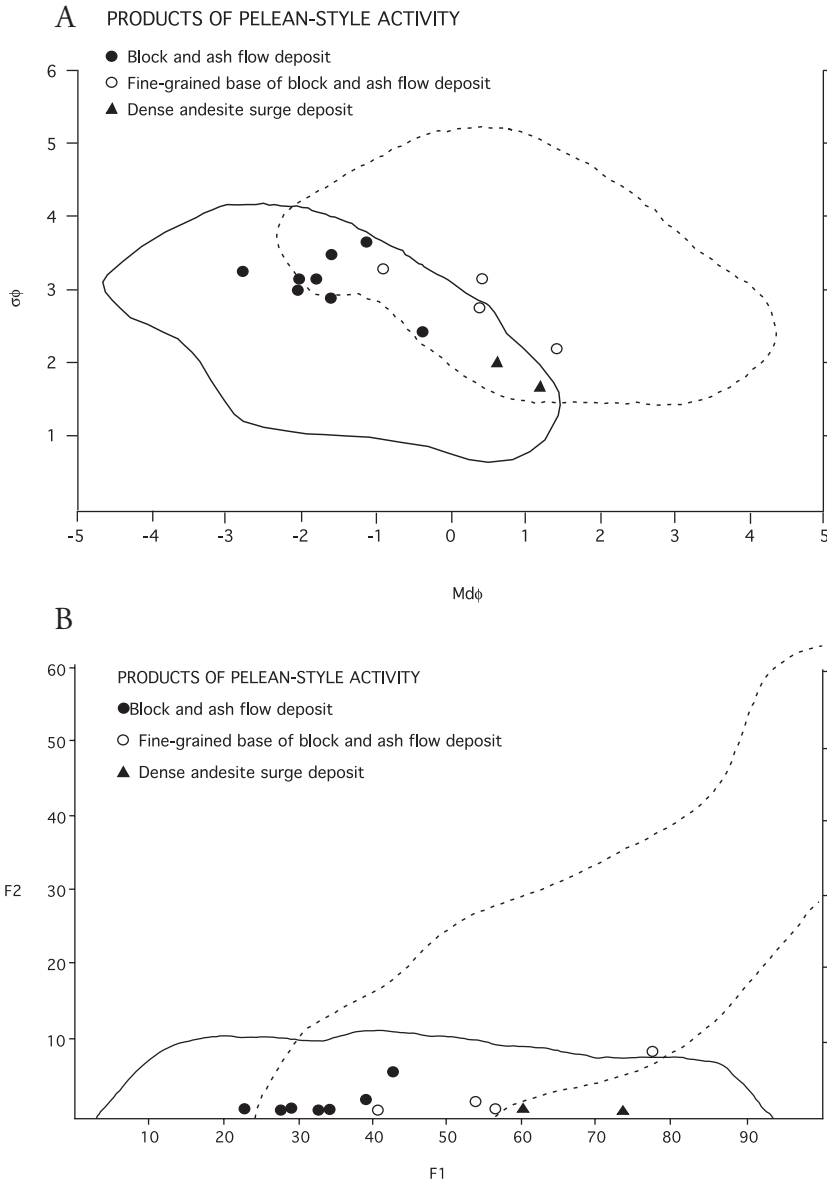


FIGURE 49A. $M\delta\phi$ - $\sigma\phi$ plot for deposits from Pelean-style activity from the Quill. Dashed line is 1% contour for pyroclastic flow field; solid line = 1% contour for fines-depleted pyroclastic flow field (after Walker, 1971, 1983). All plots are for bulk samples.

B. The same data as 49A plotted on F_1 (wt% finer than 1mm) versus F_2 (wt% finer than 1/16mm) diagram. Dashed and solid lines are as in Figure 49A.

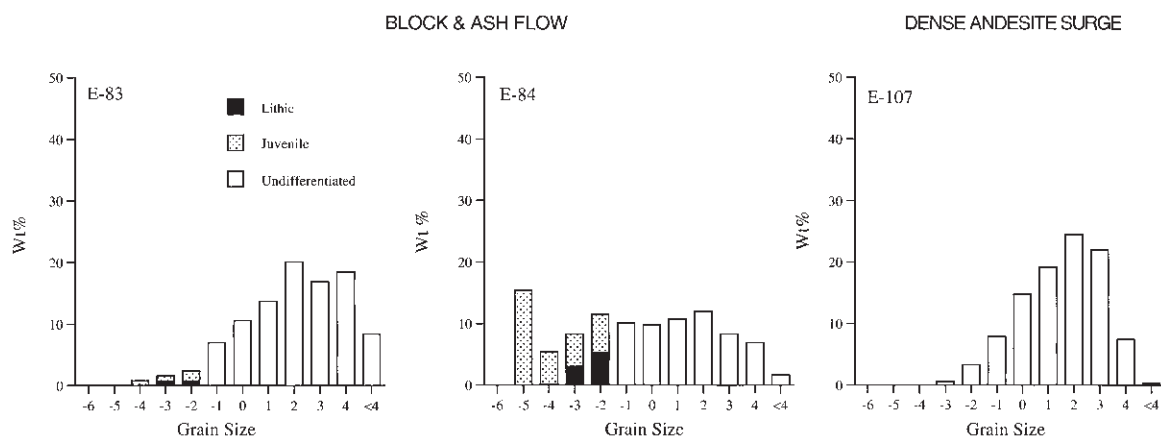


FIGURE 50. Size distribution histograms of selected deposits from Pelean-style eruptions. Grain size classes subdivided on their weight proportions of juvenile magmatic material, and lithics.

block and ash flow deposits on St. Eustatius tend to have a relatively fine-grained basal layer, with the coarser fragments in the main part of the deposit being usually reversely graded. One deposit at Compagnie Baai (stratigraphic section V. Plate 5) shows a relatively fine-grained base passing up into a relatively coarse-grained central zone overlain by a more ash-rich zone and finally by a clast-rich top. In this deposit, vesicular material (representing the juvenile component) is concentrated at the base and the top, whereas angular dense andesite clasts (representing the lithic component) are in maximum abundance near the center of the deposit (Fig. 51). This distribution of clasts can be explained if the deposit represents two pulses of reversely-graded pyroclastic flows. The first pulse, now represented by the lower part of the deposit, contains material produced by the explosive disruption of the degassed outer carapace of a dome, whereas the second pulse, represented by the upper part of the deposit, is composed of more vesicular material from the interior of the dome.

Unlike the block and ash flow deposits, which are usually polymodal, the dense andesite surge deposits are normally unimodal with a major peak around 2ϕ (0.250 mm) (Fig. 50). Surge deposits are also fines-depleted, suggesting that a significant loss of material occurred during flowage, as is

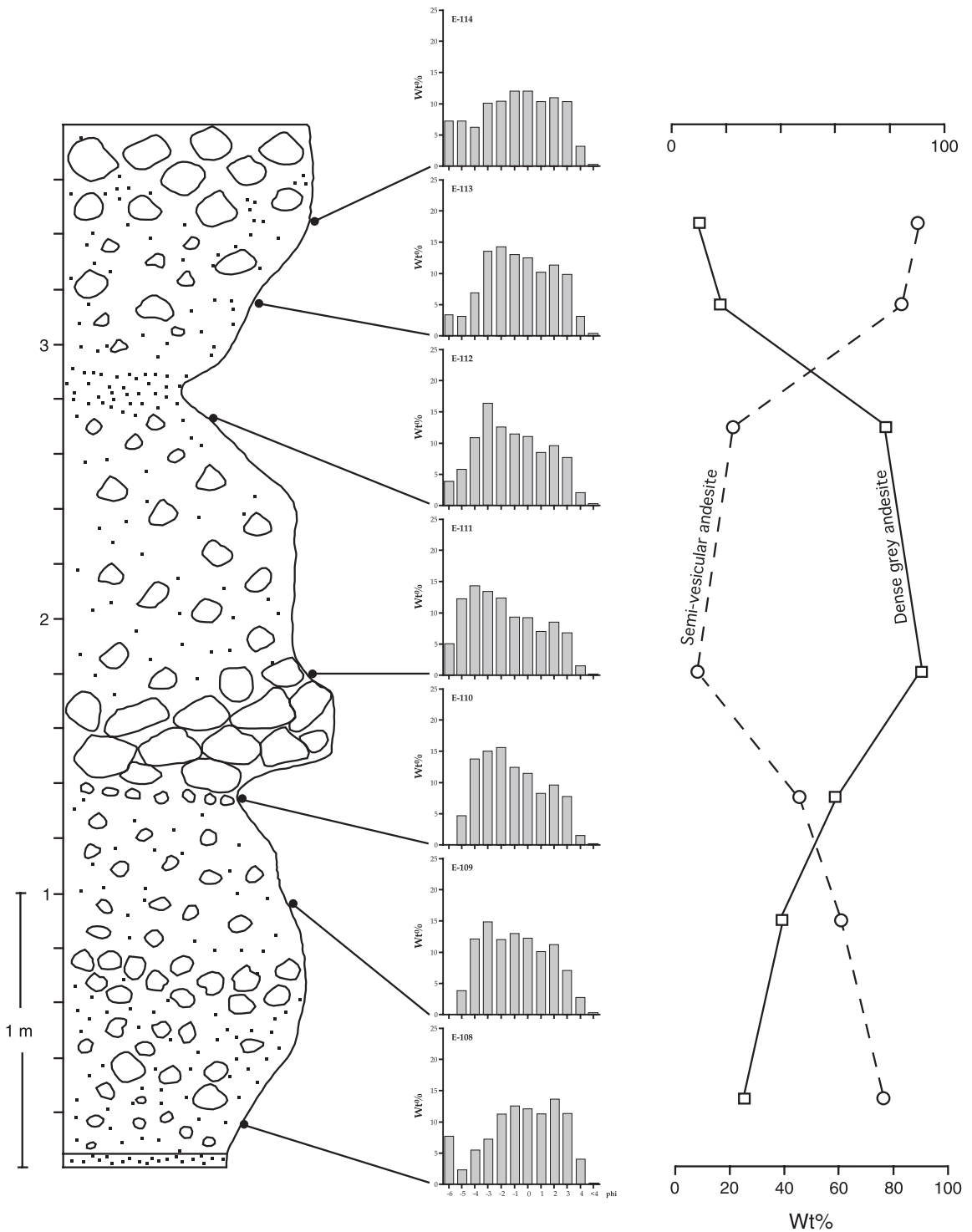


FIGURE 51. Section through a block and ash flow at Compagnie Baai, (stratigraphic section V, Plate 5), showing variation in overall grain size, and content of > 16 mm juvenile magmatic clasts (circles), and cognate lithic clasts (squares) through the deposit.

the case with surges from other Lesser Antillean volcanoes (Roobol et al., 1987; Smith and Roobol, 1990). No fall deposits associated with Pelean-style activity have been described from St. Eustatius, probably because the small size of the island results in the very fine-grained material elutriated from the pyroclastic flows and surges being deposited out to sea.

St. Vincent-style activity

St. Vincent-style activity on St. Eustatius has produced scoria and ash flow (dominated by scoria), scoriaceous ash flow (dominated by ash), scoriaceous surge and scoriaceous lapilli fall deposits. Scoria and ash flow deposits are all polymodal and show a wide range in average grain size (Fig. 52A). Although all are fine ash/dust-depleted, the amount of depletion is usually less than that shown by block and ash flow deposits (Fig. 52B). In contrast, the scoriaceous ash flow and surge deposits are rich in fine ash and dust (Fig. 52B). The relatively large amount of fine material in these deposits suggests that the St. Vincent-style flow and surge deposits on St. Eustatius were either not highly expanded, or that an excessive amount of fine material may have been produced by the interaction of water with the rising magma. The latter alternative is supported by the fact that many of the larger clasts are thickly coated with fine ash, suggesting that the flows and surges were wet when deposited (Fisher and Schminke, 1984). Fall deposits associated with St. Vincent-style activity are not as common in the stratigraphic record as flows and surges, and only one deposit was studied. This is composed of coarse-grained scoriaceous lapilli with a median grain size of -4.6ϕ . The apparent lack of fall deposits associated with St. Vincent-style activity suggests the eruption columns were probably not very high and collapsed quickly to produce flow rather than fall deposits.

For all types of deposits associated with St. Vincent-style activity, juvenile vesicular clasts are usually the dominant component in the coarser size fractions, with accessory lithic clasts being either absent or present only in subordinate amounts (Fig. 53). Small amounts of crystals are occasionally found in the 1 and 2 mm size fractions. These probably represent xenocrysts from cumulate plutonic blocks, as was also proposed for similar occurrences on Mt. Pelée (Smith and Roobol, 1990).

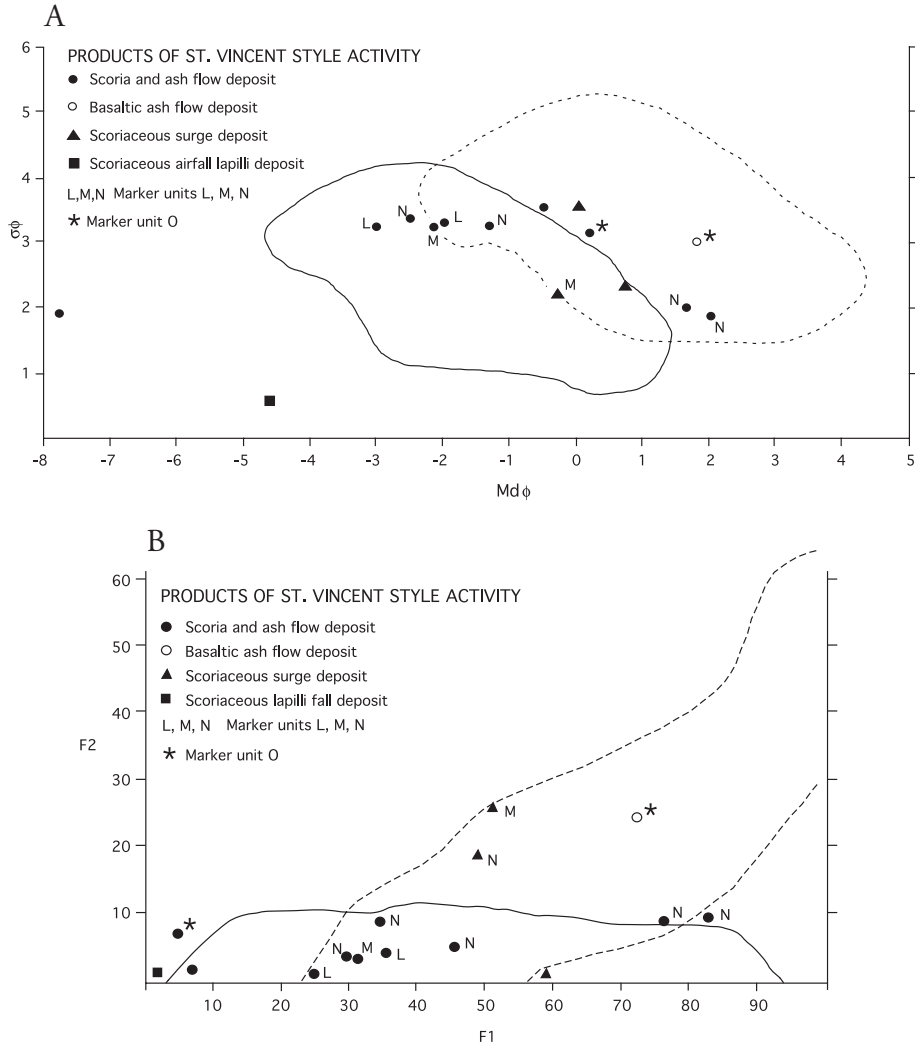


FIGURE 52A. $Md\phi$ - $\sigma\phi$ plot for deposits from St. Vincent-style activity. Dashed line is 1% contour for pyroclastic flow field; solid line is 1% contour for fines-depleted pyroclastic flow field (after Walker, 1971, 1983). All plots are for bulk samples. Marker Units of the last erupted bedset are identified.

B. The same data as 52A plotted on F_1 (wt% finer than 1mm) versus F_2 (wt% finer than 1/16mm) diagram. Dashed and sold lines are as in Figure 52A.

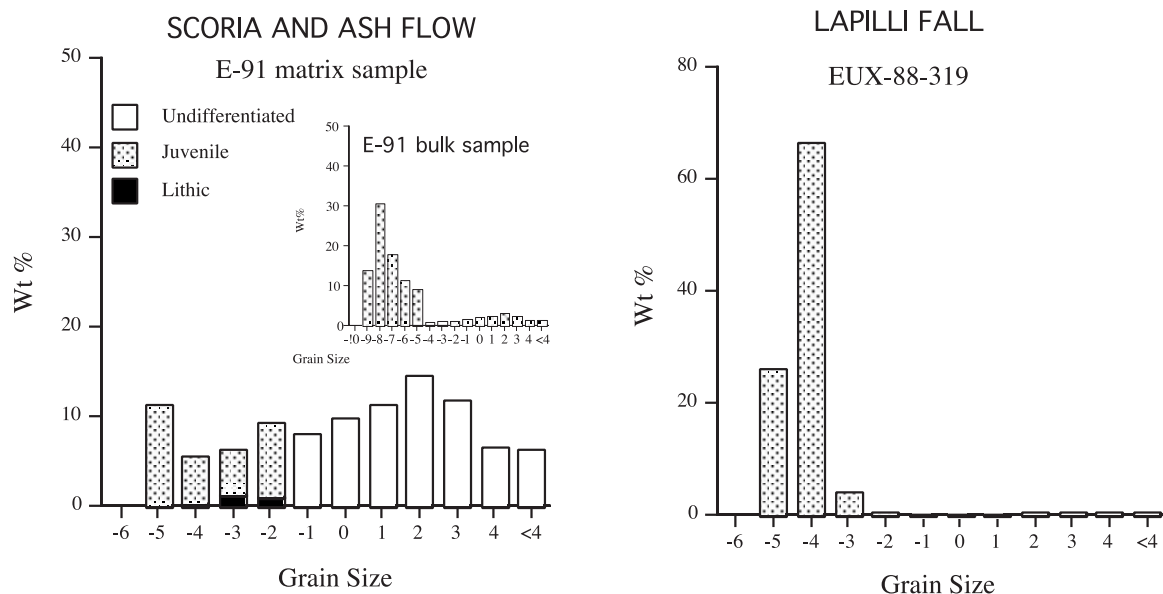


FIGURE 53. Size distribution histograms of pyroclastic samples of selected deposits from St. Vincent-style activity. Grain size classes are subdivided on their weight proportions of juvenile magmatic material, and lithics.

Plinian-style activity

Deposits from Plinian-style eruptions include ignimbrites (pumice and ash flows and ash hurricanes), pumiceous surges, and pumiceous lapilli and ash falls. Unlike the pyroclastic flows described previously, the ignimbrites are all rich in fine ash and dust, representing finely pulverized magma (Figs. 54A and B), with in some cases the <4 ϕ size fraction making up nearly 40% of the deposit. This richness in fines is similar to that observed in near-vent ignimbrites (ash hurricane deposits) from Mt. Pelée, Martinique (Smith and Roobol, 1990). At Mt. Pelée, ash hurricane deposits within 5 km of the vent are rich in fines, whereas the more distal deposits are poor in fines. This decrease in fines with distance from the vent is thought to have been caused by an increase in gas flow rates as the flows became more expanded. As the deposits on St. Eustatius are all within 5 km of the vent, their richness in fines could be explained in a similar manner. In addition, as many of the ignimbrites contain accretionary

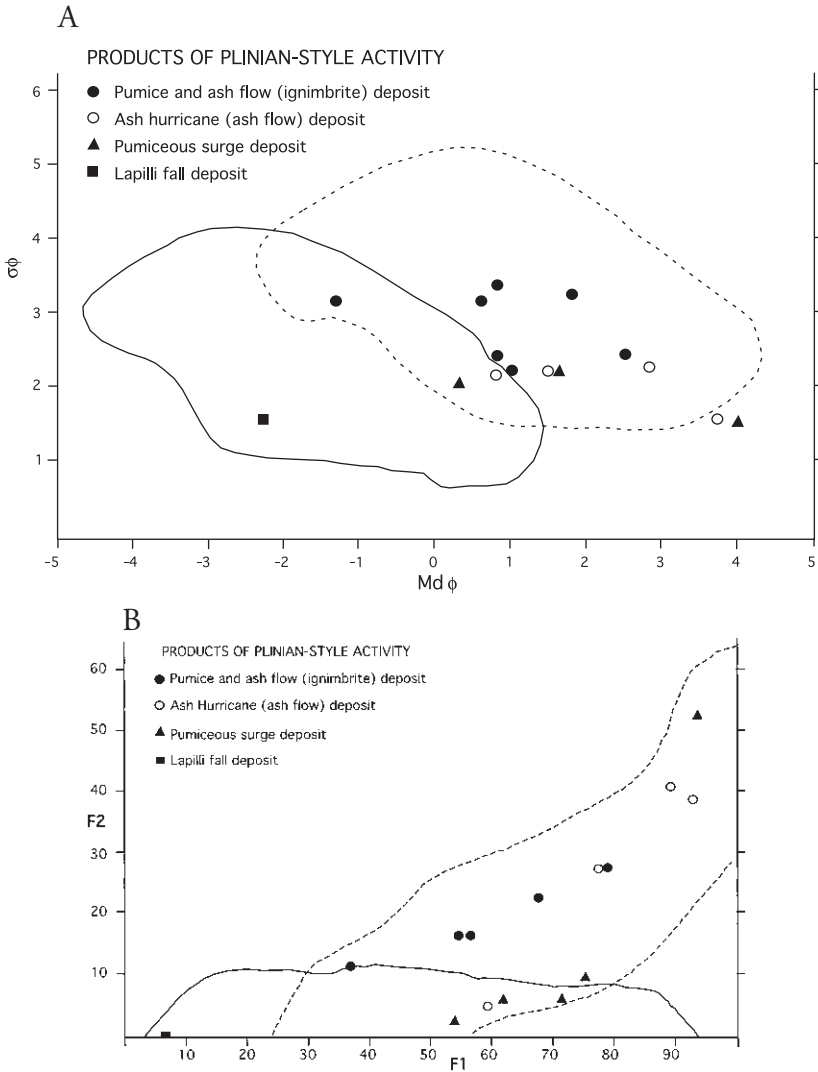


FIGURE 54A. $Md\phi$ - $\sigma\phi$ plot for deposits from Plinian-style activity. Dashed line is 1% contour for pyroclastic flow field; solid line is 1% contour for fines-depleted pyroclastic flow field (after Walker, 1971, 1983). All plots are for bulk samples.

B. The same data as 54A plotted on F_1 (wt% finer than 1mm) versus F_2 (wt% finer than 1/16mm) diagram. Dashed and solid lines are as in Figure 54A.

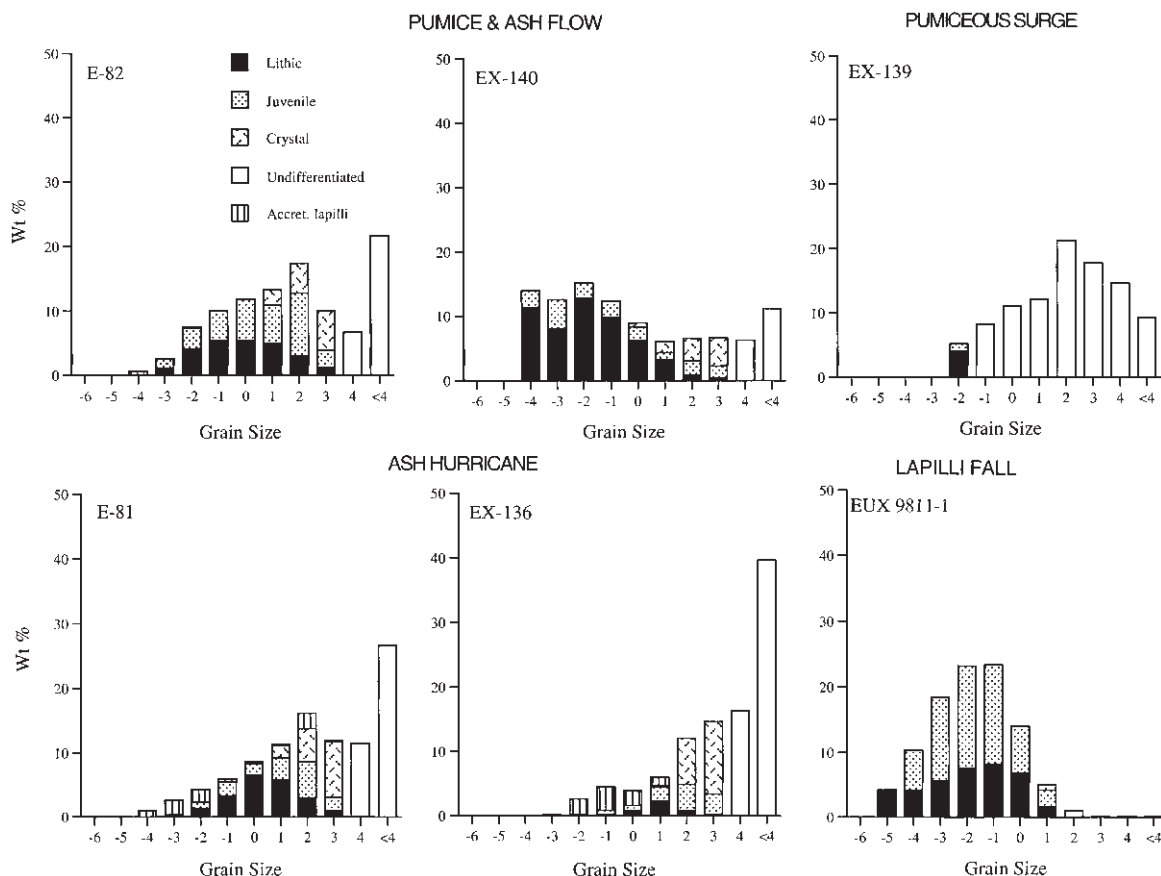


FIGURE 55. Size distribution histograms of pyroclastic samples of selected deposits from Plinian-style activity. Grain size classes are subdivided on their weight proportions of juvenile magmatic material, lithics and juvenile crystals

lapilli (Fig. 55) external water was also probably involved in their generation. The richness in fine ash characteristic of these deposits could also therefore be the consequence of reaction between vesiculating magma and an external water source. In contrast to the flows, the pumiceous surge deposits are, in general, poorer in fines, as would be expected from their more expanded nature. Plinian fall deposits are distinctly unimodal with the lapilli deposits being relatively coarse-grained (median diameter of around -2ϕ ; 4mm), and similar to other lapilli fall deposits on St. Eustatius. Associated ash fall deposits have their main peak at 2.5ϕ

(0.188 mm), with another peak in the $<4 \phi$ (<0.063 mm) size fraction, and often contain accretionary lapilli, gas cavities or are weakly lithified suggesting they were formed by phreatoplinian activity.

Some of the best sections through the products of Plinian activity in the Lesser Antilles are the pumiceous rhyolite deposits, which form part of Stratigraphic Division 2. These deposits are sufficiently unique to justify a more detailed description. The best exposures are at Bargine Bay (stratigraphic section II, Plate 5) and Oranjestad (stratigraphic section XVIII, Plate 5), and include a wide variety of different types of deposits, one of which is a coarse, white, lithic-rich pumice fall layer, Marker Unit A. The various pyroclastic units of this rhyolitic eruption, which are all characterized by a white flour-like appearance, are shown in Plate 5 and in detail in Figure 56.

Layer a which is seen only on the northeast coast at Bargine Bay is a very fine-grained, stratified ash deposit containing some ballistic bombs and impact sags, and can be divided into two sub-layers. The lower sublayer is a structureless ash fall of constant thickness all along the northeast coast. The upper sublayer is generally a planar laminated ash, however along the coast from Bargine Bay towards Zeelandia Baai it develops small wavy dune bed-forms suggesting northerly transport.

Layer b (Marker Unit A) is composed of coarse-grained, moderately well-sorted pumice clasts (Figs. 57A and B). Limited outcrop prevents drawing isopach and isopleths for this layer, however, although the thickness of this bed varies between the two locations shown in Plate 5 and Figure 56, variation in maximum clast size is small suggesting that the two measured sections are on the back vent-side of the dispersal axis. Such a dispersal to the south-east would be typical of a 10-20 km high eruption column in the Lesser Antilles affected by the upper Troposphere anti-Trade winds (Sigurdsson et al., 1980; Roobol et al., 1985).

Layer c (Marker Unit B) is composed of white stratified ashes up to 3 m thick. In the Oranjestad section (stratigraphic section XVIII, Plate 5) they are fine-grained and dominantly planar-laminated base surge deposits, which at the top contains a distinctive 30 cm thick layer of

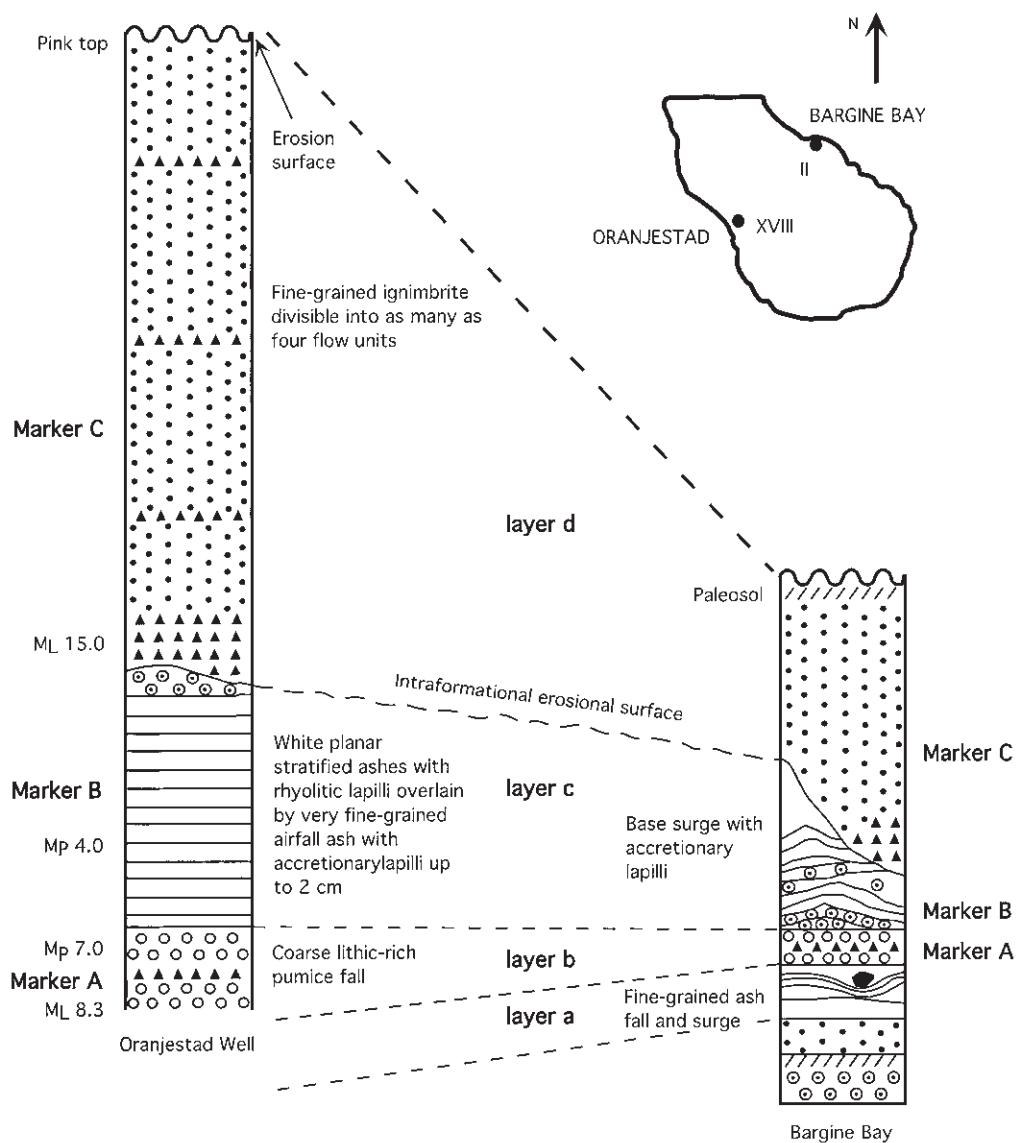


FIGURE 56. Stratigraphy of the deposits from a rhyolitic Plinian eruption (Marker Units A, B, and C). Stratigraphic sections measured at Oranjestad (stratigraphic section XVIII, Plate 5) on the west coast, and at Bargine Bay (stratigraphic section V, Plate 5) on the east coast of St. Eustatius.

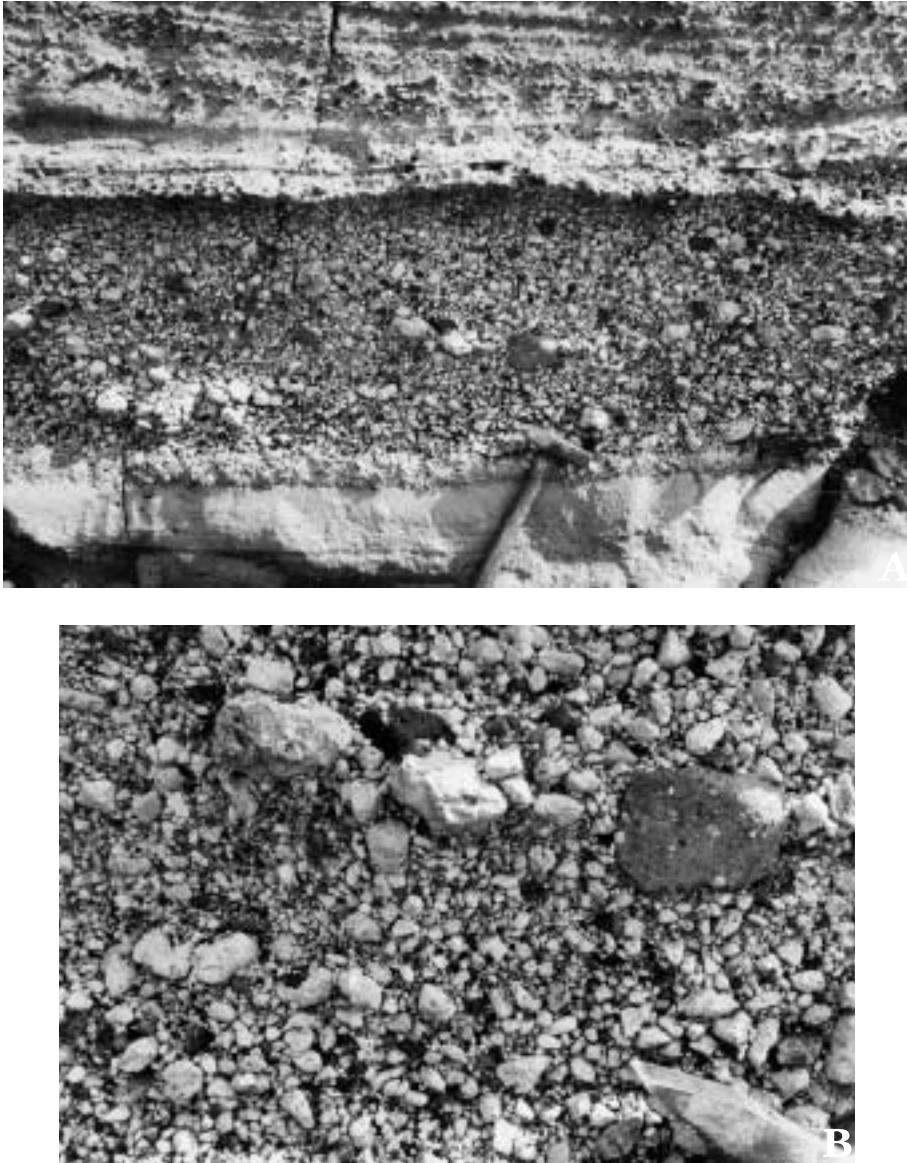


FIGURE 57A. Rhyolitic pumice lapilli fall (Marker Unit A), exposed on the east coast of St. Eustatius. The deposit is about 1 meter thick at this locality in Bargine Bay. 65 cm-long hammer shows scale.

B. Close-up of the same layer as above, showing white rhyolitic lapilli and dark andesite lithic clasts. Hammerhead indicates scale.

very fine white ash fall with accretionary lapilli up to 2 cm in diameter (Fig. 58). On the northeast coast at Bargine Bay, *Layer c* contains well-developed climbing dune bed forms again suggesting transportation northwards (Fig. 59). Along Bargine Bay, dune amplitude varies between 30 and 50 cm and wavelengths between 6 and 20 m, however there appears to be no systematic change in the transport direction. Some bed forms contain coarse-grained laminae and accumulations of accretionary lapilli and lithics.

Layer d (Marker Unit C) is a massive fine-grained white pumice and ash flow deposit (ignimbrite) which at Oranjestad shows a slightly pinkish top due to oxidation. The base of the deposit is erosional especially at Bargine Bay where it strongly downcuts into the underlying deposits. Four flow units have been recognized at Oranjestad by the presence of lithic concentration zones (layer 2b₁ of Sparks et al., 1973). However as there is a notable lack of large (>5 cm) pumice clasts, pumice-rich tops (layer 2 b_p) are not present.



FIGURE 58. Well-developed large accretionary lapilli in a rhyolitic surge deposit (Marker Unit C) at Oranjestad (stratigraphic section XVIII, Plate 5).



FIGURE 59. Lapilli bed Marker Unit A (behind hammer) is overlain by pumiceous surge deposits with small dune structures (Marker Unit B). The latter is rich in lithic clasts towards the base. The entire section belongs to Lower Pumice Division 2 exposed on the northeast coast of St. Eustatius between Zeelandia Baai and Bargine Bay.

Studies of deposits of other large-scale silicic eruptions, especially those in which water is thought to have had an important role in the explosive activity (e.g. Self and Sparks, 1978; Sparks et al., 1981; Self, 1983), make it possible to interpret the eruptive sequence described above. *Layer a* is interpreted as being formed by phreatomagmatic activity. At the beginning of the eruption water must have had free access to the vent, probably in the form of a well-established water table, a crater lake, or even access to the sea. Initial phreatomagmatic explosions produced a high 'wet' eruption column which was driven mainly by convection and which deposited the lower sublayer of fine-grained ash fall. This layer, on the basis of limited outcrop observations, shows characteristics consistent with phreatoplinian ash layers as described by Self and Sparks (1978), Walker (1981) and Self (1983), although it lacks accretionary lapilli. At the end of the explosions that produced *Layer a*, the supply of water probably became exhausted, however the eruption continued with the generation of a high eruption column and the deposition of *Layer b*, which shows typical Plinian characteristics (Walker 1973, 1981) formed by fall-out from a 'dry' eruption plume with little water-magma interaction taking place at the vent. *Layer c* records a return to phreatomagmatic activity as water regained access to the vent, possibly due to replenishment of the water table following a pause in activity. Phreatomagmatic explosions produced a series of base surges which swept radially outwards from the vent, and a high eruption column deposited another very fine-grained phreatoplinian-type ash fall. Eventually, either the vent widened, or the eruption column became so overloaded with steam and fine particles generated in the vent, that the effective density of the column became greater than that of the atmosphere and collapse occurred generating a series of pumice and ash flow (ignimbrite) units (Sparks and Wilson, 1976; Sparks et al., 1978; Wilson et al., 1980) that make up *Layer d*. The fine-grained nature of the pumice and ash flow deposit (ignimbrite) and the presence of accretionary lapilli indicate that water continued to interact with the magma during its generation.

Asama-style activity

Deposits assigned to Asama-style activity are termed semi-vesicular andesite deposits due to the characteristic field appearance of the clasts which have a pale gray color and contain spherical vesicles of around 1 mm in diameter

(Table 4). The original description of this style of activity in the Lesser Antilles was from Mt. Pelée, Martinique where only semi-vesicular andesite block and ash flow deposits were identified (Smith and Roobol, 1990). On St. Eustatius, in addition to flow deposits, surge and lapilli fall deposits have also been observed.

The semi-vesicular andesite block and ash flows on St. Eustatius, as on Mt. Pelée, produced medium- to coarse-grained polymodal deposits, composed of subrounded to subangular vesicular juvenile clasts ranging in density from 0.8 to 1.7 gm/cm³, with a median value of 1.6 gm/cm³. The deposits also contain angular lithic clasts and, in the 1 mm and finer size-fractions, crystals (Fig. 60). The surges in contrast, are relatively unimodal in character (Fig. 60). Both flows and surges are poor in fines and plot in the field of fines-depleted flows (Figs. 61A and B).

The amount of dense andesite clasts is very variable in the flow and surge deposits, and in some samples it becomes the dominant component of the coarser size fractions (EUX 971-12, Fig. 60). Such samples may be considered as transitional between Asama-style deposits dominated by semi-vesicular clasts and Pelean-style deposits dominated by dense andesite clasts. Similar deposits have been described from the pre-historic

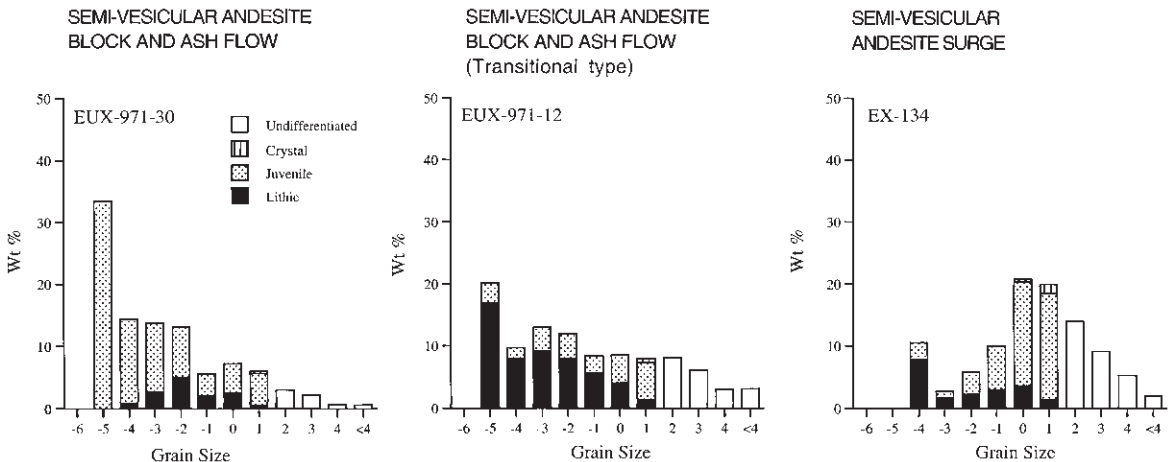


Figure 60. Size distribution histograms of pyroclastic samples of selected deposits from Asama-style activity. Grain size classes are subdivided on their weight proportions of juvenile magmatic material, lithics and juvenile crystals.

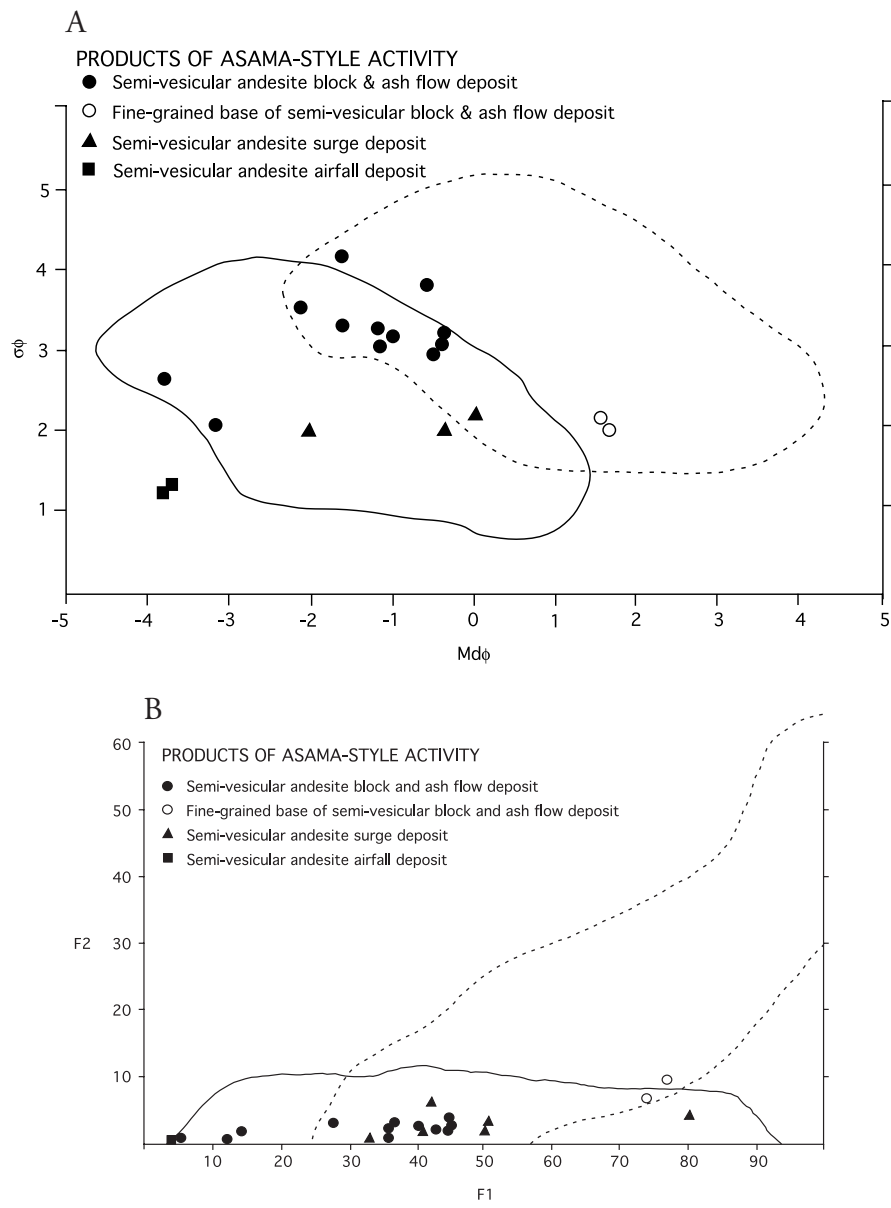


FIGURE 61A. $Md\phi$ - $\sigma\phi$ plot for deposits from Asama-style activity. Dashed line is 1% contour for pyroclastic flow field; solid line is 1% contour for fines-depleted pyroclastic flow field (after Walker, 1971, 1983). All plots are for bulk samples.

B. The same data as 61A plotted on F_1 (wt% finer than 1mm) versus F_2 (wt% finer than 1/16mm) diagram. Dashed and solid lines are as in Figure 61A.

stratigraphy of the Soufriere Hills, Montserrat (Roobol and Smith, 1998), and have also been observed to form during the current eruption where they were generated by fountain collapse of an eruption column produced by an explosion through the actively growing dome (Clarke et al., 2002).

Semi-vesicular andesite lapilli fall deposits have only been observed as part of Marker Unit K of the most recent erupted bedset of the Quill, and as such will be described in detail under that heading.

Phreatomagmatic-style activity

A distinctive feature of the deposits of the Quill, especially in the products ascribed to Plinian-style activity, is the extensive evidence, manifested by the presence of extremely fine-grained laminated ash layers containing accretionary lapilli, armored lapilli, entombed gas cavities, and an abundance of ash, of the interaction of external water with the erupting magma. The laminations are commonly on the scale of millimeters but can be up to several centimeters in thickness. The thin laminations are clearly ash falls and the thicker units base surges, but it is not always possible to decide in the field the nature of each lamination. For this reason, representative samples were collected for grain size analysis and the data are plotted on discrimination diagrams (Figs. 62A and B) (Walker, 1983). As evidenced from their $Md\phi$ and $\sigma\phi$ values of >2.5 and <2.0 , respectively, the ash fall deposits are well-sorted and extremely rich in fine ash. In contrast, the base surge deposits are distinctly coarser in grain size and show a range in sorting from 1.0 to 3.5 (Fig. 62A).

On the $F_1 - F_2$ discriminant diagram (Fig. 62B), the ash fall deposits from the Quill are all very fine-grained and plot within the field defined by the deposits from the 1979 phreatomagmatic eruption of Soufriere, St. Vincent (Brazier et al., 1982), with the finest ashes also plotting in the lower part of the field of the Wairakei phreatoplinian deposit (Self, 1983). The base surge deposits which include those associated with Plinian activity, as well as a single sample of a basaltic base surge from the Stratigraphic Division 1 are poorer in ash than the fall beds with maximum values of around 70% (F_1) and 15% (F_2). Of the surges, the base surge sampled from Division 1 is somewhat more coarser grained than those associated with phreatoplinian activity.

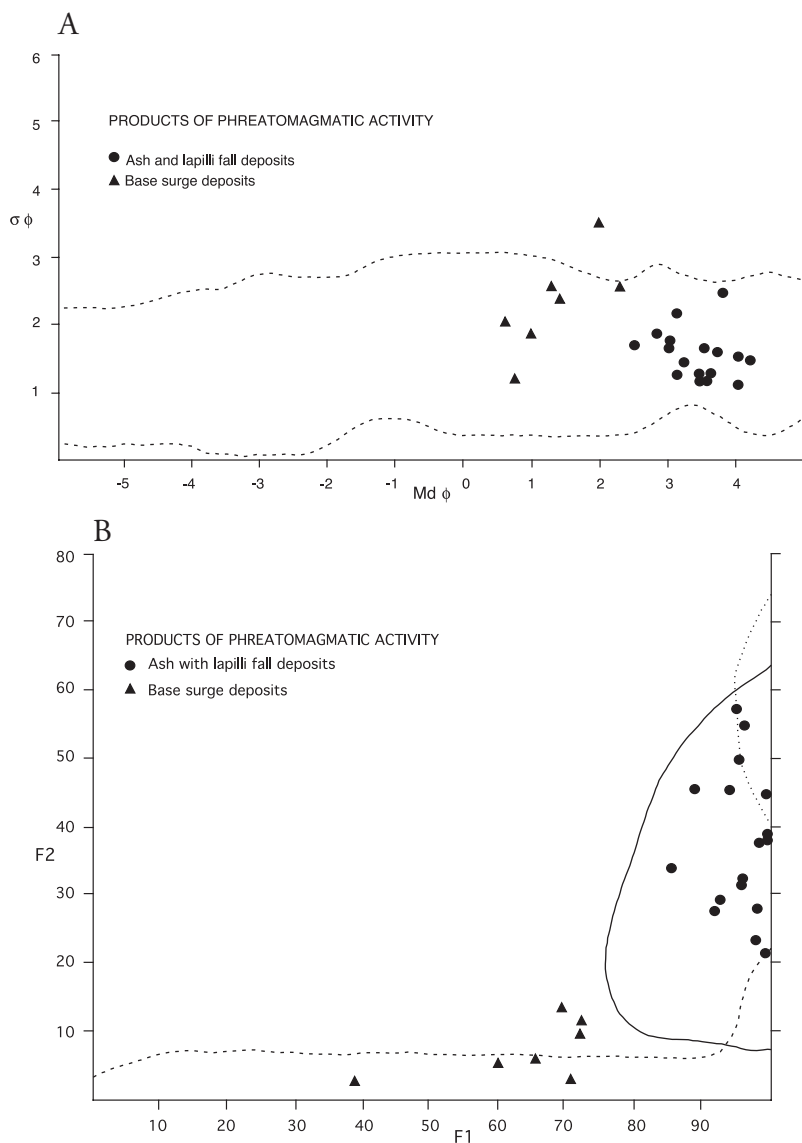


FIGURE 62A. $Md\phi$ - $\sigma\phi$ plot for deposits from phreatomagmatic activity. Dotted line is 1% contour for pyroclastic fall field (after Walker, 1983). All plots are for bulk samples.

B. The same data as 62A plotted on $F1$ (wt% finer than 1 mm) versus $F2$ (wt% finer than 1/16 mm) diagram. Dashed line is 1% contour for Plinian fall field (after Walker, 1983); solid line is field of fall deposits from the 1979 eruption of Soufriere, St. Vincent (after Brazier et al., 1982); dotted line is Wairakei phreatoplinian fall field (after Self, 1983).

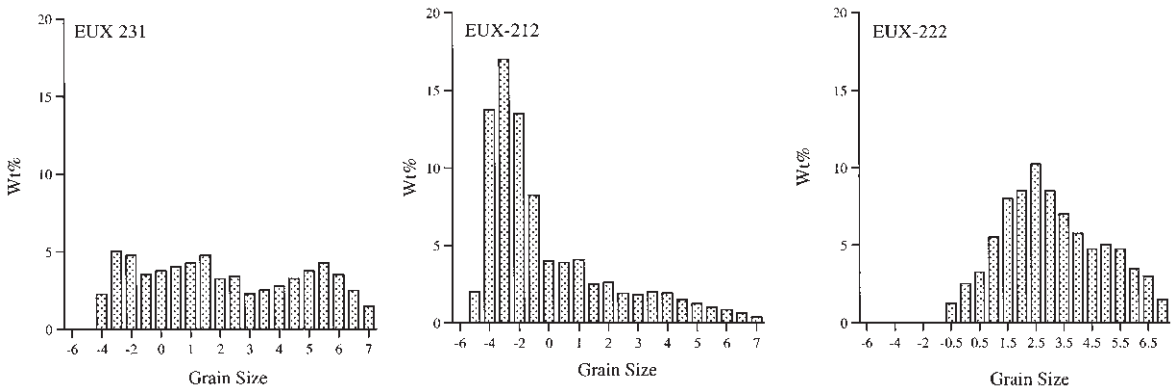


FIGURE 63. Size distribution histograms of pyroclastic samples of selected deposits showing the distribution of the <4phi size fraction. Samples have been sieved at 1/2 phi intervals down to 4 phi, with finer grain sizes determined using a particle analyzer to more accurately show their grain size distributions.

The thin laminated ash layers described above are not the only deposits thought to have resulted from phreatomagmatic activity. Many of the Plinian-style eruption columns in the Lesser Antilles are also believed to have been at least partially driven by interaction with groundwater (Roobol et., al 1985). In order to better document these deposits, grain size analyses of selected samples were carried out at half-phi intervals for the range 0 to 4.0 ϕ . For the finest grained material (4.0 to 7.5 ϕ) the size distribution was carried out using a particle size analyzer. An example of a pyroclastic flow deposit believed to have formed from phreatoplinian activity, is the ignimbrite associated with the rhyolitic eruption described in detail in a previous section. A sample from the middle of this deposit (EUX 231) shows a very distinct, fine-grained mode (4.0-7.5 ϕ) with the modal peak in the 5.5 to 6.0 ϕ size range (Fig. 63). In contrast, the basal layer of this deposit is highly positively skewed, with a well-sorted coarse mode and a long finer-grained tail (1.0 to 7.5 ϕ), which shows a secondary mode in the 4.5 to 7.5 ϕ size classes (EUX 212, Fig 63). The coarse mode of this deposit is composed mainly of lithic fragments and represents the material moved by traction in the basal part of the flow, whereas the finer-size classes were carried as a turbulent suspension load.

A characteristic feature of phreatomagmatic ash fall deposits is that they often show a bimodal grain size distribution (Self and Sparks, 1978; Self, 1983; Brazier et al., 1982). A similar feature is shown by many of the ash fall deposits of the Quill (EUX 222, Fig. 63). The two grain size populations in such deposits are thought to have different origins. The coarse population is interpreted as largely the result of transport and fall-out of individual particles that are size- and density-sorted in the down-wind eruption plume. In contrast, the finer peak is thought to represent ash that aggregated in the eruption plume to form accretionary lapilli and/or unstructured clumps that were prematurely flushed out of the wet plume, and which subsequently disintegrated.

THE MOST RECENT ERUPTED BEDSET OF THE QUILL

Introduction

The most recent erupted bedset from the Quill is composed of five well-preserved, conspicuous, extensive, and distinct lithologic units identified as Marker Units K, L, M, N and O. Several of these lithologic units are composed of multiple deposits of different pyroclastic type, however each unit has a distinctive lithology. The deposits form the main top surface of the flanks of the Quill and are particularly prominent in the upper parts of the sea cliffs between Kay Bay and Oranjestad on the west coast, where they reach a total maximum thickness in the sea cliffs of 12 m. They also are present as a distinct pyroclastic apron which radiates downslope from the prominent notch/breach on the western crater rim. The bedset overlies, locally unconformably, a wide variety of deposits including a 30-cm-thick paleosol, pumiceous deposits (in the sea cliffs at the northern part of Oranjestad), and to the south above the harbor, a conspicuous crimson-colored scoria and ash flow deposit (Marker Unit J), which in turn unconformably overlies pumiceous deposits on which a thin paleosol is poorly developed.

The deposits of the most recent erupted bedset lack internal discontinuities and there are no paleosols between the Units. This absence of paleosols implies that the deposits were formed from a series of separate explosive events between which the time intervals were inadequate for

soil formation. Thus from the point of view of stratigraphic analysis, in the absence of historic records, this most recent erupted bedset of the Quill, comprising Marker Units K to O must be regarded as the products of a single eruption.

Thirty stratigraphic sections logging Marker Units K to O, from all parts of the Quill, are included in Plate 5, and are shown in simplified form in Figure 64. The Marker Units are described in the following sections from oldest to youngest. Maps have been constructed for each Marker Unit, plotting all data from the thirty stratigraphic sections. As preservation of these youngest deposits of the Quill is excellent, it has proved possible to reliably reconstruct the distribution of each Marker Unit. These maps provide the main basis for evaluating the geohazard posed by the dormant Quill volcano.

Marker Unit K

Marker Unit K comprises a variety of distinct deposits, all resulting from Asama-style activity. The unit contains semi-vesicular andesite clasts, basaltic andesite clasts, as well as co-mingled clasts in which dark basaltic andesite is intimately flow banded with light-colored andesite. Since light-colored semi-vesicular andesite clasts exceed those of basaltic andesite in abundance, the most common deposits, although of co-mingled type, are essentially semi-vesicular andesite block and ash flows and surges.

Marker Unit K deposits are best developed at stratigraphic section XII (Fig. 64) at Bouile. Here a 30 cm-thick semi-vesicular andesite surge deposit overlies a paleosol, and is in turn overlain by three semi-vesicular andesite block and ash flow deposits, each with a thickness of 150 cm. In stratigraphic section XXV at Mansion Pasture (Fig. 64), although the base is not exposed the diagnostic co-mingled clasts identify the lower three deposits as belonging to Marker Unit K. At this location, 100 cm of semi-vesicular andesite block and ash flow deposit is overlain by 40 cm of lapilli fall which in turn is overlain by 10 cm of semi-vesicular andesite surge. This co-mingled lapilli fall bed is highly distinctive and has also been recognized at stratigraphic sections XIV, XVII, XVIII, XIX, XX, XXI, XXV, XXVII, and XXX (Fig. 64). The locations of the sections containing the pyroclastic fall layers are plotted in Figure 65A. The thicknesses which are

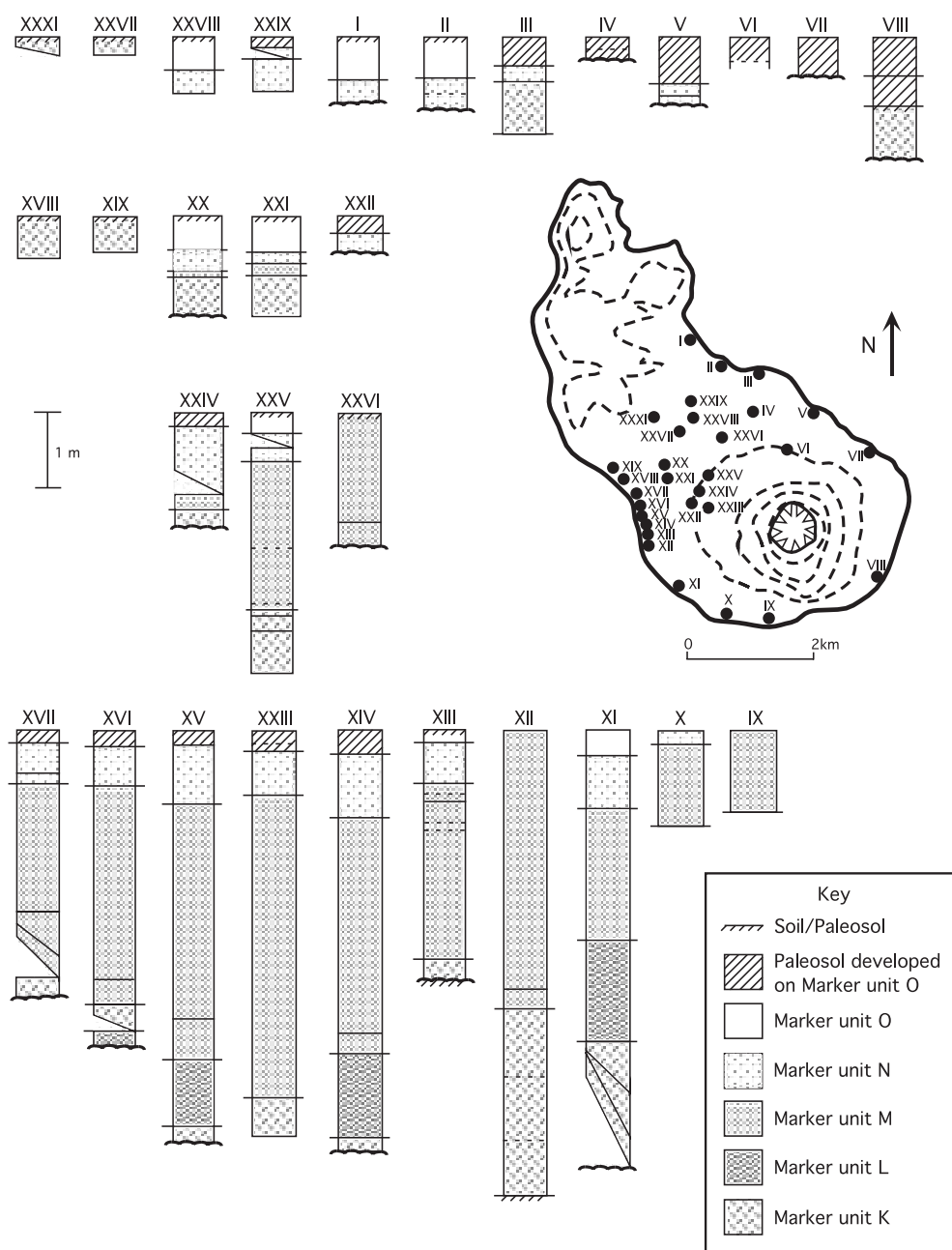


FIGURE 64. Partial stratigraphic sections showing the distribution and thickness of deposits of Marker Units K to O of the last erupted bedset of the Quill, St. Eustatius. Almost all layers are pyroclastic flow deposits. The identity of the layers and location names are given in Plate 5. Variable thickness of some layers is indicated.

also shown in this figure clearly indicates the distribution of the deposit, and permits the 50 cm isopach to be constructed, which shows that the lapilli fall layers of Marker Unit K have a strong westerly dispersal axis, indicating lower Tropospheric dispersal of the material in the eruptive column.

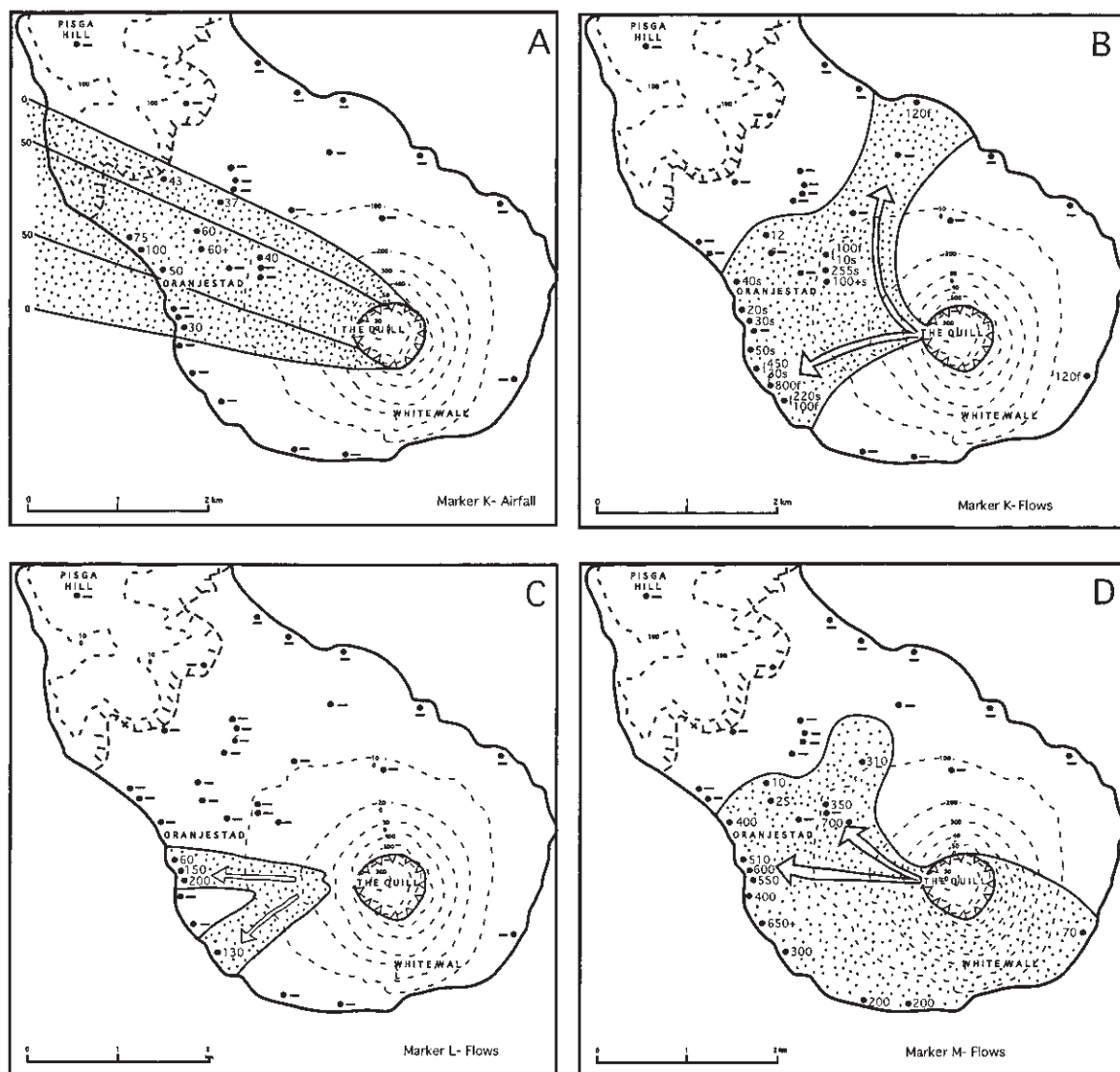
The distribution and thicknesses of the surge and pyroclastic flow deposits of Marker Unit K are shown in Figure 65B. The deposits extend from the notch (or 400 m low point) in the crater rim of the Quill as two tongues. The main tongue is directed towards the southern part of Oranjestad, in the vicinity of the harbor, where the flow deposits achieve a maximum thickness of 800 cm, with a maximum juvenile clast size (Mj) of 30 cm. The other tongue extends towards the north and east past Round Hill to reach the coast at Schildpadden Baai (stratigraphic section III, Fig. 64), where the deposits have a thickness of 120 cm, with juvenile clasts (Mj) of up to 30 cm in diameter. In Figure 65B, the pyroclastic surge(s) and flow(f) deposits of Marker Unit K have been distinguished and, as far as can be reconstructed, they both appear to have an identical distribution.

Marker Unit L

This Marker Unit is best exposed in a gut near Kay Bay (stratigraphic section XI, Fig. 64) where it occurs as a single 130 cm-thick scoria and ash flow deposit composed essentially of clasts, up to 50 cm in diameter, of basaltic andesite scoria with rounded ropy surfaces. The deposit is relatively rich in ash and, unlike the underlying deposit of Marker Unit K, contains only a very small amount of co-mingled clasts. Its distribution is shown in Figure 65C. This deposit, which is of very limited extent, is essentially confined to the pyroclastic flow apron below the crater rim notch of the Quill. It is also composed of two tongues, one reaching the coast near Kay Bay, and the other reaching the southern limit of the town of Oranjestad in the vicinity of the harbor.

Marker Unit M

This Marker Unit is a thick scoria and ash flow deposit that generally contains less ash than the underlying Marker Unit L. Co-mingled clasts again form a minor component. In many locations the lower part of Marker



- 75 Measured stratigraphic section; thickness of deposit in cm
- — Deposit absent
- 100+ Minimum thickness of deposit as base not seen
- 100 — Attitude in meters
- Crater rim of The Quill
- Limit of Northern Centers
- 5 — Isopach of airfall deposit before erosion
- ↖ Main direction of pyroclastic

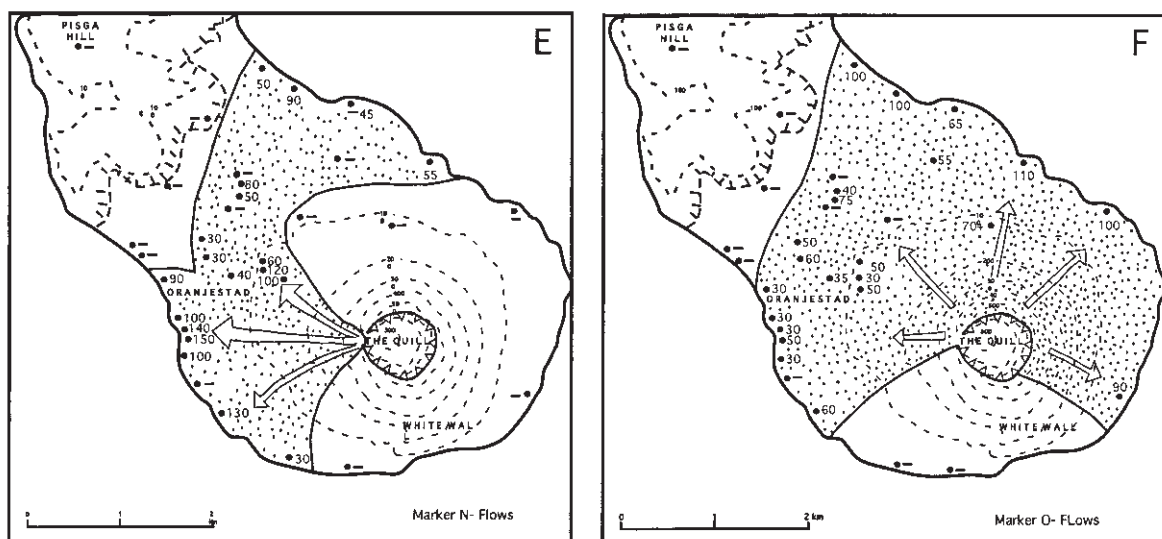


FIGURE 65. Maps showing distribution of Marker Units K to O of last erupted bedset of the Quill, St. Eustatius. These individual maps are also shown in Appendix 3, pages 305 to 310.

Unit M is rich in angular blocks of dense gray andesite. The presence of these dense blocks indicates that the pyroclastic explosions that formed Marker Unit M enlarged the crater of the Quill by destroying at least one Pelean dome remnant. The distribution of the deposit is shown in Figure 65D, from which it can be seen to considerably exceed the aerial extent of Marker Unit L. The main pyroclastic flows of Marker Unit M also appear to have been directed through the crater rim notch of the Quill, as two tongues. One tongue was directed towards the southern end of the town of Oranjestad in the vicinity of the harbor, where the deposit attains a thickness of 600 cm and a M_j size of 30 cm. The other tongue turned at Round Hill and again flowed towards Schildpadden Baai but did not reach the coast. The deposits from this tongue have a thickness of 700 cm in the vicinity of Round Hill, and a M_j of 30 cm. Pyroclastic flows produced by the collapse of the St. Vincent-style open crater eruptive column also must have overwhelmed the crater rim of the Quill at least on the south side, as a 70 cm thick scoria and ash flow deposit belonging to Marker Unit M occurs on the east coast at Kid Sadler (stratigraphic section VIII, Plate 5, and Fig. 64).

Marker Unit N

This Marker Unit is a relatively thin, fine-grained scoria and ash flow deposit which can be distinguished from the underlying Units as it is entirely lacking in co-mingled clasts. The distribution of the Marker Unit N deposit is shown in Figure 65E. Again, the distribution of the deposit clearly indicates that pyroclastic flows of St. Vincent-style activity were largely directed through the western crater rim notch of the Quill, and down the main pyroclastic flow fan. The deposit is best developed on the site of the town of Oranjestad in the vicinity of the harbor, where it reaches a maximum thickness of 150 cm with a Mj of 20 cm. A second tongue of pyroclastic flow turned to the north at Round Hill and reached the north-east coast at Bargine Bay. This flow tongue has a more northerly distribution than that of flows from previous Marker Units. In terms of future hazard planning, it must be noted that this flow traversed across the site of the island's only airport (situated on the distal flank deposits of the Quill volcano), and through the entire area of housing recently constructed on the island.

Marker Unit O

Marker Unit O forms the present-day topsoil of the island, and it is usually weathered to a brown or orange color throughout. However soilification is insufficiently advanced in the lower and middle portions of the Unit to hide its original pyroclastic texture. Marker Unit O is composed of juvenile clasts of vesicular basaltic lapilli (Mj of 10 cm) and abundant small lithic clasts, both coated with ash, in a fine ash-rich matrix. Where best developed (e.g. in stratigraphic sections V, XXIV and XXV, Plate 5 and Fig. 64), Marker Unit O is represented by several separate scoriaeous ash flows, suggesting that there were several distinct explosions each of which produced a pyroclastic flow. Where several of these thin flow deposits are present, the lower flow units are always richer in lithics than those higher in the sequence.

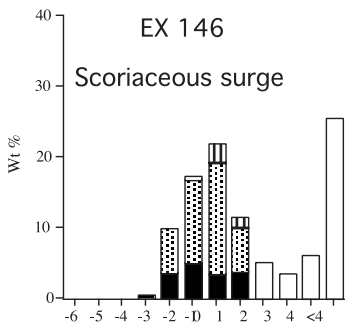
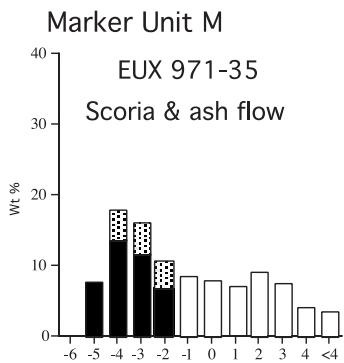
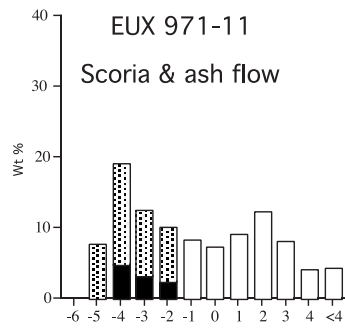
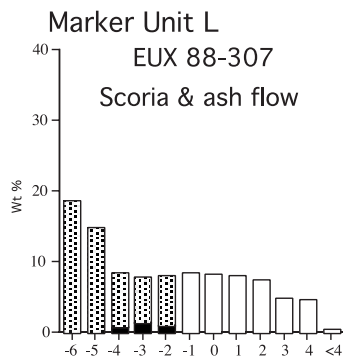
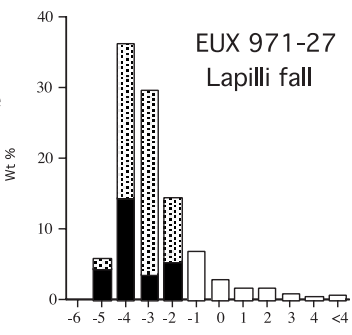
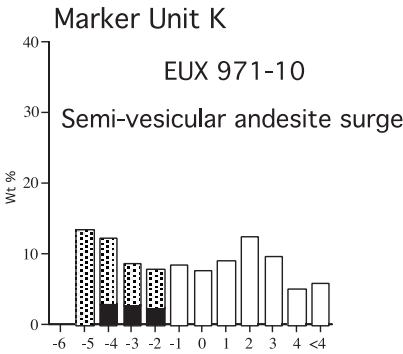
The distribution of the Unit is plotted in Figure 65F, where it can be seen to cover most of the flanks of the Quill, except for a narrow sector south of the crater rim; the flow also did not quite reach the hills of the Northern Centers. Its widespread radial distribution, its total thickness of usually less than 1 m, its very fine grain size, and the fact that both the

juvenile and lithic clasts are all coated in ash, suggests that Marker Unit O records a phreatomagmatic eruption probably caused by the entry of groundwater into the crater of the Quill which had been successively deepened as the eruption progressed.

Grain size analysis of samples from the most recent erupted bedset of the Quill
Grain size analyses were carried out on representative samples from all of the Marker Units. Those from Marker Unit K include semi-vesicular andesite block and ash flow, semi-vesicular andesite surge, and lapilli fall deposits. The flow and surge deposits are all polymodal with a deficiency in fines, with the surges generally being better sorted and with finer median grain sizes than the flows. The lapilli fall deposits, in contrast, are distinctly unimodal, and coarse-grained (Fig. 66). The juvenile components in all of these deposits include semi-vesicular and vesicular andesite clasts, variable amounts of scoriaceous clasts of basaltic andesite, and co-mingled clasts. Although co-mingled clasts are present in all of the deposits from Marker Unit K, they are especially abundant in the fall deposits, where they make up more than seventy percent of the >4 mm size fraction.

Fines-depleted scoria and ash flow deposits composed of scoriaceous basaltic andesite juvenile clasts with minor amounts of lithic clasts (Fig. 66) make up Marker Unit L. Co-mingled clasts are lacking entirely in the samples studied but were observed in outcrop. Many of the larger clasts are coated in ash suggesting the pyroclastic flows were 'wet' when formed, however the lack of fine ash suggests that external water played only a minor role during this eruption. The flow and surge deposits from overlying Marker Unit M are dominantly fines-depleted, however at least one surge unit is rich in fine ash (Fig. 66). Lithic clasts as noted previously are much more abundant in this Unit than in the underlying ones, suggesting an episode of vent erosion.

Deposits from Marker Unit N appear to fall into two groups. Those from the west coast near Oranjestad are relatively coarse-grained ($Md\phi = -2.5$) and noticeably fines-depleted (EX 168), in contrast those from the eastern tongue of the unit are much finer-grained and richer in ash with $Md\phi$ values as small as 2.0 (EX 175). Such a difference in grain size between the two tongues suggests they were produced by a stratified



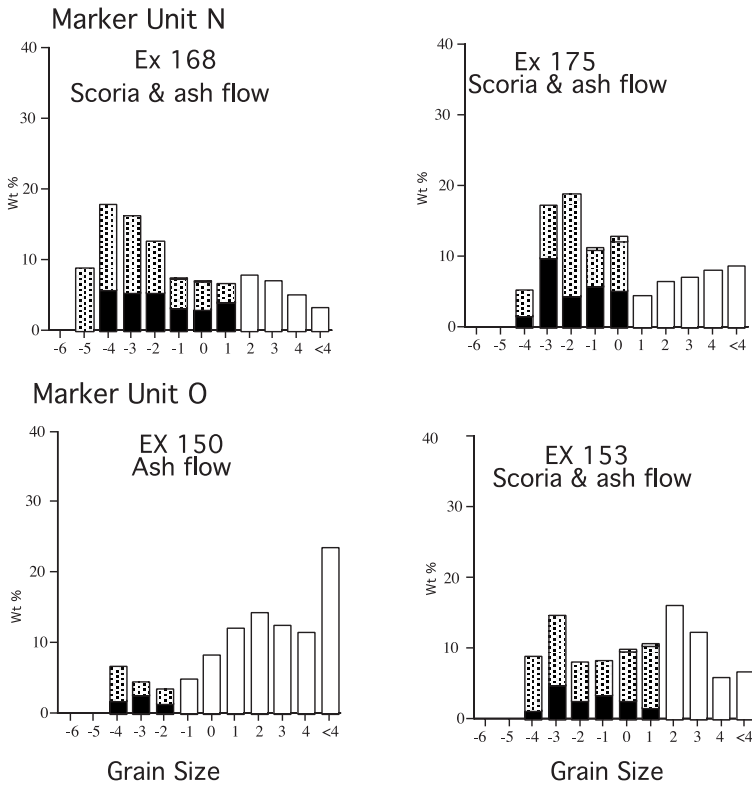


FIGURE 66. Representative histograms of deposits from Marker Units K through O of the last erupted bedset of the Quill. Grain size classes are subdivided on their weight proportions of juvenile magmatic material, lithics, and juvenile crystals.

pyroclastic flow composed of a lower, coarser, fines-depleted unit which was entirely controlled by topography and flowed directly away from the notch, and a upper unit which became unchanneled and thereby covered a much larger area. A similar suggestion has been made to account for the differences between the coarse valley-fill block and ash flows and the more extensive finer-grained block and ash flows of Mt. Pelée (Smith and Roobol, 1990). Marker Unit O is composed of several distinct flows. The lower flows although relatively coarse-grained contain abundant medium ash, e.g. EX 153, in contrast the uppermost flow (EX 150) is very rich in fine-grained ash (Fig. 66), which also coats all of the larger clasts.

Relations between the Marker Units of the most recent erupted bedset of the Quill.

The five Marker Units form a single bedset defined by the absence of recognizable paleosols between them, suggesting they represent the products of a single eruption or a closely spaced series of related eruptions. The initial eruption, which is dominated by semi-vesicular andesite clasts is thought to have been produced by Asama-style activity, i.e., an open-crater eruption of a moderately gas-rich magma. No complete stratigraphic succession through Marker Unit K has been found at any one location. But it is suggested from the occurrence, in nearly all cases, of the lapilli fall bed on top of the flow and surge deposits, that the eruption began with a series of flows and surges produced by collapse of a low eruption column which progressively increased in height to finally produce the lapilli fall deposits. The scoria and ash flow and surge deposits characteristic of Marker Units L, M, N and O are all thought to have been formed by St. Vincent-style eruptions, i.e., the collapse of an eruption column produced by open-crater explosions. The pyroclastic flows of Marker Units L and N were both controlled and directed by the notch/breach in the crater rim of the Quill (which is still preserved at the present day). In contrast, the distribution of Marker Unit M deposits suggests collapse from a higher column as the flows overtopped the crater rim on the southern and eastern sides of the volcano. Such a scenario is also supported by the presence of a lapilli fall bed within Marker Unit M. Although fall deposits also probably resulted from fall-out from the eruption columns that produced Marker Units L, and N, their absence from the stratigraphy of these Units probably reflects both the thin nature of the fall deposits and the erosive power of the succeeding pyroclastic flows. The final eruption producing Marker Unit O also produced flows that overtopped the crater rim of the Quill, but this time on its northern and eastern sides. The deposits from Marker Units L and O suggest that magma-water interaction played a role in their formation. In both cases deepening of the crater so as to allow ground water into the vent would seem the most likely scenario. The significance of the co-mingled deposits with the change from andesitic to basaltic magma will be discussed in a later section.

Age of the most recent erupted bedset of the Quill

The age of what appears to be the most recent eruption of the Quill is particularly important to this small island, in view of the development of an oil storage facility on the extinct Northern Centers, and the resulting increase in population from around 1,000 in 1979 to 2,400 in 1996. This population increase resulted in an expansion of urban settlement in the center part of the island across the flat lower flanks of the Quill. It is unfortunate that at the present time the age of the most recent erupted bedset is in dispute. We have proposed an age of less than 2,000 years B.P. for this eruption, whereas van der Valk (1992) has interpreted the extensive charcoal-rich horizon designated here as Marker Unit E, and dated around 8,000 years B.P., to be the most recent eruptive activity of the Quill. The matter is discussed in detail next, as the age of the most recent activity plays a crucial role in deciding the stage of activity of the Quill.

The problem of the age of the most recent eruption of the Quill arises partly because it has only proved possible to find charcoal suitable for dating from Marker Unit O. The absence of paleosols and erosion surfaces within the most recent erupted bedset however, suggests that we are looking at either a single volcanic eruption of several years duration or several distinct eruptions separated by short periods of dormancy. The absence of paleosols indicates that if there were any periods of dormancy between the eruptions they would have to have been less than 50 years duration based on the absence or very poor development of soil on deposits generated by both the 1902-05 and 1929-32 eruptions of Mt. Pelée, Martinique (Smith and Roobol, 1990).

In 1979 we collected a charcoal sample from house foundations immediately in front of the former air terminal buildings (Fig. 67). Here, carbonized wood with the appearance of an in-situ tree root was contained in Marker Unit O. Dating of this charcoal yielded an age of 1550 ± 35 years B.P., and was cited as the probable age of the most recent erupted bedset in a report on the pyroclastic stratigraphy of the island prepared at the request of the Netherlands Geological Survey (Roobol et al., 1981a). This report was classified as confidential by the Government of the Netherlands Antilles, and was not published until 1997 (Roobol et al., 1997). During that long interval, archeological surveys were carried



FIGURE 67. Stratigraphic section XXVIII as exposed in 1979 at Golden Rock. Two dark colored fine-grained pyroclastic flow deposits corresponding to Marker Units O and N overlie a coarser-grained andesitic block and ash flow deposit. Marker Unit O comprises 75cm of weathered basaltic ash with a coarse grained base, and the underlying Marker Unit N comprises 50cm of basaltic andesite ash with sparse lapilli.

out on the site of Golden Rock, very close to the location of our original charcoal, and were reported by Versteeg and Schinkel (1992). A survey of another site at Smoke Alley was reported by Versteeg et al. (1993).

The critical paper in the archeological volume of Versteeg and Schinkel (1992) for the interpretation of the age of the last erupted bed set is that of van der Valk (1992), in which he concludes that, the last eruption of the Quill occurred 8,000 years ago. The 8,000 year old horizon corresponds to our Marker Unit E for which we have five radiocarbon dates. This conclusion that the Quill has been dormant for 8,000 years

has caused considerable difficulties for the archeologists, as they were given no opportunity to consider any other interpretations for their younger radiocarbon ages other than that they were man-made. Further, Versteeg (pers. comm. 1999) adheres to this interpretation for the age of the last eruption of the Quill. We have therefore assembled in Figure 68, eight stratigraphic columns the full details of which are shown in Plate 5. These are used here to show that the Marker Unit E horizon is overlain by numerous pyroclastic deposits including those of our Stratigraphic Divisions 4, 5, 6, and 7 (the last alone is the last erupted bedset). For example, at the cistern at the shore line in Oranjestad (stratigraphic section XVII, Plate 5, Fig. 68) Marker Unit E in Stratigraphic Division 3 is overlain by thirty-five logged deposits belonging to Stratigraphic Divisions 3, 4, 5, 6, and 7. The reasoning of van der Valk (1992) that all deposits above his 8,000 year dated deposit (our Marker Unit E) formed in the same eruption is an absence of paleosols. However the sections illustrated in Figure 68 show several paleosol horizons above Marker Unit E in Stratigraphic Divisions 3, 4 and 6, invalidating this argument. We are unable to accept the conclusion of van der Valk that Stratigraphic Divisions 3, 4, 5, 6, and 7 all formed within one eruption dated at 8,000 years. Unfortunately, despite return visits to the island and careful searches, we have been unable to find any charcoal to enable us to date the many deposits above the 8,000 year horizon. The only charcoals that were recovered from these deposits were found in the soil developed on top of the exposures of Marker Unit O in the east coast sea cliffs. The two dated samples unfortunately yielded modern ages of 230 ± 60 and 120 ± 60 years B.P., suggesting that the samples were plant roots that charred in the ground due to man's activity.

In order to try and resolve the age of the most recent erupted bed set we carefully reviewed all available radiocarbon ages, including those obtained during the archeological studies. This review uses data contributed by Drs. Versteeg and Schinkel on the details of posthole and post-mold stratigraphy that was not included in the original publication of van der Valk (1992). In Figure 69A, the stratigraphy and radiocarbon dating of the Golden Rock archeological site is summarized. The terminology of the Layers 1a to 3 is that of van der Valk (1992). In this publication he describes Layers 2a and 2b as soil material older than Indian occupation.

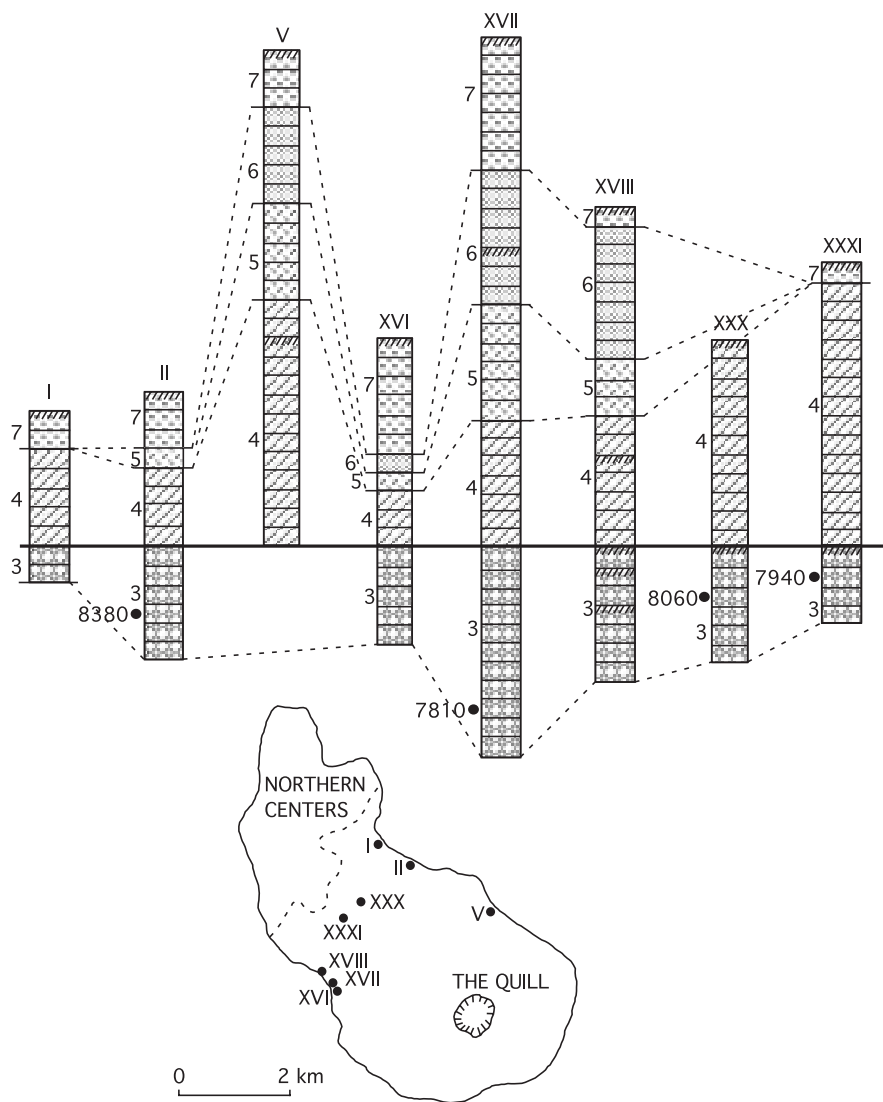


FIGURE 68. Summary of the stratigraphy of the Quill for the past 8,000 years. 3, 4, 5, 6, and 7 — Stratigraphic Divisions; 8380 — radiocarbon age in years B.P.

Box pattern distinguish Statigraphic Divisions.

Based on a comparison of his photographs with our 1979 stratigraphic sections, we consider Layer 2b to be the dark soilified upper part of Marker ash flow Unit O and Layer 2a to be the weakly soilified base of the same unit, and have positioned the carbonized tree root from which we obtained a radiocarbon age of 1550 ± 35 years B.P. at its appropriate location in his stratigraphy (Fig. 69A). Schinkel (1992) describes radiocarbon ages of 1415 and 1545 years B.P. as being obtained from hearths or cooking sites at an occupation level at the base of Layer 2c. These data clearly suggest that the carbonized tree root that we dated at 1550 years B.P. might also record Indian activity and that the sample we dated is most likely to have been a tree root that smoldered in the ground and thus does not represent the age of the last eruption of the Quill. Schinkel (pers. comm., 1999) has carefully explained to us the difference between postmold and posthole fills. When a posthole is dug and a post inserted, the backfill around the post would be a mixture of the different layers excavated, together with surface debris. When a dwelling is destroyed by fire the postmold may retain charcoal, dating the fire. As shown in Figure 69A the postmold ages at Golden Rock range from 1205 to 1350 years B.P. (Schinkel, 1992). What is particularly interesting to us is the posthole backfill ages of 1635 and 1755 years B.P. These charcoals could have been derived from backfill derived from Layers 2a or 2b or from surface debris at the base of Layer 2c. The stratigraphy summarized in Figure 69A clearly indicates that the Golden Rock site was occupied by Indians from 1550 years B.P. onwards and that dwellings were burned between 1350 and 1205 B.P. Nearby at the Smoke Alley site (Fig. 69B) a midden has yielded a human bone fragment dated at 1105 years B.P. (Versteeg et al., 1993). The midden also contains pottery sherds that have been dated at around 1000 years AD. Interestingly a charcoal at the base of the midden believed to have lain on the ancient surface beneath the midden has yielded an age of 1720 ± 30 years B.P.

There is abundant pottery and archeological remains to independently confirm the Indian occupation of St. Eustatius island from 1550 years B.P. onwards. It is however the significance of the older radiocarbon ages of 1635, 1720 and 1755 obtained from posthole backfill at Golden Rock and from beneath the Smoke Alley midden that interests us the most. Because of the constraint placed on the archeologists by the work of van

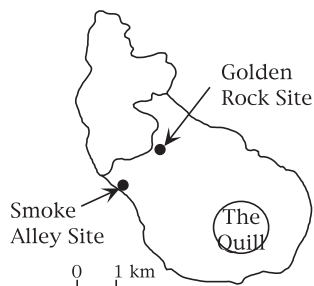
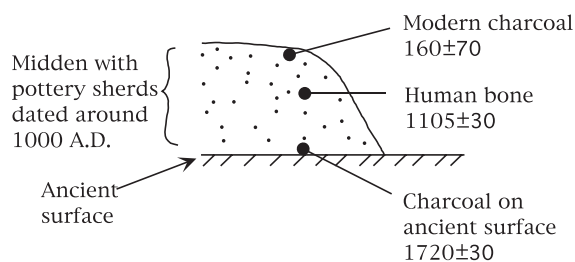
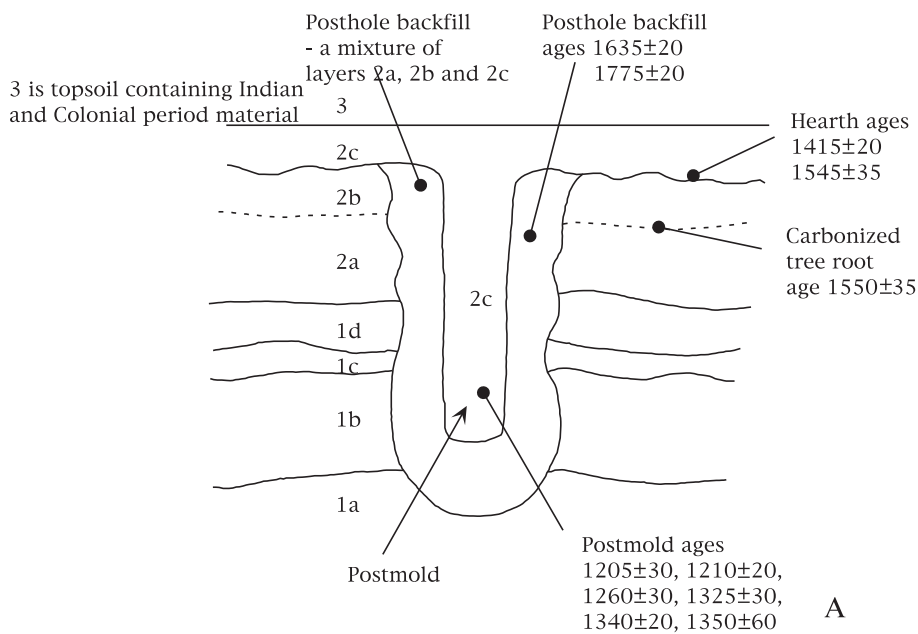


FIGURE 69A. Summary of stratigraphy and radiocarbon ages (in years B.P.) for the Golden Rock archeological site (mainly after Versteeg and Schinkel, 1992).

B. Summary of stratigraphy and radiocarbon ages (in years B.P.) for the Smoke Alley archeological site (after Versteeg et al., 1993, and Schinkel, pers. comm., 1999).

der Valk (1992) that no eruptions had occurred since 8,000 years B.P., these ages were interpreted by the archeologists without question as man-made. Versteeg et al. (1993) interpret them as originating as a first burning down of vegetation, possibly reflecting the time of arrival and first exploitation of St. Eustatius by Indian groups. However, there are some problems with this interpretation for no pottery associated with these early Indians has yet been identified (Schinkel, pers. comm., 1999). We would like to suggest an alternative possibility that these older radiocarbon ages are from charcoal in pyroclastic deposits. This suggestion is based on the fact that the topsoil of the center part of the island is developed on Marker ash flow Unit O and might contain charcoal from vegetation picked up by the pyroclastic flow. At Golden Rock such charcoal could occur in the posthole backfill from disturbed Layers 2a and 2b, and at Smoke Alley be present on the surface of the top soil (developed in Marker Unit O) immediately underlying the midden.

At the present time therefore we consider the age of the most recent erupted bedset to be still unproven but we also consider Marker Units K to O to be considerably younger than 8,000 years.

Petrography of the most recent erupted bedset of the Quill

Representative modal analyses of the volcanic rocks of the most recent erupted bedset are given in Table 17 (in which they are ordered in terms of their relative stratigraphic positions). Photomicrographs of these rocks are presented in Figure 70.

— *Marker Unit K.* This Marker Unit is dominantly composed of low-silica andesite and basaltic andesite both as individual clasts and in comingled clasts.

The andesites all have phenocrysts of plagioclase, hypersthene and augite with the last generally being the most abundant mafic mineral. The plagioclase phenocrysts include both inclusion-free varieties as well as those containing inclusions. The latter can be further subdivided into those containing cores or zones rich in small dusty inclusions, and those with abundant elongated patches of clear brown glass that often occur along boundaries between optically visible compositional zones. These latter crystals usually also show corroded rims suggesting reaction with

TABLE 17. Modal analyses of volcanic rocks from Marker Units K to O of the Quill

	UNIT K							UNIT L	UNIT M		UNIT N	UNIT O
	1		2		3		4					
	EX 162	EX 163	EX 164	EX 165	EX 166	EX 167	E 29	EX 169	EX 170	EX 171	EX 152	EX 148
Plagioclase	32.4	28.0	18.8	19.0	10.8	14.6	18.8	18.4	18.8	19.6	38.2	25.2
Olivine	Tr	Tr	0.0	0.0	0.0	0.0	0.2	0.4	0.0	Tr	Tr	Tr
Hypersthene	4.2	3.4	3.2	1.4	0.2	2.4	2.2	2.6	3.2	3.2	7.0	3.4
Augite	6.8	1.4	2.4	2.2	1.6	4.0	3.4	3.2	1.4	2.6	5.8	0.6
Hornblende	Tr	2.4*	0.0	Tr	0.0	0.0	Tr	0.0	1.0	1.2	0.0	1.6
Oxide	2.4	2.8	0.4	2.6	0.2	1.2	1.2	1.2	2.0	0.6	2.8	0.6
Groundmass	54.2	62.0	74.4	74.8	87.2	74.8	74.2	74.2	73.6	72.8	46.2	68.6

Units indicated by upper horizontal line
Individual beds by lower horizontal line
1,2,3,4 Subunits of Marker Unit K
Tr Trace amounts
* Completely altered to oxides

the host magma. Plagioclase and augite also occur in glomeroporphyritic clusters, which in some cases contain interstitial patches of light brown glass. Pyroxene phenocrysts may also contain glass inclusions. Rare phenocrysts of olivine and microphenocrysts of olive-brown hornblende are sometimes present. Olivine shows reaction rims composed of an inner rim of iron-titanium oxide, surrounded by an outer rim of augite. The groundmass in the andesites varies from intersertal (E-165) to hyalophitic (E-162), with both textures sometimes occurring in the same sample (E-164). The groundmasses also show variable vesicularity. Intersertal groundmass glass is a dusty brown color, whereas the hyalophitic groundmass glass is light brown and clear and occurs either as thin rims around individual crystals or as extensive patches (Fig. 70A).

The basaltic andesites are petrographically similar to the andesites as they also contain phenocrysts of plagioclase, augite, hypersthene, and olivine (similarly altered and rimmed by augite), together with microphenocrysts of iron-titanium oxide. One sample (E-163) also contains phenocrysts of hornblende, which are almost completely replaced by granular aggregates of iron oxide and augite (Fig. 70B). Hyalophitic textures do not occur in the basaltic andesites and the characteristic groundmass texture is intersertal with dusty brown glass.

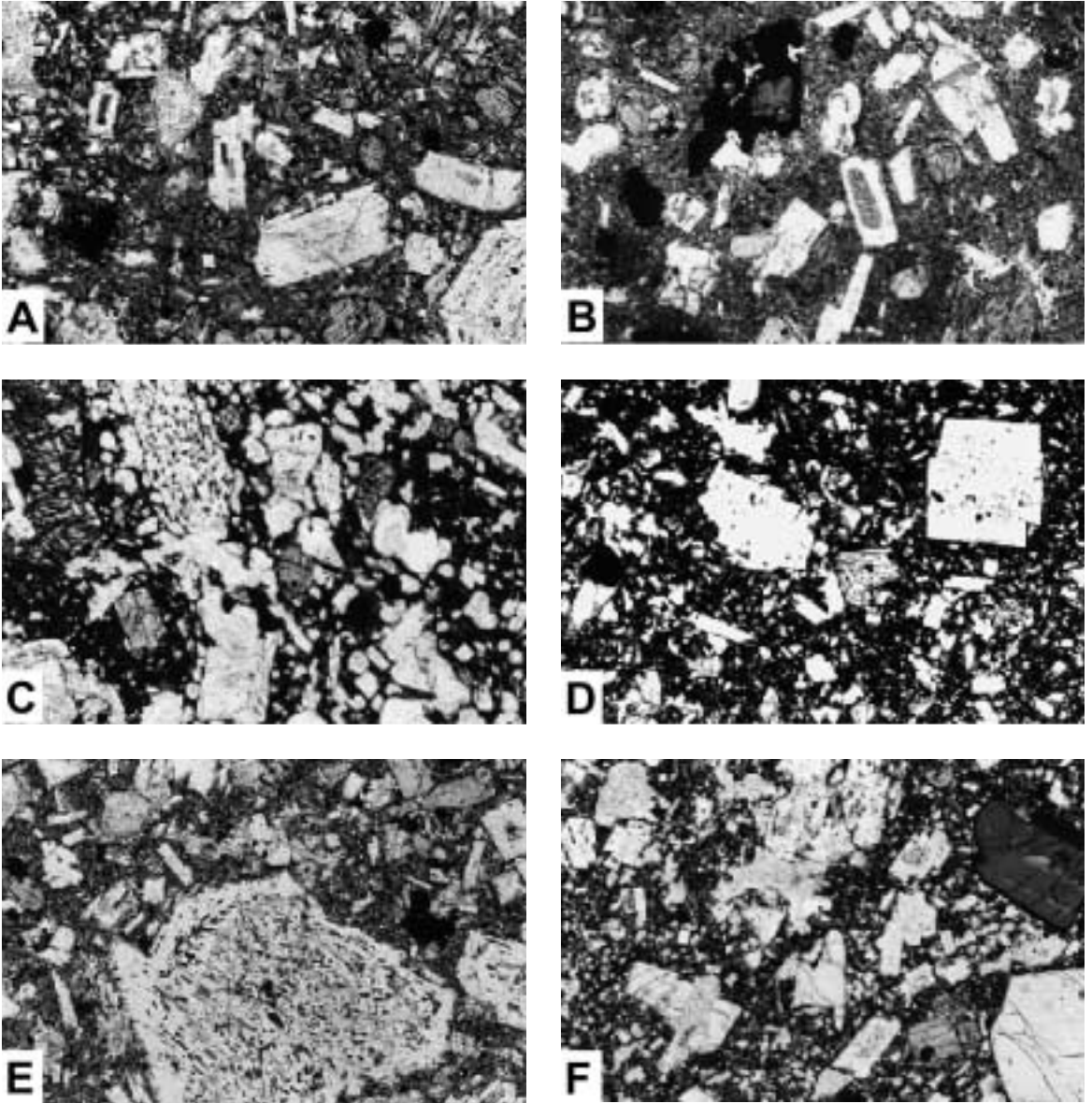


FIGURE 70. Photomicrographs of volcanic rocks from Marker Units K to O. A) Marker Unit K andesite (EX 162) showing plagioclase, augite and Fe-Ti oxide in a glassy groundmass. B) Marker Unit K basaltic andesite (EX 163) showing hornblende rimmed by Fe-Ti oxide, plagioclase and augite in a fine-grained intergranular groundmass. C) Marker Unit L basaltic andesite (EX 169) showing crystals of plagioclase, augite and Fe-Ti oxide. The left and right margins of the photograph show an intersertal groundmass, whereas the center of the photograph shows a hyalophitic groundmass. D) Marker Unit M basaltic andesite (EX 171) M showing crystals of plagioclase and augite in a glassy groundmass. E) Marker Unit N basaltic andesite (EX 152) showing a large inclusion-rich plagioclase, and crystals of augite in a glassy groundmass. F) Marker Unit O (EX 148) showing crystals of plagioclase, augite and hornblende.

— *Marker Unit L.* The rocks from this unit are all basaltic andesites showing two types of plagioclase phenocrysts. One is inclusion-free, and the other has corroded margins and internal elongated solution slots filled with glass. Mafic minerals include phenocrysts of augite, hypersthene, and olivine, and rare microphenocrysts of olive-green hornblende. The phenocrysts are set in a vesicular groundmass composed of plagioclase, pyroxene, and oxide with intersertal dusty brown glass, which passes into irregular patches of highly vesicular dark brown glass (Fig. 70C). Plagioclase crystals in the latter are generally well-formed and inclusion free.

— *Marker Unit M.* This unit is also composed of basaltic andesite with phenocrysts of plagioclase, hypersthene, augite, olive-green hornblende, and sparse olivine (rimmed by hornblende and iron oxide). The plagioclase phenocrysts on the whole are relatively free of glass inclusions (Fig. 70D). The groundmass has an intersertal texture composed of laths of plagioclase, granules of pyroxene and oxide, and dusty brown glass.

— *Marker Unit N.* The basaltic andesites of this unit are composed of plagioclase phenocrysts rich in inclusions of brown glass, hypersthene, augite, and rare olivine (Fig. 70E). Iron-titanium oxide occurs as microphenocrysts. The phenocrysts and microphenocrysts are contained in a hyalophitic groundmass of abundant clear brown glass with small crystals of plagioclase, pyroxene and iron oxide.

— *Marker Unit O.* This unit is composed of basalt containing small inclusion-free plagioclase together with larger crystals containing internal slots filled with glass. Hypersthene, augite, rare olivine, and olive-green hornblende showing thin oxide reaction rims are also present (Fig. 70F). The groundmass texture is intersertal with brown glass filling the spaces between plagioclase, pyroxene and iron oxide crystals.

Mineralogy of the most recent erupted bedset of the Quill

Electron microprobe analyses of phenocryst minerals from volcanic rocks from Marker Units K to O are presented in Tables 18 to 21, and plotted in Figures 71, 72, and 80.

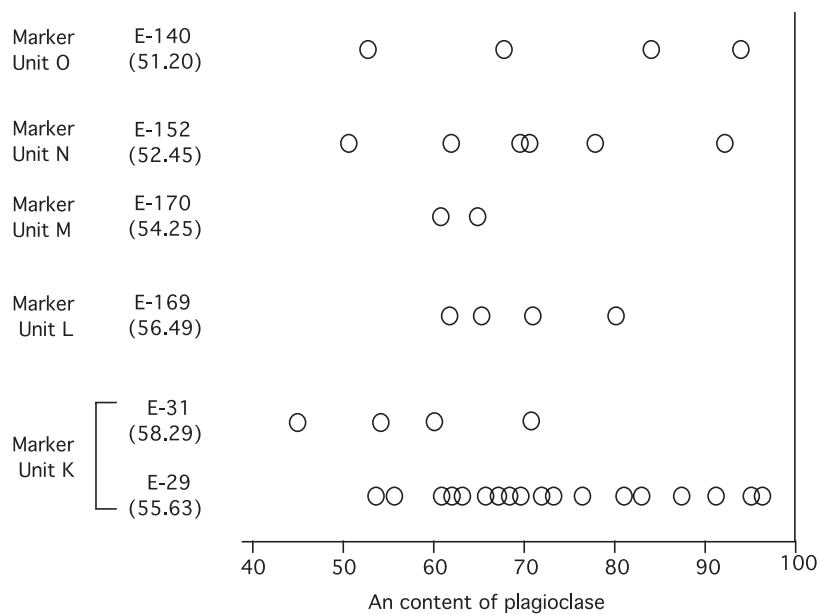


FIGURE 71. Plot of microprobe compositional ranges for plagioclase phenocrysts from the last erupted bedset. Analyses are arranged in stratigraphic sequence from Marker Unit K to Marker Unit O.

TABLE 18. Representative analyses of plagioclases from volcanic rocks from Marker Units K to O of the Quill

	Marker Unit K 4		Marker Unit L	Marker Unit M	Marker Unit N	Marker Unit O
	E-29	E-31	EX-169	EX-170	EX-152	EX-148
SiO ₂	44.36	49.45	47.92	51.00	44.38	43.36
Al ₂ O ₃	34.61	30.85	32.81	29.84	34.81	34.81
Fe ₂ O ₃	0.55	0.62	0.65	0.55	0.36	0.44
CaO	18.70	14.68	16.43	13.33	18.64	19.27
Na ₂ O	0.96	3.24	2.22	3.98	0.87	0.63
K ₂ O	0.00	0.09	0.02	0.05	0.02	0.00
Total	99.18	98.93	100.05	98.75	99.08	98.51
Range in An Content	91-53	71-45	80-62	64-60	92-50	94-52

Analyses by Dr. D. Blatter at UC Berkeley
4 Subunit of Marker Unit K

Plagioclase compositions range from anorthite to andesine, with the majority of analyses falling into the bytownite to labradorite range (An_{80-53}) (Table 18). Anorthite compositions (An_{91}) are only found in the basaltic andesite (E 29) from Marker Unit K, and in the two youngest (and most basic) Marker Units N (An_{92}) and O (An_{94}), whereas plagioclase of andesine composition (An_{45}) has only been recorded from an andesite (E 31) from Marker Unit K.

Mafic minerals include both ortho- and clinopyroxenes (Table 19), olivine (Table 19) and amphibole (Table 20). The pyroxenes which are found in deposits from all Marker Units have similar compositions to those from other volcanic rocks of the Quill, and seem to show no change with stratigraphic position (Fig. 72). Olivine has only been recorded from two samples, E 29 and EX 148, both are fosteritic in composition. Amphiboles from all Marker Units lie between tschermakite and pargasite end members, and are all relatively rich in Al_2O_3 .

Except for an andesite (E 31) from Marker Unit K, which also contained crystals of ilmenite, magnetite was the only iron-titanium oxide analyzed from the most recent erupted bedset (Table 21). Analyses of these two co-existing oxides has allowed the temperature and fugacity of oxygen to be calculated for this sample. The values obtained indicate that the oxides equilibrated at similar temperatures but at slightly lower fO_2 values to the other analyzed Quill volcanic rocks (Fig. 80).

Geochemistry of the most recent erupted bedset of the Quill

Fourteen whole rock chemical analyses were made of large juvenile clasts from Marker Units K to O of the most recent erupted bedset. The chemical analyses are listed according to their relative stratigraphic positions in Table 22, and plotted against stratigraphic position in Figure 73.

Marker Unit K has been subdivided stratigraphically into four subunits (Table 22). Samples from the lower three subunits were collected from three stacked pyroclastic flows from stratigraphic section XII (Plate 5 and Fig. 64). As the lowest flow lies directly on a prominent paleosol it is interpreted as representing the initial eruptive product of Marker Unit K. The fourth subunit, which is interpreted to overlie the other subunits is represented by a lapilli fall bed from stratigraphic section XVIII (Plate 5 and Fig. 64).

TABLE 19. Representative analyses of pyroxenes and olivines from volcanic rocks of Marker Units K to O from the Quill

Marker Unit K 4						Marker Unit L		Marker Unit M		Marker Unit N		Marker Unit O		
	E-29 Cpx	E-29 Opx	E-29 Ol	E-31 Cpx	E-31 Opx	EX-169 Cpx	EX-169 Opx	EX-170 Cpx	EX-170 Opx	EX-152 Cpx	EX-152 Opx	EX-148 Cpx	EX-148 Opx	EX-148 Ol
SiO ₂	51.50	52.89	37.56	51.90	52.29	51.82	52.49	51.73	53.02	52.14	52.62	51.19	52.87	37.85
TiO ₂	0.34	0.17	N.D.	0.45	0.19	0.23	0.27	0.62	0.18	0.35	0.17	0.36	0.11	N.D.
Al ₂ O ₃	2.00	1.08	N.D.	1.96	1.05	1.09	1.11	1.95	0.96	1.62	0.91	1.98	0.65	N.D.
FeO	9.75	20.01	29.52	9.17	20.72	10.45	19.91	9.18	19.89	9.36	20.39	9.53	20.34	19.38
MnO	0.45	0.74	0.63	0.43	0.96	0.63	0.76	0.45	0.83	0.47	0.83	0.41	0.85	0.27
MgO	14.63	23.70	31.74	14.80	23.05	13.82	23.47	14.64	23.36	14.53	23.43	14.27	23.64	41.59
CaO	20.77	1.36	0.40	20.60	1.22	20.69	1.24	21.18	1.40	21.01	1.38	20.81	1.27	0.14
Total	99.44	99.95	99.85	99.31	99.48	98.73	99.25	99.75	99.64	99.48	99.73	98.55	99.73	99.23

Analyses by Dr. D. Blatter at UC Berkeley, except E-29 olivine by A.L. Smith at UPRM
Cpx Clinopyroxene
Opx Orthopyroxene
Ol Olivine
N.D. Not determined
4 Subunit of Marker Unit K

TABLE 20. Representative analyses of amphiboles from volcanic rocks of Marker Units K to O from the Quill

	Marker Unit K	Marker Unit L	Marker Unit M	Marker Unit N	Marker Unit O
	E-29	EX-169	EX-170	EX-152	EX-148
SiO ₂	40.71	40.64	40.48	40.34	39.27
TiO ₂	2.51	2.26	2.31	2.18	2.15
Al ₂ O ₃	14.01	13.08	13.53	13.81	14.58
FeO	11.09	11.54	10.43	10.23	10.50
MnO	N.D.	0.15	0.15	0.08	0.10
MgO	14.16	14.20	14.85	14.93	14.17
CaO	12.35	11.44	11.92	12.10	12.25
Na ₂ O	2.09	2.36	2.50	2.45	2.47
K ₂ O	0.19	0.19	0.22	0.22	0.25
Total	97.12	95.86	96.39	96.34	95.74

Analyses by Dr. D. Blatter at UC Berkeley, except E-29 by A.L. Smith at UPRM
N.D. Not determined

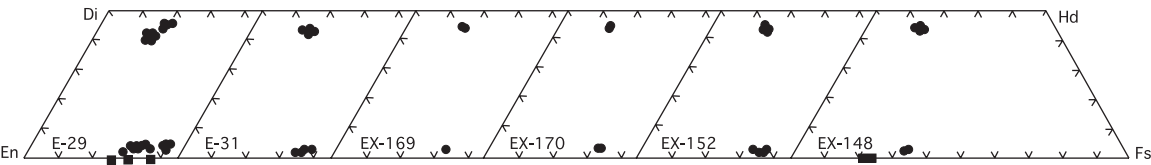


FIGURE 72. Plot of microprobe analyses of pyroxene (●) and olivine phenocrysts (■) from the last erupted bedset. Analyses are arranged in stratigraphic sequence from Marker Unit K to Marker Unit O.

TABLE 21. Representative analyses of Fe-Ti oxides from volcanic rocks of Marker Units K to O of the Quill

	Marker Unit K 4			Marker Unit L	Marker Unit M	Marker Unit N	Marker Unit O
	E-29	E-31	E-31	EX-169	EX-170	EX-152	EX-148
SiO ₂	0.04	0.09	0.04	0.09	0.08	0.08	0.09
TiO ₂	10.76	12.92	44.71	10.54	10.86	12.00	10.92
Al ₂ O ₃	2.86	1.04	0.15	2.79	2.78	2.04	2.79
Cr ₂ O ₃	0.01	0.04	0.04	0.03	0.04	0.03	0.05
Fe ₂ O ₃	45.42	42.30	14.37	45.02	44.49	43.41	44.20
FeO	37.00	40.86	35.83	37.51	37.86	39.37	37.61
MnO	0.51	0.68	0.90	0.55	0.54	0.62	0.53
MgO	2.41	1.09	1.94	2.28	2.26	1.85	2.42
CaO	0.04	0.03	0.05	0.00	0.01	0.00	0.00
Total	99.05	99.05	98.03	98.81	98.92	99.40	98.61
% Usp	26.2	37.3		30.3	31.2	34.3	31.4
% R ₂ O ₃			14.0				
T°C		900					
fO ₂		-11.8					

Analyses by Dr. D. Blatter at UC Berkeley, except E-29 by A.L. Smith at UPRM
Analyses corrected for Fe₂O₃:FeO distribution after Carmichael, 1967.
4 Subunit of Marker Unit K

The initial eruptive product of Marker Unit K (subunit 4) is a co-mingled deposit containing clasts of light-colored andesite flow banded together with dark-colored basaltic andesite, as well as distinct clasts of both rock types (Table 22, Fig. 73). This lower subunit is overlain by andesites (subunits 3 and 2) which have slightly lower SiO_2 contents than the andesite from the first erupted subunit (Fig. 73). The uppermost subunit of Marker Unit K is dominantly composed of co-mingled and basaltic andesite clasts (Table 22). Geochemically the major element compositions of the andesites from Marker Unit K show only minor variations except for TiO_2 and P_2O_5 which decrease and increase up section respectively. Trace elements show somewhat greater variation with V, Cr, and Ni showing an overall decrease, and Sr an increase with higher stratigraphic position, Ba and Rb show essentially no variation with stratigraphic position (Fig. 73). The basaltic andesites from subunits 4 and 1 show somewhat more variation than their associated andesites, Al_2O_3 , Fe_2O_3 , P_2O_5 , V, Rb, and Sr all increase up section, whereas Cr, Ni, and Ba all decrease (Fig. 73).

Unlike Marker Unit K, which is dominantly andesite in composition, the overlying Marker Units L, M, and N are composed of basaltic andesite, whereas the uppermost Marker Unit O is basaltic in composition. These four Marker Units appear to form a related series as they show a systematic change in composition with increasing stratigraphic position (Fig. 73). SiO_2 , Na_2O , K_2O , and Rb all decrease up section, whereas TiO_2 , Al_2O_3 , Fe_2O_3 , MgO , CaO , Cr, and Sr all show a concurrent decrease. The observed variations in P_2O_5 , an initial increase (Marker Units K through M) followed by a decrease (Marker Units N and O) suggest that apatite became a liquidus phase during or subsequent to the eruption of Marker Unit M. Marker Unit M also shows significant increases in V, and Ni when compared to the Units above and below suggesting possible accumulation of magnetite and spinel respectively.

Chondrite-normalized REE analyses from the five Marker Units are shown in Figure 74. All show similar patterns of slight light REE enrichment characteristic of the island arc tholeiitic suite that increases with increasing SiO_2 , and therefore shows a general depletion up the stratigraphy towards the more mafic rocks.

TABLE 22. Chemical composition of volcanic rocks from Marker Units K to O of the Quill

	UNIT K								UNIT L	UNIT M		UNIT N		UNIT O
	4	3		2		1								
	EX 162	EX 163 ¹	EX 164	EX 165	EX 166	EX 167	E 31 ¹	E 29 ¹	EX 169 ²	EX 170 ²	EX 171	EX 172	EX 152 ¹	EX 148 ²
SiO ₂	58.08	56.03	57.76	57.38	57.95	57.63	58.29	55.63	56.49	54.25	53.35	53.96	52.45	51.20
TiO ₂	0.79	0.80	0.72	0.78	0.73	0.77	0.70	0.81	0.80	0.90	0.92	0.89	0.97	0.99
Al ₂ O ₃	17.79	18.24	17.71	18.04	17.75	17.94	17.57	18.84	18.17	18.44	18.97	19.05	19.50	20.65
Fe ₂ O ₃ *	7.55	7.84	7.65	7.75	7.66	7.71	7.59	8.63	8.16	9.21	8.83	8.61	9.13	9.47
MnO	N.D.	0.17	0.18	0.17	0.17	0.17	0.19	0.19	0.17	0.17	0.17	0.18	0.17	0.18
MgO	3.59	4.24	3.45	3.64	3.53	3.70	3.41	3.84	3.82	4.27	4.59	4.52	4.72	4.91
CaO	7.94	8.86	8.23	8.10	7.92	7.96	7.98	8.79	8.32	8.98	9.48	9.13	9.64	9.63
Na ₂ O	3.39	3.27	3.60	3.46	3.59	3.49	3.64	3.41	3.36	3.12	3.07	3.03	2.95	2.64
K ₂ O	0.62	0.46	0.57	0.60	0.59	0.58	0.59	0.54	0.57	0.52	0.48	0.49	0.38	0.25
P ₂ O ₅	0.08	0.07	0.12	0.07	0.11	0.15	0.13	0.12	0.14	0.15	0.13	0.14	0.07	0.07
S	N.D.	N.D.	135	N.D.	N.D.	N.D.	400	540	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Sc	N.D.	N.D.	17	N.D.	N.D.	N.D.	17	20	19	22	N.D.	N.D.	25	26
V	162	186	156	171	159	183	155	201	198	224	244	248	201	206
Cr	37	40	13	37	28	30	15	12	23	17	28	31	29	31
Ni	31	46	9	36	33	42	9	17	31	98	57	71	41	40
Cu	25	15	34	17	14	23	30	36	16	44	10	37	287	316
Rb	11	<10	12	11	11	15	12	11	13	12	11	11	10	10
Sr	253	274	271	261	247	251	275	291	262	274	286	287	274	292
Y	N.D.	N.D.	21	N.D.	N.D.	N.D.	22	21	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Zr	N.D.	N.D.	71	N.D.	N.D.	N.D.	74	65	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Nb	N.D.	130	N.D.	118	2	123	N.D.	129	N.D.	133	N.D.	130	3	129
Ba	3	108	N.D.	123	N.D.	103	N.D.	110	N.D.	114	N.D.	98	N.D.	102
La	N.D.	N.D.	4.5	N.D.	N.D.	N.D.	5.0	4.3	4.6	4.26	N.D.	N.D.	3.78	3.71
Ce	N.D.	N.D.	12	N.D.	N.D.	N.D.	14	12	12.2	12.5	N.D.	N.D.	11.4	10.8
Nd	N.D.	N.D.	9	N.D.	N.D.	N.D.	9	9	8.8	8.9	N.D.	N.D.	7.2	7.1
Sm	N.D.	N.D.	2.15	N.D.	N.D.	N.D.	2.40	2.22	2.44	2.52	N.D.	N.D.	2.29	2.20
Eu	N.D.	N.D.	0.83	N.D.	N.D.	N.D.	0.88	0.78	0.87	0.91	N.D.	N.D.	0.87	0.81
Tb	N.D.	N.D.	0.5	N.D.	N.D.	N.D.	0.5	0.6	0.46	0.53	N.D.	N.D.	0.51	0.42
Yb	N.D.	N.D.	2.29	N.D.	N.D.	N.D.	2.43	2.35	2.21	2.29	N.D.	N.D.	2.09	1.94
Lu	N.D.	N.D.	0.33	N.D.	N.D.	N.D.	0.36	0.33	0.37	0.34	N.D.	N.D.	0.31	0.30
Hf	N.D.	N.D.	2.0	N.D.	N.D.	N.D.	1.9	2.0	1.83	1.79	N.D.	N.D.	1.65	1.68
Th	N.D.	N.D.	0.6	N.D.	N.D.	N.D.	0.6	0.6	0.65	0.56	N.D.	N.D.	0.51	0.62
U	N.D.	N.D.	N.D.	N.D.	0.2	0.5	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.5	0.8
Ta	0.3	0.8	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

Units indicated by upper horizontal line.

Individual beds indicated by lower horizontal line.

4, 3, 2, 1 Subunits of Marker Unit K

N.D. Not determined

¹ Analyzed at ACTLABS

² Selected trace elements analyzed at MIT

³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

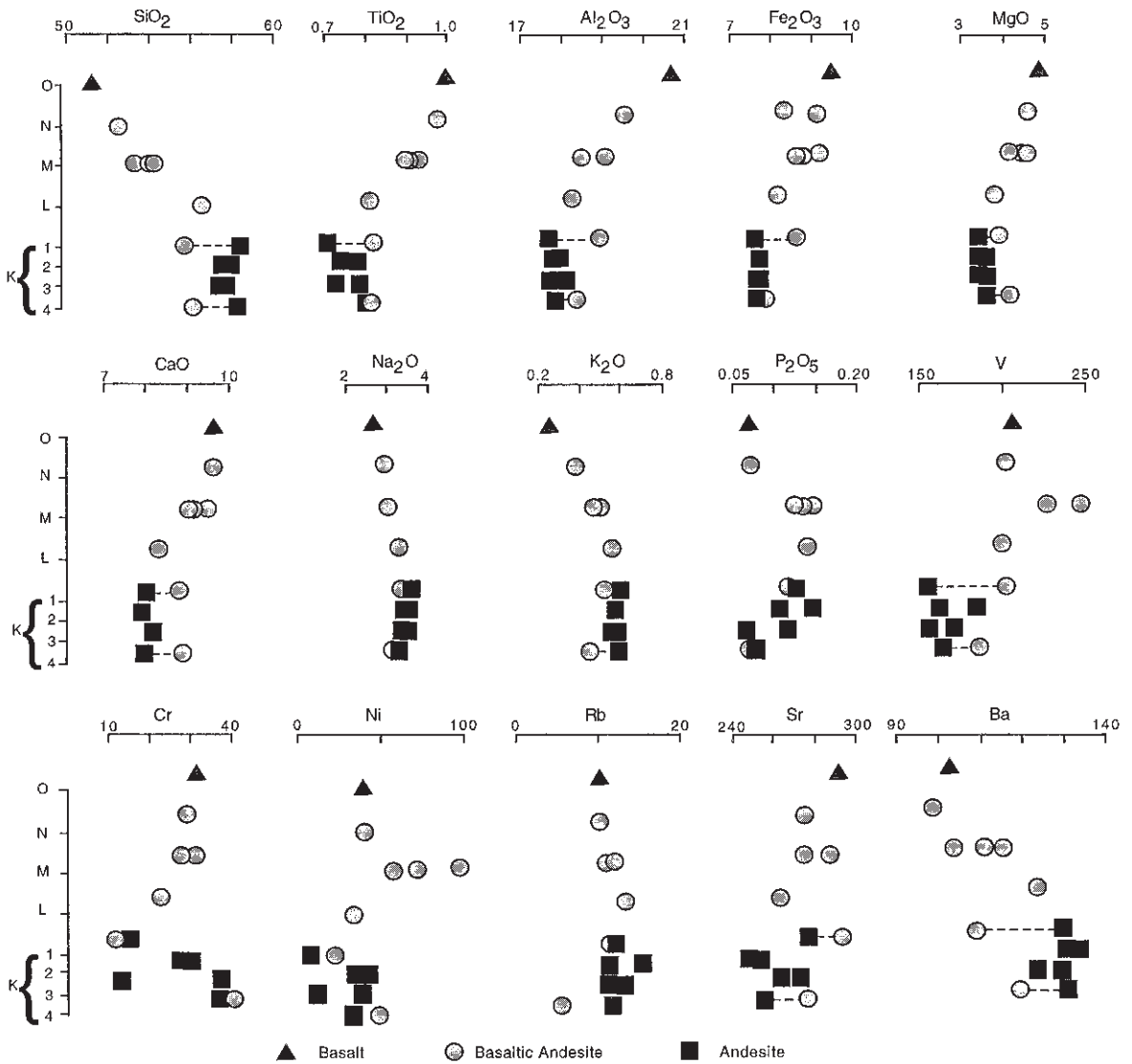


FIGURE 73. Geochemical variations of the last erupted bedset of the Quill. Analyses are arranged in stratigraphic sequence from Marker unit K to Marker unit O.

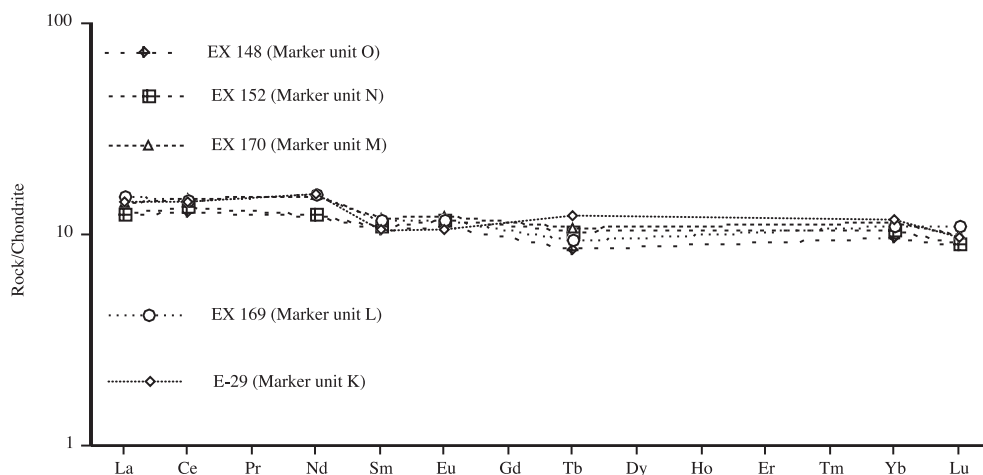


FIGURE 74. Chondrite-normalized REE plots of the last erupted bedset of the Quill (chondrite normalizing factors from Taylor, in Donnelly and Rogers, 1980).

Significance of the geochemical variation of the most recent erupted bedset of the Quill

The deposits of the last erupted bedset show evidence of both fractional crystallization and magma mixing/co-mingling. Variation diagrams indicate that the geochemical variations shown by the suite can be explained by fractionation of the phenocryst phases from a more primitive parent. In addition, magma co-mingling and reheating is amply evidenced by the occurrence of abundant co-mingled clasts in Marker Unit K, with lesser amounts in Marker Units L and M, the occurrence of multiple zones of glass inclusions in plagioclase and pyroxene phenocrysts, the resorption of the margins of plagioclase crystals, and the variability of groundmass textures, glass content, and vesicularity within the same rock.

These characteristics can be explained by invoking the simultaneous emptying and recharge of a high-level magma chamber. It is assumed that prior to the eruption of the last erupted bedset there existed beneath the Quill a compositionally zoned magma chamber. Following the models of Sparks et al. (1981) and Huppert et al. (1982) entry of a fresh batch of basaltic magma into this chamber would heat up the already

existing magma producing overturning and magma mixing, and triggering the eruption of Marker Unit K. The initial products of this eruption provided evidence for the availability of both andesite and basaltic andesite magma as well as clasts showing evidence of incomplete mixing of both compositions. As the eruption of this first unit proceeded basaltic andesite and co-mingled clasts became more abundant (subunit 1) suggesting that most of the andesite had been expelled early on in the eruption. This conclusion is supported by the fact that no andesites and only a small amount of co-mingled clasts have been found from the overlying Marker Units. Marker Units L, M, N, and O in contrast to K show a steady change in composition from basaltic andesite to basalt, suggesting that as the eruption proceeded, deeper and deeper levels of the chamber were being tapped.

Although the above scenario appears to explain the overall eruptive sequence, in detail the geochemical changes are more complex. Variation diagrams indicate the presence of two distinct lineages, suggesting that some of the erupted compositions may represent the newly injected magma (Marker Units O, N, and parts of M and K), whereas the other compositions represent the differentiated magma which was in the chamber at the start of the eruption.

Petrology and petrogenesis of St. Eustatius

PETROGRAPHY OF THE NORTHERN CENTERS

Westermann and Kiel (1961), in their study of St. Eustatius described the Northern Centers as being composed of both olivine-pyroxene phyric andesites and pyroxene-hornblende phyric andesites. In this study a small suite of eight samples was collected from the Northern Centers in order to characterize their petrologic and chemical compositions. Two samples (EUX 408 and EX 141) are from Gilboa Hill, two (EUX 409 and EUX 95-51) from the Mary's Glory center, one (EX 144) from the west side of Signal Hill at Fort Royal and another (EUX 95-50) from the east side of this center, the final two samples (EX 142 and 143) are from Pisgah Hill on the south side of Bergje's dome. Of the eight samples studied, three are olivine-pyroxene andesites, and five are two-pyroxene andesites, unfortunately no hornblende bearing andesites were sampled. Plagioclase is the dominant phenocryst and most crystals are relatively free of small dusty inclusions. The mafic minerals are orthopyroxene and clinopyroxene, with the former being generally the most abundant. Some orthopyroxene crystals are rimmed by clinopyroxene, indicating disequilibrium. Microphenocrysts of iron oxides are present in all samples. Two of the olivine-bearing samples (EX 142 and EX 144) contain large, altered olivine crystals surrounded by reaction rims of elongated iron oxide crystals which are in turn surrounded by granular pyroxenes, the third sample contains microphenocrysts of olivine only. In one sample, a small coarse-grained inclusion composed mainly of plagioclase and pyroxene was observed. The groundmass in all samples is composed dominantly of

plagioclase laths, and granules of pyroxene and oxide. The groundmass plagioclases show both felted and flow textures. Modal analyses of these samples are shown in Table 23, and photomicrographs of typical andesites are shown in Figures 75A and B.

TABLE 23. Modal analyses of selected volcanic rocks from the Northern Centers

	Bergje/Pisgah center	Gilboa center	Mary's Glory center	Signal Hill center
	EX-142	EX-141	EUX 95-51	EUX 95-50
Plagioclase	23.6	36.6	39.0	28.2
Olivine	1.4	0.0	0.0	0.0
Hypersthene	4.2	1.8	2.4	4.4
Augite	5.0	9.2	5.2	6.0
Hornblende	0.0	0.0	0.0	0.0
Oxide	1.0	1.8	2.2	3.0
Groundmass	64.6	50.6	51.2	58.4

PETROGRAPHY OF THE WHITE WALL-SUGAR LOAF VOLCANIC ROCKS

A suite of ten samples was collected from the pyroclastic strata interbedded with the sedimentary rocks of the White Wall-Sugar Loaf ridge. Those from the White Wall range from basaltic andesite through andesite to dacite, whereas those from the Sugar Loaf are dacite and rhyolite only. All of the rocks studied are glass rich and highly vesicular. In the basaltic andesites, andesites, and dacites, the phenocrysts and microphenocrysts are plagioclase, clinopyroxene±orthopyroxene, and iron-titanium oxides. In contrast, the rhyolites contain very sparse microphenocrysts of plagioclase, iron-titanium oxide and pleochroic (colorless to green) amphibole. Modal analyses of the volcanic rocks from the White Wall-Sugar Loaf are shown in Table 24, and photomicrographs of representative samples are shown in Figures 75C to F.

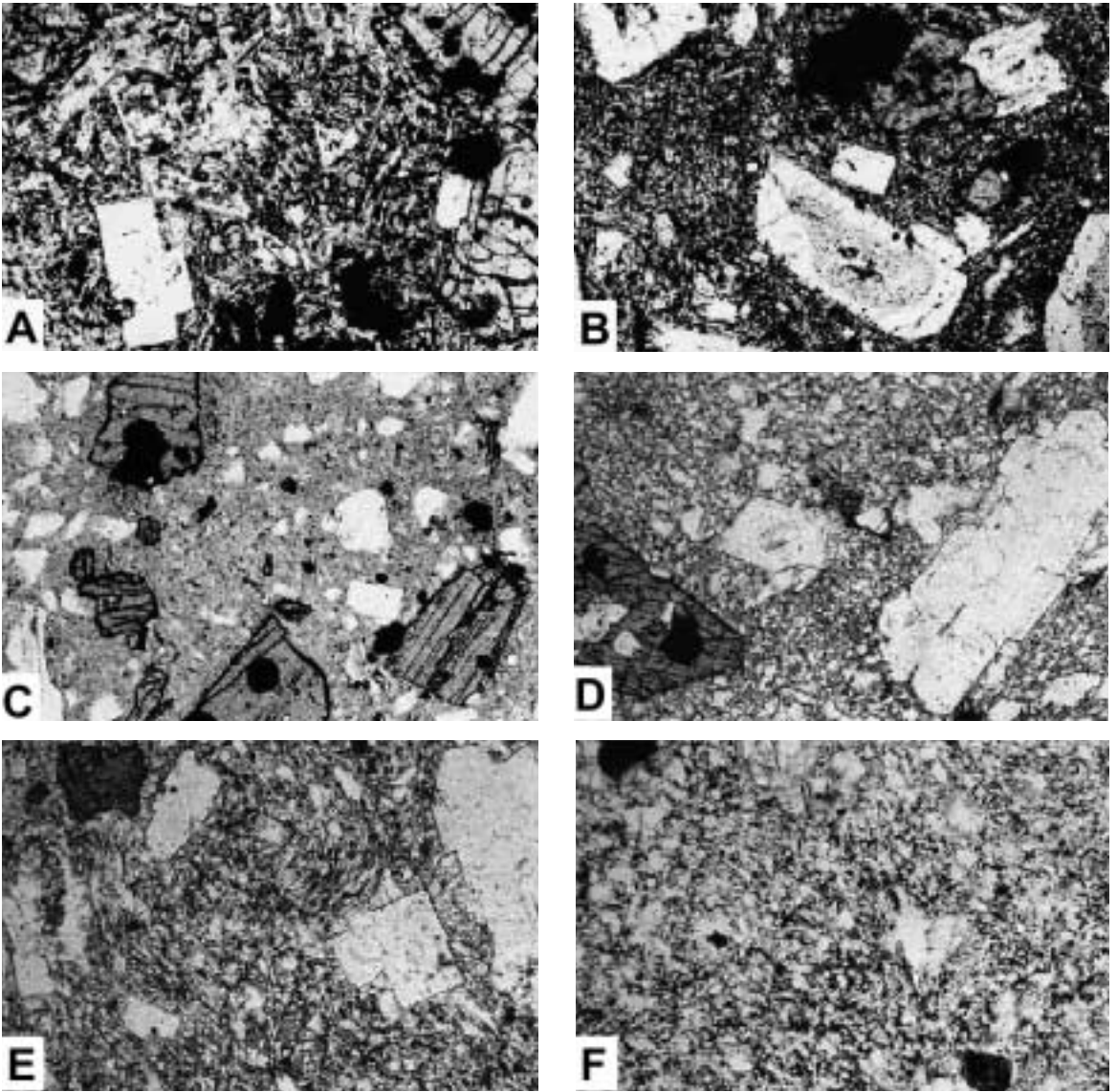


FIGURE 75. Photomicrographs of volcanic rocks from the Northern Centers and the White Wall-Sugar Loaf succession. A) Northern Centers andesite (EX 142) showing phenocrysts of augite, hypersthene, altered olivine, and plagioclase in an intergranular groundmass of plagioclase, clinopyroxene, and oxide. B) Northern Centers andesite (EUX 95-50) showing augite, plagioclase and oxide in an intergranular groundmass with plagioclase laths showing weak felted texture. C) White Wall basaltic andesite (EUX 95-4) showing plagioclase, hypersthene, and augite in a fine-grained glassy groundmass. D) White Wall andesite (EUX 95-17) showing phenocrysts of plagioclase and augite in a vesicular glassy groundmass. E) White Wall dacite (EUX 95-13) showing plagioclase and augite in a vesicular glassy groundmass. F) Sugar Loaf rhyolite (EUX 203) showing microphenocrysts of plagioclase and green hornblende in a highly vesicular glassy groundmass.

TABLE 24. Modal analyses of selected volcanic rocks from the White Wall-Sugar Loaf Succession

	EUX 95-4	EUX 95-17	EUX 95-13	EUX 203
Plagioclase	28.2	13.6	12.0	1.8
Olivine	0.0	0.0	0.0	0.0
Hypersthene	3.6	2.2	0.2	0.0
Augite	5.8	3.4	1.6	0.0
Hornblende	0.0	0.0	0.0	0.2
Oxide	2.2	1.4	1.0	0.2
Groundmass	60.2	79.4	85.2	97.8

PETROGRAPHY OF THE QUILL

The rocks from the Quill range from basalt (2 samples) through basaltic andesite (15 samples), andesite (57 samples), dacite (3 samples), to rhyolite (5 samples). A representative suite was collected with stratigraphic control so that the distribution of the different rock types represents the abundance of the different types of deposits rather than their relative volumes. All samples are porphyritic, although the dacites and rhyolites usually contain only sparse phenocrysts. The dominant minerals in nearly all rocks are plagioclase, hypersthene, augite and iron-titanium oxide, with olivine and hornblende showing a more sporadic distribution. Typical groundmass textures range from microcrystalline to glassy, with plagioclase, pyroxene and oxides being the dominant groundmass minerals in all rock types except the dacites and rhyolites. Representative modal analyses are presented in Table 25, and photomicrographs in Figure 76.

Basalt

In the two basalts, plagioclase is the dominant phenocryst, occurring both as inclusion-free and inclusion-bearing crystals. The most abundant mafic mineral is pyroxene, with augite exceeding hypersthene in abundance. Clinopyroxene also occurs as reaction rims around the hypersthene phenocrysts. Other mafic minerals include colorless to olive green pleochroic

TABLE 25. Modal analyses of selected volcanic rocks from the Quill

	Basalt				Basaltic Andesite								
	EUX 209			EUX 95-2			E 51	E 58.1			E 90		
Plagioclase	19.2			6.2			17.8	23.4			29.0		
Quartz	0.0			0.0			0.0	0.0			0.0		
Olivine	1.0			0.0			0.4	Tr			0.0		
Hypersthene	0.4			0.0			1.8	2.0			1.4		
Augite	4.8			Tr			5.2	7.6			3.8		
Hornblende	7.4			0.4			0.8	1.0*			0.0		
Iron Oxide	0.6			0.6			0.4	1.6			1.8		
Groundmass	66.6			92.8			73.6	64.4			64.0		
Stratigraphic Unit	1			1			2	4			6		
SiO ₂ (Wt%)	50.46			55.92			55.30	55.92			56.09		
Andesite													
	E 35	EUX 403	E 49	E 47	E 12	E 56	E 1	E 10	E 63	E 44	E 93	E 21	E 85
Plagioclase	4.8	3.8	14.0	22.4	15.0	22.0	22.0	13.2	11.0	19.0	38.6	20.8	12.4
Quartz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Olivine	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
Hypersthene	0.0	0.0	0.2	0.6	1.6	2.8	1.4	1.0	4.6	0.4	2.4	1.0	1.0
Augite	0.6	Tr	4.8	5.2	5.6	3.2	4.8	3.6	2.8	6.0	6.4	3.0	2.8
Hornblende	0.4	0.2	0.8	0.6*	2.4	1.6	0.0	0.2	0.4	0.0	0.0	0.0	0.4
Iron Oxide	0.4	0.8	1.4	1.4	0.8	1.8	2.4	1.6	1.0	1.0	3.4	0.2	1.0
Groundmass	93.8	95.8	78.0	69.8	74.6	68.6	69.4	80.4	80.2	73.6	49.2	74.0	82.4
Stratigraphic Unit	1	1	2	2	4	4	4	5	5	5	6	6	6
SiO ₂ (Wt%)	58.45	59.63	58.56	59.41	57.44	61.20	61.31	57.31	58.92	60.35	57.59	59.23	61.08
Dacite													
Rhyolite													
	E 18			E 13			E 15			E 19			
Plagioclase	6.0			6.2			1.8			1.0			
Quartz	1.0			0.0			0.0			0.0			
Olivine	Tr			0.0			0.0			0.0			
Hypersthene	0.0			0.4			0.0			0.0			
Augite	0.0			0.0			0.0			0.0			
Hornblende	1.0			1.2			0.4			Tr			
Iron Oxide	0.4			1.0			0.0			0.0			
Groundmass	91.6			91.2			97.8			99.0			
Stratigraphic Unit	3			3			2			2			
SiO ₂ (Wt%)	64.92			67.68			72.13			72.26			

* All or most crystals completely replaced by iron oxides
Tr Trace amounts

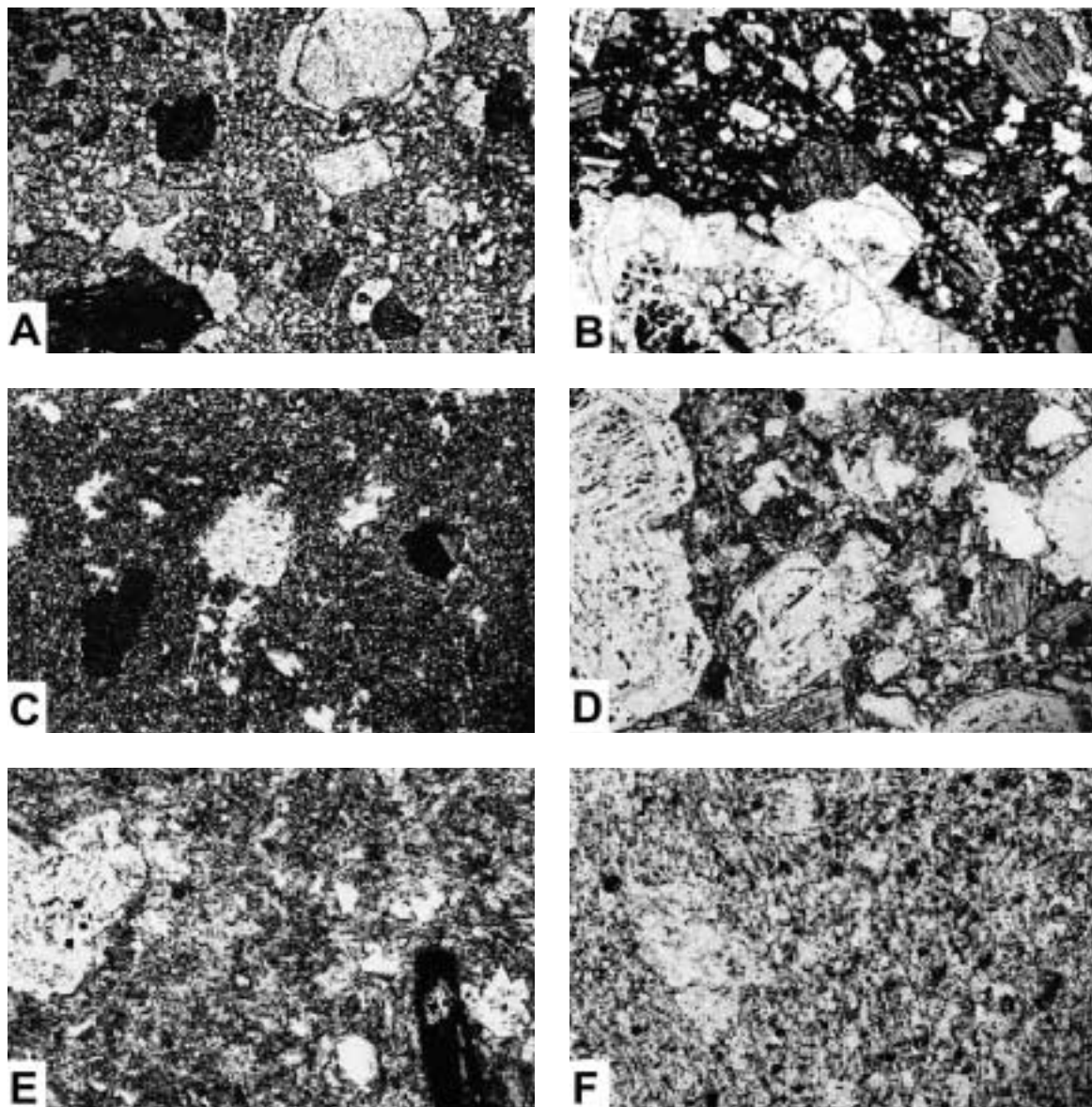


FIGURE 76. Photomicrographs of volcanic rocks of the Quill. A) Basalt (EUX 209) showing phenocrysts of plagioclase, olive green hornblende and augite in a vesicular glassy groundmass. B) Basaltic andesite (E 90) showing plagioclase phenocrysts (rich in inclusions of glass, pyroxene and oxide), hypersthene, and augite in a vesicular glassy groundmass. C) Andesite (EUX 403) showing phenocrysts of olive green hornblende and plagioclase in a fine-grained glassy groundmass. D) Andesite (E 93) showing inclusion-rich plagioclase phenocrysts, hypersthene, and augite in an intersertal groundmass. E) Dacite (E 13) showing phenocrysts of plagioclase and hornblende (almost totally replaced by iron oxides) in a fine-grained glassy groundmass. F) Rhyolite (E 19) showing plagioclase phenocrysts in a highly vesicular glassy groundmass.

hornblende, and sporadic crystals of olivine. The former are usually surrounded by thin reaction rims of oxide. (Table 25). The groundmass is composed of plagioclase, pyroxene, iron-titanium oxide and interstitial brown glass.

Basaltic Andesite

All of the basaltic andesites studied are highly porphyritic, with plagioclase as the most abundant phenocryst. In some samples, glomerophyritic clusters of plagioclase containing abundant glass-rich inclusions are common. The mafic mineral assemblage is the same as that described for the basalts, but in the case of the basaltic andesites, hypersthene is usually the dominant mafic phenocryst. Hornblende, which occurs in two-thirds of the samples, is found as three varieties, which are sometimes all present in the same sample. The most common variety are crystals surrounded by reaction rims of iron-titanium oxide and pyroxene. The other varieties are those that show no reaction relationship, and those that have been completely replaced by iron-titanium oxides and pyroxene. Olivine, with modal percentages of <1.0%, is again only a minor accessory mineral (Table 25). Groundmass compositions are the same as those described for basalts.

Andesite

Andesite is the dominant rock type on St. Eustatius as it was on Saba. Plagioclase is the most abundant phenocryst varying from 4.8 to 38.6% (Table 25). It again is found as inclusion-free and inclusion-rich varieties. Two pyroxenes are present in most samples, with augite usually being the more abundant. Olivine is again relatively scarce, and when it does occur, it usually shows a reaction rim of pyroxene. Hornblende, which usually only makes up a small percentage of the phenocrysts (up to 2.4%), shows the same three varieties as described from the basaltic andesites – completely replaced by iron-titanium oxides and pyroxene, partly replaced by these minerals, or with no reaction relationship. The groundmass in pumiceous varieties is composed of abundant plagioclase lathes, often showing fluidal texture, granules of pyroxene and iron-titanium oxide in a vesicular clear glass. The groundmass in non-pumiceous andesites is also composed of plagioclase, pyroxene and oxide but this time set in a brown glass. In the latter however the pyroxenes appear to be somewhat more abundant, and the plagioclase less abundant than in the former.

Dacite

All of the dacites studied are phenocryst poor (<8% total phenocrysts), glass-rich highly-vesicular pumices. Hornblende and plagioclase occur as euhedral phenocrysts lacking a reaction relationship. Microphenocrysts of hypersthene $\pm$ augite are also present. The groundmass is composed entirely of colorless, vesicular glass. One sample (E 18) also contains rounded, partially resorbed bipyramidal quartz, as well as olivine with reaction rims of hornblende suggesting mixing of magmas.

Rhyolite

The rhyolites are composed almost entirely of highly vesicular colorless glass. Sparse phenocryst phases include inclusion-rich plagioclase and green pleochroic hornblende without any reaction rims.

EXOTIC BLOCKS EJECTED FROM THE QUILL VOLCANO

Like Saba, the Quill has ejected a variety of inclusions which reveal much about the substructure of the volcano. Characteristically the rounded hypabyssal inclusions, so common on Saba, are entirely absent from the lavas of the Quill. The different types of inclusions are next described, and are shown in photomicrographs in Figure 77.

Ejected cumulate blocks

Coarse-grained plutonic blocks are sparsely present in the pyroclastic deposits of the Quill. Westermann and Kiel (1961) petrographically identified as a hornblende diorite an inclusion from the western slopes of the Quill. The sample was described as containing plagioclase, green pleochroic hornblende and minor opaque oxides. They also mention gabbroic inclusions in a scoria deposit near Round Hill. Wills (1974), and Arculus and Wills (1980) also described plutonic blocks from the Quill, which they ascribed to a cumulate origin. The blocks were dominantly composed of plagioclase, hornblende and oxide, although a few samples were noted to contain minor clinopyroxene, orthopyroxene, and olivine.

During the present study, ten blocks were collected from the pyroclastic deposits around the Quill volcano. With one exception (E 36),

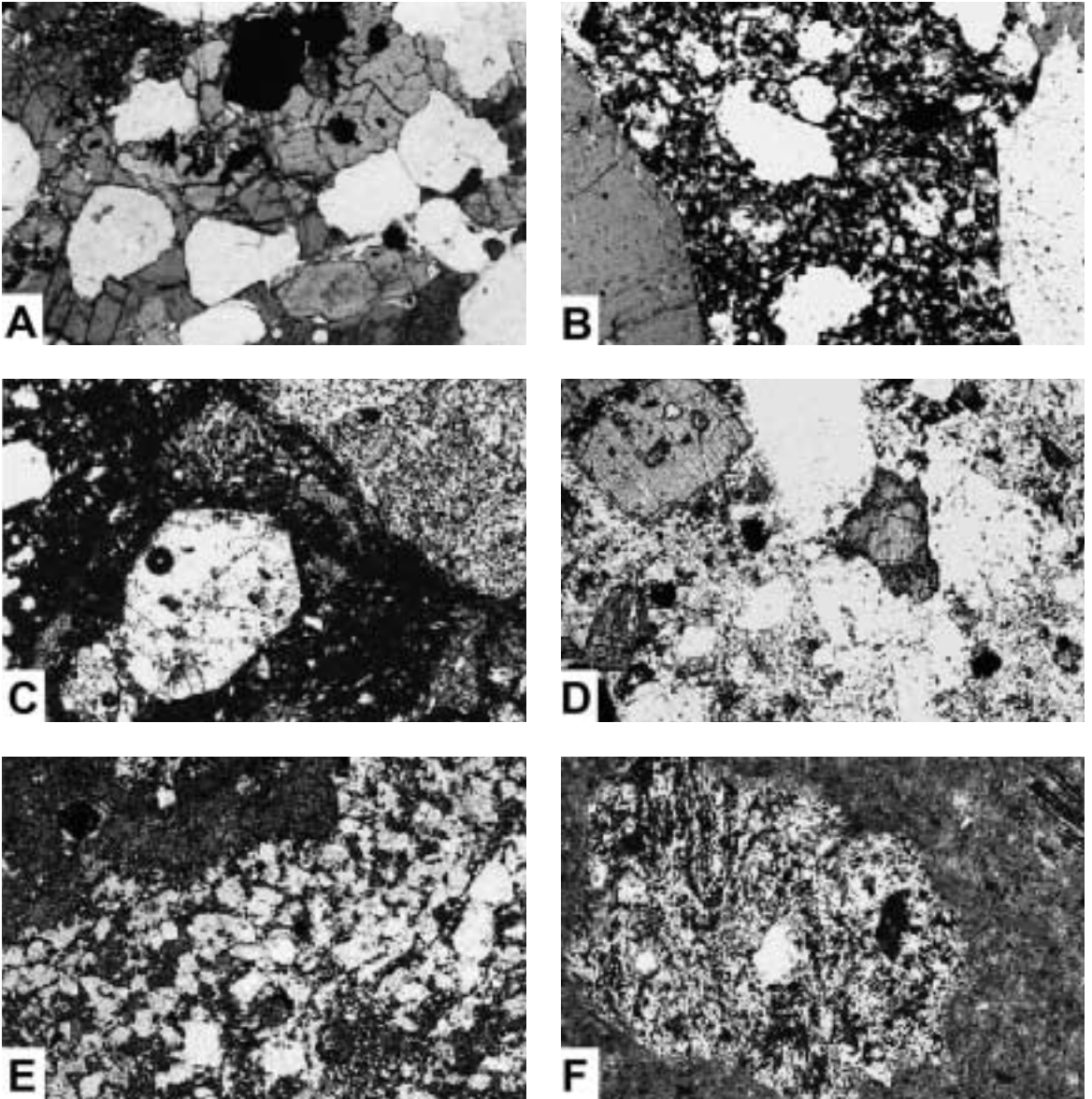


FIGURE 77. Photomicrographs of inclusions in volcanic rocks from the Quill. A) Hornblende-augite-plagioclase-oxide cumulate (EUX 407). B) Hornblende-plagioclase cumulate (EUX 420) with extensive areas of interstitial vesicular basalt. C) Volcaniclastic sandstone (EUX 98-11-14) showing various volcanic clasts. The large triangular-shaped clast contains patches of epidote and contains as an inclusion an older quartz-feldspar clast (white clast). D) Plagioclase-augite crystal tuff (EUX 971-32). E) Plagioclase-amphibole (acicular crystals) metalava (EUX 971-4). F) Fragment of pumice in a fine-grained limestone from the Sugar Loaf succession (EUX 401). Width of field is 2 mm.

TABLE 26. Modal analyses of selected plutonic blocks from the Quill

	EUX 406	EUX 407	EUX A	EUX B
Plagioclase	63.6	69.2	9.0	40.8
Olivine	0	0	0	0
Hypersthene	0	0.2	0	0
Augite	17.6	14.2	1.4	1.0
Hornblende	13.8	10.0	53.6	57.6
Biotite	0	0	0	0
Oxide	0	5.0	0	0
Glass/Groundmass	5.0	1.4	36.0	0.6

the blocks are composed of unzoned plagioclase; equant, colorless to olive green amphibole; augite; minor iron-titanium oxides, and variable amounts of interstitial fine-grained basalt/basaltic andesite composed of skeletal crystals of plagioclase, granules of pyroxene and oxide in a dark vesicular glass. Following the work of Arculus and Wills (1980), the blocks described here have also been interpreted as having a cumulate origin. In contrast, sample E-36, is a coarse-grained holocrystalline gabbroic inclusion composed of optically zoned plagioclase, clinopyroxene, orthopyroxene, and iron-titanium oxide, and probably represents the products of crystallization of magma at a high level in the volcanic edifice. Representative modal analyses are shown in Table 26. Photomicrographs of typical cumulate blocks are shown in Figures 77A and B.

There appears to be therefore two types of plutonic blocks ejected from the Quill. The most common are coarse-grained cumulate blocks whose chemistry is described in a later section but which range in SiO_2 content from 41 to 45%. It is believed that the sample described by Westermann and Kiel (1961) as a hornblende diorite is probably also a cumulate. With very few exceptions the cumulate blocks from the Quill appear to have a constant mineralogy of plagioclase, hornblende, augite and iron-titanium oxides, in contrast, cumulate blocks from Mt. Pelée, Martinique show a much greater range of cumulate mineral assemblages

(Smith and Roobol, 1990, Table 10). A possible explanation for this difference is that under Mt. Pelée there could exist multiple magma chambers at different depths within the crust, thus allowing a variety of cumulate minerals to crystalize, whereas under the Quill the crustal magma chamber(s) are either fewer, or occur at a restricted depth range, thus limiting the minerals that could crystalize from the magma. The other type of plutonic block being ejected from the Quill is a normal coarse-grained gabbro lacking hornblende, and probably represents the crystallization of phenocrystal minerals at a high level in the volcanic edifice.

Ejected blocks of green metavolcanic and metavolcaniclastic rocks

Along the eastern shore of St. Eustatius between Behind the Mountain and Compagnie Bay, and on the west coast at Kay Bay, green metavolcanic and metavolcaniclastic rocks are found as lithic clasts in the pyroclastic deposits. Such clasts are particularly common as beach pebbles eroded from the eastern sea cliffs. Similar rocks, in the vicinity of the harbor at Oranjestad on the west coast were not collected as a breakwater was recently constructed there of volcaniclastic rocks brought from off-island.

The green metavolcanic and metavolcaniclastic lithic blocks in the pyroclastic deposits of the Quill are thought to have been derived from the submarine banks beneath the volcano. These blocks are dominantly tuffs and volcanic sandstones (Fig. 77C), although a few fragments of lava were also collected. The former are composed of various combinations of crystals (plagioclase $\pm$ pyroxene $\pm$ amphibole) and lava fragments (basalt/andesite) set in a fine-grained matrix of plagioclase and epidote (Fig. 77D), with a few samples also containing chlorite and a brown amphibole of secondary origin. One sample was somewhat distinct in that it was composed of green amphibole and plagioclase, with minor epidote and white mica (Fig. 77E). In most of the greenstones, apart from some replacement of the margins of the mafic crystals by chlorite, the crystal and lithic fragments are relatively unaltered, with their characteristic green color being imparted by the abundant epidote in the matrix. The abundance of epidote and the paucity of hydrous minerals in the majority of these rocks suggest that they were metamorphosed in a low-grade anhydrous metamorphic environment that did not reach

greenschist facies. Possible exceptions to this conclusion are those samples containing the green and brown amphiboles, which suggest that both greenschist and amphibolite facies could also be present in the banks beneath the volcano.

Ejected blocks of limestone

Angular blocks and fragments of white limestone ranging up to 30 cm diameter are commonly found in the older pyroclastic deposits of the Quill. Small limestone fragments are very common in the base surge deposits of Stratigraphic Division 1, whereas larger blocks are common in the lower pumiceous deposits of Stratigraphic Division 2. A large white limestone block from the lower ignimbrite in Compagnie Bay (stratigraphic section V, Plate 5) contained a crushed fossil crab measuring 8 cm in diameter. Petrographically the limestones are composed of a matrix of granular calcite containing lithic and biological fragments. The former includes lava fragments and pumice. The latter are made up of red algae, shell fragments and foraminifera. The foraminifera have been identified as possible hayaline varieties suggestive of a saline environment (H. Santos, pers. comm., 1998). In some samples the organic fragments have been dissolved leaving only a mold of their original shape. The origin of these limestone blocks is obviously the platform carbonate cover of the marine bank on which the Quill is built, and which is exposed in the uptilted limestones of the White Wall-Sugar Loaf ridge.

MINERALOGY OF THE QUILL

Electron microprobe analyses of representative minerals in the volcanic rocks of the Quill, St. Eustatius were carried out on a Cambridge Geoscan instrument at the University of Manchester, and on a Cameca instrument at the University of Puerto Rico. Selected representative analyses are presented in Tables 27 to 32 where they are ordered in terms of the increasing silica content of their host rocks. The boundaries between the different rock types are also shown in these tables. Analyses of minerals from plutonic blocks are shown in Table 33.

TABLE 27. Representative microprobe analyses of plagioclases from volcanic rocks of the Quill

Basaltic Andesite					Andesite										Dacite			Rhyolite
	E-51	E-20	E-27	E-26	E-10	E-23	E-12	E-6	E-9	E-52	E-11	E-5	E-53	E-4	E-17	E-18	E-13	E-19
SiO ₂	46.05	51.51	50.07	54.60	50.01	50.75	49.91	44.12	51.57	49.26	48.61	46.51	49.92	43.72	51.40	58.88	49.38	55.89
Al ₂ O ₃	34.15	30.66	32.04	28.09	30.83	30.86	31.59	35.19	30.70	31.43	33.18	33.23	32.35	34.74	30.95	25.80	30.90	27.66
Fe ₂ O ₃	0.84	0.31	0.48	0.71	0.67	0.58	0.39	0.27	0.58	0.42	0.27	0.60	0.34	0.43	0.51	0.21	0.39	0.14
CaO	17.93	14.05	15.03	11.48	14.64	13.97	15.05	18.29	13.91	14.90	15.02	17.99	14.94	19.65	13.33	7.93	14.68	9.98
Na ₂ O	1.38	3.64	2.66	5.14	3.31	3.51	2.85	0.51	3.75	3.27	2.44	1.37	2.76	0.55	3.74	7.42	3.26	5.81
K ₂ O	0.06	0.04	0.07	<0.01	0.08	0.09	<0.01	<0.01	0.11	0.06	0.01	<0.01	0.03	<0.01	0.02	<0.01	<0.01	0.09
Total	100.41	100.21	100.35	100.02	99.54	99.76	99.79	98.38	100.02	100.62	99.53	99.70	100.34	99.09	99.95	100.24	98.61	99.57
Range in An Content	92-59	86-51	88-54	93-53	92-46	88-35	77-57	95-53	90-53	83-43	93-54	91-43	74-26	90-49	86-54	52-36	74-48	70-46

Plagioclase

Representative microprobe analyses of plagioclase are shown in Table 27, and plotted in Figure 78, where they are divided into three groups:

- 1) Relatively large unzoned crystals free of inclusions which are present in the basalts, basaltic andesites and andesites but apparently absent from the more silicic volcanic rocks. These plagioclases have relatively homogeneous anorthitic compositions essentially the same as that recorded from the plutonic blocks (Table 33), and are regarded as xenocrysts.
- 2) Large to medium sized, strongly zoned crystals which may or may not contain zones or cores of dusty inclusions. These crystals which are interpreted as phenocrysts, generally show normal zoning, although both oscillatory and/or reverse zoning are present in some samples. Although plagioclase phenocrysts in the more silicic rocks are generally more sodic than those in the more basic, there appears to be no systematic relationship between the composition of the plagioclase phenocrysts and that of their host rock.
- 3) Small plagioclase laths confined to the groundmass. Again, although somewhat erratic, there does seem to be a general shift in groundmass plagioclase composition towards more albitic compositions from basaltic andesites to rhyolites.

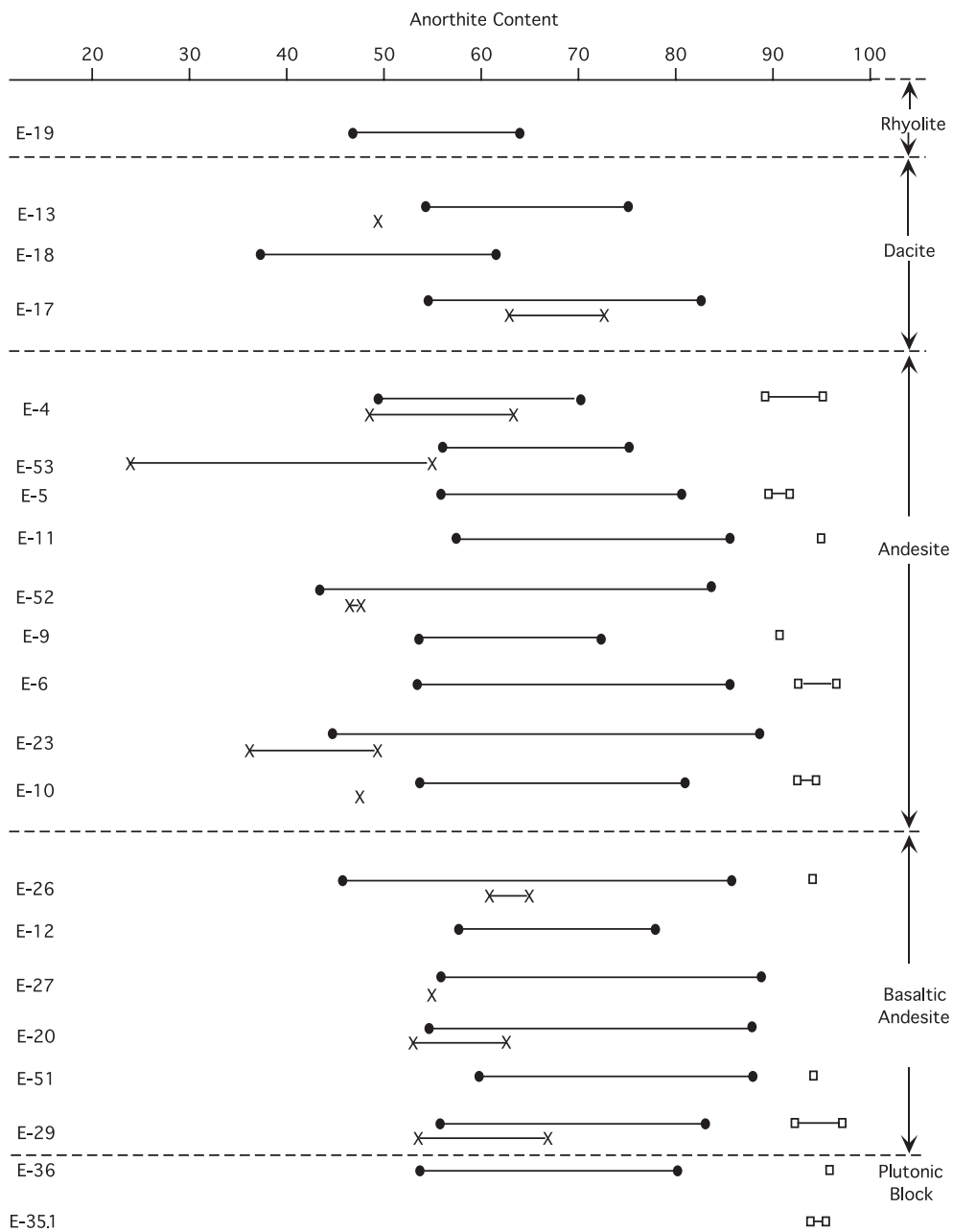


FIGURE 78. Plot of microprobe compositional ranges for plagioclase phenocrysts and groundmass crystals of volcanic rocks of the Quill. □— large, essentially unzoned anorthite crystals; • — phenocrysts; × — groundmass

TABLE 28. Representative microprobe analyses of clinopyroxenes from volcanic rocks of the Quill

	Basaltic Andesite				Andesite										Dacite	
	E-51	E-20	E-27	E-26	E-10	E-23	E-12	E-6	E-9	E-52	E-11	E-5	E-53	E-4	E-17	E-13
SiO ₂	52.30	52.02	51.46	52.22	51.90	52.59	51.46	48.14	51.02	52.33	51.87	50.65	49.11	50.79	52.40	52.42
TiO ₂	0.50	0.14	0.40	0.22	0.57	0.18	0.21	1.25	0.30	0.32	0.28	0.50	0.78	0.48	0.14	0.16
Al ₂ O ₃	3.64	1.19	1.69	1.07	1.97	1.04	1.06	6.43	1.30	1.24	1.40	4.76	5.40	2.86	1.20	1.48
FeO	6.32	10.54	10.61	10.32	9.71	10.55	11.08	9.07	9.44	10.56	10.99	6.78	8.49	8.45	10.76	9.62
MnO	0.05	0.59	0.49	0.48	0.44	0.59	0.59	0.34	0.41	0.23	0.55	N.D.	0.33	0.30	0.55	0.44
MgO	16.00	14.19	14.55	13.85	14.44	14.30	13.56	12.86	14.13	14.24	14.12	15.48	14.32	14.29	13.43	14.26
CaO	20.85	21.06	20.05	21.91	20.55	20.08	20.66	21.19	20.84	19.63	19.83	21.66	21.57	22.28	21.06	18.85
Total	99.66	99.73	99.25	100.07	99.58	99.33	98.62	99.28	97.44	98.55	99.04	99.83	100.00	99.45	99.54	97.23

N.D. Not determined

All of the three plagioclase types are very poor in potassium, with the highest values being recorded in the more albitic phenocrysts and ground-mass crystals.

Clinopyroxene

Selected representative microprobe analyses of clinopyroxenes are shown in Table 28. The clinopyroxene phenocrysts are augites with a very small compositional range irrespective of the composition of their host rock (Fig. 79). No clinopyroxenes have been observed in the rhyolites. In some basaltic andesites and andesites, occasional phenocrysts and more commonly groundmass pyroxenes of subcalcic augite occur (Fig. 79).

Orthopyroxene

Selected representative analyses of orthopyroxenes are shown in Table 29. In contrast to the clinopyroxenes, the orthopyroxenes in the basaltic andesites, andesites and dacites occupy partially overlapping fields that become richer in ferrosilite with increasing silica content of the host rock (Fig. 79). The composition of orthopyroxene in a cumulate block (Arculus and Wills, 1980) is similar to that from the basic and intermediate

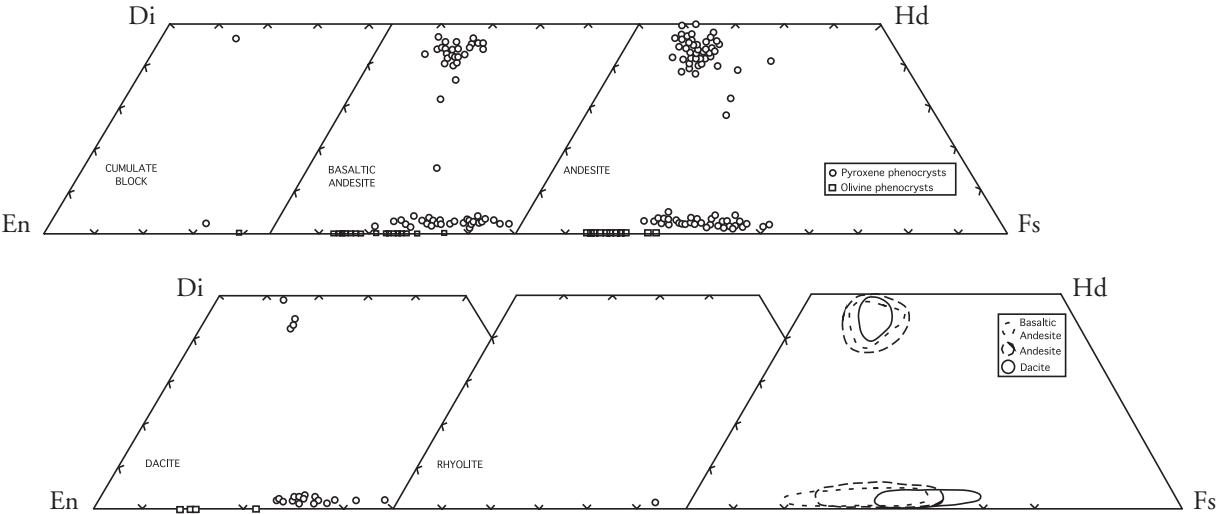


FIGURE 79. Plot of microprobe analyses of pyroxene (○) and olivine (□) phenocrysts in the volcanic rocks of the Quill, and from a cumulate block.

TABLE 29. Representative microprobe analyses of orthopyroxenes from volcanic rocks of the Quill

Basaltic Andesite					Andesite										Dacite			Rhyolite
E-51	E-20	E-27	E-26		E-10	E-23	E-12	E-6	E-9	E-52	E-11	E-5	E-53	E-4	E-17	E-18	E-13	E-19
SiO ₂	52.51	52.74	53.91	53.31	54.08	53.47	52.76	51.94	52.14	52.85	53.13	52.36	54.04	52.54	51.82	52.37	52.42	50.99
TiO ₂	0.06	N.D.	0.11	N.D.	0.17	0.12	0.19	N.D.	0.10	0.19	0.17	0.20	0.21	N.D.	0.07	0.09	0.13	0.09
Al ₂ O ₃	0.71	0.35	0.96	0.63	0.94	0.79	0.41	0.48	0.87	1.40	0.55	2.22	1.85	0.27	0.32	0.40	1.06	1.23
FeO	24.05	21.78	19.98	21.64	19.94	19.69	22.80	25.62	22.13	19.15	22.72	20.44	17.08	25.95	24.16	27.56	23.71	30.60
MnO	1.49	1.23	0.91	0.69	0.88	1.11	0.87	1.84	0.89	0.68	1.13	0.63	0.70	1.42	1.51	1.81	1.58	2.10
MgO	20.44	22.15	23.14	23.10	23.73	23.39	21.54	18.56	21.68	24.61	20.86	21.96	25.59	19.78	20.51	17.05	19.76	15.46
CaO	0.95	1.24	1.13	1.25	1.37	1.23	1.35	0.74	1.14	1.18	1.25	1.74	1.36	0.90	0.88	1.10	1.31	0.85
Total	100.21	99.49	100.14	100.62	101.11	99.80	99.92	99.18	98.95	100.06	99.81	99.58	100.83	100.86	99.27	100.32	99.73	101.32

N.D. Not determined

TABLE 30. Representative microprobe analyses of olivines from volcanic rocks of the Quill

	Basaltic Andesite				Andesite								Dacite	
	E-51	E-20	E-27	E-26	E-10	E-12	E-6	E-9	E-52	E-5	E-53	E-4	E-17	E-13
SiO ₂	41.09	39.95	38.87	38.76	39.16	40.14	39.15	39.90	39.56	40.68	39.59	38.92	39.48	37.61
FeO	16.60	15.22	22.85	24.28	24.53	15.63	17.01	14.87	16.30	13.76	20.45	20.22	18.42	27.88
MnO	0.25	0.17	0.29	0.74	0.55	0.22	0.18	N.D.	0.22	0.19	0.39	0.28	0.36	0.64
MgO	42.64	45.33	38.69	36.62	34.68	44.72	42.54	44.19	44.61	46.00	39.68	40.52	40.83	33.35
CaO	0.19	0.25	0.20	0.32	0.41	0.14	0.15	0.16	0.17	0.13	0.06	0.15	0.17	0.13
Total	100.77	100.92	100.90	100.72	99.33	100.85	99.03	99.12	100.86	100.76	100.17	100.69	99.26	99.61

N.D. Not determined

volcanic rocks. In a number of samples, groundmass orthopyroxenes are richer in enstatite than their associated phenocrysts suggesting that the larger orthopyroxene crystals could either be xenocrysts in a hybrid magma, or the compositional differences could be the result of reheating of the magma by injection of hotter more basic magma, as proposed for the most recent erupted bedset, and for similar changes shown by the andesites of the current eruption of the Soufriere Hills, Montserrat (Murphy et al., 1998, 2000).

Olivine

Selected representative analyses of olivines are shown in Table 30 and are plotted along the base of the pyroxene quadrilateral (Fig. 79). Olivine compositions range from Fo₈₆ to Fo₆₅ but there appears to be little or no relation between fosterite content of the olivines and the silica content of the rocks. Olivines from the dacites, for example, have similar compositions to those from andesites and basaltic andesites suggesting that the former could be xenocrysts in a hybrid magma. The olivine in the cumulate block lies at the fayalitic end of the olivine composition in the lavas, suggesting it crystallized from an evolved rather than a primitive magma.

TABLE 31. Representative microprobe analyses of amphiboles from volcanic rocks of the Quill

	Basaltic Andesite			Andesite							Dacite			Rhyolite
	E-51	E-27	E-26	E-12	E-6	E-52	E-11	E-5	E-53	E-4	E-17	E-18	E-13	E-19
SiO ₂	46.97	40.89	40.79	45.73	43.10	41.57	42.10	42.22	42.37	43.69	46.52	45.51	40.36	43.14
TiO ₂	1.68	2.61	2.56	1.75	2.55	2.40	2.35	2.31	2.48	1.45	1.89	1.49	2.39	1.41
Al ₂ O ₃	8.15	14.14	14.11	7.52	11.28	13.97	13.55	12.02	12.80	8.49	8.31	7.89	9.73	11.36
FeO	14.66	11.94	11.04	14.33	10.94	9.16	9.79	12.51	12.20	16.13	14.52	18.95	20.23	16.61
MnO	0.3	0.18	N.D.	0.31	0.15	0.15	0.07	0.11	0.30	0.48	0.26	0.65	0.26	0.55
MgO	14.06	14.38	14.22	13.40	14.48	15.66	15.43	13.90	14.24	12.42	13.21	11.19	11.77	11.78
CaO	11.02	11.10	11.56	10.88	11.50	11.79	11.35	11.30	10.60	10.17	11.04	10.17	8.93	10.84
Na ₂ O	1.55	2.36	2.16	1.56	2.17	2.46	2.50	2.20	2.73	1.66	1.61	1.65	2.37	2.12
K ₂ O	0.11	0.20	0.18	0.12	0.15	0.16	0.21	0.14	0.18	N.D.	0.11	0.07	0.17	0.13
Total	98.53	97.80	96.62	95.60	96.32	97.32	97.35	96.71	97.90	94.49	97.47	97.57	96.21	97.94

N.D. Not determined

Amphibole

Selected representative analyses are shown in Table 31. Mineralogically they range in composition from hornblende to ferrotschermakite-pargasite, and appear to be divisible into two groups based on their Al₂O₃ contents. One group has relatively low concentrations of Al₂O₃ and have similar compositions to amphiboles analyzed from lavas on Saba and Montserrat. The other group has relatively high values of Al₂O₃ and is similar in composition to amphiboles in both the cumulate blocks (Table 33) and the hypabyssal inclusions on Saba and Montserrat. It is suggested therefore that the high Al₂O₃ amphibole crystals in the lavas of the Quill probably represent xenocrysts derived from the breakdown of cumulate blocks. Such a suggestion would imply that all of the amphiboles analyzed from the rocks of the last erupted bedset must also be xenocrysts. Although due to compositional differences, no direct comparison of the magma ascent rates between the Quill and the Soufriere Hills, Montserrat can be made (Rutherford et al., 1998), the common occurrence of hornblendes lacking reaction rims in the basaltic andesites, andesites, and especially the dacites and rhyolites of the Quill would imply that the rates of ascent of the majority of these magmas were relatively rapid.

Iron-titanium oxide and spinel

Selected representative analyses of magnetite, ilmenite and spinel are shown in Table 32. The opaque oxides all occur as discrete grains. Magnetite is the most common mineral, followed in abundance by ilmenite and chrome spinel. Only magnetite is found in the basaltic andesites, whereas both magnetite and ilmenite are present in the andesites and dacites. The relatively rare chrome spinels which show a decrease in chromium with increasing silica content of the host rock, all appear to come from a single eruptive sequence near the base of the section at Compagnie Bay (stratigraphic section V, Plate 5). A plot is shown in Figure 80 of temperature against fO_2 for the co-existing iron-titanium oxide microphenocrysts. Temperatures of equilibration of these oxides range from 777° to 900° C, with fO_2 values generally being one or two log units above the Ni-NiO buffer curve. With one exception (E-31), which has a slightly lower fO_2 value than the rest of the samples studied, all of the iron-titanium oxide equilibration results fall within the field of iron-titanium compositions from the Quill determined by D'Arco (1982), which also extends the data to higher temperatures. Both the data presented here, and that of D'Arco suggests that, with decreasing temperature there is a corresponding decrease in fO_2 values, which become closer to the Ni-NiO buffer as temperature decreases.

Comparison of the data presented here with that obtained from other Lesser Antillean volcanoes (Smith and Roobol, 1990; Devine et al., 1998) indicates that the values obtained from the Quill are typical of those characteristic of andesitic volcanoes in the Lesser Antilles. Data from two plutonic blocks from Mt. Pelée, Martinique (Smith and Roobol, 1990) are also included in Figure 80 for comparison. One of the blocks shows similar fO_2 values, but with a somewhat lower temperature to those obtained from the volcanic rocks of the Quill, but comparable to the analyzed volcanic rocks from Mt. Pelée. The data from the other plutonic block however suggests equilibration at much higher fO_2 values.

Mineralogy of plutonic blocks

Representative microprobe analyses of the minerals in ejected plutonic blocks from the Quill are shown in Table 33. The compositions are plotted on the relevant mineral diagrams described previously so that they can be compared with the phenocryst compositions of the Quill.

TABLE 32. Representative analyses of Fe-Ti oxides and spinels from volcanic rocks of the Quill

E-51			E-27	E-26	E-10		E-23	E-12	E-6		E-9	E-52		
SiO ₂	0.04	0.07	0.05	0.07	0.04	0.04	0.14	0.34	0.00	0.04	0.22	0.02	0.02	0.00
TiO ₂	9.16	0.18	11.04	11.23	10.99	47.82	13.57	9.67	10.43	42.65	15.45	11.01	43.27	0.08
Al ₂ O ₃	2.51	55.42	2.92	2.70	2.87	0.08	1.04	2.52	3.00	0.40	1.29	1.93	0.25	51.54
Cr ₂ O ₃	0.02	6.73	0.05	0.00	0.09	0.12	0.09	0.00	0.00	0.00	0.00	0.00	0.12	9.80
Fe ₂ O ₃	48.02	7.58	44.94	43.98	45.58	9.82	39.94	47.69	47.25	20.35	37.78	47.83	18.85	7.36
FeO	36.52	12.96	37.39	37.43	37.84	37.76	41.11	38.94	37.35	31.99	44.00	38.95	33.75	15.36
MnO	0.61	0.11	0.46	0.54	0.59	1.46	0.61	0.40	0.42	0.38	0.39	0.25	0.78	0.19
MgO	1.52	18.31	2.41	2.19	2.19	2.17	0.79	1.60	2.44	3.51	1.25	1.95	2.58	16.11
CaO	0.03	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.09	0.01
Total	98.43	101.36	99.26	98.14	100.19	99.27	97.29	101.16	100.89	99.36	100.38	101.94	99.71	100.45
% U _{sp}	23.3		27.2	28.5	27.1		38.4	28.4	24.7		44.3	27.2		
% R ₂ O ₃						10.5				22.4			20.2	
T ^o C					777				892			900		
fO ₂					-14.4				-10.9			-11.0		

E-11			E-5	E-53			E-4		E-17		E-13
SiO ₂	0.02	0.00	0.18	0.06	0.00	0.07	0.00	0.00	0.10	0.04	0.28
TiO ₂	10.03	45.04	7.48	9.78	43.27	0.17	10.68	44.85	9.42	43.77	10.83
Al ₂ O ₃	3.09	0.27	5.35	0.74	0.08	54.86	2.02	0.20	2.33	0.20	2.47
Cr ₂ O ₃	0.00	0.01	0.00	0.00	0.00	6.86	0.05	0.00	0.01	0.00	0.00
Fe ₂ O ₃	47.10	15.99	49.03	50.15	16.09	6.33	46.45	16.30	48.99	18.83	44.74
FeO	36.48	34.85	35.13	38.48	35.26	14.68	38.54	35.15	38.18	32.98	40.99
MnO	0.38	0.56	0.34	0.67	0.90	0.11	0.48	0.59	0.57	0.48	0.76
MgO	2.55	2.96	3.18	0.84	1.57	16.85	1.42	2.65	1.19	3.39	0.71
CaO	0.00	0.05	0.00	0.00	0.01	0.04	0.01	0.00	0.00	0.00	0.00
Total	99.65	99.73	100.68	100.72	97.18	99.97	99.65	99.74	100.79	99.69	100.78
% U _{sp}	23.6		21.5	25.5			27.9		24.4		31.7
% R ₂ O ₃		17.2			17.1			17.3		20.5	
T ^o C	865			873			888		885		
fO ₂	-11.7			-11.5			-11.3		-11.2		

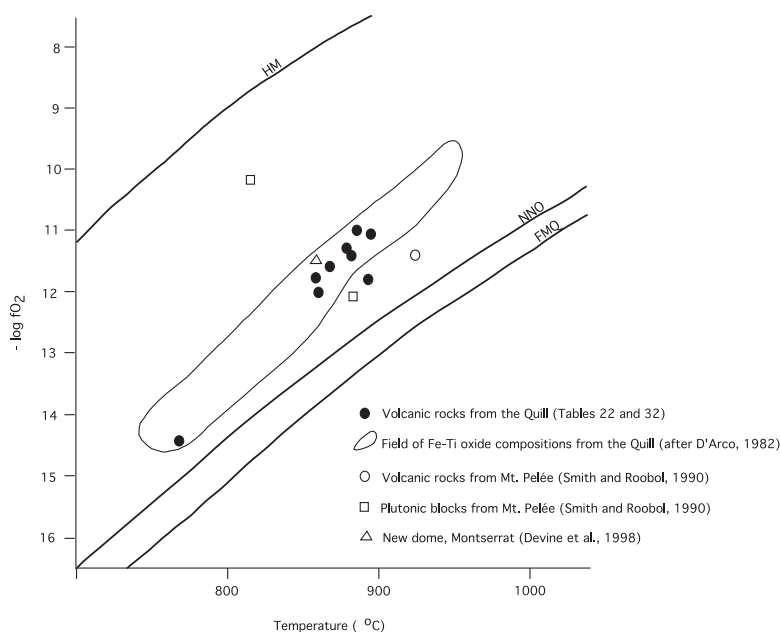


FIGURE 80. Plot of $-\log fO_2$ against $T^{\circ}C$ for coexisting magnetite-ilmenite crystals of volcanic rocks of the Quill. Also plotted are data from Montserrat and Martinique. Data sources: Tables 22 and 32; D'Arco, 1982; Smith and Roobol, 1990; Devine et al., 1998.

The plagioclase crystals from the two analyzed cumulate blocks are unzoned anorthites similar to the xenocrysts of the basaltic andesites and andesites. In contrast, those from the gabbroic inclusion show a range in anorthite content similar to that shown by the plagioclase phenocrysts in the volcanic rocks (Fig. 78). The analyzed clinopyroxenes, orthopyroxenes and olivines are plotted in Figure 79, and can be seen to be similar to those of the volcanic rocks. Crystals of amphibole, which are not present in the gabbroic inclusion, are relatively rich in Al_2O_3 and are thought to be the source of the high Al_2O_3 amphiboles described from the Quill lavas. Unfortunately only magnetite has been recorded from plutonic blocks from St. Eustatius so that temperature and fO_2 of equilibration cannot be determined. The compositions of magnetite in the two types of plutonic blocks are however quite different. The magnetites in the gabbro being much richer in TiO_2 , and poorer in Al_2O_3 and MgO than those from the cumulate blocks.

TABLE 33. Representative microprobe analyses of minerals in plutonic blocks from the Quill

	Plagioclase			Amphibole		Clinopyroxene		Orthopyroxene		Olivine	Magnetite	
	E 35.1	E 2	E 36	E 35.1	E 2	E 2	E 36	E 2	E 36	E 2	E 2	E 36
SiO ₂	45.27	45.62	54.73	40.76	42.11	50.95	51.36	53.43	52.71	38.07	0.24	0.22
TiO ₂	N.D.	0.04	N.D.	2.54	2.50	0.48	0.35	0.12	0.20	N.D.	7.60	14.53
Al ₂ O ₃	34.40	33.88	27.79	14.08	12.78	3.03	1.51	2.07	1.00	0.12	7.15	0.80
Fe ₂ O ₃	N.D.	N.D.	0.48	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	45.88	39.81
FeO	0.46*	0.61*	N.D.	11.32*	10.96*	7.94*	9.52*	16.69*	19.86*	27.28*	33.81	43.63
MnO	N.D.	N.D.	N.D.	N.D.	0.17	0.23	0.39	0.49	0.57	0.55	0.37	0.56
MgO	N.D.	0.05	N.D.	13.94	15.20	14.93	13.90	25.89	23.18	34.28	3.40	0.68
CaO	19.39	18.67	10.81	12.37	11.68	21.87	21.89	1.16	1.49	0.28	0.02	N.D.
Na ₂ O	0.85	1.13	5.17	2.54	2.70	N.D.	N.D.	0.03	N.D.	N.D.	N.D.	N.D.
K ₂ O	N.D.	0.01	0.23	0.27	0.16	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cr ₂ O ₃	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.87	N.D.
V ₂ O ₃	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.65	N.D.
Total	100.38	100.01	99.21	97.83	98.26	99.43	98.92	98.95	99.01	99.58	99.19	100.23

* Total iron as FeO
 E 35.1 and E 36 This paper
 E 2 Arculus and Wills (1980)
 E 35.1 and E 2 — Cumulate blocks
 E 36 — Gabbroic block

Arculus and Wills (1980) from a study of a single cumulate block from the Quill calculated, assuming the equilibrium coexistence of olivine and orthopyroxene, that the mineral assemblage of the block equilibrated for a fixed temperature of 1000° C at a pressure of 6 kb, i.e. at depth of 20 km below the surface. Unfortunately the sample used for these calculations is not representative of the Quill cumulate blocks, which do not usually contain these minerals, so that the depth of formation of the more typical cumulates of the Quill is still in doubt. In addition, not only is the mineral assemblage used for this calculation now regarded as probably non-equilibrium, but the thermodynamic data for magnetite used in the calculations has been found to be incorrect (J. Devine, pers. comm., 2000) casting further doubt on the conditions of formation of this particular rock.

GEOCHEMISTRY OF ST. EUSTATIUS

A suite of 121 rock samples from St. Eustatius has been analyzed. Thirty-three samples were analyzed by XRF at the University of Puerto Rico at Mayaguez following the method of Gunn (Gunn et al., 1974; Gunn and Roobol, 1976). Forty-two samples were analyzed at the Centre National de la Recherche Scientifique, at Nancy, France, with REE, Hf and Sc analyses on selected samples undertaken by F. Frey at MIT. A further forty-six samples were analyzed at Activation Labs, Canada. Details of the analytical methods are already given in the equivalent section on the geochemistry of Saba.

As in the case of Saba, only juvenile clasts were selected from the pyroclastic deposits for analysis. All samples are porphyritic, so the analyses do not necessarily represent melt compositions. The types of deposits and locality data for samples are listed in Appendix 2.

The volcanic rocks of St. Eustatius (Tables 34, 35, 36, 37, and 38) form two distinct magma series on the SiO_2 - K_2O diagram (Fig. 81) corresponding to the low-K calc-alkaline and medium-K calc-alkaline series

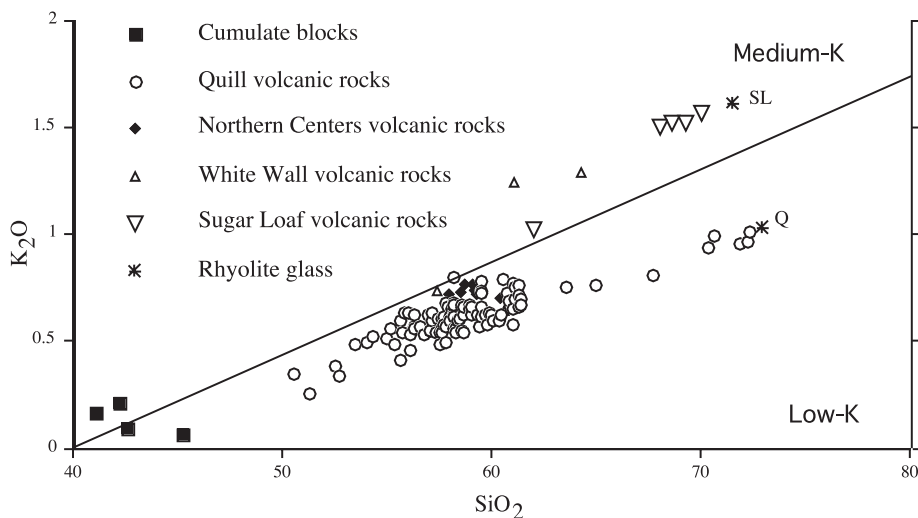


FIGURE 81. K_2O versus SiO_2 plot for volcanic rocks and cumulate blocks from St. Eustatius. Boundary between low-K and medium-K suites after Gill (1981). SL – Sugar Loaf rhyolitic glass; Q – Quill rhyolitic glass.

(Gill, 1981). The oldest rocks from the Northern Centers form a tight cluster of low-K andesites. The White Wall-Sugar Loaf series of intermediate age form a medium-K calc-alkaline series. The youngest suite from the Quill again shows a low-K calc-alkaline trend. In addition to the lavas of the Northern Centers and the Quill, the only other volcanic centers in the Lesser Antilles that belong to the low-K calc-alkaline series, are Mt. Liamugia, St. Kitts, and the South Soufriere Hills, Montserrat (Smith and Roobol, 1990). A single specimen from an angular inclusion in a lava flow on Saba has also been described in as a low-K dacite.

In order to be certain that the porphyritic lavas of St. Eustatius represent two chemically distinct magma series rather than one series with variable phenocryst contents, two glass samples, one from the Quill and one from the Sugar Loaf, were crushed and phenocryst-free glass concentrates (selected by hand-picking) were analyzed (whole rock analysis). Sample EUX 203 is glass from a pumice fragment of the Sugar Loaf succession, collected from the pumice breccia bed with blocks up to 70 cm in size (Fig. 35). The second sample EUX 98-11-4 was collected from the stratigraphic marker lapilli fall horizon (Marker Unit A) at Bargine Bay (stratigraphic section II, Plate 5, Figs. 56 and 57). The phenocryst-free glass samples are plotted in Figure 81 where the Sugar Loaf glass plots in the medium-K calc-alkaline field, and the glass from the Quill lapilli fall deposit from Bargine Bay plots in the low-K calc-alkaline field, thus confirming the existence of the two magma series. Although the rocks from St. Eustatius can be divided into two distinct magma series on the basis of their K_2O contents, all of these rocks, in terms of their CaO contents belong to Davidson's high-Ca series which also includes St. Kitts, Redonda, St. Lucia, and the Grenada C-series (Davidson, 1996; Macdonald et al., 2000).

Apart from the St. Eustatius examples, rhyolites are not common in the Lesser Antilles. The only other known examples are the Pliocene Les Mamelles domes on Basse Terre, Guadeloupe (Gunn et al., 1980) and the Miocene Bise lava flow/plug on St. Lucia (Le Guen de Kerneizon et al., 1982). St. Eustatius is therefore unique in the Lesser Antilles by having two chemically distinct rhyolites preserved in its stratigraphy. The rhyolites of both the medium- and low-K series are characterized by relatively high Na_2O values ranging from 4.14 to 4.32% for the Sugar Loaf and

4.45 to 6.21% for the Quill. This richness in Na_2O can easily be seen by calculating the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio for the rhyolites from both suites. Thus the ratio for the Sugar Loaf rhyolites ranges from 2.57 to 3.03, with the glass concentrate (2.67) falling within this range. In contrast the low-K Quill rhyolites have much higher ratios ranging from 4.51 in the glass concentrate to 6.27 in the pyroclastic deposits. Thus both suites can be regarded as having been derived from soda-rich magmas.

GEOCHEMISTRY OF THE NORTHERN CENTERS AND THE WHITE WALL-SUGAR LOAF RIDGE

The chemical compositions of eight analyzed porphyritic lavas from the Northern Centers are listed in Table 34. They form a single homogeneous group of andesitic lavas with a small silica range from 57.92 to 60.39%. Nearly all major and trace elements are remarkably uniform in value, so that the rocks all plot in a fairly tight cluster on Harker variation diagrams (Fig. 82).

Five analyzed samples from the White Wall series, and a further five samples from the Sugar Loaf series are listed in Table 35, and also plotted in Figure 82. The samples from the White Wall vary with stratigraphic position from basaltic andesite at the base through andesite to dacite. In contrast, the analyzed rocks from the Sugar Loaf show a more restricted range from dacite, at the base of the succession, to rhyolite. The latter represent the last eruptive product within the White Wall-Sugar Loaf succession.

On most chemical variation diagrams (Fig. 82), the rocks of the Northern Centers overlap the variation trend shown by the White Wall-Sugar Loaf succession. The Northern Center deposits can however be distinguished from the White Wall-Sugar Loaf series on both the Sr and V plots, where they lie off the trend defined by the rocks of the White Wall-Sugar Loaf series confirming their division into two distinct series (low- and medium-K).

The chondrite-normalized REE patterns for the Northern Centers, White Wall and Sugar Loaf series are shown in three separate plots in Figure 83. It can be seen that the Northern Centers and White Wall plots

TABLE 34. Chemical composition of volcanic rocks from the Northern Centers

	EX 142 ¹	EX 144 ¹	EUX 95-51 ¹	EUX 409 ¹	EUX 408 ¹	EX 143 ¹	EX 141 ¹	EUX 95-50 ¹
SiO ₂	57.92	58.47	58.65	59.10	59.13	59.26	59.34	60.39
TiO ₂	0.88	0.86	0.96	0.78	0.75	0.86	0.92	0.75
Al ₂ O ₃	17.82	17.00	16.80	17.50	17.50	17.53	16.85	16.87
Fe ₂ O ₃ *	8.28	8.12	8.63	7.95	7.81	6.84	8.12	7.74
MnO	0.14	0.15	0.15	0.17	0.17	0.15	0.17	0.16
MgO	3.23	3.10	2.88	2.71	2.61	3.11	2.81	2.69
CaO	7.38	7.61	7.25	7.09	7.29	7.61	7.10	6.93
Na ₂ O	3.51	3.84	3.75	3.82	3.89	3.84	3.81	3.64
K ₂ O	0.71	0.72	0.76	0.76	0.73	0.71	0.76	0.70
P ₂ O ₅	0.09	0.13	0.14	0.13	0.13	0.09	0.11	0.13
S	<50	<50	<50	<50	<50	<50	50	1490
Sc	27	24	26	19	18	25	28	19
V	194	196	224	159	157	192	221	151
Cr	57	8	4	<0.5	<0.5	45	4	2
Ni	26	7	5	6	2	16	3	4
Cu	56	69	87	42	46	27	114	45
Zn	61	67	66	72	65	59	77	66
Rb	15	14	14	13	12	14	14	12
Sr	173	206	179	199	200	194	173	187
Y	30	32	34	30	31	35	38	27
Zr	89	117	104	91	95	103	101	88
Nb	3	3	3	2	<2	3	<2	3
Ba	158	178	159	164	166	172	170	154
La	5.6	5.8	5.4	5.7	5.7	5.7	6.0	5.7
Ce	15	17	15	15	15	15	16	15
Nd	10	11	11	11	10	10	12	10
Sm	3.10	3.23	3.32	2.88	2.90	3.19	3.91	2.96
Eu	1.01	0.97	0.99	0.93	0.94	0.98	1.25	0.96
Tb	0.7	0.7	0.8	0.7	0.7	0.8	0.9	0.7
Yb	3.19	3.47	3.50	3.26	3.12	3.52	4.49	3.14
Lu	0.46	0.52	0.51	0.48	0.45	0.50	0.66	0.47
Hf	2.0	3.0	2.6	2.5	2.4	2.0	2.7	2.6
Th	0.9	0.9	0.7	0.9	0.7	0.8	0.7	0.9
U	0.2	0.2	0.5	0.4	0.3	0.2	<0.1	0.3
Ta	<0.3	<0.3	0.5	0.6	<0.3	<0.3	0.4	0.5

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

Center	Sample
Bergje/Pisgah	EX 142, EX 143
Gilboa	EUX 408, EX 141
Mary's Glory	EUX 95-51, EUX 409
Signal Hill	EX 144, EUX 95-50
¹	Analyzed at ACTLABS

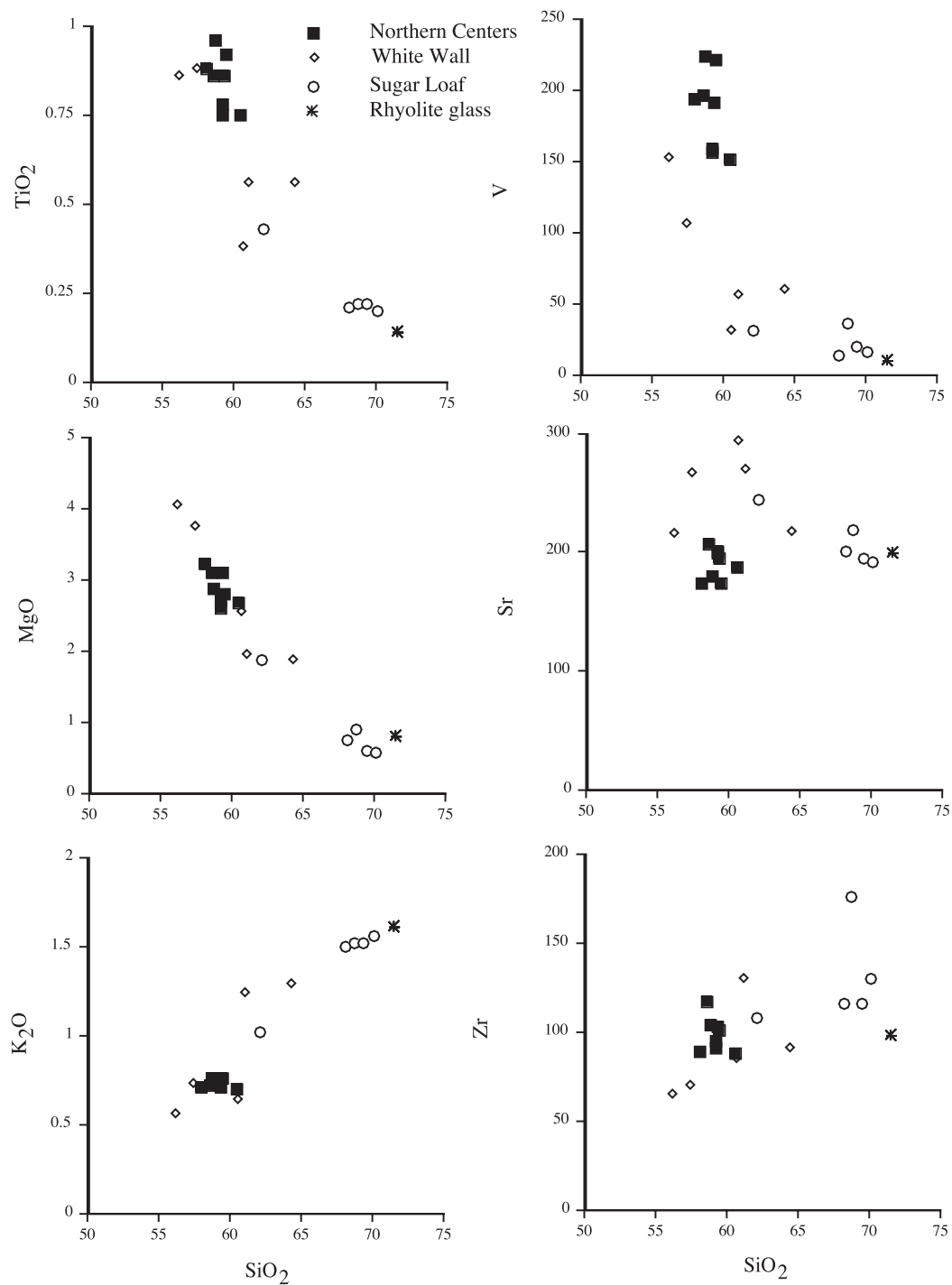


Figure 82. Selected major and trace element analyses of volcanic rocks from the Northern Centers and the White Wall-Sugar Loaf succession plotted against SiO_2 .

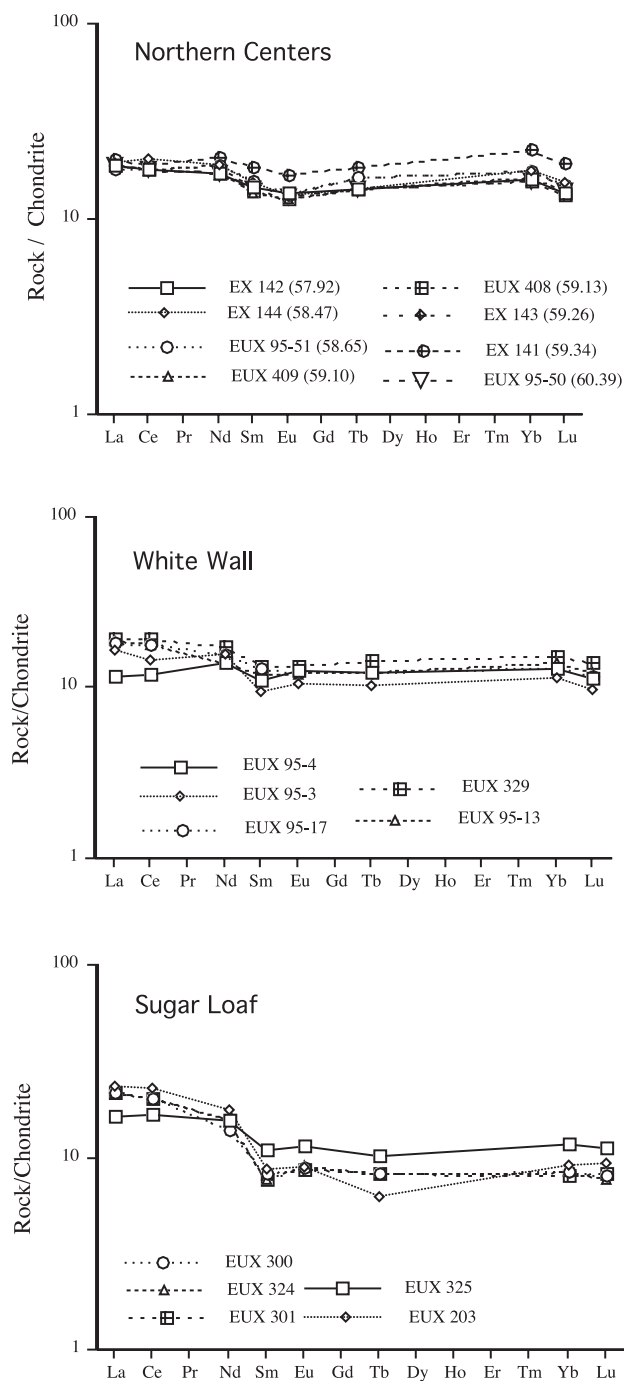


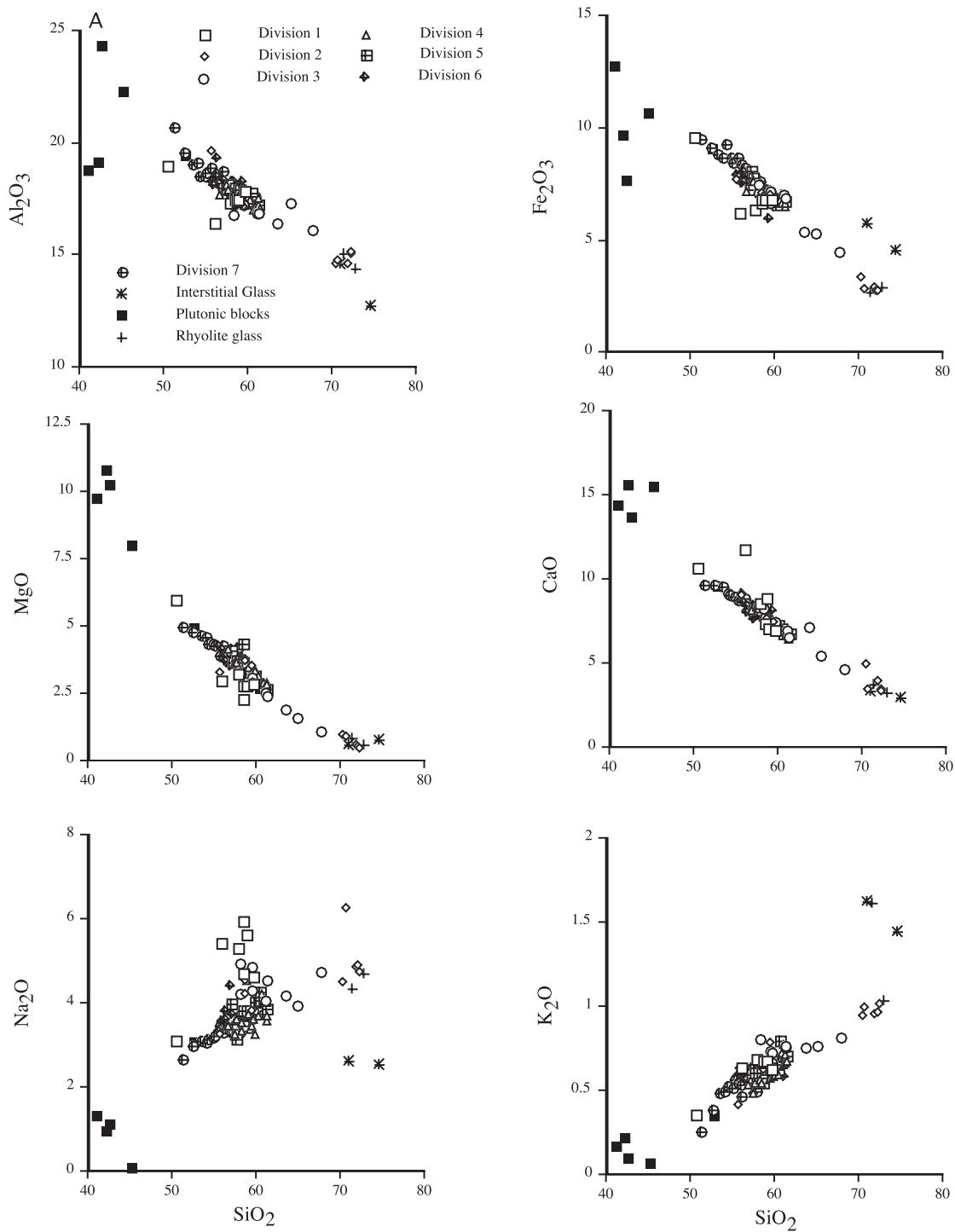
FIGURE 83. Chondrite-normalized REE analyses of volcanic rocks from the Northern Centers and the White Wall-Sugar Loaf succession. (chondrite normalizing factors from Taylor, in Donnelly and Rogers, 1980).

are similar with relatively flat REE patterns, the former having a slight negative Eu anomaly and the latter a slightly negative Sm anomaly. For the Sugar Loaf, the dacite has a similar pattern to those already described for the White Wall, however the rhyolites of the Sugar Loaf show a somewhat different pattern with similar light REE element values but distinctly lower intermediate and heavy REE. The flatter patterns characteristic of the Northern Centers, the White Wall series and the dacites of the Sugar Loaf may be explained by fractionation of plagioclase and clinopyroxene, whereas that shown by the Sugar Loaf rhyolites could represent fractionation of plagioclase and amphibole (Hanson, 1980). The REE pattern shown by the rhyolites of the Sugar Loaf is very distinct from that shown by the rhyolite of the Bise lava/plug on St. Lucia which has a flat distribution for both the light and heavy REE and a pronounced negative Eu anomaly (Le Guen de Kerneizon et al., 1982), suggesting different origins for at least two of the three rhyolite occurrences in the Lesser Antilles.

GEOCHEMISTRY OF THE QUILL

The Quill shows one of the broadest silica ranges of any island arc volcano, varying from 52.0% to 72.3% (Table 36). On the Harker variation diagrams (Figs. 84A and B) the suite has essentially a bimodal character with the main cluster of analyses lying in the basaltic andesite-andesite range (55 to 63% silica), and a smaller number of analyses of rhyolites in the 70 to 73% SiO₂ range. Only three samples span the gap between these groups suggesting that dacites are not commonly produced by the Quill.

The suite as a whole is characterized by low K₂O (0.6 at 60% SiO₂), whereas Na₂O is high, ranging from 2.64 in the basalts to 6.21% in the rhyolites. Most major and trace elements show simple straight line trends with TiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Sc, V, Cr, Sr, and Y all decreasing with increasing SiO₂, whereas Na₂O, K₂O, Rb, Zr, Ba, Hf and Th all increase. Rb is low in all rocks reaching a maximum value of only 30 ppm in the rhyolites, in contrast Zr shows strong fractionation from 20 ppm in basic rocks to 200 ppm in rhyolites. Ni does not show a consistent trend when plotted against SiO₂, and many intermediate rocks have high values.



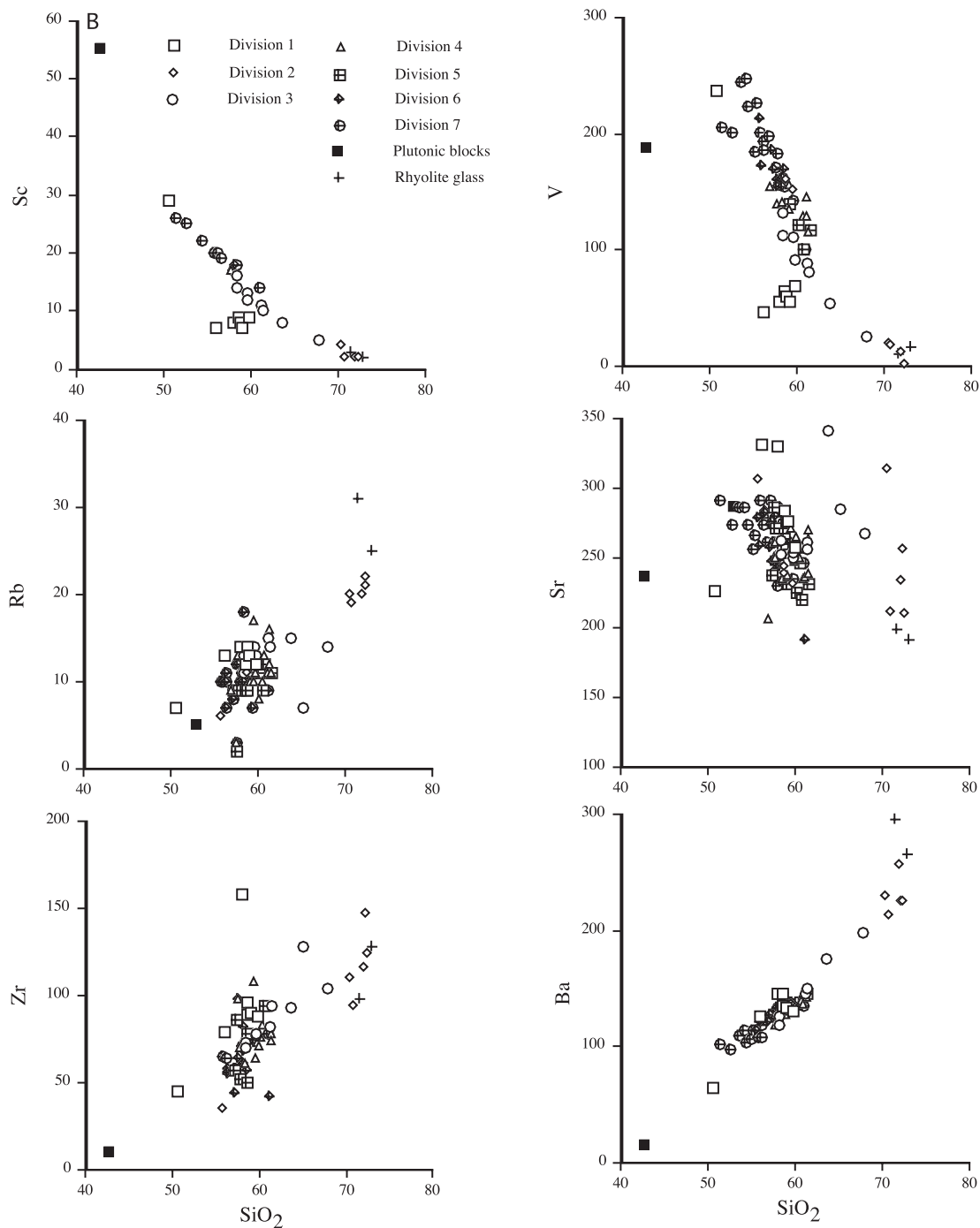


FIGURE 84. Selected major (A) and trace element (B) analyses of volcanic rocks (subdivided into Stratigraphic Divisions) and cumulate blocks from the Quill plotted against SiO_2 .

TABLE 35. Chemical composition of volcanic rocks of the White Wall-Sugar Loaf Succession

	White Wall					Sugar Loaf				
	EUX 95-4 ¹	EUX 95-3 ¹	EUX 95-17 ¹	EUX 95-13 ¹	E 329 ¹	E 325 ¹	E 203 ¹	E 300 ¹	E 324 ¹	E 301 ¹
SiO ₂	56.13	60.54	57.34	64.27	63.72	64.22	71.71	71.99	70.78	71.26
TiO ₂	0.86	0.38	0.88	0.56	0.58	0.45	0.23	0.21	0.22	0.23
Al ₂ O ₃	17.07	16.31	15.52	15.48	16.00	16.60	15.21	15.21	15.34	15.04
Fe ₂ O ₃ *	9.93	4.48	10.57	6.23	6.12	5.08	2.65	2.47	2.60	2.53
MnO	0.21	0.19	0.25	0.16	0.17	0.18	0.11	0.10	0.11	0.10
MgO	4.05	2.55	3.75	1.88	2.05	1.95	0.63	0.60	0.79	0.93
CaO	7.70	8.75	6.62	5.92	6.08	6.07	3.62	3.60	3.79	3.93
Na ₂ O	3.38	5.62	4.13	4.11	3.91	4.30	4.16	4.14	4.72	4.32
K ₂ O	0.56	0.64	0.73	1.29	1.29	1.06	1.57	1.61	1.56	1.58
P ₂ O ₅	0.10	0.17	0.17	0.11	0.08	0.10	0.10	0.08	0.08	0.08
S	2685	3980	3565	2660	5420	870	75	50	820	1120
Cs	0.6	0.6	0.4	0.7	1.0	1.1	1.4	1.2	1.2	1.2
Sc	20.6	4.6	15.3	10.4	12.0	6.0	2.9	2.5	2.8	2.5
V	153	32	106	60	56	32	20	16	14	36
Cr	8	11	15	11	3	<2	21	<2	<2	3
Ni	2	2	2	2	<20	<10	<10	<20	<10	<20
Cu	133	17	14	15	10	<5	10	<10	<5	20
Zn	54	50	104	37	30	45	40	20	10	50
Rb	10	13	11	17	13	16	29	28	25	25
Sr	215	294	266	217	270	244	195	192	201	218
Y	21	19	26	24	24	18	14	12	16	16
Zr	65	85	70	91	130	108	116	130	116	176
Nb	<2	<2	2	<2	4	3	3	3	3	4
Ba	82	153	93	206	334	185	273	276	256	262
La	3.5	4.9	5.4	5.6	5.8	4.9	6.9	6.5	6.4	6.4
Ce	10	12	15	15	16	14	19	17	17	17
Nd	8	9	9	8	10	9	10	8	9	9
Sm	2.28	1.98	2.67	2.49	2.8	2.3	1.8	1.7	1.6	1.6
Eu	0.92	0.78	0.90	0.89	0.98	0.85	0.65	0.65	0.66	0.64
Tb	0.6	0.5	0.6	0.6	0.7	0.5	0.3	0.4	0.4	0.4
Yb	2.58	2.26	2.60	2.78	3.04	2.36	1.80	1.67	1.66	1.59
Lu	0.38	0.33	0.39	0.41	0.47	0.38	0.31	0.27	0.26	0.28
Hf	1.9	2.1	1.8	2.5	3.1	2.5	3.3	3.1	2.9	3.0
Th	0.3	0.5	0.4	0.6	1.4	1.0	1.6	1.5	1.5	1.3
U	0.3	0.5	0.4	0.6	0.8	0.3	1.0	0.7	1.0	1.0
Ta	<0.3	<0.3	<0.3	<0.3	1.5	0.8	1.4	1.5	1.5	1.1

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

¹ Analyzed at ACTLABS

Ni does however show a positive relationship with MgO suggesting, as was proposed for Saba, that Ni values are controlled by the MgO content of the lavas. A comparison of the high-Ca suite of the Quill with the low-Ca suite characteristic of Saba shows that for equivalent MgO values the former are richer in TiO_2 , FeO , Al_2O_3 , and poorer in SiO_2 and K_2O than the latter. Suites belonging to the high Ca trend have been interpreted to represent the products of extensive olivine fractionation from a parent magma of picritic composition (Macdonald et al., 2000). Such a process would imply that the Quill parent magmas were relatively anhydrous compared to those of Saba, which would also explain the more common occurrence of orthopyroxene in the Quill lavas (Macdonald et al., 2000). The more anhydrous nature of the Quill magmas can also be used to explain the relative paucity of hornblende in the lavas in spite of their high Na_2O contents (Sisson and Grove, 1993).

Stratigraphic Division 1 lavas with intermediate silica tend to lie off the overall trend shown by the Quill volcanic rocks for a number of elements, e.g. MgO, Na_2O , V, and Sc, suggesting they were derived either from a distinct parent magma or that their process of differentiation was different. As these samples do not show any consistent relationship with either the rocks from the Northern Centers or the White Wall-Sugar Loaf succession they cannot be regarded as representatives of the last eruptive products of either of these two centers.

The majority of samples analyzed for sulfur from St. Eustatius show relatively high values reaching 8,825 ppm (up to 8.8%). Lava samples from the Quill show a sulfur range from <50 to 8,825 ppm, with an average of 1,737 ppm for the twenty-three analyzed samples. In contrast, only one of the eight analyzed samples from the Northern Centers has a high sulfur content of 1,490 ppm (EUX 95-50), with all others having ≤ 50 ppm (Table 34). The five analyzed samples from the White Wall have the highest overall sulfur contents ranging from 2,660 to 5,520 ppm, with an average of 3,662 ppm (Table 35), whereas the five analyzed volcanic samples from the overlying Sugar Loaf have relatively low sulfur values (50 to 1,120 ppm), with an average of 587 ppm (Table 35). This distribution of sulfur is extremely variably, with samples from the Quill showing both the highest and lowest analyzed values. This variation does not appear to have been produced by variable amounts of

hydrothermal alteration, because only one hydrothermal aureole is observed in St. Eustatius occurring on the Boven center at the north end of the island (Plate 4). Lavas from this center were not included in the sampling program, which was confined to petrographically unaltered rocks. The possibilities of contamination of the samples by evaporation of groundwater, the precipitation of caliche, or sediment after their eruption is believed to have been eliminated by the process of sampling only the freshest possible material. In Figure 33, gypsum layers one to two meters thick are recorded near the base of the White Wall stratigraphy as part of the shallow submarine succession. This occurrence suggests that sedimentary gypsum forms part of the basement strata underlying the volcanic centers on St. Eustatius. The rather random occurrence of high sulfur values in the blocks of ejected lava in the pyroclastic deposits of the Quill suggests that the source of the sulfur could be through contamination of magmas as they rise through these sedimentary gypsum layers into the volcanic edifice. Within the crater wall of the Quill, gypsum was also observed as a matrix to lithified pyroclastic deposits. Care was taken to avoid sampling this type of material but it does suggest that within the vent area of the Quill dissolution and reprecipitation of sedimentary gypsum may occur due to local hydrothermal activity.

As has already been mentioned a very striking feature of the lavas of the Quill (Table 36) are the anomalously high Na_2O contents, which attain values, for example in the andesite (E-35) of 5.89%, and in the rhyolite (E-216) of 6.21%. Such rocks should probably more appropriately be called soda andesites and soda rhyolites. Close scrutiny of the chemical analyses in Table 36 reveals however that the rocks having the highest Na_2O values also have high S values. The anomalously high Na_2O values of some of the lavas of the Quill could thus be explained in the same manner as the anomalously high S values, i.e. due to contamination of the magmas and thus may not to be an original magmatic characteristic. Therefore the terms soda andesite and soda rhyolite have not been used in this account.

Microprobe analyses were made of interstitial glasses from two samples from the Quill (Table 37A). Analysis E-5 is an interstitial glass from an andesite with 59.44% SiO_2 , whereas E-26 is an interstitial glass

TABLE 36. Chemical composition of volcanic rocks from the Quill

	EUX 209 ¹	E 104	EX 173	E 51	E 59A	E 16 ³	E 90	EUX 95-2 ¹	E-30 ¹
SiO ₂	50.46	54.86	55.10	55.30	55.52	55.59	55.79	55.92	56.01
TiO ₂	0.83	0.90	0.83	0.75	0.77	0.79	0.78	0.47	0.77
Al ₂ O ₃	18.89	18.48	18.63	17.87	18.27	19.62	18.09	16.38	18.24
Fe ₂ O ₃ *	9.54	8.64	8.44	7.87	7.92	7.67	7.79	6.20	8.32
MnO	0.18	0.17	0.17	0.16	0.16	0.22	0.16	0.20	0.17
MgO	5.92	4.27	4.25	5.17	4.24	3.26	4.09	2.91	3.88
CaO	10.65	8.91	8.69	8.91	9.13	9.06	8.65	11.70	8.67
Na ₂ O	3.08	3.16	3.18	3.37	3.30	3.23	3.55	5.40	3.31
K ₂ O	0.35	0.51	0.56	0.48	0.59	0.41	0.63	0.63	0.53
P ₂ O ₅	0.09	0.09	0.15	0.12	0.10	0.14	0.46	0.19	0.11
S	450	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	5485	60
Sc	29	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	6.5	20
V	237	185	227	184	213	N.D.	172	46	194
Cr	102	28	29	82	33	N.D.	34	12	9
Ni	32	48	97	62	38	9	64	2	7
Cu	50	179	66	13	28	53	20	19	41
Zn	61	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	64	51
Rb	7	<10	12	11	10	6	10	13	9
Sr	226	257	267	225	279	307	259	332	279
Y	20	N.D.	N.D.	N.D.	N.D.	20	N.D.	21	20
Zr	45	N.D.	N.D.	N.D.	N.D.	35	N.D.	79	64
Nb	<2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	3	<2
Ba	64	107	114	105	114	N.D.	121	126	108
La	2.5	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	5.1	4.7
Ce	8	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	14	13
Nd	6	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	9	8
Sm	1.94	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	2.23	2.48
Eu	0.79	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.84	0.90
Tb	0.6	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.5	0.6
Yb	2.35	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	2.32	2.68
Lu	0.35	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.35	0.40
Hf	1.3	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	2.0	1.7
Th	0.3	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.5	0.4
U	<0.1	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.8	0.6
Ta	<0.3	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	<0.3	1.1

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS

² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 36 (continued). Chemical composition of volcanic rocks from the Quill

	E 20 ³	E 22 ³	E 27 ³	E 58.1	E 26 ³	E 28 ³	E 60	E 45 ³	E 42 ³
SiO ₂	56.18	56.25	56.27	56.70	56.93	56.95	56.95	57.02	57.05
TiO ₂	0.69	0.72	0.77	0.72	0.76	0.71	0.83	0.76	0.68
Al ₂ O ₃	19.33	18.64	18.50	17.62	17.84	18.70	17.85	18.34	17.94
Fe ₂ O ₃ *	7.50	7.61	8.02	7.18	7.91	7.66	7.79	7.53	7.20
MnO	0.23	0.23	0.25	0.17	0.26	0.25	0.17	0.23	0.23
MgO	3.69	3.89	3.66	4.11	3.48	3.67	4.08	3.90	4.05
CaO	8.13	8.38	7.98	8.11	7.65	8.10	8.38	8.20	8.16
Na ₂ O	3.52	3.57	3.77	3.42	4.39	3.26	3.28	3.31	3.93
K ₂ O	0.57	0.56	0.62	0.53	0.62	0.55	0.55	0.55	0.59
P ₂ O ₅	0.16	0.15	0.15	0.08	0.16	0.16	0.11	0.16	0.17
S	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Sc	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
V	N.D.	N.D.	N.D.	155	N.D.	N.D.	186	N.D.	N.D.
Cr	N.D.	N.D.	N.D.	72	N.D.	N.D.	36	N.D.	N.D.
Ni	19	15	14	20	16	15	49	16	23
Cu	64	65	51	42	47	nd	21	57	62
Zn	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Rb	11	10	7	9	8	16	<10	8	9
Sr	282	284	283	207	274	291	258	276	238
Y	24	25	27	N.D.	22	28	N.D.	27	23
Zr	58	55	56	N.D.	57	58	N.D.	44	57
Nb	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ba	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	122	N.D.	N.D.
La	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ce	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Nd	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Sm	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Eu	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Tb	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Yb	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Lu	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Hf	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Th	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
U	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ta	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 36 (continued). Chemical composition of volcanic rocks from the Quill

	E 92	E 10 ³	E 23 ³	E 12 ³	E 8 ³	E 93	EUX 215 ¹	EX 103	EUX 305 ¹	EX 155
SiO ₂	57.11	57.31	57.44	57.44	57.59	57.59	57.59	57.61	57.76	57.77
TiO ₂	0.79	0.77	0.71	0.72	0.78	0.75	0.68	0.76	0.51	0.79
Al ₂ O ₃	17.90	17.91	18.04	18.11	18.11	17.92	17.90	17.94	17.28	17.85
Fe ₂ O ₃ *	7.50	8.05	7.58	7.70	7.78	7.49	7.57	7.62	6.32	7.36
MnO	0.17	0.24	0.23	0.24	0.17	0.17	0.18	0.17	0.21	0.17
MgO	3.85	3.61	3.91	3.61	3.65	3.76	3.63	3.64	3.20	4.17
CaO	8.27	8.05	8.28	8.29	8.13	8.22	8.24	8.10	8.55	8.01
Na ₂ O	3.71	3.36	3.12	3.23	3.11	3.44	3.58	3.43	5.28	3.30
K ₂ O	0.63	0.54	0.54	0.48	0.60	0.56	0.54	0.61	0.68	0.49
P ₂ O ₅	0.06	0.17	0.15	0.17	0.07	0.10	0.11	0.12	0.21	0.09
S	N.D.	N.D	N.D	N.D	N.D	N.D	620	N.D	8825	N.D.
Sc	N.D.	N.D	N.D	N.D	N.D	N.D	17	N.D	8.1	N.D.
V	169	N.D	N.D	N.D	N.D	160	140	155	56	158
Cr	37	N.D	N.D	N.D	N.D	32	38	29	5	55
Ni	36	13	19	19	17	44	15	31	<20	54
Cu	14	68	68	63	64	18	32	31	10	14
Zn	N.D.	N.D	N.D	N.D	N.D	N.D	50	N.D	40	N.D.
Rb	<10	2	12	3	9	12	13	<10	14	14
Sr	248	287	280	250	272	242	262	245	330	230
Y	N.D.	27	28	24	24	N.D	20	N.D	24	N.D.
Zr	N.D.	86	64	98	52	N.D	70	N.D	158	N.D.
Nb	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	<2.	N.D.	4	N.D.
Ba	127	N.D.	N.D.	N.D.	N.D.	125	119	124	146	126
La	N.D	N.D	N.D	N.D	N.D	N.D	4.2	N.D	5.7	N.D.
Ce	N.D	N.D	N.D	N.D	N.D	N.D	12	N.D	18	N.D.
Nd	N.D	N.D	N.D	N.D	N.D	N.D	8	N.D	10	N.D.
Sm	N.D	N.D	N.D	N.D	N.D	N.D	2.05	N.D	2.8	N.D.
Eu	N.D	N.D	N.D	N.D	N.D	N.D	0.81	N.D	1.04	N.D.
Tb	N.D	N.D	N.D	N.D	N.D	N.D	0.5	N.D	0.7	N.D.
Yb	N.D	N.D	N.D	N.D	N.D	N.D	2.18	N.D	2.88	N.D.
Lu	N.D	N.D	N.D	N.D	N.D	N.D	0.31	N.D	0.44	N.D.
Hf	N.D	N.D	N.D	N.D	N.D	N.D	1.8	N.D	2.9	N.D.
Th	N.D	N.D	N.D	N.D	N.D	N.D	0.6	N.D	1.0	N.D.
U	N.D	N.D	N.D	N.D	N.D	N.D	0.3	N.D	1.0	N.D.
Ta	N.D	N.D	N.D	N.D	N.D	N.D	<0.3	N.D	1.4	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS

² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 36 (continued). Chemical composition of volcanic rocks from the Quill

	EX 102	EX 101	E 24 ³	EX 161 ¹	E 95	E 61 ³	E 25 ³	EUX 214A ¹	EUX 214A1 ¹	E 37 ³
SiO ₂	57.87	57.92	58.01	58.08	58.07	58.08	58.13	58.14	58.14	58.17
TiO ₂	0.85	0.79	0.71	0.71	0.74	0.68	0.73	0.73	0.68	0.70
Al ₂ O ₃	17.81	17.77	18.28	17.65	17.69	17.98	18.28	16.76	17.22	18.04
Fe ₂ O ₃ *	7.55	7.57	7.36	7.32	7.37	7.16	7.61	7.04	7.43	7.43
MnO	0.17	0.17	0.24	0.18	0.17	0.24	0.24	0.18	0.18	0.24
MgO	3.58	3.64	3.48	3.56	3.62	3.75	3.34	3.22	3.23	3.56
CaO	7.93	7.94	7.88	8.37	7.91	7.96	7.64	8.24	8.18	7.75
Na ₂ O	3.47	3.49	3.22	3.41	3.69	3.42	3.19	4.90	4.17	3.38
K ₂ O	0.66	0.61	0.65	0.61	0.65	0.56	0.68	0.80	0.67	0.56
P ₂ O ₅	0.12	0.10	0.16	0.11	0.09	0.17	0.16	0.12	0.10	0.17
S	N.D.	N.D.	N.D.	<50	N.D.	N.D.	N.D.	1900	970	N.D.
Sc	N.D.	N.D.	N.D.	18	N.D.	N.D.	N.D.	14	16	N.D.
V	161	160	N.D.	162	154	N.D.	N.D.	112	132	N.D.
Cr	29	30	N.D.	16	31	N.D.	N.D.	18	20	N.D.
Ni	44	36	16	13	39	10	15	5	4	10
Cu	16	18	63	45	18	50	43	24	20	58
Zn	N.D.	N.D.	N.D.	46	N.D.	N.D.	N.D.	46	43	N.D.
Rb	10	11	13	10	11	13	18	13	11	9
Sr	249	249	269	271	233	264	287	263	253	280
Y	N.D.	N.D.	32	21	N.D.	26	25	19	18	29
Zr	N.D.	N.D.	68	71	N.D.	82	61	73	70	59
Nb	N.D.	N.D.	N.D.	3	N.D.	N.D.	N.D.	<2	5	N.D.
Ba	131	1134	N.D.	122	126	N.D.	N.D.	126	118	N.D.
La	N.D.	N.D.	N.D.	4.4	N.D.	N.D.	N.D.	5.1	5.0	N.D.
Ce	N.D.	N.D.	N.D.	11	N.D.	N.D.	N.D.	14	13	N.D.
Nd	N.D.	N.D.	N.D.	8	N.D.	N.D.	N.D.	9	8	N.D.
Sm	N.D.	N.D.	N.D.	2.17	N.D.	N.D.	N.D.	2.45	2.44	N.D.
Eu	N.D.	N.D.	N.D.	0.76	N.D.	N.D.	N.D.	0.84	0.89	N.D.
Tb	N.D.	N.D.	N.D.	0.5	N.D.	N.D.	N.D.	0.6	0.6	N.D.
Yb	N.D.	N.D.	N.D.	2.29	N.D.	N.D.	N.D.	2.80	2.75	N.D.
Lu	N.D.	N.D.	N.D.	0.34	N.D.	N.D.	N.D.	0.43	0.42	N.D.
Hf	N.D.	N.D.	N.D.	1.6	N.D.	N.D.	N.D.	2.1	1.8	N.D.
Th	N.D.	N.D.	N.D.	0.6	N.D.	N.D.	N.D.	0.6	0.5	N.D.
U	N.D.	N.D.	N.D.	<0.1	N.D.	N.D.	N.D.	0.9	0.5	N.D.
Ta	N.D.	N.D.	N.D.	0.8	N.D.	N.D.	N.D.	0.4	2.5	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 36 (continued). Chemical composition of volcanic rocks from the Quill

	E 6 ³	E 55	EX 160	E 43 ³	E 35 ¹	E 46 ³	EUX 95-1 ¹	E 9 ³	E 49	EX 50
SiO ₂	58.24	58.25	58.30	58.38	58.45	58.47	58.53	58.54	58.56	58.59
TiO ₂	0.69	0.70	0.80	0.66	0.52	0.69	0.51	0.65	0.69	0.72
Al ₂ O ₃	17.75	17.63	17.56	17.94	17.44	17.65	17.37	17.36	17.26	17.17
Fe ₂ O ₃ *	7.40	7.49	7.47	7.16	6.60	7.48	6.75	7.22	7.08	6.93
MnO	0.28	0.16	0.17	0.26	0.21	0.24	0.20	0.25	0.17	0.17
MgO	3.89	3.74	3.59	3.59	2.74	3.52	2.26	4.28	3.74	3.67
CaO	7.73	7.85	7.89	7.43	7.29	7.78	8.85	7.57	7.55	7.59
Na ₂ O	3.29	3.51	3.54	3.80	5.89	3.46	4.66	3.43	4.19	4.50
K ₂ O	0.56	0.54	0.59	0.60	0.66	0.55	0.67	0.54	0.62	0.66
P ₂ O ₅	0.17	0.13	0.09	0.18	0.21	0.17	0.18	0.16	0.14	N.D.
S	N.D	N.D	N.D	N.D	6700	N.D	1670	N.D	N.D	N.D
Sc	N.D	N.D	N.D	N.D	8.7	N.D	8	N.D	N.D	N.D.
V	N.D	141	169	N.D	64	N.D	60	N.D	161	160
Cr	N.D	39	35	N.D	6	N.D	14	N.D	52	47
Ni	15	34	47	16	<20	N.D	2	12	41	40
Cu	58	<10	<10	47	20	61	24	51	<10	<10
Zn	N.D	N.D	N.D	N.D	40	N.D	77	N.D	N.D	N.D
Rb	14	11	11	9	12	9	14	9	12	11
Sr	253	235	254	256	284	280	284	268	239	244
Y	22	N.D	N.D	25	24	29	24	25	N.D	N.D
Zr	61	N.D	N.D	78	96	57	89	50	N.D	N.D
Nb	N.D.	N.D.	N.D.	N.D.	4	N.D.	<2	N.D.	N.D.	N.D.
Ba	N.D.	121	31	N.D.	146	N.D.	135	N.D.	131	145
La	N.D	N.D	N.D	N.D	6.2	N.D	5.8	N.D	N.D	N.D.
Ce	N.D	N.D	N.D	N.D	18	N.D	15	N.D	N.D	N.D.
Nd	N.D	N.D	N.D	N.D	11	N.D	9	N.D	N.D	N.D.
Sm	N.D	N.D	N.D	N.D	2.9	N.D	2.51	N.D	N.D	N.D.
Eu	N.D	N.D	N.D	N.D	1.01	N.D	0.97	N.D	N.D	N.D.
Tb	N.D	N.D	N.D	N.D	0.6	N.D	0.5	N.D	N.D	N.D.
Yb	N.D	N.D	N.D	N.D	3.01	N.D	2.69	N.D	N.D	N.D.
Lu	N.D	N.D	N.D	N.D	0.47	N.D	0.40	N.D	N.D	N.D.
Hf	N.D	N.D	N.D	N.D	2.4	N.D	2.4	N.D	N.D	N.D.
Th	N.D	N.D	N.D	N.D	1.0	N.D	0.8	N.D	N.D	N.D.
U	N.D	N.D	N.D	N.D	0.5	N.D	0.6	N.D	N.D	N.D.
Ta	N.D	N.D	N.D	N.D	1.2	N.D	0.3	N.D	N.D	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS

² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 36 (continued). Chemical composition of volcanic rocks from the Quill

	EUX 95-20 ¹	E 54	E 63	E 52	E 21 ³	E 11 ³	E 47	EUX 221 ¹	E 5 ³	EX 157
SiO ₂	58.87	58.89	58.92	58.98	59.23	59.34	59.41	59.43	59.44	59.45
TiO ₂	0.51	0.68	0.71	0.70	0.69	0.66	0.64	0.65	0.65	0.70
Al ₂ O ₃	17.41	17.59	17.86	17.55	18.25	18.04	17.13	17.17	17.82	17.52
Fe ₂ O ₃ *	6.77	6.86	7.14	7.15	5.97	7.22	7.01	7.11	7.22	7.14
MnO	0.21	0.17	0.17	0.17	0.23	0.25	0.17	0.18	0.28	0.17
MgO	2.75	3.27	3.26	3.43	3.43	2.98	3.49	3.02	3.22	3.29
CaO	7.03	7.27	7.40	7.65	8.10	7.43	7.46	7.31	7.17	7.39
Na ₂ O	5.59	4.52	3.78	3.69	3.33	3.34	3.80	4.25	3.42	3.59
K ₂ O	0.67	0.65	0.62	0.66	0.62	0.57	0.78	0.73	0.61	0.66
P ₂ O ₅	0.19	0.10	0.14	0.02	0.14	0.16	0.11	0.13	0.17	0.09
S	4380	N.D	N.D	N.D	N.D	N.D	N.D	1155	N.D	N.D
Sc	7	N.D	N.D	N.D	N.D	N.D	N.D	13	N.D	N.D.
V	55	135	140	156	N.D	N.D	152	111	N.D	143
Cr	14	32	31	38	N.D	N.D	28	30	N.D	35
Ni	2	27	64	36	15	17	36	8	19	46
Cu	23	<10	12	<10	59	54	<10	20	50	<10
Zn	75	N.D	N.D	N.D	N.D	N.D	N.D	46	N.D	N.D
Rb	13	11	11	10	7	17	12	14	10	12
Sr	277	236	231	238	261	271	232	250	256	235
Y	24	N.D	N.D	N.D	25	26	N.D	20	21	N.D
Zr	90	N.D	N.D	N.D	73	108	N.D	77	64	N.D
Nb	3	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	2	N.D.	N.D.
Ba	134	127	138	131	N.D.	N.D.	136	132	N.D.	136
La	5.4	N.D	N.D	N.D	N.D	N.D	N.D	5.3	N.D	N.D.
Ce	16	N.D	N.D	N.D	N.D	N.D	N.D	15	N.D	N.D.
Nd	9	N.D	N.D	N.D	N.D	N.D	N.D	9	N.D	N.D.
Sm	2.50	N.D	N.D	N.D	N.D	N.D	N.D	2.39	N.D	N.D.
Eu	1.05	N.D	N.D	N.D	N.D	N.D	N.D	0.84	N.D	N.D.
Tb	0.6	N.D	N.D	N.D	N.D	N.D	N.D	0.5	N.D	N.D.
Yb	2.60	N.D	N.D	N.D	N.D	N.D	N.D	2.39	N.D	N.D.
Lu	0.39	N.D	N.D	N.D	N.D	N.D	N.D	0.36	N.D	N.D.
Hf	2.2	N.D	N.D	N.D	N.D	N.D	N.D	2.3	N.D	N.D.
Th	0.6	N.D	N.D	N.D	N.D	N.D	N.D	1.2	N.D	N.D.
U	<0.1	N.D	N.D	N.D	N.D	N.D	N.D	0.3	N.D	N.D.
Ta	<0.3	N.D	N.D	N.D	N.D	N.D	N.D	<0.3	N.D	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 36 (continued). Chemical composition of volcanic rocks from the Quill

	EUX 214A2 ¹	EUX 403 ¹	E 2 ³	E 3 ³	E 86	E 40 ³	E 41 ³	E 44 ³	E 64	EX 156 ¹
SiO ₂	59.48	59.63	59.67	59.79	59.92	59.96	60.29	60.35	60.52	60.57
TiO ₂	0.56	0.50	0.66	0.64	0.69	0.65	0.61	0.63	0.65	0.74
Al ₂ O ₃	17.20	17.80	17.81	17.72	17.30	17.57	17.46	17.75	17.37	17.33
Fe ₂ O ₃ *	6.62	6.74	7.01	7.04	6.85	6.93	6.82	6.55	6.69	6.75
MnO	0.18	0.21	0.28	0.27	0.17	0.24	0.25	0.22	0.16	0.17
MgO	2.88	2.81	3.01	3.32	3.14	2.99	3.09	2.70	2.73	2.91
CaO	7.46	6.94	7.23	7.18	7.20	7.11	7.06	6.98	6.74	7.02
Na ₂ O	4.81	4.58	3.58	3.24	3.97	3.80	3.67	4.02	4.21	3.66
K ₂ O	0.72	0.62	0.58	0.63	0.62	0.59	0.59	0.62	0.79	0.76
P ₂ O ₅	0.11	0.16	0.17	0.17	0.14	0.17	0.17	0.18	0.14	0.09
S	1170	3125	N.D	N.D	N.D	N.D	N.D	N.D	N.D	380
Sc	12	9	N.D	N.D	N.D	N.D	N.D	N.D	N.D	14
V	91	69	N.D	N.D	122	N.D	N.D	N.D	100	137
Cr	15	2	N.D	N.D	32	N.D	N.D	N.D	22	29
Ni	4	2	16	17	46	14	15	14	31	39
Cu	17	19	50	52	<10	56	50	52	29	<10
Zn	41	71	N.D	N.D	N.D	N.D	N.D	N.D	N.D	45
Rb	13	12	11	13	11	8	10	9	12	12
Sr	254	258	248	249	225	265	250	247	220	243
Y	19	22	23	25	N.D	29	27	25	N.D	19
Zr	78	88	73	71	N.D	76	83	94	N.D	78
Nb	8	<2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	<2
Ba	135	131	N.D.	N.D.	137	N.D.	N.D.	N.D.	138	145
La	5.6	6.3	N.D	N.D	N.D	N.D	N.D	N.D	N.D	5.9
Ce	14	17	N.D	N.D	N.D	N.D	N.D	N.D	N.D	13
Nd	9	10	N.D	N.D	N.D	N.D	N.D	N.D	N.D	8
Sm	2.52	2.91	N.D	N.D	N.D	N.D	N.D	N.D	N.D	2.58
Eu	0.93	1.08	N.D	N.D	N.D	N.D	N.D	N.D	N.D	0.96
Tb	0.6	0.7	N.D	N.D	N.D	N.D	N.D	N.D	N.D	0.6
Yb	2.64	2.90	N.D	N.D	N.D	N.D	N.D	N.D	N.D	2.89
Lu	0.40	0.43	N.D	N.D	N.D	N.D	N.D	N.D	N.D	0.44
Hf	2.0	2.4	N.D	N.D	N.D	N.D	N.D	N.D	N.D	2.2
Th	0.6	0.6	N.D	N.D	N.D	N.D	N.D	N.D	N.D	0.8
U	0.7	0.6	N.D	N.D	N.D	N.D	N.D	N.D	N.D	0.7
Ta	3.5	0.6	N.D	N.D	N.D	N.D	N.D	N.D	N.D	0.6

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS

² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 36 (continued). Chemical composition of volcanic rocks from the Quill

	E 58	E 53	E 59	E 62 ³	EUX 214 ¹	E 85	EUX 220 ¹	E 56	E 4 ³	E 87
SiO ₂	60.65	60.89	60.93	60.98	61.05	61.08	61.20	61.20	61.21	61.29
TiO ₂	0.64	0.64	0.63	0.60	0.59	0.61	0.59	0.69	0.62	0.63
Al ₂ O ₃	16.99	17.15	17.02	17.53	16.86	17.43	16.86	17.50	17.23	17.18
Fe ₂ O ₃ *	6.77	6.59	6.62	6.99	6.96	6.75	6.86	6.47	6.90	6.69
MnO	0.18	0.18	0.17	0.25	0.19	0.17	0.19	0.17	0.30	0.17
MgO	2.82	2.84	2.86	2.58	2.48	2.64	2.36	2.57	2.85	2.61
CaO	6.93	6.96	6.87	6.43	6.93	6.73	6.52	6.65	6.46	6.73
Na ₂ O	4.19	4.02	4.01	3.90	4.03	3.75	4.51	3.99	3.53	3.84
K ₂ O	0.72	0.65	0.77	0.58	0.75	0.70	0.76	0.66	0.71	0.70
P ₂ O ₅	0.11	0.08	0.12	0.17	0.14	0.14	0.14	0.10	0.19	0.16
S	N.D.	N.D.	N.D.	N.D.	165	N.D.	530	N.D.	N.D.	N.D.
Sc	N.D.	N.D.	N.D.	N.D.	11	N.D.	10	N.D.	N.D.	N.D.
V	129	146	129	N.D.	88	109	81	116	N.D.	117
Cr	27	31	28	N.D.	26	19	21	21	N.D.	20
Ni	25	33	28	12	3	31	2	28	11	66
Cu	<10	<10	<10	44	15	<10	18	<10	47	<10
Zn	N.D.	N.D.	N.D.	N.D.	44	N.D.	44	N.D.	N.D.	N.D.
Rb	13	11	11	9	15	11	14	12	16	11
Sr	235	257	236	192	262	217	256	239	264	231
Y	N.D.	N.D.	N.D.	20	21	N.D.	22	N.D.	26	N.D.
Zr	N.D.	N.D.	N.D.	42	82	N.D.	94	N.D.	78	N.D.
Nb	N.D.	N.D.	N.D.	N.D.	<2	N.D.	3	N.D.	N.D.	N.D.
Ba	140	146	137	N.D.	146	140	150	142	N.D.	146
La	N.D.	N.D.	N.D.	N.D.	5.2	N.D.	5.2	N.D.	N.D.	N.D.
Ce	N.D.	N.D.	N.D.	N.D.	14	N.D.	14	N.D.	N.D.	N.D.
Nd	N.D.	N.D.	N.D.	N.D.	9	N.D.	10	N.D.	N.D.	N.D.
Sm	N.D.	N.D.	N.D.	N.D.	2.24	N.D.	2.33	N.D.	N.D.	N.D.
Eu	N.D.	N.D.	N.D.	N.D.	0.83	N.D.	0.85	N.D.	N.D.	N.D.
Tb	N.D.	N.D.	N.D.	N.D.	0.5	N.D.	0.6	N.D.	N.D.	N.D.
Yb	N.D.	N.D.	N.D.	N.D.	2.44	N.D.	2.52	N.D.	N.D.	N.D.
Lu	N.D.	N.D.	N.D.	N.D.	0.36	N.D.	0.37	N.D.	N.D.	N.D.
Hf	N.D.	N.D.	N.D.	N.D.	2.2	N.D.	2.3	N.D.	N.D.	N.D.
Th	N.D.	N.D.	N.D.	N.D.	0.6	N.D.	0.8	N.D.	N.D.	N.D.
U	N.D.	N.D.	N.D.	N.D.	0.5	N.D.	0.3	N.D.	N.D.	N.D.
Ta	N.D.	N.D.	N.D.	N.D.	<0.3	N.D.	<0.3	N.D.	N.D.	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 36 (continued). Chemical composition of volcanic rocks from the Quill

	E 1 ¹	E 17 ¹	E 18 ¹	E 13 ¹	E 14 ¹	EUX 216 ¹	EUX 217 ¹	E 15 ¹	E 19 ¹
SiO ₂	61.31	63.48	64.92	67.68	70.32	70.61	71.83	72.13	72.26
TiO ₂	0.61	0.38	0.41	0.36	0.23	0.19	0.17	0.19	0.19
Al ₂ O ₃	17.06	16.41	17.25	16.08	14.59	14.71	14.60	14.99	15.07
Fe ₂ O ₃ *	6.62	5.35	5.24	4.41	3.31	2.78	2.86	2.71	2.74
MnO	0.28	0.20	0.28	0.17	0.17	0.15	0.17	0.16	0.15
MgO	2.77	1.88	1.56	1.07	0.92	0.84	0.52	0.49	0.45
CaO	6.81	7.10	5.47	4.61	4.97	3.40	3.96	3.40	3.33
Na ₂ O	3.68	4.14	3.90	4.69	4.45	6.21	4.83	4.88	4.69
K ₂ O	0.67	0.75	0.76	0.81	0.94	0.99	0.95	0.96	1.01
P ₂ O ₅	0.20	0.31	0.20	0.13	0.10	0.11	0.12	0.10	0.10
S	N.D.	410	N.D.	245	90	690	665	495	130
Sc	N.D.	8	N.D.	5	4	2	2	2	2
V	N.D.	54	N.D.	25	20	18	12	2	<2
Cr	N.D.	3	N.D.	N.D.	5	12	27	3	3
Ni	15	2	11	2	<10	<10	<20	<10	<10
Cu	48	14	44	6	<5	<5	<10	5	<5
Zn	N.D.	62	N.D.	49	45	35	50	25	30
Rb	11	15	7	14	20	19	20	22	21
Sr	270	341	285	268	314	211	234	256	210
Y	23	20	29	22	20	18	16	22	18
Zr	74	93	128	104	110	94	116	147	124
Nb	N.D.	2	N.D.	2	3	10	3	3	3
Ba	N.D.	175	N.D.	198	230	213	256	225	225
La	N.D.	7.1	N.D.	7.5	6.6	6.5	6.5	6.4	6.9
Ce	N.D.	20	N.D.	20	19	19	20	19	20
Nd	N.D.	11	N.D.	10	11	11	12	12	12
Sm	N.D.	2.78	N.D.	2.80	2.3	2.2	2.3	2.2	2.3
Eu	N.D.	0.97	N.D.	0.95	0.81	0.75	0.76	0.87	0.87
Tb	N.D.	0.6	N.D.	0.7	0.5	0.4	0.5	0.5	0.5
Yb	N.D.	2.91	N.D.	3.10	2.53	2.36	2.42	2.42	2.48
Lu	N.D.	0.44	N.D.	0.45	0.39	0.38	0.40	0.37	0.41
Hf	N.D.	2.7	N.D.	3.0	2.9	3.5	3.3	3.6	3.8
Th	N.D.	0.9	N.D.	0.9	1.1	1.0	1.1	1.2	1.3
U	N.D.	<0.1	N.D.	0.4	0.6	0.3	0.8	0.3	0.4
Ta	N.D.	0.5	N.D.	1.0	1.6	6.9	0.5	1.4	1.1

Major elements recalculated to 100% volatile free for comparison

 * Total iron as Fe₂O₃

N.D. Not determined

¹ Analyzed at ACTLABS

² Analyzed at Centre National de la Recherche Scientifique. Selected trace elements analyzed at MIT

³ Analyzed at UPRM

All other analyses by Centre National de la Recherche Scientifique

TABLE 37. Analyses of glasses from volcanic rocks of St. Eustatius

A. Microprobe analyses of interstitial glass from volcanic rocks of the Quill

	E-5	E-26
SiO ₂	71.02	74.57
TiO ₂	0.62	0.64
Al ₂ O ₃	14.57	12.67
Fe ₂ O ₃ *	5.69	4.55
MnO	N.D.	N.D.
MgO	0.57	0.76
CaO	3.32	2.88
Na ₂ O	2.60	2.49
K ₂ O	1.62	1.44

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

B. Whole rock analyses of glass from rhyolites from the Sugar Loaf succession and from the Quill

	EUX 203	EUX 98-11-4
SiO ₂	71.47	72.90
TiO ₂	0.14	0.16
Al ₂ O ₃	15.02	14.37
Fe ₂ O ₃ *	2.67	2.89
MnO	0.13	0.17
MgO	0.80	0.52
CaO	3.77	3.23
Na ₂ O	4.30	4.65
K ₂ O	1.61	1.03
P ₂ O ₅	0.09	0.07
S	N.D.	N.D.
Sc	3	2
V	10	16
Cr	14	11
Co	N.D.	N.D.
Ni	N.D.	N.D.
Cu	N.D.	N.D.
Zn	N.D.	N.D.
Rb	31	25
Sr	199	191
Y	13	19
Zr	98	128
Nb	3	<2
Ba	296	266
La	6.5	7.1
Ce	16	18
Nd	9	9
Sm	1.66	2.34
Eu	0.60	0.73
Tb	0.3	0.4
Yb	1.71	2.52
Lu	0.28	0.40
Hf	2.7	3.2
Th	1.3	1.1
U	0.9	0.7
Ta	<0.3	0.4

Major elements recalculated to 100 Wt % volatile-free for comparison

* Total iron as Fe₂O₃

N.D. Not determined

EUX 203 — Sugar Loaf; EUX 98-11-4 — The Quill

in a basaltic andesite with a silica content of 56.93%. The two glasses, which are both rhyolitic in composition, lie on the trend shown by the volcanic rocks for Al_2O_3 , MgO and CaO , but off the trend for TiO_2 , Fe_2O_3 and Na_2O (Fig. 84A). For the first two oxides the glasses are enriched with respect to the volcanic rocks ($\text{TiO}_2 \times 3$; $\text{Fe}_2\text{O}_3 \times 2$), whereas Na_2O is depleted in the glasses. The latter could be due to the loss of Na during microprobe analysis. For K_2O , although the glasses are enriched by a factor of ~ 1.5 when compared to the rhyolitic volcanic rocks, they appear to lie on the continuation of the trend shown by the majority of the andesites and basaltic andesites.

The whole rock chemical analyses of five plutonic blocks from the Quill, two of which (EUX 406 and E 36) have also been analyzed for trace elements are listed in Table 38, and are plotted along with the volcanic rocks on Figures 84A and B. With the exception of V and possibly Sr, the plutonic blocks all lie on or near the low silica extension of the volcanic trend suggesting that fractional crystallization of cumulate minerals could have generated the chemical variations seen in the Quill volcanic rocks.

Chondrite-normalized REE plots are shown in Figure 85. A representative cumulate block (EUX 406) composed of magnetite, hornblende, augite and plagioclase shows enrichment in LREE, with La being slightly depleted when compared to Ce, as well as a very strong depletion in the MREE and HREE. Such a pattern is compatible with the essential mineralogy of the cumulate block and contrasts strongly with that of the analyzed basalt (EUX 209, Fig. 85). The latter is characterized by a flat pattern for the middle and heavy REE, with the LREE being slightly depleted. The basaltic andesites, andesites, dacites and rhyolites in contrast, all show relatively flat or slightly curved patterns for the middle REE, with a slight enrichment in the HREE, and a more extensive enrichment of the LREE suggesting that amphibole and/or pyroxene extraction played a role in their formation. There also appears to be slight increase in LREE with increasing SiO_2 (Fig. 85) between the andesites, dacites and rhyolites. The differences between the cumulate and basalt REE patterns shown in Figure 85 suggests that removal of magnetite, hornblende, augite, and plagioclase from a parent basalt should result in depletion of LREE and enrichment in the HREE. The fact that such

TABLE 38. Chemical composition of plutonic blocks from the Quill

	EUX 406 ¹	SE 31B#	SE 48A#	SE 48B#	E 36 ²
SiO ₂	42.56	45.15	41.05	42.17	52.68
TiO ₂	0.53	0.35	1.90	1.58	0.76
Al ₂ O ₃	24.24	22.25	18.73	19.07	19.39
Fe ₂ O ₃ *	7.63	10.57	12.71	9.61	9.04
MnO	0.11	0.15	0.13	0.10	0.27
MgO	10.18	7.92	9.68	10.71	4.88
CaO	13.66	15.46	14.30	15.54	9.50
Na ₂ O	1.07	0.01	1.26	0.92	3.02
K ₂ O	0.09	0.06	0.16	0.21	0.34
P ₂ O ₅	0.01	0.09	0.08	0.09	0.12
S	<50	N.D.	N.D.	N.D.	N.D.
Sc	55	N.D.	N.D.	N.D.	N.D.
V	187	N.D.	N.D.	N.D.	N.D.
Cr	470	N.D.	N.D.	N.D.	N.D.
Ni	57	N.D.	N.D.	N.D.	10
Cu	9	N.D.	N.D.	N.D.	70
Zn	27	N.D.	N.D.	N.D.	N.D.
Rb	<2	N.D.	N.D.	N.D.	5
Sr	236	N.D.	N.D.	N.D.	287
Y	6	N.D.	N.D.	N.D.	N.D.
Zr	10	N.D.	N.D.	N.D.	N.D.
Nb	<2	N.D.	N.D.	N.D.	N.D.
Ba	15	N.D.	N.D.	N.D.	N.D.
La	9.4	N.D.	N.D.	N.D.	N.D.
Ce	28	N.D.	N.D.	N.D.	N.D.
Nd	19	N.D.	N.D.	N.D.	N.D.
Sm	4.41	N.D.	N.D.	N.D.	N.D.
Eu	1.44	N.D.	N.D.	N.D.	N.D.
Tb	0.6	N.D.	N.D.	N.D.	N.D.
Yb	0.40	N.D.	N.D.	N.D.	N.D.
Lu	0.06	N.D.	N.D.	N.D.	N.D.
Hf	3.9	N.D.	N.D.	N.D.	N.D.
Th	0.9	N.D.	N.D.	N.D.	N.D.
U	<0.2	N.D.	N.D.	N.D.	N.D.
Ta	0.4	N.D.	N.D.	N.D.	N.D.

Major elements recalculated to 100% volatile free for comparison

* Total iron as Fe₂O₃

From Wills, 1974

EUX 406, SE 31B, SE 48A, SE 48B — Cumulate blocks

E 36 — Gabbroic block

¹ Analyzed at ACTLABS² Analyzed at UPRM

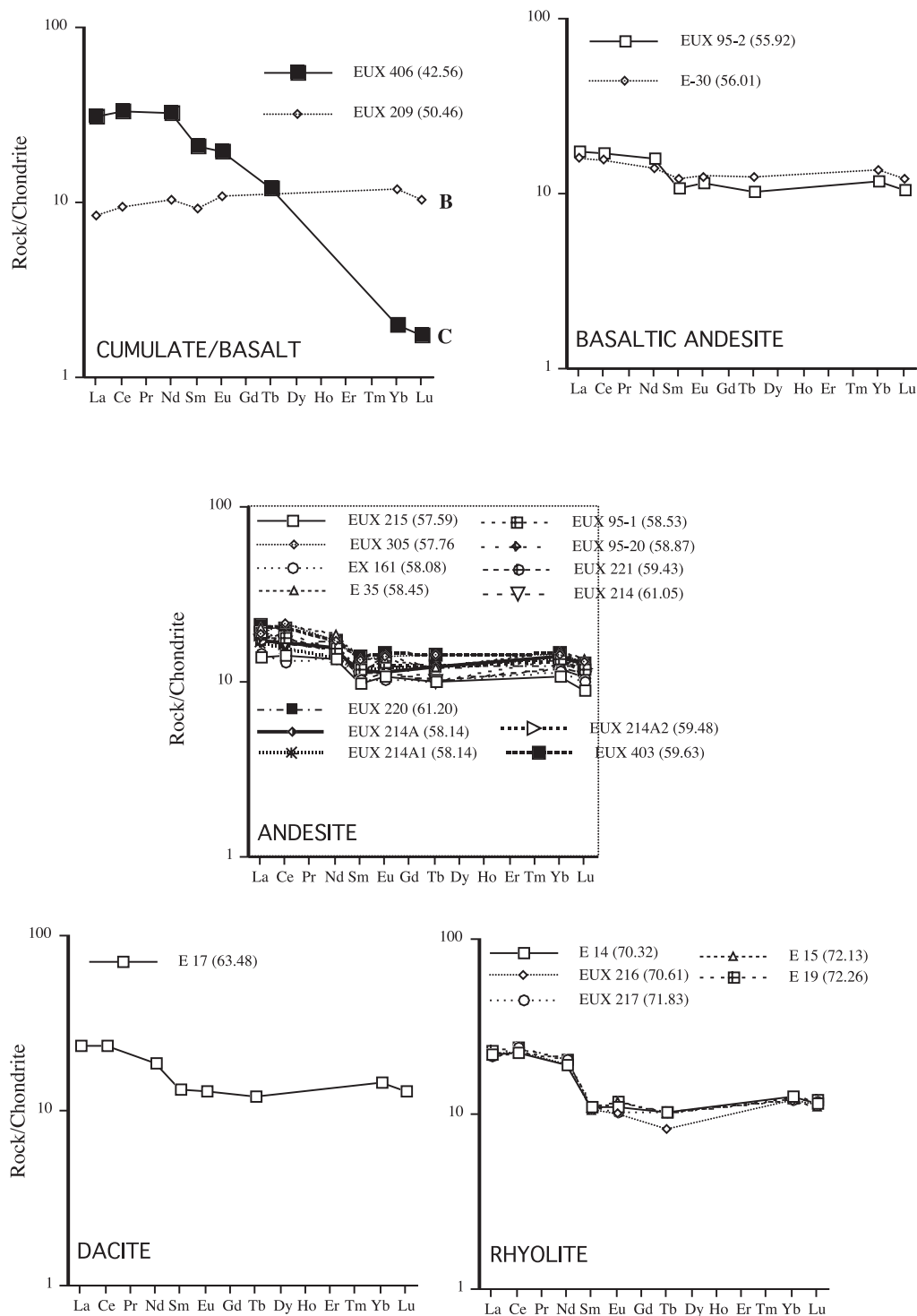


FIGURE 85. Chondrite-normalized REE plots of juvenile clasts from the Quill (chondrite normalizing factors from Taylor, in Donnelly and Rogers, 1980). On the cumulate/basalt plot filled symbols represent cumulate block (C), and open symbols basalt (B).

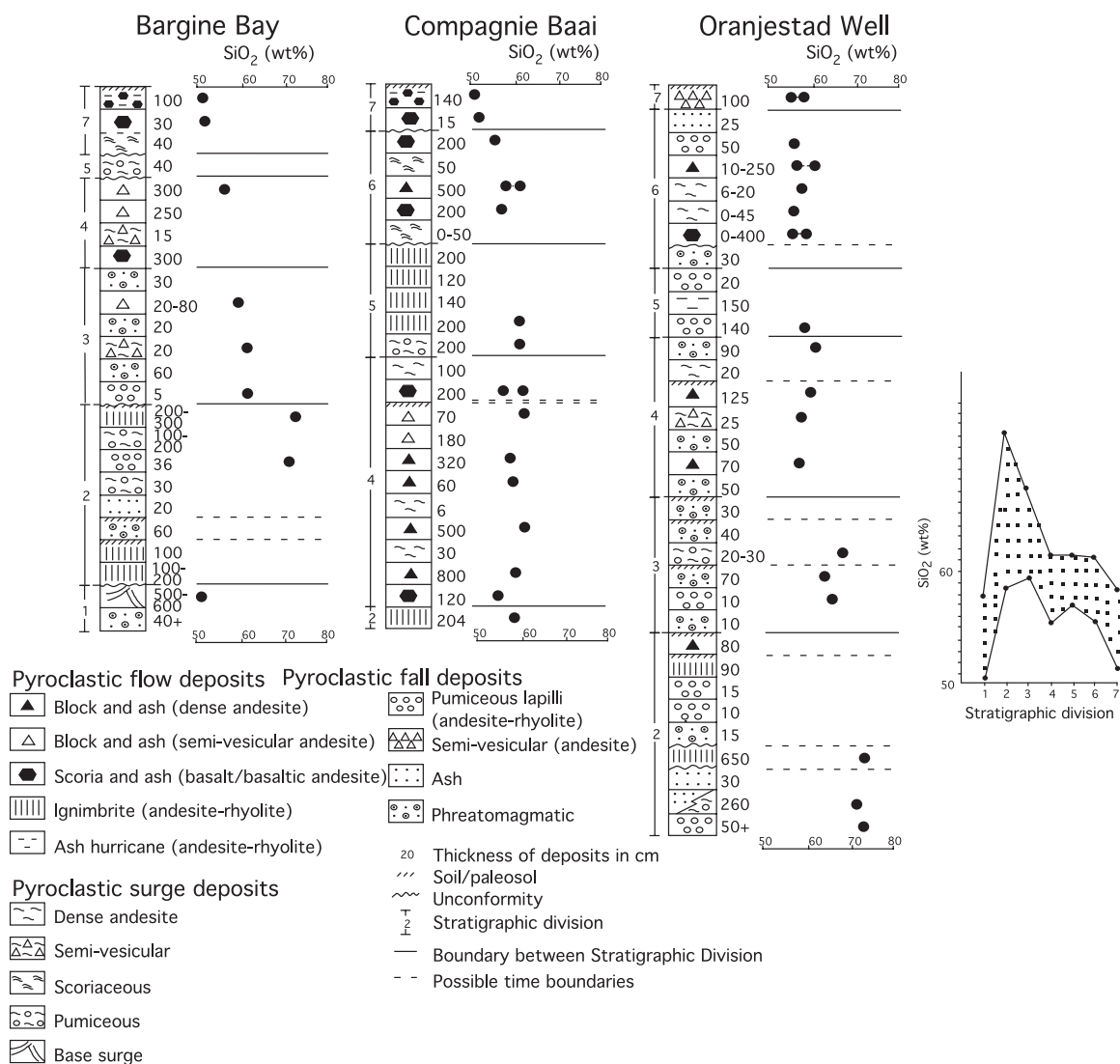


FIGURE 86. Variation of SiO₂ against stratigraphic position for three stratigraphic sections with an inset showing the range of silica for all analyzed rocks for Stratigraphic Divisions 1 to 7:

- 1 — Bargine Bay (stratigraphic section II, Plate 5)
- 2 — Compagnie Baai (stratigraphic section V, Plate 5)
- 3 — Oranjestad Well (stratigraphic section XVIII, Plate 5).

a pattern is not seen in the more fractionated basaltic andesite to rhyolite compositions suggests that this basalt (EUX 209) does not represent a parental basaltic composition but rather a differentiated product after the removal of the cumulate material. Such a conclusion is also supported by the low MgO values shown by the Quill basalts which suggests that they are not primary melts (Macdonald et al., 2000).

CHEMICAL STRATIGRAPHY OF THE QUILL

The seven Stratigraphic Divisions of the Quill show considerable variation in the compositions of the deposits that make up each Division. In order to have some idea as to how systematic these variations are, the SiO₂ content of analyzed juvenile clasts have been plotted against stratigraphic position for the three key stratigraphic sections: Bargine Bay (stratigraphic section II) and Compagnie Bay (stratigraphic section V) on the east coast, and Oranjestad Well (stratigraphic section XVIII) on the west coast (Fig. 86). Only Stratigraphic Divisions 2, 4, 5 and 7 are present in all three sections, Stratigraphic Division 1 is only found in the section at Bargine Bay, Division 3 is found both at Bargine Bay and Oranjestad Well, whereas Division 6 only occurs at Compagnie Baai and Oranjestad Well.

The section at Bargine Bay shows Stratigraphic Division 1 to be composed of basalt which is followed stratigraphically, but with at least three time breaks, by the rhyolitic compositions characteristic of Division 2. On top of Division 2 are deposits from Divisions 3 through 7 which show a steady decrease in silica content up the section. The Compagnie Baai section in contrast, shows a relatively restricted range in SiO₂ values, around 60 %, throughout Stratigraphic Divisions 2, 4, and 5. Divisions 6 and 7 again are more basic than the other Divisions. Examples of deposits from co-mingled eruptions can be seen in Divisions 4 and 6, indicating the availability of basic magma throughout the history of the volcano. The Oranjestad Well section shows the rhyolitic compositions of Division 2, followed by dacitic composition of Division 3, which are then followed by andesitic compositions for the remainder of the stratigraphy (Divisions 4 to 7). Co-mingled deposits again occur in Divisions 6

and 7. All three sections are condensed and little correlation can be made on geochemical grounds between the different sections. A summary of the range in silica values for the different Stratigraphic Divisions is also shown in Figure 86 where it can be seen that Stratigraphic Divisions 2 and 3 show the greatest range, followed by Divisions 1 and 7, and then by Divisions 4, 5, and 6. It should be pointed out however that for Division 2 there is a compositional gap between the most siliceous andesites, which are similar in composition to those in the other Divisions, and the rhyolites. In contrast, Division 3 shows a complete range in compositions between the least siliceous and most siliceous samples.

ISOTOPIC COMPOSITIONS OF VOLCANIC ROCKS FROM THE QUILL

Strontium isotopic compositions of volcanic rocks spanning the whole compositional range of the Quill are listed in Table 39. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios vary from 0.70343 to 0.70501, suggesting only modest sediment contribution. A review of the strontium isotopic ratios of the volcanic arc of the Lesser Antilles is described by Smith and Roobol (1990, their Fig. 77). Comparison with these data indicates that the small range for the Quill is typical for the northern Lesser Antilles. On a plot of $^{87}\text{Sr}/^{86}\text{Sr}$ against SiO_2 (Fig. 27) lavas from the Quill, as was seen for Saba, show an essentially flat pattern with increasing silica content suggesting that the main process in the formation of the Quill volcanic rocks was crystal fractionation rather than assimilation-fractional crystallization (Davidson, 1987).

In Figure 87, plots of variations in strontium, neodymium and lead isotopes of the volcanic rocks from the Quill are compared with similar isotopic data from the volcanic rocks of other islands of the Active Arc of the Lesser Antilles, the Atlantic sea floor sediments in front of the arc, and with MORB. On the $^{143}\text{Nd}/^{144}\text{Nd}$ - $^{87}\text{Sr}/^{86}\text{Sr}$ plot (Fig. 87A and B), the Quill samples plot at the low strontium - high neodymium end of the field of the Lesser Antilles volcanic rocks typical of the volcanic rocks of the northern Lesser Antilles, and furthest away from the values obtained from the Atlantic ocean floor sediments, suggesting that the Quill magmas were generated with limited sediment contamination.

TABLE 39. Strontium isotopic analyses of volcanic rocks from the Quill

Sample Number	SiO ₂ (Wt %)	⁸⁷ Sr/ ⁸⁶ Sr	Standard Deviation
E 36 [#]	52.68	0.70359	±0.00009
E 29	55.63	0.70350	±0.00006
E 26	56.93	0.70356	±0.00006
E 297*	57.1	0.70380	±0.00006
E 313*	57.1	0.70343	±0.00006
E 315*	57.2	0.70406	±0.00006
E 294*	57.6	0.70380	±0.00006
E 302*	57.8	0.70370	±0.00006
E 306*	58.0	0.70385	±0.00006
E 310*	58.1	0.70422	±0.00006
E 303*	58.2	0.70390	±0.00006
E 309*	58.4	0.70403	±0.00006
E 9	58.54	0.70350	±0.00006
E 3	59.79	0.70362	±0.00002
E 4	61.21	0.70353	±0.00003
E 17	63.48	0.70501	±0.00001
E 18	64.92	0.70418	±0.00008
E 13	67.68	0.70386	±0.00006
E 15	72.13	0.70386	±0.00006

* Unpublished analyses of Stipp and Nagle, used with permission.

Other analyses by Z. Peterman, U.S.G.S.

[#] Gabbroic Inclusion

A similar conclusion can be obtained from the ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb against ²⁰⁶Pb/²⁰⁴Pb plots (Figs. 87C and D), where the Quill samples plot near the end of the fields of the Lesser Antilles volcanic rocks closest to MORB field. These data also suggest that the sedimentary rocks of the subvolcanic crust under St. Eustatius (fragments of which are found as greenstone and limestone lithic inclusions in the Quill pyroclastic deposits) must have played only a very limited role in the evolution of the Quill magmas.

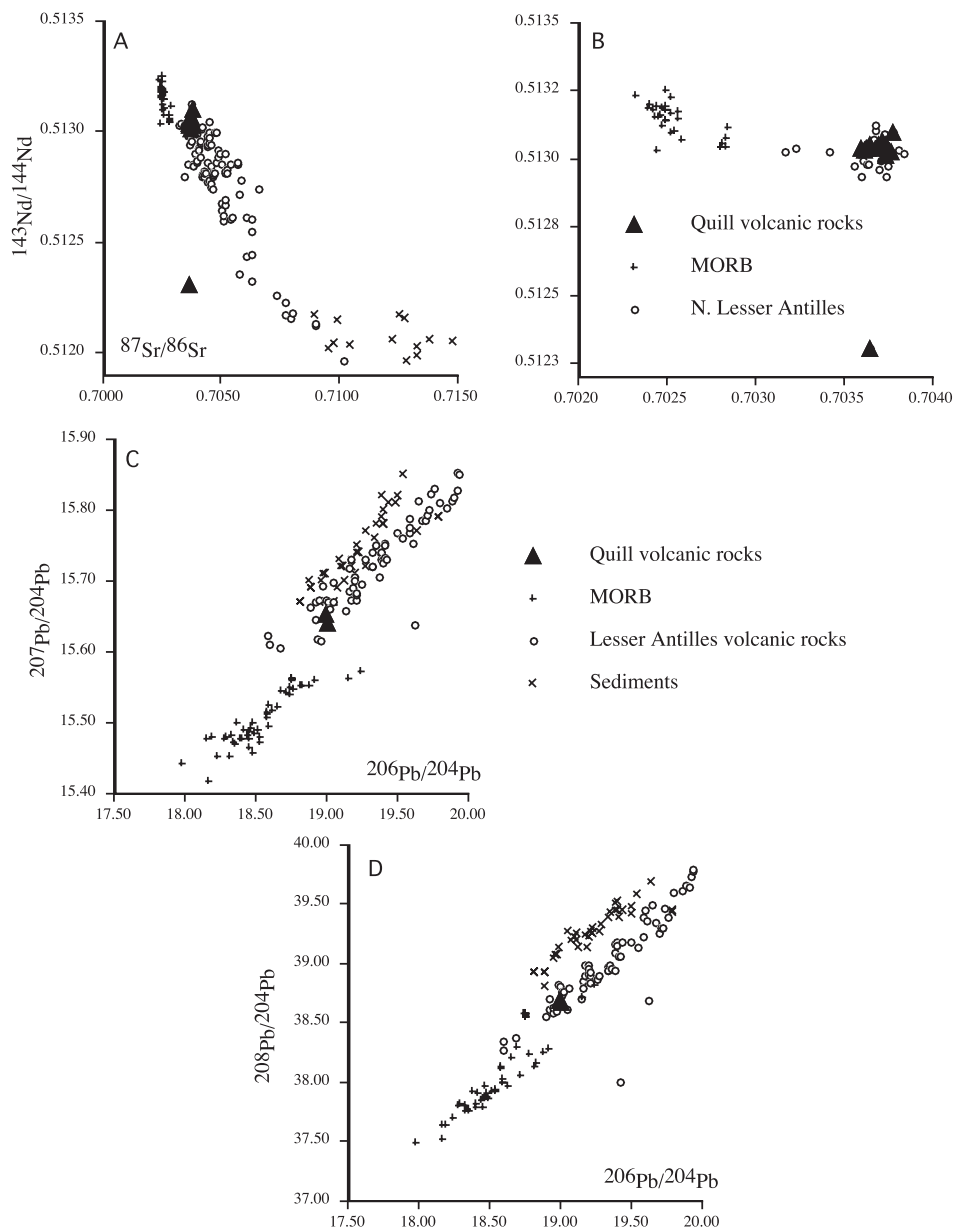


FIGURE 87. Isotopic compositions of volcanic rocks from the Quill compared to volcanic rocks from other islands of the Active Arc of the Lesser Antilles. Composition of Atlantic Ocean floor sediments, and MORB plotted for comparison. Data sources: Davidson (1983, 1984, 1986, 1987); White and Dupre (1986); White and Patchett (1984); and White et al., (1985).

- Sr-Nd isotopes.
- Expansion of part of A showing MORB, the Quill volcanic rocks, and data from the Northern Lesser Antilles (St. Eustatius, St. Kitts, Nevis, Montserrat).
- $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ isotopes
- $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ isotopes

PETROGENESIS

Northern Centers and the White Wall-Sugar Loaf Series

The rocks of the Northern Centers, which are the oldest on the island, form a chemically coherent group of low-K calc-alkaline series andesites (Fig. 82). The samples included in this study were all two-pyroxene andesites, although amphibole-phyric rocks were described by Westermann and Kiel (1961). The REE patterns of the rocks from the Northern Centers are all very similar with relatively flat patterns with slight negative Eu anomalies suggesting a probable origin by fractionation of plagioclase and pyroxene, rather than amphibole.

Of intermediate age is the White Wall-Sugar Loaf succession ranging from low-K calc-alkaline basaltic andesites and andesites to medium-K felsic andesites, dacites and rhyolites (Fig. 82). On Harker variation diagrams the rocks of the White Wall-Sugar Loaf show a reasonably well defined differentiation trend suggestive of crystal fractionation. For the rocks from the White Wall, REE patterns are similar to those of the Northern Centers, i.e. relatively flat patterns suggestive of pyroxene fractionation. In contrast, the rhyolites of the Sugar Loaf show patterns more suggestive of amphibole fractionation (Fig. 87).

The positive correlation between the ratios Ba/La and La/Sm shown by the rocks from both the Northern Centers and the White Wall-Sugar Loaf (Fig. 29) suggest that assimilation of sedimentary material may have played a role in their formation.

The Quill

The lavas of the Quill range in composition from basalt to rhyolite and belong to the low-K (Gill, 1981), high-Ca (Macdonald et al., 2000) calc-alkaline series. On the Harker diagrams (Figs. 81 and 84A and B) the lavas show well-defined differentiation trends for all of the Stratigraphic Divisions.

The cumulate blocks of the Quill, the presence of which we regard as a fundamental difference between this volcano and that of the Saba center, when plotted on Harker differentiation diagrams (Figs. 84A and B) plot on the extension of the basic end of the differentiation trend, a relationship indicating that the different magma compositions of the Quill

can be formed simply by the subtraction of the minerals present in the cumulate blocks (plagioclase-amphibole-clinopyroxene-oxide, Tables 26 and 33). At the opposite end of the differentiation trend lie the compositions of the interstitial glasses. The fact that they lie for most elements directly on the extension of the trend provides support that additional variations in composition can be explained by the fractionation of the phenocryst phases. Additional support for a fractional crystallization origin for the lavas of the Quill can be seen in Figure 29, where they exhibit a trend similar to the calculated trends (A and B, Fig. 29) involving fractionation of phenocrystal and cumulate minerals (Defant et al., 2001).

Mass-balance calculations based on selected compositions of basalt, basaltic andesite, andesite, dacite, and rhyolite (Table 36) together with selected mineral compositions from cumulate blocks (Table 33) indicate clearly that the subtraction of amphibole, plagioclase and magnetite must have played a significant role in the generation of the more differentiated compositions. However, the fact that both olivine and clinopyroxene generally need to be added in order to produce acceptable results suggests that the parental magma has to be more basic in composition than any of the basalts and basaltic andesites analyzed from the Quill, a conclusion already suggested based on geochemical data.

The isotopic values (Fig. 87) shown by the Quill volcanic rocks suggests there has been only limited contamination of primary magmas. Whether this contamination is from the subducted slab or the arc crust cannot be resolved at this time, however the relatively constant ratios between such elements as Rb and K do not support a significant role for crustal assimilation in the origin of the Quill magmas, although the high sulfur contents shown by some of the Quill volcanic rocks suggest some interaction between the Quill magmas and upper crustal sediments did occur.

CONTRASTED MODELS FOR THE MAGMA RECHARGE SYSTEMS FOR SABA AND THE QUILL

For the past 50,000 years the Quill volcano was active at the same time as much of the post-sector collapse stratigraphy of Saba was erupted. The

differences between these two adjacent volcanoes of the northern Lesser Antilles during this time interval draws attention to two controlling factors.

- a) The role of the mantle in controlling the composition of batches of magmas generated beneath the volcanoes;
- b) The role of the crust in controlling the number, form, depth, and nature of the conduits by which the magma travels from the mantle to the surface, that is — the crustal plumbing system beneath each volcano.

The mantle factor

An explanation is required as to why two adjacent volcanic complexes — the Quill and Saba — situated only 35 km apart along the arc axis have, for the past 50,000 years, simultaneously produced two chemically distinct magma series. Such differences are not uncommon in the Lesser Antilles where, for example, the three morphologically distinct volcanoes comprising northern Martinique — Mt. Pelée, Pitons du Carbet, and Morne Jacob centers — are chemically distinct (Gunn et al., 1974; Smith and Roobol, 1990). Similarly, morphologically distinct volcanic centers of Basse Terre, Guadeloupe can also be distinguished chemically (Gunn et al., 1980). However in the case of both the Martinique and Guadeloupe examples as the different volcanic centers are of different ages their chemical differences can be explained by variations in magma chemistry with time. Such an explanation cannot be used to explain the production of medium-K, low-Ca and low-K, high-Ca calc alkaline magmas of Saba and the Quill however, as both centers were active over the same time period.

The differences between these two centers could be explained by differing amounts or sources of contamination of parent magmas or by differing degrees of partial melting of the mantle wedge. Evidence to suggest the former comes from the different trends shown by the volcanic rocks of Saba and the Quill in Figure 29. The Saba trend suggests contamination by crustal sedimentary rocks, whereas the trend of the Quill appears to be more indicative of fractional crystallization of primary mantle magmas. Evidence for the latter can be obtained by comparing trace element contents of the two suites (Macdonald et al., 2000). For similar depths, pressures and mantle composition, a low-K parental

tholeiitic magma would be produced by higher degrees of partial melting than a medium-K tholeiitic magma (McBirney, 1993). Thus assuming a spinel-peridotite mantle, the Zr/Yb ratios of the derived magmas (unpublished method of Jolly, as quoted in Smith et al., 1998) could provide an indication of the relative amounts of partial melting. The most basic rocks on Saba and St. Eustatius have Zr/Yb ratios of 29 and 19 respectively, suggesting that parent basalts on Saba could have been formed by considerably lower amounts of melting of the mantle wedge than those of St. Eustatius.

The high-Ca nature of the Quill suite and the low-Ca nature of the Saba volcanic rocks also suggest a fundamental difference in the conditions of fractionation of the parent magmas of each suite (Macdonald et al., 2000). For the Quill, high pressure fractionation is thought to have been dominated by olivine whereas for Saba, pyroxene appears to have played a more important role. These differing high pressure fractionation schemes would also imply that the Saba parent magmas were more hydrous than those for the Quill, as evidenced by the sparse occurrence of orthopyroxene and the ubiquitous occurrence of amphibole in the Saba lavas. Magmas from both centers however appear to have been sufficiently hydrous to restrict the high pressure crystallization of plagioclase.

The crustal factor

Stratigraphic studies of Saba and the Quill, St. Eustatius have demonstrated that fundamental differences exist between the eruptive styles of each volcano which are thought to have been caused by differences of how magma rises through the crust, i.e. in differences in the plumbing system beneath each volcano.

These differences in the plumbing systems are thought to also cause the characteristic differences between the types of inclusions contained in the lavas from each volcano. Saba is characterized by the presence of abundant rounded hypabyssal nodules and the absence of cumulate blocks, whereas the Quill shows the reverse relationship. The presence of hypabyssal inclusions on Saba has been correlated with the intrusion of composite dikes into the volcanic substructure, which in turn is thought to have been controlled by the occurrence of a major crustal fracture zone

beneath Saba. The rounded hypabyssal inclusions are thought to represent the crystallized basic margins of such dikes that were eroded by their more felsic cores. Simple mixing of magma cannot account for the presence of the inclusions on Saba as both Saba and the Quill show ample evidence of the coexistence and mixing of basic and intermediate/felsic magmas. In contrast, the crust beneath the Quill is thought to lack such major fracture zones, and the occurrence of hornblende-bearing cumulate blocks in the lavas is taken to indicate the presence of high-level magma chambers.

The differences in the types of inclusions included in the lavas from Saba and the Quill are not unique to these two centers. For example, the Soufriere Hills, Montserrat, which is also underlain by a major fracture zone (Aspinal et al., 1998; Mattioli et al., 1998), is characterized by the presence of hypabyssal nodules (Murphy et al., 2000), whereas volcanoes such as Mt. Pelée, Martinique, Soufriere, St. Vincent, Mt. Liamugia, St. Kitts, and the South Soufriere Hills, Montserrat, which do not appear to overlie major crustal fracture zones, are characterized by the ejection of cumulate blocks (Lewis, 1964, 1973 a, b; Rea, 1974; Arculus and Wills, 1980; Baker, 1984; Smith and Roobol, 1990).

Two contrasted models for different plumbing systems represented by the Saba-type and Quill-type volcanoes are shown in Figures 88A and B. Both Saba and the Quill are thought to be underlain by magma chambers at the mantle/crust boundary in which crystal fractionation of parental basaltic magma occurs. Both volcanoes are also underlain by a thin crust (~20 km), which appears to be layered based on seismic velocities. The uppermost 5 km having a P-wave seismic velocity of 5.4 km/sec, the next 5 km a velocity of approximately 6.0 km/sec, and the lowest 10 km a seismic velocity of approximately 6.5 km/sec (Officer et al., 1959; Maury et al., 1990). The crust beneath the northern Lesser Antilles can also be divided into an upper zone, which would show brittle deformation, and a lower zone of ductile deformation (Figs. 88A and B).

These two different plumbing systems arise from the mechanism of transporting the magma through the crust. For Saba (and similar volcanoes) the presence of a major fracture zone would facilitate the rise of magma through a series of dike-like bodies. These dikes would probably widen at depth to produce tall narrow magma chambers. Discharge of these chambers, probably triggered by the influxes of new batches of

magma, is achieved through the intrusion of composite dikes into the volcano's superstructure. The surface expression of these dikes shown by the numerous vents characteristic of the Saba volcanic center (Plate 2), suggests that the fracture zone has a width of about 4 km. Based on the Montserrat example, the elongated magma chambers probably reach to depths of around 5 to 6 km, with the dikes extending to shallower levels of around 3 km (Barclay et al., 1998; Mattioli et al., 1998).

In the case of the Quill where there is no apparent fault zone, magma has to find its way through at least 15 km of brittle layered crust. Passages would be fracture controlled and highly irregular, and magma chambers are likely to form at the boundaries between the different crustal layers. Magma would preferentially tend to rise through previously developed conduits linking long-term magma chambers as these would have been thermally perturbed (Johnson and Draper, 1992; Heath et al., 1998a). Such a situation would lead to a volcano with a single central vent as is found on the Quill.

Another distinction between Saba-type and Quill-type volcanoes is that the former are dominated by the eruption of andesites of essentially monotonous composition. For Saba, andesites of almost constant composition have been erupted for the past 500,000 years, a similar situation is also evident for the Soufriere Hills, Montserrat which has erupted almost exclusively andesite with around 61% SiO₂ for the last 300,000 years (Smith et al., 2000, 2002). In contrast, volcanoes such as the Quill and Mt. Pelée, Martinique commonly produce a very wide variety of rock compositions, which in the case of the Quill ranges from basalt to rhyolite, and in the case of Mt. Pelée, Martinique, basaltic andesite to dacite (Smith and Roobol, 1990).

It is proposed here therefore, that the Saba-type centers are characterized by the repeated injection of composite dikes into the substructure of the volcano as a consequence of the presence of a major crustal fracture zone beneath the volcano. High-level fractionation within the dike-like magma chambers would be relatively minor and andesite produced by fractionation in a lower crustal/upper mantle chamber would be the dominant rock type. In contrast, the Quill-type of plumbing involves the formation of multiple high-level magma chambers, several of which might co-exist at any one time. In these chambers crystal fractionation

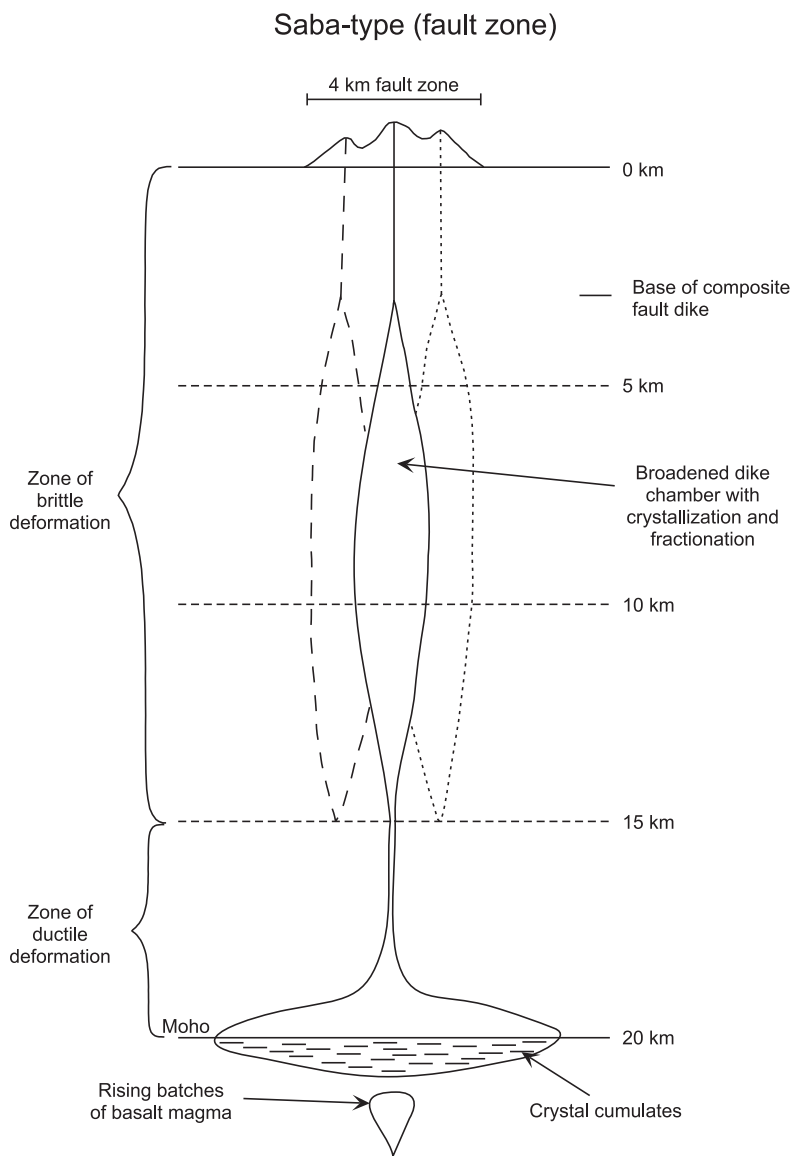


FIGURE 88. Contrasted models for the magma recharge systems of Saba and Quill type volcanoes.

A. Saba-type (fault zone).

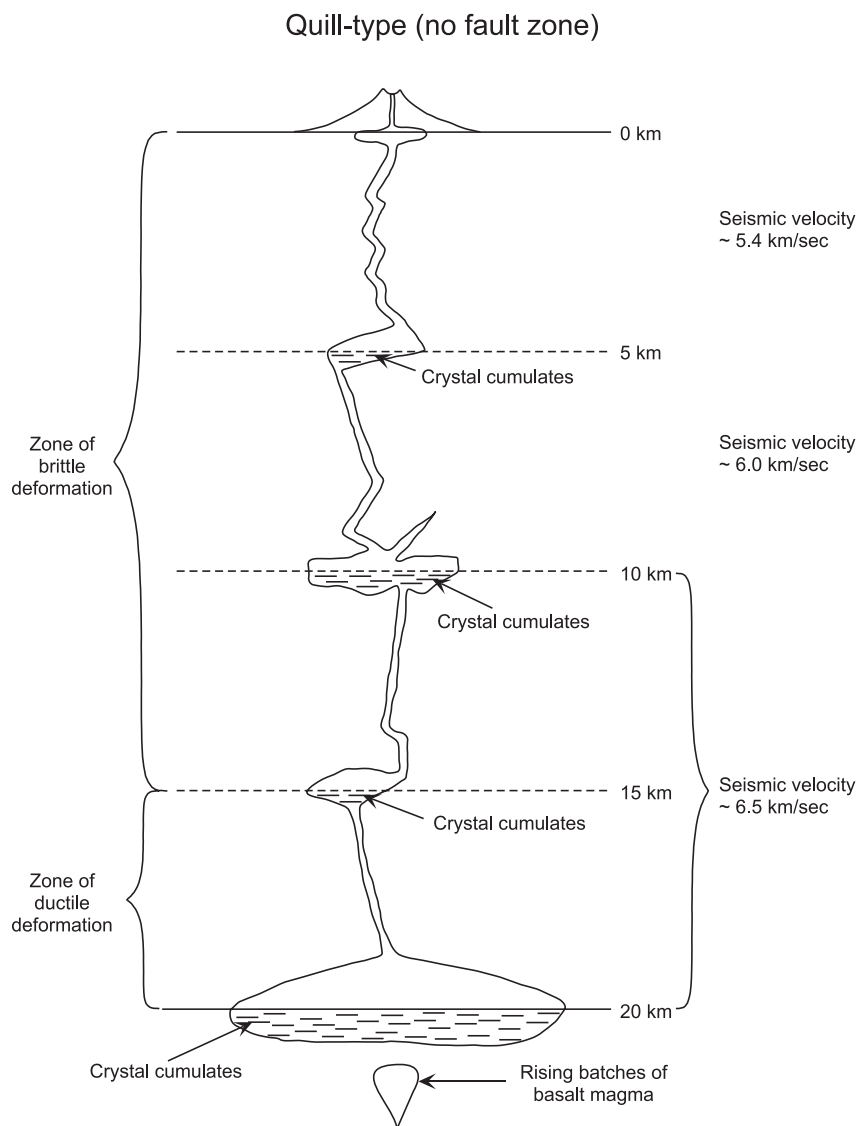


FIGURE 88. Contrasted models for the magma recharge systems of Saba and Quill type volcanoes.

B. Quill-type (no fault zone).

would proceed to produce more felsic magmas and crystal cumulates. Such chambers permit the eruption of magmas of a wide variety of compositions as well as the ejection of cumulate blocks produced by this fractionation.

Some indication of the time required for the extreme fractionation to produce significant volumes of felsic lavas can be obtained from the age dating of the stratigraphic sections on St. Eustatius. In the Sugar Loaf succession, the lowest pumice bed of dacitic composition overlies a limestone horizon dated at 251,000 years B.P., higher in the stratigraphy, a rhyolitic pumice horizon overlies another limestone bed dated at 210,000 to 234,000 years B.P. (Fig. 35), suggesting that it could have taken from 20,000 to 30,000 years to generate the rhyolites. For the Quill, the rhyolites at Bargine Bay have been radiocarbon dated at 22,240 years B.P. (Fig. 40). If, based on the youngest ages obtained from the underlying limestones, the initial products of the Quill were erupted around 50,000 years B.P., then approximately 30,000 years were also available to generate the Quill rhyolites. Magma residence times of approximately similar orders of magnitude have been calculated for Soufriere, St. Vincent (Heath et al., 1998b).

Present day geothermal and
seismic activity on Saba and St. Eustatius,
the status of activity of the volcanoes,
and possible future precursor activities

INTRODUCTION

Since the European settlement of St. Eustatius in 1636 and Saba in about 1640 there has been no eruptive activity on either island (Hartog, 1975, 1976). Westermann and Kiel (1961) regarded the domes on Saba as forming permanent seals to the volcanic conduits, which over time had led to a decrease and finally to the termination of the volcanic activity. The same authors considered that a 'period of decadence and extinction of the Saba volcano' had occurred in the middle of the Holocene, and that the younger Holocene showed only post-volcanic solfataric activity and the formation of the sulfur deposits. Further, Westermann and Kiel (1961) regarded a hot water spring north of Ladder Point to be the sole manifestation of the post-volcanic activity on the island. With regard to the Quill on St. Eustatius, the same authors considered the volcano, based on erroneous radiocarbon ages of corals from the Sugar Loaf, to be younger than 21,000 years and regarded the Quill as undergoing a final extinction between 5,000 and 3,000 years ago.

These conclusions regarding the eruptive history of Saba and the Quill, as well as the ages of the corals, are no longer supported by the results of the present stratigraphic studies on both islands. It is our view that due to the paucity of charcoal on both Saba, and in the younger pyroclastic deposits of St. Eustatius, that our reconstruction of the youngest pyroclastic history of both volcanoes is probably fragmentary and incomplete. However the new data presented here are sufficient to

indicate that Saba probably last erupted just prior to European settlement of the island, whereas the Quill was probably last active around 1,600-1,700 years B.P. Since there has been no long-term nor detailed monitoring of the islands, the only way of determining the present-day status of activity of the volcanoes is by studying the historic records for both geothermal phenomena and felt seismic activity.

VOLCANIC HEAT ESCAPE ON SABA

Introduction

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 sulfur mine adit high in the sea cliffs between Lower Hell's Gate and Green Island off the north coast. The mine occurs in an andesite block and ash flow deposit underlying basaltic andesite lava flows (Plate 2). Sulfur was mined here for short periods between 1875-76 and 1904-07. The full history of discovery and mining of these deposits and the chemistry of the sulfur and gypsum minerals were described by Westermann (1949), and summarized by Westermann and Kiel (1961).

The locations of the hot springs of Saba together with areas of former fumarolic activity are shown on the geologic map (Plate 2). These areas are indicated by outcrops of orange, brown, yellow and green altered volcanic rocks. A summary of all known geothermal data for Saba is given in Table 40, and each location is next described.

Hot springs at Well Bay

Hot springs at Well Bay were reported by Sapper (1903). In 1939 however, Kruythoff (1939) reported that the sea had destroyed a barrier separating them from the sea and that water reported as previously 'hot enough to poach an egg' had been overwhelmed by the sea. Recent searches for these springs have failed to locate them, so we have no record of their present-day temperature. Today the area is no longer remote, as a new concrete driving road has been built to the beach. Any reappearance of hot springs in this area is therefore likely to be rapidly noted.

TABLE 40. Measurements of volcanic heat emission on Saba

Date	Hot spring, Well Bay	Hot spring, 900m south of Ladder		Hot Spring opposite Green Island	Air temperature inside sulfur mine	Measured by:
		#1	#2			
1903	reported					Sapper (1903)
1903			54.2°C			Sapper (1903)
15/3/1950			55-57°C			Westermann & Keil (1961)
22/7/1979					31.5°C (20m inside)	Roobol & Smith
25/7/1979			51°C			Roobol & Smith
27/7/1979				72°C		Roobol & Smith
27/7/1979			55°C			Roobol & Smith
26/8/1981			55°C	66.5°C		Gunnlaugsson (1981)
9/3/1994				54°C*	32.5°C (deepest part)	Roobol & Smith
10/3/1994		32°C	54.2°C			Roobol & Smith
13/4/1996				80°C		Johnson
24/9/1996				82°C		Buchan
30/1/1997		covered	62°C			Roobol & Smith
27/8/1997			62° C			Smith
9/4/1998				79°C		Johnson

* Submerged, probably minimum 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. This causes problems in visiting the locality in winter when a strong ground swell covers the springs with surf and boulders. Their location is however facilitated by the occurrence of a black coating (algae?) on pebbles exposed to warm water. One of these springs was visited by Sapper (1903), when he measured a temperature of 54.2°C. The spring was measured again in March 1950 when temperatures between 55-57°C were recorded (Westermann and Kiel, 1961). On

August 26, 1981, Gunlaugsson (1981) determined the temperature to be 55°C, with a flow rate of less than 0.1 liter per second. The temperature of this spring has since been measured several times (Table 40). For most of this century the temperature appears to have been constant at or around 55° C (Table 40), however in January 1997, it was found to have increased to 62° C. A further temperature measurement in August 1997 indicated that the temperature was still at this elevated value (Table 40). In March 1994 when the main spring had a temperature of 54.2° C, a second spring with a temperature of 32°C was located to the south of the main spring. Recent attempts to relocate this second spring have failed because of local conditions.

A hot spring opposite Green Island

This hot spring is situated on the northern shoreline immediately below the abandoned sulfur 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 can be seen rising from the shore at this point.

This hot spring was located by us on July 27, 1979, using a boat and swimming ashore, and the temperature found to be 75°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. We revisited it on March 9, 1994, when 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 by probing the sand with a thermometer. This measurement also does not reflect the true temperature of the spring, which was not determined. In April, and again in September 1996, the spring was measured by residents of the island and its temperature 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.

Heat escape from the sulfur mine adit

An abandoned sulfur mine adit at the top of the northern sea cliffs near Lower Hells Gate, situated directly above the shoreline hot spring opposite Green Island, is also the site of heat escape. When first visited by us without torches on July 22, 1979, the outside air temperature was 27.5° C, and at distances of 6, 10, 14 and 20 m into the adit the air temperatures near the roof were 29°, 30°, 31° and 31.5° C respectively. We revisited the mine with torches in March 9, 1994 when the maximum air temperature inside was found to be at the deepest point at the back of the mine in a short vertical shaft leading up from the adit. In this shaft, an air temperature of 32.5° C was recorded.

Submarine hot springs

The formation of the Saba Marine Park around the island in 1987 has resulted in an increase in tourism on the island, with SCUBA diving one of the main tourist activities. This in turn has led to the identification of two areas of heat escape on the sea bed, where divers report pushing their hands into the sand of the sea bed in order to warm themselves. One of these locations, which is described in a book on the Saba Marine park (van't Hof, 1991) and named the Hot Springs Dive Site number 15, is in 10 m of sea water 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 sulfur mine; again there are no temperature measurements for this location.

Other reported areas of heat escape on Saba

There exist other reports of heat escape on Saba island, only one of these is regarded by us as reliable. A newspaper report in 1995 noted that a cave on the upper northeast side of Great Hill had rocks at depth that were too hot to touch. On a visit to the island in June 1995 one of us (Smith) interviewed one of the residents, Mr. James Johnson, who had descended into the cave, who confirmed the newspaper report. A visit to the cave in the company of Mr. Johnson was made at this time. As the site of the hot rocks was reported to be at a depth of at least 200 m, no

TABLE 4I. Composition of geothermal waters (in ppm) from the Lesser Antilles

SABA ¹				ST. EUSTATIUS ²		MONTSERRAT ³		GUADELOUPE ⁴		ST. LUCIA ⁵	
Location	Spring opposite Green Island	Ladder Bay (spring)	Spring Bay (spring)	Cherry Tree (well D)	Concordia (well E)	Galways (soufriere)	Plymouth (spring)	d'Entrecast -eaux dome (sea floor emission)	Shoe Rock scarp (sea floor emission)	Sulfur Springs	Diamond Spring
Temp °C	66	40	25	36.0	33.7	98	89.8	25.9	25.6	72	43.1
Li	N.D.	N.D.	N.D.	0.0276	0.0246	0.030	8.90	N.D.	N.D.	0.09	0.22
Na	11665.	9500.	761.	362.96	369.66	114.	7880.	12000.	11000.	54.	129
K	486.1	347.2	44.8	14.283	13.680	12.0	1,030.	392.	337.	13.7	11.0
Mg	800.0	1255.0	65.5	64.62	47.92	42.8	302	1410	1370	9.3	42.3
Ca	1111.0	405.0	107.8	129.97	104.77	207	2,510	395.0	359.0	72.3	69.2
Sr	N.D.	N.D.	N.D.	14.27	12.11	N.D.	N.D.	N.D.	N.D.	0.66	0.47
Mn	N.D.	N.D.	N.D.	0.0002	0.0002	N.D.	N.D.	N.D.	N.D.	0.81	0.29
Fe	N.D.	N.D.	N.D.	0.0119	0.0162	N.D.	N.D.	N.D.	N.D.	16.4	0.20
HCO ₃	N.D.	N.D.	N.D.	N.D.	N.D.	55	128	159	159	0	6.86
SO ₄	1802.3	2172.3	50.4	N.D.	N.D.	1018.	161.	3260.	3020.	1,085.	21.8
Cl	19290.	14548.	1118.	768.21	760.00	21.2	18220	20500	21400	32.9	40.0
F	1.0	0.7	0.2	N.D.	N.D.	0.148	0.22	N.D.	N.D.	0.05	0.15
I	N.D.	N.D.	N.D.	0.1202	0.2065	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
SiO ₂	130.8	78.3	56.6	47.05	45.32	216.	315.	N.D.	N.D.	186.	171.
B	11.50	5.10	0.65	N.D.	N.D.	0.30	22.9	N.D.	N.D.	15.1	11.1
Al	N.D.	N.D.	N.D.	0.0014	0.0017	N.D.	N.D.	N.D.	N.D.	22	<0.05
Ba	N.D.	N.D.	N.D.	0.0837	0.0909	N.D.	N.D.	N.D.	N.D.	0.13	0.09
Br	N.D.	N.D.	N.D.	2.624	3.045	N.D.	N.D.	N.D.	N.D.	<0.1	<0.1
Co	N.D.	N.D.	N.D.	0.0002	0.0002	N.D.	N.D.	N.D.	N.D.	0.004	<0.001
Cr	N.D.	N.D.	N.D.	0.0274	0.0278	N.D.	N.D.	N.D.	N.D.	0.026	<0.001
Rb	N.D.	N.D.	N.D.	0.0113	0.0075	N.D.	N.D.	N.D.	N.D.	0.11	<0.01
Zn	N.D.	N.D.	N.D.	0.0009	<d	N.D.	N.D.	0.044	0.053	0.09	<0.02
CO ₂	320.0	424.0	503.0	N.D.	N.D.	N.D.	N.D.	0.0	0.0	N.D.	N.D.

N.D.

Not Determined

<d

Less than detection limit of 0.00002 ppm

1.

Data from Gunnlaugsson, (1981)

2.

Data this paper (analyses by Activation Laboratories).

3.

Data from Chiodini et al. (1997)

4.

Data from Polyak et al. (1992)

5.

Data from Ander et al. (1984)

surface expression was noted and no descent was made into the cave, as climbing gear was not available. Mr. Johnson regarded the original descent, which was made using ropes, as extremely dangerous and he said that he would not make the descent again. This report is considered reliable by us, as the position of the hot rocks inside the Great Hill dome is approximately 400 m horizontally from the hot springs at Ladder Bay.

Westermann and Kiel (1961) reported another location where hot air without sulfurous gases was believed to escape from fissures in the hillside on the road between Crispen and Windwardside village. However at the time of their visit due to road widening and removal of rock they were unable to confirm this occurrence. However the reports of this hot air escape persist on the island, and in 1979 we were taken to the location by Mr. Petersen of Windwardside village. Air was blowing out of an opening between blocks of a weakly lithified block and ash flow deposit at a height of about 2 m above the concrete road surface. The air temperature in the shade was 31° C and the temperature of the air blowing out of the ground was 28° C. It seems probable that this is simply air, which enters the ground below the road between boulders and cools on its way to the outlets, and is not related to fumerolic activity. We do not regard this report as reliable evidence of heat escape.

Chemistry of hot springs on Saba

Gunlaugsson (1981) analyzed samples from the hot springs at Ladder Bay and opposite Green Island together with a cool, fresh-water spring at Spring Bay. His data are shown in Table 41 and compared with two samples from hot water wells on St. Eustatius, with cool, submarine springs off Guadeloupe, and hot springs on Montserrat and St. Lucia. The sodium content of the analyses shows that only the samples from Spring Bay (Saba), St. Eustatius, Galways Soufriere (Montserrat) and St. Lucia are fresh water. The others, including both hot springs analyzed on Saba, contain high contents of Na, Ca, Cl and SO₄ and are thought, as concluded by Gunlaugsson (1981), to be highly contaminated by sea water. This is a common problem when springs are partially awash in surf. In previous literature the hot springs near the Ladder on Saba have been described as saline, however on March 10, 1994, we were fortunate to visit the Ladder Bay spring at low tide. The hot spring water was emerging from a fissure

in the Great Hill andesite at a point normally covered by the sea. At the same time the sea was calm, and the spring water was found to be fresh and potable. It seems likely that the records in the literature that the springs are saline are in fact records of emerging fresh water springs that are being contaminated by seawater at high tide.

Helium and carbon isotopic studies from the Lesser Antilles (van Soest et al., 1998) included data from a hot spring on Saba. The Saba results showed helium isotopic ratios (4.89) that were slightly lower than mantle values, suggesting an enhanced crustal contamination, whereas the $\delta^{13}\text{C}$ values were similar to mantle values (-2.8). Although these data gave an arc-like $\text{CO}_2/{}^3\text{He}$ ratio (3.0×10^{12}) for the Saba sample, the authors concluded that because of the low helium concentration in this water sample, the ratio could not be used to determine volatile provenance, as it probably had been influenced by fluid partitioning, probably as a consequence of boiling.

Westermann and Kiel (1961) report an account by Benest in 1899 of a submarine upwelling of fresh water off the coast of Saba. About 0.5 km to the southwest of the island, fresh water was reported bubbling up on the surface of the sea and there were reports of boats filling their water barrels from this submarine stream of fresh water. Today, in spite of the increased boating and SCUBA activity in the Saba Marine Park no trace of this spring is evident.

Distribution of heat escape on Saba

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 are the sulfur 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 positioning of recent earthquake epicenters in

the area, and also by the orientation of the horseshoe shaped sector collapse scar. The orientation of the alignment of hot springs also closely corresponds to the longest axis of the rhomb-shaped Saba island.

It is interesting to speculate on the effect of this possible fault or fracture underlying the island on the aquifer of Saba. Saba is an island deficient in groundwater and attempts to drill producing water wells have not been successful. If a northeast-southwest fault occurs, much of the island's fresh water may be escaping into this fault zone, and the report by Benest in 1899 of fresh water off the southwest coast of Saba may be a rare observation of the escape of fresh water from the island.

HEATED GROUNDWATER ON ST. EUSTATIUS

There are no hot springs or fumeroles on St. Eustatius. Until the 1980's heated groundwater was also unknown. Then seven shallow water wells were drilled into the lower flanks of the Quill to supply water to the growing population. Heated groundwater was found in all seven wells. This is the first indication of geothermal activity on the Quill, St. Eustatius — an important indication that the volcano is dormant and not extinct. The locations of the wells (labeled A to G) are shown on the geological map (Plate 4). The wells were visited in November, 1994, April 1995, July, 1995, and February, 1997. Measurements taken of the wells at these times are the only geothermal record of the island to date (Table 42). In the table, the wells have been ordered in terms of increasing horizontal distance from the lowest point on the crater rim of the Quill. From this it can be seen that the Upper Lynch well (A) at a distance of 1,155 m from the notch/breach has the highest temperature, whereas the Golden Rock (F) and Concordia (E) wells at distances of 2,560 and 2,710 m from the notch respectively have the lowest temperatures. The geothermal zonation of the temperatures in the wells with relation to the crater of the Quill is shown in Figure 89, which clearly indicates that the heat source lies towards the crater of the Quill.

The Upper Lynch's well (A) was capped shortly after drilling because water temperatures were reported to be 60-70°C. The well was reopened in June 1995, and had a minimum temperature of 52.6°C from water raised to the surface in a container from a depth of approximately 133 m. English

TABLE 42. Temperature measurements of heated groundwater on St. Eustatius

Location**	Upper Lynch (well A)	English Quarter (well B)	Fair Play* (well G)	Roots (well C)	Cherry Tree* (well D)	Golden Rock* (well F)	Concordia* (well E)
Date of measurement	1,155m#	1,540m#	2,080m#	2,120m#	2,215m#	2,560m#	2,710m#
Drilling of Well (1980s)	60-70°C	40-50°C	no information	no information	no information	no information	no information
11/20/94	c	Dry	N.D.	c	35.6°C	N.D. ¹	34.0°C
4/13/95	c	N.D.	N.D.	c	36.0°C	30.3°C	33.7°C
6/29/95	52.6°C ²	N.D.	N.D.	38.2°C ³	36.3°C	30.9°C	34.5°C
2/2/97	N.D.	N.D.	34°C	N.D.	36°C	N.D. ¹	33°C
*	Temperatures were measured on water pumped to the surface. Temperature given is maximum stable temperature obtained after water had been pumped for a few minutes.						
**	For location of wells see Plate 4						
N.D.	Temperature not measured.						
c	Well capped by welded steel plate.						
1	Temperature was not measured as pump was not working.						
2	After steel plate was removed, water was brought to the surface in a container from a depth of approximately 133 m before measurement was made.						
3	After steel plate was removed, water was brought to the surface in a container from a depth of approximately 100 m before measurement was made.						
#	Horizontal distance from lowest point on the crater rim of the Quill						

Quarter well (B) in November, 1994 had become dry or blocked since drilling of the well. Temperatures recorded for this well at the time of drilling to a depth of about 180 m were 40-50°C. Fair Play well (G) is a pumping well in regular use, and had a stable temp of 34°C in 1997. Roots well (C) was also capped after drilling. On opening the well in June, 1995, it had a minimum temperature of 38.2°C on water raised to the surface in a container from a depth of 100 m. The other three wells, Cherry Tree well (D), Concordia well (E) and Golden Rock well (F), are pumping wells with stable temperatures of 36°C, 33°-34°C, and 30°-31° C respectively. For pumping wells a stable temperature was achieved by switching on the pump and measuring the temperature on outflowing water until it stabilized.

Groundwater Geochemistry of St. Eustatius

Water samples from Cherry Tree well (D) and Concordia well (E) were collected in 1995 and were submitted to Activation Labs., Canada, for analysis. The analyses, which are listed in Table 41, are relatively low in Na, Ca, K, Mg, and Cl suggesting that they represent rainwater that has infiltrated into the volcano's superstructure.

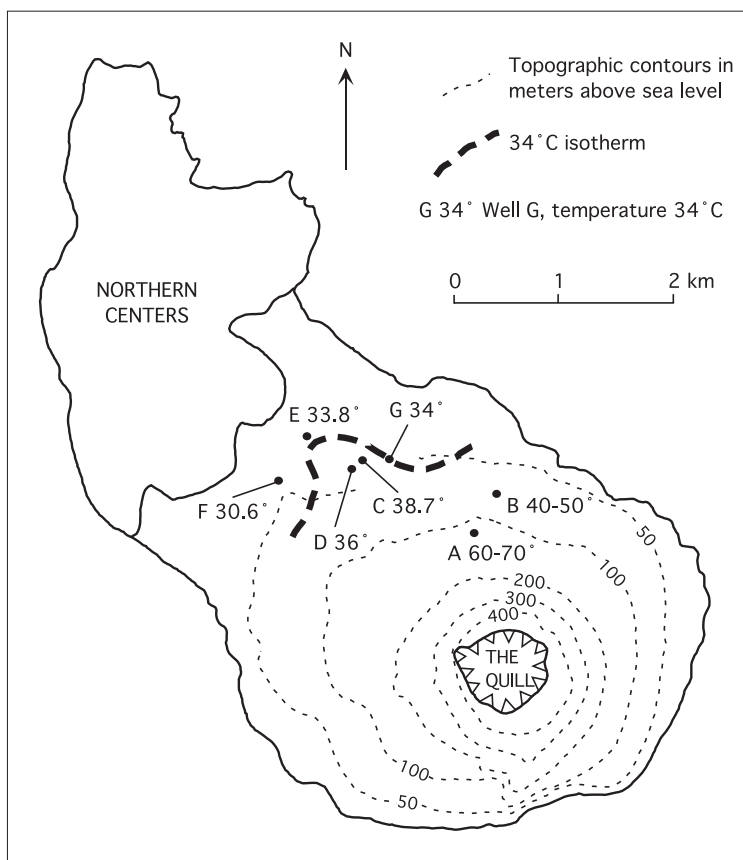


FIGURE 89. Map showing elevated groundwater temperatures around the northern flanks of the Quill, and northwesterly extension of the 34°C isotherm.

SEISMIC ACTIVITY ON SABA AND ST. EUSTATIUS

Since the settlement of Saba and St. Eustatius, and up to and including the publication of the work of Westermann and Kiel in 1961 there appear to be no records on the islands of felt seismic activity. During the late 1970s and early 1980s Lamont-Doherty Geological Observatory (LDGO) operated a single, one-component seismometer on Saba as part of their northeastern Caribbean network. No records of local micro-seismic activity on the island of Saba have been reported for the period of operation of the LDGO station.

Regional seismic events in the northeastern Caribbean have been well-documented primarily by the Seismic Research Unit of Trinidad, as well as a number of other organizations including the LDGO, the Puerto Rico Seismic Network (operated initially by the USGS and later by the University of Puerto Rico at Mayaguez), and the volcanic observatories of Martinique and Guadeloupe. Major events are covered by the World Seismic Network based in Golden, Colorado. A plot of the data from 1964 to 1992 for the northeast Caribbean is shown in Figures 90A to C. The plot shows that the deepest epicenters are mainly centered under the islands of the volcanic arc, that intermediate centers are clustered under the extinct Limestone Caribbee Arc and that shallow epicenters are scattered throughout the whole region but concentrated east of the islands. These data are consistent with a Wadati-Benioff zone dipping towards the west, together with shallow, near-surface events, which probably reflect activity on high-level crustal faults.

The 1992 felt seismic swarm

In June 1992, a minor earthquake swarm occurred near the island of Saba and was felt and heard by the population of the islands of Saba and St. Martin. Residents of Saba reported hearing noises and feeling the ground move beneath their feet, although there were no reports of damage. The initial period of seismic activity was recorded at the permanent eastern Caribbean seismic stations, the nearest of which is located on St. Kitts some 55 km from Saba. On June 14, 1992 at the invitation of the Netherlands Antilles Government, the Seismic Research Unit installed one seismograph on each of the islands of Saba, St. Martin and St. Eustatius in order to improve the detection and location capabilities of the permanent network.

According to Ambeh and Lynch (1993, 1995), 60 events were detected of which only 15 were located (Fig. 91A). The largest event of this swarm occurred on June 11, 1992 with a duration magnitude (M_D) of 4.5 and was felt at Modified Mercalli Intensities of IV-V on Saba, and III on St. Kitts. A plot of epicenters for the period June 5-16 is shown in Figure 90D, where they can be seen to plot along a southwest-northeast trend. The focal depths for these events clustered in the range of 10-16 km (Ambeh and Lynch, 1993, 1995). This orientation, when compared

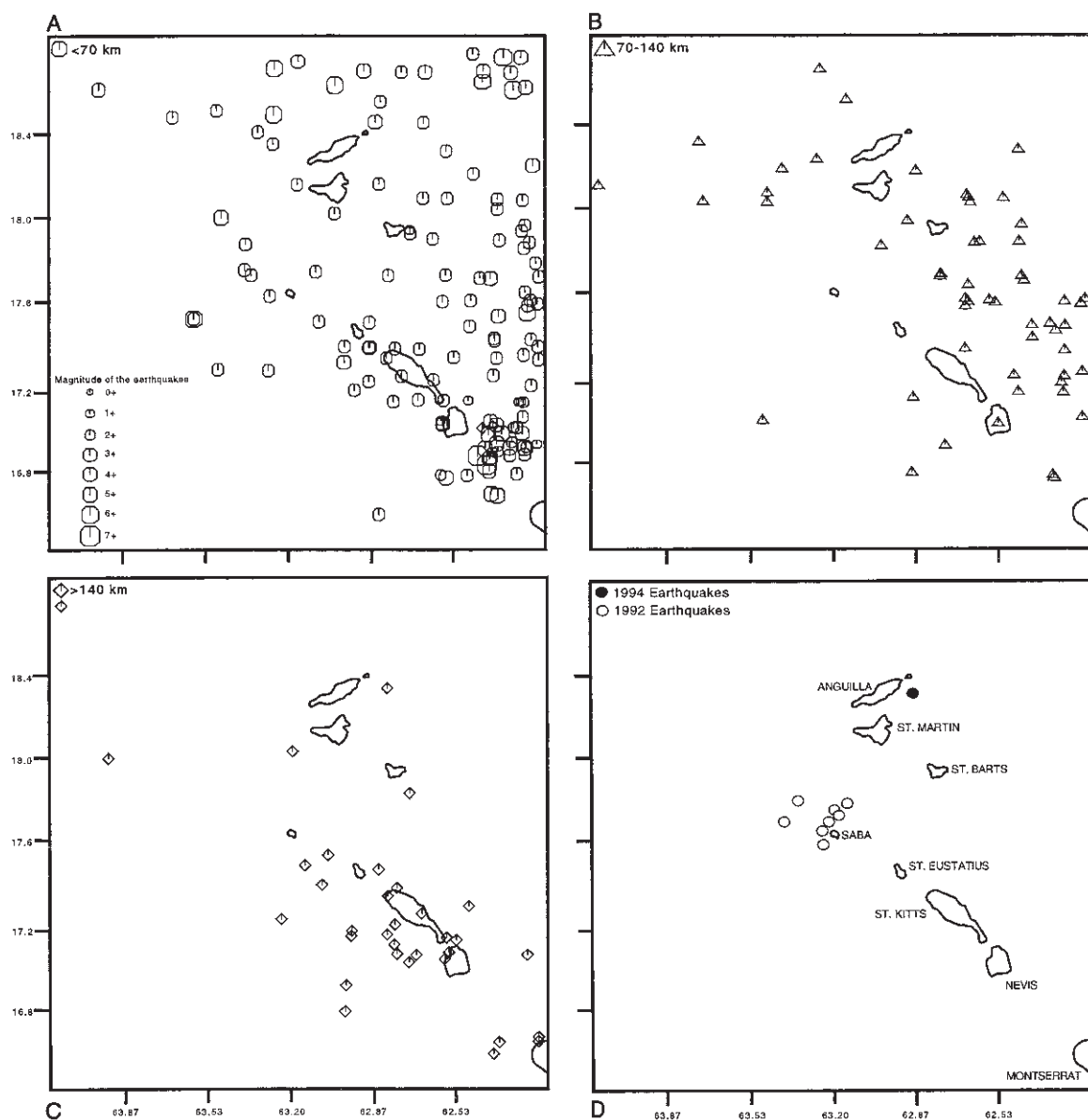


FIGURE 90. Regional seismicity (1964-1992) of the northeastern Caribbean (after Ambeh and Lynch, 1993, 1995; Puerto Rico Seismic Network, unpublished data; Seismic Research Unit, unpublished data):

- epicenters <70km;
- epicenters 70-140 km;
- epicenters >140 km;
- plot of 1992 and 1994 earthquake swarms that were felt on Saba.

to the faults and lineaments of the submarine banks (Plate 1; Fig. 3) suggests that the swarm 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. This fault may directly underlie Saba island as discussed in the section on hot springs.

The April 1994 felt seismic tremors

An earthquake and six aftershocks occurred in the northern Lesser Antilles on April 21-25, 1994. The main shock had a magnitude of 4.8 and a hypocenter at a depth of 14 km at a latitude 18.20.2°N and longitude 62.69.6° W, and was felt with a Modified Mercalli Intensity of V on the islands of Saba, St. Kitts and St. Martin (Seismic Research Unit, and University of Puerto Rico at Mayaguez, unpub. data). The position of the epicenter of the main shock is shown in Figure 90D where it is seen to lie near to the islands of Anguilla and St. Martin, on the direct extension of the southwest-northeast alignment of the 1992 swarm. The 1992 and 1994 hypocenter plots provide the first confirmation that the island of Saba may have formed astride one of the many faults cutting directly through the arc as shown in Figure 3. Again the 1994 earthquakes are regarded as purely tectonic, related to faulting, and having no relationship to magma movement.

The microseismic swarm of 1995 to 1997

The single seismometer installed on the island of Saba since 1992 recorded an earthquake swarm, which commenced in May 1995 and lasted until April 1997. The activity peaked during December 1996 with a total of 64 tremors being recorded during that month. A histogram of these events is plotted in Figure 91B. 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 geothermal measurements made in 1994 and 1996. The 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.

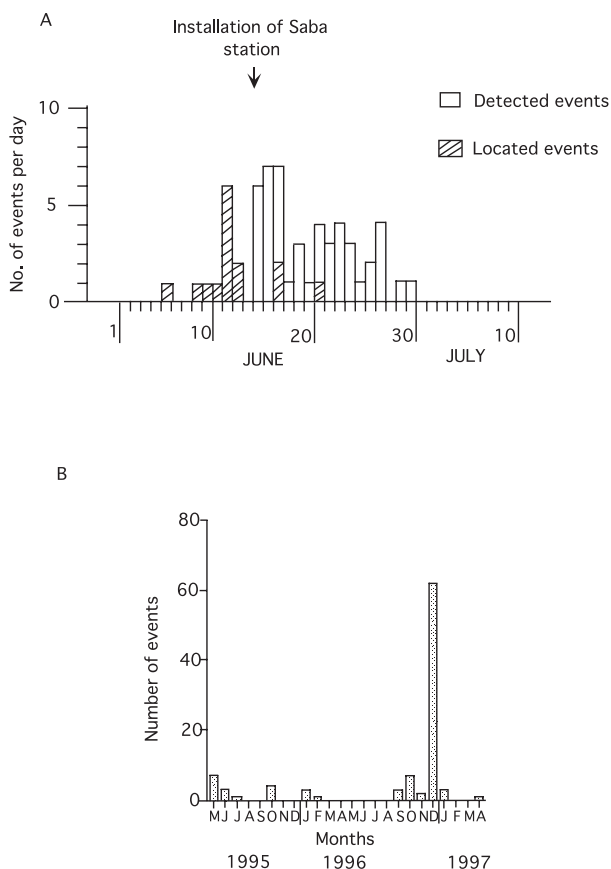


FIGURE 91A. Daily number of events of the 1992 Saba earthquake swarm (after Ambeh and Lynch, 1993, 1995).

B. Microseismic events recorded on Saba island from 1995 to 1997 (unpublished data collected by the Seismic Research Unit under contract to TNO, and released to authors).

In summary, the geothermal evidence indicates the presence of at least hot rocks beneath Saba and the Quill, so that both volcanoes must be classified as dormant rather than extinct (the latter was suggested by Westerman and Kiel, 1961). The recent seismic activity appears to be mainly tectonic in nature, and related to movements on faults in the submarine banks rather than movement in high-level magma chambers,

although the 1995-1997 activity beneath Saba definitively appears to have been a volcano-seismic event.

A first assessment of volcanic hazards on both islands was made by Roobol et al, (1981a), and submitted to the Netherlands Geological Survey. This report was made confidential by the Netherlands Antilles Government, but was finally published in 1997 (Roobol et al., 1997). As a result of this report, a proposal was submitted for monitoring of both islands, and providing an educational program on volcanic and seismic hazards for the local populations. To date no funds have been assigned for this purpose.

STATUS OF SABA AND THE QUILL, ST. EUSTATIUS

The new stratigraphic sections presented here for both Saba and St. Eustatius strongly suggest that the latest volcanic activity corresponds at least to the period of the Amerindian settlement of the arc. Further study, and radiocarbon dating of deposits exposed in new excavations on both islands, can only improve on the present picture. It must be noted that the few charcoal dates obtained on both islands were obtained in hand dug pits on Saba, in excavations for foundations for homes near the airport on St. Eustatius, and in archeological trenches. Saba with only three radiocarbon dates remains one of the most poorly dated islands in the Lesser Antilles, although the problem here is not lack of searching nor paucity of excavations rather one of the lower charcoal-rich flank deposits being submarine.

The observations of heat escape on Saba and the occurrence of heated groundwater with increasing temperature zonation towards the Quill on St. Eustatius, strongly support the case for activity in the very recent past. Although it has not been possible to reconstruct in detail the recent eruptive history for Saba, in a manner similar to that for Mt. Pelée, Martinique (Smith and Roobol, 1990) and the Soufriere Hills, Montserrat (Roobol and Smith, 1998), sufficient data are available to determine the most likely style of future activity. In contrast, the stratigraphic history of the Quill can be readily reconstructed from the flank stratigraphic sections exposed in the sea cliffs around the island so that the style of future activity can be more readily assessed.

The evolution of Saba has been dominated by repeated Pelean-style volcanic eruptions leading to the formation of andesite domes with surrounding aprons of andesitic block and ash flow deposits. In addition, there are three andesite domes which do not appear to have produced major pyroclastic deposits but have produced only dome flows. St. Vincent-style pyroclastic activity is very minor, as is the production of basaltic andesite lava flows. The major risk of renewed activity on Saba is likely to be of Pelean-style. Maps showing the distribution of the deposits of the different styles of activity on Saba, and an assessment of its volcanic hazard are described in Roobol et al. (1997). Their conclusion is that on a small steep-sided cone of only 4 km diameter there is nowhere on the island that can be regarded as safe from any type of volcanic activity. Any future precursor activity requires immediate evacuation of the entire population of 1,400 persons. The nearest Netherlands Antilles possessions are St. Eustatius and part of the island of St. Martin.

In contrast to the Pelean dome complexes on Saba, the Quill is a different type of volcano, with the latest eruptive products forming from an open crater and being of basaltic andesite composition. It can thus be regarded as being in a St. Vincent stage of activity and it is likely that future activity will be very similar to that of the most recent erupted bed-set (Marker Units K through O). Unlike Saba, many other types of pyroclastic activity are however possible from the Quill, including Pelean-, Asama-, and Plinian-styles, including the eruption of ignimbrites. The main area of settlement between the Quill and the Northern Centers is particularly vulnerable to all types of pyroclastic activity. Some element of safety however exists on the higher elevations of the extinct Northern Centers. Stratigraphic sections at Pisgah Hill on the Berjge dome center show that phreatomagmatic ashes, ash and lapilli falls, pumiceous surges, and ignimbrites (ash hurricanes and fine-grained pumice and ash flows) have all affected these hills, however the frequency of inundation of the Northern Centers by pyroclastic deposits from the Quill is considerably smaller than for the lower flanks composing the central part of the island, where the population of 2,600 now lives. Particularly at risk from future activity is the town of Oranjestad, which lies directly below the notch or low point of the Quill's crater rim. From this notch a pyroclastic flow fan can be seen to be directed towards the southern part of the present town.

Maps showing the distribution of the different types of pyroclastic deposits from the Quill are described in Roobol et al. (1997). The inescapable conclusion derived from these maps is that all areas of settlement on St. Eustatius require immediate evacuation in the event of future precursor activity. Very short-term evacuation to the Northern Centers is a possibility, however this is hampered by the fact that the only road and jetty in the area is within an extensive oil storage facility built on Pisgah Hill.

POSSIBLE PRECURSOR ACTIVITIES ON MT. PELEE/QUILL- AND SOUFRIERE HILLS/SABA-TYPE VOLCANOES

Because there are no historic records of volcanic eruptions on Saba and St. Eustatius, and because there is no systematic monitoring of these two islands unlike the remainder of the Lesser Antilles, precursor activity will probably play an important role in predicting the onset of future volcanic activity. The two different petrologic models proposed for Saba and the Quill differ greatly, and if they are correct it is possible that precursor activity or the early warning signs of the onset of a new cycle of volcanic activity will not be the same on each island. In order to explore this possibility a comparison of the precursor activities is made for volcanoes, regarded as similar to Saba and the Quill, that have erupted in the Lesser Antilles during the 20th century. The proxy to the Saba volcanic complex with its many scattered Pelean domes is found in the Soufriere Hills, Montserrat, which began its latest eruption in 1995, whereas Mt. Pelée, Martinique which last erupted in 1902-05 and 1929-32 can be used as a proxy for the Quill, St. Eustatius.

Data summarizing the main differences in precursor activity for the historic activity of Mt. Pelée, Martinique and the Soufriere Hills, Montserrat are given in Table 43. We will also attempt to explain the differences in precursor activity between these two volcanoes in terms of the two contrasted models proposed for Saba and the Quill, St. Eustatius. Mt. Pelée's precursor activity is thus explained in terms of the recharge of a system of high level magma chambers in a thin crust lacking fault zones, and the Soufriere Hills volcano's precursor activity is explained in

TABLE 43. Comparison of precursor activities for Mt. Pelée, Martinique, and Soufriere Hills, Montserrat

Activity	Mt. Pelée	Soufriere Hills
Increase in fumerolic activity prior to the onset of eruptive activity	Months to years	Variable
Felt earthquakes prior to the onset of eruptive activity	Days to months	Years
Occurrence of volcano-seismic crises	Rare	Common
Time from onset of eruptive activity to the generation of pyroclastic flows	Days	Months

terms of recharge of a dike system occupying a major crustal fracture or fault zone beneath the volcano.

Precursor activity prior to the historic activity on Mt. Pelée, Martinique

The catastrophic 1902 eruption of Mt. Pelée might be regarded as the third, and successful attempt by magma to break out of a high-level chamber, following earlier failed attempts in 1792 and 1851. Robson and Tomblin (1966) described the 1792 and 1851 events as primarily steam or phreatic explosions in the upper parts of the Riviere Claire, on the western superstructure of the cone - an area today marked by hot springs. There is no record of felt seismic activity associated with the 1792 event. The 1851 event began with several explosions in August and October, which deposited lithic ash on the volcano and caused mudflows in the Riviere Blanche. LaCroix (1904, p. 33) described the 1851 ash as mainly secondary lithic material but identified one sample as possible juvenile material, suggesting that the more powerful 1851 event may have been phreatomagmatic. Existing accounts also describe felt seismic activity. A third indication of the changing status of dormancy of Mt. Pelée was the formation of new fumeroles emitting sulfurous gases that formed in 1889 on the east side of the then open crater, known as the Etang Sec (LaCroix, 1904). The amount of gases emitted by these new fumeroles increased significantly during 1900 and 1901, so that by February 1902, such large volumes of H_2S were being emitted, that silver turned black in the town of St. Pierre eight kilometers from the crater. On April 22

1902, the first earthquake was felt in Le Precheur, but not in St. Pierre, and on April 24, the first explosion occurred when a column of ash and steam was seen to rise 500-600 m above the Etang Sec crater. The first recorded pyroclastic flow occurred on May 8, 1902, although smaller flows may have affected the summit area prior to this date.

The 1929-32 eruption of Mt. Pelée (Perret, 1937) closely followed the events of 1902-05 but on a much smaller scale. An increase in fumerolic activity was first noted in March 1929. In August, earth tremors were locally felt at the summit of the volcano only, suggesting a high-level source within the cone, and much SO₂ was being emitted from fumeroles within the crater. The explosive phase of the eruption began on September 16, 1929, and the first pyroclastic flows descended the Riviere Blanche on November 20, 1929.

Our interpretation with hindsight of these events of Mt. Pelée is that the 1792 and 1851 events were failed attempts by magma to reach the surface. Magma finally broke through in 1902, and again in 1929, with the second event possibly representing the eruption of material that had remained in a high-level chamber since the 1902 eruption. Precursor activities associated with these eruptions were a significant increase in fumerolic activity, and the occurrence of felt earthquakes days to months prior to the start of the eruption. It is not known whether an increase in microseismic activity preceded the occurrence of felt earthquakes. An additional precursor phenomenon appears to have been the rise of the water table close to the surface so that ground water was expelled into the rivers draining the volcano (Roobol and Smith, 1975a; Smith and Roobol, 1990).

Historic precursor activity of the Soufriere Hills volcano, Montserrat

The Soufriere Hills volcano, Montserrat has been the site of a number of volcano-seismic crises, none of which led to an eruption. In 1897-98 an earthquake swarm occurred beneath the volcano, and was accompanied by an increase in fumerolic activity. Much the same thing happened in 1932-1938 when there was a considerable increase in both seismic (over 3,000 earthquakes were felt) and fumerolic activity (Powell, 1938; MacGregor, 1938; Perret, 1939), and again in 1966-67 (Shepherd et al., 1971). For this crisis, 723 local earthquakes were recorded, of which 32 were felt on

the island from May 1966 to the end of 1967. The hypocenters of these earthquakes showed a steady decrease in depth from around 15 km at the beginning of the activity to a minimum of 2.8 km from July to September 1966, after which depths again increased. In addition it was also noticed that heat escape at Galway's Soufriere increased to a maximum in October 1966.

The 1995 eruption of the Soufriere Hills, Montserrat is the first since European settlement of the island in 1636 AD. The activity began in November 1992 (Ambeh et al., 1998) with increased seismic activity which sporadically continued until July 18, 1995, when a series of phreatic explosions occurred from a fissure on the northwestern lower slopes of the Castle Peak dome. There does not seem to be any record of significant change in fumerolic activity prior to the start of this explosive activity (Hammouya et al., 1998; Boudon et al., 1998).

For the Soufriere Hills, the historic record suggests that there were at least three failed attempts, all represented by volcano-seismic crises, prior to the 1995 eruption. Thus, in contrast to Mt. Pelée, an increase in seismic activity appears to be a very characteristic precursor for the Soufriere Hills, with felt earthquakes occurring years prior to the onset of explosive activity. An increase in fumerolic activity also appears to be associated with the volcano-seismic crises, but was apparently not a significant precursor to the 1995 eruption due to the possible isolation of the magma conduits from the hydrothermal system as a consequence of the precipitation of vapor transported silica (Boudon et al., 1998).

Discussion

The historic record indicates that the Soufriere Hills, Montserrat is characterized by frequent volcano-seismic crises associated with increases in fumerolic activity but that these usually do not lead to an eruption. In contrast, Mt. Pelée, Martinique is characterized by frequent increases in fumerolic activity that leads to phreatic activity without necessarily leading to magmatic volcanic eruptions. These differences between the precursor activity of Mt. Pelée and the Soufriere Hills can be explained in terms of the nature of their plumbing systems immediately beneath the volcanic edifice. The models presented here propose at least one magma chamber situated at a high crustal level below the central vent of a volcano

such as Mt. Pelée, or the Quill. This chamber remains active throughout the life of the volcano. The rise of magma into this high level chamber requires simply the movement of magma into the crust and the subsequent inflation of the superstructure of the volcano. Such a process need not result in any notable seismic activity prior to the final stages of ascent, when magma has to open a passage to the surface. The rise of such a plug-like body of magma would lead to an increase in fumerolic activity as it heated up the groundwater, and could lead to a rise in the water table and an expulsion of the ground water from the superstructure of the volcano.

In contrast, the Soufriere Hills or Saba examples require that each volcanic eruption be related to the rise of a thin, fissure-filled dike. Recharge into a fault zone beneath Saba or the Soufriere Hills may require the formation of a new dike, or at least the opening of a pre-existing narrow vertical sheet-like dike, sealed perhaps over 2-3 km depth after the last eruption. Such a model would predict the likely occurrence of swarms of earthquakes as the fracture re-opened. Also the presence of a thin dike would not be conducive for a significant increase in fumerolic activity.

The short duration between the onset of steam explosions and the formation of pyroclastic flows in the Mt. Pelée/Quill case can also be explained by the availability of relatively large volumes of magma in a high-level chamber possibly within the substructure of the volcano itself, i.e. abundant magma is readily available for expulsion to the surface. Also differentiation of this magma could lead to the accumulation of volatiles in the top of the magma chamber which would favor explosive eruptions. In contrast, the long interval between steam explosions and pyroclastic flows in the case of the Soufriere Hills/Saba type can be accounted for by the difficulty in physically opening and clearing a fissure through the substructure of the volcano where only small volumes of magma are available at any time for expulsion. The measured inflation of the NW-SE fissure-filled dike beneath the Soufriere Hills, Montserrat was determined to be only of the order of one meter (Mattioli et al., 1998). Also the rise of this thin sheet of magma along a fissure to the surface provides ample opportunity for degassing of the magma before it reaches the surface. For the Soufriere Hills, the first magma to reach the surface in November 1995 was relatively degassed, and it was not until March 1966 that gas-rich magma capable of explosive eruptions finally reached the surface.

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Note added in proof stage

Since acceptance of the manuscript for publication a number of articles have appeared that are directly relevant to the geology of Saba and St. Eustatius. These cover two areas.

1. The authors make a case for a major sector collapse scar on Saba island and compare its morphology with other proposed examples in the Lesser Antilles arc. Until the French Aguadomar cruises in 1998/1999 clearly showed the presence of extensive debris avalanche deposits on the floor of the Grenada Basin west of the active volcanoes on Martinique, Dominica and St. Lucia, independent evidence for the presence of such structures was lacking. The data resulting from these cruises considerably strengthens the understanding and origin of the morphological depressions found on West Indian volcanoes such as Saba Island.

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

Le Friant, A., Boudon, G., Deplus, C., and Villemant, B., 2003, Large-scale flank collapse events during the activity of Montagne Pelée, Martinique, Lesser Antilles: *Journal of Geophysical research*, v. 108, p. ECV 13-1 – 13-15.

Le Friant, A., Boudon, G., Komorowski, J-C, Deplus, C., 2002, L'île de la Dominique, à l'origine des avalanches de debris les plus volumineuses de l'arc des Petites Antilles: *C.R. Geoscience* v. 334, p. 235-243.

2. On Montserrat island the stratovolcano of the Soufriere Hills, which is compared by the authors to Saba Island, continues to erupt and provide first hand evidence as to the conditions under which Saba island is believed to have evolved.

Druitt, T.H., and Kokelaar, B.P, eds., 2002, *The Eruption of Soufriere Hills Volcano, Montserrat from 1995 to 1999: Geological Society Memoirs No. 21*, 645p.

APPENDIX I.

SPECIMEN LIST FOR SABA

Sample	Gran.	Pet.	Dat.	Location	Comments
S-1		X		Between Fort Bay and Tent Bay	Beach boulder
S-3		X		Between Fort Bay and Tent Bay	Beach boulder
S-4		X		Between Fort Bay and Tent Bay	Beach boulder
S-5		X		Between Fort Bay and Tent Bay	Beach boulder
S-6		X		Between Fort Bay and Tent Bay	Beach Boulder
S-11		X		Tent Bay (Sec. XVI)	Inclusion in S-13
S-12		X		Tent Bay (Sec. XVI)	Inclusion in S-13
S-13		X		Tent Bay (Sec. XVI)	Lava flow
S-14		X		Tent Bay (Sec. XVI)	Inclusion in S-13
S-15		X		Tent Bay (Sec. XVI)	Avalanche deposit
S-16		X		Ladder Point (Sec. XVI)	Lava flow
S-17		X		Ladder Point (Sec. XVI)	Hydrothermally altered
S-18		X		Ladder Point (Sec. XVI)	Limestone inclusion
S-19		X		Ladder Point (Sec. XVI)	Block and ash flow
S-20		X		Ladder Point (Sec. XVI)	Block and ash flow
S-21		X		Ladder Point (Sec. XVI)	Inclusion in S-20
S-22		X		Ladder Bay	Block and ash flow
S-23		X		Ladder Bay	Inclusion, beach cobble
S-24		X		Torrens Point	Lava flow
S-25		X		Torrens Point	Lithics in block and ash flow
S-26		X		Torrens Point	Fluviatile pumice, overlying S-25
S-27		X		Torrens Point	Fluviatile pumice, overlying S-25
S-28		X		Torrens Point	Block and ash flow
S-29		X		Well's Bay	Block and ash flow
S-30		X		Between Well's and Ladder Bays	Inclusion, beach boulder
S-31		X		Between Well's and Ladder Bays	Inclusion, beach boulder
S-32		X		Between Well's and Ladder Bays	Beach boulder
S-33		X		Between Well's and Ladder Bays	Beach boulder
S-34		X		Between Well's and Ladder Bays	Inclusion, Beach boulder
S-35		X		Between Well's and Ladder Bays	Inclusion, Beach boulder
S-36		X		Tent Bay (Sec. XVI)	Inclusion in S-13
S-37		X		Tent Bay (Sec. XVI)	Inclusion in S-13
S-38		X		Tent Bay (Sec. XVI)	Inclusion in S-13
S-39		X		Tent Bay (Sec. XVI)	Inclusion in S-13
S-40		X		Fort Hill dome	
S-41		X		Dome NE of Fort Hill	
S-42		X		Road to harbor	Block and ash flow
S-43		X		Road to harbor	Dense andesite surge
S-44		X		Near Crispen (Sec. IX)	Ash fall
S-45		X		Near Crispen (Sec. IX)	Lapilli fall
S-46		X		Near Crispen (Sec. IX)	Inclusion in S-45
S-47		X		Peter Simmons dome	
S-48		X		Old sulfur mine	
S-49		X		Hell's Gate	Lava flow
S-50		X		Peak Hill	Block and ash flow
S-51		X		Thai's Hill dome	
S-55		X		Bunker Hill dome	
S-56		X		Great Hill dome (Sec. XVI)	
S-70		X		Road at base of Peak Hill	Inclusion

Gran. Samples for granulometric analyses

SVA Semi-vesicular andesite

Pet. Samples for petrologic analyses

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
S-71	X			Giles Quarter	Vitric ash
S-72		X		Giles Quarter	Inclusion, same location as S-71
S-73		X		Shore below Windwardside (Sec. VII)	Mixed magma clast
S-74		X		Shore below Windwardside (Sec. VII)	Mixed magma clast
S-75		X		Shore below Windwardside (Sec. VII)	Reworked deposit
S-76		X		Shore below Windwardside (Sec. VII)	Inclusion, thermally altered
S-77		X		Shore below Windwardside (Sec. VII)	Rubbly base of lava flow
S-78		X		Shore below Windwardside (Sec. VII)	Fluviatile pumice
S-79		X		Shore below Windwardside (Sec. VII)	Block and ash flow
S-80		X		Shore below Windwardside (Sec. VII)	Dense andesite surge
S-81		X		Shore below Windwardside (Sec. VII)	Block and ash flow
S-82		X		Shore below Windwardside (Sec. VII)	Block and ash flow
S-83		X		Shore below Windwardside (Sec. VII)	Block and ash flow
S-84		X		Shore below Windwardside	Inclusion, beach boulder
S-85			X	Road between The Bottom and Fort Bay	Conch-shell handaxe
S-86	X			Near Crispen	Pumice-lithic surge
S-87	X			Near Crispen	Lithic-pumice surge
S-88	X			Near Crispen	Lapilli fall
S-89	X			Road between The Bottom and Fort Bay	Vitric ash
S-89A		X		St. Johns Flat	Lava flow
S-90		X		Dome immediately W. of Great Level Bay	
S-91		X		Dome between Thais Hill and Fort Hill	
S-92		X		Mt. Scenery	
S-93		X		Giles Quarter	Pumice and ash flow
S-95	X			Quarry at harbor	Block and ash flow
S-96		X		Behind the Ridge	Lava flow
S-97		X		Behind the Ridge	Lava flow
S-98		X		Lower Hell's Gate	Lava flow
S-99		X		Lower Hell's Gate	Lava flow
SA-100		X		Peak Hill dome	
SA-101		X		Dome east of Fort Bay	
SA-102		X		Fort Bay Dome	
SA-103		X		Roadcut English Quarter	Block and ash flow
SA-104		X		Between U. Hell's Gate & English Quar.	Scoria and ash flow
SA-105	X			The Bottom (Sec. XIV)	Block and ash flow
SA-106			X	The Bottom (Sec. XIV)	Amerindian pottery
SA-107	X			The Bottom (Sec. XIV)	Fine fluviatile sand
SA-108	X			The Bottom (Sec. XIV)	Coarse fluviatile sand
SA-109	X			The Bottom (Sec. XIV)	Medium fluviatile sand
SA-110	X			The Bottom (Sec. XIV)	Coarse fluviatile sand
SA-111			X	The Bottom (Sec. XIV)	Amerindian pottery
SA-112	X			The Bottom (Sec. XIV)	Medium fluviatile sand
SA-113	X			The Bottom (Sec. XIV)	Dense andesite surge
SA-114			X	The Bottom (Sec. XIV)	Charcoal from SA-113
SA-115			X	The Bottom (Sec. XIV)	European pottery
SA-116		X		The Bottom (Sec. XIV)	Block and ash flow
SA-117			X	The Bottom (Sec. XIV)	Charcoal, same layer as SA-111
SA118		X		Road to harbor	Vitric ash
SA-119		X		Quarry near harbor	Block and ash flow

Gran. Samples for granulometric analyses

Pet. Samples for petrologic analyses

SVA Semi-vesicular andesite

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
SA-120		X		The Cove	Scoria and ash flow
SA-121		X		The Cove	Inclusion, same location as SA-120
SA-122		X		Booby Hill dome	
SA-123		X		Booby Hill dome	Inclusion in dome
SA-124		X		The Level dome	
SA-125		X		The Level dome	Inclusion in dome
SA-126		X		The Level	SVA. block & ash flow
SA-127		X		Pirate Rock	Block and ash flow
SA 128		X		Behind the Ridge	Lava flow
SA-129		X		Old sulfur mine	Mineralogical samples
SA -130		X		Giles Quarter	Block and ash flow
SA-131		X		Giles Quarter (Sec. VIII)	Pumice horizon
SA-132		X		Shore below Windwardside (Sec. VII)	Mixed magma clast
SA-133		X		Shore below Windwardside (Sec. VII)	Mixed magma clast
SA-134		X		Shore below Windwardside (Sec. VII)	Inclusion, in block & ash flow
SA-135		X		Behind Generator house (Sec. IX)	Lapilli fall
SA-136		X		The Ladder (Sec. XVII)	Block and ash flow
SA_137		X		The Ladder (Sec. XVII)	Fluviatile reworked pumice
SA-138		X		The Ladder (Sec. XVII)	Block and ash flow
SA-139		X		Torrens Point (Sec. XX)	Lava flow
SA-140			X	Torrens Point (Sec. XX)	Lava flow
SA-141		X		Torrens Point (Sec. XX)	Lapilli fall
SA-142		X		Torrens Point (Sec. XX)	Block and ash flow
SA-143	X			Torrens Point (Sec. XX)	Fluviatile laminated ash bed
SA-144	X			Torrens Point (Sec. XX)	Fluviatile laminated ash bed
SA-145		X		Mary's Point (Sec. XXI)	Upper Pumice Horizon
SA-146		X		Maskehorne Hill dome	
SA-147		X		St. John's Flat	Lava flow
SA-148	X			St. John's Flat	Dense andesite surge
SA-149		X		St. John's Flat	Mixed magma clast
SA-150		X		Mt. Scenery	S.E. peak
SA-151		X		Mt. Scenery	N.E. peak
SA-152		X		Mt. Scenery	Base of W. peak
SA-153		X		Great Point	Block and ash flow
SA-154		X		Great Point	Lava flow
SA-155		X		Torrens Bay	Block and ash flow
SA-156		X		Torrens Bay	SVA block & ash flow
SA-157		X		Torrens Bay	Inclusion in SA-156
SA-158		X		Torrens Bay	Inclusion in SA-156
SA-159		X		Diamond Rock	
SA-160		X		Booby Hill, (Sec. IV)	Block and ash flow
SA-160B		X		Booby Hill (Sec. IV)	Inclusion in SA-160
SA-161	X			Booby Hill (Sec. IV)	SVA surge
SA-162		X		The Level (Sec. II)	Block and ash flow
SA-163		X		Spring Bay (Sec. I)	Block and ash flow
SA-164		X		Spring Bay (Sec. I)	Lava flow
SA-165		X		Spring Bay (Sec. I)	Scoria and ash flow
SA-166		X		Spring Bay (Sec. I)	Inclusion in SA-165
SA-167		X		Spring Bay (Sec. I)	Block and ash flow

Gran. Samples for granulometric analyses

SVA Semi-vesicular andesite

Pet. Samples for petrologic analyses

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
SA-168		X		Old Booby Hill	Inclusion in dome lava
SA-169		X		Kate's Hill dome	
SA-170		X		Spring Bay Flat	Upper Hell's Gate lava flow
SA-171		X		Upper Hell's Gate	Lava boulder
SA-172		X		Lower Hell's Gate	Lava channel
SA-173		X		Lower Hell's Gate	Lava levee
SA-174		X		Kelby's Ridge dome	
SA-175		X		Kelby's Ridge	Inclusion in dome lava
SA-176	X			Giles Quarter	Ignimbrite
SA-177	X			St. John's Flat (Sec. X)	Dense andesite surge
SA-178	X			St. John's Flat (Sec. X)	Dense andesite surge
SA-179	X			St. John's Flat (Sec. X)	Dense andesite surge
SA-180	X			St. John's Flat (Sec. X)	Dense andesite surge
SA-181	X			St John's Flat (Sec. X)	Dense andesite surge
SA-182	X			St. John's Flat (Sec. X)	Pumice surge
SA-183	X			Road Windwardside to The Level	SVA block & ash flow
SA-184	X			Great Hill	Ash channel
SA-185	X			Great Hill	Ash channel
SA-186	X			Great Hill	Ash channel
SA-187		X		Great Hill	Vesiculated dome rock
SA-188		X		Great Hill	Vesiculated dome rock
SA-189		X		Windwardside (Sec. V)	Block and ash flow
SA-190A	X			Windwardside (Sec. V)	Block and ash flow
SA-190			X	The Level	Charcoal from a pit
SA-191		X		Old Booby Hill	Ash channel
SA-192	X			Old Booby Hill	Ash channel
SA-971-1		X		Well Bay	Inclusion, beach boulder
SA-971-2	X			Road to Well Bay (Sec. XVIII)	SVA block & ash flow
SA-971-3		X		Road to Well Bay	SVA block & ash flow
SA-971-4	X			Behind quarry at harbor (Sec. XII)	SVA block & ash flow
SA-971-5		X		Behind quarry at harbor (Sec. XII)	SVA block & ash flow
SA-971-6		X		Beach between harbor and Tent Bay	Inclusion, beach boulder

Gran. Samples for granulometric analyses

SVA Semi-vesicular andesite

Pet. Samples for petrologic analyses

Dat. Samples for dating analyses

APPENDIX 2.

SPECIMEN LIST FOR ST. EUSTATIUS

Sample	Gran.	Pet.	Dat.	Location	Comments
E-1		X		Oranjestad Well (Sec. XVIII)	Ash fall
E-2		X		Oranjestad Well (Sec. XVIII)	Block and ash flow
E-3		X		Oranjestad Well (Sec. XVIII)	Block and ash flow
E-4		X		Oranjestad Well (Sec. XVIII)	Block and ash flow
E-5		X		Oranjestad Well (Sec. XVIII)	Block and ash flow
E-6		X		Oranjestad Well (Sec. XVIII)	Semi-vesicular andesite surge
E-7		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-8		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-9		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-10		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-11		X		Oranjestad Well (Sec. XVIII)	Block and ash flow
E-12		X		Oranjestad Well (Sec. XVIII)	Block and ash flow
E-13		X		Oranjestad Well (Sec. XVIII)	Pumiceous surge
E-14		X		Oranjestad Well (Sec. XVIII)	Pumiceous surge
E-15		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-16		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-17		X		Oranjestad Well (Sec. XVIII)	Ash fall
E-18		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-19		X		Oranjestad Well (Sec. XVIII)	Ignimbrite
E-20		X		Oranjestad Well (Sec. XVIII)	Scoria and ash flow
E-21		X		Oranjestad Well (Sec. XVIII)	Scoria and ash flow
E-22		X		Oranjestad Well (Sec. XVIII)	Dense andesite surge
E-23		X		Oranjestad Well (Sec. XVIII)	Dense andesite surge
E-24		X		Oranjestad Well (Sec. XVIII)	Dense andesite surge
E-25		X		Oranjestad Well (Sec. XVIII)	Dense andesite surge
E-26		X		Oranjestad Well (Sec. XVIII)	Block and ash flow
E-27		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-28		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-29		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-30		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-31		X		Oranjestad Well (Sec. XVIII)	Lapilli fall
E-32		X		Sugar Loaf	Limestone with corals
E-33		X		Sugar Loaf	Limestone with corals
E-34		X		Sugar Loaf	Limestone with corals
E-35		X		Sugar Loaf	Base surge
E-35.1		X		Cliffs between Kay Bay & White Wall	
E-36		X		Cliffs between Kay Bay & White Wall	
E-40		X		Fort de Windt (Sec. IX)	Pumiceous surge
E-41		X		Fort de Windt (Sec. IX)	Block and ash flow
E-42		X		Fort de Windt (Sec. IX)	Ignimbrite
E-43		X		Fort de Windt (Sec. IX)	Ignimbrite
E-44		X		Fort de Windt (Sec. IX)	Lapilli fall
E-45		X		Fort de Windt (Sec. IX)	Block and ash flow
E-46		X		Fort de Windt (Sec. IX)	Scoria and ash flow
E-47		X		Compagnie Baai (Sec. V)	Ignimbrite
E-48		X		Compagnie Baai (Sec. V)	Ignimbrite
E-49		X		Compagnie Baai (Sec. V)	Ignimbrite
E-50		X		Compagnie Baai (Sec. V)	Ignimbrite
E-51		X		Compagnie Baai (Sec. V)	Scoria and ash flow

Gran. Samples for granulometric analyses

SVA Semi-vesicular andesite

Pet. Samples for petrologic analyses

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
E-52		X		Compagnie Baai (Sec. V)	SVA block and ash flow
E-53		X		Compagnie Baai (Sec. V)	Block and ash flow
E-54		X		Compagnie Baai (Sec. V)	SVA block and ash flow
E-55		X		Compagnie Baai (Sec. V)	Block and ash flow
E-56		X		Compagnie Baai (Sec. V)	SVA block and ash flow
E-57		X		Compagnie Baai (Sec. V)	Scoria and ash flow
E-58		X		Compagnie Baai (Sec. V)	Pumiceous surge
E-58.1		X		Compagnie Baai (Sec. V)	Scoria and ash flow
E-59		X		Compagnie Baai (Sec. V)	Scoria and ash flow
E-59A		X		Compagnie Baai (Sec. V)	Scoria and ash flow
E-60		X		Compagnie Baai (Sec. V)	Scoria and ash flow
E-61		X		Compagnie Baai (Sec. V)	Block and ash flow
E-62		X		Compagnie Baai (Sec. V)	Block and ash flow
E-63		X		Compagnie Baai (Sec. V)	Ignimbrite
E-64		X		Compagnie Baai (Sec. V)	Ignimbrite
E-80		X		Crater rim, Quill	
E-81	X			Oranjestad Well (Sec. XVIII)	Pumiceous surge
E-82	X			Oranjestad Well (Sec. XVIII)	Ignimbrite
E-83	X			Oranjestad Well (Sec. XVIII)	Block and ash flow
E-84	X			Oranjestad Well (Sec. XVIII)	Block and ash flow
E-85		X		Oranjestad Well (Sec. XVIII)	Block and ash flow
E-85A	X			Kid Sadler (Sec. VIII)	Pumiceous surge
E-86		X		Kid Sadler (Sec. VIII)	Lapilli fall
E-87		X		Kid Sadler (Sec. VIII)	Pumiceous surge
E-88	X			Kid Sadler (Sec. VIII)	Dense andesite surge
E-89	X			Kid Sadler (Sec. VIII)	SVA block and ash flow
E-90		X		Kid Sadler (Sec. VIII)	Scoria and ash flow
E-91	X			Kid Sadler (Sec. VIII)	Scoria and ash flow
E-92		X		Kid Sadler (Sec. VIII)	Scoria and ash flow
E-93		X		Kid Sadler (Sec. VIII)	Block and ash flow
E-94		X		Kid Sadler (Sec. VIII)	Scoria and ash flow
E-95		X		Kid Sadler (Sec. VIII)	Scoria and ash flow
E-96		X		Kid Sadler (Sec. VIII)	Scoria and ash flow
E-97		X		Kid Sadler (Sec. VIII)	Scoria and ash flow
E-98		X		Kid Sadler (Sec. VIII)	Scoria and ash flow
E-99	X			Kid Sadler (Sec. VIII)	Dense andesite surge
E-100	X			Kid Sadler (Sec. VIII)	Dense andesite surge
E-101		X		Kid Sadler (Sec. VIII)	Block and ash flow
E-102		X		Kid Sadler (Sec. VIII)	Block and ash flow
E-103		X		Kid Sadler (Sec. VIII)	Block and ash flow
E-104		X		Kid Sadler (Sec. VIII)	SVA block and ash flow
E-105	X			Compagnie Baai (Sec. V)	SVA block and ash flow
E-106	X			Compagnie Baai (Sec. V)	Dense andesite surge
E-107	X			Compagnie Baai (Sec. V)	Dense andesite surge
E-107A		X		Mary's Glory (Sec. XXXII)	Ash hurricane
E-108	X			Compagnie Baai (Sec. V)	Block and ash flow
E-109	X			Compagnie Baai (Sec. V)	Block and ash flow
E-110	X			Compagnie Baai (Sec. V)	Block and ash flow
E-111	X			Compagnie Baai (Sec. V)	Block and ash flow
E-112	X			Compagnie Baai (Sec. V)	Block and ash flow

Gran. Samples for granulometric analyses

Pet. Samples for petrologic analyses

SVA Semi-vesicular andesite

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
E-113	X			Compagnie Baai (Sec. V)	Block and ash flow
E-114	X	X		Compagnie Baai (Sec. V)	Block and ash flow
EX-120			X	Quarry near airport (Sec. XXXI)	Charcoal
EX-121			X	Quarry near airport (Sec. XXXI)	Charcoal
EX-122			X	Quarry near airport (Sec. XXXI)	Charcoal
EX-123			X	Mary's Glory (Sec. XXXII)	Charcoal
EX-124			X	Mary's Glory (Sec. XXXII)	Charcoal
EX-125			X	Mary's Glory (Sec. XXXII)	Charcoal
EX-127			X	Oranjestad Cistern (Sec. XVII)	Charcoal
EX-128			X	Pisgah Hill (Sec. XXXIII)	Charcoal
EX-129			X	Pisgah Hill (Sec. XXXIII)	Shells
EX-130			X	Pisgah Hill (Sec. XXXIII)	Shells
EX-131		X		Pisgah Hill	Echinoid shell
EX-132	X		X	Pisgah Hill (Sec. XXXIII)	Pumiceous surge
EX-133	X			Golden Rock Estate (Sec. XXVII)	SVA block and ash flow
EX-134	X			Golden Rock Estate (Sec. XXVII)	Semi-vesicular andesite surge
EX-135		X		Pisgah Hill	Shells
EX-136	X			Pisgah Hill (Sec. XXXIII)	Ash fall
EX-137	X			Pisgah Hill (Sec. XXXIII)	Ash fall
EX-138		X		Oranjestad Well (Sec. XVIII)	Ash hurricane
EX-139	X			Pisgah Hill (Sec. XXXIII)	Pumiceous surge
EX-140		X		Pisgah Hill (Sec. XXXIII)	Ignimbrite
EX-141			X	Gilboa Hill	K/Ar dating
EX-142			X	Pisgah Hill	K/Ar dating
EX-143			X	Bergje Dome	K/Ar dating
EX-144			X	Fort Royal	K/Ar dating
EX-145	X			South of Gallows Bay (Sec. XIII)	Scoriaceous surge
EX-146	X			South of Gallows Bay (Sec. XIII)	Scoriaceous surge
EX-147			X	Golden Rock Estate (Sec. XXVIII)	Charcoal
EX-148		X		Golden Rock Estate (Sec. XXVIII)	Basaltic ash flow
EX-149			X	Golden Rock Estate (Sec. XXIX)	Charcoal
EX-150	X			Golden Rock Estate (Sec. XXIX)	Basaltic ash flow
EX-151	X			Golden Rock Estate (Sec. XXIX)	Scoria and ash flow
EX-152		X		Golden Rock Estate (Sec. XXIX)	Scoria and ash flow
EX-153	X			Bargine Bay (Sec. II)	Basaltic ash flow
EX-154	X			Bargine Bay (Sec. II)	Scoria and ash flow
EX-155		X		Bargine Bay (Sec. II)	Scoria and ash flow
EX-156		X		Bargine Bay (Sec. II)	Scoria and ash flow
EX-157		X		Bargine Bay (Sec. II)	Scoria and ash flow
EX-158	X			Quarry near airport (Sec. XXXI)	Accretionary lapilli
EX-159	X			Oranjestad Well (Sec. XVIII)	Accretionary lapilli
EX-160			X	Corre Corre Bay (Sec. VII)	Block and ash flow
EX-161		X		Gully at Kay Bay (Sec. XI)	Scoria and ash flow
EX-162		X		Gully at Kay Bay (Sec. XI)	Semi-vesicular andesite surge
EX-163		X		Gully at Kay Bay (Sec. XI)	Semi-vesicular andesite surge
EX-164		X		Gully at Kay Bay (Sec. XI)	SVA block and ash flow
EX-165		X		Gully at Kay Bay (Sec. XI)	SVA block and ash flow
EX-166		X		Gully at Kay Bay (Sec. XI)	Semi-vesicular andesite surge

Gran. Samples for granulometric analyses

SVA Semi-vesicular andesite

Pet. Samples for petrologic analyses

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
Ex-167		X		Gully at Kay Bay (Sec. XI)	Semi-vesicular andesite surge
EX-168	X			Gully at Kay Bay (Sec. XI)	Scoria and ash flow
EX-169		X		Gully at Kay Bay (Sec. XI)	Scoria and ash flow
EX-170		X		South of Gallows Bay (Sec. XIII)	Scoria and ash flow
EX-171		X		South of Gallows Bay (Sec. XIII)	Scoria and ash flow
EX-172		X		Antillean View Hotel (Sec. XXIV)	Lapilli fall
EX-173		X		Antillean View Hotel (Sec. XXIV)	Semi-vesicular andesite surge
EX-174	X			Golden Rock Estate (Sec. XXVIII)	Scoria and ash flow
EX-175	X			Schillpaden Baai (Sec. III)	Scoria and ash flow
EX-176	X			Compagnie Baai (Sec. V)	Scoriaceous surge
EUX-203		X		Sugar Loaf	Pumice flow
EUX-209		X		Bargine Bay (Sec. II)	Base surge
EUX-210	X			Bargine Bay (Sec. II)	Lapilli fall
EUX-211	X			Bargine Bay (Sec. II)	Ignimbrite
EUX-212	X			Bargine Bay (Sec. II)	Pumiceous surge
EUX-213	X			Bargine Bay (Sec. II)	Ash fall
EUX-214		X		Bargine Bay (Sec. II)	Lapilli fall
EUX-214A		X		Bargine Bay (Sec. II)	Lapilli fall
EUX-214A1		X		Bargine Bay (Sec. II)	Ignimbrite
EUX-214A2		X		Bargine Bay (Sec. II)	Ignimbrite
EUX-215		X		Bargine Bay (Sec. II)	SVA block and ash flow
EUX-216		X		Bargine Bay (Sec. II)	Lapilli fall
EUX-217		X		Bargine Bay (Sec. II)	Ignimbrite
EUX-218	X			Bargine Bay (Sec. II)	Ash fall
EUX-219	X			Bargine Bay (Sec. II)	Ignimbrite
EUX-220		X		Bargine Bay (Sec. II)	Semi-vesicular andesite surge
EUX-221		X		Bargine Bay (Sec. II)	SVA block and ash flow
EUX-222	X			Bargine Bay (Sec. II)	Ash fall
EUX-223	X			Bargine Bay (Sec. II)	Pumiceous surge
EUX-224	X			Oranjestad Well (Sec. XVIII)	Pumiceous surge
EUX-225	X			Oranjestad Well (Sec. XVIII)	Ash fall
EUX-226	X			Oranjestad Well (Sec. XVIII)	Ash fall
EUX-227	X			Oranjestad Well (Sec. XVIII)	Ash fall
EUX-228	X			Oranjestad Well (Sec. XVIII)	Ash fall
EUX-229	X			Oranjestad Well (Sec. XVIII)	Ash fall
EUX-230	X			Oranjestad Well (Sec. XVIII)	Block and ash flow
EUX-231	X			Oranjestad Well (Sec. XVIII)	Ignimbrite
EUX-232	X			Oranjestad Well (Sec. XVIII)	Ash fall
EUX-300		X		Sugar Loaf	Pumice flow
EUX-88-301		X		Sugar Loaf	Pumice breccia
EUX-88-302	X			Sugar Loaf	Laminated ashes
EUX-88-303		X		Sugar Loaf	Andesite lithic block
EUX-88-304			X	Sugar Loaf	Coral
EUX-88-305		X		Sugar Loaf	Bomb
EUX-88-306		X		White Wall	Pumice flow
EUX-88-307	X			Gallows Bay (Sec. XIV)	Scoria and ash flow
EUX-88-308	X			Gallows Bay (Sec. XIV)	Scoriaceous surge
EUX-88-309	X			Pisgah Hill (Sec. XXXIV)	Ash fall
EUX-88-310	X			Pisgah Hill (Sec. XXXIV)	Ash fall

Gran. Samples for granulometric analyses

Pet. Samples for petrologic analyses

SVA Semi-vesicular andesite

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
EUX-88-311	X			Pisgah Hill (Sec. XXXIV)	Ash fall
EUX-88-312		X		Pisgah Hill (Sec. XXXVI)	Ash hurricane
EUX-88-313	X			Pisgah Hill (Sec. XXXVI)	Ash hurricane
EUX-88-314	X			Pisgah Hill (Sec. XXXVI)	Ash fall
EUX-88-315	X			Pisgah Hill (Sec. XXXVI)	Ash fall
EUX-88-316	X			Pisgah Hill (Sec. XXXVII)	Ash fall
EUX-88-317	X			Pisgah Hill (Sec. XXXVII)	Ash fall
EUX-88-318	X			Pisgah Hill (Sec. XXXVII)	Ash fall
EUX-88-319	X			Pisgah Hill (Sec. XXXV)	Lapilli fall
EUX-88-320	X			Pisgah Hill (Sec. XXXV)	Ash fall
EUX-88-321	X			Pisgah Hill (Sec. XXXV)	Ash fall
EUX-88-322	X			Pisgah Hill (Sec. XXXV)	Ash fall
EUX-88-323	X			Pisgah Hill	Pumice and ash flow
EUX-88-324		X		Sugar Loaf	Pumice flow
EUX-88-325		X		Sugar Loaf	Pumice flow
EUX-88-326	X			Sugar Loaf	Laminated ash
EUX-88-327	X			White Wall	Laminated ash
EUX-88-328		X		White Wall	Pumice breccia
EUX-88-329		X		White Wall	Pumice breccia
EUX-88-330			X	Sugar Loaf	Coral
EUX-88-331			X	Sugar Loaf	Coral
EUX-88-332			X	Sugar Loaf	Coral
EUX-400		X		Sugar Loaf	Rhyolite ash
EUX-401		X		Sugar Loaf	Reworked ash
EUX-402		X		Sugar Loaf	Limestone conglomerate
EUX-403		X		Sugar Loaf	Volcanic bomb
EUX-404		X		Sugar Loaf	Base surge
EUX-405		X		Gut near Sugar Loaf	Inclusion in andesite clast
EUX-406		X		Gut near Sugar Loaf	Cumulate block
EUX-407		X		Gut near Sugar Loaf	Cumulate block
EUX-408		X		Gilboa Hill	Lava flow
EUX-409		X		Mary's Glory	Lava flow
SE-24			X	Sugar Loaf	Coral
SE-25			X	Sugar Loaf	Coral
SE-26			X	Sugar Loaf	Coral
SE-27			X	Sugar Loaf	Coral
SE-28			X	Sugar Loaf	Coral
SE-29			X	Sugar Loaf	Coral
SE-30			X	Sugar Loaf	Coral
SE-31			X	Sugar Loaf	Coral
SE-32			X	Sugar Loaf	Coral
SE-33			X	Sugar Loaf	Coral
SE-34			X	Sugar Loaf	Coral
SE-35			X	Sugar Loaf	Coral
EUX-95-1		X		Sugar Loaf	Base surge
EUX-95-2		X		Sugar Loaf	Base surge
EUX-95-3		X		White Wall	Pumice-ash sandstone
EUX-95-4		X		White Wall	Pumice breccia
EUX-95-5			X	White Wall	Coral

Gran. Samples for granulometric analyses

Pet. Samples for petrologic analyses

SVA Semi-vesicular andesite

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
EUX-95-7		X		White Wall	Pumice breccia
EUX-95-8		X		White Wall	Pumice breccia
EUX-95-9		X		White Wall	Gypsum block
EUX-95-13		X		White Wall	Ash-pumice sandstone
EUX-95-14		X		White Wall	Coarse sandstone
EUX-95-15		X		White Wall	Fine-grained calcarenite
EUX-95-16			X	White Wall	Coral
EUX-95-17		X		White Wall	Pumice breccia
EUX-95-18			X	White Wall	Coral
EUX-95-19		X		Sugar Loaf	Base surge
EUX-95-20		X		Sugar Loaf	Base surge
EUX-95-21		X		Sugar Loaf	Base surge
EUX-95-22		X		Sugar Loaf	Base surge
EUX-95-23		X		Sugar Loaf	Base surge
EUX-95-24		X		Sugar Loaf	Base surge
EUX-95-50		X		Signal Hill	Lava flow
EUX-95-51		X		Mary's Glory	Lava flow
EUX-97-1-1			X	Cultur Valkte (Sec. XXX)	Charcoal
EUX-97-1-2		X		Cultur Valkte (Sec. XXX)	Cumulate block
EUX-97-1-3			X	Golden Rock estate	Charcoal
EUX-97-1-4		X		East coast	Greenstone clasts
EUX-97-1-5		X		East coast	Cumulate blocks
EUX-97-1-6		X		Beach south of Oranjestad	Greenstone clasts
EUX-97-1-7		X		Beach south of Oranjestad	Cumulate block
EUX-97-1-8		X		Smoke Alley (Sec. XIX)	Greenstone clast
EUX-97-1-9		X		Gully at Kay Bay (Sec. XI)	Greenstone clast
EUX-97-1-10	X			Gully at Kay Bay (Sec. XI)	Semi-vesicular andesite surge
EUX-97-1-11	X			Gully at Kay Bay (Sec. XI)	Scoria and ash flow
EUX-97-1-12	X			Concordia Baai (Sec. I)	SVA block and ash flow
EUX-97-1-13	X			Concordia Baai (Sec. I)	SVA block and ash flow
EUX-97-1-14		X		Concordia Baai (Sec. I)	Basaltic ash flow
EUX-97-1-15			X	East Coast cliffs	Charcoal
EUX-97-1-16			X	East Coast cliffs	Charcoal
EUX-97-1-17			X	East Coast cliffs	Charcoal
EUX-97-1-18			X	East Coast cliffs	Charcoal
EUX-97-1-19			X	East Coast cliffs	Charcoal
EUX-97-1-20		X		Bouille (Sec. XII)	Scoria and ash flow
EUX-97-1-21		X		Bouille (Sec. XII)	Scoria and ash flow
EUX-97-1-22		X		Bouille (Sec. XII)	Scoria and ash flow
EUX-97-1-23	X			Bouille (Sec. XII)	SVA block and ash flow
EUX-97-1-24	X			Bouille (Sec. XII)	Semi-vesicular andesite surge
EUX-97-1-25			X	Pisgah Hill	Charcoal
EUX-97-1-26			X	Bargine Bay (Sec. II)	Shells
EUX-97-1-27		X		Smoke Alley (Sec. XIX)	Lapilli fall
EUX-97-1-28		X		Pisgah Hill	Lava flow
EUX-97-1-29	X			Compagnie Baai (Sec. V)	SVA block and ash flow
EUX-97-1-30	X			Compagnie Baai (Sec. V)	SVA block and ash flow
EUX-97-1-31		X		Compagnie Baai (Sec. V)	SVA block and ash flow
EUX-97-1-32		X	X	Compagnie Baai (Sec. V)	Lithic clasts

Gran. Samples for granulometric analyses

Pet. Samples for petrologic analyses

SVA Semi-vesicular andesite

Dat. Samples for dating analyses

Sample	Gran.	Pet.	Dat.	Location	Comments
EUX-97-1-33		X		Compagnie Baai (Sec. V)	Lithic clasts
EUX-97-1-34		X		Compagnie Baai (Sec. V)	Fossil crab
EUX-97-1-35	X			Quarry SW of Round Hill (Sec. XXIII)	Scoria and ash flow
EUX-97-1-36	X			Blue Bead Quarry (Sec. XXV)	Semi vesicular andesite surge
EUX-97-1-37	X			Blue Bead Quarry (Sec. XXV)	Semi vesicular andesite surge
EUX-97-1-38	X			Cultur Vlakte (Sec. XXX)	Ash fall
EUX-97-1-39	X			Cultur Vlakte (Sec. XXX)	Ash fall
EUX-97-1-40	X			Cultur Vlakte (Sec. XXX)	Ash fall
EUX-97-1-41	X			Cultur Vlakte (Sec. XXX)	Ash fall
EUX-97-1-41A	X			Cultur Vlakte (Sec. XXX)	SVA surge
EUX-97-1-42			X	Bargine Bay (Sec. II)	Charcoal
EUX-97-1-43		X		Sugar Loaf	Base surge
EUX-97-1-44		X		Sugar Loaf	Ash claystone
EUX-97-1-45		X		Sugar Loaf	Ash claystone
EUX-97-1-46		X		Sugar Loaf	Ash claystone

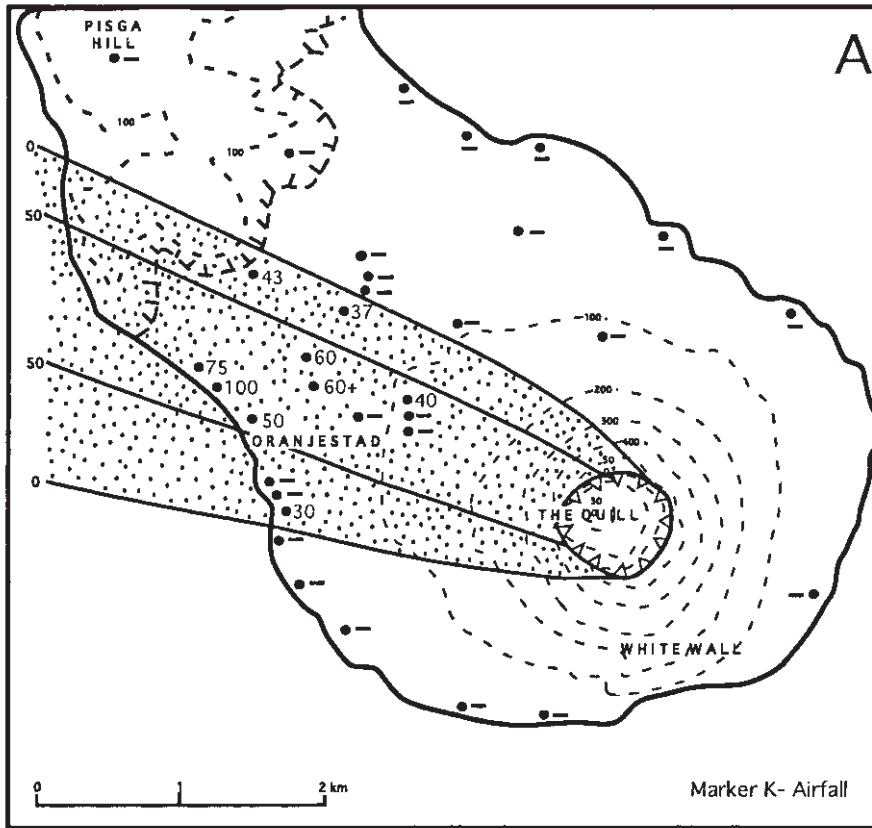
Gran. Samples for granulometric analyses

SVA Semi-vesicular andesite

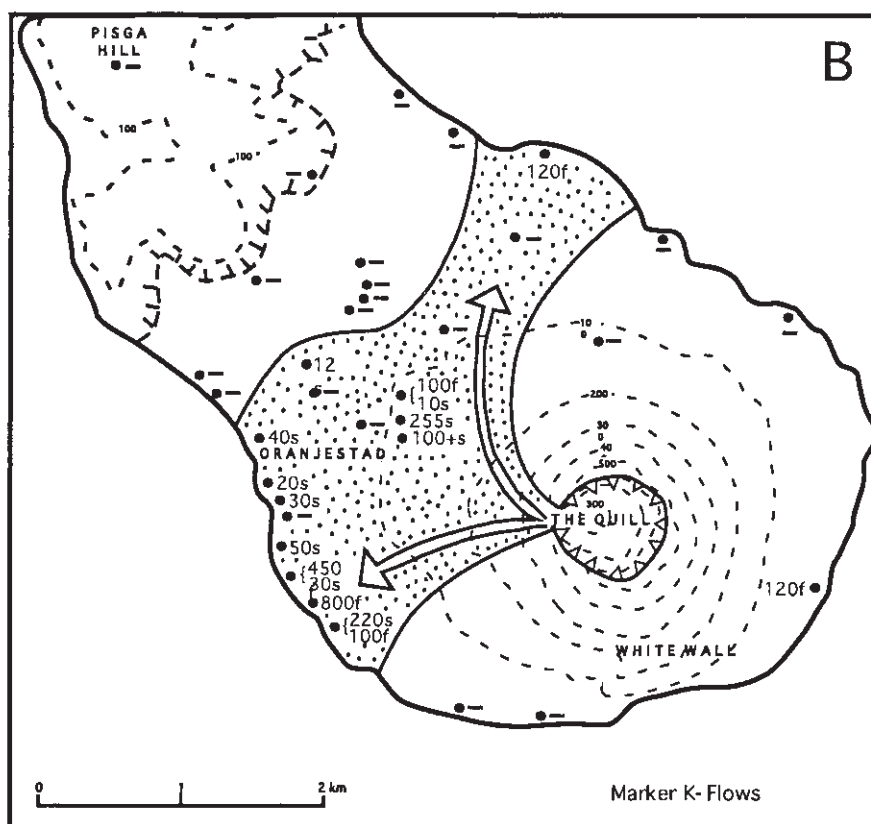
Pet. Samples for petrologic analyses

Dat. Samples for dating analyses

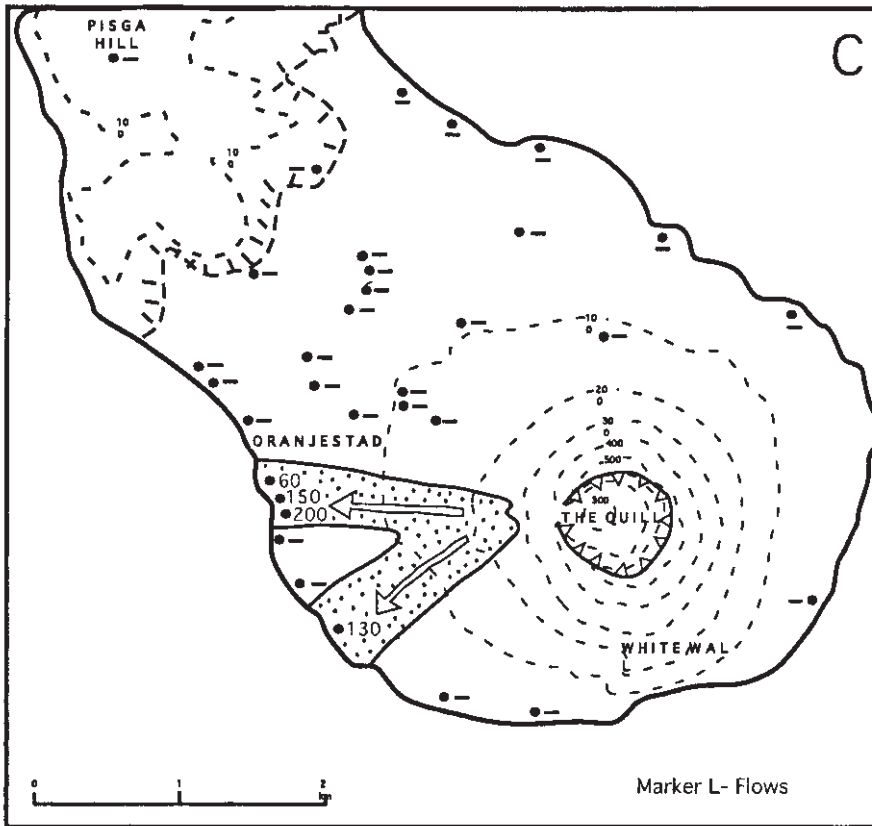
APPENDIX 3.



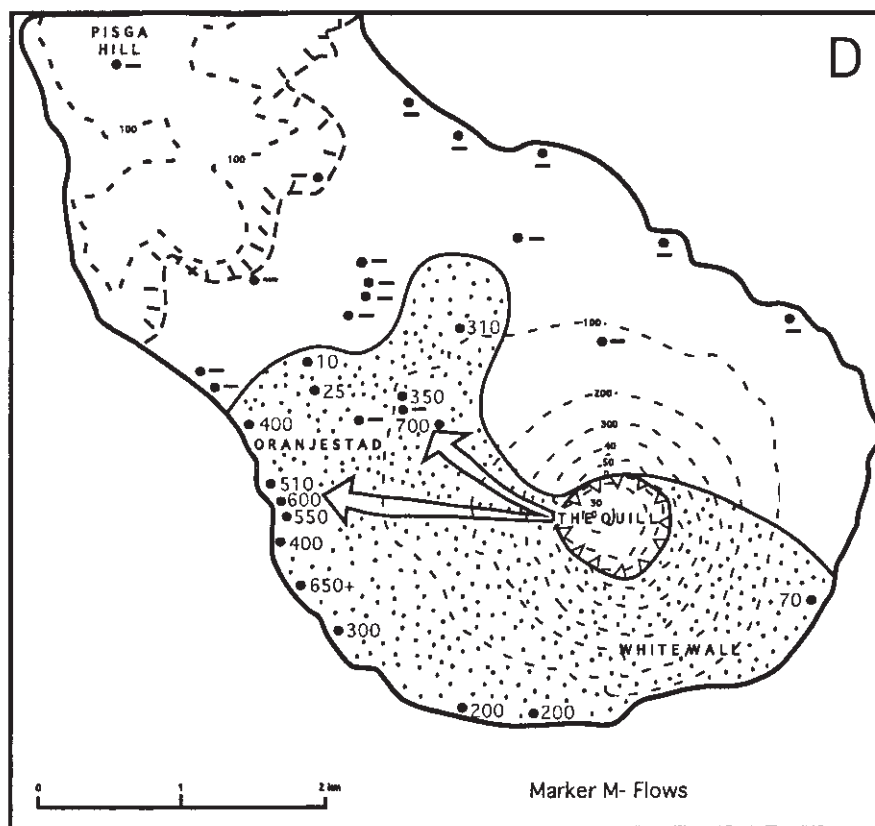
- 75 Measured stratigraphic section; thickness of deposit in cm
- — Deposit absent
- 100+ Minimum thickness of deposit as base not seen
- 100 Attitude in meters
- ⌋ Crater rim of The Quill
- ⌋ Limit of Northern Centers
- 5 0 Isopach of airfall deposit before erosion
- ↖ Main direction of pyroclastic



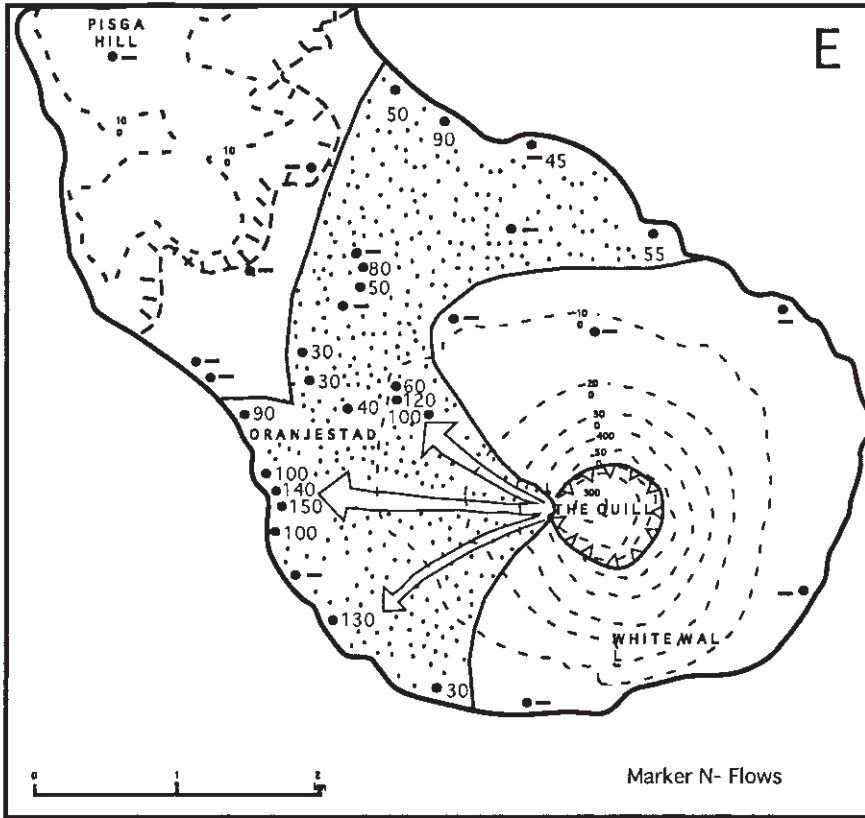
- 75 Measured stratigraphic section; thickness of deposit in cm
- — Deposit absent
- 100+ Minimum thickness of deposit as base not seen
- 100 Attitude in meters
- ⌋ Crater rim of The Quill
- ⌋ Limit of Northern Centers
- 5 0 Isopach of airfall deposit before erosion
- ⇐ Main direction of pyroclastic



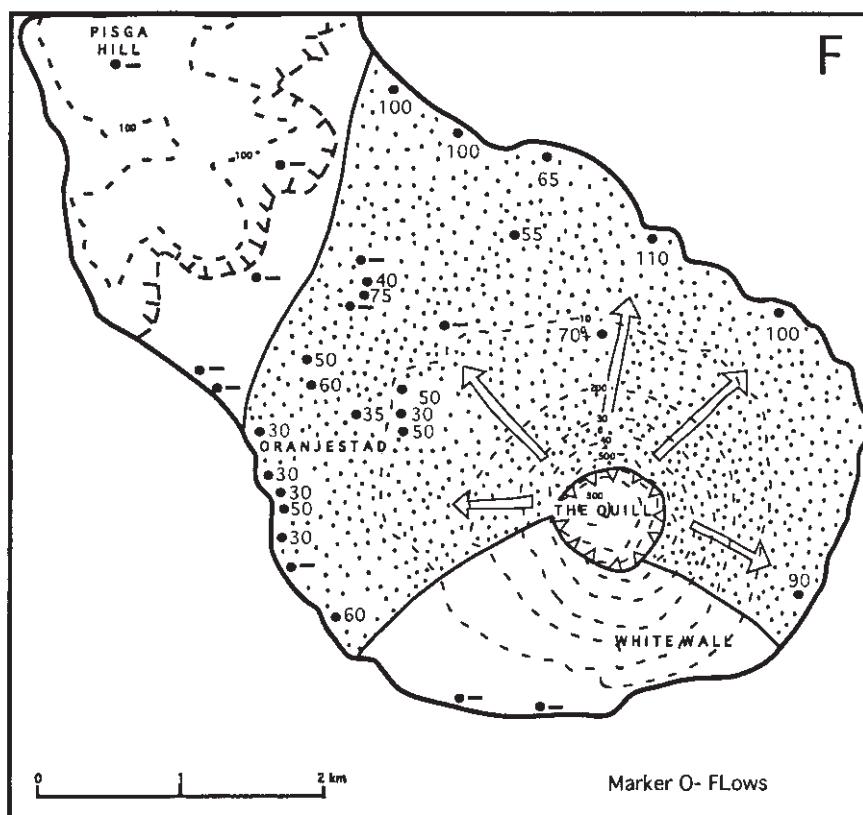
- 75 Measured stratigraphic section; thickness of deposit in cm
- — Deposit absent
- 100+ Minimum thickness of deposit as base not seen
- 100 Attitude in meters
- ⌋ Crater rim of The Quill
- ⌋ Limit of Northern Centers
- 5 0 Isopach of airfall deposit before erosion
- ↖ Main direction of pyroclastic



- 75 Measured stratigraphic section; thickness of deposit in cm
- — Deposit absent
- 100+ Minimum thickness of deposit as base not seen
- 100 Attitude in meters
- ⌵ Crater rim of The Quill
- Limit of Northern Centers
- 5 0 Isopach of airfall deposit before erosion
- ↔ Main direction of pyroclastic



- 75 Measured stratigraphic section; thickness of deposit in cm
- — Deposit absent
- 100+ Minimum thickness of deposit as base not seen
- 100 Attitude in meters
- ⌒ Crater rim of The Quill
- - - Limit of Northern Centers
- 5 0 Isopach of airfall deposit before erosion
- ↙ Main direction of pyroclastic



- 75 Measured stratigraphic section; thickness of deposit in cm
- — Deposit absent
- 100+ Minimum thickness of deposit as base not seen
- 100 Attitude in meters
- ⌋ Crater rim of The Quill
- ⌋ Limit of Northern Centers
- 5 — Isopach of airfall deposit before erosion
- 0 — Main direction of pyroclastic

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