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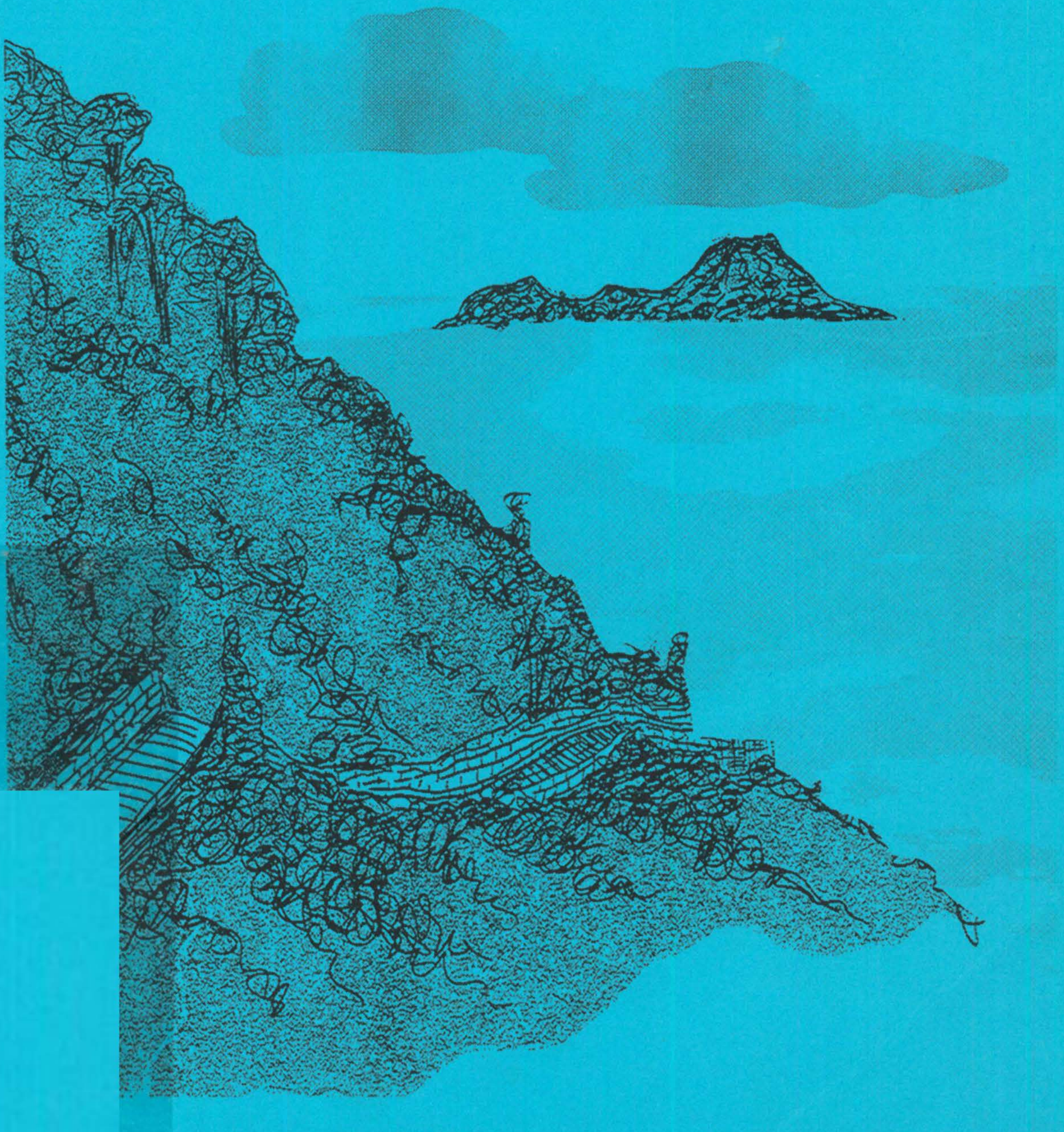
M.J. Roobol, A.L. Smith and J.F. Tomblin



AN ASSESSMENT OF VOLCANIC HAZARD ON THE ISLANDS OF SABA AND ST. EUSTATIUS IN THE NORTHERN LESSER ANTILLES

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Foreword

In 1976 Dr. John Roobol informed the Geological Survey of the Netherlands that the volcanoes of Saba and St. Eustatius are not extinct but dormant, i.e. still have the potential to become active again. This was confirmed by Messrs E.M. Fournier d'Albe and J.F. Tomblin, who visited the islands on behalf of the UNESCO in 1977. Their findings led to the assignment of J. Roobol, A.L. Smith and J.F. Tomblin to make a comprehensive volcanologic study of Saba and St. Eustatius for the government of the Netherlands Antilles. Their task was completed in 1981 with the submission of a confidential report 'An assessment of the volcanic hazard on the islands of Saba and St. Eustatius in the northern Lesser Antilles'. A supplement with petrologic and geochemical data was added in 1982. However, this report was never published. Only the scientific part of the volcanologic study was released.

The 1992 earthquakes near Saba made the inhabitants of the island and the authorities of the Netherlands Antilles aware to the existence of a seismic risk in that area.The Meteorological Service Netherlands Antilles and Aruba was involved, which soon found a link with the volcanic structure of the area. This brought renewed interest for the volcanologic study by Roobol, Smith and Tomblin. Further information was obtained from the SRU in Trinidad, which had positioned the earthquakes of early June using four stations of their Eastern Caribbean seismic network. The closest station is located on St. Kitts. The SRU had subsequently placed additional seismometers on St. Maarten and Saba to monitor further earth tremors in the following weeks.

The next year an international fact-finding mission was invited by the government of the Netherlands Antilles to investigate the present volcanological situation of Saba and St. Eustatius and to come to tangible recommendations on monitoring the activity of the volcanic islands, a programme on education and public awareness, and disaster preparedness. The mission took place in the late autumn of 1994, and reported its findings in September 1995. One of the recommendations was to publish the 1981/82 study report by Roobol, Smith and Tomblin integrally. This was adopted by the present government of the Netherlands Antilles, which we gratefully acknowledge. With the financial and editorial support of the Geological Survey of the Netherlands (RGD) and the Royal Netherlands Meteorological Institute (KNMI) this has now taken place.

The present volcanic eruption of the Soufriere Hills volcano on Montserrat stresses the importance of constant monitoring of all volcanic islands of the active arc of the Lesser Antilles. Thanks to timely evacuation of the population of a threatened zone, as indicated by the participating volcanologists, casualties could be avoided.

Though written close to one and a half decades ago, the contents of the report are still very accurate and scientifically valuable. It will serve as a solid basis for the planned volcano monitoring and disaster preparedness programmes. To avoid delays by rewriting and redrafting, the choice was made to publish it basically as a facsimile of the original report. Only a few minor corrections and additions have been made in the present edition. We are convinced that this publication is a highly valued addition to the literature on the volcanology of the Lesser Antilles, looked forward to by both the specialists in this field, and the interested laymen and administrators.

Haarlem/De Bilt, 20 December 1996

Dr. H.A. van Adrichem Boogaert (RGD)
Dr. H.W. Haak (KNMI)

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Summary

1. The Lesser Antilles island arc from Saba and St. Eustatius in the north, through St. Kitts, Nevis, Montserrat, Basse Terre of Guadeloupe, Dominica, Martinique, St. Lucia, St. Vincent to Grenada in the south is a chain of volcanoes built up along the boundary between two crustal plates underlying the Atlantic Ocean and Caribbean Sea. These islands are known as the Volcanic Caribbees or Active Arc. In contrast Sombrero, Dog, Anguilla, St. Maarten, St. Barts, Barbuda, Antigua to Grande Terre of Guadeloupe are an older extinct volcanic arc without present-day volcanic hazard known as the Limestone Caribbees.

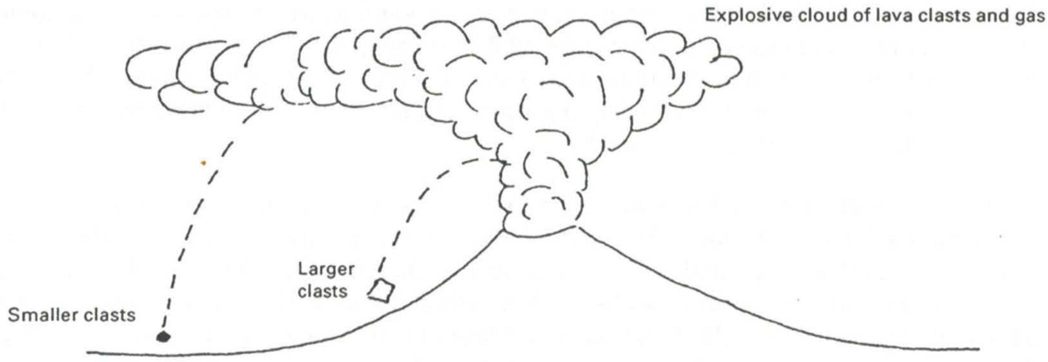
2. Since European settlement about 350 years ago there have been 36 volcanic episodes in the active arc, mainly on the islands of Guadeloupe, Martinique and St. Vincent. Other islands of the active arc can be considered as being dormant rather than extinct because of the presence of hot springs and fumeroles resulting from hot rock or magma (molten rock) below the surface. Saba has two hot springs at temperatures of 72^{o} and 51-55^{o}C while St. Eustatius has none, although groundwater on the island reaches 70^{o}C.

3. The studies of Saba and St. Eustatius reveal that over the past 50,000 years the main types of activity have been pyroclastic (i.e. explosions producing lava fragments similar to Mt. St. Helens, 1980) rather than producing lava flows.

4. For islands without written records an estimate of the volcanic hazard can be made by a study of the occurrence and distribution of the pyroclastic deposits. Individual deposits or groups of deposits can be traced out away from the volcanic center to obtain a measure of how far a hazard extends. Evidence of the frequency of eruptions (which may be in the order of one every few centuries) can be reconstructed by means of radiocarbon dating of charred tree remains often found in Caribbean pyroclastic deposits. This type of study has only been possible during the past decade when much research into pyroclastic volcanology has been undertaken. Such a study could not have been undertaken at the time of the previous geological report on the islands published by Drs. Westermann and Kiel in 1961. As the field of volcanology continues to expand new types of deposit are being recognized so that the present study must not be regarded as the final work on hazard.

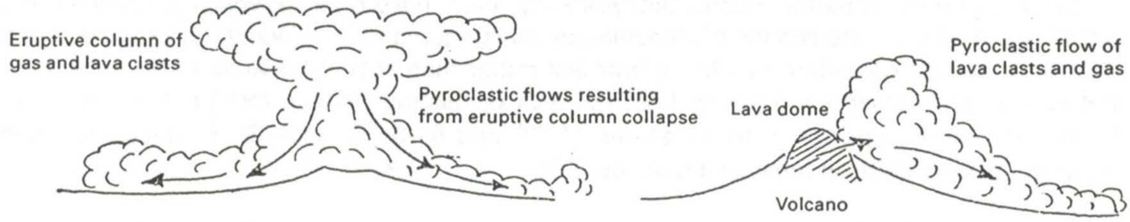
5. Three main types of pyroclastic activity are known and deposits representing each were found on both of the Dutch islands. The three types are:

Pyroclastic airfall deposits
These result from the explosive ejection of gas and lava so that the fragments (or clasts) are deposited as showers. Each clast follows its own trajectory depending on its physical characteristics. The largest clasts fall near the vent and the deposits become finer grained away from the volcanic center.



Pyroclastic airfall deposits

Pyroclastic flow deposits
These result from eruptions where the lava clasts are transported in hot gas as a dense flow which can attain high speeds and be highly destructive. This type of flow is characteristically gravity controlled and contains a high concentration of lava clasts, some up to 6 m in diameter. The flows are usually channeled by topography and affect certain sectors of the volcano's flanks. The largest clasts can be transported to the most distant parts of the deposit. These pyroclastic flows may be laterally ejected from around the base of a dome or may result from the collapse of an eruptive column which can reach as high as 20 to 50 km, as indicated in the sketches below.



Pyroclastic flow deposits

Pyroclastic surge deposits
These are usually thin, fine-grained deposits which also originate by a flow mechanism, but here the flows are of low density being expanded and gas rich. Surges, rather than the more destructive pyroclastic flows, destroyed the city of St. Pierre and other villages in the 1902 eruption of Mt. Pelée, Martinique.

There are many different types of deposit which can be fitted into the above three groups. The different types were mapped and identified during this study but are not included in this summary. Hazard maps for each type of activity are included in the main report.

6. Age dating and stratigraphic study reveal that the last activity on Saba was the deposition of a thin ash surge layer on the area of The Bottom village. This ash layer overlies Amerindian archeological levels and immediately underlies the first European levels. It must have been erupted shortly before the first Europeans settled the island and has been radiocarbon dated at around 1600 A.D. On St. Eustatius the youngest deposits of the Quill are very well exposed, and have been radiocarbon dated at 1550±35 years B.P. or 400 A.D. (B.P. means years before present, which is taken at 1950).

7. The Quill and Saba island are both volcanoes capable of a variety of different types of pyroclastic activity. The nature and relative frequencies have been estimated in this report from the frequency of deposits identified in measured stratigraphic sections. The main hazard on Saba is from pyroclastic flows of a particular type known as Pelean-type nuées ardentes, which are named after the type example of the 1902 eruption of Mt. Pelée, Martinique. Such eruptions usually last 2-4 years and produce a lava dome. Each of the many round hills on Saba is a Pelean dome. As Saba is essentially a single volcanic cone with submarine flanks the hazard from all volcanic activity is island wide.

On St. Eustatius the last activity was pyroclastic flows and surges but of a different type to those presenting a hazard on Saba. The last St. Eustatius pyroclastic flows were like those erupted from St. Vincent in 1902 and 1979. These are produced by column collapse from open crater eruptions. As the last events have been radiocarbon dated at 1550±35years B.P., the hazard is probably still significant. The older dated deposits of St. Eustatius give a rough estimate of the frequency of the Quill as around one event per 200-300 years.

8. It is concluded that a pyroclastic hazard exists on both Saba and on St. Eustatius. This hazard is no greater than on other islands of the Active Volcanic Arc.

The following recommendations are made:

a. Having completed this detailed study so that the information on hazard is now available, we feel it is the responsibility of the Netherlands Antilles Government to have available evacuation plans and funds for the small populations of these islands (totalling around 2,600 persons) should they ever be required at short notice. On both islands the main access today is by aircraft and there are few boats on the islands. In the event of renewed activity, airstrips are vulnerable to earth tremor and burial by pyroclastic debris so that in the event of future activity any delay in evacuation may result in the necessity to use boats. Probably St. Maarten is the best location for evacuees. Saba is the most hazardous island being a simple cone; on St. Eustatius a short term evacuation to the extinct and hilly north end of the island would be possible.

b. Volcanic observation of the islands could be improved perhaps in coordination with the Seismic Research Unit in Trinidad or the volcanologic observatories in Martinique and Guadeloupe. Also the temperature of the hot springs on Saba could be measured monthly or every 2-3 months by the staff of the Administrator's Office. The temperature of these springs should increase prior to any future activity.

c. The Administrators' Offices on both islands should have lists of geologists trained on Caribbean or Caribbean-type volcanoes who could travel to either island at short notice in the event of an opinion being needed on renewed activity. As renewed activity might first occur as a heating up of springs or local steam escape, we believe the best records of change might be noted by the small populations of each island if they were made aware of the need for this type of reporting.

d. We do not agree with the withholding of such information from the island populations who were pleased to meet us and to learn that an interest was being taken in their islands, especially in the light of the recent activity in St. Vincent, Guadeloupe, Mt. St. Helens (U.S.A.), and Montserrat.

Table 1 Subaerial historic activity of the volcanoes of the Lesser Antilles

Date	Volcano	Type of volcanic activity#
1680	Soufrière, Guadeloupe	Phreatic
1692?	Mt. Liamuiga**, St. Kitts	Phreatic
1696	Soufrière, Guadeloupe	Phreatic
1718	Soufriere, St. Vincent	St. Vincent-style
1766	Qualibou, St. Lucia	Phreatic/Phreatomagmatic
1784	Soufriere, St. Vincent	Dome
1792	Mt. Pelée, Martinique	Phreatic
1797	Soufrière, Guadeloupe	Phreatomagmatic
1798-99	Soufrière, Guadeloupe	Pelean-style
1809	Soufrière, Guadeloupe	Phreatomagmatic
1812*	Soufriere, St. Vincent	St. Vincent-style
1837	Soufrière, Guadeloupe	Phreatic
1843?	Mt. Liamuiga**, St. Kitts	Phreatic
1843	Soufrière, Guadeloupe	Phreatic/Phreatomagmatic
1851	Mt. Pelée, Martinique	Phreatomagmatic
1880	Valley of Desolation	Phreatic
1880?	Soufriere, St. Vincent	Dome
1897-98	Soufriere Peak, Montserrat	Volcano-seismic crisis
1902-03*	Soufriere, St. Vincent	St. Vincent-style
1902-05*	Mt. Pelée, Martinique	Pelean-style
1903	Soufrière, Guadeloupe	Phreatic
1929-32	Mt. Pelée, Martinique	Pelean-style
1933-36	Soufriere Peak, Montserrat	Volcano-seismic crisis
1950	Nevis Peak, Nevis	Volcano-seismic crisis
1956	Soufrière, Guadeloupe	Phreatic
1961-62	Nevis Peak, Nevis	Volcano-seismic crisis
1962	Soufrière, Guadeloupe	Volcano-seismic crisis
1966-67	Soufriere Peak, Montserrat	Volcano-seismic crisis
1971-72	Soufriere, St. Vincent	Dome
1976	Micotrin, Dominica	Volcano-seismic crisis
1976-77	Soufrière, Guadeloupe	Phreatic
1979	Soufriere, St. Vincent	Phreatomagmatic/Dome
1986	Morne Patates, Dominica	Volcano-seismic
1988	Mt. Liamuiga**, St. Kitts	Volcano-seismic
1990	St. Lucia	Volcano-seismic
1995	Soufriere Hills, Montserrat	Phreatic/Dome

Data from Robson and Tomblin (1964) and monthly Bulletin of Global Volcanism Network.

See glossary of terms - Appendix B
* Denotes loss of life
** Formerly Mt. Misery

1 General information

1.1 Introduction

From a volcanological standpoint, the islands of the Lesser Antilles may be divided into two groups: the Windward Islands or Limestones Caribbees; and the Leeward Islands or Volcanic Caribbees (Martin-Kaye, 1969). The former from Sombrero in the north, through Dog, Anguilla, St. Maarten, St. Barts, Barbuda, Antigua to Grande Terre of Guadeloupe represent a long extinct limestone-capped pre-Miocene volcanic arc without any present day volcanic hazard. The Volcanic Caribbees or Active Arc extend from Saba and St. Eustatius through the islands of St. Kitts, Nevis, Montserrat, Basse Terre of Guadeloupe, Dominica, Martinique, St. Lucia, and St. Vincent to Grenada. These islands make up the present day active volcanic arc and the volcanoes on them are all potentially dangerous. Since the permanent arrival of Europeans in the region, around the middle of the 17th century, there have been a total of 36 eruptive episodes, or reported eruptions of which at least 3 have caused loss of life (Table 1). Most of these eruptions, as can be seen from Table 1, have occurred on three volcanoes, Soufrière in Guadeloupe, Mt. Pelée in Martinique and Soufriere in St. Vincent. However this does not mean that the other volcanic centers are dead, because there are many examples in the geologic literature of volcanoes erupting after more than a 1000 years of dormancy. Thus the widespread belief that there is no volcanic hazard on the islands of Saba (European settlement around 1640) and St. Eustatius (European settlement 1636) is without foundation. In addition to actual eruptions, a number of the volcanic centers in the Lesser Antilles have been subjected to local earthquake swarms associated with the rise of magma high into the volcanic edifice but without any actual eruption (Table 1). Such a phenomenon is called a volcano-seismic crisis.

In the following sections a discussion of the geology and volcanic history of Saba and St. Eustatius is presented together with an assessment of the potential volcanic hazard for each island.

1.2 Previous work

The geology, petrology and chemistry of Saba and St. Eustatius have been described in great detail by Westermann and Kiel (1961). This first report produced geologic maps, cross-sections, much detailed mineralogy and petrography of the lavas and some chemistry. During the last decade and long after the 1961 report, the subject of pyroclastic stratigraphy was introduced into the Lesser Antilles by a number of workers. The first measurements of stratigraphic sections identifying the different types of pyroclastic deposits in the Netherlands Antilles were made in 1976 during a personally financed research trip by Drs. B. Gunn and M. J. Roobol (University of Montreal) and Dr. A. L. Smith (University of Puerto Rico) aboard the ketch Pelorus Jack. Field work on St. Eustatius (B. G., M. J. R. and A. L. S.) was carried out between January 21-24th, 1976, when three sections were measured and 64 samples of pyroclastic material were collected, and taken to the University of Puerto Rico for analysis. Similar preliminary work was carried out on the pyroclastic deposits of Saba (B. G. and M. J. R.) from February 3-6th, 1976. The conclusions of this preliminary work were that on both islands the main type of activity was pyroclastic. Although no carbonized wood was found suitable for C^{14} dating the abundance of fresh and unconsolidated pyroclastic deposits indicated activity in the period shortly before European settlement. The presence of the hot springs on Saba indicated that this island was still active, retaining at least hot rocks and that the heat escape was not due to reactions of the sulfur minerals as widely believed on the island. The possibility therefore exists that the near 350 year period of inactivity does not indicate extinction of the volcanoes but rather, infrequent eruptions and that a considerable time has passed since the last activity. A letter concerning these points and requesting whether Dutch geologists were available to carry out a modern pyroclastic hazard study was sent from the University of Puerto Rico in March 1976 by Roobol to the Director of the Netherlands Geological Survey. At the same time the letter was copied and circulated in the International Geodynamics Project Working Group for Caribbean Studies - Recent and Ancient Volcanic Activity Newsletter. This generated a number of replies including one from the Director of the Netherlands Geological Survey in which the carrying out of adequate investigations was recommended but that there were no young Dutch volcanologists to do so. Another letter from Dr. Westermann suggested that there was no volcanic hazard. The matter was subsequently referred to UNESCO through the Government of the Netherlands Antilles. As a result the islands were visited by Drs. E.M. Fournier d'Albe of UNESCO and J.F. Tomblin of the Seismic Research Unit of the University of the West Indies, Trinidad between March 21-25, 1977. This visit led to the UNESCO restricted technical report 'Volcanic risk and monitoring on the islands of Saba and St. Eustatius' (Fournier dÁlbe and Tomblin, 1977). The report concluded that there was 'a small but not negligible risk of a new eruption occurring at any time on either island' and went on to suggest a study of the pyroclastic deposits, geophysical monitoring and the preparation of evacuation plans.

Further study of the pyroclastic deposits was carried out on both islands in 1978 by Drs. Roobol and Smith supported by a grant from the National Science Foundation with the objective of making a reconnaissance study of the stratigraphy and type of deposits characteristic of the active volcanoes in the active arc. Dr. K. Rowley of the Seismic Research Unit participated in this stage of the work. The studies were made on Saba from 28th July to 2nd August 1978 and on St. Eustatius from 2nd to 5th August 1978.

Following a proposal from Dr. Tomblin of the Seismic Research Unit to the Netherlands Government, funds were made available to carry out a detailed study of the pyroclastic deposits with the purpose of preparing a hazard report. Fieldwork was carried out by Drs. Roobol, Smith and Tomblin on Saba between 19th July and 3rd August 1979 and by Roobol and Smith on St. Eustatius between 3rd and 9th August 1979. Additional fieldwork, supported by the National Science Foundation, was conducted during August 1980 on St. Eustatius (M. J. R. and A. L. S.) and Saba (M. J. R.). This report includes all data collected during the 1976, 1978, 1979 and 1980 studies.

1.3 Methods of study

The active arc of the Lesser Antilles as a whole presents a problem for volcanic hazard studies in having a very short period of recorded history so that many of the different types of pyroclastic deposits found on the various volcanoes have not as yet been observed to form. During the period of European settlement, which at best is only 350 years, many of the islands have no recorded activity, so that it is not possible to consider frequency of activity and whether there is any cyclic sequence of events from the histories alone. Studies on the active volcanoes suggest that pyroclastic activity is the dominant style and that the production of lava flows is secondary. Some volcanoes such as Mt. Pelée, Martinique are made up almost entirely of pyroclastic deposits with only a few domes and dome remnants around the central vent. The Quill on St. Eustatius is another example of an entirely pyroclastic volcano. The method that has to be used to reconstruct the history of a volcano is the measurement of stratigraphic sections and the identification of the different types of deposit. For most volcanoes sufficient stratigraphic sections for this purpose are found in sea cliffs, river gorges, roadcuts and quarries, the one exception to date has been the Peak on Nevis Island which lacked any suitable exposures in 1976. Many of the pyroclastic flow deposits contain carbonized wood suitable for radiometric dating. These dates can sometimes be used to give an estimate of periodicity as well as aid in the correlation of the different stratigraphic sections. Estimates of the area affected by each type of activity can be made by mapping individual types of deposits. Such information can then be used to construct potential hazard maps for the volcanoes. All of the above methods were employed in the study of Saba and St. Eustatius thus making them two of the better studied islands in the Caribbean. Only few other Lesser Antillean volcanoes have received this attention, these are Mt. Liamuiga (formerly Mt. Misery), St. Kitts (Baker, 1969; Baker and Holland, 1973; Baker, 1980), Soufriere, St. Vincent (Hay, 1959; Rowley, 1978) and Mt. Pelée, Martinique (Roobol and Smith, 1976; Westercamp, D., 1983; Smith and Roobol, 1990).

1.4 Classification and terminology of the pyroclastic deposits of Saba and St. Eustatius

There are three main types of pyroclastic deposits each produced by a different mechanism of formation or transport and each with distinct physical characteristics. These are pyroclastic fall, flow and surge deposits, which are next considered separately.

1.4.1 Pyroclastic fall deposits

These are produced when material is explosively ejected from the vent into the atmosphere producing an eruption column. Each pyroclast behaves independently and falls back under the influence of gravity. The geometry and size of the deposits reflects the eruption column height, and wind velocity and direction (Eaton, 1964; Wilson, 1976). As each clast behaves independently, the resulting deposits are usually internally stratified, individually well sorted and show mantle bedding over underlying topographic irregularities. Clast size and thickness of individual beds decrease away from the central vent. Such deposits usually are found covering all flanks but are generally elongated downwind. These deposits built up by showers of airfall material are generally the least dangerous to human life.

I.4.2 Pyroclastic flow deposits

Pyroclastic flows involve the lateral movement of pyroclasts as a gravity controlled, hot, high concentration gas/solid dispersion. They were first adequately described from the 1902 eruptions of Mt. Pelée, Martinique (LaCroix, 1904) and Soufriere, St. Vincent (Anderson and Flett, 1903). A pyroclastic flow can be seen to be composed of two main parts, an underflow in which the coarsest material travels and an overriding ash cloud which contains material elutriated from the underflow. Pyroclastic flows are topographically controlled in their movement and tend to fill valleys and depressions. They usually only affect narrow sectors of the volcanoes' flanks. The deposits are typically unsorted with large blocks or bombs contained in an ashy matrix. The ash cloud covers a much wider sector of the volcano giving rise to ash-cloud surge deposits and vitric airfall ashes. The ash clouds can become separated and move independently of their associated pyroclastic flows. A fuller account of these deposits and their formation is given by Smith and Roobol (1982). Pyroclastic flows represent extreme danger to both life and property.

1.4.3 Pyroclastic surge deposits

Surges involve the lateral movement of pyroclasts as expanded, turbulent, low-concentration gas/solid dispersions. Deposits mantle the topography but tend to accumulate thickest in depressions. Characteristically they are thin, usually less than 1m thick and often pinch and swell in thickness. They are generally fine grained but occasionally can be relatively coarse grained (Fisher et al., 1980). Characteristically they show unidirectional sedimentary bed forms (cross-stratification, dunes, antidunes and planar lamination). There are three main types of surges: a) base surges, b) groundsurges and c) ash-cloud surges. Base surges are the result of phreatic of phreatomagmatic eruptions. Groundsurges are formed either directly from the crater or from a collapsing eruptive column and may precede a pyroclastic flow. Ash cloud surges have been mentioned above. Surges can also be subdivided on the basis of composition and type of associated pyroclastic flow. These represent the greatest volcanic hazard in the Lesser Antilles. It was ash-cloud surges that destroyed St. Pierre, Martinique, on May 8th, 1902, and a groundsurge that destroyed Morne Rouge, Martinique, on August 30th, 1902. Surge deposits are, nonetheless, far less conspicuous and unimpressive in appearance when compared to pyroclastic flow deposits.

The classification of the pyroclastic deposits used in our work in the Netherlands Antilles represents an extension of an earlier one developed by Roobol and Smith (1976) for Mt. Pelée, Martinique. All of the above types of pyroclastic deposits are found on Saba and St. Eustatius and these can be subdivided into four main lithological types. These are:

a. A coarsely vesicular black basaltic andesite (density range 1.3 to 1.7 gm/cm^3.)
b. A dense grey andesite (density range 2.1 to 2.4 gm/cm^3)
c. A semi-vesicular grey andesite (density range 1.1 to 1.4 gm/cm^3)
d. A highly vesicular white andesite to rhyolitic pumice (density range 0.7 to 1.1 gm/cm^3)

Table 2 Classification of pyroclastic deposits in the Netherlands Antilles

Lithology	Pyroclastic flow/*deposit*	Pyroclastic surge/*deposit*	Airfall deposit	Type of eruption
Black scoria (basaltic andesite)	Scoria flow, e.g. St. Vincent, 1902, 1979/ *Scoria and ash deposit*	Scoriaceous ash-cloud & groundsurge, e.g. St. Vincent, 1902, 1979/ *Scoriaceous surge deposit*	Scoriaceous airfall { lapilli, ash }	**St. Vincent**
Dense grey andesite	Nuée ardente (block and ash flow), e.g. Mt. Pelée, 1902, 1929/ *Block and ash deposit*	Dense andesite ash-cloud and groundsurge (minor), e.g. Mt. Pelée, 1902, 1929/ *Dense andesite surge deposit*	nd*	**Pelean**
Semi-vesicular andesite	Semi-vesicular andesite block and ash flow/ *Semi-vesicular andesite block and ash deposit*	nd*	nd*	**Asama**
White pumice and ash	Pumice and ash flow/ *Pumice and ash flow deposit*	Pumiceous ash-cloud and groundsurge/ *Pumice-ash surge deposit*	Pumiceous airfall { lapilli, ash }	**Plinian**

nd* No deposits of this type have yet been found in the Netherlands Antilles

The full classification of pyroclastic deposits for the Netherlands Antilles is obtained by combining the above variants and is presented in Table 2. It can be seen from Table 2 that for the whole of the active arc for the time period of European settlement (350 years), that only three of the above types have been observed to form.

In addition to the various types of deposit something should be said about the characteristics of the various types of eruption that produced these deposits. A brief summary of the characteristics of the different types of eruption that have occurred or have been inferred to have occurred on Caribbean volcanoes is given below:

Phreatic/phreatomagmatic
Eruptions in which no fresh magma is discharged so that the clasts are fragments of older solid rock. Such activity is termed phreatic and a good example was observed at Soufrière, Guadeloupe in 1976. They may be caused by near-surface magma/groundwater interaction. If the eruption brings about a discharge of fresh magmatic ejecta along with older solid debris, the eruptions are called phreatomagmatic. Phreatomagmatic eruptions can also be caused by the contact of magma with sea or lake water e.g. Soufriere, St. Vincent 1979. Such eruptions can produce a wide variety of products - airfall deposits, pyroclastic flows and surges (base, ground and ash-cloud-types) and can range in intensity from weak to extremely powerful.

St. Vincent
These are vertical eruptions of magmatic materials from an open crater where the eruptive column collapses to produce pyroclastic flows (scoria flows) and groundsurges. The type example is Soufriere, St. Vincent 1902-03 (Roobol and Smith, 1975). Deposits produced by such eruptions include airfall lapilli and ash beds, scoria and ash flow deposits and scoriaceous surge deposits. Flows and surges can affect most of the volcano's flanks or only a restricted sector depending on local conditions.

Plinian
These are vertical eruptions of a gas-rich magma from an open crater, the type example was the eruption of Vesuvius in 79 AD. Such eruptions often show a sequence of events beginning with the formation of airfall deposits followed by groundsurges, then pyroclastic flows (with associated ash-cloud surges) and sometime the extrusion of lava flows. Thick sequences of pyroclastic fall deposits are often produced especially near the crater. The pyroclastic flows and surges are very mobile and can affect most sectors of the volcano and also travel for long distances even over topography showing considerable relief.

Pelean
These eruptions are dominated by the generation of pyroclastic flows and surges produced by the explosive or gravitational collapse of an actively growing dome or lava flow. The best known example is Mt. Pelée, Martinique 1902. Some explosions, especially when the dome is small may be vertical producing thin airfall deposits and groundsurges as well as pyroclastic flows. As the dome grows larger many of the later pyroclastic flows are caused by low-angle blasts. The products of most eruptions tend to be concentrated in narrow sectors of a volcano's flanks with the coarser grained deposits being confined to topographic depressions. The associated surges however can affect much wider areas.

Asama
These eruptions and the deposits they produce are transitional between those of Pelean- and Plinian type. The type example is the 1789 eruption of Asama, Japan. The eruptions occur from open craters and the initial phases may be airfall. The dominant products are however pyroclastic flows that 'foam' over the crater rim and move downslope under gravity.

Associated with all these eruptions is the possibility of the generation of mudflows e.g. Soufriere, St. Vincent 1902 and 1979; Mt. Pelée, Martinique 1902; Soufrière, Guadeloupe 1976.

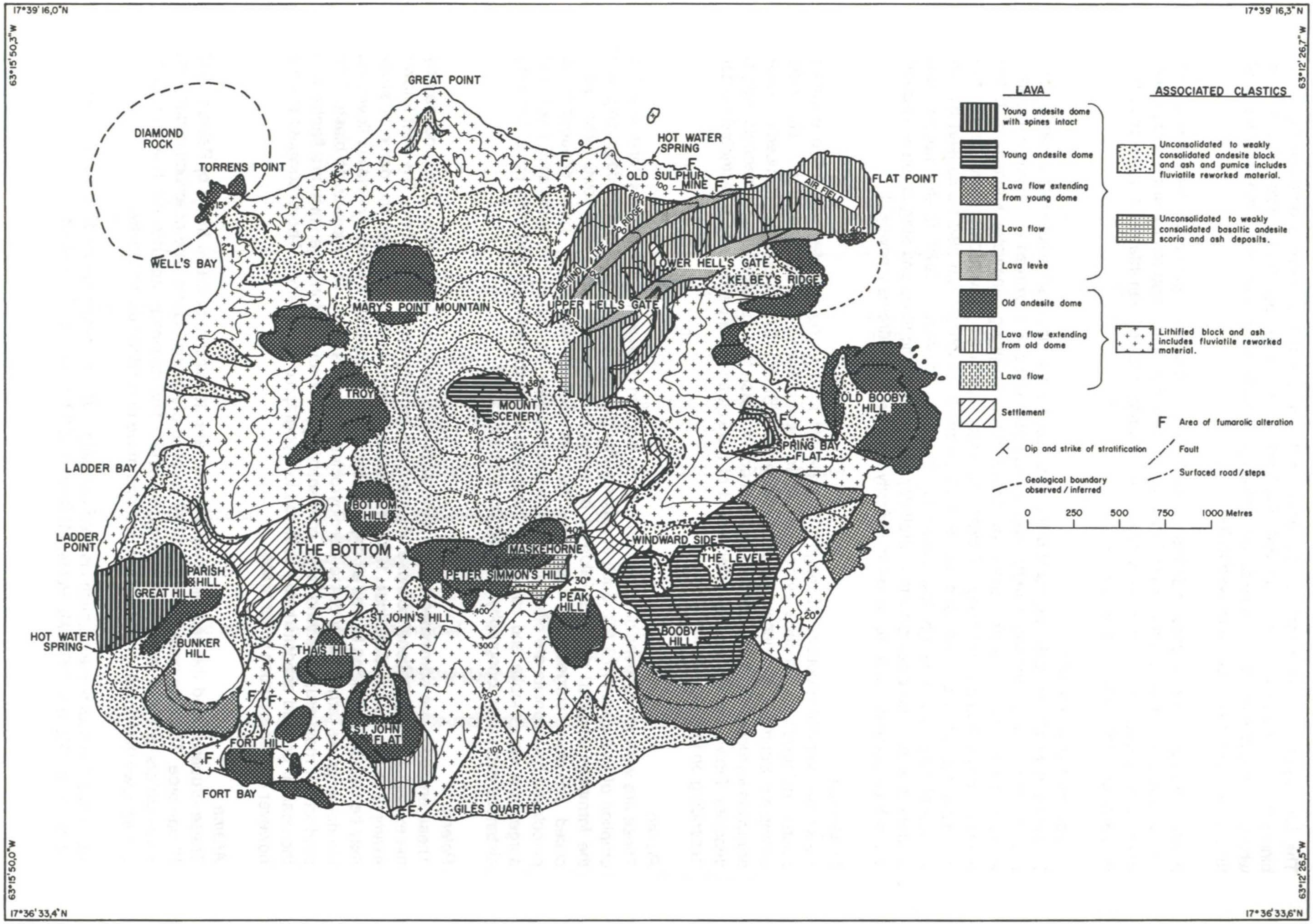


Figure 1. Geological map of Saba.

2 Saba Island

2.1 Geological map

A new geologic map (Figure 1) was prepared with the aim of better subdividing the stratigraphy of the island and in particular to identify the youngest centers. The major drawback to stratigraphic studies on Saba is the general paucity of carbonized wood within the pyroclastic deposits compared to other Caribbean volcanoes. The main reason for this is that wood when caught up in a pyroclastic flow is carried downslope and is thus most commonly found in the nearly flat-lying outer flank deposits. For Saba island these lower flanks lie below sea level.

In the absence of this important correlative tool the deposits of the island have been divided into two major units. A younger sequence of unlithified and weakly lithified deposits and an older sequence of lithified deposits in which the pyroclastic texture is still well preserved. On Mt. Pelée, one of the better studied Lesser Antillean volcanoes where more than 50 radiocarbon dates have been obtained, the lithified rocks are known to be somewhat older than the limits of the radiocarbon dating method (Roobol and Smith, 1976). Thus by analogy with Mt. Pelée it is suggested that the age of the boundary between the two sequences mapped on Saba is around 70,000 years.[1]

The many andesite domes on the island were also grouped by age according to the state of lithification of their associated pyroclastic deposits which form aprons around the domes. The relationship between dome growth and the simultaneous formation of nuées ardentes is well described in the accounts of the 1902 and 1929 eruptions of Mt. Pelée, Martinique (LaCroix, 1904; Perret, 1937). The dome of Great Hill immediately west of The Bottom village is conspicuous and unique for the island, as it still retains its original spines (Westermann and Kiel, 1961, Plate 11). This is considered to be the youngest dome on the island as far as the vegetation cover permitted inspection. This dome is partially dissected in the steep sea cliffs to the west.

By far the oldest center exposed on the island is that of Torrens Point, where the succession dips inland towards the south-east indicating that almost all of the center has been removed by erosion. Diamond Rock was sampled and found to be a remnant of an andesite dome petrographically very similar to the remnant at Torrens Point.

2.2 The stratigraphic sections

The 17 measured stratigraphic sections and their locations for Saba island are shown and coded in Figures 2 and 3. The degree of correlation between the different sections is unusually low, owing to the fact that all of Saba is dominated by steep slopes and the pyroclastic deposits, especially the younger ones, are only present as small patches. Also many of the deposits have been reworked by movement downslope. The rather fragmentary picture presented by the sections does however permit the calculation of the approximate relative abundances of the different types of deposit and therefore the different styles of volcanic activity (Table 3). For the calculation of the relative abundances of deposits, one deposit was added which is not shown on the stratigraphic columns. This was a solitary isolated outcrop of a pumice flow deposit found in the gut just downstream of locality V. Beds of identical lithology probably formed during one eruption (bracketed in the stratigraphic columns) are counted as a single unit. No correction was made for repetitions of beds in different sections so that the airfall beds, in particular, are over-represented. Nonetheless the figures obtained confirm the field observations as well as the data on the map (Fig. 1). By far the most common types of eruption of Saba (about 8 out of 10)

[1] During the course of the field work an attempt was made to subdivide the stratigraphy into a three-fold division of lithified, weakly lithified and unlithified deposits. The three fold division was abandoned when it was found that young pyroclastic flow deposits high on the volcano at the level of Windward Side village or higher, were weakly lithified whereas the downslope extension of these deposits, near sea-level, were unlithified. The different rates of lithification (due to the breakdown of volcanic glass) are due to the higher rainfall and dense vegetation on the upper slopes which assist devitrification.

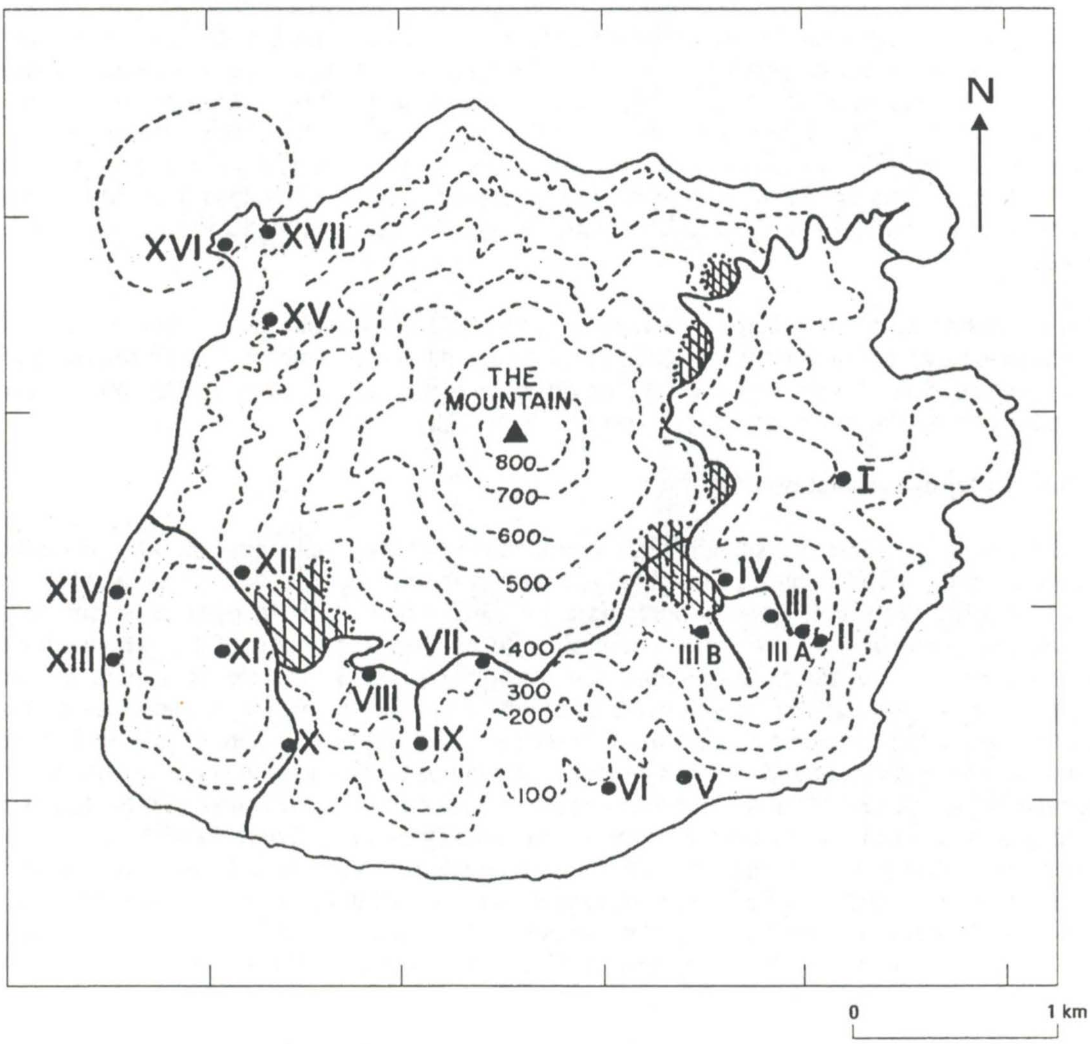


Figure 2 Saba. Locations of stratigraphic sections.

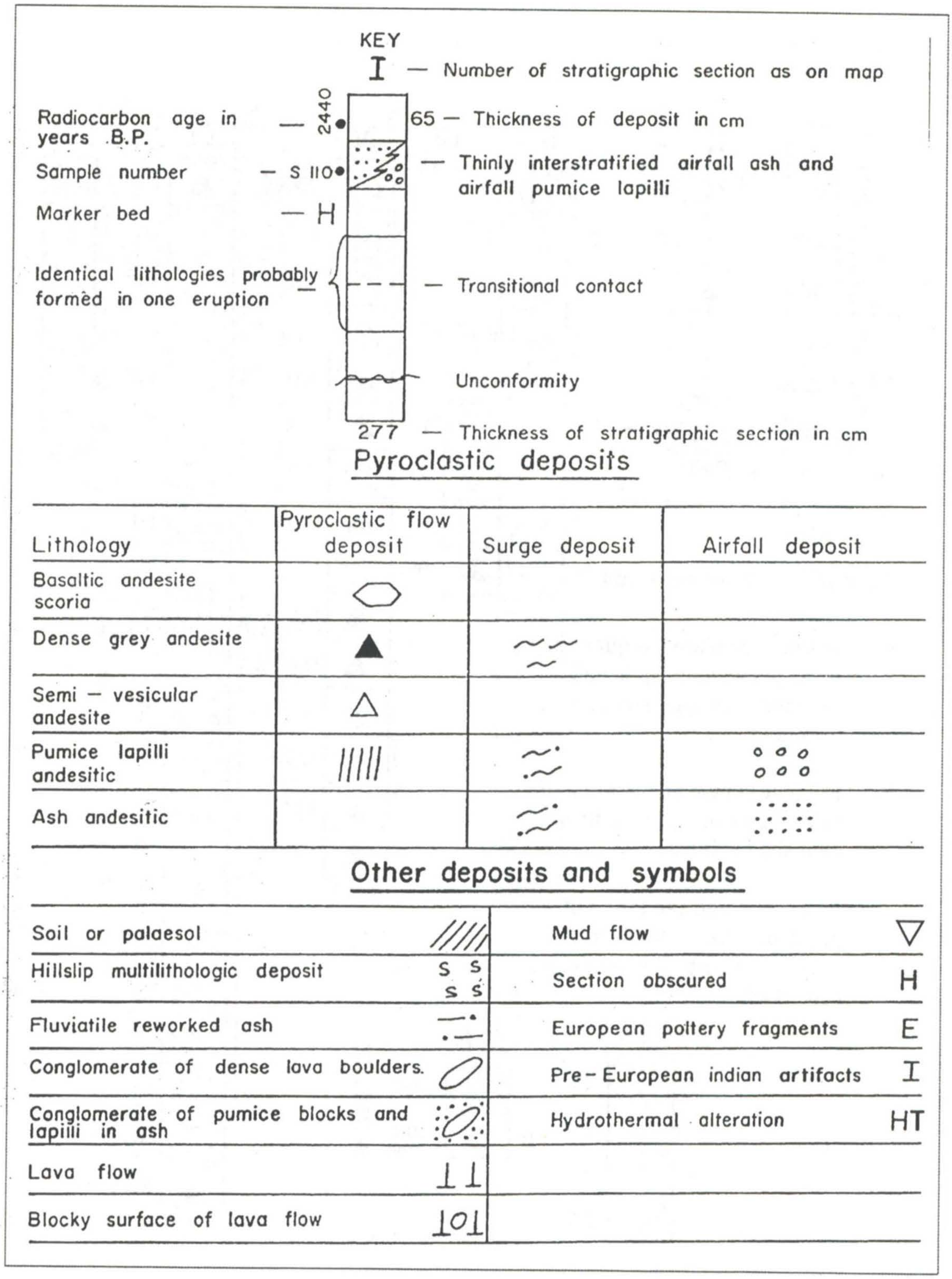


Figure 3 Saba. Stratigraphic sections.

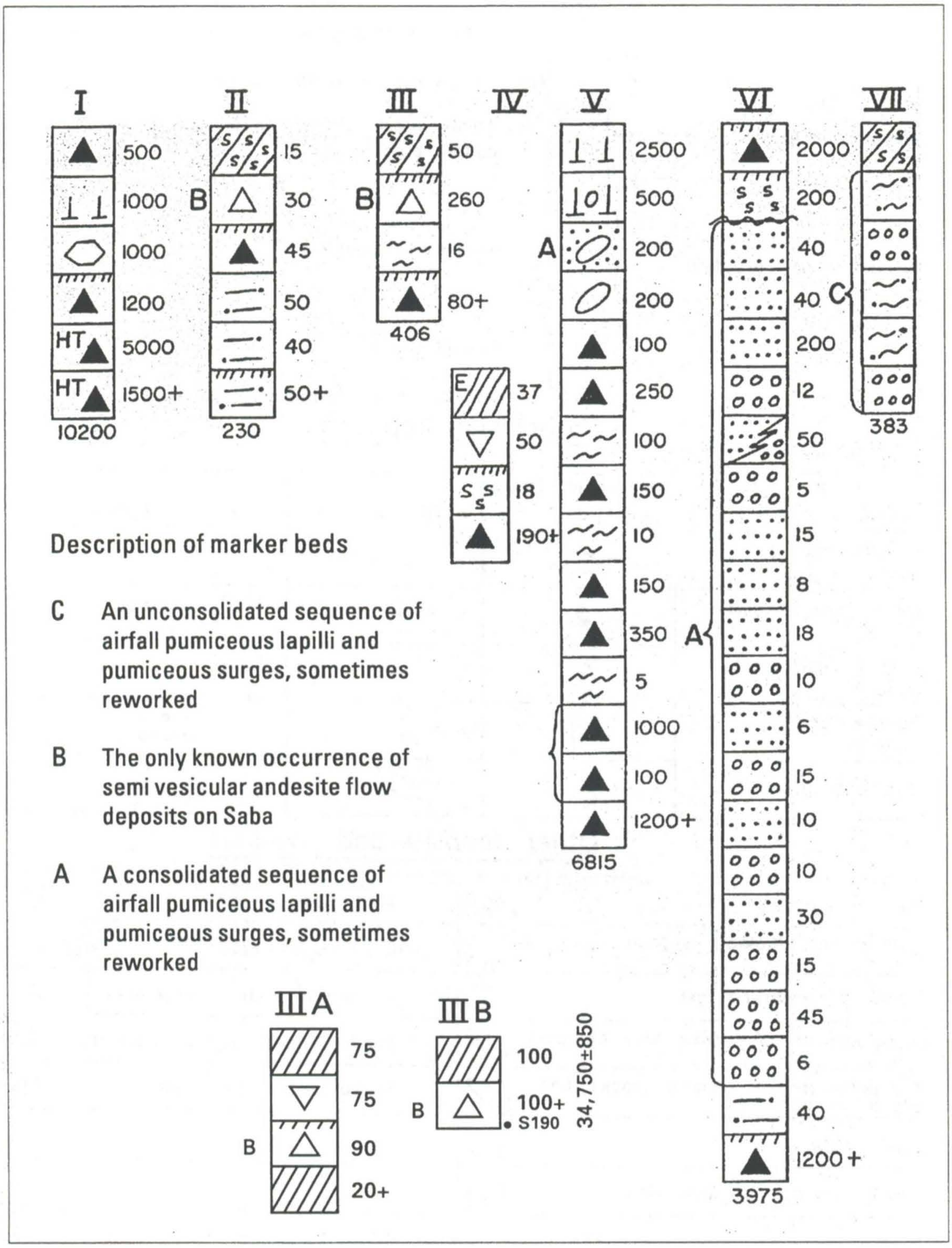


Figure 3 Saba. Stratigraphic sections (continued).

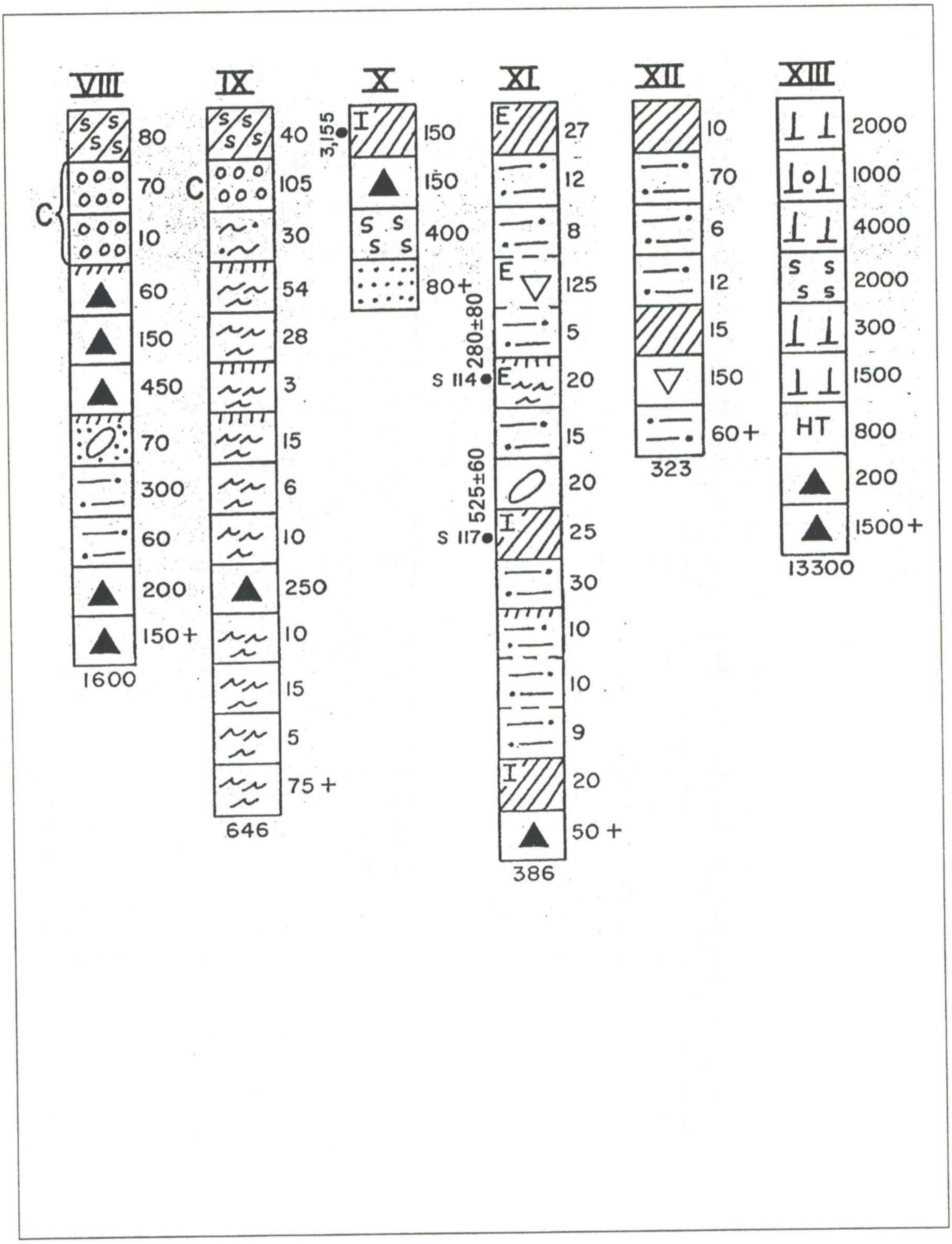


Figure 3 Saba. Stratigraphic sections (continued).

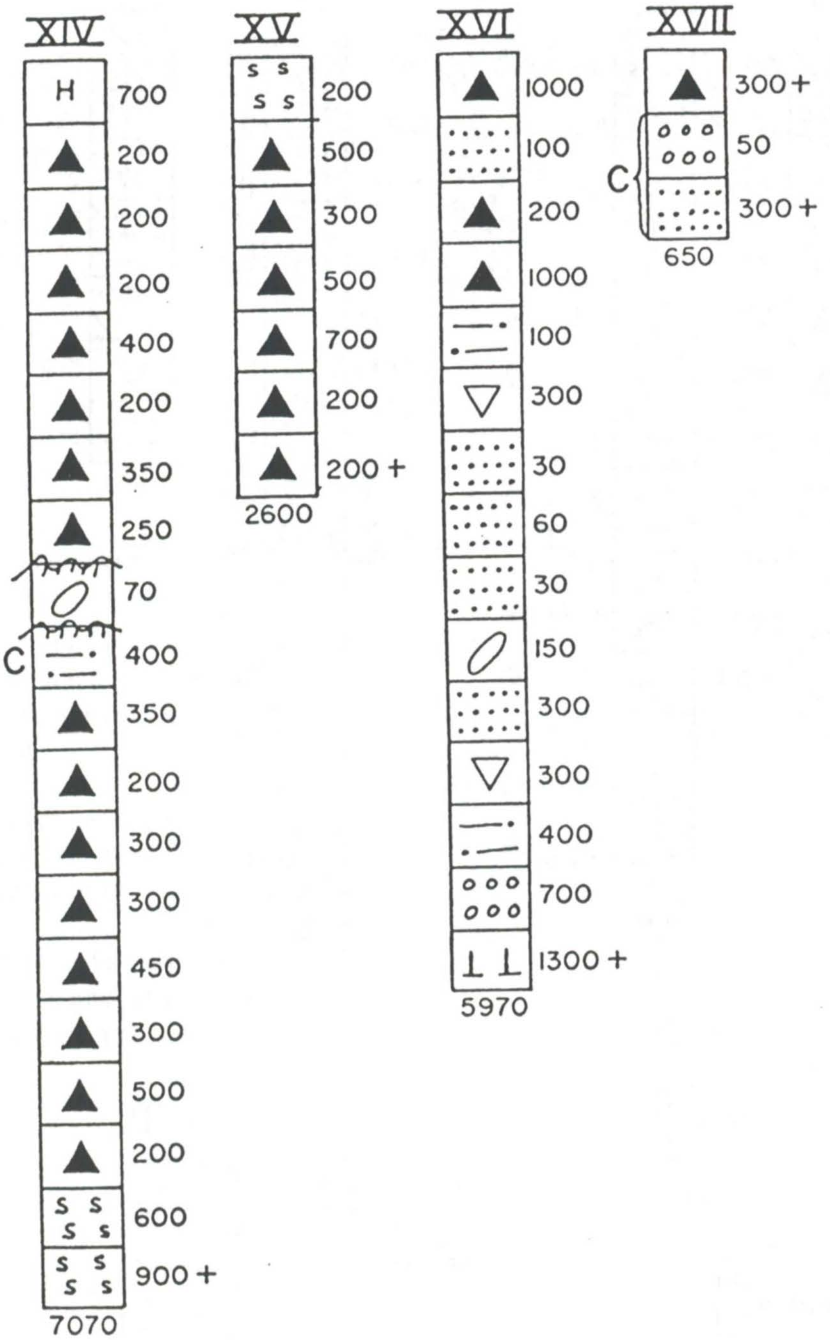


Figure 3 Saba. Stratigraphic sections (continued).

were Pelean-type with the generation of nuées ardentes producing block and ash and dense andesite surge deposits. All other types are uncommon, so that the other seven types of volcanic activity which have occurred on Saba contribute only a total of about one fifth of the frequency of activity. Thus Saba can be regarded as mainly a complex of Pelean domes and associated pyroclastic flow deposits. In this respect it is quite different to the Quill of St. Eustatius. Complexes of Pelean domes and associated pyroclastic deposits also occur in other parts of the Lesser Antilles e.g. Soufriere Hills, Montserrat (Rea, 1974) and the Pitons of Carbet center, Martinique (Westercamp, 1974).

2.3 Age of the deposits

One of the objectives of the present work was to establish the age of the deposits exposed on the island. The youngest pyroclastic deposit is a thin possible andesite surge 20 cm thick which is rich in accretionary lapilli up to 2 mm in diameter. The deposit represents phreatomagmatic pyroclastic activity. The presence of accretionary lapilli are taken to indicate that the surge was 'wet' (R.V. Fisher, pers. comm. 1979). The appropriate stratigraphic section is labeled XI in Figure 3 and is shown in more detail in Figure 4. The locality is within The Bottom village in the grounds of the new hospital building under construction in 1979. A similar section was measured 100m due west in 1976 and is numbered XII. This section was measured in a pit dug for the foundations of the Peter Elenor Hassel Home which was under construction at that date. A map showing the detailed location of these two sections is shown in Figure 5. Section XI was exposed in a cistern pit 2 m deep which was deepened, by hiring two local men (Ellis Sagers and Marcus Collins), to a final depth of almost 4m. Deeper penetration was impossible because of the presence of large blocks of andesite contained in the block and ash deposit encountered at the bottom. The surge deposit, which represents the last activity on Saba for which there is evidence, is partly converted to a soil which contains sparse European pottery fragments. Carbonized wood from the surge yielded an age of 280±80 years B.P. This charcoal is probably natural as it was evenly scattered throughout the surge deposit in small fragments, although the young age does not rule out the possibility that it is man made. Below this level are two paleosol horizons containing Amerindian pottery fragments, the upper one of which contained charcoal fragments which gave an age of 525±60 years B.P. The age of this last event is therefore post 1425 A.D. and probably occurred immediately prior to the European settlement in 1640 A.D. (All archeological material although sparse was submitted to Dr. Christopher Goodwin of the Smithsonian Museum). The areal extent of this surge could not have been very large as immediately down-gully from The Bottom village is a flat area immediately behind Fort Hill crossed by the concrete road to Fort Bay. There the top-soil overlies a very young, fine grained block and ash deposit about 150 cm thick (Figure 3, Column X). Amerindian conch shell tools from the top-soil were radiocarbon dated at 3,155±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).

Another young unconsolidated block and ash deposit was found in a pit dug in Windward Side village (Section IV, Figure 3), the location of which is given in Figure 6. Although the pit was dug to a depth of approximately 4 m, no carbonized wood was found and this deposit remains undated.

A third charcoal sample was presented to Dr. Smith by Mr. G.A. Seaman. It came from a depth of approximately 3 m in a pit dug in the Level (above Windward Side village). Although the authors did not see the pit, from the clasts brought with the charcoal and the study of nearby pits (Sections IIIA and IIIB), the deposit containing the charcoal is a semi-vesicular grey andesite pyroclastic flow, the age of which is 34,750±850 years B.P.

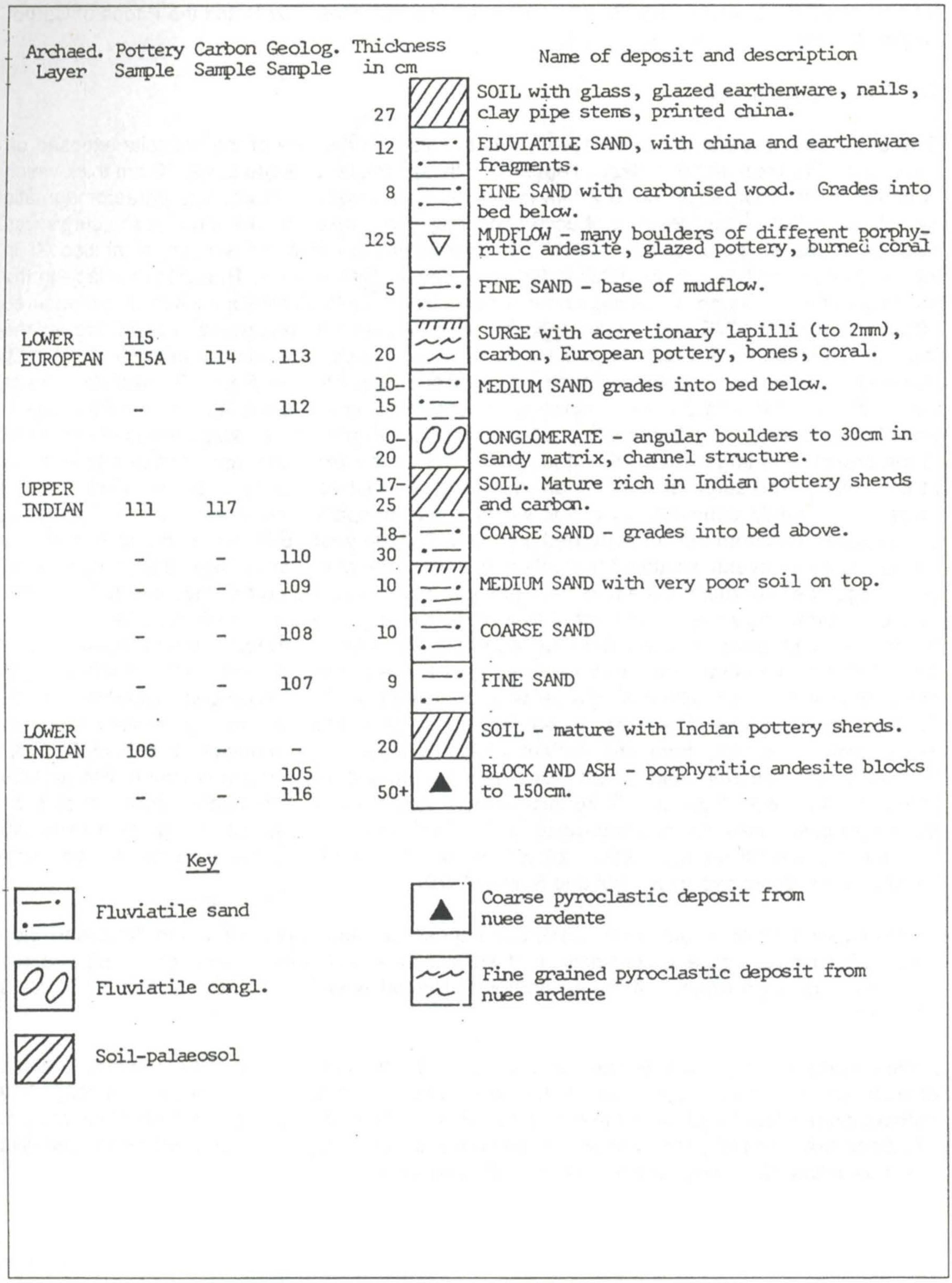


Figure 4 Stratigraphic section in cistern pit for Hospital in The Bottom (Section XI). SA 114 was dated at 280±80 and SA 117 at 525±60 years B.P.

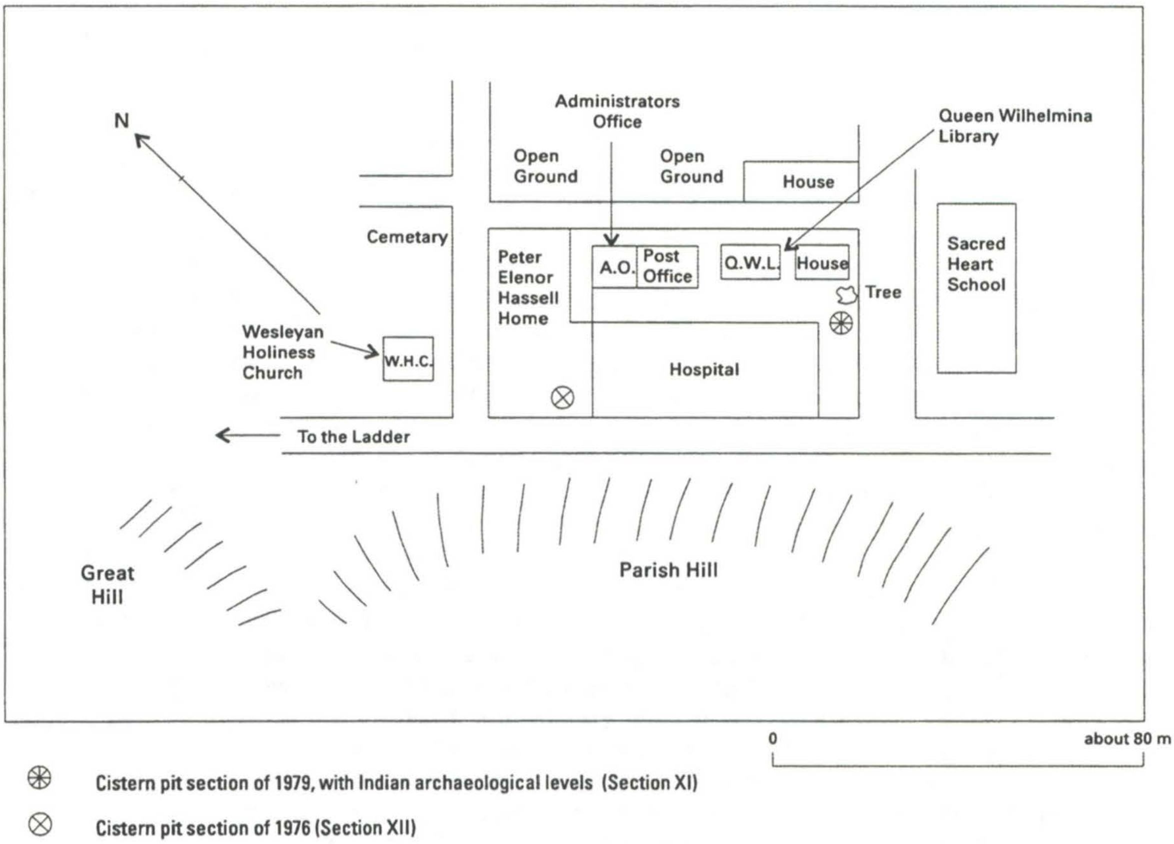


Figure 5 Location map for stratigraphic sections XI and XII in The Bottom (see Figure 4).

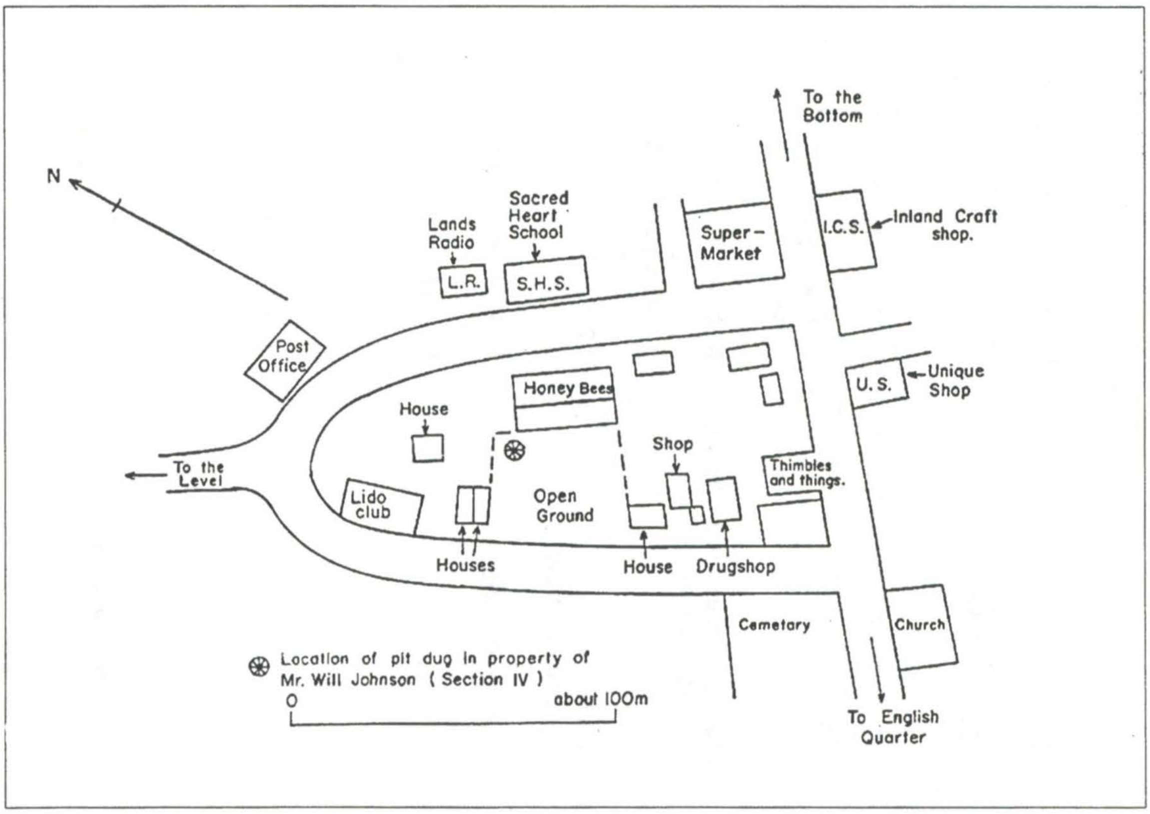
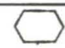


Figure 6 Location map of stratigraphic section IV in Windward Side village.

Table 3 Abundance of the different types of pyroclastic deposits on Saba

Type of activity	Deposit(s)	Symbols used in stratigraphic columns	Number of occurrences		Percentage of occurrences
St. Vincent pyroclastic flow, e.g. St. Vincent 1902	a. Scoria and ash flow		1		1
	b. Scoriaceous airfall lapilli and ash		1		1
Pelean nuées ardentes, e.g. Mt. Pelée 1902	a. Block and ash		51	66	77
	b. Dense andesite surge		15		
Asama-type pyroclastic flow*	Semi-vesicular andesite flow		2		2
Plinian eruption*	a. Pumice and ash		1		
	b. Ash surge		2		
	c. Airfall white pumiceous lapilli		5	16	17
	d. Airfall ash		8		
Total			86		99

* Not witnessed by Europeans in the Lesser Antilles

2.4 Structural evolution of Saba

Superficially Saba has the form of a simple volcanic cone of the classic stratovolcano built up by repeated eruptions from a central vent. A glance at the geology map (Figure 1) however reveals that Saba at the level of around 500m has a pronounced shoulder along which the road runs from St. John's Hill to Upper Hells Gate. Figure 7 is a sketch of Saba from the north-west showing this pronounced shoulder (sketch is from a oblique airphoto shown in the tourist brochure of Saba, 1979). Below this shoulder the island consists essentially of a complex of many old Pelean domes sitting in their lithified aprons of andesitic block and ash deposits. This is essentially the pre-70,000 year part of the volcano. Many of these old centers on Saba are considerably destroyed by erosion which has affected not only the pyroclastic aprons but the massive domes as well. The most deeply dissected domes are those of Torrens Point-Diamond Rock, the two dome remnants at Fort Bay and the dome of Kelbeys Ridge (an isolated remnant survives on the seaward side of the Cove). Above the shoulder is the central cone complex of the Mountain[2] , which was built in the past 70,000 years. The central cone is not just a simple Pelean dome but a small conical volcano with a surrounding pyroclastic apron. At English Quarter the new road being blasted (summer 1979) revealed the presence of a weakly lithified andesite block and ash deposit which represents the pyroclastic apron from one of the morphologically distinct domes on the top of the Mountain. This deposit is immediately underlain by a weakly lithified basaltic andesite scoria and ash deposit which is well exposed in the guts along the road between English Quarter and Upper Hells Gate. Other exposures of this same deposit can be seen in the roadcuts immediately west of Windward Side village towards St. John's Flat and at the west side of the Cove, near the airport, where it is unconsolidated (Figure 1). Also originating from the Mountain are a sequence of white andesite pumice beds (Marker Unit C in the stratigraphic sections). Situated in the north-east of the island are two lava flows which were also erupted from the Mountain. The youngest of these flows originates from the side of the cone above Upper Hells Gate and has pronounced lava levées all along its length. The airstrip is built on the end of this flow.

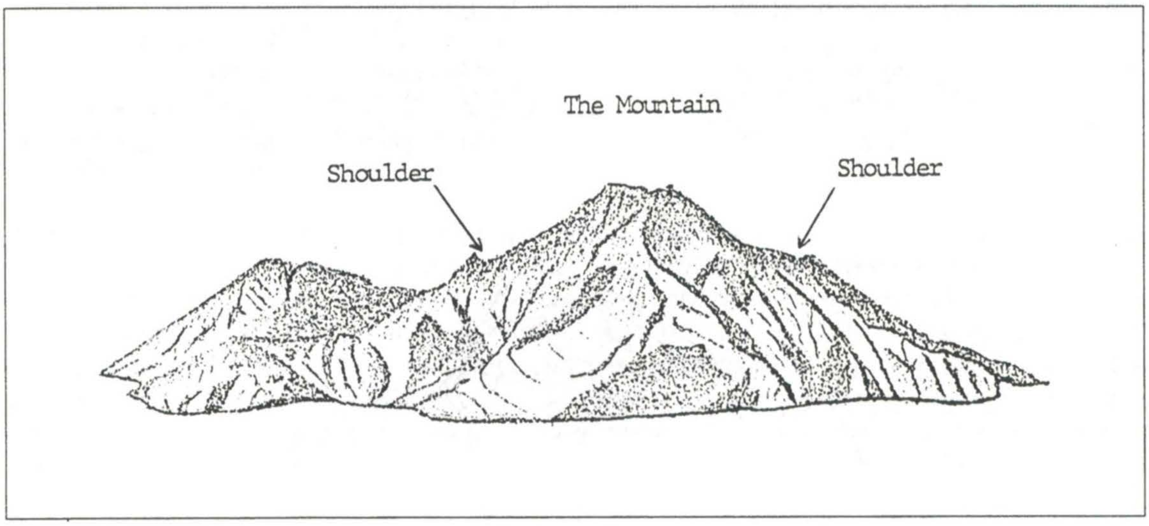


Figure 7 Sketch of Saba illustrating the prominent shoulder referred to in the text.

The distribution of the recent deposits shown in the geologic map (Figure 1) shows that the younger pyroclastic flows from the Mountain 'jumped' the 500 m level shoulder to produce deposits on the coast near sea level. Much of this young unconsolidated material has been eroded from the shoulder which is mainly composed of older lithified material. The Mountain can thus be described as a small central cone which has erupted with many different styles to produce a variety of rock types as well as deposits. Whether such a small central vent existed in the pre-70,000 year stage is unknown as the older central part of the island is now completely

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[2] Lately better known as Mt. Scenery.

buried. However, the presence of a pumiceous airfall deposit within the lithified section of the stratigraphy (section V) would seem to indicate the existence of such a vent.

In the post-70,000 year period a number of flank Pelean domes with associated aprons of andesitic block and ash deposits were erupted. In contrast to the history of the central vent (the Mountain), the formation of a typical Pelean dome is a single event generally lasting only a few years and producing identical lava in both the dome and the surrounding pyroclastic aprons.

The post-70,000 years stage of Saba can thus be summarized as the formation of a small central cone of mixed deposits built on top of an earlier Pelean dome complex. Parasitic or flank eruptions of Pelean type accompanied the formation of the Mountain. The last main eruptive event on the island was probably that which formed Great Hill and the coarse block and ash deposit at the base of the sections dug in The Bottom village This conclusion about the site of the last major event cannot be proven with certainty because of the paucity of carbonized wood in the deposits of the island. Another possible deposit showing characters of extreme youth was found in the pit dug in Windward Side village. A summary of the proposed evolutionary stages of Saba Island based on the geologic map and stratigraphic sections is shown in Figure 8.

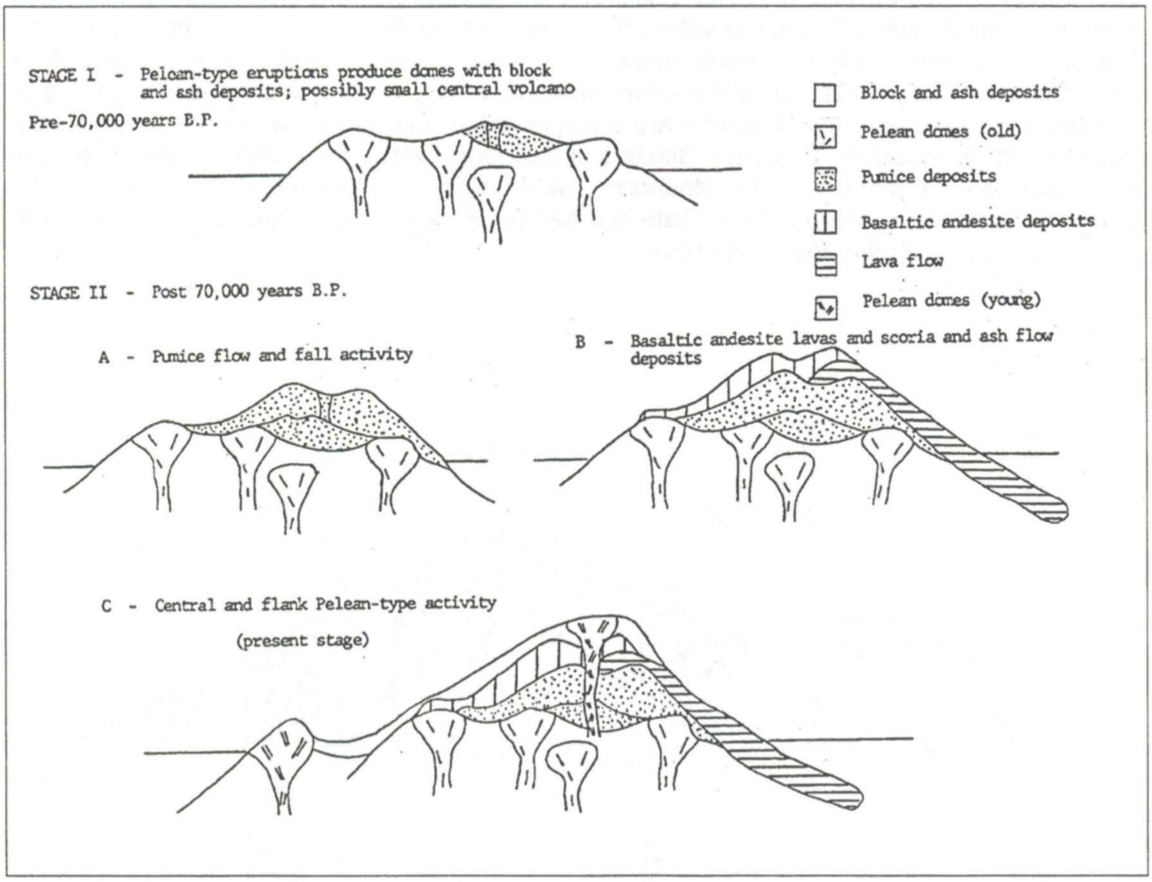

Figure 8 Two stages in the structural evolution of Saba Island. Stage II is characterized by three different types of activity which have been repeated several times.

2.5 The hot springs

The hot springs on Saba are marked on the geologic map (Figure 1). There are two on the island today. Both are at sea level and are just covered by seawater at high tide. One is situated on the south-west coast 900 m south of the Ladder (the stone steps leading down the seacliff from The Bottom village to Ladder Bay). The other is on the northern shore immediately below the abandoned sulfur mine and opposite Green Island. In the past there have been other areas of fumerolic activity as indicated by areas of orange, brown, yellow and green alteration, which have also been marked on the geology map (Figure 1). The most extensive area of fumerolic alteration is immediately below the 'Behind the Ridge' lava flow, where in addition to alteration, native sulfur and other minerals have been deposited in a zone immediately underlying the base of the lava flow. It is in this zone of mineralization that the old sulfur mines are located and where one of the two present day hot springs occurs.

The hot spring on the shore immediately below the old sulfur mines and opposite Green Island was visited (by boat) on the 27th July 1979 at about 09:00 am. At the time (half tide) sand was dug away to reveal wet sand with a maximum temperature of 72°C. Local people report that from time to time steam is seen rising from this site possibly indicating variations in the water temperature. No steam was visible during this visit. The hot spring was not mentioned by Sapper (1903) nor Westermann and Kiel (1961). The reason for this omission is not known as apparently the presence of the spring was known to Westermann.

On 22nd July 1979 the old sulfur mine (some 170m above the previously described hot springs) was visited and entered by the same adit photographed by Westermann and Kiel (1961, Plate 9 b). The adit was tested for heat escape. The outside air temperature in the afternoon was 27.5°C. At distances of 6, 10, 14 and 20 m into the adit from the entrance the inside air temperatures, just below the roof, were 29°, 30°, 31° and 31.5°C, respectively. These results clearly suggest that heat is also escaping from the old sulfur workings.

The hot spring south of the Ladder occurs in rocks which show no signs of fumerolic alteration. The water temperature was measured on 25th July 1979 at 14:15 p.m. at half tide when a maximum temperature of 51°C was found. The same spring was also measured on 27th July 1979 at 10:30 a.m. at high tide when it was awash with waves. By inserting the bulb of the thermometer into the upwelling water a reading of 55°C was obtained. This result indicates that the water temperature had increased since the previous measurement perhaps due to a decrease in the volume of hot water escaping.

A report of hot air blowing out of the ground on the road between Crispin and Windward Side was mentioned by Westermann and Kiel (1961). The locality was shown to us by Mr. Petersen of Windward Side. Air was blowing out of an opening between blocks of a weakly lithified block and ash deposit at a height of about 2m above the concrete road surface. The temperature of the atmosphere (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 the boulders and cools on its way to the outlets, and is not related to fumerolic activity.

Previous reported measurements of the temperatures of the hot springs of Saba refer only to the locality south of the Ladder (Westermann and Kiel, 1961, p. 47) where Sapper (1903) recorded a temperature of 54.2°C. Westermann and Kiel (1961) measured a temperature there on March 15th, 1950 of 55-57°C having dug away the beach material. Other hot springs reported by Sapper (1903) from Well Bay had apparently disappeared by 1939 (Westermann and Kiel, 1961, p. 47).

Table 4 Probability of occurrence of future activity on Saba

Eruptive type	Possible resulting activity	Type of deposit	Symbol in stratigraphic column	Probability of future occurrence
Pelean	Nuée ardente	Block and ash	▲	80%
	Dense andesite surge	Dense andesite surge	~ ~ ~	
	Airfall ash	np*	np*	
St. Vincent	Scoria flow	Scoria and ash	⬡	20%
	Scoriaceous surge	Scoriaceous surge	np*	
	Airfall lapilli (scoriaceous) and ash	Airfall lapilli	• • • • • •	
		Airfall ash	np*	
Plinian	Pumice-ash flow	Pumice and ash	| | | | |	10%
	Pumiceous surge	Pumiceous surge	~ • ~ •	
	Airfall lapilli (pumiceous) and ash	Airfall lapilli	o o o o o o	
		Airfall ash	: : : : :	
Phreatic	Airfall lapilli (lithic) and ash	Lithic lapilli Lithic ash	np* np*	90%
	Base surge	Lithic surge	np*	
	Block flow	Lithic block and ash	np*	
Lava emision	Lava flow Lava dome	Lava flow Dome (accompanying Pelean activity)	⊥ ⊥	<5% 80%

np* Not present in stratigraphic sections

2.6 Volcanic hazard on Saba Island

An active volcano is defined as one having either historic records of activity or present day fumerolic activity and hot springs. Saba can thus be considered an active volcano based on the presence of hot springs on the island. Because of the short period of European history in the Lesser Antilles and the relatively infrequent eruptions of the volcanoes, there are few records of large eruptions. This part of the history of a volcano can only be filled in by stratigraphic studies of the young unconsolidated deposits.

The several different types of volcanic activity inferred from the deposits exposed in the stratigraphic sections around the island each constitutes a separate volcanic hazard. The probability of which type may occur in the future is related to the relative abundances of the different types of deposit. This calculation has already been made in the report (Table 3) but must be modified here to take into account types of activity which do not leave significant deposits but which nevertheless represent a definite volcanic hazard. Thus should activity be renewed on Saba the probability of the generation of the different types of deposits is given in Table 4.

As can be seen from Table 4, the major difference between it and Table 2 (frequency of types of deposits) lies in the high probability of phreatic or steam explosion activity. As can be seen from Table 1, phreatic/phreatomagmatic activity has been the most common eruptive style during the historic period of the Lesser Antilles. The most recent occurrences of phreatic activity were the 1976 eruption of Soufrière, Guadeloupe, and the 1995 eruption of Soufriere Hills, Montserrat. The latest phreatomagmatic activity was the 1979 eruption of Soufriere, St. Vincent. These eruptions although posing a major hazard often do not leave any conspicuous deposits and thus their occurrence can only be guessed.

It should also be pointed out that in the stratigraphic columns only the deposits from the larger eruptions or those preserved through special circumstances are found. It is almost certain that eruptions may occur, which would be hazardous to human occupation of the island, the deposits of which are completely destroyed within a very short period of time. An excellent modern example of this problem is that of the 1979 eruption of Soufriere, St. Vincent. This event caused the evacuation of the whole of the northern part of St. Vincent. The explosive phase of the eruption produced airfall ash deposits and pyroclastic flows and surges. The explosive phase ended on April 17th, by the beginning of August most the deposits had been eroded away. Thus in a few years time there may be no geologic record of the explosive phase of this eruption except for the immediate crater rim.

The hazards from the different types of eruption are next considered individually on the grounds that Saba fits the definition of an active volcano.

2.6.1 Hazard due to Pelean-type activity

From the evidence provided both by the stratigraphic columns and the geological map, this type of activity is by far the greatest potential hazard for Saba. There are two main types of pyroclastic deposit resulting from this type of activity as witnessed by the 1902 eruption of Mt. Pelée, Martinique (LaCroix, 1904; Roobol and Smith, 1975; Fisher et al., 1980). These are nuées ardentes (block and ash flows) and surges (ground and ash-cloud type). The deposits which form from this type of activity are the coarse block and ash deposits (blocks to 6m diameter) deposited from the main part of the flow. Less conspicuous but presenting possibly an even greater hazard are the dense andesite surge deposits. These two types of deposit form the dominant rock type on Saba in both the ancient lithified deposits as well as the youngest non-lithified deposits.

Pelean-type eruptions usually last 2-4 years (Tomblin, 1968) and are accompanied by dome growth. Figure 9 is a map of the island showing the distribution of all mapped Pelean domes. They are roughly divided into age groups on the degree of erosion. This is an approximate division as those on the coast are more rapidly eroded than those exposed inland. It can be seen from the map that the distribution is island wide and it is not possible to predict the site of any future vent area.

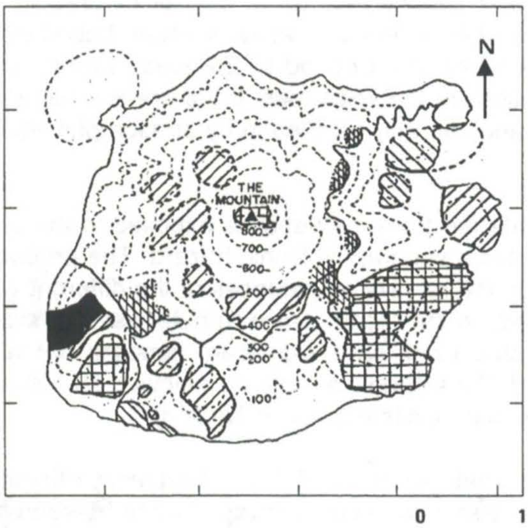

Figure 9 Distribution of Pelean domes on Saba.

- Old and deeply dissected by erosion
- Young, contained in unconsolidated to weakly lithified deposits (prob. > 70,000 years)
- Observed boundary
- Inferred boundary
- Old, not deeply dissected, contained in lithified pyroclastic deposits
- Very young, spines survive erosion
- Road
- Village
- -100 Contours (m)

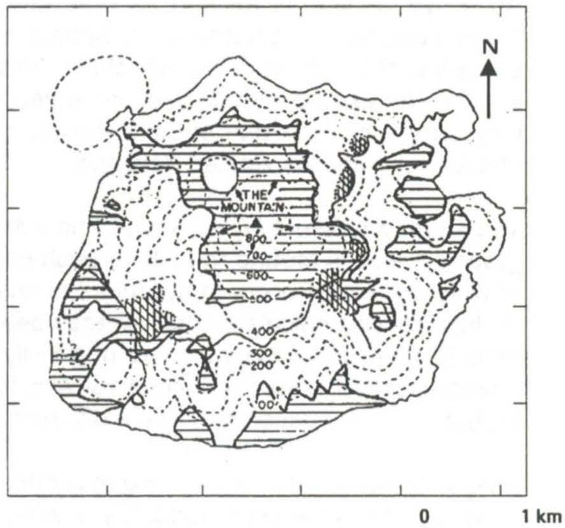

Figure 10 Distribution of weakly to non-lithified pyroclastic deposits from Pelean type nuées ardentes.

- Direction of flow
- The Mountain
- Weakly to non-lithified nuées ardente deposits
- Road
- Village
- -100 Contours (m)

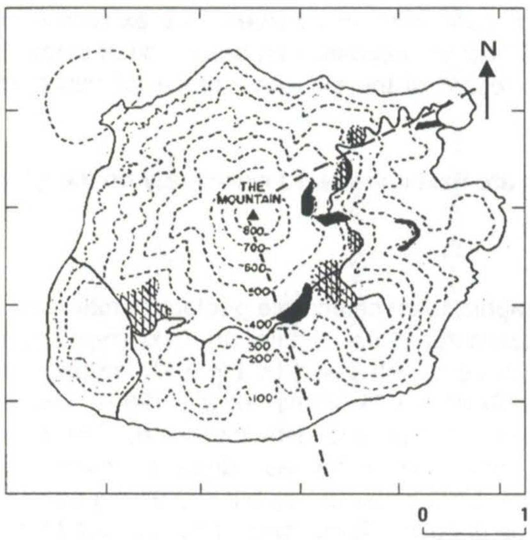

Figure 11 Distribution of scoria and ash deposits - all are weakly to non-lithified.

- Scoria and ash deposit
- Limits of sector affected by scoria and ash flows
- Road
- Village
- -100 Contours (m)

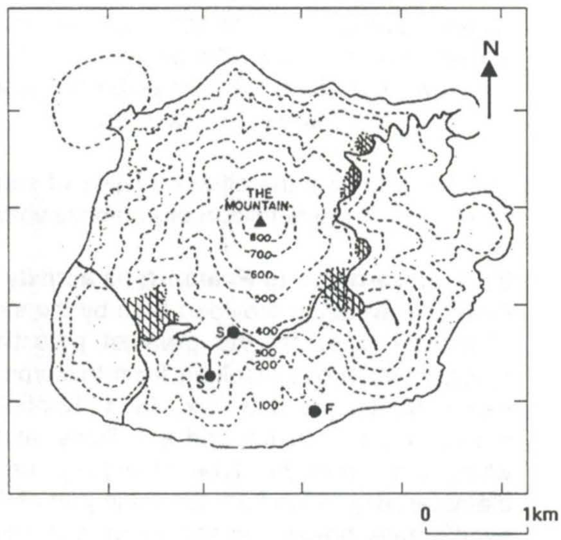

Figure 12 Distribution of pumiceous flow and surge deposits.

- ● S Surge deposit
- ● F Pumice flow deposit (50m downgulley from section VI)
- Road
- Village
- -100 Contours (m)

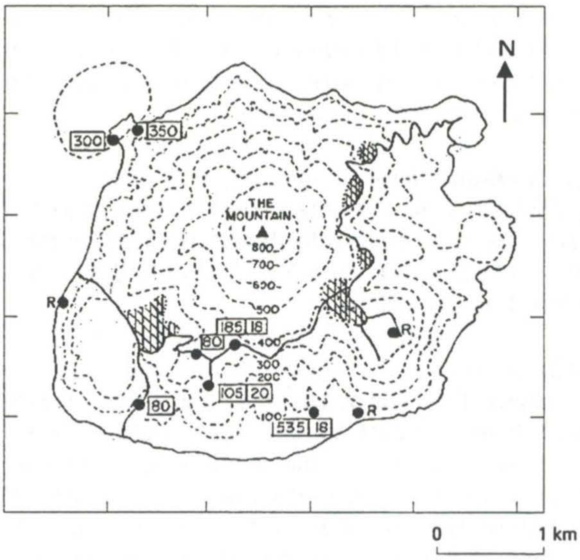

Figure13 Distribution of airfall pumice and ash.

- ● Locality where found
- [105][ ] First box shows thickness of airfall deposits of one eruption in cm
- [ ][20] Second box shows averaged maximum diameters of the 5 largest airfall pumice clasts
- ● R Fluviatile reworked
- Road
- Village
- -100 Contours (m)

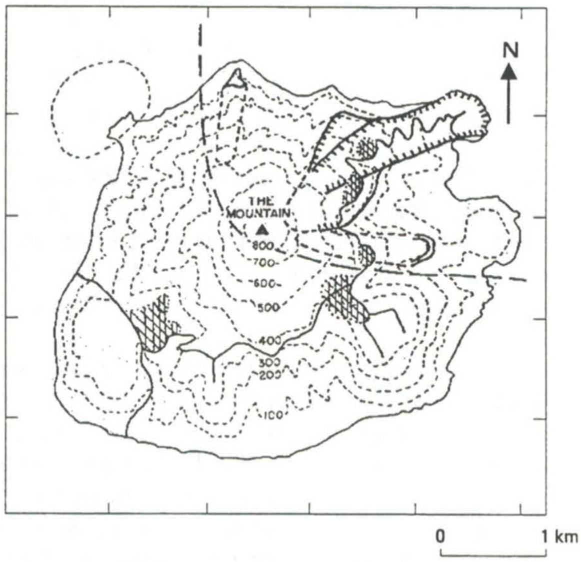

Figure 14 Distribution of lava flows on Saba.

- Inferred buried extension of flow
- Original edge of lava flow
- Eroded edge
- Limit of sector containing lava flows
- Road
- Village
- -100 Contours (m)

Figure 10 is a map showing the distribution of the youngest unlithified and weakly lithified block and ash and dense andesite surge deposits (probably younger than 70,000 years). Again the dispersal of these deposits is radial. It is significant that the two pits dug in the two main areas of settlement, The Bottom and Windward Side villages both bottomed in young, fresh unaltered and unconsolidated block and ash deposits with blocks up to 1.5 m in diameter. The occurrence of these deposits underlying the village sites does not indicate vent areas, rather they are both areas of flat ground where the pyroclastic flow materials can accumulate.

2.6.2 Hazard due to St. Vincent-type scoria and ash flows

Basaltic andesite pyroclastic flow deposits result from open crater activity of the type experienced during the Soufriere, St. Vincent eruption of 1902 (Anderson and Flett, 1903; Roobol and Smith, 1975). These deposits are not common on Saba and the probability of renewal of this type of activity in the next few centuries is probably minor. In Figure 11 the occurrences of this type of pyroclastic flow deposit are shown. It can be seen that the deposits are only found in the south-eastern quadrant of the island. All occurrences are non- or weakly lithified and were probably erupted during the last 70,000 years. The single quadrant limitation of these deposits probably reflects only the paucity of this type of deposit and the accessibility, i.e. most outcrops are along the road, although it could also reflect eruptive conditions. In terms of hazard, the risk is comparable to other types of pyroclastic flows.

2.6.3 Hazard due to pumice flows and pumiceous surges

From a study of other volcanoes in the Lesser Antilles Roobol and Smith (1980) concluded that pumice and ash flow deposits represent the greatest volcanic hazard. This is certainly the case for St. Eustatius (see next section). However, only three occurrences of this type of deposit have been described from Saba (Figure 12). A single post-70,000 year ash-surge occurs immediately north of Fort Hill (Section IX) while a number of ash surge deposits are interbedded with pumiceous airfall deposits at Section VII. A lithified deposit of pumice flow was found a few been described from Saba (Figure 12). A single post-70,000 year ash-surge occurs immediately north of Fort Hill (Section IX) while a number of ash surge deposits are interbedded with pumiceous airfall deposits at Section VII. A lithified deposit of pumice flow was found a few meters down gully from Section VI. The paucity of these deposits suggests that the chances of this type of activity recurring in the next few centuries is very small. However, should such activity recommence, then the hazard would be island wide and be very great.

2.6.4 Hazard due to semi-vesicular andesite pyroclastic flows

On the Level, stratigraphic sections (II, III, IIIA, IIIB) all show the only known deposit of semi-vesicular andesite block and ash deposit on Saba. This is restricted to the Level and a carbon sample from it (Figure 3, Column IIIB) was dated at 34,750±850 years B.P. The risk of this type of pyroclastic activity recurring is therefore considered as insignificant.

2.6.5 Hazard presented by Plinian airfall activity

In Plinian-type activity the eruption proceeds as a series of explosions in which pumiceous clasts are ejected high into the air to fall back onto the volcano's flanks as showers of debris. Unlike pyroclastic flows which may be limited to valleys or narrow sectors, the airfall deposits usually mantle all flanks. Again this type of deposit is uncommon and the probability of this type of activity recurring is small. In Figure 13 the distribution of this type of deposit is shown. In several places the deposits have been reworked by rainwash and fluviatile action. At each location the total thickness of the airfall deposits from individual events (i.e. thicknesses of all beds produced in a single eruption) together with the maximum clast size (obtained by averaging the maximum diameters of the 5 largest clasts per occurrence) are shown. Figure 13 shows that the hazard for the entire island is at most a 5-600 cm thick layer at the coast containing pumice clasts up to an average maximum diameter of 18 cm. These figures of thickness and size will increase towards the vent which is now probably represented by the Mountain (Mt. Scenery). This type of activity could represent a serious hazard to man-made structures if it recurs, which may be further increased by the fact that gravitational collapse of such eruptive columns (which can reach heights of 50 km) produce pumiceous surges and flows. That this type of activity has occurred during the Plinian airfall activity in the past is indicated by the interstratification of ash surge and airfall deposits in Section VII.

2.6.6 Hazard presented by basaltic/basaltic andesite airfall activity

Only one occurrence of scoriaceous basaltic andesite airfall deposit has been described from Section XVI at Torrens Point. As with other types of airfall activity, the hazard is island wide. Although post-70,000 year airfall deposits of basaltic/basaltic andesite scoria have not been observed, the fact that 'young' scoria flows, produced by the gravitational collapse of an eruptive column have occurred, indicates that the probability of recurrence of this type of airfall activity is similar to that associated with the generation of scoria flows (St. Vincent-type activity).

2.6.7 Hazard presented by lava flows

Two types of lava flows can be found on Saba. The first type are those associated with Pelean domes. These are generally of andesitic composition and form short thick flows with steep flow fronts. The probability of recurrence and volcanic hazard from this type of flow would be the same as that for Pelean domes.

The other type of flow is a more fluid basalt or basaltic andesite type. Flows of this type are restricted to the northeastern quadrant of the island where at least two, possibly three, distinct flows are found (Figure 14). These flows have probably issued from either the central vent of the Mountain or from fissures someway down its flanks. The longest flow covered a distance of at least two kilometers before it reached the sea. The main danger from this type of activity would be to structures and lines of communications. As nearly all of these lava flows appear to have been erupted within a limited time span, the probability of recurrence can be regarded as minor.

2.6.8 Hazard presented by phreatic/phreatomagmatic activity

Only one deposit produced by phreatic/phreatomagmatic eruptions has been described from Saba. However should activity recommence it is almost certain that this would at least be preceded by phreatic/phreatomagmatic eruptions, e.g. eruption of Mt. St. Helens, Washington, 1980. These eruptions may represent the material ejected during the vent clearing stage of a true magmatic eruption e.g. the initial eruptions of Mt. Pelée, Martinique 1902 (LaCroix, 1904; Roobol and Smith, 1975) or they may represent distinct eruptions themselves e.g. Soufrière, Guadeloupe 1976. In some cases magma may rise into the volcanic edifice without actually causing a volcanic eruption. Instead intense local earthquake swarms are generated producing volcano-seismic crises (Table 1).

It is very probable that any future activity on Saba will be preceded by phreatic/ phreatomagmatic activity and/or volcano-seismic crises and thus the probability for recurrence of this type of activity is very high. The main type of activity would probably be vertical steam eruptions producing lithic airfall deposits. However, it is possible for the eruptive column to collapse producing surges and block and ash flows.

2.6.9 Hazard presented by mudflows

On Saba, which is characterized by steep slopes and relatively high rainfall, the probability of the generation of mudflows associated with any type of pyroclastic activity is very high. The hazard from mudflows must be regarded as being island wide.

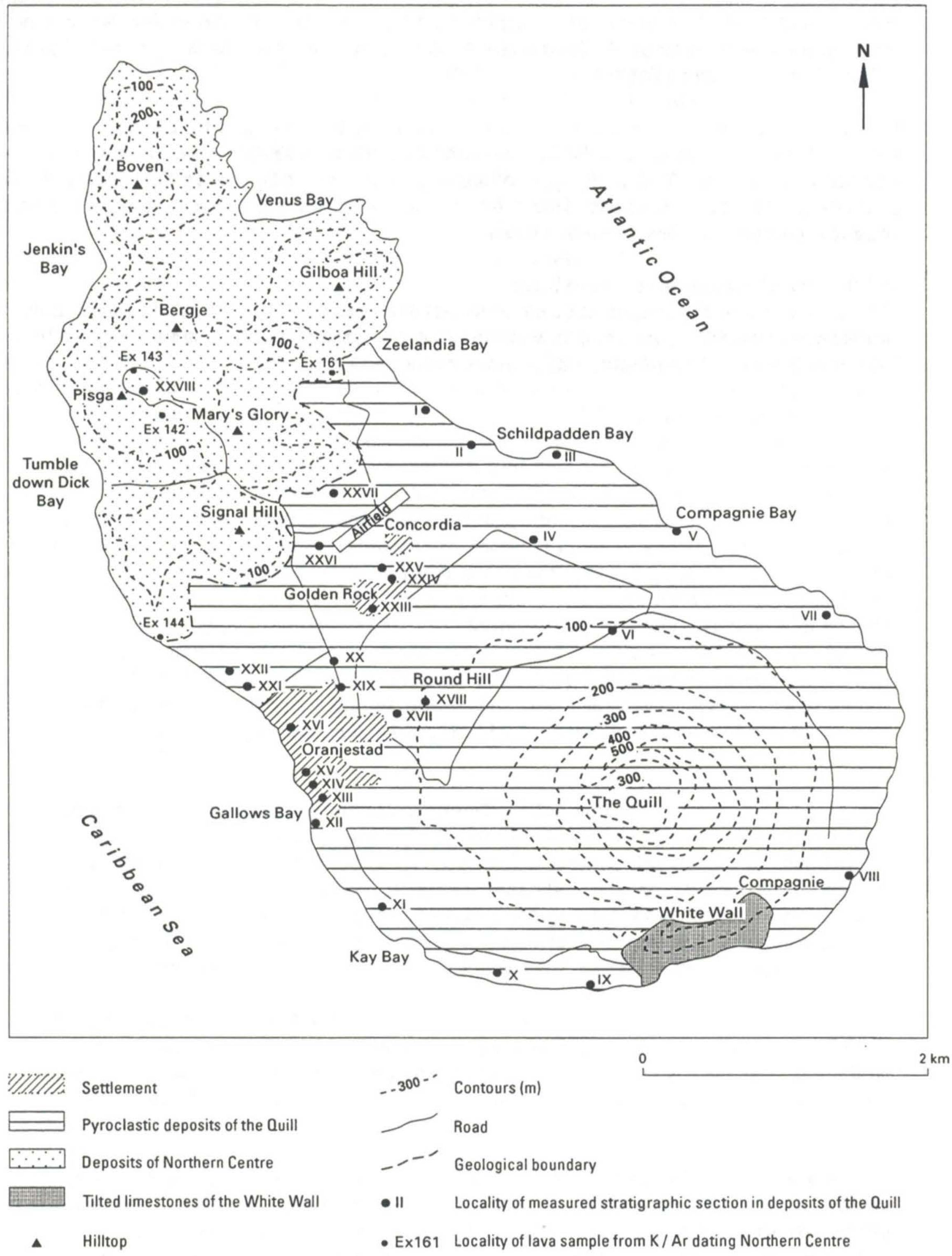

Figure 15 Geological map of St. Eustatius showing position of measured stratigraphic sections.

3 St. Eustatius

3.1 Geology of the island

Westermann and Kiel (1961) described the island as consisting of an older volcanic center in the north composed of lava flows and pyroclastic deposits and a younger single volcanic cone - the Quill - in the south. The Quill is an open-crater, central-vent type of volcano with flanks sweeping up to angles of 50° at the crater rim. The flank deposits of the Quill form the nearly flat lying central part of the island and terminate against the steep hills of the eroded Northern Center. In the south of the island the Sugar Loaf - White Wall (Figures. 15 and 16) is formed of up-tilted limestone strata due probably to a flank dome intrusion. Similar up-domed limestone surrounds Brimstone Hill andesite dome, visible to the south on St. Kitts. Westermann and Kiel (1961) dated the limestones of the Sugar Loaf - White Wall sequence by radiocarbon methods, at 21,850±100 to 32,640±300 years B.P.[3]

3.2 Stratigraphy of the Quill

The sea cliffs cut into the flank deposits of the Quill provide some of the best exposures of pyroclastic deposits in the Lesser Antilles. The volcano is composed essentially of pyroclastic deposits amongst which reworked materials are unusually scarce. A few dome remnants appear to be exposed as cliff faces in the densely-vegetated, vertical inner walls of the crater but are inaccessible. There are no exposed lava flows. During our surveys 28 stratigraphic sections (Figure 17) were measured and their locations are shown in Figure 15. Unlike Saba, carbonized wood suitable for radiocarbon dating was found in the flank deposits and a higher degree of correlation was possible around the island. The types and relative abundances of the deposits from the Quill are shown in Table 5. These data have not been corrected for repetitions of the same deposit in different sections. In the stratigraphic sections, deposits of identical lithology have been bracketed together to represent multiple deposits from one eruption, and were counted as a single event. The data show that the Quill has been built up by three main types of pyroclastic activity, each type capable of producing several different types of deposit. These are:

1. Pelean-type nuée ardente eruptions producing dense andesite deposits:
   a. Block and ash;
   b. Dense andesite surge deposits.
2. St. Vincent-type activity producing basaltic andesite deposits:
   a. Scoria and ash flow deposits;
   b. Scoriaceous surge deposits;
   c. Scoriaceous airfall lapilli and ash deposits.
3. Plinian type activity of andesite to rhyolite composition has produced:
   a. Pumiceous airfall lapilli and ash;
   b. Pumice and ash flow deposits;
   c. Pumiceous or ash surge deposits.

Plinian type activity produces deposits which cover wide sectors of a volcano's flanks. Such deposits will be repeated more frequently in the stratigraphic columns than will those of the first two types of activity, although airfalls of basaltic andesite will also show a relatively high frequency of occurrence. Although the data are somewhat rough it would seem that Plinian activity (both flow and fall) has been the most dominant with St. Vincent type pyroclastic flow and Pelean type activity being somewhat less frequent. The Quill is therefore a very different type of volcano to Saba. The latter (see section 2) is mainly the product of repeated andesite pyroclastic flow activity of the type similar to the Mt. Pelée eruption of 1902. Within the sections of the Quill, deposits indicating other types of activity are also found although their occurrence, is rather minor. The semi-vesicular andesite pyroclastic flow and surge deposits are again sparse, although more common than on Saba. There are also minor amounts of airfall beds composed of baked and altered lithic fragments which represent phreatic activity.

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[3] These rocks have recently been redated using the U-Th series method. The new dates range from 68,000 to >310,000 years B.P. (Schellekens et al., 1995).

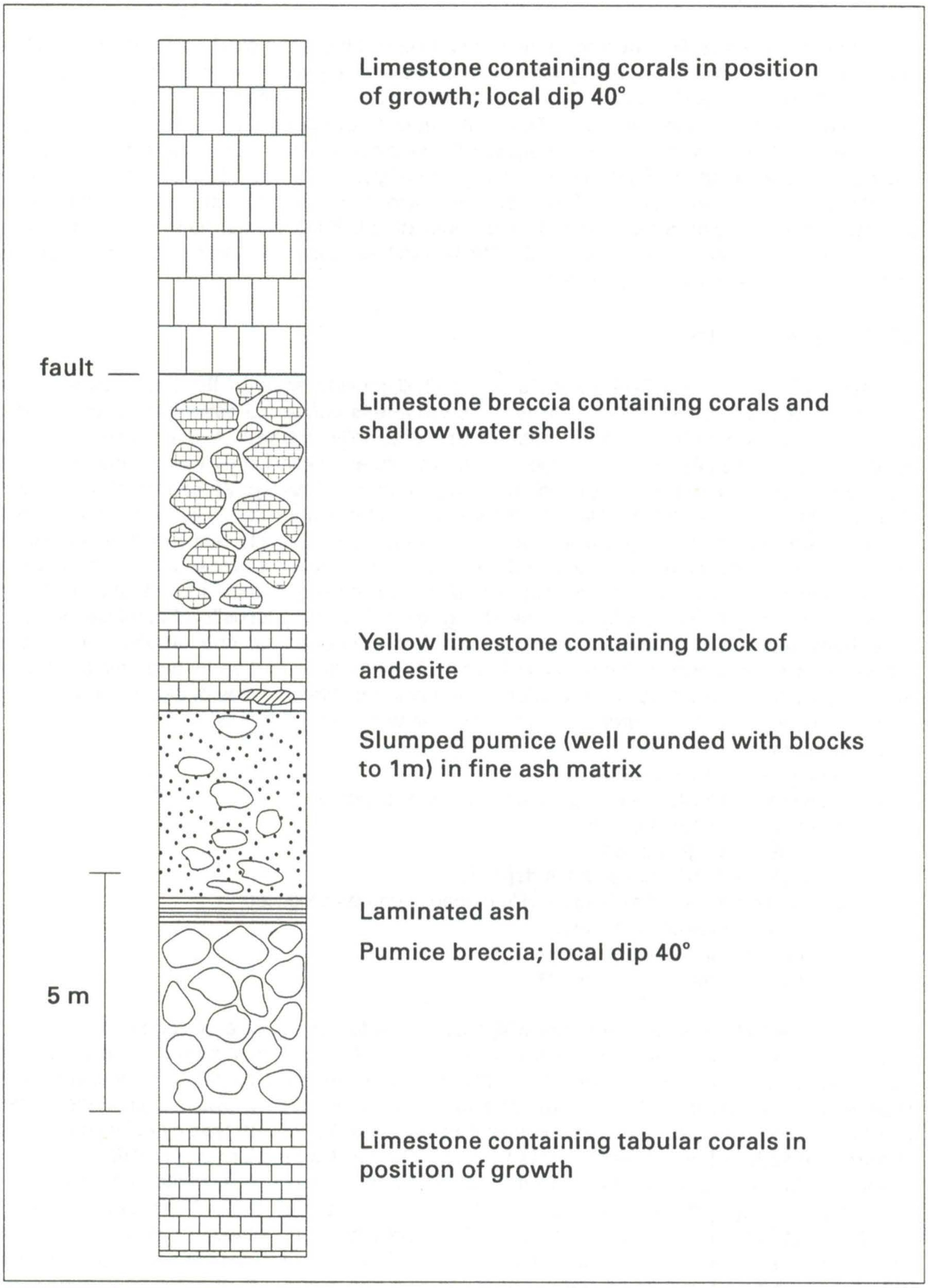

Figure 16 Stratigraphic section through the deposits of the White Wall-Sugar loaf.

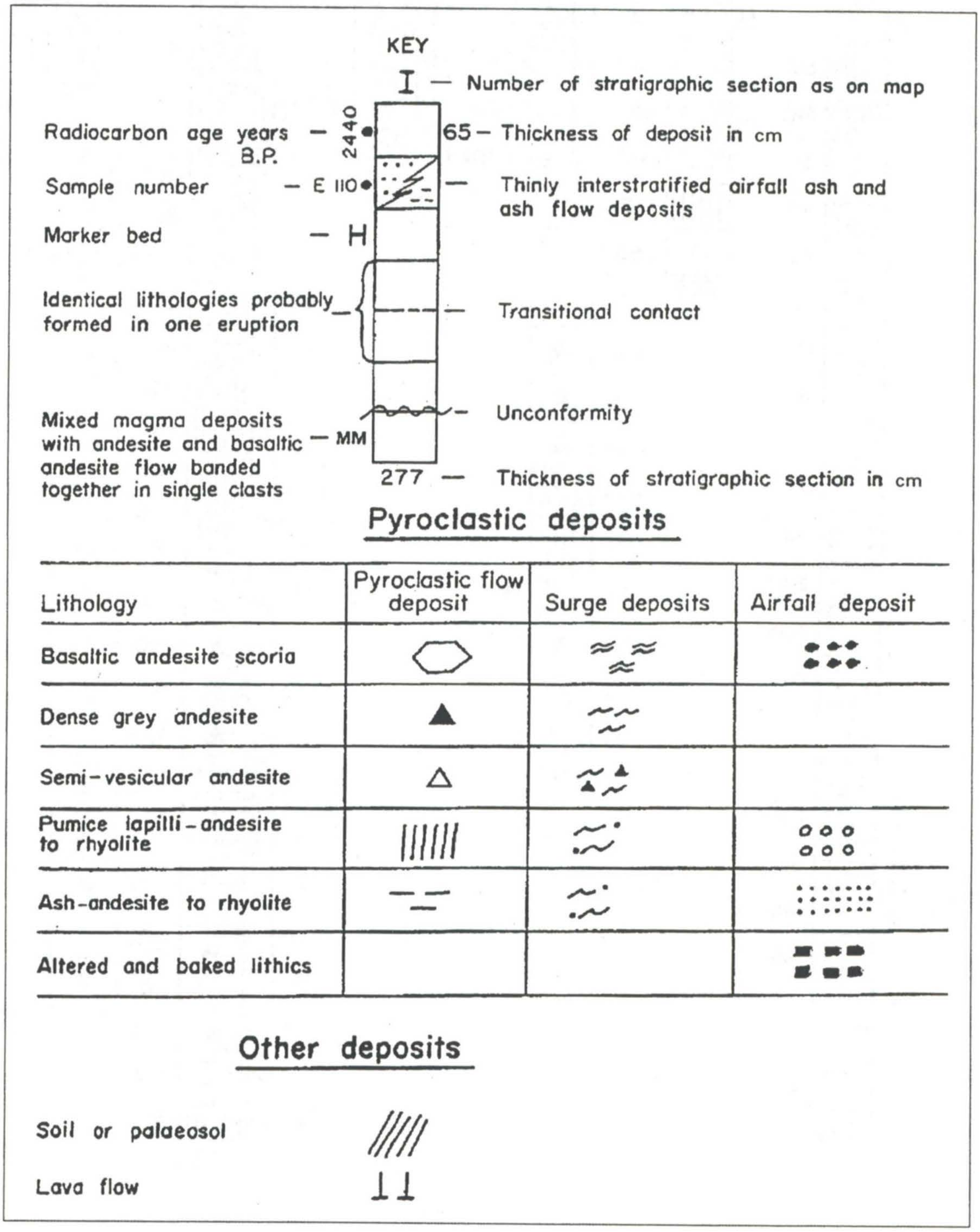

Figure 17 St. Eustatius. Stratigraphic sections.

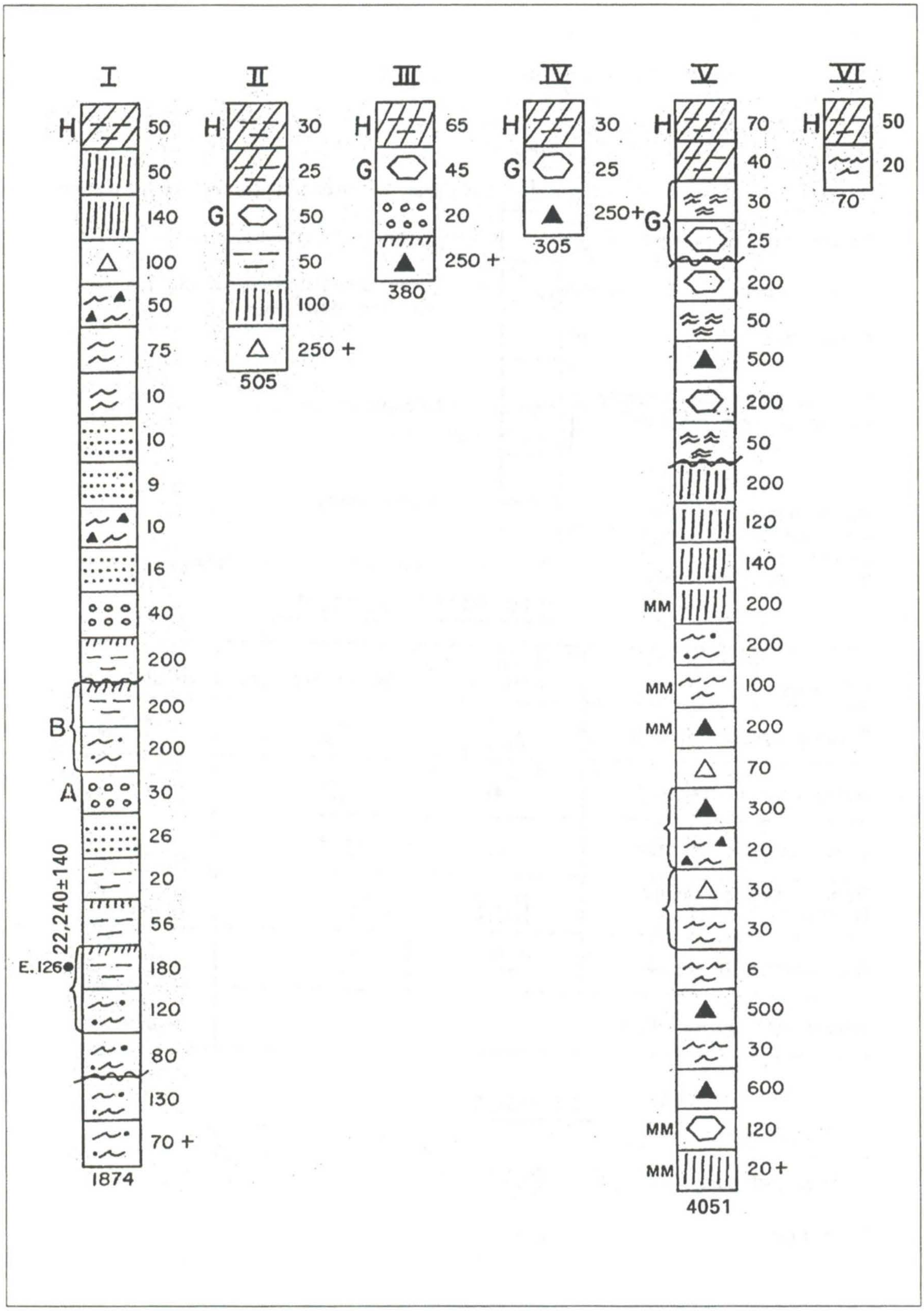

Figure 17 Stratigraphic sections (continued).

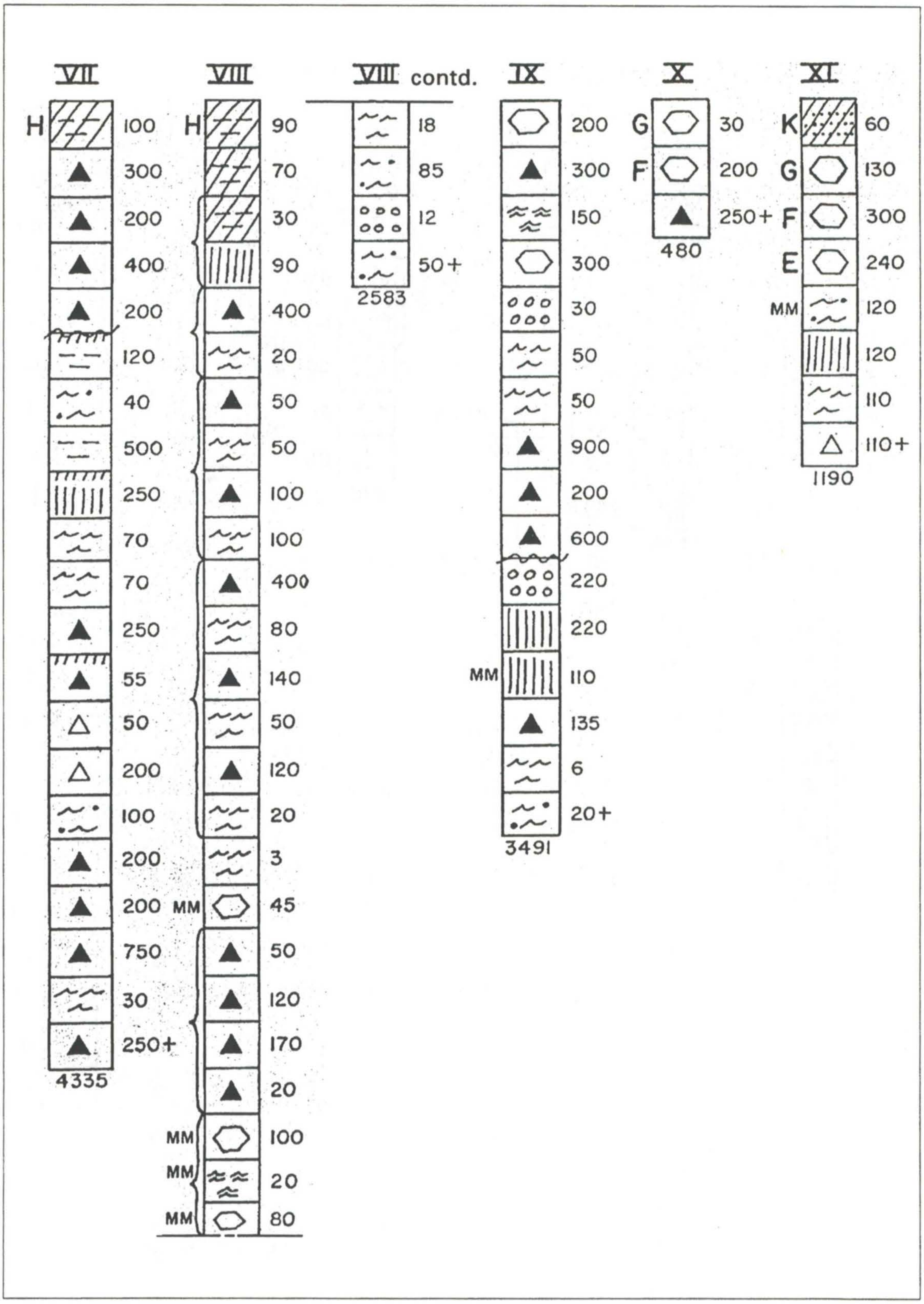

Figure 17 Stratigraphic sections (continued).

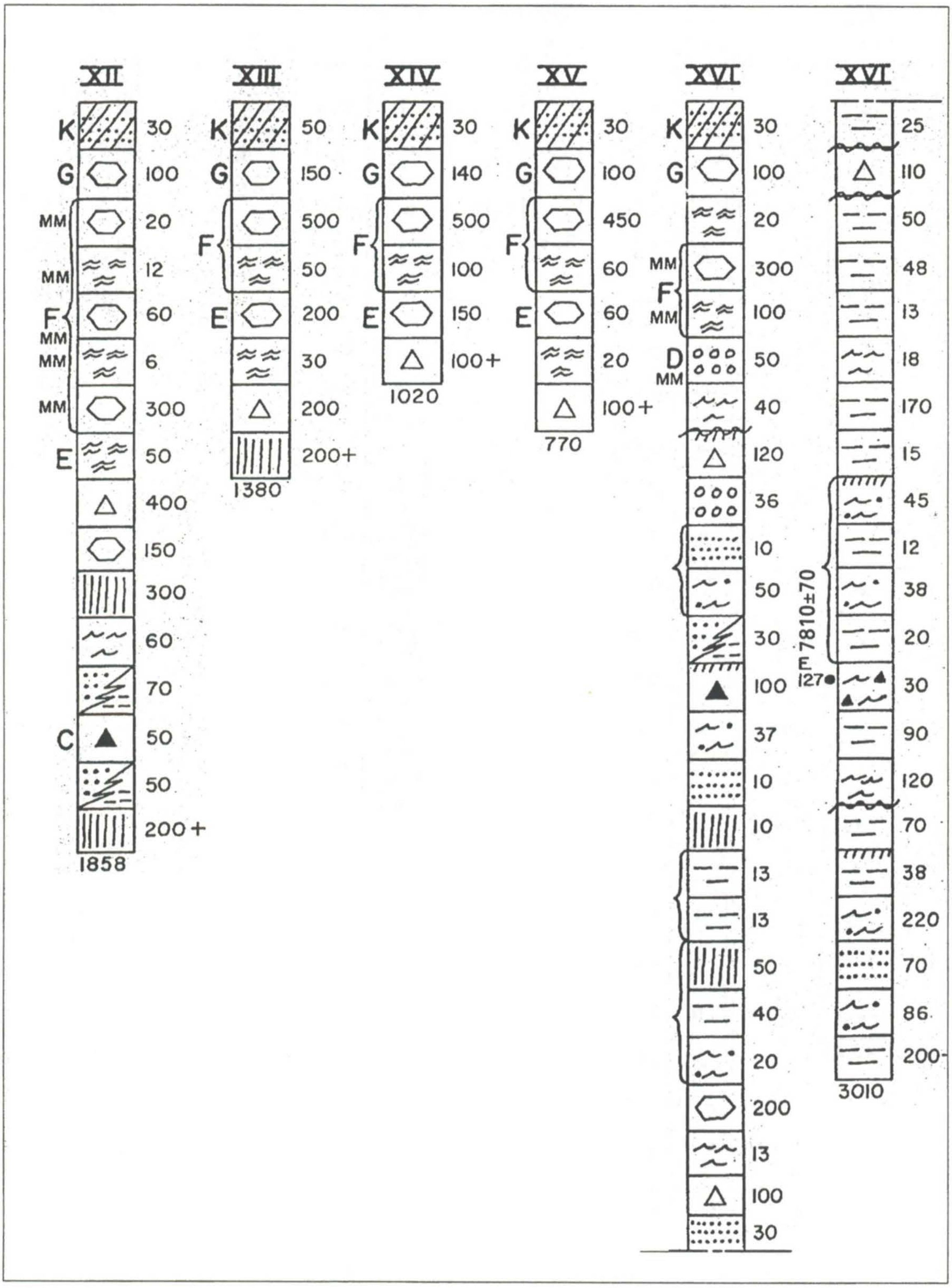

Figure 17 Stratigraphic sections (continued).

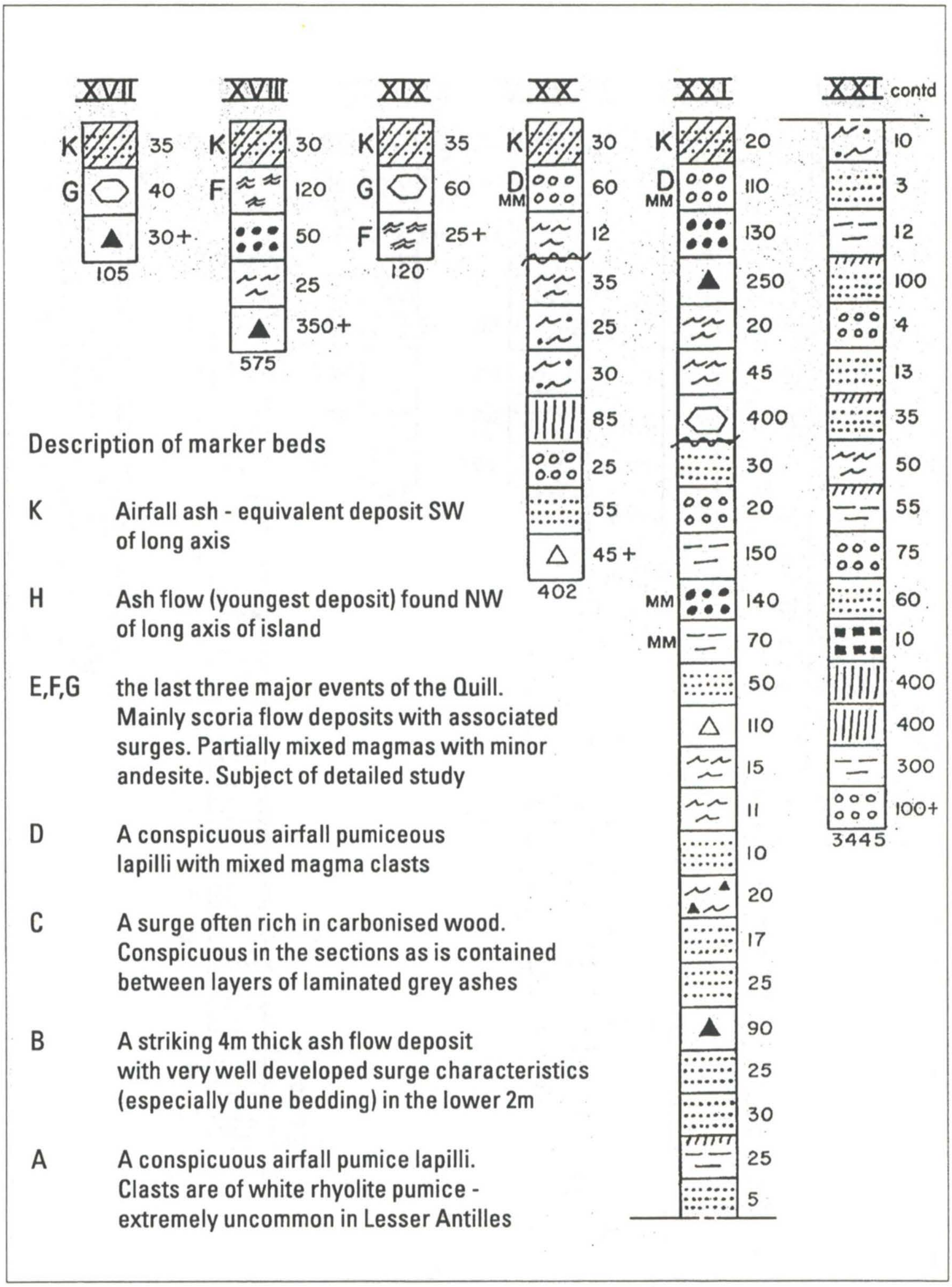

Figure 17 Stratigraphic sections (continued).

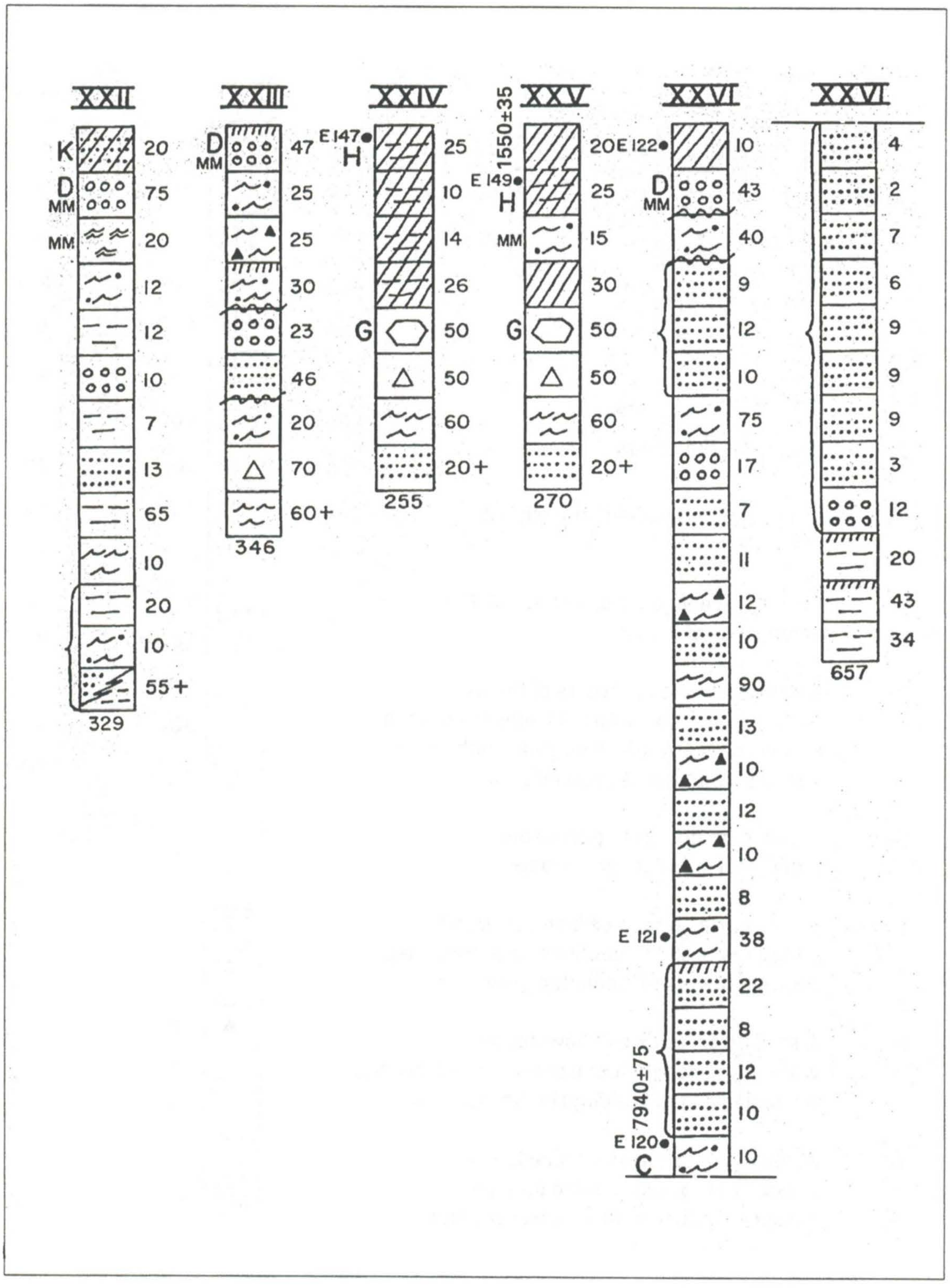

Figure 17 Stratigraphic sections (continued).

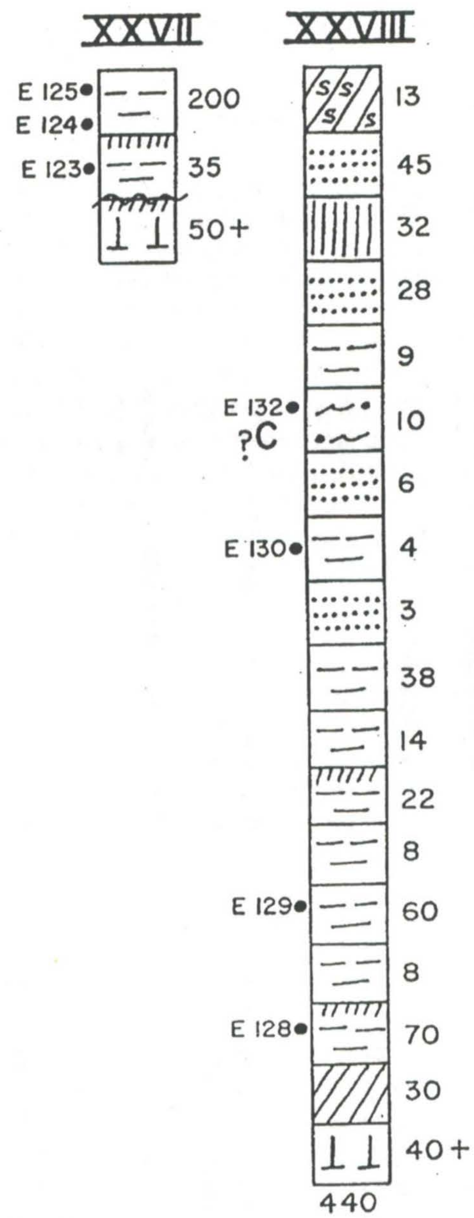

Figure 17 Stratigraphic sections (continued).

Table 5 Abundance of the different types of pyroclastic deposits on St. Eustatius

Eruptive style	Type of activity	Deposit	Symbols used in stratigraphic column	Number of occurrences	Percentage of occurrences		
Pelean	Nuée ardente e.g. Mt. Pelée 1902	Block & ash flow	▲	36	10	21	
		Dense andesite surge	~ ~ ~	38	11		
St. Vincent	Airfall*	Scoriaceous lapilli	● ● ● ● ● ●	4	1	17	
	Scoria flow e.g. St. Vincent 1902	Scoria and ash flow	⬡	37	11		
		Scoriaceous surge	≈ ≈ ≈	16	5		
Asama*	Semi-vesicular andesite pyroclastic flow*	Semi-vesicular andesite and ash flow	△	17	5	8	
		Semi-vesicular andesite surge	~ ▲ ▲ ~	9	3		
Plinian*	Pumice-ash flow*	Pumice and ash flow	| | | | |	21	6	33	55
		Ash (± pumice)	— — —	65	18		
		Ash surge	~ • • ~	32	9		
	Airfall*	Pumiceous lapilli	○ ○ ○ ○ ○ ○	21	6	22	
		Pumiceous ash	⋮ ⋮ ⋮	55	16		
Phreatic/ Phreatomagmatic	Airfall e.g. Guadeloupe 1976	Baked lithic lapilli	■ ■ ■ ■ ■ ■	1	Tr		

* Not witnessed by Europeans in the Lesser Antilles

3.3 Age of the deposits on St. Eustatius

Six new C^{14} ages have been obtained during this study. Two of these ages are however too young to represent volcanic charcoal and thus must be disregarded as far as the interpretation of the volcanic history is concerned. The four remaining dates range from 22,240±140 years B.P. to 1,550±35 years B.P. The older date comes from an ash flow deposit near the base of the exposed succession. This is considerably younger than the oldest deposits of the Quill contained in limestones of the White Wall. The youngest age represents what is probably the last eruptive event on the island (see section III 4). The other two ages (7,940±75 and 7,810±70 years B.P.) are both from a surge deposit which seems to have affected most of the island (see Figure 17, Columns XVI and XXVI).

3.4 The last eruptions of the Quill, St. Eustatius

One of the objectives of modern volcanology in the Lesser Antilles is to establish the stage of activity of each volcano. Previous work clearly indicates different volcanoes are at the present day in different stages of activity. For example, Mt. Pelée, Martinique, is a nearly-wholly pyroclastic volcano rather like the Quill. Detailed stratigraphic studies and 50 radiocarbon dates from Mt. Pelée enabled Roobol and Smith (1976) to reconstruct relatively accurately the last 9000 years of history. From this data it was found that the volcano underwent a number of alterations in style of activity with time. These were mainly alternations of periods of dense andesite pyroclastic flow activity (Pelean-type activity) with periods of pumiceous Plinian-type activity. The present episode of nuée ardente activity commenced about 600 years ago. Before this an Amerindian population experienced pumiceous activity (Roobol and Smith, 1980). The periods of one type of activity have for Mt. Pelée ranged in the past from 200 to 1800 years. In contrast, Soufriere, St. Vincent, has at least for the past 350 years, produced St. Vincent type pyroclastic flows (basaltic andesite), although prior to this it underwent a period of andesitic Pelean-type activity.

The excellent continuous exposure on St. Eustatius enabled us to make a detailed study of the five youngest deposits in order to identify the present stage of activity. These are identified as the marker beds, E, F, G, H, and K on the stratigraphic columns (Figure 17). These last deposits of the Quill are essentially of basaltic andesite pyroclastic flow type, which together with the present open crater of the Quill, clearly indicate that the last activity was of a type similar to that of Soufriere, St. Vincent, in 1902. This contrasts with Saba and Mt. Pelée which are in a dense andesite pyroclastic flow stage of activity.

Maps showing the distribution and thickness of each of the last five marker deposits are shown in Figures 18 to 21. From these it can be seen that with each successive event the pyroclastic flow activity became progressively more widespread. The oldest of the five recent deposits - marker bed E - covers a sector of 50° of the volcano's flanks. The next, F, covers a sector of 120° . The pyroclastic flow which produced deposit G was channeled around to the northwest coast to effectively cover a sector of 180° on the lower flanks. Ash flow marker bed H covers a sector of 180° lying north-west of the long axis of the island. Airfall ash marker bed K occurs at the same stratigraphical horizon as H but occurs only south-west of the long axis of the island. Clearly H and K both represent the last eruptive event of the Quill. In this eruption a lithic-rich ash flow (now represented by deposit H) was directed towards the north-east while the ash in the rising eruptive column was directed by the Trade Winds towards the north-west so that ash fell on the leeward side of the island as marker airfall bed K.

The relationships of the marker beds, E, F and G can best be seen at locality XI (Figure 15) in a vertical-walled, narrow gut near Kay Bay. The last deposit prior to this last phase of activity of the Quill is a pumice flow deposit from 0 to 120 cm thick. It is a mixed-magma deposit where vesicular black basaltic andesite and white andesite are flow banded together within single clasts and indicate that two magmas of contrasting composition were erupted simultaneously from the one central vent. White pumice clasts are up to 30 cm in diameter and exceed the basaltic andesite clasts in abundance. The deposit although it represents a mixed-magma

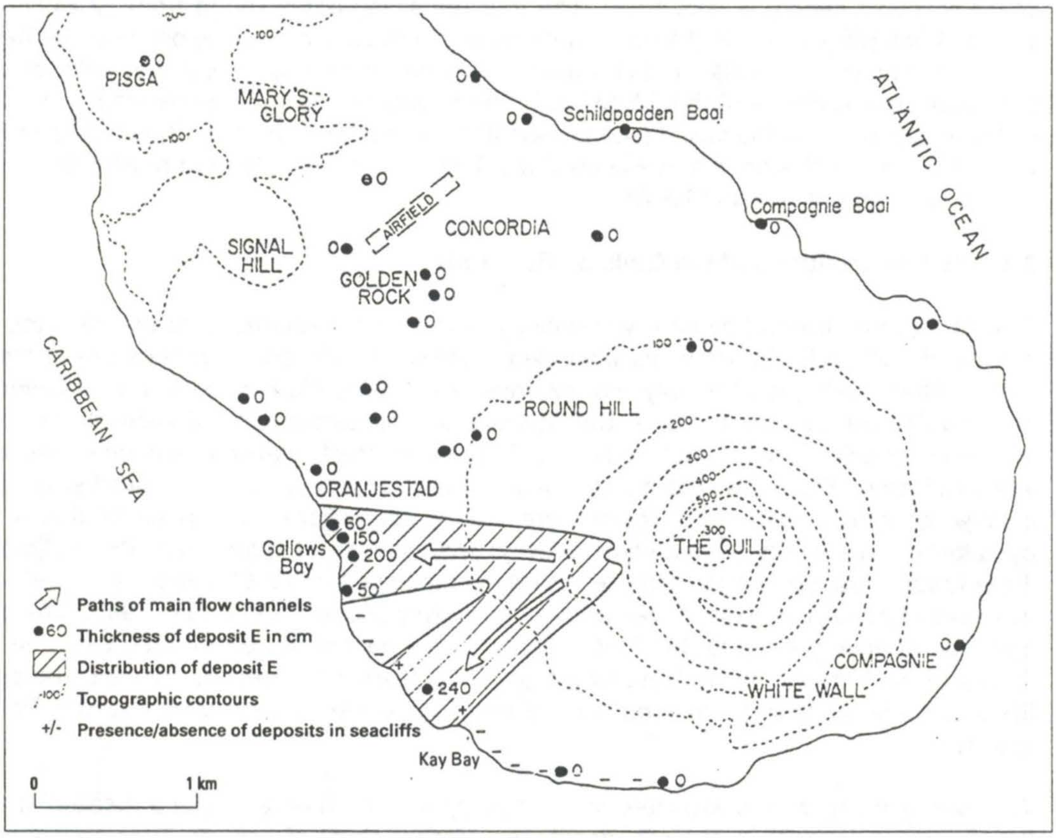

Figure 18 Distribution of deposit E.

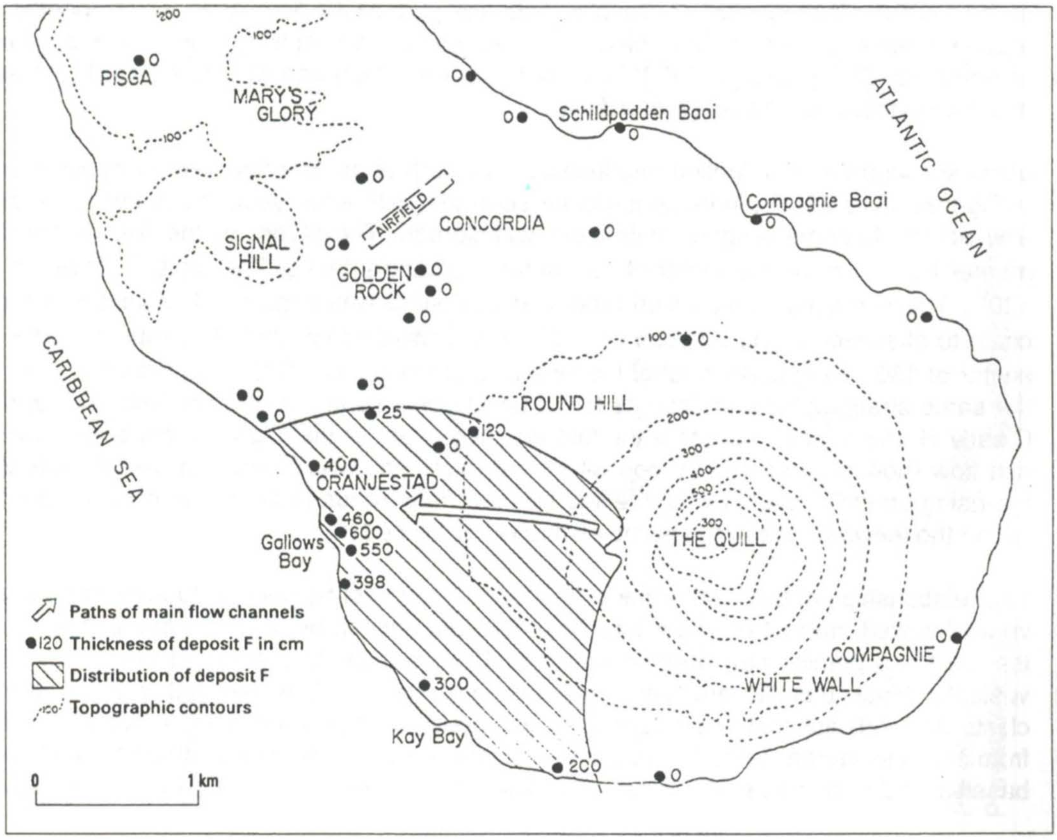

Figure 19 Distribution of deposit F.

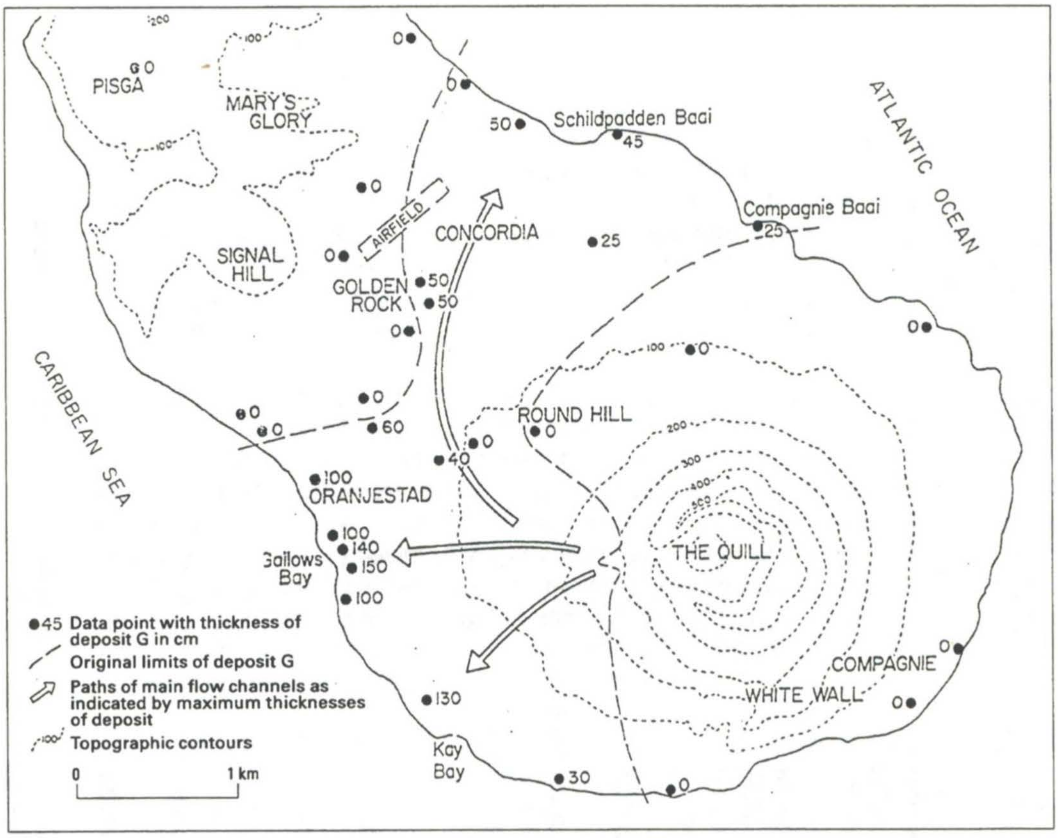

Figure 20 Distribution of deposit G.

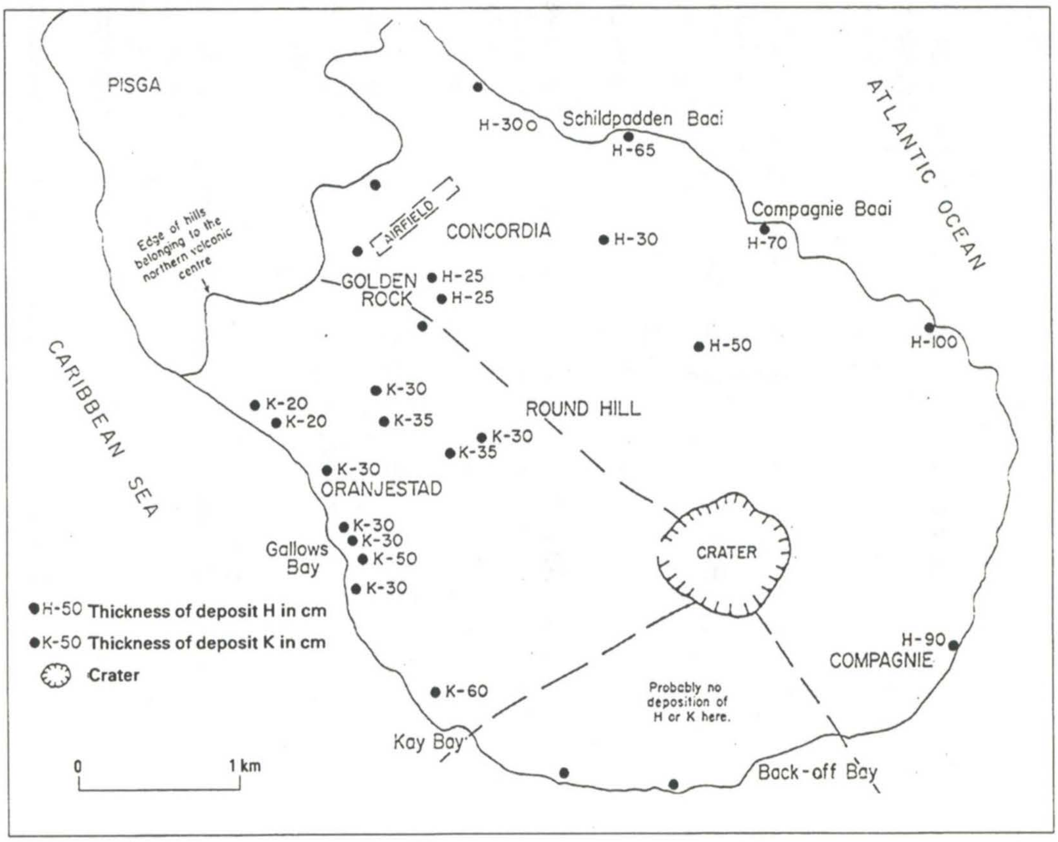

Figure 21 Distribution of deposits H and K.

Table 6 Estimated types and frequencies of volcanic activity of the Quill, St. Eustatius (estimates for entire life of volcano)

Eruptive style	Type of activity	Type of deposit	Symbols in stratigraphic column	Estimated a. relative	frequency b. recalculated to 100%
a. Pyroclastic flows and surges					
Pelean	Nuées ardentes	a. Block & ash flow (andesite) b. Dense andesite surge	▲ ～ ～	20	15%
St. Vincent	Scoria flows	a. Scoria & ash flow (basaltic andesite) b. Scoriaceous surge (basaltic andesite)	⬡ ≈ ≈	20	15%
Plinian	Pumice flow	Pumice & ash flow (andesite-rhyolite)	|||||	10	7%
	Ash flow	Ash ± pumice flow (andesite-rhyolite)	— —	20	7%
	Ash surge	Ash surge (andesite-rhyolite)	～ ·	10	7%
Asama	Semi-vesicular flow	Semi-vesicular andesite block & ash flow Semi-vesicular andesite surge	△ ～▲	10	7%
b. Phreatic eruptions					
Steam explosions		Baked lithic airfall lapilli and ash Baked lithic base surge	■ ■ ■ np*	20	15%
c. Airfall activity					
Plinian	Vertical eruptions	Airfall lapilli (andesite-rhyolite) Airfall ash (andesite-rhyolite)	○ ○ ○ · · · ·	20	15%
Basic	Vertical eruptions	Airfall lapilli (basaltic andesite)	● ● ●	<5	<5%

np* Not present in stratigraphic sections eruption is essentially an andesitic pumice flow deposit. It is overlain by a surge deposit which also represents a mixed-magma eruption. Again in this deposit, which varies in thickness from 18 to 120 cm, the white andesite pumice exceeds the basaltic andesite scoriaceous component. This surge is overlain by the 240 cm thick marker bed E which is a scoria and ash flow deposit composed essentially of basaltic andesite scoria with rounded ropey surfaced clasts up to 50 cm in diameter. The deposit is rich in ash and mixed-magma clasts make up a minor part. Marker bed E is in turn overlain by the 300 cm thick marker bed F. This too is a scoria and ash flow deposit but it contains less ash than E. Mixed-magma clasts also form a minor component. The lower 100 cm of bed F are rich is angular blocks of dense andesite. The latter suggest that the explosions which produced the pyroclastic flow destroyed a pre-existing Pelean dome or dome remnant. (The latter must have been present at various times on the Quill as indicated by the presence of block and ash deposits which typically are erupted during dome growth and contain dense blocks derived from the dome). Marker bed F is overlain by marker bed G. At locality XI, the gut near Kay Bay, bed G is a 130 cm thick scoria and ash flow deposit with clasts up to 20 cm in diameter. Unlike those below it, there are no mixed-magma clasts.

The deposits already described clearly indicate a progressive change in the type of activity from pumice flow to scoria flow with intermediate mixed-magma deposits which become progressively richer in the basaltic andesite component. The successive eruptions became more destructive and covered progressively larger areas of the island. The dense andesite clasts in deposit F indicate that the crater of the Quill was enlarged at that time. Unfortunately the time interval presented by these deposits is unknown as no carbonized wood was found in them. However there is no indication of paleosols or erosion of the deposits (variations in thicknesses reported here are original features of the pyroclastic flow deposits) so that the time span between each deposit would at the most be a few years and all the deposits of the pumice flow might represent a single eruption lasting several years.

Marker beds H and K overlie E, F and G and cover considerably wider sectors of the volcano's flanks. H and K form the present day top-soil of the island and although weathered they are seldom sufficiently disturbed that their respective origins as an unsorted lithic-rich ash flow deposit (H) and a laminated airfall ash (K) are lost. The ash flow deposit appears to be basaltic andesitic in composition but it is extremely rich in lithic fragments and fine ash, which coat all the larger fragments. This deposit probably represents a phreatomagmatic eruption in which most of the magma was pulverized into a fine ash. Where best developed (Sections V, XXIV and XXV) deposit H is found to be represented by several ash flows, suggesting that there were probably several flow units in this last event, with the lower flow units appearing to be richer in lithics than those higher in the sequence. Ash flow H was found to be locally rich in carbonized wood (Sections XXIV and XXV), located immediately in front of the air terminal building, and was dated at 1550$\pm$35 years B.P.

3.5 Volcanic hazard on St. Eustatius

Unlike Saba there are no historic nor present day hot springs or fumeroles on the island. However this does not constitute absolute proof that the Quill is extinct.[4] St. Eustatius is one of the volcanic islands which make up the Active Arc of the Lesser Antilles. The arc as a whole is regarded as active and every recent volcano must be regarded as potentially active. The hazard of renewed activity by the Quill can be regarded as typical for any volcano in the Active Arc.

The stratigraphic sections through the deposits of the Quill show several paleosol horizons (ancient soils now buried beneath later erupted material). These ancient soils are developed as well or better than the present day surface soils. This indicates that in the past there were periods of dormancy for the Quill which compare with the present state. On the basis of the radiocarbon dates the subaerial portion of the Quill has been active from at least 22,240 to 1,550 years B.P. This age range is not very long when compared to other volcanic centers in the region e.g. Saba, Mt. Pelée, Soufrière, and Guadeloupe. However much of its early history

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[4] Subsequent drilling for groundwater identified six shallow water wells with a temperature range from 30° to 70°C indicating geothermal sources.

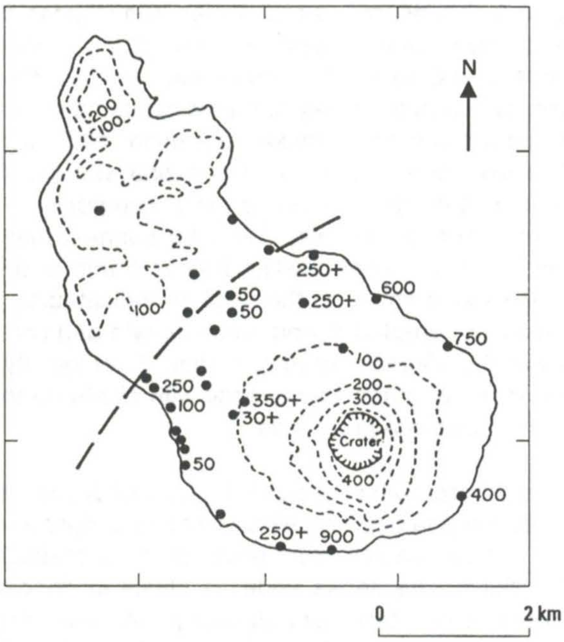

Figure 22 Distribution and maximum thicknesses of block and ash deposits resulting from Pelean type nuée ardente activity.

- ● Location of stratigraphic section without block and ash deposits
- ● 250 Location and maximum thickness of block and ash deposit in cm
- ● 250+ Base of block and ash deposit not found
- – – Limit of block and ash deposits from the Quill
- -100- Topographic contours in metres

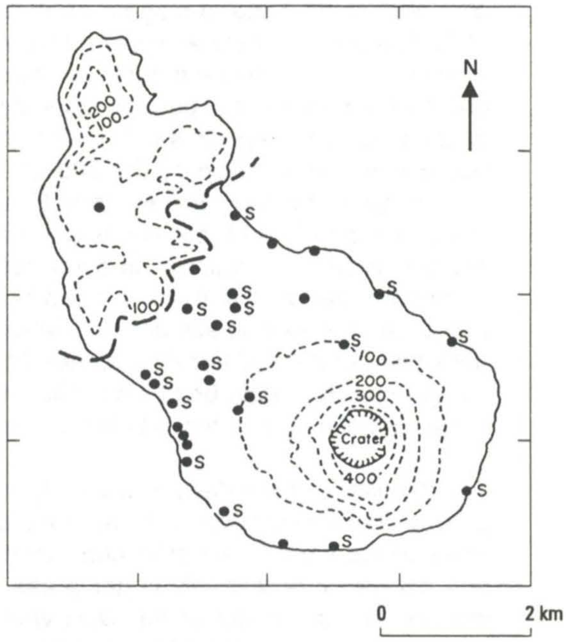

Figure 23 Distribution of dense andesite surge deposits resulting from Pelean type nuée ardente activity.

- ● Location of stratigraphic section without dense andesite surge deposit(s)
- ● S Location of stratigraphic section with dense andesite surge deposit(s)
- – – Limit of dense andesite surges
- -100- Topographic contours in metres

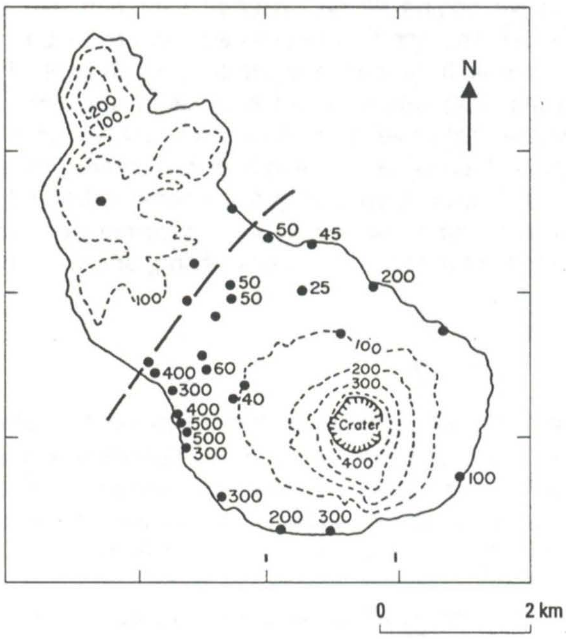

Figure 24 Distribution and maximum thicknesses of scoria and ash deposits resulting from pyroclastic flow activity of St. Vincent 1902 type.

- ● Location of stratigraphic section without scoria and ash deposit
- ● 300 Maximum thickness of block and ash deposit in cm
- – – Limit of scoria and ash deposits
- -100- Topographic contours in metres

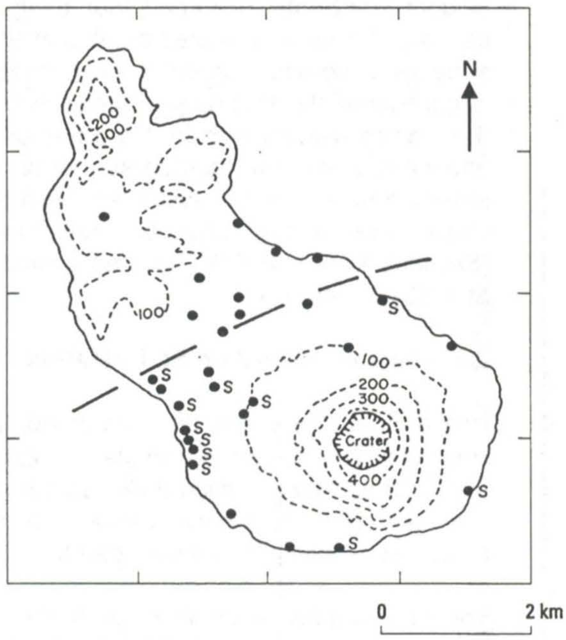

Figure 25 Distribution of scoriaceous surge deposits resulting from St. Vincent 1902 type of pyroclastic flow activity.

- ● Location of stratigraphic section without scoriaceous surge deposits
- ● S Location of stratigraphic section with scoriaceous surge deposit(s)
- – – Limit of scoriaceous surges
- -100- Topographic contours in metres

is lost in submarine deposits as indicated by U-Th series ages (see footnote 3) recently obtained from redating the White Wall - Sugar Loaf.

The data for the relative abundances of the different types of pyroclastic deposits for St. Eustatius can be modified in a similar manner as for Saba, to produce a table of past frequencies of styles of activity. Such a table of past activity can be used to anticipate any future activity as the frequencies of the different types of activity will probably not change significantly in the future. The data are shown in Table 6.

Unlike Saba which was built up mainly by repeated Pelean-type eruptions with accompanying dome growth, St. Eustatius was formed by many different types of activity and in this respect resembles Mt. Pelée (Roobol and Smith, 1976). The stratigraphic columns (Figure 17) indicate that the Quill is the result of a series of differing and contrasting types of pyroclastic activity. The detailed study of the youngest deposits of the Quill show that at present it is in an open-crater, basaltic andesite stage. Another volcano in this stage of activity is Soufriere, St. Vincent. Any future activity is most likely to be of basaltic andesite scoria and ash flow type erupted from an open crater. The table of estimated frequency of types of activity is however mainly aimed at estimating future activity over the next 1000 to 10,000 years rather than the short intervals of decades.

The presence of flank deposits from the Quill exposed and accessible in the central part of St. Eustatius and extending up the hills of the Northern Center has permitted a very detailed hazard study to be made. We were particularly fortunate on our third visit to St. Eustatius (summer 1979). Prior to this date the hills of the Northern Center has been largely abandoned and were overgrown with scrub. By summer 1979 this area was being converted into an oil storage tank farm. This had resulted in the excavation by bulldozer of a hilltop near Pisga Hill. The excavation revealed the most distal deposits from the Quill at locality XXVIII at an altitude of 150 m above sea level. Detailed studies of the type now carried out on St. Eustatius were not possible on Saba where the flat lying and largely uneroded flank deposits are beneath the sea.

3.5.1 Hazard presented by Pelean-type eruptions

The two main deposits resulting from nuées ardentes produced by Pelean-type eruptions (type example Mt. Pelée, 1902) are coarse grained thick block and ash flow deposits and relatively fine gained dense-andesite surge deposits. The excellent exposures on St. Eustatius have furnished sufficient data to construct separate maps of the distribution for each of these two types of deposit. These are shown in Figures 22 and 23. The maps show the maximum thicknesses for each type of deposit plotted against the position of the 28 stratigraphic sections. Figure 22 shows that the coarser block and ash deposits extend for a distance of 2.5 km from the crater rim of the Quill.

In contrast the associated dense andesite surge deposits (Figure 23) extend for 4.5 km, right up to the base of the hills of the Northern Center. Significantly the deposits of neither the main pyroclastic flow nor its accompanying surges are found in the Northern Hills (Section XXVIII).

As both coarse block and ash and dense andesite surge deposits form more or less simultaneously, the overall hazard presented by Pelean eruptions of the Quill is mainly restricted only to the Quill and its flanks. The hills of the Northern Center are probably relatively free from this hazard.[5]

3.5.2 Hazard presented by St. Vincent-type pyroclastic flows

Again the excellent exposures of the Quill permit separate hazard maps to be constructed for both the coarser grained scoriaceous pyroclastic flow deposits as well as the fine grained scoriaceous surge deposits. These maps are shown in Figures 24 and 25. The coarser grained scoriaceous pyroclastic flow deposits have much the same distribution as the block and ash flow deposits, extending up to 3.5 km from the rim of the Quill. In contrast, the scoriaceous surge deposits are found over a smaller area than their dense andesite counterparts and only extend for up to 4 km from the crater rim.

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[5] Continued excavations in 1989 at the oil tank farm revealed a single fine-grained block and ash flow deposit on these hills - indicating a minor risk there from Pelean-type activity.

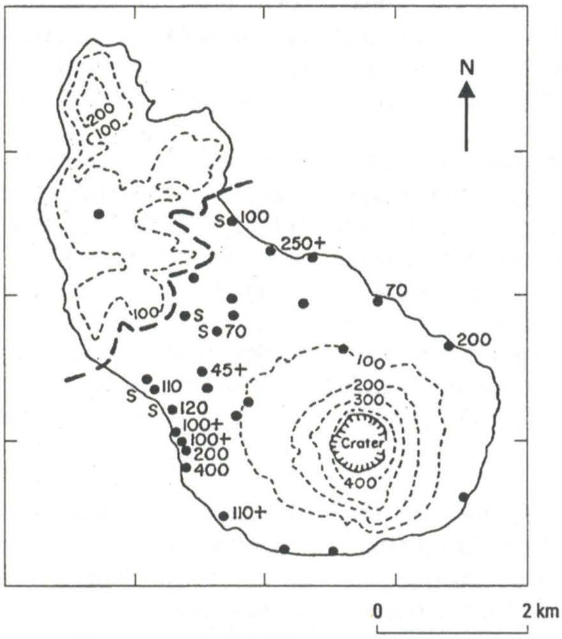

Figure 26 Distribution of semi-vesicular andesite deposits of pyroclastic flow and surge origins.

● Stratigraphic section without semi-vesicular andesite deposits
● S Locality of semi-vesicular andesite surge deposit(s)
● 100 Location and maximum thickness in cm of coarse semi-vesicular andesite flow deposit
● 45+ Base of deposit not found
Limit of the deposit.
100 Topographic contours in metres

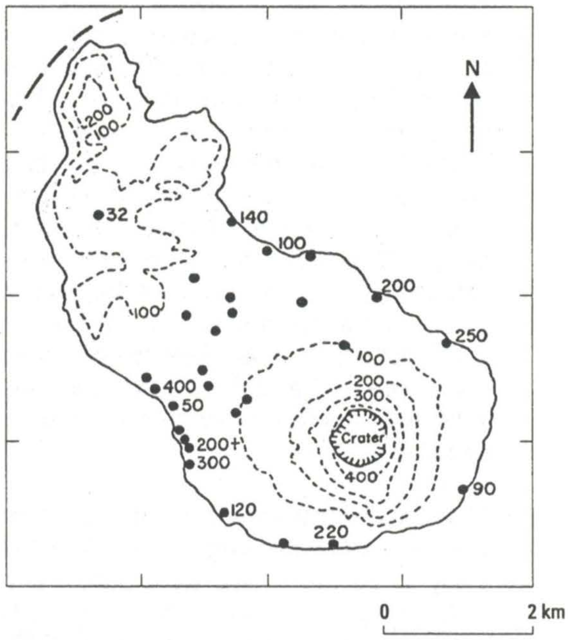

Figure 27 Distribution and maximum thicknesses of pumice flow deposits.

● stratigraphic section without pumice flow deposit
● 140 Maximum thickness in cm of pumice flow deposit
Limit of pumice flow deposit - somewhere offshore in all directions
100 Topographic contours in metres

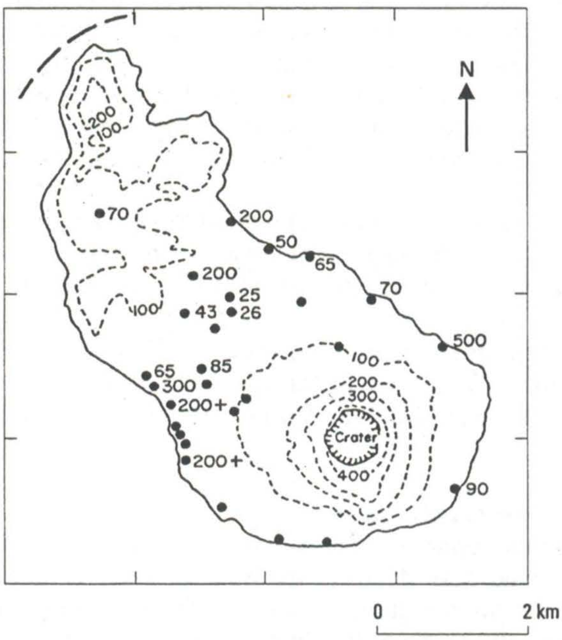

Figure 28 Distribution and maximum thicknesses of ash flow deposits.

● Location of stratigraphic section without ash flow deposits
● 300 Maximum thickness of ash flow deposit in cm
● 200+ Base of deposit not found
Limit of pumice flow deposit - somewhere offshore in all directions.
100 Topographic contours in metres

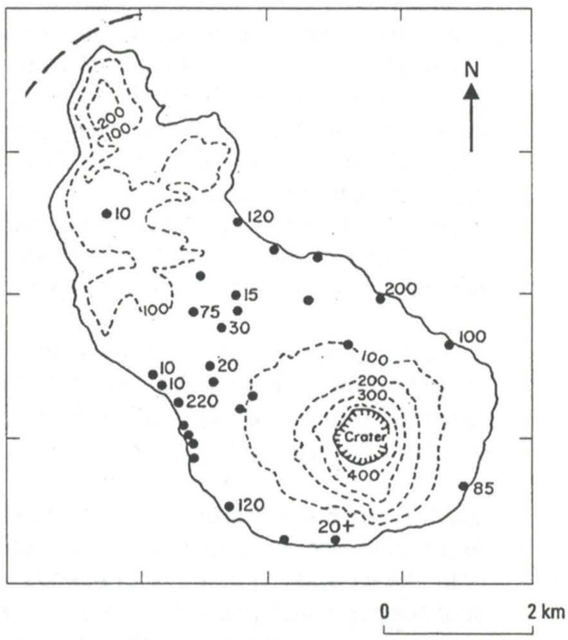

Figure 29 Distribution and maximum thicknesses of ash surge deposits.

● Location of stratigraphic section without ash surge deposits
● 120 Maximum thickness of ash surge deposit in cm
● 20+ Base of deposit not found
Limit of ash surges deposits - somewhere offshore in all directions
100 Topographic contours in metres

The hazard presented by the basaltic andesite scoria and ash flows (being the combined hazard of the above two types of deposit) for St. Eustatius is, therefore, regarded as being similar to that of andesite nuées ardentes. The main hazard zone includes the Quill and its flank deposits up to the hills of the Northern Center.

3.5.3 Hazard presented by pyroclastic flow and surge deposits of semi-vesicular andesite

These deposits are less common than the types previously discussed. The distribution of both pyroclastic flow and surge deposits of semi-vesicular andesite is presented in Figure 26. This clearly illustrates that the distribution and hazard presented by this type of activity is the same as that for the previous two types of pyroclastic flows, i.e. over the Quill and its flanks as far north as the hills of the Northern Center.

It should be pointed out that the groundsurges and ash clouds associated with nuées ardentes (3.5.1), scoria flows (3.5.2) and semi-vesicular andesite (3.5.3) could have climbed, at least part of the way up the hills of the Northern Center without leaving any appreciable deposit. Such a thin deposit could then be easily destroyed by rainfall so as to leave no trace of the passage of the cloud. Thus although no deposits of Pelean-, St. Vincent- or Asama-type eruptions are found in the hills of the Northern Center this does not necessarily mean that they have been or are completely free from any hazard.[6]

3.5.4 Hazard presented by pumice and ash flows and surges

The distribution and maximum thicknesses of pumice flow, ash flow and ash surge deposits are shown in Figures 27, 28 and 29 respectively. These deposits cover the entire flanks of the Quill and the ash flows and surge deposits were also found at locality XXVIII near Pisga Hill within the Northern Center. The latter occurrence indicates that ash flows and ash surges from the Quill were all able to surmount the hills of the Northern Center and leave behind a surviving deposit. The hazard from these types of eruption can therefore definitely be said to be island wide.

At locality XXVIII there are a total of 15 pyroclastic deposits from the Quill. Of these, ash flows are represented by 3 deposits while ash surges are represented by one deposit. Thus in the past 21,000 years only on 15 occasions have the hills in the northern part of the island been affected by pyroclastic events that left behind a deposit. As was mentioned previously, this does not mean that the northern part of the island was only affected by the products of pyroclastic eruptions 15 times but that the conditions were such that only 15 deposits have survived. The fact however that deposits of pumice and ash flows and surges are found at locality XXVIII whereas those of other types of pyroclastic flows are not, indicates that pumice and ash pyroclastic flows offer a much more significant hazard than do the previously described types.

If as we have postulated the Quill is presently in a St. Vincent-type stage of eruption then the possible recurrence of pumiceous activity is not great for the immediate future. However if sufficient time has elapsed since the last eruption, it is possible that the material in the magma chamber may have differentiated sufficiently to produce an upper zone of gas-rich andesite magma. If such a process has happened, then it is possible that pumiceous eruptions could be the initial phase of a new eruptive cycle.

3.5.5 Hazard presented by pumiceous airfall activity

Pumiceous bombs, lapilli and ash ejected vertically from the Quill fall back onto the island to build up a blanket of airfall deposits. The successive showers of airfall debris present a considerably smaller risk to human life than do the high temperature pyroclastic flows, although great thicknesses of airfall deposits can cause damage to buildings. The distribution of airfall lapilli beds (i.e. with andesite to rhyolite pumice clasts greater than 2 mm in diameter) is shown in Figure 30. The hazard presented by this type of coarse airfall deposit appears to extend to the Northern Center hills. However the finer grained airfall ash deposits of similar composition extend further afield (Figure 31). The main harm caused by airfall activity is the collapse of dwellings and the burial of fertile soils below sterile ash. The thickness given in Figures 30 and

[6] See previous footnote

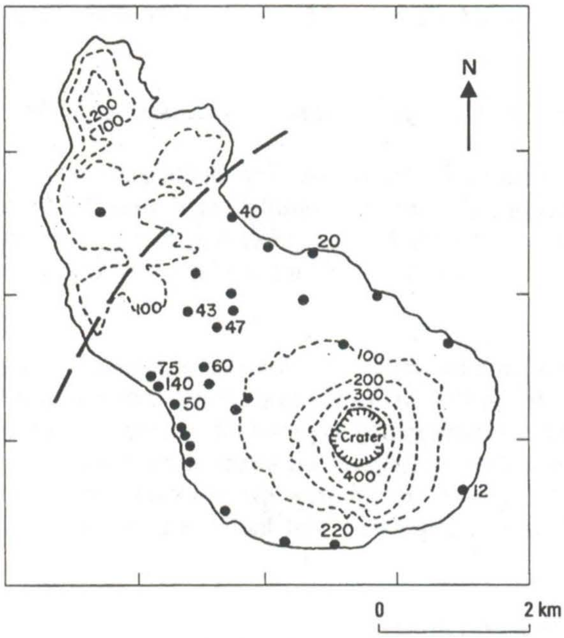

Figure 30 Distribution and maximum thicknesses of airfall pumiceous lapilli deposits (excluding basaltic andesite types).

- ● Location of stratigraphic section without airfall lapilli deposits
- ●75 Maximum thickness of airfall lapilli deposits
- - - Limit of airfall lapilli deposits
- -100 Topographic contours in metres

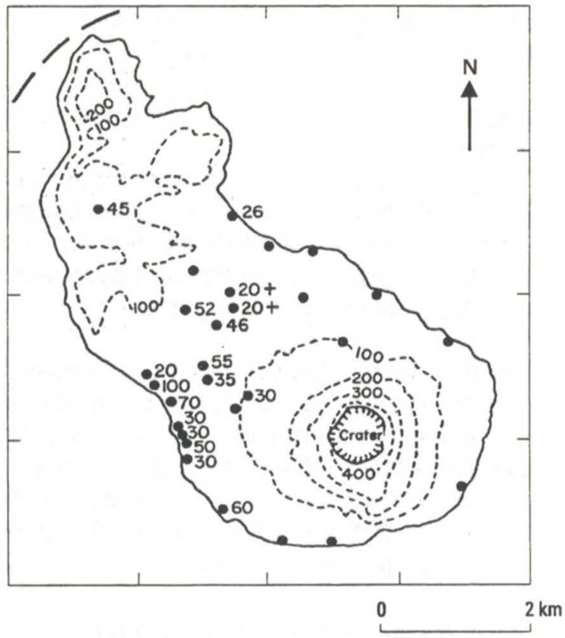

Figure 31 Distribution and maximum thickness of airfall ash deposits.

- ● Location of stratigraphic section without airfall ash deposits
- ●30 Maximum thickness of airfall ash deposits
- - - Limit of airfall ash deposit - somewhere offshore in all directions.
- -100 Topographic contours in metres
- ●20+ Bottom of deposit not found.

31 gives an idea of the order of magnitude of thicknesses which could result from a renewal of this type of activity.

3.5.6 Hazard presented by phreatic/phreatomagmatic eruptions

As in the case of all Lesser Antillean volcanoes there is always a risk of steam explosions during the opening stage of a renewal of activity. Such phreatic explosions result from the rise of magma (prior to extrusion) into water saturated rocks. Phreatic eruptions may produce very little surface deposit. One such deposit was recognized in stratigraphic column XXI. Such deposits are characteristically lacking in young magmatic materials and consist only of older mixed and altered rock fragments or baked lithics.

In the case of phreatomagmatic eruptions the steam explosions are accompanied by the ejection of new magmatic material. Some of the older flow and airfall deposits were probably formed by phreatomagmatic eruptions as many are extremely fine grained and rich in accretionary lapilli. On the basis of its grain size distribution and constituent components marker bed H is thought to be the product of a phreatomagmatic eruption. Juvenile magmatic lapilli are present in the deposit but much of the coarser material is made of lithic fragments. All of these larger clasts are coated by and contained in a very fine grained ash which is interpreted as representing very finely pulverized magma. Similar deposits were produced during the recent eruption of Soufriere, St. Vincent and were caused by the interaction of fresh magma with the water of a crater lake.

4 Conclusions and recommendations

4.1 Conclusions

The two volcanic islands of Saba and St. Eustatius both belong to the active arc of the Lesser Antilles. Both contain youthful looking volcanic cones, the Mountain on Saba and the Quill on St. Eustatius. Saba is clearly an active volcano as indicated by the presence of hot springs with temperatures around 72° and 55°C. The Quill even though it has no external manifestations, must still be regarded as an active volcano in a stage of dormancy (see footnote 4).

Each is a very different volcano. Saba has been built up mainly by repeated Pelean-type nuée ardent eruptions where dense andesite pyroclastic flows accompanied andesitic dome growth. The main hazard here is therefore from a renewal of this type of activity. Saba is very similar in structure to the active Soufriere Hills center of Montserrat and the extinct Pitons of Carbet center of Martinique.

In contrast the Quill is a complex pyroclastic volcano built up by a variety of different types of pyroclastic activity. These are pyroclastic flows of dense andesite, basaltic andesite, semi-vesicular andesite and pumiceous andesite to rhyolite, as well as surges and airfall deposits. The Quill is probably at present in an open crater basaltic andesite pyroclastic stage of activity and any renewal of activity will probably be of this type. Stratigraphically the Quill is very similar to Mt. Pelée, Martinique, but is in a different stage of activity to this volcano.

The last activity on Saba was around 1600 A.D., just before the European settlement, whereas the Quill last erupted around 400 A.D. The present periods of inactivity are not regarded by us as indicating extinction of these volcanoes but merely periods of dormancy similar to others in the past as evidenced by the presence of comparable paleosols.

One point however should be stressed again. For those volcanoes with no historic eruptions the history of the volcano has to be compiled from studying its stratigraphy. The various stratigraphic columns measured are invariably incomplete. Deposits from minor eruptions are generally not preserved and even deposits from major eruptions may be destroyed. The best example known to the writers of these features are the eruptions this century of Soufriere, St. Vincent. Within a few months after the termination of the explosive phase of the 1979 eruption of St. Vincent most of the flow deposits in the lower reaches of the valleys had been eroded away. The airfall ashes (except for sites close to the crater) had disappeared within a few weeks. This eruption caused the evacuation of the whole of the northern end of St. Vincent but geologically it will probably leave little record. An even more striking example is the deposit of the 1902 eruption of Soufriere, St. Vincent. In 1976 no primary pyroclastic deposits produced in this eruption could be positively identified in the lower parts of the Rabacca and Wallibou valleys. It was only around the crater and the top of the Larikai valley that these deposits were still preserved, and even these may now have been destroyed by the latest eruption. Thus evidence of a fairly large eruption (by modern Lesser Antillean standards) may not always appear in the geologic record.

In conclusion therefore it can be said that the overall level of volcanic hazard for Saba and St. Eustatius is typical of all islands in the Lesser Antilles active volcanic arc.

4.2 Recommendations

In view of the above conclusions we recommended that the Government of the Netherlands Antilles have available plans and funds for the evacuation of the populations of these islands in the event of a renewal of activity. Evacuation to the volcanically inactive island of St. Maarten would be best. With the present small populations (1300 on Saba and 2500 on St. Eustatius in January 1997) such an evacuation could be carried out in 1 to 2 days. In the event of signs of renewed activity (tremors, steam explosions) the population of St. Eustatius could be moved *temporarily* to the hills of the Northern Center prior to evacuation. In the case of Saba it is not possible to predict which sector of the flanks of this single cone would be affected by renewed activity. There is no short term temporary safe area as in St. Eustatius. The only evacuation

Fort Bay and the airstrip near Hells Gate both of which would probably have to be used by necessity.[7]

With the development of volcanology in the Lesser Antilles the risk to human life is not regarded as serious, although the need for evacuation may arise as has happened recently on St. Vincent, Guadeloupe and Montserrat. More attention should, if possible, be made to seismically monitor these two islands as is currently done on the French (L'Observatoire Géophysique du Globe) and former British islands (Seismic Research Unit). Such constant monitoring would provide a background with which to compare any unusual signs and also hopefully will provide an early warning of any type of renewed activity. Also on Saba the temperatures of the two hot springs should be recorded at least once a month to check for signs of steady temperature increase as might be expected in the years and months before an eruption.[8]

As soon as preliminary symptoms are noted qualified personnel should be brought in immediately to advise the local administration as to the progress of the activity. A list of qualified geologists with their addresses and telephone numbers should be given both to the local administrators on the two islands and to the central administration on St. Martin and is attached to this report. If the activity is only seismic in nature a temporary portable seismic array could be installed to monitor the frequency, location and depth of the earthquakes. Such information can help distinguish between the shocks preliminary to an eruption and a volcano-seismic crisis.

As the volcanic risk on these islands is no greater than for other islands of the volcanic arc, which have larger populations, we recommend that the population of the islands be made aware of the volcanic hazards so that, in the event of any renewal of activity, there will be a minimum of panic. We do not believe in shielding the population from this information and point out the program now in progress in the French islands where the population is being educated to volcanic hazards by means of films and lectures.

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[7] The construction of a new road to Well Bay has by 1994, provided a third evacuation point, although this bay can be much affected by surf.

[8] The same for the hot groundwater recently discovered on St. Eustatius.

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6 Appendices

Explanatory note on Appendices

The purpose of this report is primarily to assess volcanic hazard. The basic petrographic, geochemical and grain size analysis data are used mainly to confirm the terminology used in the report. These data are represented in abbreviated form as a series of appendices, including a glossary of geological terms used. This permits a wider readership of the hazard report. To include laboratory data in the report would limit the readership to specialists. We realize that the data have greater interest in the scientific fields, but feel that this is outside the scope of the report. As Roobol and Smith have freely included their National Science Foundation-funded research data in the report, it is planned that the full (non-hazard oriented) write up of the laboratory data be presented in the international scientific literature. This in an obligation which Roobol and Smith also have as recipients of N.S.F. grants.

An assessment of volcanic hazard on the islands of Saba and St. Eustatius in the northern Lesser Antilles by M.J. Roobol, A.L. Smith & J.F. Tomblin

Erratum

p. 69, Appendix A
The telephone number of Dr. A.L. Smith should read:
+1-787-832-4040 ext. 3845 (or ext. 3452).
Additional fax numbers of Dr. A.L. Smith are:
+1-787-833-8433 and +1-787-265-5408.

Appendix A

List of qualified geological organizations and volcanologists with Caribbean experience who might be contacted in case of volcanic eruption or volcano-seismic crisis (updated to January 1997):

Seismic Research Unit, University of the West Indies, St. Augustine, Trinidad, Tel. +1-809-6624659.

U.S. Geological Survey, Volcano Crisis Assessment Team (VCAT), Vancouver, Washington, U.S.A., Tel. +1-360-696 7693.

Dr. M. Feuillard: Observatoire Volcanologique de la Soufrière, 97L Saint-Claude, Guadeloupe, F.W.I., Tel. +590-991 133, Fax +590-991 134.

Dr. R. Fiske, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560, U.S.A., Tel. +1-202-357 1300.

Dr. G. Mattioli, Department of Geology, University of Puerto Rico, Mayaguez, Puerto Rico 00681, Tel. +1-787 832-4040, Ext. 3845 or 2014, Fax +1-787-265-3845.

Dr. M.J. Roobol, Department of Geology, University of Puerto Rico, Mayaguez, Puerto Rico 00681. Also: PO Box 345, Jeddah, Saudi Arabia, Fax +966-2-665 4848 and 665 1859.

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Dr. H. Sigurdsson, Graduate School of Oceanography, University of Rhode Island, Kingston, Rhode Island, 02881, U.S.A., Tel. (401) 792-6222.

Dr. A.L. Smith, Department of Geology, University of Puerto Rico, Mayaguez, Puerto Rico 00681, Tel. +1-787-832-3845, (or ext.-3452) Fax +1-787-265 3845.

Dr. J.F. Tomblin, St. John's, Antigua, West Indies (October to April), Tel. +1-268-463 6048, Fax +1-268-462 2327 or Giens, France (May to September), Tel. +33-4-9458-2201.

Dr. J.P. Viode, Observatoire Volcanologique, Morne des Cadets, Fonds Saint-Denis, Martinique, F.W.I., Tel. +596-784 141.

Dr. S. Young, British Geological Survey, Kingsley Dunham Centre, Nottingham, NG12 5GG, United-Kingdom, Tel. +44-115-936 3199, Fax +44-115-936 3475.

Appendix B
Glossary of Terms

Accretionary lapilli
Spheres composed of fine ash, up to 1 cm in diameter, often found in fine ash deposits of airfall or flow origin. They form by the accretion of fine ash due to a variety of causes: raindrops on ash, moist ash or accretion around an electrically charged particle.

Active arc
In the case of the Lesser Antilles, the arc of islands from Saba through St. Eustatius, St. Kitts, Nevis, Montserrat, Basse Terre, Dominica, Martinique, St. Lucia, St. Vincent to Grenada. This active arc is still building up by volcanic action.

Active volcano
A volcano with the potential to erupt. Usual characteristics are the presence of extremely young deposits and/or presence of hot springs or fumaroles indicating the presence of young material still in the process of cooling within the volcano.

Activity (volcanic)
Any behavior of a volcano from tremors to fumarolic to eruption.

Adit
A mining term referring to a horizontal tunnel.

Airfall (fall deposit)
A process by which fragmented molten rock ejected from a volcano arrives at the land surface. In this case, by showers of debris which fall as individual particles along trajectories depending on physical properties and gravity. This process is distinct from that of pyroclastic flows.

Amerindian
The original Indian population of the Caribbean islands believed to have migrated from South America along the Lesser Antilles and then along the Greater Antilles. These populations were largely extinguished following European discovery, hence, pre- and post-Colombian periods.

Andesite
A light colored lava usually rich in large crystals of feldspar and either pyroxene or hornblende. The most common rock in the Lesser Antilles. The cliffs of Fort Bay, Saba, are composed of andesite.

Antidune (structure)
In surge deposits, a heap of ash which migrates up current towards the vent, which is the opposite direction to that of dune migration.

Ash
Pyroclastic ejecta finer grained than 2 mm.

Ash flow
A moving pyroclastic flow, composed of a hot, dense suspension of ash-sized materials and gas. The resulting deposit is an ash flow deposit.

Ash surge
A moving pyroclastic surge, composed of a hot, low-density suspension of ash and gas. It produces a surge deposit.

BP
These letters follow all C^{14} ages given in years. They mean 'before present', which is taken at 1950 A.D.

Basalt
A dark colored, heavy rock rich in iron and magnesium which forms lava flows or black colored pyroclastic material.

Basaltic andesite
A dark, blue-black colored lava intermediate in composition between basalt and andesite. The airstrip on Saba is built on the end of a basaltic andesite lava flow.

Blocks
Angular pyroclasts of diameter greater than 64 mm (2.5 inches). These are ejected either as solids or as magma too viscous to flow.

Block and ash flow deposit
The main coarse-grained product of Pelean type nuée ardente eruptions. The deposit typically consists of angular to sub-angular clasts of dense andesite up to 6 m in diameter set in a fine gray or pink ash matrix. The deposits typically lack sorting with coarse and fine material intermixed.

Bombs
Pyroclastic ejecta with diameters greater than 64 mm (2.5 inches). Bombs are ejected as molten rocks and their shape becomes modified during their flight through air.

C^{14} dating (radiocarbon dating)
The determination of the age of a material by measuring the proportion of the isotope C^{14} (radiocarbon) in ancient carbon. The method is suitable for the determination of ages up to a maximum of about 40,000 years.

Carbonized wood
Pyroclastic flow and surge deposits usually contain fragments of wood up to tree trunk size which have been broken off and transported by the flow. On being deposited the heat of the clasts converts the wood to charcoal.

Clast
An individual fragment produced by any process of physical disintegration. On the Caribbean volcanoes, the processes are pyroclastic explosions and erosion.

Column collapse
A mechanism which can generate either pyroclastic flows or surges. An upward directed eruptive column (either sustained or intermittent) becomes overloaded with debris at a particular height and the column collapses under the effect of gravity.

Correlation of stratigraphy
The identification of the same deposit in several different places. This is done by means of any unusual features in a deposit in otherwise monotonous sequences. Such features may be type of deposit, color, texture, grain size, presence of mixed magma clasts, etc.

Crater
A bowl or funnel shaped depression usually in the top of a volcano caused by the outward explosion of material. Craters have diameters less than 5 km. Larger depressions are called calderas and form by the inward subsidence of the volcano.

Dacite
Light colored lava, rich in silica and poor in iron and magnesium.

Dome
A pile of lava heaped up around the vent because its high viscosity does not permit it to flow away as a lava flow. The many conical hills on Saba are domes.

Dormant volcano (dormancy)
A period of inactivity by a volcano which is still potentially active. It is often difficult to decide if a volcano is dormant or extinct, especially in the case of volcanoes which erupt only very infrequently (e.g., once per 1,000 years).

Dune structures
Within surge deposits these are small ash hills rather like small sand dunes which migrate away from the volcano in the gas blast.

Early warning phenomena
In the Lesser Antilles the rise of hot molten rock into the volcano is usually accompanied by inflation of the volcano, tremors, phreatic activity and even mudflows caused by expulsion of the water table. All these are early warning phenomena which can give months or even years of indications of a coming eruption.

Extinct/dead volcano
A volcano which is completely inactive and will not undergo any further activity. For example, the volcanic islands of St. Maarten, St. Barts, Barbuda, and Antigua are part of an extinct volcanic arc which has been inactive for the past 7 million years. These extinct volcanoes have been much eroded by the sea and then capped by younger limestone.

Flanks of a volcano (volcano's flanks)
These are the lower slopes of the volcano with angles of 12° and less, which usually form fertile land. On Saba, the flanks are submarine but on St. Eustatius the flanks of the Quill form the flatter central part of the island.

Frequency of activity of volcanoes
For volcanoes with centuries of historic observation, it is possible to have some idea of the frequency of activity (e.g., one eruption per century). In the Caribbean, where the period of written history is, at best, only 350 years, the frequency can only be estimated by careful stratigraphic correlation and C^{14} dating.

Fumarolic activity
The emission of fumes or vapors often associated with hot springs or geysers. This activity indicates the presence of molten or hot rock at a high level within the volcano and is a criterion for identifying active volcanoes.

Gut
A term used on St. Eustatius for the narrow, vertical walled gullies eroded into the unconsolidated pyroclastic deposits of the flanks of the Quill.

Historic records
In the Lesser Antilles, the only historic records are those written by the Europeans and subsequent settlers. The pre-Columbian Amerindians left no written records, although much information can be deduced from their archaeological remains.

Island arc
A curved chain of islands usually arcuate towards the open ocean. They are composed of either active or extinct volcanoes, or both.

Juvenile (clasts, components, magma)
Meaning the new, or youthful, magmatic material being erupted. In older deposits, clasts formed from the erupted magma as distinct from accidental clasts of even older rocks.

Lithified
The complex processes of devitrification (the breakdown of volcanic glass) that converts loose volcanic deposits, such as ash, into a rock. In the Lesser Antilles, all pyroclastic deposits older than about 70,000 years are lithified. For younger deposits, lithification depends on rainfall and vegetation cover. On Saba, deposits high on the Mountain (Mt. Scenery) are lithified, while the same deposits in the drier, more arid, coastal strips, are unlithified. Terms used are lithified, weakly lithified and un- or non-lithified.

Magma
Molten rock, rich in gases, with temperatures between 900^{o} and 1,100^{o}C, derived from within the earth. Magmas vary greatly in composition and cool to form different volcanic rocks such as basalt, basaltic andesite, andesite, dacite and rhyolite.

Mantle bedding
A diagnostic feature of airfall deposits where the pyroclastic beds or strata mantle, or blanket, the underlying topography in a similar manner to a blanket thrown over a chair.

Marker deposit (markers)
Deposits with some distinct characteristics which can be used to identify the same deposit in different places (see 'Stratigraphic correlation').

Mixed magma clast
A clast in which two different types of lava, usually pale colored andesite and dark colored basaltic andesite, are both present. The two components are flow-banded together showing that magma mixing occurred before fragmentation.

Mixed magma deposit
A deposit containing an abundance of mixed magma clasts.

Nuée ardente
Burning cloud or glowing avalanche. The term was introduced by Alfred LaCroix to describe the pyroclastic flows from Mt. Pelée in the 1902-1903 eruption. At night, these clouds glow and are incandescent.

Palaeosol
A buried ancient soil. In pyroclastic sequences, these mark the periods of dormancy and allow the different beds to be grouped into the many eruptive events.

Parasitic or flank eruption
An eruption through the side or flank of a volcano, rather than through the centrally positioned main vent.

Phreatic
Exploding groundwater due to the rise of high-temperature magma into the water table. The deposits are made up of fragments of older rocks forming the local land surface.

Phreatomagmatic
Similar to phreatic in mechanism, but here, some of the molten material, or juvenile magma, is also ejected.

Pumice (pumiceous)
Highly vesiculated rock, regardless of composition. Most pumices are usually of rhyolitic, dacitic, or andesitic compositions.

Pumice flows
A moving pyroclastic flow, rich in pumiceous lapilli and blocks. After deposition, the degassed materials are called a pumice flow deposit or ignimbrite or welded tuff.

Pyroclastic (pyroclast)
'Fire-broken' rock or magma fragmented by explosive volcanic activity while hot.

Pyroclastic activity
Explosions or extrusions producing pyroclastic materials. Such activity may be independent of, or accompany the extrusion of lava flows and domes.

Pyroclastic deposit
A deposit composed of pyroclasts, or fragments, resulting from volcanic explosions. This is the most common type of deposit which has built up the islands of the Lesser Antilles.

Pyroclastic flow (deposit)
A high-temperature, dense flow of hot lava/pumice clasts of all sizes, and gas. Coarse blocks are transported near the ground surface while the ash-gas cloud rises and spreads laterally. Such flows can be channeled by valleys and can attain velocities in excess of 100 km per hour. The resulting deposit is typically unsorted with large clasts contained in an ashy matrix.

Pyroclastic hazard
Danger presented by the various types of pyroclastic activity of which the volcano is capable. The different types of activity likely to occur in the future of an active volcano can be deduced from the careful study of the already existing deposits.

Pyroclastic stratigraphy
See 'stratigraphic' sections.

Radiocarbon dating
See 'C^{14} dating'.

Rhyolite
A light colored, light-weight lava which is poor in iron and magnesium and rich in silica. This is usually the most viscous of magmas and forms domes and explosive eruptions. It is the least common lava type in the Lesser Antilles.

Scoria
Pyroclastic ejecta of irregular form, dark in color and rich in gas cavities. In the Lesser Antilles, scoria are composed of basalt or basaltic andesite.

Scoria and ash flow (deposits)
A moving pyroclastic flow where the clasts are composed of basalt or basaltic andesite. The resulting deposit is unsorted with large, rounded clasts up to 1 m in diameter set in a fine, dark, ash matrix..

Seismic monitoring
This involves the setting up of a network of seismometers in order to detect the faintest tremors and determine their source. In this manner, the first stirrings indicating the rise of molten rock into the volcano can be detected long before any surface indications are noticed All of the Lesser Antillean volcanic islands are covered by such networks except Saba and St. Eustatius.

Semi-vesicular
A term used to describe a gray andesite with an abundance of small, spherical vesicles whose bulk density lies midway between that of pumice ($<1.0 \pm 0.1$ gm/cm^3) and dense andesite (1.8-2.0 gm/cm^3).

Spine
A steep-sided projection of lava extruded usually through a growing dome. The largest spine ever witnessed rose vertically through the 1903 dome on Mt. Pelée, Martinique. It grew for 9 months and stood almost 1,000 feet high and was known as the Great Spine of Pelé before it crumbled away.

Steam explosion
A phenomenon associated with phreatic activity. Groundwater and hot molten rock meet and a steam explosion may result.

Stratigraphic sections (stratigraphy)
The sections seen in sea cliffs, road cuts, and landslip scars which show the pyroclastic layers stacked one on top of the other. These are the pages of the stratigraphic book. The subject of stratigraphy involves measuring up or logging the different beds and identifying their age and origin to reconstruct the volcano's history.

Surge (deposit)
Also ground and base surges: a low density, pyroclastic flow, rich in gas and poor in clasts which are usually of ash size. Although these produce a relatively minor type of deposit, their high temperatures and wide distribution makes them a major volcanic hazard. It was surges, and not the main pyroclastic flow, which destroyed the city of St. Pierre in 1902, although situated 8 km from the central vent of Mt. Pelée.

Tremors
Very weak earthquakes.

Vesicular
Used to describe rock possessing gas bubbles, or vesicles.

Volcano
A hill or mountain built up by the accumulation of volcanic materials, also the site where molten rock and gas issue from the earth's interior onto the surface. In the Caribbean, there is a common belief in country people that the volcano is only the steep sided top of the cone and that the flanks, which are fairly flat lying, are unrelated to the volcano. For stratigraphic and hazard purposes, the limits of the volcano are the limits of its deposits.

Volcanic arc
An island arc.

Volcanic hazard
An assessment of areas likely to be affected by the different types of activity. These include pyroclastic hazards, phreatic and phreatomagmatic hazards, hazards of lava flows and domes, and seismic hazard.

Volcano-seismic crisis
A happening not at all uncommon in the Lesser Antilles. They result when molten material rises high into the volcano and causes all of the usual early warning phenomena but then the molten rock returns to depth without being erupted. During such crises it is not possible to decide whether an eruption will occur. The phreatic activity alone usually justifies evacuation.

Appendix C
Petrography of the Saba volcanic rocks

Introduction

The samples were classified according to the scheme of Gunn et al. (1980) into basalts (SiO_2 < 52%); basaltic andesites (SiO_2 52-56%); andesites (SiO_2 56-63%); dacites (SiO_2 63-68%) and rhyolites (SiO_2 >68%).
All of the samples examined are porphyritic and the phenocryst minerals are similar to those found in other Lesser Antillean volcanic rocks, namely plagioclase, olivine, clinopyroxene, orthopyroxene, amphibole, magnetite, and quartz. 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 oxides.

Basalts

Of the three samples classified as basalts only one (SA 141) represents a primary volcanic deposit. The other two are found as inclusions in andesitic lavas.

The dominant phenocryst in the basalts is plagioclase, which generally occurs as inclusion-free crystals. Highly pleochroic brown amphibole is the most abundant mafic mineral, which in one sample is partly replaced by clinopyroxene. The only other abundant mafic mineral is clinopyroxene; minor orthopyroxene is present in only one sample (SA 157), whereas olivine is lacking entirely.

Basaltic Andesites

As with the basalts, these are also highly porphyritic. Plagioclase is the most abundant phenocryst in the basaltic andesites and is present both as inclusion-rich and inclusion-free crystals. The dominant mafic minerals are clinopyroxene and amphibole, the former generally being the more abundant. Three varieties of amphibole are observed: in one there is no sign of reaction; while in the other two the original amphibole has been partly to completely replaced by iron oxide or pyroxene respectively. Phenocrysts of olivine are found in almost half of the basaltic andesite samples, while quartz xenocrysts rimmed by pyroxene are found in three samples.

Andesites

This is the dominant rock type on Saba. All are highly porphyritic with plagioclase, both clear and inclusion-rich, forming the dominant phenocryst phase. Clinopyroxene is present in all samples, whereas orthopyroxene is relatively uncommon and only occurs in significant amounts in the more silicic varieties. Olivine is also present in the majority of the samples and is especially abundant in the more basic andesites. Quartz xenocrysts, often rimmed by pyroxene are found in approximately two-thirds of the samples. Amphibole is again present as the three varieties already described. The fact that the unaltered variety sometimes rims the other two suggests at least two different periods of amphibole crystallization. In the more basic andesites, the amphibole crystals tend to be rather small. In rocks with 60% $Si0_2$ (or greater) amphibole becomes the dominant ferromagnesian phenocryst mineral.

Dacites

The dacite samples come from two distinct types of deposit - clasts from air-fall deposits and clasts from pyroclastic flow deposits. The former are characterized by zoned, clear plagioclase, green pleochroic amphibole and oxide phenocrysts with minor quartz xenocrysts in a vesicular glassy matrix. The latter contains in addition to the above minerals crystals of orthopyroxene and clinopyroxene generally in a microcrystalline groundmass.

Reference

Gunn, B.M., Roobol, M.J. and Smith, A.L., 1980: Geochemistry of the volcanoes of Basse Terre, Guadeloupe - an example of intra-island variation.- Bull. Volcanol., 43-2, p.403-411.

Appendix D
Petrography of the St. Eustatius volcanic rocks

Introduction
The samples were classified according to the scheme of Gunn et al. (1980) into basalts ($Si0_2$ <52%); basaltic andesites ($Si0_2$ 52-56%); andesites ($Si0_2$ 56-63%) and rhyolites ($Si0_2$ >68%).

All of the samples examined are porphyritic, although the dacites and rhyolites usually contain only a few phenocrysts. The dominant minerals in nearly all rocks are plagioclase, orthopyroxene, clinopyroxene and magnetite, with olivine and amphibole showing a more sporadic distribution. Typical groundmass textures range from microcrystalline to glassy, with the dominant groundmass minerals in all but the dacites and rhyolites, being plagioclase, pyroxene and oxides.

Basalt
Only one sample studied can be classified as a basalt. The dominant phenocryst in this sample is plagioclase which occurs both as inclusion-free and inclusion-bearing crystals. The most abundant mafic mineral is pyroxene, with clinopyroxene exceeding orthopyroxene in abundance. Clinopyroxene also occurs as rims around orthopyroxene phenocrysts. The other mafic minerals present include pleochroic amphibole (colorless to olive green) which has a slight reaction rim around it, and sporadic crystals of olivine.

Basaltic Andesites
The nine samples of basaltic andesite studied are all highly porphyritic, with, as in all other volcanics from St. Eustatius, plagioclase representing the most abundant phenocryst. In some samples glomeroporphyritic clusters of plagioclase rich in glass inclusions are common. The mafic minerals are the same as those already described from the basalts. However, in the case of the basaltic andesites, it is usually orthopyroxene that is the dominant mafic phenocryst. Olivine is still only a minor accessory mineral, whereas amphibole, present as both partly to completely replaced crystals as well as those showing no sign of reaction, occurs in two-thirds of the samples.

Andesites
As on Saba this is the dominant rock type on St. Eustatius. Plagioclase is again the dominant phenocryst phase. Two pyroxenes are present in all samples, with orthopyroxene usually being the more abundant. Olivine appears to be more abundant in the andesites than in the more basic rocks, although in nearly every sample it shows a reaction rim of pyroxene. Amphibole is present as both pleochroic (colorless to olive green) and non- pleochroic varieties and occurs in crystals that may show partial replacement by pyroxene and oxide or lack such reaction relationships. Amphibole phenocrysts are only sporadically developed in rocks with less than 60% $Si0_2$. In the more silica-rich andesites, amphibole although present in all samples, only makes up a small percentage of the phenocryst phases.

Dacites
All the dacites studied are glass-rich highly vesicular rocks containing phenocrysts of amphibole, plagioclase and microphenocrysts of orthopyroxene set in a pumiceous groundmass.

Rhyolites
The rhyolites are all pumiceous rocks containing inclusion-rich plagioclase and pleochroic amphibole with or without orthopyroxene. However in those samples that contain orthopyroxene it is usually this mineral that is the most abundant mafic component.

Reference

Gunn, B.M., Roobol, M.J. and Smith, A.L., 1980: Geochemistry of the volcanoes of Basse Terre, Guadeloupe - an example of intra-island variation.- Bull. Volcanol., 43-2, p. 403-411.

Appendix E
Geochemistry of Saba and St. Eustatius

Fifty-six samples from Saba and forty-three samples from St. Eustatius were crushed for chemical analysis at the Seismic Research Unit, University of the West Indies, Trinidad. Major and eight trace element analyses were made commercially at the Centre National de la Recherche Scientifique, Centre de Recherches Pétrographiques et Géochimiques, 15 Rue Notre Dames des Pauvres, Vandoeuvre-les-Nancy, France. A full description of the laboratory methods known as 'automated optical emission spectrochemical bulk analysis with microwave plasma excitation' together with data for accuracy and precision is described by Govindaraju et al. (1976) and Govindaraju (1979). All analyses are thought to represent porphyritic magmatic compositions. As many of the samples are from pyroclastic deposits this was achieved by selecting one or more large clasts. In this manner the ratio of phenocrysts to groundmass glass is preserved. In no case were mixed samples of ash (crystals and glass) and larger clasts analyzed, as such bulk samples have undergone mechanical separation at the time of eruption and the bulk compositions are not the same as the magma prior to eruption (Roobol, 1976).

The recalculated anhydrous analyses together with the trace elements and hydrous totals are listed for the two islands in Tables E1 and E2 (analyses arranged in order of increasing silica content). Two additional analyses of soda rhyolite from St. Eustatius, selected from unpublished data of Smith and Roobol, are included as Table E3. The correct rock names and locality data for the analyzed samples are listed in Tables E4 and E5. Further locality data is also shown in Figures E1 and E2.

Normative calculations were made for the analyzed samples by Dr. F. Beunk of the University of Amsterdam. The norms were calculated following the rules set out by C.S. Hutchinson (1975, Schweiz. Min. Petrogr. Mitt. 55, p. 243-256). A fixed oxidation ratio of $Fe_20_3/(Fe_20_3 + Fe0) = 0.27$ was assumed, following G.M. Brown et al. (1977). Six different types of norms were calculated:

a. CIPW standard norm
b. Niggli cata-norm
c. A volume norm based on the CIPW standard
d. CIPW norm with biotite and hornblende
e. Barth meso-norm
f. A volume norm based on the CIPW norm with biotite and hornblende

Differentiation Index and Crystallization Index were calculated from the CIPW standard norm. The CIPW standard norms and indices are listed in Tables E6 and E7.

The analyzed suite of rocks from Saba spans the silica range from 51 to 65% while those from St. Eustatius range from 51-71%. Thus on Saba basalts (up to 52% silica), basaltic andesites (52-56% silica), andesites (56-63% silica) and dacites (63-69% silica) are present. Similar rocks on St. Eustatius are present but also rhyolites (more than 69% silica). The rhyolites are present only as pyroclastic deposits on St. Eustatius. The chemical data serves to demonstrate the ranges in composition of magmas erupted on each island, however it does not indicate the relative proportions of the different rocks on the islands. For example basalts are very rare on Saba. Only one of the analyzed Saban samples (SA 141) represents an erupted basaltic magma. This sample was collected from the deeply eroded Torrens Point center where it is present as an airfall lapilli and ash deposit. The other basalt analyses from Saba are all of small inclusions found within andesite lavas. No other basalts are known on Saba and it must be concluded that these basaltic inclusions are derived from the older submarine core of Saba and are picked up by the viscous andesite magmas as they move up through the cone. Some of these inclusions may also represent the oceanic crust upon which the island is built.

The new geochemical data from each island represents only one volcanic center in each case - the Saban complex, and the Quill of St. Eustatius. There is no mixing of data such as combining the chemistry of the Quill with that of the older Northern Center of St. Eustatius.

In Figure E3 ($Na_20 + K_20$ vs. $Si0_2$ or Kuno diagram) each volcano has a distinct and different trend. The rocks from Saba plot slightly obliquely across the lower boundary of the high-alumina magma series. The Quill series as a whole has lower soda plus potash and plots below this boundary. None of the samples can be regarded as truly representing the high-alumina series because they contain abundant phenocrysts. In Figure E4 the data are plotted on K_20 - $Si0_2$ diagrams showing the field boundaries of Peccerillo and Taylor (1976). Again the two volcanoes are distinct, with the Quill showing a low-K magma series, whereas the Saban rocks are all calc-alkaline. The two volcanoes are again distinct in the Ca0 - Na_20 - K_20 and AFM diagrams of Figures E5 and E6. On the AFM diagram the tholeiitic trend of Thingmuli is plotted, as is the calc-alkaline trend of the Cascades (after Carmichael, 1964). The volcanics from both Saba and the Quill can be seen to be not sufficiently enriched in iron to be termed tholeiitic. For a fuller discussion of this subject the reader is referred to Brown et al. (1977) and Smith and Roobol (1990, p. 74).

It can be concluded that major element diagrams as well as trace element plots (not shown here) can be used to show that the magma series of Saba and the Quill are distinct and belong to a different magma series in the sense of Peccarillo and Taylor (1976). This distinction in chemical type between two volcanic cones is similar to that reported for different volcanoes on the larger islands of the central Lesser Antilles such as in Martinique and Guadeloupe (Smith et al., 1980 and Gunn et al., 1980).

On all variation diagrams the rocks of Saba were divided into the older lithified deposits (i.e. older than about 70,000 years) shown in open circles and younger deposits shown in filled circles. This was done to check if there has been any change in magma chemistry with time. There is no evidence for this on the diagrams and each volcano has erupted one distinct magma series throughout its history. Any future activity on Saba is therefore expected to produce more calc-alkaline magmas, as in the past. In contrast, in the case of the Quill any future magmas will, like all others for this volcano, be of the low-K magma series.

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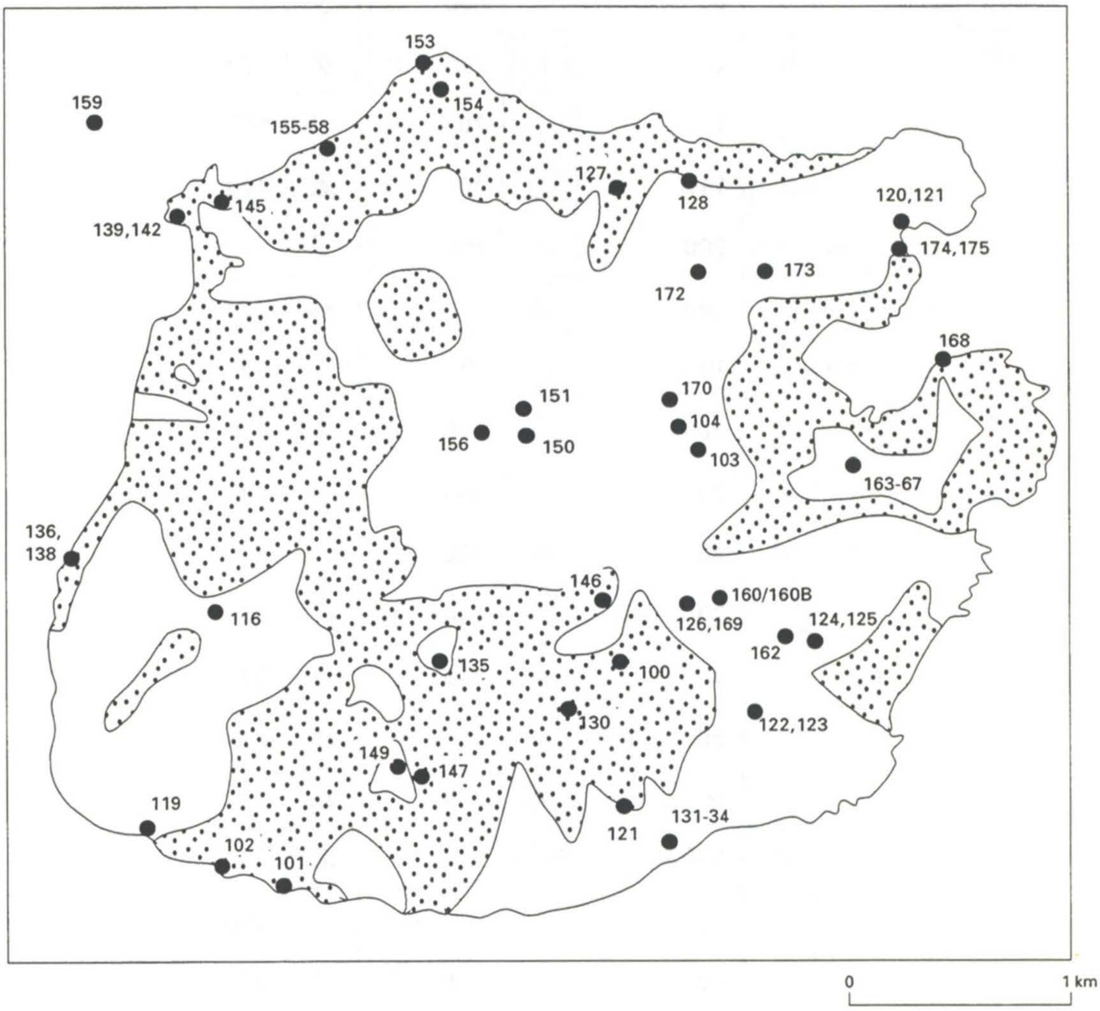


Figure E1 Sample locality map of Saba showing positions of analysed samples. Stippled areas are 'older' lithified deposits, probably older than 70,000 years. Blank areas are younger deposits.

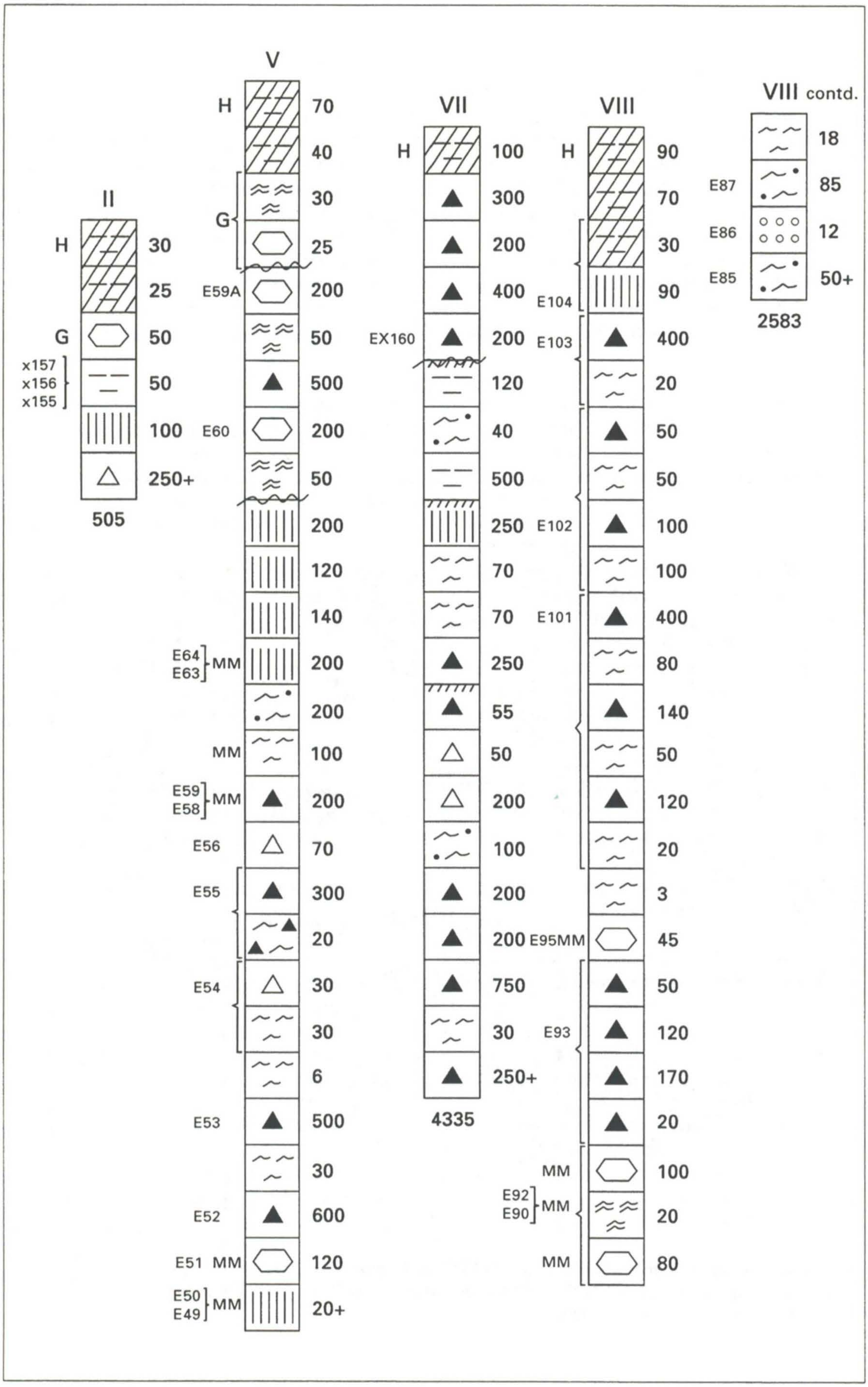


Figure E2 Selected stratigraphy columns from St. Eustatius showing locations of analyzed samples.

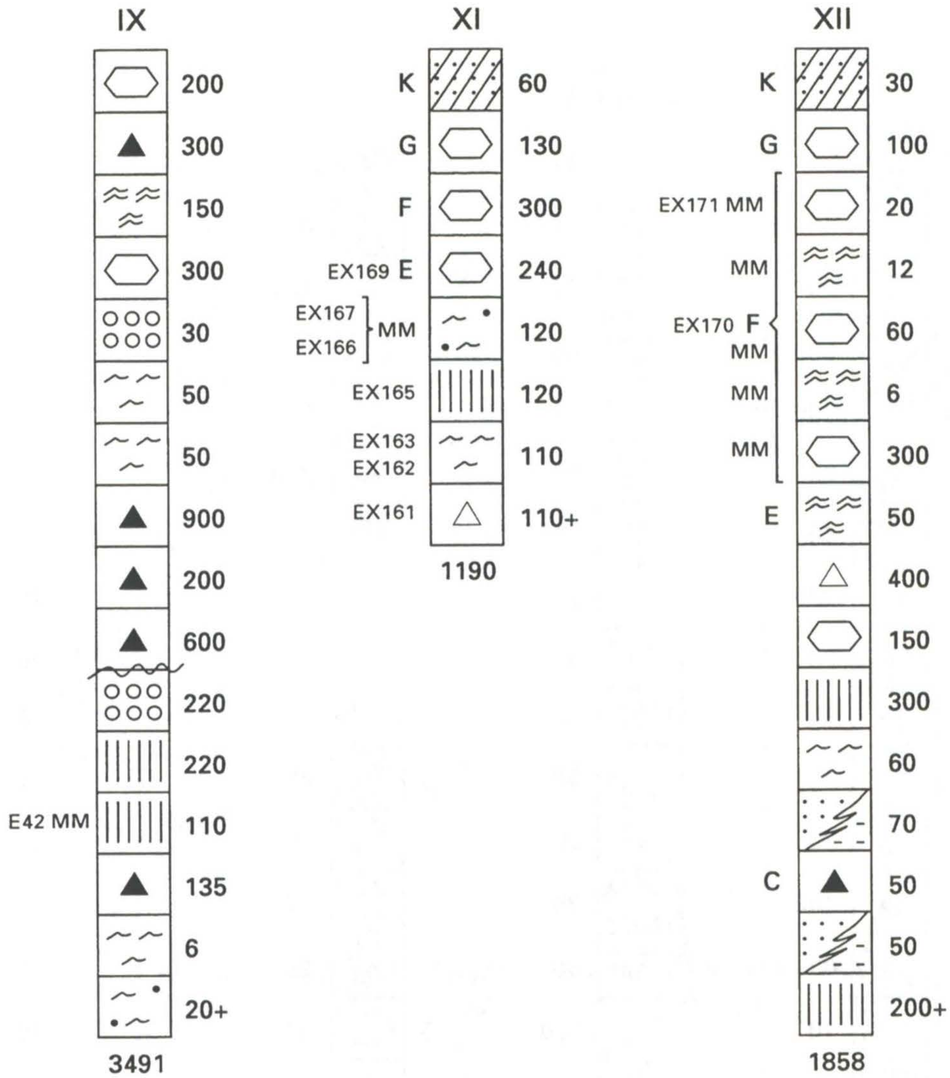


Figure E2 (continued)

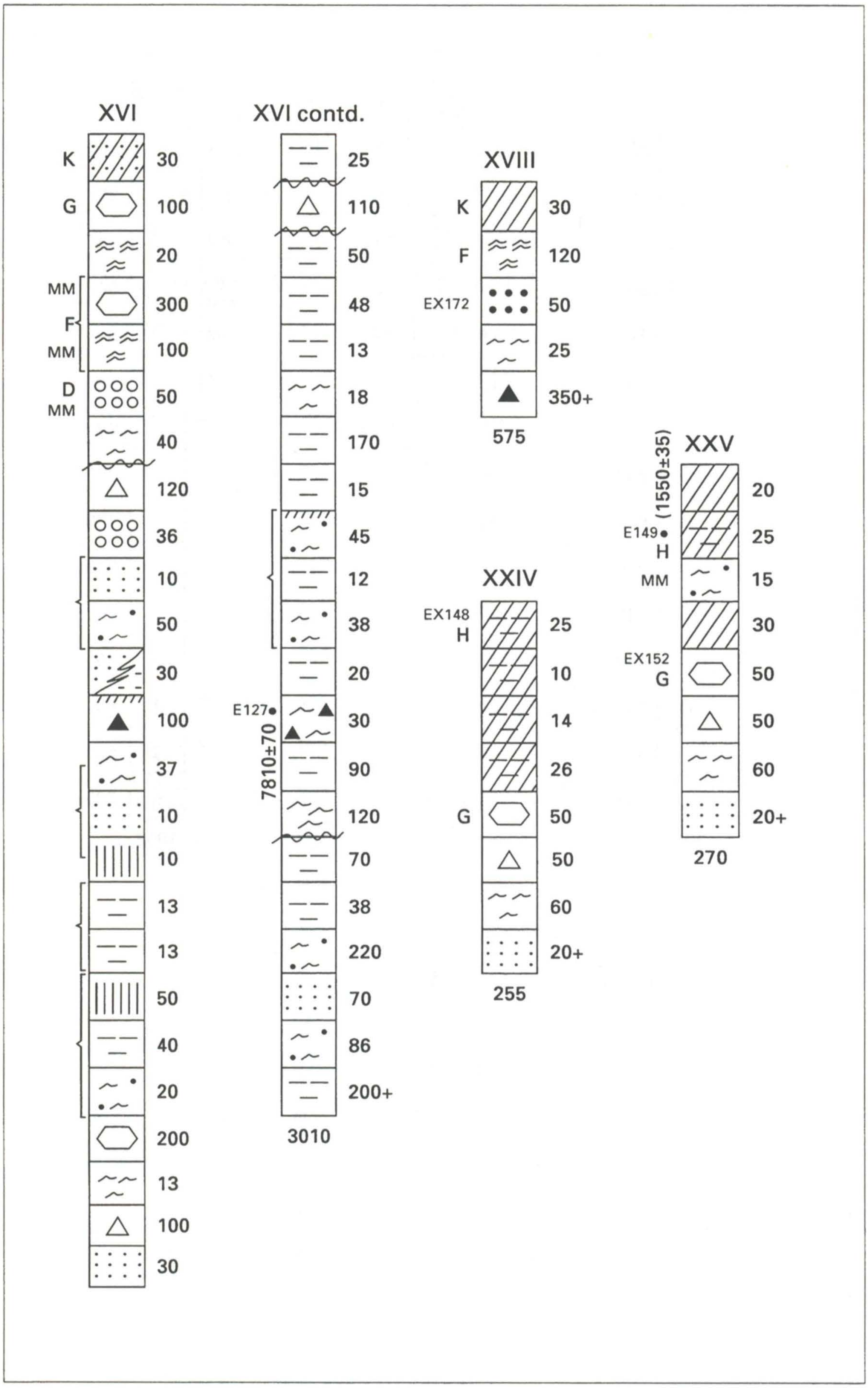


Figure E2 (continued)

TABLE E1 Chemical analyses of volcanic rocks of Saba (analyses arranged in order of increasing silica content)

	SA141	SA175	SA157	SA134	SA123	SA104	SA160B
SiO_2	51.00	51.05	51.17	53.02	53.86	54.17	54.41
Al_2O_3	19.97	16.35	17.63	18.18	17.82	17.30	17.52
$Fe_2O_3^*$	8.44	8.78	9.07	8.62	7.84	7.57	7.29
MnO	0.16	0.17	0.15	0.16	0.17	0.17	0.17
MgO	4.82	8.92	6.28	5.33	6.83	6.85	6.90
CaO	11.00	10.51	10.94	9.99	9.01	9.05	8.74
Na_2O	3.03	2.70	2.84	2.96	2.95	3.06	3.33
K_2O	0.63	0.56	0.85	0.82	0.98	0.84	0.71
TiO_2	0.90	0.87	0.93	0.91	0.41	0.99	0.86
P_2O_5	0.05	0.07	0.12	0.01	0.12	Tr	0.06
Hydrous Total	98.74	99.16	98.51	98.15	98.53	99.89	98.23
Ba	188	182	225	251	238	269	282
Co	95	71	123	81	144	93	82
Cr	33	519	83	38	206	239	195
Cu	70	77	81	106	62	43	<10
Ni	40	165	79	38	182	106	110
Sr	306	262	521	437	275	287	252
V	254	266	317	283	246	231	235
Rb	12	10	12	14	<10	<10	14
Zn	87	73	68	70	67	73	63

	SA168	SA160	SA121	SA158	SA152	SA166	SA165
SiO_2	54.88	54.96	55.28	55.47	55.63	55.71	55.88
Al_2O_3	17.69	17.39	16.91	18.74	17.32	18.23	17.17
$Fe_2O_3^*$	7.46	7.28	7.94	7.85	7.51	7.59	7.06
MnO	0.15	0.20	0.25	0.22	0.16	0.18	0.14
MgO	5.93	6.77	6.62	3.76	5.97	4.71	6.27
CaO	9.04	8.47	8.38	8.71	8.54	8.50	8.48
Na_2O	3.22	3.34	3.17	3.58	3.15	3.38	3.18
K_2O	0.80	0.80	0.96	0.82	0.88	0.86	0.91
TiO_2	0.66	0.77	0.33	0.74	0.73	0.72	0.78
P_2O_5	0.16	0.01	0.15	0.10	0.14	0.11	0.12
Hydrous Total	98.60	98.53	98.74	98.33	97.85	98.50	97.99
Ba	271	305	324	318	316	305	296
Co	127	110	66	136	64	142	257
Cr	170	196	217	22	157	85	205
Cu	33	<10	65	71	14	72	39
Ni	107	124	97	64	90	98	176
Sr	314	258	289	385	313	364	312
V	205	234	199	207	192	194	203
Rb	17	12	25	15	<10	15	14
Zn	75	74	84	79	71	81	70

$Fe_2O_3^*$ All iron as ferric oxide
Tr Trace
Hydrous Total Total of above oxides in hydrous analysis
nd Not determined
Major elements in weight percent, trace elements in ppm

TABLE E1 (continued)

	SA164	SA172	SA173	SA120	SA163	SA128	SA154
SiO_2	56.00	56.05	56.15	56.31	56.67	56.71	56.74
Al_2O_3	17.08	17.03	17.16	17.31	17.36	17.20	16.18
$Fe_2O_3^*$	7.15	7.07	7.22	6.99	6.92	7.11	6.97
MnO	0.17	0.14	0.14	0.17	0.15	0.16	0.13
MgO	6.27	6.43	5.97	6.27	5.52	5.68	6.85
CaO	8.35	8.32	8.25	8.29	8.29	8.09	8.22
Na_2O	3.18	3.13	3.18	3.25	3.30	3.32	3.16
K_2O	0.96	1.07	1.01	1.08	0.89	1.00	0.98
TiO_2	0.66	0.70	0.72	0.27	0.75	0.68	0.75
P_2O_5	0.18	0.06	0.21	0.07	0.15	0.06	Tr
Hydrous Total	100.07	99.03	97.51	99.43	99.88	99.31	99.20
Ba	289	325	333	324	320	359	299
Co	70	59	82	124	95	79	97
Cr	212	201	194	204	162	192	312
Cu	19	37	41	61	33	55	39
Ni	177	109	105	188	104	100	145
Sr	310	303	304	297	332	320	251
V	194	206	197	204	175	285	242
Rb	20	18	18	21	13	16	19
Zn	nd	73	71	68	73	80	59

	SA146	SA142	SA101	SA127	SA124	SA170	SA103
SiO_2	57.42	58.07	58.41	58.42	58.64	58.80	58.95
Al_2O_3	16.75	17.53	18.02	17.55	17.28	17.31	17.21
$Fe_2O_3^*$	6.60	6.70	6.41	6.68	6.28	6.43	6.36
MnO	0.15	0.15	0.14	0.17	0.14	0.15	0.16
MgO	5.85	4.07	3.56	3.82	4.43	4.28	4.33
CaO	8.26	8.13	7.75	7.94	7.80	7.93	7.57
Na_2O	3.26	3.36	3.45	3.53	3.27	3.36	3.52
K_2O	1.03	1.21	1.29	1.14	1.21	1.05	1.19
TiO_2	0.64	0.66	0.83	0.75	0.79	0.54	0.71
P_2O_5	0.05	0.11	0.13	Tr	0.15	0.14	Tr
Hydrous Total	99.32	97.78	99.96	98.51	98.67	97.87	100.39
Ba	310	340	403	412	321	356	390
Co	71	82	59	58	107	87	164
Cr	149	70	26	44	102	84	105
Cu	46	30	34	40	36	35	29
Ni	240	45	52	33	140	52	144
Sr	253	288	306	334	263	333	321
V	216	181	205	214	199	181	176
Rb	17	20	23	24	<10	21	24
Zn	64	67	69	82	64	74	78

$Fe_2O_3^*$	All iron as ferric oxide
Tr	Trace
Hydrous Total	Total of above oxides in hydrous analysis
nd	Not determined

Major elements in weight percent, trace elements in ppm

TABLE E1 (continued)

	SA125	SA119	SA156	SA174	SA138	SA149	SA150
SiO_2	58.99	59.22	59.23	59.26	59.42	59.46	59.63
Al_2O_3	17.94	17.74	18.29	16.97	17.26	16.48	17.34
$Fe_2O_3^*$	6.25	5.87	6.16	6.22	6.82	6.48	6.34
MnO	0.11	0.14	0.13	0.13	0.14	0.16	0.15
MgO	3.73	3.81	3.15	4.60	3.44	4.91	4.30
CaO	7.21	7.79	7.43	7.42	7.43	7.47	7.08
Na_2O	3.37	3.56	3.77	3.49	3.48	3.29	3.39
K_2O	1.37	1.19	1.22	1.26	1.30	1.08	1.02
TiO_2	0.90	0.68	0.58	0.62	0.64	0.55	0.59
P_2O_5	0.11	Tr	0.03	0.03	0.06	0.12	0.15
Hydrous Total	97.54	99.33	99.67	98.35	99.41	97.04	97.27
Ba	341	389	433	401	409	349	397
Co	49	73	123	52	67	56	97
Cr	72	82	41	183	24	108	88
Cu	290	26	50	24	77	91	<10
Ni	83	48	54	72	30	76	71
Sr	282	281	377	316	425	300	306
V	189	200	203	150	196	162	150
Rb	<10	27	22	21	21	18	<10
Zn	67	68	64	69	68	58	70

	SA151	SA155	SA136	SA133	SA139	SA102	SA147
SiO_2	59.65	60.05	60.12	60.25	60.30	60.47	60.59
Al_2O_3	17.52	17.27	17.66	17.19	17.09	17.80	17.58
$Fe_2O_3^*$	6.39	6.27	6.66	6.27	5.95	5.80	6.64
MnO	0.15	0.13	0.17	0.17	0.12	0.13	0.15
MgO	4.10	3.27	2.74	3.28	3.61	2.98	2.69
CaO	6.97	7.42	7.29	7.32	7.28	7.05	7.01
Na_2O	3.36	3.60	3.54	3.46	3.58	3.52	3.60
K_2O	1.01	1.25	1.10	1.37	1.38	1.40	1.13
TiO_2	0.57	0.59	0.58	0.63	0.58	0.78	0.52
P_2O_5	0.26	0.13	0.14	0.06	0.10	0.05	0.07
Hydrous Total	98.22	97.55	99.09	97.29	99.43	99.58	99.87
Ba	387	444	377	410	415	454	390
Co	70	109	73	69	178	57	55
Cr	78	40	17	33	76	22	21
Cu	<10	61	<10	31	32	18	10
Ni	58	54	25	28	73	34	33
Sr	299	379	338	347	310	296	343
V	145	204	142	173	158	141	152
Rb	<10	24	16	23	26	16	21
Zn	73	66	78	65	62	61	77

$Fe_2O_3^*$	All iron as ferric oxide
Tr	Trace
Hydrous Total	Total of above oxides in hydrous analysis
nd	Not determined

Major elements in weight percent, trace elements in ppm

TABLE E1 (continued)

	SA116	SA153	SA126	SA122	SA159	SA130	SA100
SiO_2	60.67	60.81	60.94	61.06	61.07	61.08	61.36
Al_2O_3	18.02	16.86	17.83	17.32	17.15	17.56	17.11
$Fe_2O_3^*$	6.14	6.13	5.61	5.52	5.62	6.12	5.32
MnO	0.16	0.15	0.15	0.12	0.14	0.17	0.11
MgO	2.52	3.25	2.62	3.94	3.05	2.47	3.61
CaO	6.97	7.14	6.93	6.73	6.83	7.16	6.73
Na_2O	3.66	3.53	3.62	3.53	3.70	3.65	3.64
K_2O	1.20	1.38	1.37	1.35	1.42	1.18	1.45
TiO_2	0.58	0.63	0.75	0.30	0.60	0.54	0.61
P_2O_5	0.09	0.15	0.01	Tr	0.12	Tr	0.06
Hydrous Total	99.83	98.29	98.73	98.78	99.28	98.05	98.18
Ba	424	421	396	379	488	413	421
Co	317	154	43	53	102	45	62
Cr	19	33	19	98	55	16	72
Cu	68	14	15	<10	15	<10	19
Ni	221	72	40	54	33	15	135
Sr	345	359	330	257	328	357	262
V	154	172	141	162	174	126	154
Rb	25	14	22	35	25	21	21
Zn	77	64	69	55	63	76	64

	SA169	SA162	SA131	SA145	SA167	SA132	SA135
SiO_2	62.90	63.18	64.17	64.22	64.28	64.52	64.62
Al_2O_3	16.21	17.06	16.63	16.36	16.97	16.76	16.53
$Fe_2O_3^*$	5.22	5.42	4.69	4.91	5.00	4.78	4.96
MnO	0.11	0.16	0.13	0.14	0.15	0.16	0.14
MgO	3.50	2.37	2.73	2.58	1.93	2.06	2.22
CaO	6.45	6.11	5.98	5.91	5.83	5.75	5.78
Na_2O	3.54	3.74	3.13	3.73	3.86	3.82	3.60
K_2O	1.47	1.24	2.03	1.69	1.43	1.66	1.58
TiO_2	0.49	0.58	0.49	0.46	0.42	0.47	0.49
P_2O_5	0.09	0.15	0.01	Tr	0.12	Tr	0.06
Hydrous Total	99.15	97.48	95.89	96.97	97.60	97.35	96.72
Ba	405	456	449	455	486	541	459
Co	54	105	50	70	48	63	68
Cr	75	36	34	34	17	20	18
Cu	<10	<10	16	98	<10	<10	<10
Ni	44	62	22	40	19	20	17
Sr	259	333	265	259	334	289	310
V	160	127	124	137	117	99	105
Rb	26	20	33	29	25	28	24
Zn	64	67	61	60	66	59	69

$Fe_2O_3^*$ All iron as ferric oxide
Tr Trace
Hydrous Total Total of above oxides in hydrous analysis
nd Not determined
Major elements in weight percent, trace elements in ppm

TABLE E2 Chemical analyses of volcanic rocks of St. Eustatius (analyses arranged in order of increasing silica content)

	EX148	EX152	EX171	EX172	EX170	E104	EX173
SiO_2	51.20	52.45	53.35	53.96	54.25	54.86	55.10
Al_2O_3	20.65	19.50	18.97	19.05	18.44	18.48	18.63
$Fe_2O_3^*$	9.47	9.13	8.83	8.61	9.21	8.64	8.44
MnO	0.18	0.17	0.17	0.18	0.17	0.17	0.17
MgO	4.91	4.72	4.59	4.52	4.27	4.27	4.25
CaO	9.63	9.64	9.48	9.13	8.98	8.91	8.69
Na_2O	2.64	2.95	3.07	3.03	3.12	3.16	3.18
K_2O	0.25	0.38	0.48	0.49	0.52	0.51	0.56
TiO_2	0.99	0.97	0.92	0.89	0.90	0.90	0.83
P_2O_5	0.07	0.07	0.13	0.14	0.15	0.09	0.15
Hydrous Total	97.91	97.16	99.29	99.37	99.16	98.39	99.57
Ba	102	98	110	114	103	107	114
Co	121	120	67	54	68	164	54
Cr	31	29	28	31	17	28	29
Cu	316	287	10	37	44	179	66
Ni	40	41	57	71	98	48	97
Sr	292	274	286	287	274	257	267
V	206	201	244	248	224	185	227
Rb	<10	<10	11	11	12	<10	12

	E51	E59A	E90	EX163	EX169	E60	E92
SiO_2	55.30	55.52	55.79	56.03	56.45	56.89	57.11
Al_2O_3	17.87	18.27	18.09	18.24	18.18	17.83	17.90
$Fe_2O_3^*$	7.87	7.92	7.79	7.84	8.17	7.78	7.50
MnO	0.16	0.16	0.16	0.17	0.17	0.17	0.17
MgO	5.17	4.24	4.09	4.24	3.82	4.08	3.85
CaO	8.91	9.13	8.65	8.86	8.33	8.38	8.27
Na_2O	3.37	3.30	3.55	3.27	3.36	3.28	3.71
K_2O	0.48	0.59	0.63	0.46	0.57	0.55	0.63
TiO_2	0.75	0.77	0.78	0.80	0.80	0.83	0.79
P_2O_5	0.12	0.10	0.46	0.07	0.14	0.11	0.06
Hydrous Total	98.56	98.65	99.17	99.59	100.19	100.00	98.58
Ba	105	114	121	118	123	122	127
Co	94	77	116	108	44	111	86
Cr	82	33	34	40	23	36	37
Cu	13	28	20	15	16	21	14
Ni	62	38	64	46	31	49	36
Sr	225	279	259	274	262	258	248
V	184	213	172	186	198	186	169
Rb	11	10	10	<10	13	<10	<10

$Fe_2O_3^*$	All iron as ferric oxide
Tr	Trace
Hydrous Total	Total of above oxides in hydrous analysis
nd	Not determined

Major elements in weight percent, trace elements in ppm

TABLE E2 (continued)

	EX165	EX167	E93	EX103	EX155	EX102	EX101
SiO_2	57.38	57.53	57.59	57.61	57.77	57.87	57.92
Al_2O_3	18.04	17.94	17.92	17.94	17.85	17.81	17.77
$Fe_2O_3^*$	7.75	7.71	7.49	7.62	7.36	7.55	7.57
MnO	0.17	0.17	0.17	0.17	0.17	0.17	0.17
MgO	3.64	3.70	3.76	3.64	4.17	3.58	3.64
CaO	8.10	7.96	8.22	8.10	8.01	7.93	7.94
Na_2O	3.46	3.49	3.44	3.43	3.30	3.47	3.49
K_2O	0.60	0.58	0.56	0.61	0.49	0.66	0.61
TiO_2	0.78	0.77	0.75	0.76	0.79	0.85	0.79
P_2O_5	0.07	0.15	0.10	0.12	0.09	0.12	0.10
Hydrous Total	98.60	99.19	99.92	99.08	98.85	100.29	100.09
Ba	129	130	125	124	126	131	134
Co	74	81	143	75	92	100	92
Cr	37	30	32	29	55	29	30
Cu	17	23	18	31	14	16	18
Ni	36	42	44	31	54	44	36
Sr	261	251	242	245	230	249	249
V	171	183	160	155	158	161	160
Rb	11	15	12	<10	14	10	11

	EX166	EX161	E95	EX162	E55	EX160	E49
SiO_2	57.95	58.01	58.07	58.07	58.25	58.29	58.56
Al_2O_3	17.75	17.83	17.69	17.79	17.63	17.56	17.26
$Fe_2O_3^*$	7.66	7.54	7.37	7.55	7.49	7.47	7.08
MnO	0.17	0.17	0.17	0.17	0.16	0.17	0.17
MgO	3.53	3.64	3.62	3.59	3.74	3.59	3.74
CaO	7.92	7.96	7.91	7.94	7.85	7.89	7.55
Na_2O	3.59	3.40	3.69	3.39	3.51	3.54	4.19
K_2O	0.59	0.56	0.65	0.62	0.54	0.59	0.62
TiO_2	0.73	0.81	0.74	0.79	0.70	0.80	0.69
P_2O_5	0.11	0.08	0.09	0.08	0.13	0.09	0.14
Hydrous Total	97.25	99.92	99.12	99.96	98.59	99.48	97.44
Ba	133	128	126	130	121	131	131
Co	55	60	82	65	112	79	101
Cr	28	33	31	37	39	35	52
Cu	14	33	18	25	<10	21	<10
Ni	33	36	39	31	34	47	41
Sr	247	245	233	253	235	254	239
V	159	160	154	162	141	169	161
Rb	11	10	11	11	11	11	12

$Fe_2O_3^*$ All iron as ferric oxide
Tr Trace
Hydrous Total Total of above oxides in hydrous analysis
nd Not determined
Major elements in weight percent, trace elements in ppm

TABLE E2 (continued)

	E50	E54	E63	E52	EX157	E42	E86
SiO_2	58.60	58.89	58.92	58.97	59.40	59.40	59.91
Al_2O_3	17.17	17.59	17.86	17.55	17.51	17.13	17.30
$Fe_2O_3^*$	6.93	6.86	7.14	7.15	7.13	7.01	6.85
MnO	0.17	0.17	0.17	0.17	0.16	0.17	0.17
MgO	3.67	3.27	3.26	3.43	3.29	3.49	3.14
CaO	7..59	7.27	7.40	7.65	7.38	7.46	7.20
Na_2O	4.50	4.52	3.78	3.69	3.59	3.80	3.97
K_2O	0.66	0.65	0.62	0.66	0.66	0.78	0.62
TiO_2	0.72	0.68	0.71	0.70	0.70	0.64	0.69
P_2O_5	Tr	0.10	0.14	0.02	0.09	0.11	0.14
Hydrous Total	96.49	94.69	99.50	98.45	97.89	98.53	96.94
Ba	145	127	138	131	136	136	137
Co	52	37	113	83	78	68	115
Cr	47	32	31	38	35	28	32
Cu	<10	<10	12	<10	<10	<10	<10
Ni	40	27	64	36	46	36	46
Sr	244	236	231	238	235	232	225
V	160	135	140	156	143	152	122
Rb	11	11	11	10	12	12	11

	E64	EX156	E58	E53	E59	E85	E56	E87
SiO_2	60.51	60.57	60.65	60.90	60.93	61.08	61.21	61.30
Al_2O_3	17.37	17.33	16.99	17.15	17.02	17.43	17.50	17.18
$Fe_2O_3^*$	6.69	6.75	6.77	6.59	6.62	6.75	6.47	6.69
MnO	0.16	0.17	0.18	0.18	0.17	0.17	0.17	0.17
MgO	2.73	2.91	2.82	2.84	2.86	2.64	2.57	2.61
CaO	6.74	7.02	6.93	6.96	6.87	6.73	6.65	6.73
Na_2O	4.21	3.66	4.19	4.02	4.01	3.75	3.99	3.84
K_2O	0.79	0.76	0.72	0.65	0.77	0.70	0.66	0.70
TiO_2	0.65	0.74	0.64	0.64	0.63	0.61	0.69	0.63
P_2O_5	0.14	0.09	0.11	0.08	0.12	0.14	0.10	0.16
Hydrous Total	97.31	98.47	96.87	100.04	97.95	98.50	97.44	99.03
Ba	138	145	140	146	137	140	142	146
Co	81	79	73	79	66	53	82	153
Cr	22	29	27	31	28	19	21	20
Cu	29	<10	<10	<10	<10	<10	<10	10
Ni	31	39	25	33	28	31	28	66
Sr	220	243	235	257	236	217	239	231
V	100	137	129	146	129	109	116	117
Rb	12	12	13	11	11	11	12	11

$Fe_2O_3^*$	All iron as ferric oxide
Tr	Trace
Hydrous Total	Total of above oxides in hydrous analysis
nd	Not determined

Major elements in weight percent, trace elements in ppm

TABLE E3 Soda rhyolites from St. Eustatius

	E14	E 15
SiO_2	69.36	71.48
Al_2O_3	14.78	14.97
Fe_2O_3*	3.38	2.89
MnO	0.23	0.22
MgO	0.83	0.36
CaO	5.09	3.46
Na_2O	5.10	5.40
K_2O	0.89	0.92
TiO_2	0.23	0.18
P_2O_5	0.13	0.13
Cu	43	40
Ni	12	11
Sr	346	271
Rb	16	16
Y	24	25
Zr	184	217

Fe_2O_3* All iron as ferric oxide

Major elements in weight percent, trace elements in ppm

TABLE E4 Specimen list of analysed samples from Saba

O denotes older lithified stratigraphic units
Y denotes younger weakly lithified to non-lithified stratigraphic units

O-SA 100	Andesite dome	Peak Hill
O-SA 101	Andesite dome	East of Fort Bay
O-SA 102	Andesite dome	Fort Bay
Y-SA 103	Andesite block & ash	New roadcut, English Quarter
Y-SA 104	Basaltic andesite scoria & ash	Between Upper Hell's Gate & English Quarter
Y-SA 116	Andesite block & ash	Cistern pit of hospital, The Bottom
Y-SA 119	Andesite block & ash	West of Fort Bay
Y-SA 120	Andesite scoria & ash	The Cove
Y-SA 121	Basaltic andesite	Inclusion in SA 120, The Cove
Y-SA 122	Andesite dome	Booby Hill
Y-SA 123	Basaltic andesite	Inclusion in SA 122, Booby Hill
Y-SA 124	Andesite dome	The Level
Y-SA 125	Andesite	Inclusion in SA 124
Y-SA 126	Andesite semi-vesicular block & ash	Between Windward Side and the Level
O-SA 127	Andesite block & ash	Island Gut
Y-SA 128	Basaltic andesite/andesite lava	Behind the Ridge flow
O-SA 130	Andesite block & ash	Ridge above Fence Quarter
Y-SA 131	Dacite pumice airfall lapilli	Fence Quarter
Y-SA 132	Dacite mixed-magma block	Between Wash & Swanna Guts
Y-SA 133	Andesite mixed magma block	Between Wash & Swanna Guts
Y-SA 134	Basaltic andesite nodules	In the above deposit
Y-SA 135	Dacite airfall lapilli	Behind generator house
Y-SA 136	Andesite block & ash	Gulley immediately north of Ladder
Y-SA 138	Andesite block & ash	Gulley immediately north of Ladder
O-SA 139	Andesite lava	Torrens Point
O-SA 141	Basalt airfall bombs & lapilli	Torrens Point
O-SA 142	Andesite block & ash	Torrens Point
Y-SA 145	Dacite pumice airfall lapilli	Mary's Point
O-SA 146	Andesite lava	Maskehorne Hill
O-SA 147	Andesite lava	St. John's Flat
Y-SA 149	Andesite pumice, mixed-magma	St. John's Flat
Y-SA 150	Andesite dome	The Mountain
Y-SA 151	Andesite dome	The Mountain
Y-SA 152	Basaltic andesite/andesite dome	The Mountain
O-SA 153	Andesite block & ash	Great Point
O-SA 154	Andesite lava	Grey Hill
O-SA 155	Andesite block & ash	Northwest coast
O-SA 156	Andesite block & ash	Northwest coast
O-SA 157	Basalt inclusion in block & ash	Northwest coast
O-SA 158	Basaltic andesite, inclusion	Northwest coast
O-SA 159	Andesite lava	Diamond Rock, NW of Saba
Y-SA 160	Andesite/basaltic andesite block & ash	Booby Hill, R. Hassel's garden
Y-SA 160B	Basaltic andesite	Inclusion in SA 160, Booby Hill
Y-SA 162	Dacite block & ash	The Level (100m from Lookout)
Y-SA 163	Andesite block & ash	Spring Bay
Y-SA 164	Red andesite lava flow	Spring Bay
Y-SA 165	Basaltic andesite scoria & ash	Spring Bay
Y-SA 166	Basaltic andesite	Inclusion in SA 165, Spring Bay
Y_SA 167	Dacite block & ash	Spring Bay
O-SA 168	Andesite/basaltic andesite	Old Booby Hill (inclusion in lava)
Y-SA 169	Andesite dome	Kate's Hill

TABLE E4 (continued)

Y-SA 170	Andesite lava	Spring Bay Flat
Y-SA 172	Basaltic andesite/andesite	Lava channel, Lower Hell's Gate
Y-SA 173	Basaltic andesite/andesite	Lava levée, Lower Hell's Gate
O-SA 174	Andesite dome	Kelbey's Ridge
O-SA 175	Basalt	Inclusion in SA 174, Kelbey's Ridge

TABLE E5 Specimen list of analyses samples from St. Eustatius

E 42	Dark andesite from mixed-magma flow banded pumice & ash flow deposit	Section IX
E 49	Dark andesite from mixed-magma flow banded pumice & ash flow deposit	Section V
E 50	Dark andesite. Same deposit as E 49	Section V
E 51	Basaltic andesite. Scoria & ash flow deposit	Section V
E 52	Andesite breadcrust bomb. Block & ash flow deposit	Section V
E 53	Andesite. Block & ash flow deposit	Section V
E 54	Andesite. Block & ash flow deposit	Section V
E 55	Andesite. Block & ash flow deposit	Section V
E 56	Andesite. Block & ash flow deposit	Section V
E 58	Andesite. Pumiceous surge deposit	Section V
E 59	Andesite. Block & ash flow deposit	Section V
E 59A	Andesite. Block & ash flow deposit	Section V
E 60	Basaltic andesite. Scoria & ash flow deposit	Section V
E 63	Dark andesite. Pumice and ash flow	Section V
E 64	Light andesite. Pumice & ash flow	Section V
E 85	Andesite. Pumiceous surge deposit	Section VIII
E 86	Andesite. Airfall lapilli deposit	Section VIII
E 87	Andesite. Pumiceous surge deposit	Section VIII
E 90	Basaltic andesite. Scoria & ash flow deposit	Section VIII
E 92	Basaltic andesite. Same deposit as E 90	Section VIII
E 93	Andesite. Block & ash flow deposit	Section VIII
E 95	Andesite. Block & ash flow deposit	Section VIII
E 101	Andesite. Block & ash flow deposit	Section VIII
E 102	Andesite. Block & ash flow deposit	Section VIII
E 103	Andesite. Block & ash flow deposit	Section VIII
E 104	Basaltic andesite. Mixed-magma pumice & ash flow deposit	Section VIII
EX 148	Basalt. Marker bed H	Section XXIV
EX 152	Basalt. Marker bed G	Section XXV
EX 155	Andesite. Pumice & ash flow deposit	Section II
EX 156	Andesite. Same deposit as EX 155	Section II
EX 157	Andesite. Same deposit as EX 155	Section II
EX 160	Andesite. Block & ash flow deposit	Section VII
EX 161	Andesite. Block & ash flow deposit	Section XI
EX 162	Andesite. Surge deposit with dense clasts	Section XI
EX 163	Andesite. Same deposit as EX 162	Section XI
EX 165	Andesite. Mixed-magma pumice & ash flow deposit	Section XI
EX 166	Andesite. Mixed magma surge deposit. Basal marker bed E	Section XI
EX 167	Dark andesite. Mixed-magma surge deposit. Basal marker bed E	Section XI
EX 169	Basaltic andesite. Scoria & ash flow deposit	Section XI
EX 170	Basaltic andesite. Scoria & ash flow deposit. Marker bed F	Section XII
EX 171	Basaltic andesite. Scoria & ash flow deposit. Marker bed F	Section XII
EX 172	Basaltic andesite. Airfall lapilli. Under bed F	Section XII
EX 173	Basaltic andesite. Surge deposit	Section XVIII

TABLE E6 CIPW Standard Norms, Differentation Indices (D.I.) and Crystallization Indices (C.I.) for volcanic rocks of Saba

Sample No	SA141	SA175	SA157	SA137	SA123	SA104	SA160B
Salic Group							
Q	0.20			3.17	2.69	3.58	3.17
Or	3.73	3.36	5.07	4.08	5.85	4.99	4.23
Ab	25.78	22.99	24.20	25.24	25.11	26.05	28.30
An	39.28	30.97	33.04	34.08	32.63	31.12	30.90
Femic Group							
Mg-Di	8.12	12.92	11.72	8.59	6.73	8.54	7.53
Fe-Di	4.44	4.01	5.30	4.36	2.68	2.83	2.46
En	8.31	12.18	9.41	9.37	13.98	13.18	13.78
Fs	5.21	4.33	4.88	5.45	6.37	5.01	5.16
Fo		2.93	0.63				
Fa		1.15	0.36				
Mt	3.07	3.19	3.30	3.14	1.85	2.76	2.65
Cm	0.01	0.11	0.02	0.01	0.05	0.05	0.04
Il	1.72	1.69	1.78	1.73	0.77	1.89	1.63
Ap	0.12	0.17	0.29	0.02	0.29		0.15
D.I.	29.71	26.35	29.27	33.25	33.65	34.62	35.70
C.I.	53.23	55.36	51.98	49.24	49.15	48.90	48.09

Sample No	SA161	SA160A	SA121	SA158	SA152	SA166	SA165
Salic Group							
Q	4.87	3.77	4.54	6.32	6.36	6.66	6.28
Or	4.76	4.76	5.71	4.89	5.22	5.12	5.45
Ab	27.33	28.39	26.96	30.45	26.85	28.75	27.06
An	31.61	30.22	29.23	32.81	30.53	32.19	29.96
Femic Group							
Mg-Di	7.19	7.25	6.63	4.95	6.50	5.15	6.94
Fe-Di	2.93	2.48	2.84	3.36	2.62	2.68	2.44
En	11.51	13.60	13.51	7.13	11.92	9.40	12.46
Fs	5.37	5.34	6.64	5.56	5.50	5.61	5.02
Fo							
Fa							
Mt	2.72	2.65	2.89	2.86	2.74	2.77	2.57
Cm	0.04	0.04	0.05		0.03	0.02	0.05
Il	1.28	1.47	0.64	1.42	1.38	1.38	1.48
Ap	0.39	0.02	0.36	0.24	0.34	0.27	0.29
D.I.	36.96	36.92	37.22	41.66	38.43	40.53	38.79
C.I.	46.88	47.01	45.32	42.76	45.39	43.93	45.63

TABLE E6 (continued)

Sample No	SA172	SA173	SA120	SA163	SA128	SA154
Salic Group						
Q	6.02	7.02	5.57	7.88	7.28	6.94
Or	6.35	5.97	6.39	5.29	5.92	5.80
Ab	26.60	27.02	27.61	28.08	28.24	26.81
An	29.37	29.71	29.60	30.04	29.20	27.21
Femic Group						
Mg-Di	7.07	5.91	6.59	6.06	6.27	8.44
Fe-Di	2.47	2.27	2.61	2.38	2.51	2.69
En	12.81	12.19	12.62	10.99	11.30	13.23
Fs	5.14	5.36	5.74	4.94	5.20	4.84
Fo						
Fa						
Mt	2.57	2.63	2.55	2.52	2.58	2.54
Cm	0.04	0.04	0.04	0.04	0.04	0.07
Il	1.33	1.37	0.52	1.43	1.31	1.42
Ap	0.14	0.51	0.17	0.36	0.14	
D.I.	39.05	40.01	39.56	41.24	41.44	39.55
C.I.	45.42	44.17	45.03	43.80	43.39	44.93

Sample No	SA146	SA142	SA101	SA127	SA124	SA120	SA103
Salic Group							
Q	8.22	10.20	14.42	10.42	11.52	11.54	10.82
Or	6.09	7.16	8.58	6.75	7.15	6.24	7.03
Ab	27.71	28.60	30.87	30.03	27.81	28.56	29.87
An	28.15	29.29	26.19	28.81	29.01	29.15	27.80
Femic Group							
Mg-Di	7.57	5.68	3.91	5.76	5.09	5.22	5.60
Fe-Di	2.74	2.98	1.79	3.16	2.20	2.58	2.58
En	11.12	7.55	7.20	6.88	8.71	8.29	8.24
Fs	4.61	4.54	3.77	4.33	4.33	4.69	4.36
Fo							
Fa							
Mt	2.40	2.44	1.93	2.42	2.29	2.34	2.31
Cm	0.03	0.02	0.02	0.01	0.02	0.02	0.02
Il	1.23	1.27	1.16	1.43	1.51	1.03	1.37
Ap	0.12	0.27	0.17		0.36	0.34	
D.I.	42.03	45.95	53.87	47.20	46.48	46.34	47.73
C.I.	43.51	40.27	35.14	39.29	40.21	40.18	39.17

TABLE E6 (continued)

Sample No	SA125	SA119	SA156	SA174	SA138	SA149	SA150
Salic Group							
Q	12.19	11.32	11.11	11.01	12.38	12.46	13.28
Or	8.15	7.05	7.23	7.48	7.70	6.42	6.04
Ab	28.66	30.27	32.01	29.62	29.58	27.93	28.82
An	29.88	29.01	29.51	27.03	27.77	27.12	29.21
Femic Group							
Mg-Di	3.00	5.47	3.79	5.62	4.55	5.33	2.88
Fe-Di	1.46	2.62	2.38	2.41	2.90	2.33	1.38
En	7.94	6.98	6.13	8.89	6.50	9.80	9.41
Fs	4.44	3.83	4.41	4.38	4.76	4.90	5.18
Fo							
Fa							
Mt	2.27	2.14	2.24	2.26	2.48	2.36	2.30
Cm	0.02	0.02	0.01	0.04	0.01	0.02	0.02
Il	1.72	1.31	1.11	1.18	1.23	1.04	1.12
Ap	0.27		0.07	0.07	0.14	0.29	0.37
D.I.	49.00	48.64	50.35	48.11	49.67	46.81	48.14
C.I.	38.44	39.37	37.59	38.88	36.87	39.32	38.68

Sample No	SA151	SA155	SA136	SA133	SA139	SA102	SA147
Salic Group							
Q	13.92	13.20	14.51	13.72	12.99	14.28	14.89
Or	5.98	7.42	6.53	8.11	8.17	8.28	6.72
Ab	28.54	30.57	30.10	29.43	30.41	29.94	30.64
An	29.87	27.40	29.17	27.42	26.58	28.75	28.58
Femic Group							
Mg-Di	1.78	4.51	2.93	4.47	4.91	3.21	2.76
Fe-Di	0.91	2.78	2.34	2.76	2.58	1.87	2.26
En	9.43	6.08	5.51	6.13	6.75	5.97	5.46
Fs	5.49	4.30	5.04	4.34	4.07	3.98	5.12
Fo							
Fa							
Mt	2.33	2.28	2.43	2.27	2.17	2.10	2.42
Cm	0.02	0.01		0.01	0.02		
Il	1.09	1.13	1.10	1.20	1.11	1.49	0.99
Ap	0.63	0.32	0.34	0.15	0.24	0.12	0.17
D.I.	48.45	51.18	51.14	51.26	51.57	52.50	52.24
C.I.	38.27	36.18	35.96	36.18	36.22	36.14	35.17

TABLE E6 continued)

Sample No	**SA116**	**SA153**	**SA122**	**SA159**	**SA130**	**SA100**	**SA169**
Salic Group							
Q	14.77	14.49	14.00	14.93	15.40	14.42	17.33
Or	7.13	8.21	7.98	8.42	7.02	8.58	8.73
Ab	31.06	29.99	30.00	31.39	31.02	30.87	30.05
An	29.32	26.17	37.52	26.11	28.15	26.19	24.07
Femic Group							
Mg-Di	2.36	4.52	3.07	2.78	3.32	3.91	4.19
Fe-Di	1.88	2.73	1.49	1.62	2.71	1.79	2.01
En	5.22	6.02	8.42	6.34	4.63	7.20	6.80
Fs	4.76	4.16	4.70	4.24	4.33	3.77	3.75
Fo							
Fa							
Mt	2.23	2.24	2.02	2.04	2.23	1.93	1.89
Cm		0.01	0.02	0.01		0.02	0.02
Il	1.11	1.20	0.58	1.15	1.03	1.16	0.94
Ap	0.17	0.27	0.19	0.98	0.15	0.17	0.22
D.I.	52.96	52.69	51.98	54.74	53.44	53.87	56.12
C.I.	35.34	34.91	36.50	33.33	34.72	35.14	33.02

Sample No	**SA162**	**SA131**	**SA145**	**SA167**	**SA132**	**SA135**
Salic Group						
Q	18.47	19.88	18.86	19.93	19.56	20.92
Or	7.36	12.11	10.03	8.51	9.86	9.38
Ab	31.79	27.24	31.69	32.80	32.43	30.54
An	26.17	24.99	22.95	24.81	23.75	24.37
Femic Group						
Mg-Di	1.57	2.55	3.35	1.61	2.38	2.00
Fe-Di	1.15	1.40	2.08	1.38	1.80	1.44
En	5.19	5.64	4.89	4.07	4.05	4.63
Fs	4.34	3.55	3.48	3.99	3.52	3.82
Fo						
Fa						
Mt	1.97	1.70	1.79	1.80	1.73	1.80
Cm	0.01	0.01				
Il	1.11	0.93	0.88	0.80	0.90	0.95
Ap	0.37	0.02		0.29		0.15
D.I.	58.12	59.22	60.57	61.24	61.85	60.84
C.I.	31.38	31.49	29.73	29.28	28.97	29.61

TABLE E7 CIPW Standard Norms, Differentation Indices (D.I.) and Crystallization Indices (C.I.) for volcanic rocks of St. Eustatius

Sample No	EX148	EX152	EX171	EX172	EX170	E104	E51
Salic Group							
Q	4.04	4.44	5.32	6.64	7.06	7.74	6.57
Or	1.52	2.26	2.87	2.93	3.12	3.02	2.83
Ab	22.45	25.16	26.15	25.78	26.54	26.91	28.66
An	44.06	39.08	36.79	37.15	35.02	34.94	32.40
Femic Group							
Mg-Di	1.87	4.43	4.97	3.87	4.33	4.53	6.19
Fe-Di	1.13	2.68	3.01	2.33	2.97	2.88	3.02
En	11.45	9.79	9.20	9.53	8.68	8.60	10.09
Fs	7.95	6.79	6.39	6.59	6.84	6.28	5.64
Fo							
Fa							
Mt	3.46	3.33	3.22	3.14	3.36	3.14	2.87
Cm	0.01	0.01	0.01	0.01		0.01	0.02
Il	1.89	1.85	1.75	1.69	1.72	1.73	1.43
Ap	0.17	0.17	0.31	0.34	0.36	0.22	0.29
D.I.	28.01	31.86	34.35	35.35	36.72	37.67	38.06
C.I.	53.96	50.37	48.21	47.69	45.44	45.50	45.66

Sample No	E59A	E90	EX163	EX169	E60	E92	EX165
Salic Group							
Q	7.64	8.01	9.04	9.84	10.62	8.99	10.90
Or	3.49	3.71	2.74	3.38	3.27	3.74	3.56
Ab	28.12	30.19	27.85	28.62	27.91	31.58	29.42
An	33.46	31.75	33.91	33.00	32.76	30.49	32.11
Femic Group							
Mg-Di	5.91	4.31	5.10	3.79	4.31	5.29	3.89
Fe-Di	3.52	2.61	2.99	2.58	2.58	3.25	2.63
En	7.87	8.25	8.25	7.82	8.22	7.20	7.31
Fs	5.38	5.73	5.54	6.11	5.65	5.07	5.68
Fo							
Fa							
Mt	2.88	2.84	2.85	2.98	2.83	2.74	2.82
Cm	0.01	0.01	0.01		0.01	0.01	0.01
Il	1.47	1.48	1.53	1.53	1.59	1.51	1.49
Ap	0.24	1.10	0.17	0.33	0.26	0.14	0.17
D.I.	39.26	41.92	39.64	41.84	41.80	44.30	43.88
C.I.	44.89	41.84	44.79	42.27	42.82	40.83	41.13

TABLE E7 (continued)

Sample No	EX167	E93	E103	EX155	E102	E101	EX166
Salic Group							
Q	11.19	11.21	11.41	12.08	11.78	11.73	11.49
Or	3.47	3.33	3.60	2.88	3.91	3.62	3.48
Ab	29.68	29.28	29.19	28.05	29.52	29.66	30.53
An	31.73	31.97	31.91	32.62	31.24	31.21	30.75
Femic Group							
Mg-Di	3.51	4.24	3.84	3.58	3.77	3.88	3.92
Fe-Di	2.33	2.69	2.57	1.99	2.48	2.56	2.74
En	7.64	7.46	7.34	8.77	7.22	7.31	7.01
Fs	5.82	5.46	5.62	5.60	5.44	5.54	5.62
Fo							
Fa							
Mt	2.81	2.73	2.78	2.68	2.75	2.75	2.79
Cm	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Il	1.46	1.43	1.45	1.51	1.62	1.49	1.39
Ap	0.36	0.24	0.29	0.22	0.28	0.24	0.27
D.I.	44.35	43.82	44.20	43.01	45.21	45.02	45.50
C.I.	40.59	41.43	40.90	42.35	40.06	40.21	39.59

Sample No	EX161	E95	EX162	E55	EX160	E49	E50
Salic Group							
Q	12.34	10.93	12.36	12.24	12.21	9.73	8.11
Or	3.33	3.84	3.68	3.19	3.52	3.66	3.94
Ab	28.95	31.40	28.85	29.85	30.09	35.60	38.24
An	31.90	29.93	31.64	30.92	30.44	26.62	24.83
Femic Group							
Mg-Di	3.66	4.48	3.72	3.72	4.17	5.18	6.69
Fe-Di	2.38	2.91	2.47	2.40	2.73	3.16	4.02
En	7.43	6.99	7.27	7.64	7.05	6.95	6.08
Fs	5.54	5.20	5.54	5.64	5.30	4.86	4.19
Fo							
Fa							
Mt	2.74	2.69	2.76	2.72	2.72	2.57	2.52
Cm	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Il	1.55	1.41	1.51	1.34	1.54	1.31	1.36
Ap	0.19	0.22	0.19	0.31	0.22	0.34	
D.I.	44.62	46.17	44.89	45.29	45.83	48.99	50.29
C.I.	40.76	39.31	40.46	40.00	39.55	36.67	35.78

TABLE E7 (continued)

Sample No	E54	E63	E52	EX157	E42	E86	E64
Salic Group							
Q	9.15	12.59	12.43	14.09	12.46	13.50	13.48
Or	3.89	3.70	3.92	3.94	4.64	3.67	4.70
Ab	38.43	32.13	31.35	30.49	32.27	33.76	35.82
An	25.91	30.08	29.54	29.87	27.53	27.68	26.26
Femic Group							
Mg-Di	4.80	2.89	4.21	3.13	4.48	3.56	3.00
Fe-Di	3.23	2.03	2.81	2.14	2.92	2.49	2.36
En	5.97	6.81	6.64	6.73	6.66	6.19	5.45
Fs	4.61	5.47	5.09	5.28	4.98	4.97	4.91
Fo							
Fa							
Mt	2.49	2.59	2.61	2.59	2.56	2.49	2.44
Cm	0.01	0.01	0.01	0.01	0.01	0.01	
Il	1.29	1.36	1.34	1.52	1.22	1.32	1.24
Ap	0.23	0.33	0.05	0.22	0.27	0.34	0.34
D.I.	51.46	48.42	47.70	48.52	49.37	50.94	53.99
C.I.	34.89	37.74	38.41	37.71	36.68	35.58	33.08

Sample No	EX156	E58	E53	E59	E85	E56	E87
Salic Group							
Q	15.76	13.74	14.85	14.83	16.66	16.02	16.73
Or	4.52	4.29	3.87	4.55	4.16	3.90	4.14
Ab	31.08	35.63	34.27	32.11	31.85	33.93	32.61
An	28.75	25.54	27.06	26.29	28.81	28.01	27.71
Femic Group							
Mg-Di	2.73	3.87	2.66	3.42	1.76	2.09	2.18
Fe-Di	1.99	3.02	2.30	2.56	1.47	1.68	1.82
En	6.03	5.26	5.89	5.57	5.79	5.45	5.50
Fs	5.05	4.70	5.84	4.78	5.54	5.01	5.27
Fo							
Fa							
Mt	2.46	2.47	2.41	2.41	2.46	2.35	2.44
Cm	0.01	0.01	0.01	0.01			0.01
Il	1.29	1.36	1.34	1.52	1.22	1.32	1.24
Ap	0.22	0.27	0.67	0.29	0.34	0.24	0.38
D.I.	51.36	53.66	53.00	53.48	52.66	53.86	53.48
C.I.	35.70	33.09	33.85	33.61	34.63	33.92	33.75

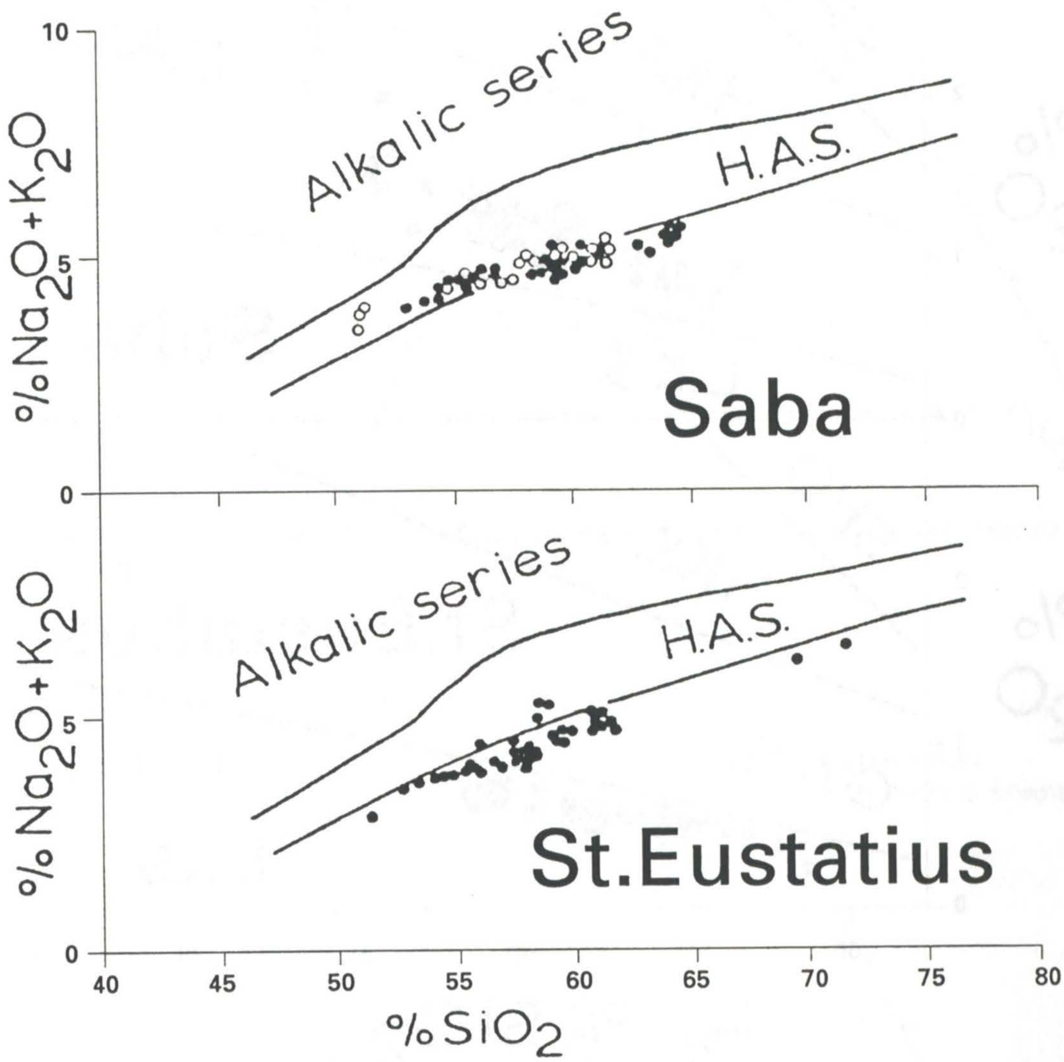


Figure E3 Plot of (Na_2 + K_2O) versus SiO_2 for Saba and the Quill, St. Eustatius. The field boundaries are after Kuno (1966). H.A.S. = High-Al series. The lower unlabelled field is for tholeiitic and calc-alkaline series. The Saban samples are divided into 'older' in open circles and 'younger' in filled circles.

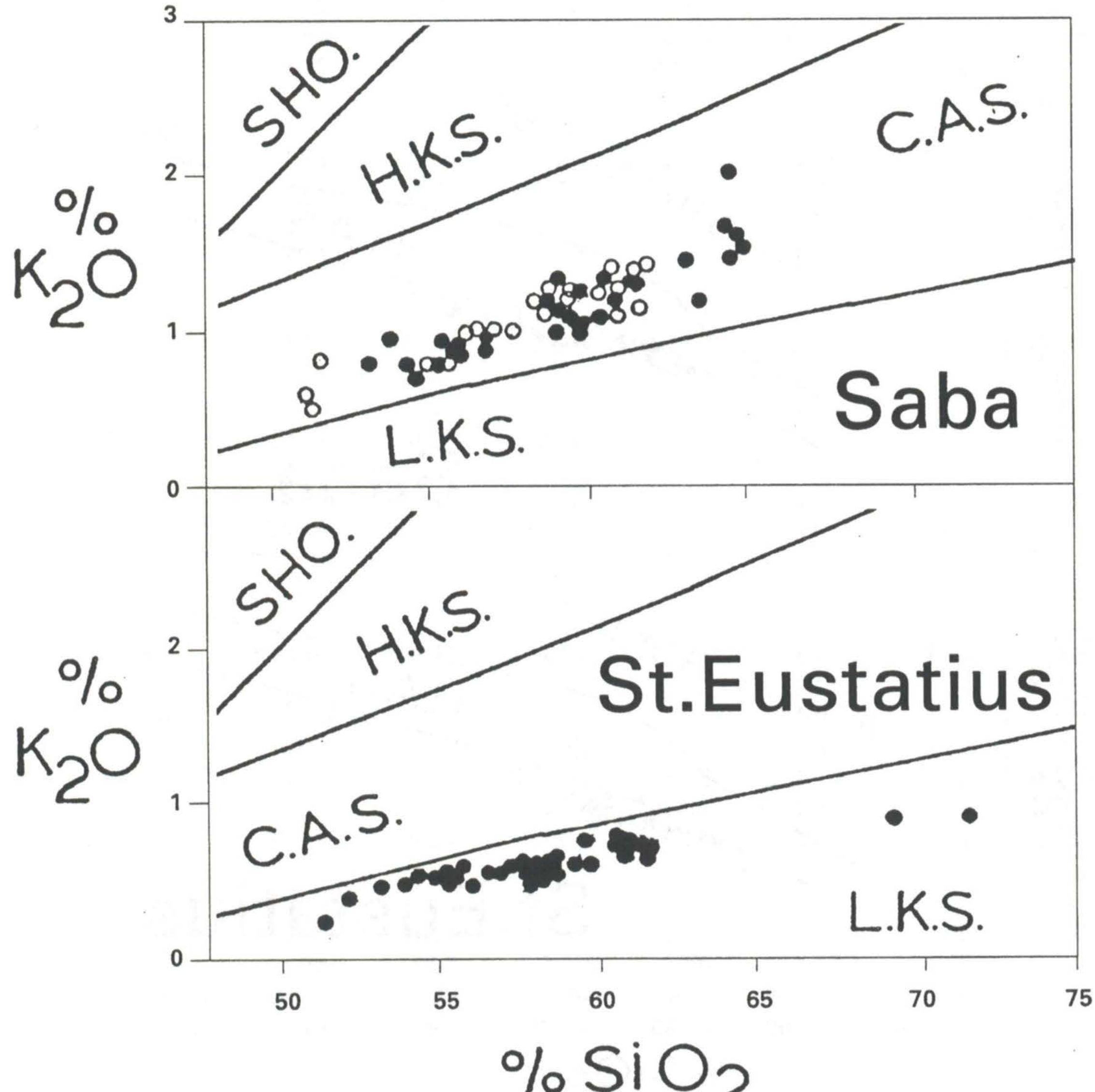


Figure E4 Plot of K_2O versus SiO_2 for Saba and the Quill, St. Eustatius.
The field boundaries are after Peccerillo and Taylor (1976). SHO = Shoshonite series; H.K.S. = High-K series; C.A.S. = Calc-alcaline series; L.K.S. = Low-K series.
The Saban samples are divided into 'older' in open circles and 'younger' in filled circles.

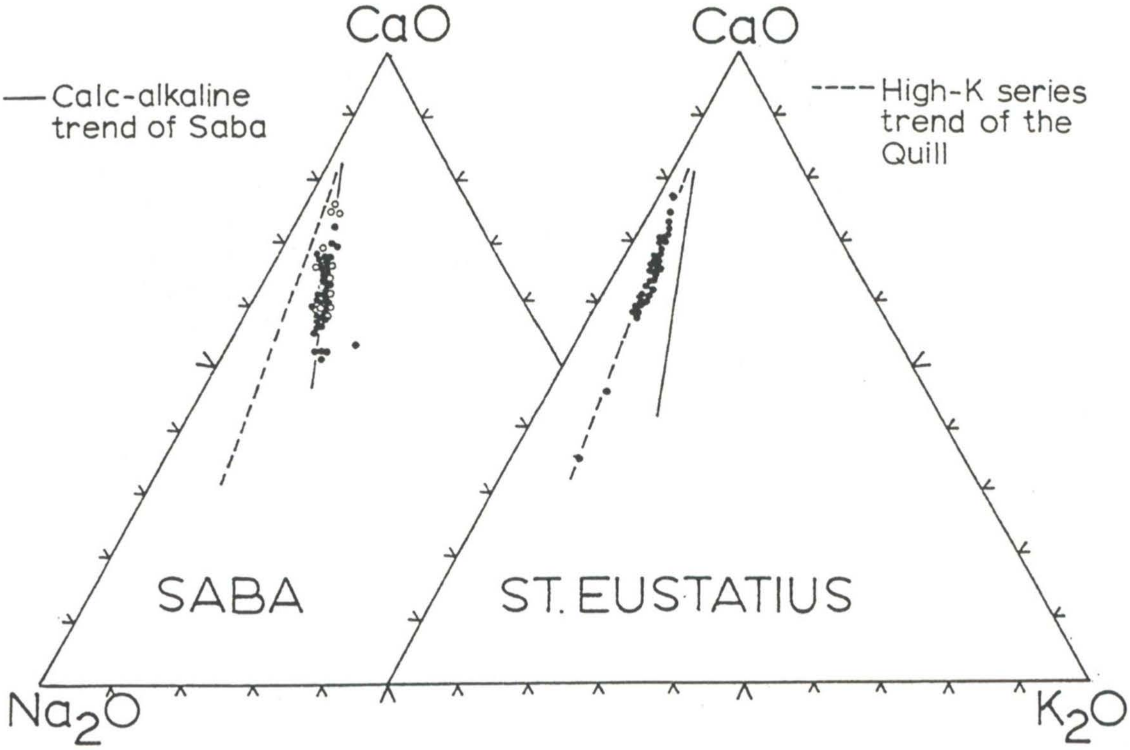


Figure E5 Plot of CaO-Na_2O-K_2O for Saba and the Quill, St. Eustatius. The two different trends are very distinct.

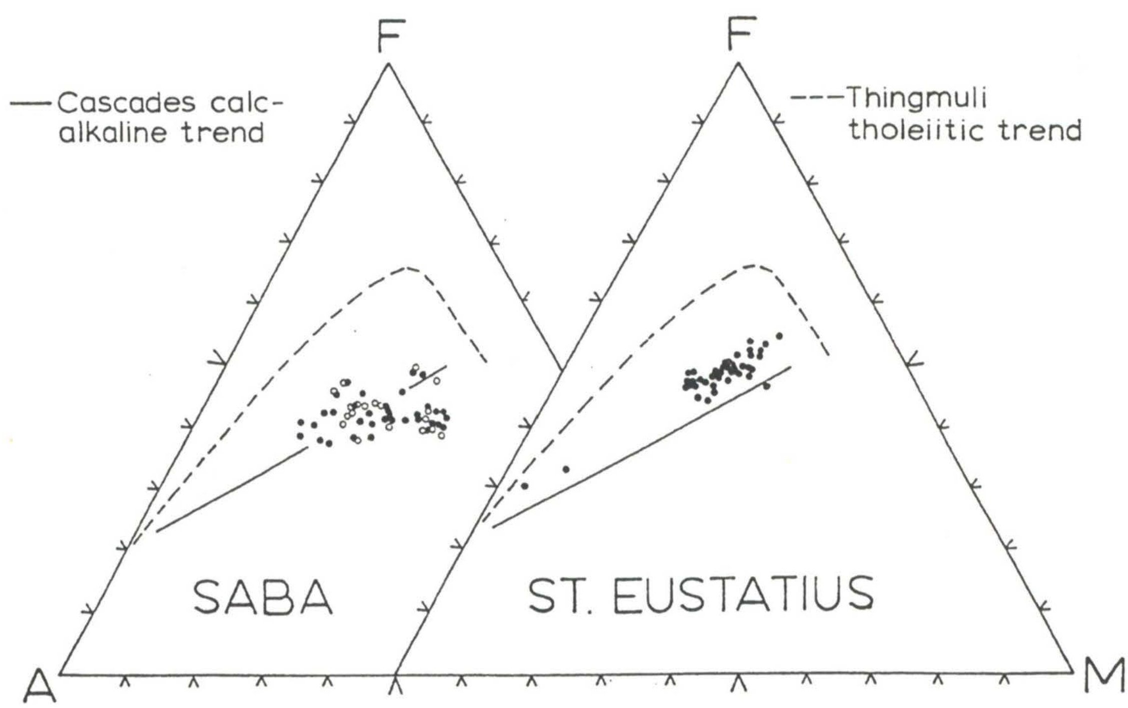


Figure E6 AFM diagram for Saba and the Quill, St. Eustatius. A = $Na_2O + K_2O$; F = ΣFe_2O_3; M = MgO. Tholeiitic and calc-alcaline trends are after Carmichael (1964).

Appendix F
Grain size analyses

A grain size study has been made of forty-five samples from Saba and St. Eustatius representing the main types of pyroclastic deposits.

Sufficient sample to be representative of the deposit was collected and sieved at one phi intervals, where $\phi = -\log_2 M$ (M= grain size in millimeters), down to 4ϕ (0.063mm), which is the finest size sieved in convential mechanical analysis of this type. Samples which contained clasts of greater than 4mm size were partially sieved in the field for the coarser size fractions. The less than 4mm fraction was then usually divided in the field and a representative split was sieved in the laboratory at Puerto Rico.

The results of the grain size studies are presented in Table F1. From cumulative curves drawn on probability paper the distribution factors of median diameter ($Md\phi = \phi_{50}$) and graphical standard deviation, which is a measure of sorting [$\sigma\phi = (\phi_{84} - \phi_{16}) /2$], were calculated. A plot of $Md\phi$ against $\sigma\phi$ is drawn in Figure 1, and histograms of selected samples are shown in Figure F2.

The fields outlined in Figure F1 represent those of pyroclastic flows (Fl) and airfall deposits (Fa), the boundaries being drawn at the 1% contour line (after Sparks and Wright, 1979). From this figure it can be seen that the airfall deposits all fall within their respective field, however some of the pyroclastic flow samples plot outside of their field. This feature is due in part to the very coarse nature of some of the flow deposits, e.g. sample S 95. It should also be noted that the surge deposits all tend to fall in the area in which the two fields overlap. This is as should be expected since the grain size distribution in surges is somewhat intermediate between flow and fall deposits.

From the histograms presented in Figure F2 it can be seen that the various kinds of pyroclastic flow deposit are usually polymodal, whereas the airfall deposits are more unimodal, although some show bimodality. The surges on the other hand can be either uni-or polymodal. For the block and ash deposits the various peaks represent (from coarse to fine grain size) dense angular andesite clasts (fragmented dome material), vesicular andesite clasts (magmatic material) and crystals, whereas the pumiceous, and scoriaceous flow deposits are characterized by peaks representing magmatic material and crystals.

Reference

Sparks, R.S.J. and Wright, J.V., 1979: Welded airfall tuffs.- Geol. Soc. Amer. Spec. Paper 180, p.155-166.

TABLE F1 Grain size analyses (in grams) of pyroclastic rocks from Saba and St. Eustatius

	S86	S87	S88	S89	S95	SA105	SA107	SA108	SA109
64mm									
32mm			145.0		1980.0				
16mm			820.0		2520.0				
8mm			1353.0		1462.0				
4mm	40.6	241.1	905.6		1340.0	211.9	11.5		13.4
2mm	96.1	220.2	1365.8	1.6	1188.1	296.1	7.1	0.2	3.7
1mm	183.2	200.0	1424.3	1.7	957.5	379.1	5.0	0.5	2.7
500μ	160.4	133.5	1010.0	6.3	692.8	177.5	0.2	2.4	4.1
250μ	210.4	143.5	1019.6	24.0	614.6	211.1	1.4	47.5	35.3
125μ	151.8	83.9	552.7	95.7	438.4	161.5	22.7	108.7	68.2
63μ	77.4	36.9	273.1	76.1	383.7	132.2	60.0	100.0	48.9
Dust	2.2	3.3	144.4	77.0	337.3	65.5	54.9	58.6	22.3
Total	922.1	1061.6	8983.5	282.4	11914.5	1634.6	162.9	317.8	198.5

S86 Pumiceous surge deposit, between Windward Side and The Bottom, Saba
S87 Pumiceous surge deposit, between Windward Side and The Bottom, Saba
S88 Pumiceous airfall lapilli deposit, between Windward Side and The Bottom, Saba
S89 Vitric ash deposit, road to harbour (Section X), Saba
S95 Block and ash flow deposit, quarry near harbour at base of Bunker Hill, Saba
SA105 Block and ash flow deposit, The Bottom (Section XI), Saba (see Fig. 4)
SA107 Water deposited laminated ash, The Bottom (Section XI), Saba (see Fig. 4)
SA108 Water deposited laminated ash, The Bottom (Section XI), Saba (see Fig. 4)
SA109 Water deposited laminated ash, The Bottom (Section XI), Saba (see Fig. 4)

	SA110	SA112	SA113	SA148	SA161	SA176	SA177	SA178	SA180
64mm									
32mm									
16mm									
8mm									
4mm	100.2	42.8	78.0	28.9	23.5	211.7	25.4	64.3	183.5
2mm	124.6	57.6	116.4	55.5	35.1	153.9	36.9	102.3	151.7
1mm	104.6	76.2	81.9	97.2	55.3	149.2	19.0	146.0	171.2
500μ	64.5	56.3	38.3	127.9	55.0	172.5	42.3	105.0	139.3
250μ	59.6	48.1	52.2	160.6	54.7	232.7	58.3	137.1	142.9
125μ	44.2	30.5	37.3	124.7	58.5	157.3	56.2	108.8	94.0
63μ	36.4	26.5	26.6	115.6	75.3	82.0	52.8	84.7	58.2
Dust	20.6	21.6	9.4	42.4	46.8	12.8	23.4	39.3	37.3
Total	554.5	359.6	440.1	752.8	404.1	1172.1	314.4	787.3	984.0

SA110 Fluviatile sand, The Bottom (Section XI), Saba (see Fig. 4)
SA112 Fluviatile sand, The Bottom (Section XI), Saba (see Fig. 4)
SA113 Dense andesite surge deposit, The Bottom (Section XI), Saba (see Fig. 4)
SA148 Dense andesite surge deposit, St. John's Flat (Section IX), Saba
SA161 Semi-vesicular andesite block & ash deposit, The Level (Section IIA), Saba
SA176 Pumice and ash flow deposit, ridge below Windward Side, Saba
SA177 Dense andesite surge deposit, St. John's Flat (Section IX), Saba
SA178 Dense andesite surge deposit, St. John's Flat (Section IX), Saba
SA180 Dense andesite surge deposit, St. John's Flat (Section IX), Saba

TABLE F1 (continued)

	E81	E82	E83	E84	E85A	E88	E89	E91	E99
64mm									
32mm				1130.0			1450.0	490.0	150.0
16mm				385.0			1060.0	225.0	320.0
8mm				652.0			1196.0	346.0	446.0
4mm	117.0	239.7	103.4	798.5	82.6	198.9	683.4	325.7	432.5
2mm	110.2	231.5	137.9	821.2	70.1	191.9	1017.6	501.7	503.3
1mm	108.5	244.9	208.7	792.9	95.9	253.3	3652.5	641.0	555.4
500μ	120.6	254.2	262.2	746.3	138.5	280.6	426.3	676.6	1243.7
250μ	202.6	314.5	385.3	842.0	229.3	353.7	454.0	880.8	951.9
125μ	304.5	416.1	323.2	583.9	201.5	196.4	245.9	708.1	1037.3
63μ	130.1	166.1	354.5	479.6	144.1	75.4	125.7	385.0	502.4
Dust	14.8	85.8	159.8	119.4	61.0	11.6	6.6	383.2	19.3
Total	1108.4	1952.8	1935.0	7350.8	1023.0-	1561.8	1031.0	5563.1	6161.8

E81 Ash flow deposit, (Section XXI), St. Eustatius
E82 Pumice and ash flow deposit, (Section XXI), St. Eustatius
E83 Block and ash flow deposit, (Section XXI), St. Eustatius
E84 Block and ash flow deposit, (Section XXI), St. Eustatius
E85A Pumiceous surge deposit, (Section VIII), St. Eustatius
E88 Dense andesite surge deposit, (Section VIII), St. Eustatius
E89 Scoria and ash flow deposit, (Section VIII), St. Eustatius
E91 Scoria and ash flow deposit, (Section VIII), St. Eustatius
E99 Dense andesite surge deposit, (Section VIII), St. Eustatius

	E100	E105	E106	E107	E108	E109	E110	E111	E112
64mm								560.0	300.0
32mm	200.0	450.0			170.0	310.0	400.0	1385.0	440.0
16mm	430.0	395.0			410.0	100.0	1190.0	1615.0	840.0
8mm	487.0	536.0			541.0	1219.0	1306.0	1165.0	405.0
4mm	539.6	708.6	401.3	36.9	854.0	989.1	1365.5	1406.1	964.3
2mm	590.5	664.5	127.3	41.0	947.5	1077.8	1075.1	1050.6	883.2
1mm	594.6	757.9	79.1	55.4	905.2	1017.9	987.7	1041.1	850.8
500μ	670.7	669.4	57.4	55.9	845.5	838.2	723.2	790.8	653.2
250μ	938.4	782.8	60.4	71.4	1026.1	928.3	832.9	951.2	729.1
125μ	1020.3	571.2	34.7	64.2	852.7	585.1	679.4	759.6	581.7
63μ	652.1	478.0	13.9	21.5	303.7	217.7	122.2	151.7	142.0
Dust	87.7	120.9	2.9	1.0	10.5	15.7	4.4	9.1	11.5
Total	6210.9	6134.3	777.0	347.3	7446.2	8198.8	8686.4	11235.2	7650.8

E100 Dense andesite surge deposit, (Section VIII), St. Eustatius
E105 Block and ash flow deposit, (section V), St. Eustatius
E106 Semi-vesicular andesite surge deposit, (Section V), St. Eustatius
E107 Dense andesite surge deposit, (Section V), St. Eustatius
E108 Block and ash flow deposit, (Section V), St. Eustatius
E109 Block and ash flow deposit, (Section V), St. Eustatius
E110 Block and ash flow deposit, (Section V), St. Eustatius
E111 Block and ash flow deposit, (Section V), St. Eustatius
E112 Block and ash flow deposit, (Section V), St. Eustatius

TABLE F1 (continued)

	E113	E114	EX 132	EX 133	EX 134	EX 136	EX 138	EX 139	EX 140
64mm	290.0	290.0							
32mm	270.0	290.0							
16mm	590.0	250.0		224.0	71.2				77.1
8mm	1165.0	405.0	25.9	200.7	18.3				137.1
4mm	1230.0	417.2	118.0	177.0	39.3	15.3	27.0	11.9	184.6
2mm	1114.5	480.4	179.1	167.0	68.0	20.0	34.0	18.7	150.6
1mm	1063.0	481.8	236.0	187.2	140.3	27.4	22.5	25.0	111.9
500μ	865.3	411.8	182.1	140.4	174.3	18.1	13.9	27.2	59.5
250μ	961.5	437.0	236.2	170.3	243.5	40.5	20.9	47.9	67.5
125μ	834.9	415.5	149.4	112.7	160.1	58.9	25.9	40.1	74.2
63μ	250.1	123.3	70.4	72.0	94.8	77.9	50.3	33.0	86.1
Dust	25.6	7.2	20.7	31.9	34.6	80.6	77.4	20.9	64.6
Total	8659.9	4009.2	1217.8	1483.1	1044.3	338.6	271.8	224.6	1013.2

E113 Block and ash flow deposit, (Section V), St. Eustatius
E114 Block and ash flow deposit, (Section V), St. Eustatius
EX 132 Pumiceous surge deposit, (Section XXVIII), St. Eustatius
EX 133 Semi-vesicular andesite block and ash flow deposit, (Section XXIII), St. Eustatius
EX 134 Semi-vesicular andesite surge deposit, (Section XXIII), St. Eustatius
EX 136 Pumice and ash flow deposit, (Section XXVIII), St. Eustatius
EX 138 Pumice and ash flow deposiot, (Section XXVIII), St. Eustatius
EX 139 Pumiceous surge deposit, (Section XXVIII), St. Eustatius
EX 140 Pumiceous and ash flow deposit, (Section XXVIII), St. Eustatius

	EX 146	EX 150	EX 151	EX 153	EX 154	EX 168	EX 174	EX 175	EX 176
64mm									
32mm							135.5		
16mm		39.5	18.4	66.3	10.7	354.7	172.1	64.6	140.5
8mm		3.5	2.1	110.8	22.5	306.2	245.2	211.1	216.6
4mm	29.5	32.9	3.3	60.1	31.8	256.2	172.1	233.6	208.0
2mm	87.2	31.4	9.3	61.6	72.2	178.3	140.4	139.4	156.3
1mm	96.0	60.7	52.4	72.9	165.0	131.7	138.7	159.4	115.9
500μ	32.4	51.3	51.3	79.8	194.3	101.4	151.5	54.2	96.4
250μ	17.0	80.6	128.1	120.9	281.5	142.0	212.6	80.5	103.5
125μ	17.2	71.3	107.6	92.8	233.7	129.5	209.8	87.7	84.5
63μ	36.9	74.7	108.9	44.2	178.6	89.0	193.0	99.8	266.5
Dust	48.9	85.3	47.0	50.3	107.9	95.1	85.9	106.7	130.7
Total	364.9	530.3	528.5	759.9	1298.3	1958.8	1856.8	1236.7	1518.8

EX 146 Scoriaceous surge, (Section XII), St. Eustatius
EX 150 Ash flow deposit, (Section XXV), St. Eustatius
EX 151 Scoria and ash flow deposit, (Section XXV), St. Eustatius
EX 153 Ash flow deposit, (Section II), St. Eustatius
EX 154 Scoria and ash flow deposit, (Section II), St. Eustatius
EX 168 Scoria and ash flow deposit, (Section XI), St. Eustatius
EX 174 Scoria and ash flow deposit, (Section XXIV), St. Eustatius
EX 175 Scoria and ash flow deposit, (Section III), St. Eustatius
EX 176 Scoriaceous surge deposit, (Section V), St. Eustatius

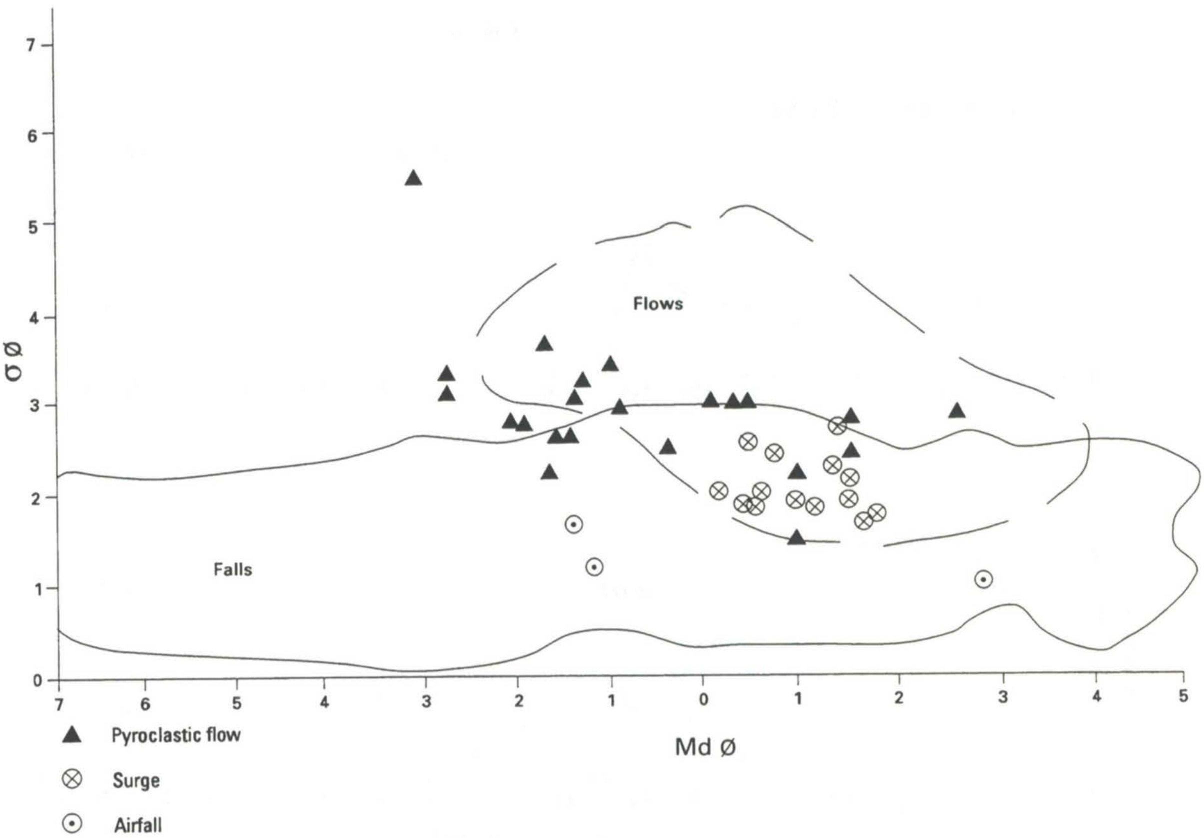


Figure F1 Mdϕ-σϕ plot for pyroclastic deposits of Saba and St. Eustatius.

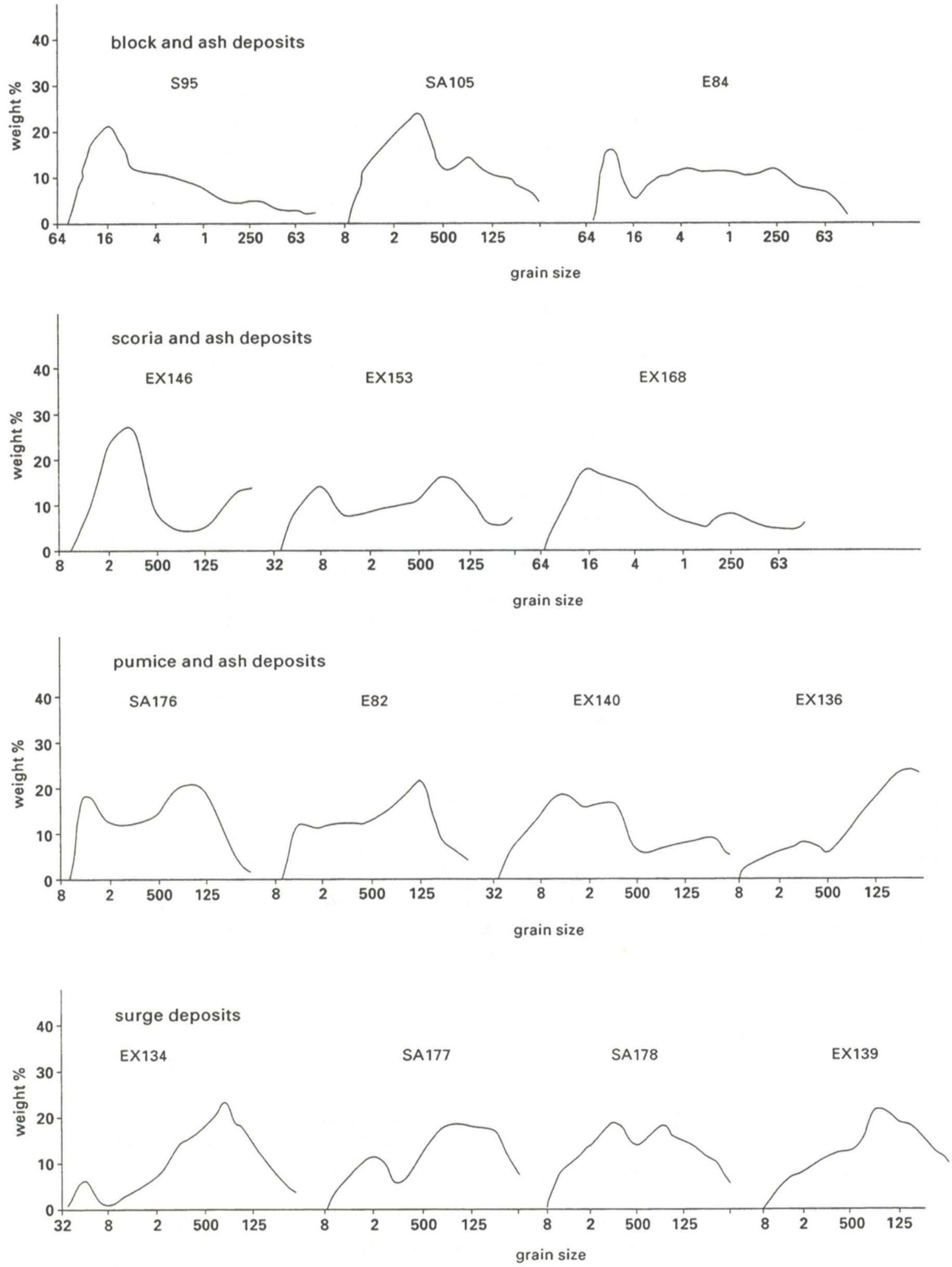


Figure F2 Representative histograms of pyroclastic deposits of Saba and St. Eustatius.

Appendix G
Photographic plates

Plate I Saba

a.
Southern Saba. Bunker Hill on left and St. John's Flat on right. Harbour and Fort Bay in between.

b.
Southern Saba. Booby Hill showing pyroclastic succession of location V below the lava flow.

c.
Southern Saba. View looking west showing the apron of pyroclastic debris of Giles Quarter. In the distance is St. John's Flat.

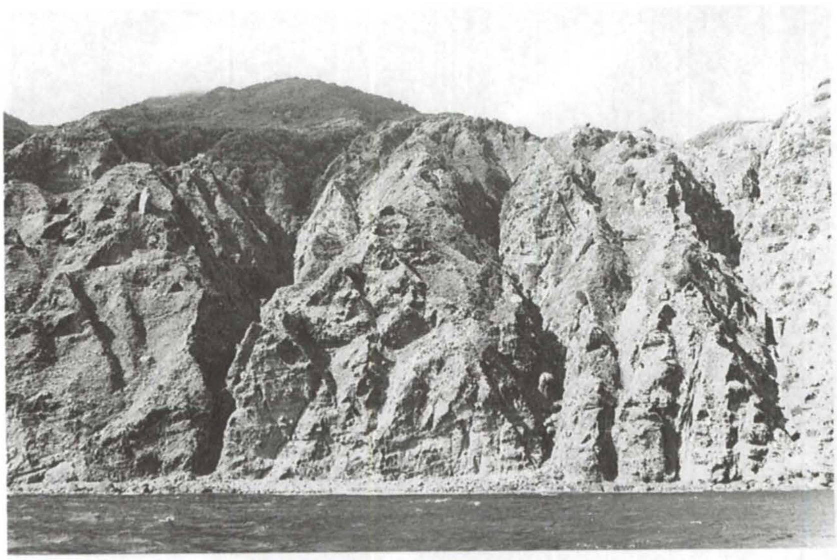
Plate II Saba

a.
Northeast Saba. Flat Point in foreground is the end of the basaltic andesite lava flow on which the airport is built. Behind this, the lava flow rises to the villages of Lower and Upper Hells Gate (visible in photograph). Mt. Scenery is partly covered by cloud. Windward Side village is just visible on left.

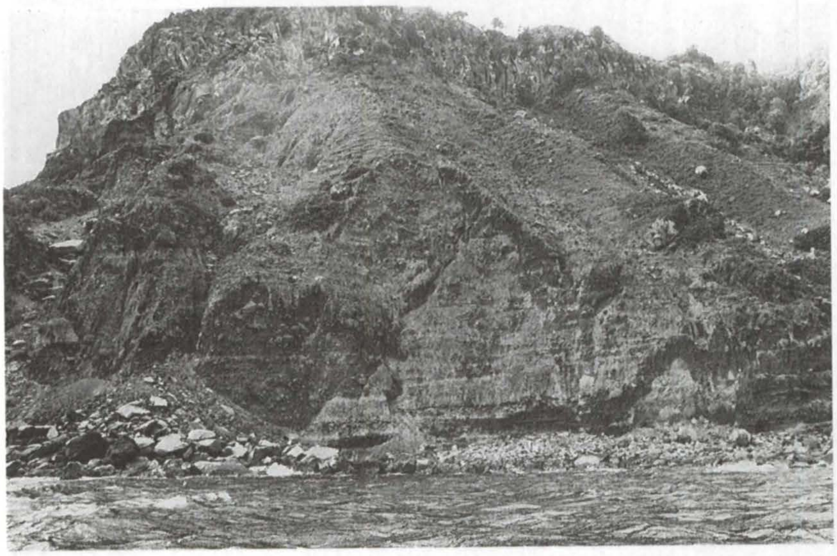
b.
Northeast Saba. Spring Bay with lava dome of old Booby Hill on left. Spring Bay Flat and the Level in center and Kelbey's Ridge on right.

c.
Northeast Saba. Sulfur mineralization and fumarolic alteration below the basaltic andesite lava flow of the old sulfur mine area.

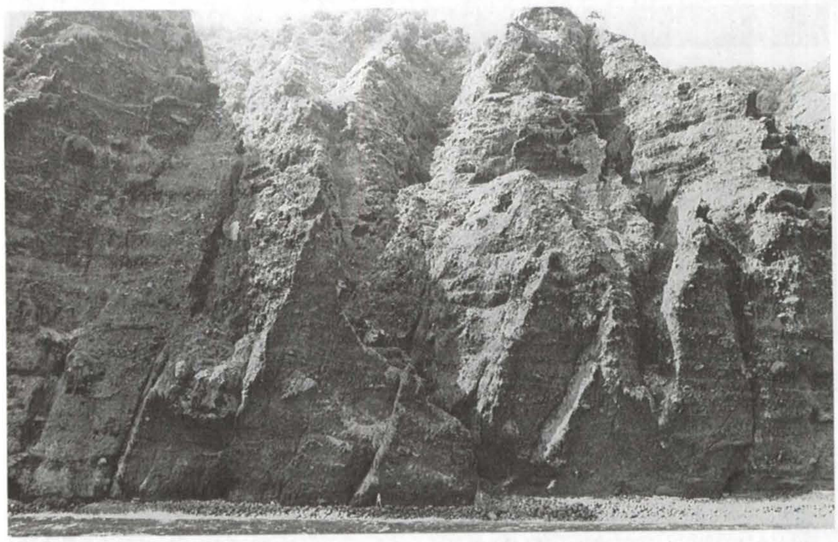
Plate III Saba



a.
North Saba. Coastline immediately west of old sulfur mine area showing prominent gulley cut into a thick succession of lithified block and ash flow deposits.



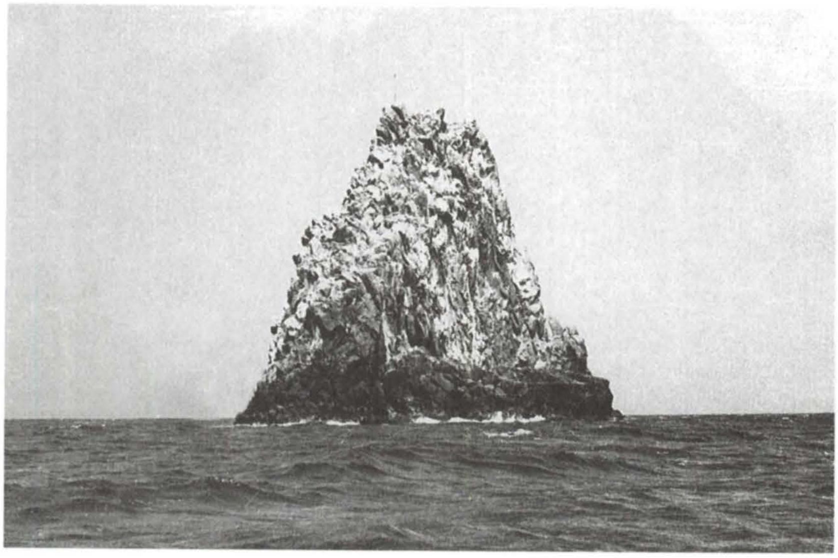
b.
North Saba. West side of Great Point showing a thick succession of block and ash flow deposits overlain by a columnar-jointed andesite lava flow.



c.
Northwest Saba. Between Great Point and Torrens Point. A 60 m thick, faulted, massive succession of block and ash flow deposits.
The geologist standing below the cliffs gives scale.

Plate IV Saba

a.
Northwest Saba. A 60 m thick succession of block and ash flow deposits adjacent to Torrens Point, which is partly visible on right.



b.
Northwest Saba. Diamond Rock. This is an erosional remnant of the Torrens Point center.

c.
West Saba. Ladder Bay. The Ladder is in the low point before the domes of Great Hill.

Plate V Saba

Deepening of the cistern pit section in the grounds of the new hospital in The Bottom village, Saba. Section XI was measured here, and the youngest pyroclastic deposit on Saba was found here. A detailed section of the pit is shown in Figure 4 of this report. Visible is the mudflow and the upper fluviatile deposits.

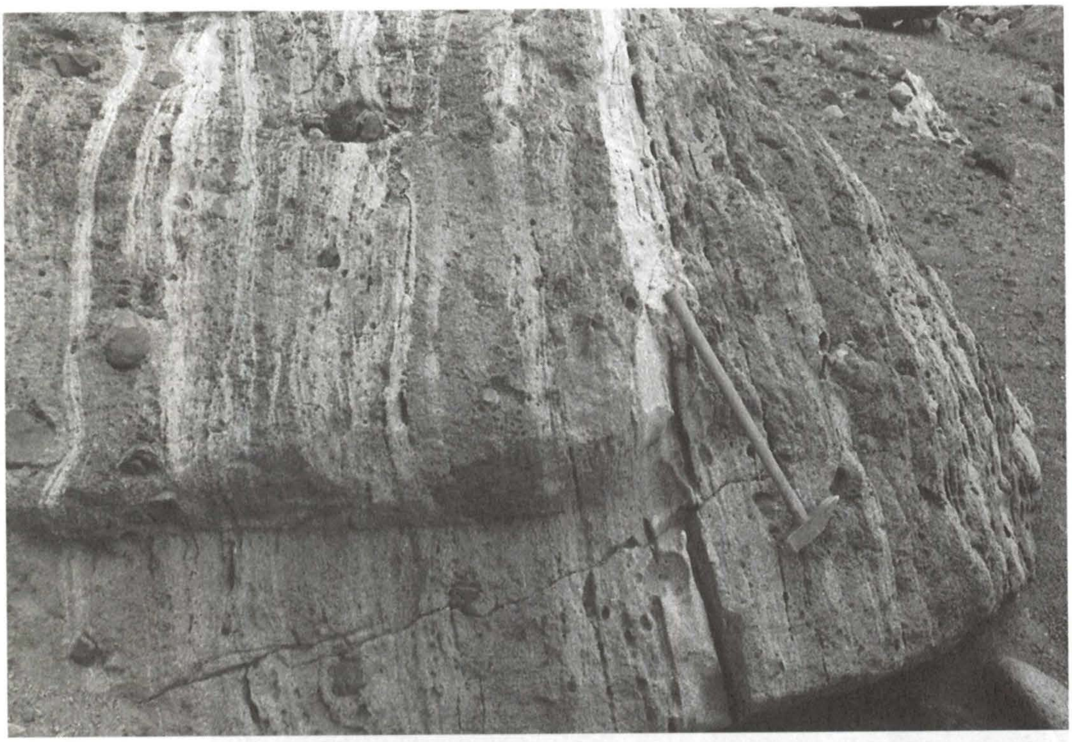


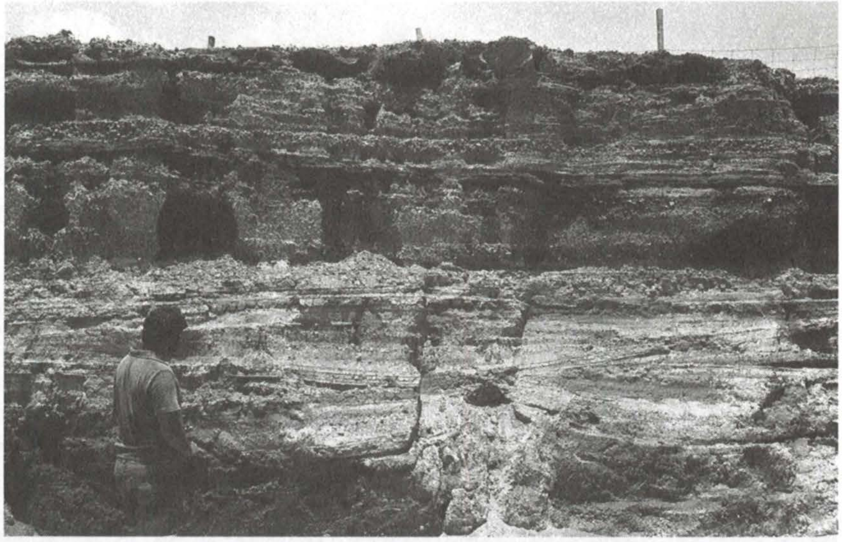
Plate VI Saba

a. A large mixed-magma clast from a block and ash flow deposit. White vesicular dacite is flow-banded together with darker andesite. The latter is rich in subrounded basaltic inclusions.
The deposit is found on the south coast of Saba, below Booby Hill. The host block and ash flow deposit is a gulley infill, but now the topography has been reversed so that it forms a ridge between Savanna and Wash Guts.

b. Pumiceous airfall ash and lapilli deposits showing a seaward dip. The location is the Fence Quarter, southern Saba, where sample SA131 was collected (see sample location map, Figure E1).

Spring Bay Flat from Old Booby Hill. Stratigraphic section I was measured on the top of this ridge which is also the location of analyzed samples SA163-167. In the lower part of the photograph, the rocks are much altered and discolored red, brown, orange and yellow by now extinct fumarolic activity. Such areas are marked F on the geological map (Figure 1).

Plate VIII
St. Eustatius



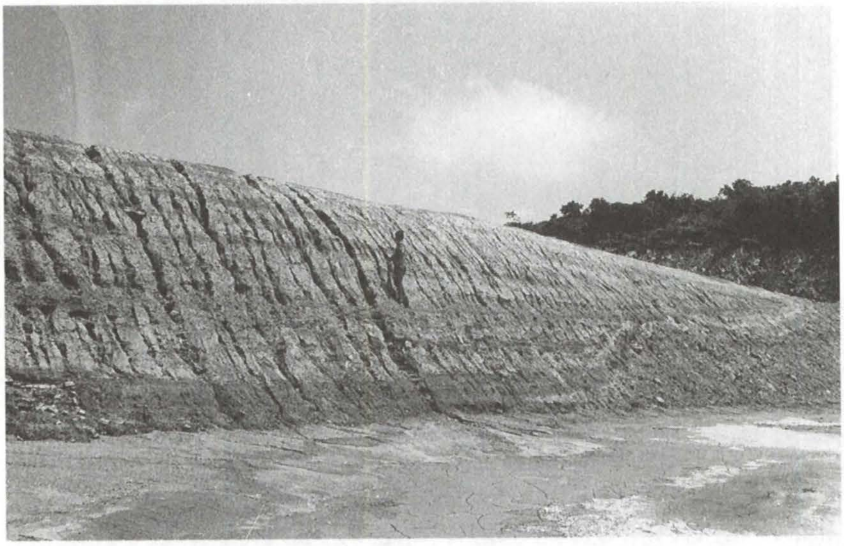
a.
A 2 m thick sequence of pyroclastic surge and airfall ash and lapilli beds at the quarry behind the airport, St. Eustatius (Loc. XXVI).

b.
Detail from same location showing position of dated (7940±75 years B.P.) pumiceous surge horizon.

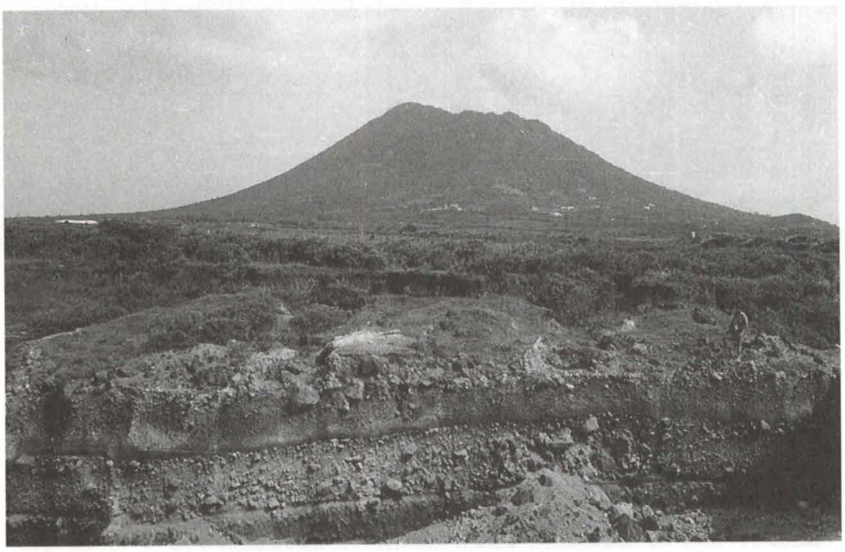
c.
Detail of surge bed showing pieces of carbonized wood that were used to date this pyroclastic event.

Plate IX
St. Eustatius

a.
Cliffs below fort at Oranjestad, St. Eustatius. Section XVI was measured here.
The slightly darker beds at the top of the section represent marker beds K, G, and F.

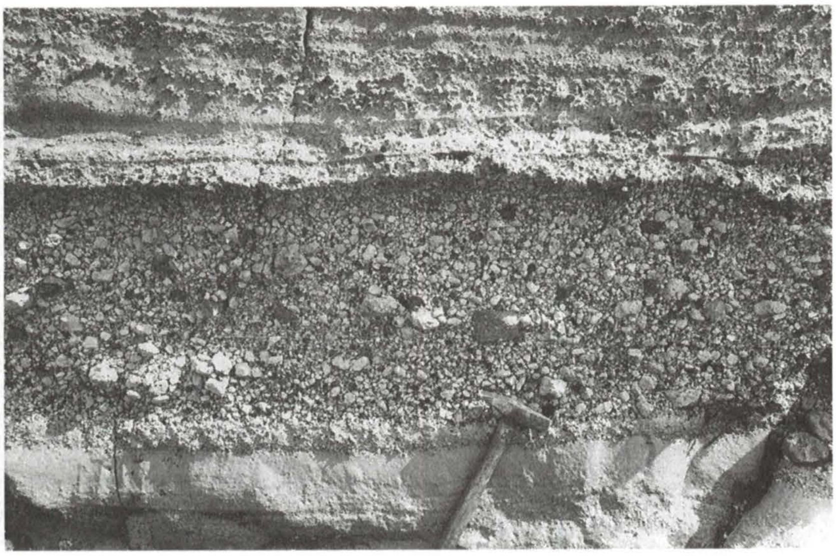


b.
Section XXVIII at the gasoline tank farm on Pisga Hill. This is the furthest measured exposure of deposits from the Quill. Here they overlap a weathered lava flow of the Northern Center (extreme right). The deposits are mainly airfall but with some interbedded pumiceous flows and surges especially near the base.

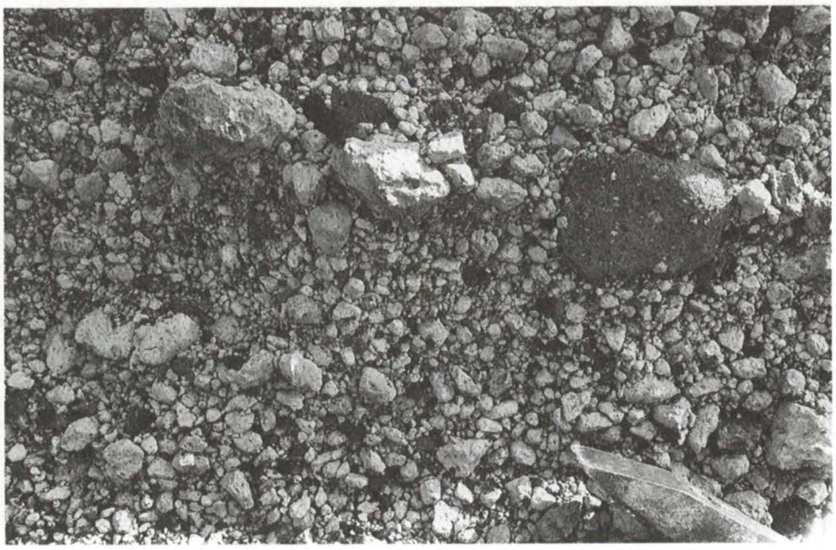


c.
The Quill from eastern St. Eustatius. In the foreground are the pyroclastic deposits, exposed in the cliffs at Schildpadden Bay. Round Hill, which probably represents a buried dome, can be seen on the skyline at the extreme right.

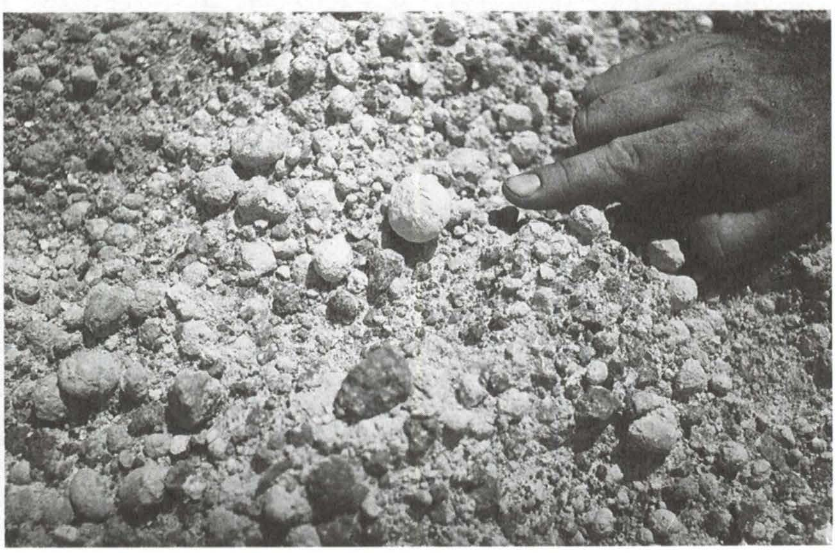
Plate X
St. Eustatius



a.
Rhyolitic pumice airfall lapilli bed exposed on the east coast of St. Eustatius. The deposit is about 1 m thick at this locality. It is marker bed A in stratigraphic section I.

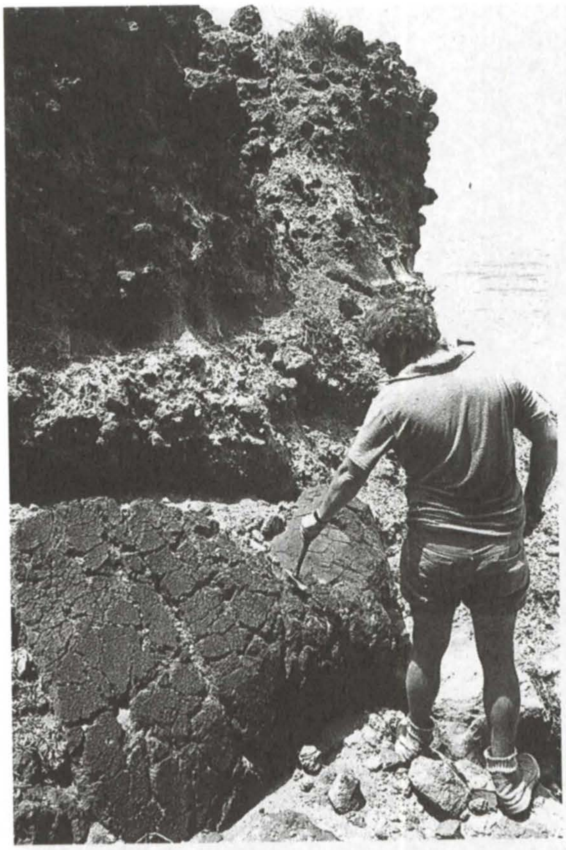


b.
Close up of the same bed as a. showing the white rhyolitic lapilli and the dark colored lithic blocks.

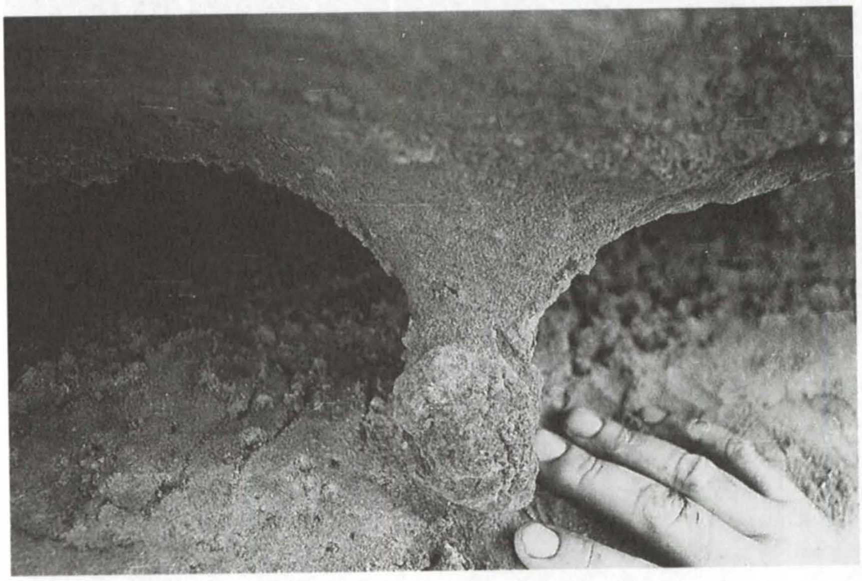


c.
Rhyolitic pyroclastic flow showing well developed, large, accretionary lapilli. Presence of accretionary lapilli indicate that the deposit was probably formed by a phreatomagmatic eruption. Stratigraphic section XXI at Oranjestad.

Plate XI
St. Eustatius



a.
Large breadcrust bomb in a block and ash flow deposit, east coast of St. Eustatius.



b.
Close-up of a bomb sag in a base surge bed near base of section on east coast of St. Eustatius.

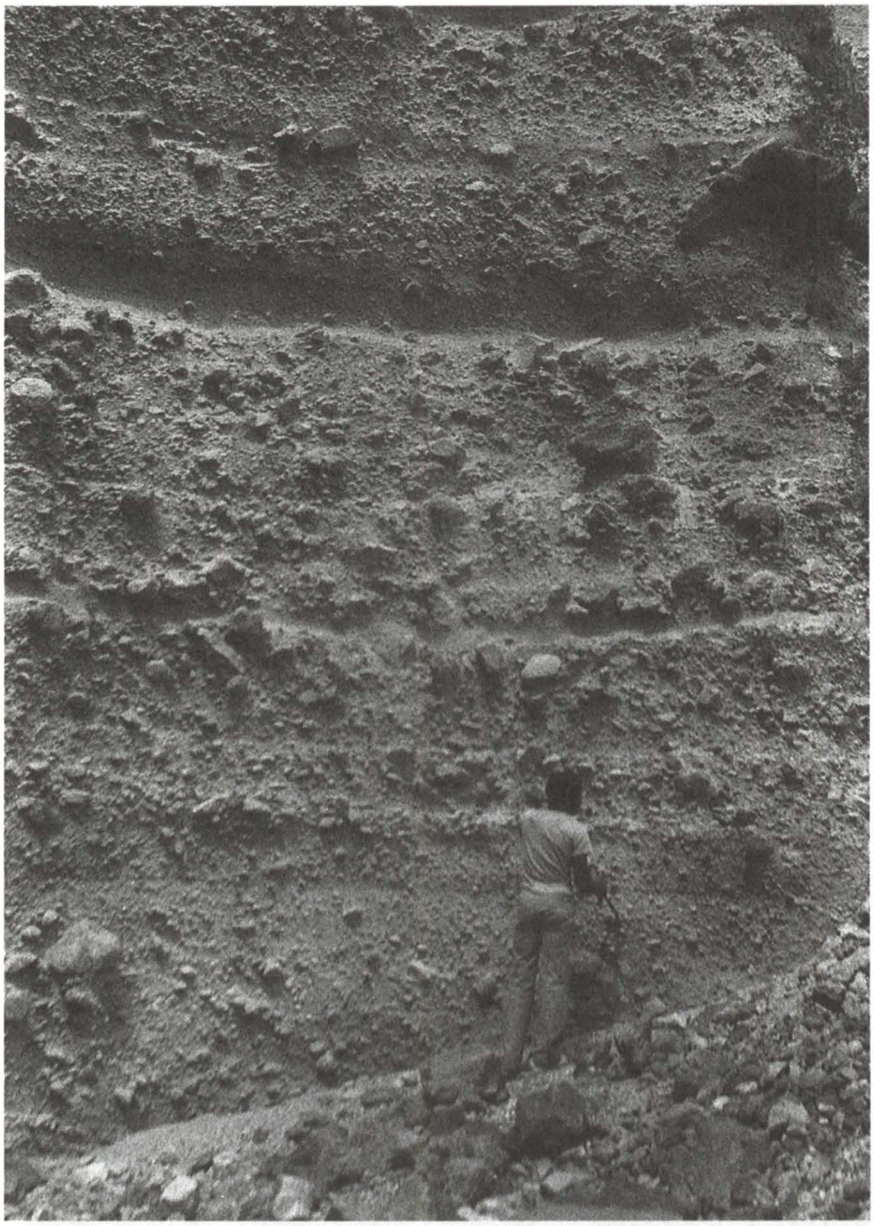


Plate XII St. Eustatius

Section of thin andesitic block and ash flow deposits. Most deposits show reverse grading of larger clasts with finer grained bases. A single thin ash surge deposit occurs in the middle. This is the middle of Section V in the sea cliffs of Compagnie Bay.

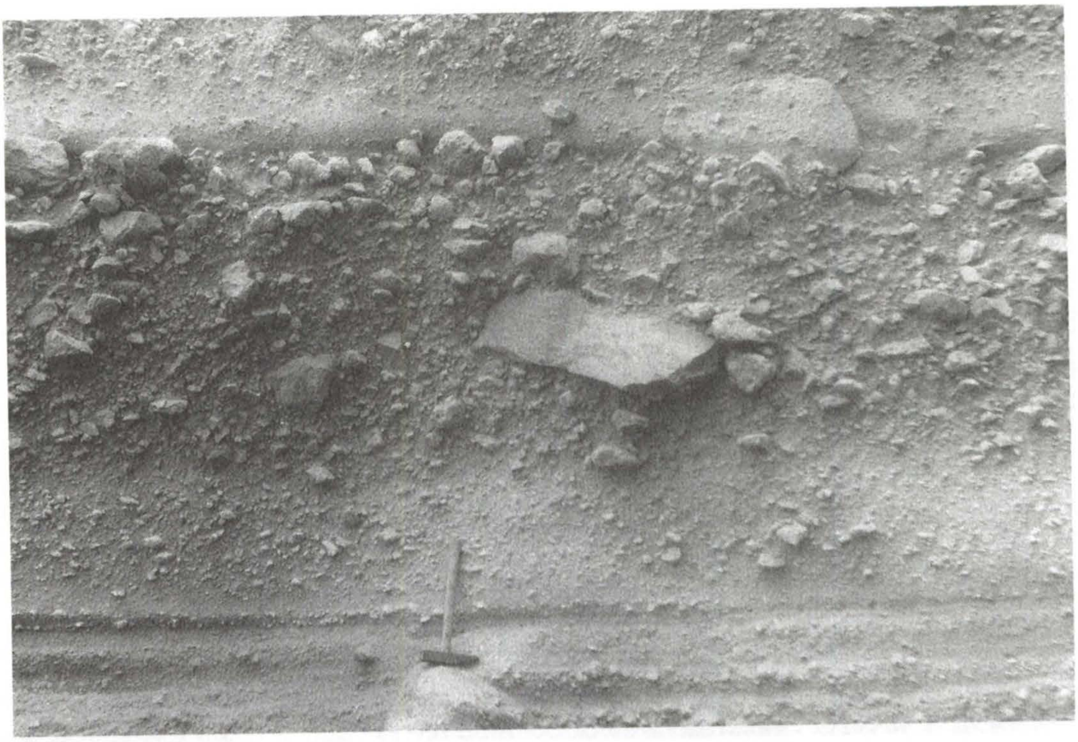


Plate XIII St. Eustatius

a. and **b.** Reverse graded andesitic block and ash flow deposits. The angular to subangular large clasts of andesite are concentrated in the upper part of the deposits. Locality is Compagnie Bay in the middle of Section V.

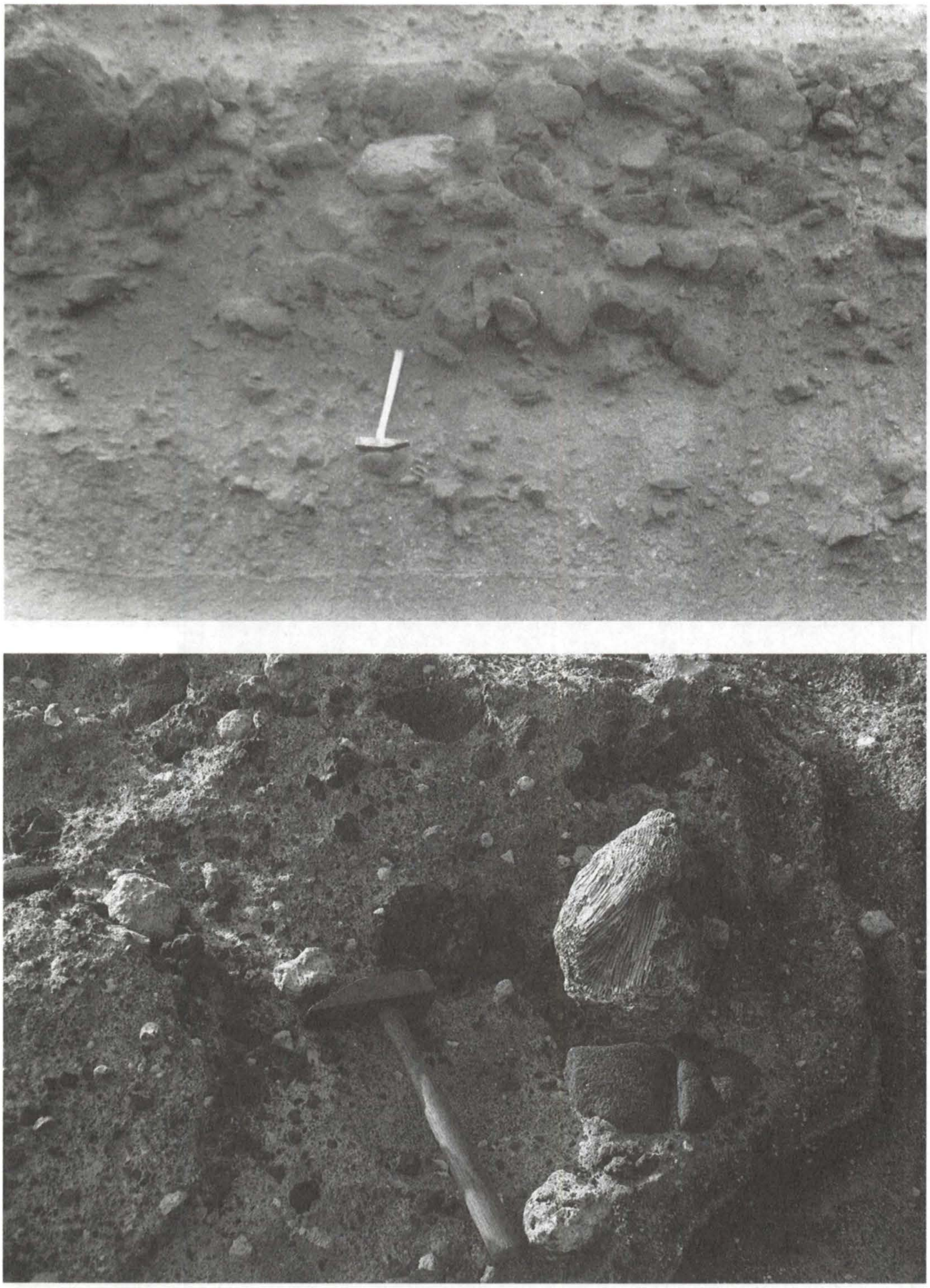


Plate XIV St. Eustatius

a. 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 hammer is 100 cm long and the deposit is 450 cm thick. Location is the east coast of the Quill between stratigraphic sections VII and VIII.

b. Base surge deposits at the south side of the White Wall, south St. Eustatius, in the gulley opposite Fort de Windt. The top deposits of the White Wall - Sugar Loaf section are base surge deposits containing ejected coral head fragments and shattered basaltic bombs of phreatomagmatic type.

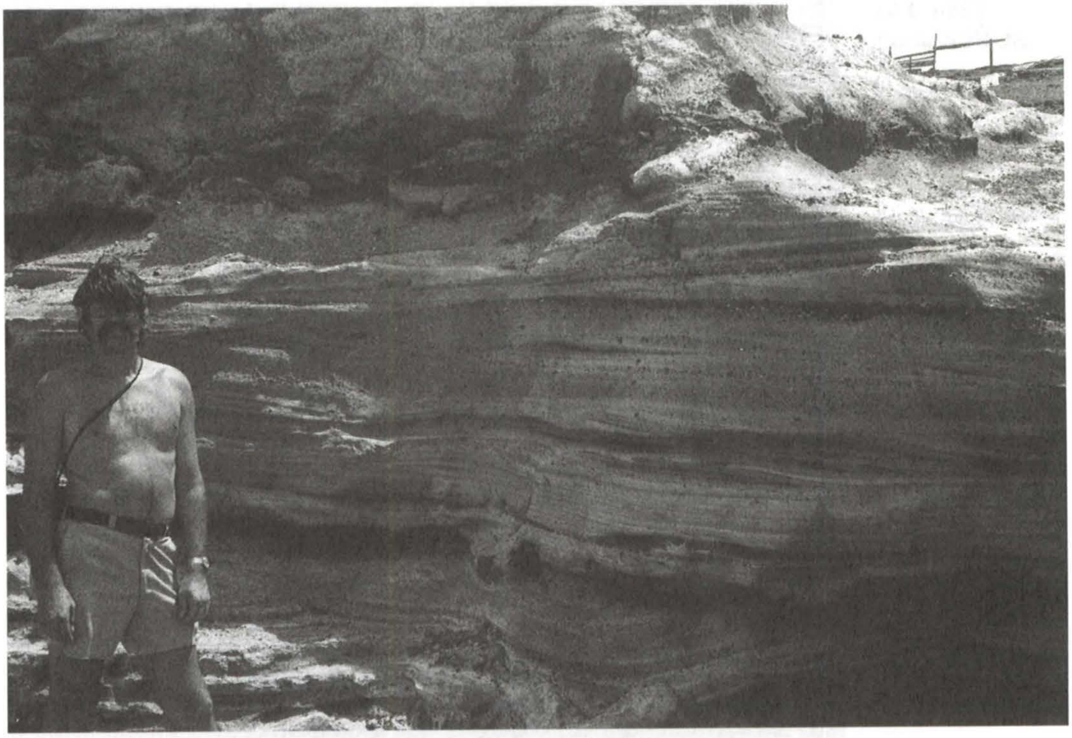
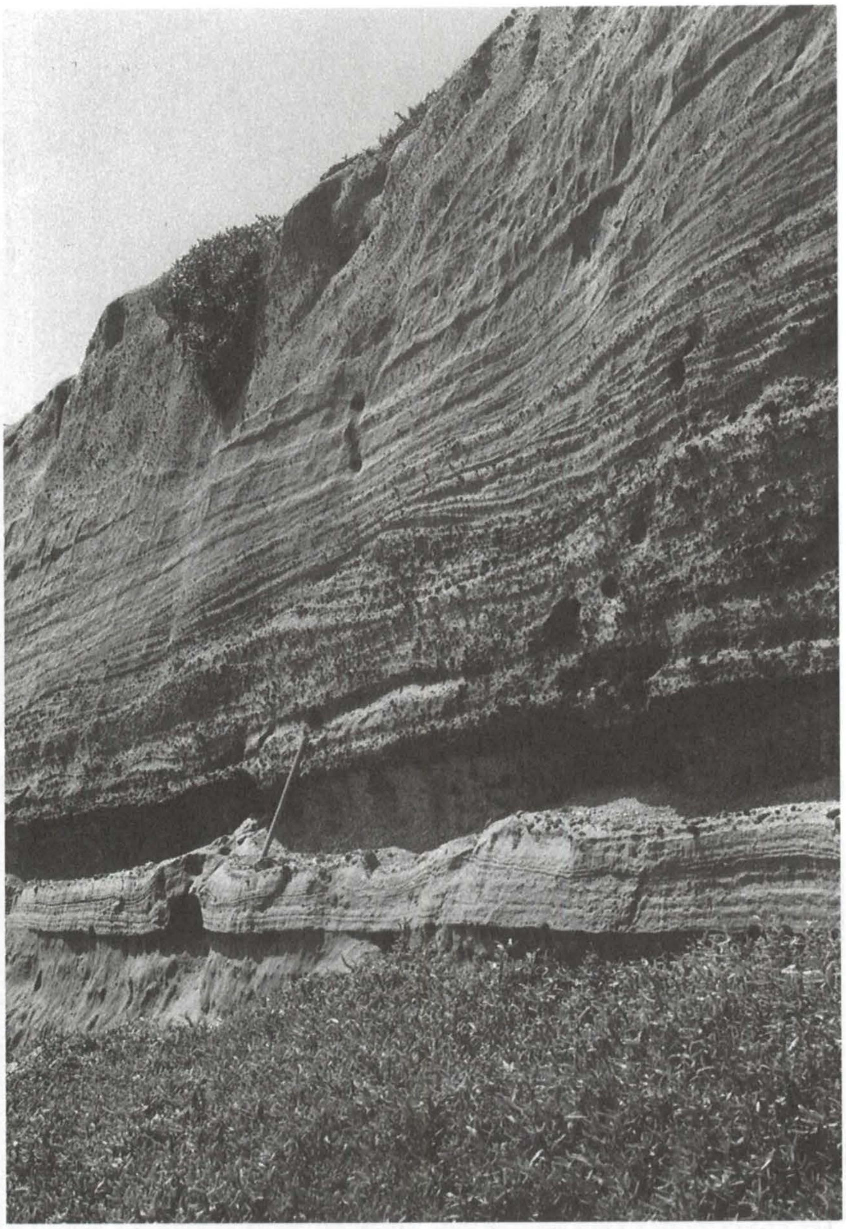


Plate XV St. Eustatius

a. Surge deposits containing black clasts of basaltic andesite and small white clasts of limestone. The deposits are characterized by internal discontinuities and lens like stratification. A single bomb and impact structure is visible near the middle of the photograph (see Plate XI). The location is the sea cliffs of northeast St. Eustatius at Section II.

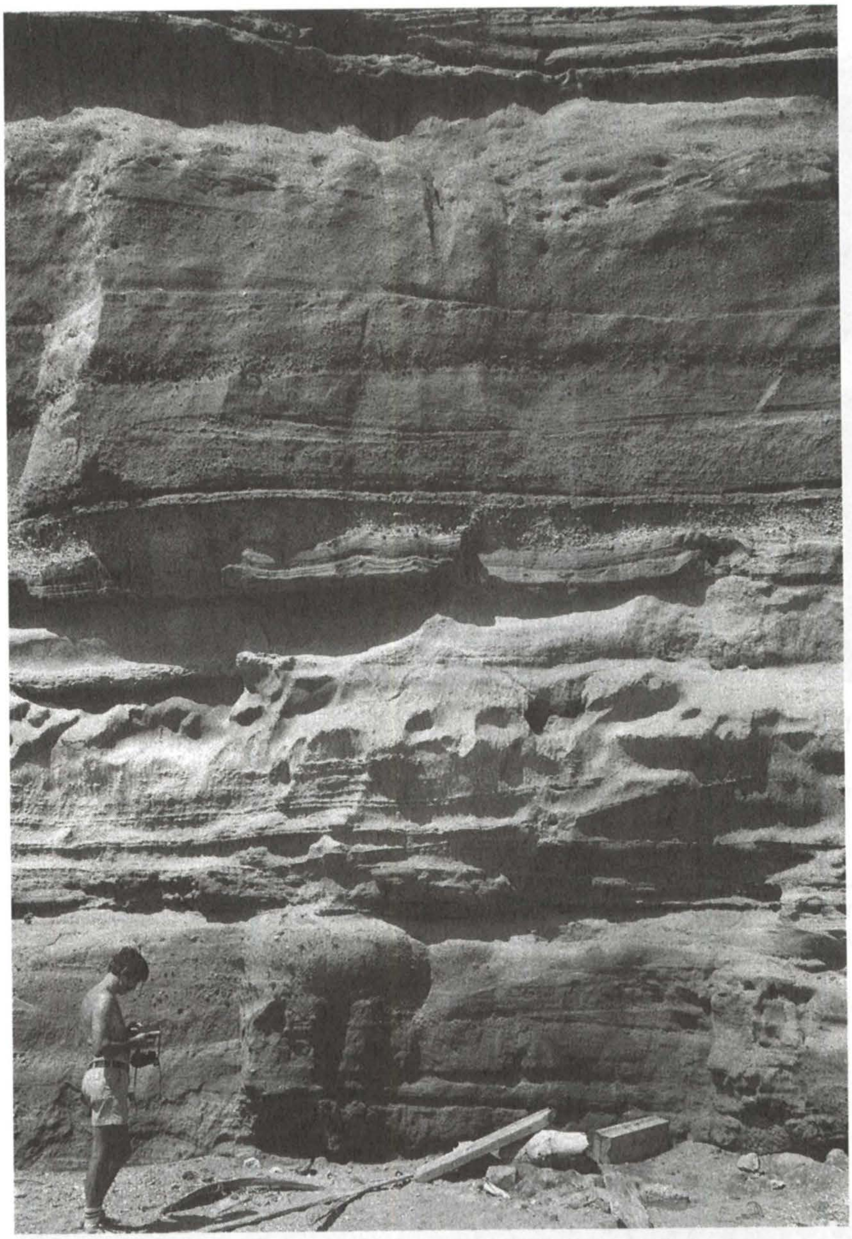
b. Pit excavated for the sewage tank of a house immediately in front of the airport terminal in central St. Eustatius. This is stratigraphic Section XXV and shows the youngest deposits on St. Eustatius. The uppermost thin deposit is a phreatomagmatic flow, which was radiocarbon dated at 1550$\pm$35 years B.P. It is underlain by scoria and ash flows.

Plate XVI
St. Eustatius



Small dune structures in surge deposits on NE coast of St. Eustatius between Zeelandia Bay and Section I. The amplitudes and spacings of these structures average 40 cm and 10 cm respectively. The photographer is facing the Quill and the structures indicate migration away from the Quill.

Plate XVII
St. Eustatius



Stratigraphic Section I on the NE coast of St. Eustatius. The lower 4 m represent a series of base surge horizons, the uppermost of which have been dated at 22,240±140 years B.P. (carbon log obtained from hole in cliffs just below marked bedding plane). Coarse-grained, light colored bed about 6 m high is rhyolitic airfall bed. Above this is a sequence of surge and flow horizons.

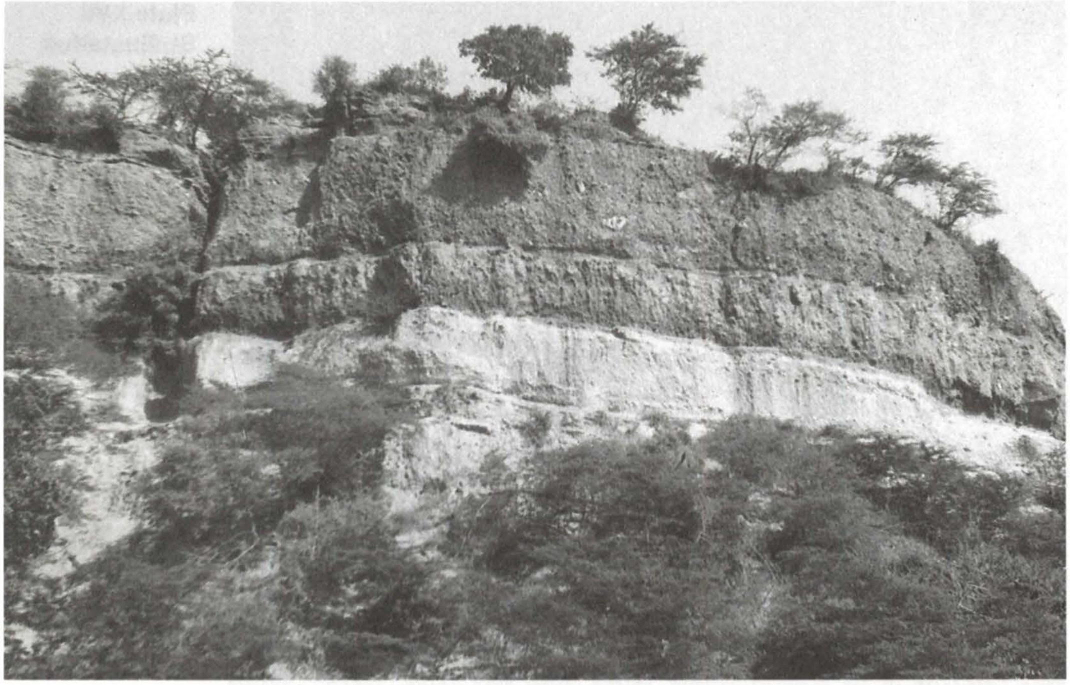


Plate XVIII St. Eustatius

a. Stratigraphic section XII in the sea cliffs of SW St. Eustatius immediately behind the new deepwater jetty for Oranjestad. The younger basaltic andesite scoria and ash flow deposits (marker beds E, F, G, and K) are visible in the top of the cliff. The thickness of basaltic andesite deposits is here 950 cm, which is the maximum development. As these deposits were produced by the last eruptive events of the Quill and underlie the southern part of Oranjestad, they indicate the unsuitable location of the capital. This problem is also shared with Portsmouth (Montserrat) and Roseau (Dominica).

b. The sea cliff section V in Compagnie Bay, NE St. Eustatius. The block and ash deposits of Plate XII were taken at the top of the scree at the far left of the photograph.