dubbel
kaarte in boek

THE GEOLOGY OF SABA AND ST. EUSTATIUS

THE GEOLOGY
OF SABA AND ST. EUSTATIUS

WITH NOTES ON THE GEOLOGY OF ST. KITTS, NEVIS AND MONTSERRAT (LESSER ANTILLES)

BY

J. H. WESTERMANN AND H. KIEL

UITGAVEN "NATUURWETENSCHAPPELIJKE STUDIEKRING VOOR SURINAME EN DE NEDERLANDSE ANTILLEN", UTRECHT, No. 24

1961

UITGAVEN „NATUURWETENSCHAPPELIJKE STUDIEKRING VOOR SURINAME EN DE NEDERLANDSE ANTILLEN"

PUBLICATIONS OF THE FOUNDATION FOR SCIENTIFIC RESEARCH IN SURINAM AND THE NETHERLANDS ANTILLES

Secretariat: c/o Zoological Laboratory of the State University, Utrecht, Holland

1 *Jaarboek 1945—1946.* (publ. Dec. 1946) [out of print]

2 G. J. H. Amshoff, *Enumeration of the Herbarium Specimens of a Suriname Wood Collection.* (May 1948). Suppl. (Jan. 1950) . . . . *f* 3.—

3 A. M. W. Mennega, *Suriname Timbers.* (May 1948) . . . . . *f* 7.50

4 *Jaarboek 1946—1948.* (June 1948) . *f* 4.—

5 *Studies on the Fauna of Curaçao, Aruba, Bonaire and the Venezuelan Islands,* Vol. III, edited by P. Wagenaar Hummelinck. (Nov. 1948) . . . . *f* 9.—

6 *Jaarboek 1948—1951.* (Nov. 1951) . *f* 4.—

7 J. H. Westermann, *Conservation in the Caribbean.* (Aug. 1952) *f* 4.—

8 *Studies on the Fauna of Curaçao and other Caribbean Islands,* Vol. IV. (June 1953) . . . . *f* 12.—

9 J. H. Westermann, *Nature Preservation in the Caribbean.* (Dec. 1953) . . . . *f* 4.—

10 *Studies on the Fauna of Curaçao and other Caribbean Islands,* Vol. V. (Oct. 1954) . . . . *f* 12.—

11 J. S. Veenenbos, *A Soil and Land Capability Survey of St. Maarten, St. Eustatius, and Saba.* (May 1955) . . . . *f* 4.—

12 *Studies on the Fauna of Curaçao and other Caribbean Islands.* Vol. VI. (March 1955) . . . . . . *f* 12.—

13 F. Haverschmidt, *List of the Birds of Surinam.* (Nov. 1955) . *f* 8.—

14 *Studies on the Fauna of Curaçao and other Caribbean Islands.* Vol. VII. (Jan. 1957) . . . . *f* 12.—

15 *Studies on the Flora of Curaçao and other Caribbean Islands.* Vol. I. (Sept. 1956). A. L. Stoffers, *The Vegetation of the Netherlands Antilles* . . . . *f* 12.—

16 *Studies on the Fauna of Suriname and other Guyanas,* Vol. I, edited by D. C. Geijskes & P. Wagenaar Hummelinck. (March 1957) . . . . *f* 6.—

17 *Studies on the Fauna of Curaçao and other Caribbean Islands.* Vol. VIII. (July 1958) . . . . *f* 12.—

18 *Studies on the Fauna of Suriname and other Guyanas,* Vol. II. (Feb. 1959) . . . . *f* 9.—

19 *Studies on the Fauna of Curaçao and other Caribbean Islands.* Vol. IX. (April 1959) . . . . *f* 12.—

20 *Studies on the Fauna of Suriname and other Guyanas,* Vol. III. (Dec. 1959) . . . . *f* 12.—

21 *Studies on the Fauna of Curaçao and other Caribbean Islands.* Vol. X. (Feb. 1960) . . . . *f* 12.—

22 *Studies on the Fauna of Curaçao and other Caribbean Islands.* Vol. XI. (Dec. 1960) . . . . *f* 9.—

23 *Studies on the Fauna of Curaçao and other Caribbean Islands.* Vol. XII. (Dec. 1961) . . . . *f* 27.25

24 J. H. Westermann & H. Kiel, *The Geology of Saba and St. Eustatius.* (Dec. 1961) . . . . *f* 16.—

25 *Flora of the Netherlands Antilles,* Part I: *Pteridophyta* (in press). . *f* 6.—

26 *Studies on the Fauna of Curaçao and other Caribbean Islands.* Vol. XIII (in press).

27 *Studies on the Fauna of Suriname and other Guyanas,* Vol. IV (in press).

THE GEOLOGY OF SABA AND ST. EUSTATIUS

Published with financial aid from the Government of the Netherlands Antilles.

THE GEOLOGY OF SABA AND ST. EUSTATIUS

WITH NOTES ON THE GEOLOGY OF ST. KITTS, NEVIS AND MONTSERRAT (LESSER ANTILLES)

BY

J. H. WESTERMANN AND H. KIEL

With 11 text illustrations, 10 tables, 33 plates and 6 appendices (maps and sections)

Societas investigatrix historiae naturalis Surinamae et Antillarum Neerlandicarum

UITGAVEN "NATUURWETENSCHAPPELIJKE STUDIEKRING VOOR SURINAME EN DE NEDERLANDSE ANTILLEN", UTRECHT

No. 24, December 1961

Printed by Kemink & Zn, Utrecht
Obtainable at Martinus Nijhoff, The Hague

CONTENTS

ST. EUSTATIUS

LIST OF ILLUSTRATIONS IN THE TEXT

LIST OF TABLES

LIST OF PLATES (PHOTOGRAPHS)

The photographs of 1, 17, 18, 19 and 28 were made available by KLM Aerocarto, Schiphol (1957, 1960); 2, 3a, 3b, 6a, 10, 23, 24 and 25a by Centraal Toeristen Comité, Curaçao; 16 by the Royal Tropical Institute, Amsterdam (1960); 7c by H. L. van Scheepen, Saba (1958); 9b by P. Wagenaar Hummelinck, Utrecht (1949); 27 by J. I. S. Zonneveld, Utrecht (1956).

The photograph of 29 was taken by G. A. F. Molengraaff in 1885 (published in 1886), and 13a by I. Boldingh in 1906.

All other photographs were taken by J. H. Westermann (1958).

Blocks were obtained on loan of photographs 6a (W.I.G. 37, 1957); 6b, 9a, 20a, 25b (Jaarbericht Wosuna 1958); 10 (T.K.N.A.G. July 1958), and 27 (T.K.N.A.G. January 1961).

LIST OF APPENDICES (MAPS AND SECTIONS)

INTRODUCTION. ITINERARY OF THE LESSER ANTILLES TOUR 1958. ACKNOWLEDGEMENTS

Introduction (Figs. 1 & 2)

Until 1958 St. Martin was the only island of the three north-eastern Netherlands Antilles which had been surveyed geologically in some detail and on modern lines (Christman 1953).

In 1885 G. A. F. Molengraaff carried out a survey of St. Eustatius, the results of which he published as his doctoral thesis in 1886. The latter is undoubtedly a valuable monograph, and gives a fine general geological description of this neo-volcanic island. However, no geological details and no localities of rock samples are shown on the sketch-map accompanying the text. Again, Molengraaff's work was published in the Dutch language, and consequently, although the main conclusions of his description have been referred to in English, French and German literature on the Caribbean area, it remains difficult for non-Dutch students to consult this book. Besides, it has been out of print for many years. The article on St. Eustatius which Molengraaff published in English in 1931 is merely a short recapitulation of his older work, adapted here and there to bring it into line with more modern theories.

Until 1958 very little geological research had been done on Saba (cf. Molengraaff 1931, Veenenbos 1955, Butterlin 1956, Lexique 1956).

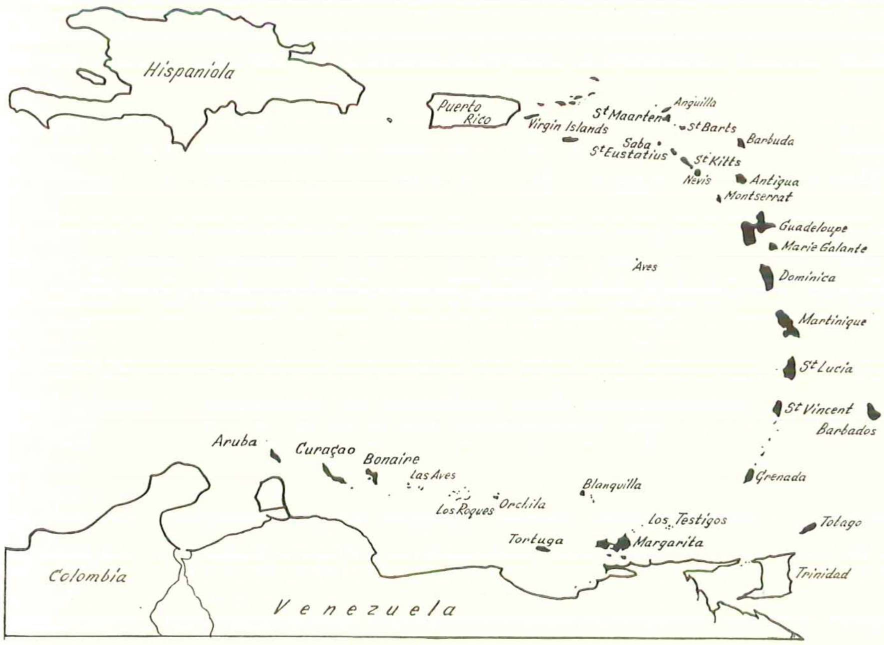


Fig. 1. Outline map of the Caribbean Area

In view of the circumstances described above, the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht (Holland) considered that a new survey of the geology of Saba and

Fig. 2. Outline map of the northern Lesser Antilles

St. Eustatius would be justified for the purpose of increasing knowledge of the geology of the Caribbean area, and particularly of the neovolcanic Lesser Antilles Arc. On account of the geological affinity between the northernmost islands of this Arc, it was also deemed desirable that the survey should involve short visits to St. Kitts, Nevis and Montserrat (Leeward Islands of the West Indies), in order to study comparable formations there. This scheme was discussed first in London, on 22 August 1957, and later on in St. Kitts, with Dr. P. H. A. Martin-Kaye, Government geologist of the Windward Islands, domiciled at Castries, St. Lucia. Dr. Martin-Kaye kindly provided the persons conducting the survey with introductions to the authorities in the Leeward Islands.

The survey of these five Leeward Islands was carried out by J. H. Westermann and H. Kiel, in the period 19 February – 9 April 1958.

The first of the two authors made the trip as an extension to a journey to Surinam and the Curaçao group of the Netherlands Antilles which he undertook in his capacity of Honorary Treasurer of the Netherlands Foundation for the Advancement of Research in Surinam and the Netherlands Antilles (Wosuna). On his journey from Surinam to the Leeward Islands Dr. Westermann visited Grenada and St. Vincent, in order to study some volcanological phenomena (see Itinerary).*

The second author, Mr. H. Kiel – a member of the staff of the Soil Laboratory of the Royal Tropical Institute, Amsterdam – reached St. Kitts via Curaçao. He carried out the petrographic and mineralogical investigations, as well as the drawing of maps and sections.**

Radiocarbon dating of some corals was done in the Physical Laboratory of the University of Groningen. The "Chemisch-Technisch Laboratorium Dr. Lobry de Bruyn", Amsterdam, produced chemical analyses of a number of selected rocks.

Sedimentological investigation of the fossiliferous strata of St. Eustatius (White Wall formation), St. Kitts (Brimstone Hill, Godwin Gut), Montserrat (Landing Bay) was kindly performed by Mr. P. H. de Buisonjé, while determination of the fossils in these formations was carried out by Professor H. Engel, Zoological Museum, Amsterdam (*Echinoidea*), Messrs. P. H. de Buisonjé and M. van den Boogaard, Geological Institute, Amsterdam (*Corallidae*), Dr. C. O. van Regteren Altena, National Museum of Natural History, Leiden (*Mollusca*), and Dr. C. W. Drooger, Mineralogical and Geological Institute, Utrecht (*Foraminifera*).

All rock and fossil samples and thin sections are being kept in the collection of the Geological Institute of the University of Amsterdam.

---

* Dr. Westermann had previously paid short visits to Saba, St. Eustatius and St. Kitts, viz. in October 1946 and March 1950.

** Mr. Kiel conducted the mineralogical study of soil samples collected by Dr. J. S. Veenenbos in 1950—1951 (1956).

Itinerary of the Lesser Antilles tour 1958, with list of places visited because of their special geological and volcanological interest.

Grenada, 9—11 February 1958

Grand Etang (crater lake); Lake Antoine (crater lake); Punchbowl (crater); Levera Pond (crater lake?).

St. Vincent, 12—19 February

Soufrière volcano, with Old and New Crater; ash deposits near the mouths of Rabaca Dry River, east coast, and Wallibou River, west coast (1902).

St. Kitts, 19—25 February, 1—3, 5—8 March

Mount Misery and crater; Brimstone Hill; Godwin Gut; Black Rocks; Monkey Hill; Canada Hills; Conaree Hills; Morne Hills; Sir Timothy's Hill; Salt Pond Peninsula.

Montserrat, 25 February — 1 March

South slope, South Soufrière Hill; fossiliferous tuffs, Landing Bay; *nuée ardente* deposits, north slope, Soufrière Hills; Cow Hill soufrière; Castles Peak; Hot Water Pond; Silver Hill.

Nevis, 3—5 March

Kade's Bay soufrière; Round Hill; Saddle Hill; Nevis Peak.

St. Eustatius, 8—21 March

North-western hills (remnants of the older volcano); the Quill volcano and its glacis; White Wall formation.

Saba, 21 March — 9 April

The Mountain; surrounding volcanic domes and peaks; old lava flows; agglomeratic and tuffaceous deposits of various characters.

Acknowledgements

The authors' thanks are due to:

the Netherlands Antilles Government for granting a subsidy to the Foundation for Scientific Research in Surinam and the Netherlands Antilles, to cover the salary and travelling expenses of Mr. Kiel, general research expenses, and the costs of publication of this treatise;

the Netherlands Foundation for the Advancement of Research in Surinam and the Netherlands Antilles (Wosuna), Amsterdam, for defraying the travelling expenses of Dr. Westermann;

the Netherlands Organization for the Advancement of Pure Research (Z.W.O.), The Hague, for allowing its Deputy Director, Dr. Westermann, to undertake the West Indian journey;

the Royal Tropical Institute, Amsterdam, for granting leave to Mr. Kiel to participate in the survey;

KLM Aerocarto N.V., Schiphol, for making available a contour map of Saba, and aerial photographs;

the local authorities of the Governments of Saba and St. Eustatius for their hospitality, coöperation and the supply of free transport;

the Administrative Secretary of the Ministry of Trade and Production of St. Kitts, Mr. O. W. Flax, for his kind assistance in making various arrangements;

Mr. J. A. Meuter, head of the Cadastral Service of the Netherlands Antilles, Curaçao, for the loan of sets of the aerial photographs of Saba and St. Eustatius.

The authors are also very much indebted to:

Mr. Ernest Payne, Soil Utilization Officer of the Department of Agriculture, Grenada, for kindly guiding Dr. Westermann to various places of geological and soil scientific interest;

Mr. Hugh McConnie, Superintendent of Agriculture of St. Vincent, and his officers, for taking Dr. Westermann round the island and showing him outstanding examples of soil and land conservation as well as sites of volcanological importance, including the Soufrière volcano;

Dr. P. H. A. Martin-Kaye, Government geologist for the Windward Islands, St. Lucia, for his help and good advice and for his general interest in the geological survey;

the late Mr. Malcolm Smith, Basseterre, St. Kitts, for his great hospitality and his pleasant guidance on trips to the crater of Mount Misery and other places;

Mr. Arthur Spanner, local guide of St. Eustatius;

Mr. Edmund Hassell, for his agreeable company during the survey of Saba;

Messrs. A. Kooistra (head of the Police), J. H. Ferwerda (physician) and H. L. van Scheepen (school headmaster) and their wives, for their kind help and hospitality at The Bottom and Windward Side, Saba;

Mr. J. H. Ferwerda, for collecting and sending, in August 1959, a special set of rock samples of the south-coast cliffs of Saba, at the request of the authors.

Thanks are further extended to:

Mr. J. G. Ubaghs, Mineralogical and Geological Museum of the Technological University of Delft, Holland, for the loan of rock and fossil samples from St. Eustatius, collected by G. A. F. Molengraaff (1885), for petrographic and palaeontological study;

Professor H. Engel, Mr. P. H. de Buisonjé, Mr. M. van den Boogaard, Dr. C. O. van Regteren Altena and Dr. C. W. Drooger, who kindly undertook determination of fossils;

Mr. P. H. de Buisonjé, for his sedimentological investigations;

Professor H. J. Mac Gillavry, Geological Institute, University of Amsterdam, who gave his coöperation in all matters pertaining to laboratory investigation of the samples by Messrs. De Buisonjé and Van den Boogaard;

Professor W. P. de Roever and Dr. A. C. Tobi, Geological Institute, University of Amsterdam, and the late Dr. Q. A. Palm, Mineralogical and Geological Institute, University of Utrecht, for their advice regarding the petrography of some rocks;

Professor W. Nieuwenkamp and Miss H. J. W. de Widt, Mineralogical and Geological Institute, University of Utrecht, for endeavouring to carry out rock analyses with a Philips röntgen-fluorescence apparatus;

Professor R. W. van Bemmelen, Utrecht, Professor B. G. Escher, Oegstgeest, and Dr. M. Neumann van Padang, The Hague, for advice on various volcanological problems;

Professor H. de Waard and his co-workers, Physical Laboratory, University of Groningen, for radiocarbon dating of some coral samples;

Dr. P. Wagenaar Hummelinck, Honorary Secretary of the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht, for his valuable assistance in preparing this treatise for the press;

Miss Louise J. van der Steen, Zoological Laboratory of the University of Utrecht, for kindly typing the manuscript;

Mr. E. R. Edwards, The Hague, for correcting the English.

CHAPTER I

REVIEW OF PREVIOUS GEOLOGICAL, PETROLOGICAL AND SOIL-SCIENTIFIC WORK WITH REGARD TO SABA AND ST. EUSTATIUS

The first geological observations concerning Saba and St. Eustatius were made at the beginning of the nineteenth century by the Scottish American W. MACLURE (1817). He gave a very short description of Saba: (p. 148) "*Saba.* This little island seems to finish the volcanic formation, and consists of one mountain, rather rougher and more rugged than St. Eustatia, but apparently of nearly the same kind of rocks."

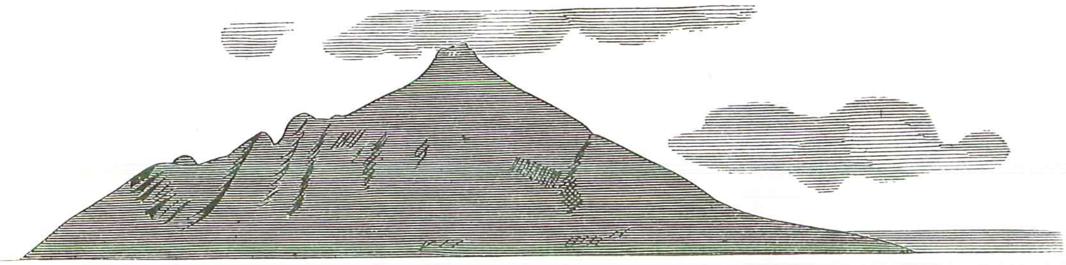
His account of St. Eustatius contains more data, and is quoted in particular because the formation of White Wall-Sugar Loaf is described in it: (pp. 147—148)
"*St. Eustatia* is formed of two hills that appear to have been both craters of volcanoes; the western one is more ancient and is filled up with earth &c; the eastern one is higher and appears to be more recent, the crater being only partially filled. The space between these two hills is filled with cinders, forming a plain with a bay on each side, the one to the leeward is the harbour, on the edge of which stands the town."
"On the south-east side of the large hill, towards St. Christopher, there is a stratification of madrepore limestone, alternating with beds of shells, similar to those found at present in the sea. The whole of this marine deposition dips to the south-west, at an angle of upward of 45 degrees from the horizon, resting upon a bed of cinders, full of pumice and other volcanic rocks, and is immediately covered by a bed of madrepore, sand and cinders, mixed together, with blocks of volcanic rocks so disseminated that there can be no doubt of the volcanic origin of the substance above and below the madrepore rock, which may be from five to six hundred yards thick. Part of this madrepore rock is changing into silex, having the part that surrounded the animal already converted into chalcedony. A considerable quantity of gypsum is found near the same place, in a crystalline state."

A similar but rather shorter description is given of the analogous beds of Brimstone Hill, St. Kitts. The dipping sedimentary formations of the two islands were considered by Maclure as "having been ejected from the bottom of the ocean".

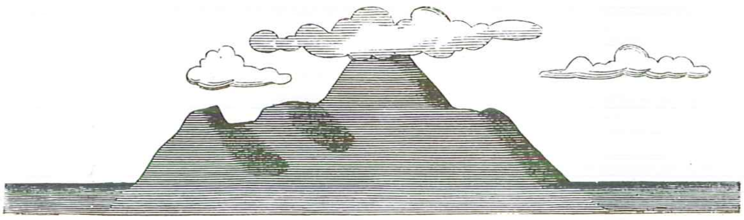
The Frenchman CH. SAINTE-CLAIRE DEVILLE visited the islands in 1841 and collected rock samples, but never published a geological description. His *Voyage géologique aux Antilles* (1847, 1864) contains only some altimetrical data.

The Colonial Secretary of St. Eustatius, A. H. BISSCHOP GREVELINK (1846), published a general, non-scientific account of this island in which chapter 7 is devoted to earthquakes and chapter 10 to soil types and rocks. The earthquake of 8 February 1843, which was also felt in Antigua, Montserrat, Guadeloupe and Dominica, is described in particular. It is amusing to read the author's peroration: "De tijd echter bragt allen weder van lieverlede tot bedaren; eenigen hadden hunnen wandel verbeterd, anderen hunne kennis van het zonnestelsel vermeerderd, allen hadden gewonnen naar den geest, hoe wonderlijk het ook in het eerst met dezen gesteld was, doch waren armer geworden in aardsche goederen."

The work of the Swede P. T. CLEVE, who visited the north-eastern Lesser Antilles in the winter of 1868—1869, is of greater geological importance. His publication of 1871 is quoted at some length in the present work. Cleve's description of Saba is accompanied by sketches and a primitive sketch-map: (pp. 18—19; Fig. 3)



The island of Saba seen from S:t Eustatius.



Saba seen from S:t Bartholomew.

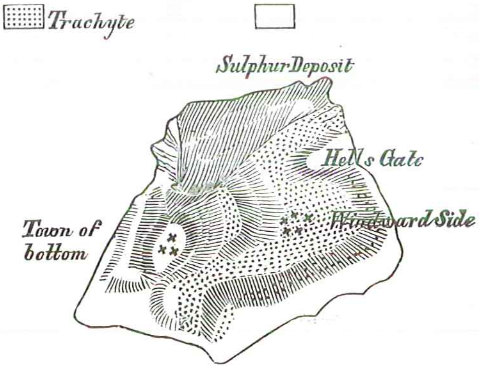
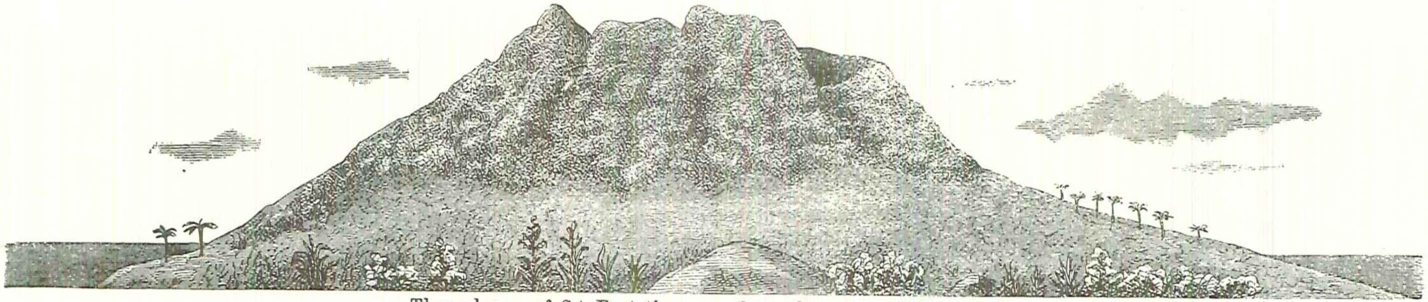


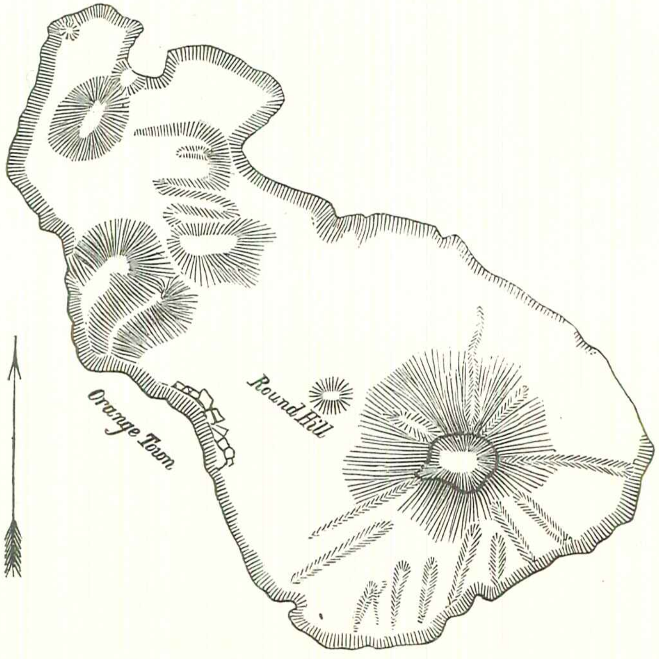
Fig. 3. P. T. Cleve's sketches of Saba, 1871

"*Saba*, a Dutch possession, is a small conical island rising abruptly from the surrounding deep sea to the height of 859 meters. The rock of the island is a more or less irregularly stratified trachytic tufa, or in the eastern and north-eastern part trachytic lava (microtinit). The trachyte has a reddish brown colour and contains white crystals of glassy oligoklase and small black needles of hornblend. Near Hell's Gate there occurs in the tufa a sulphur deposit with gypsum and alum-stone. The sulphur is evidently a remnant of an old fumarol. I could not reach the highest point of the island, which is covered by dense forests of arborescent ferns, but I do not believe that there is any crater, the summit being terminated by a crest. From S:t Eustatius the island has the appearance of a pointed cone, and from S:t Bartholomew the summit is terminated by a horizontal line. The settlement "*the town of bottom*" is a flat, almost circular space at the height of 2—300 meters above the sea, surrounded in all directions, by high steep hills of tufa. To me it appears very probable that this is the true crater."

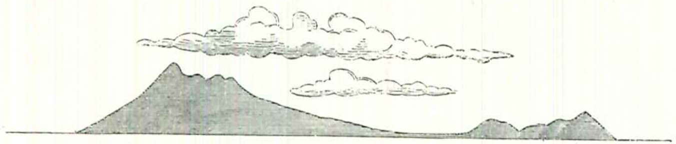
Cleve's description of St. Eustatius is illustrated by a rough drawing of the island as seen from St. Barthélemy; another of the Quill volcano; and an extremely inaccurate sketch-map: (pp. 19—20; Fig. 4)



The volcano of S:t Eustatius seen from the centre of the island.



Map of S:t Eustatius.



Sketch of S:t Eustatius from S:t Bartholomew.

Fig. 4. P. T. Cleve's sketches of St. Eustatius, 1871

"*S:t Eustatius,* also a Dutch possession, is a small, entirely volcanic, island, 6,7 kilometers in length and 4,7 kil. in breadth. In the southern part is a conical volcanic mountain called "the Quill" or the Punch Bowl. The summit is one of the most regular craters. The mountain reaches about 594 meters above the sea-level, and the opening of the crater is about 740 meters in diameter. The whole crater is overgrown with a rich tropical vegetation. The slope of the mountain is very steep, in the higher parts about 45°, but on an average about 25°. The exterior surface of the volcano is grooved by radiating furrows hollowed by rain-water. The volcano, of which no eruption is recorded, seems never to have emitted lava-currents, the whole cone being constructed of loose materials, boulders and trachytic tufa. In the lower parts surrounding the mountain the tufas is disposed in very regular strata. On the western slope is a small hill called *Round Hill,* which seems to be a parasitical cone."

Referring to Maclure's account of the White Wall formation, Cleve continues: "I have not visited the spot, but to judge from the description, the formation may be of the same kind as the limestone formation at Brimstone Hill in S:t Kitts. That fossiliferous deposit, as well as the regular stratification of the tufa in the land around the cone, seem to prove that the lower part of the volcano is formed by submarine eruptions and that the island has been raised afterwards. In the northern part of the island are several hills and rocks, all of volcanic origin. Some consist of trachyte or old lava-currents, and others of trachytic tufas. They are evidently of an older date than the Quill, as tufas from the latter cover some parts of the trachytic rocks. No regular craters are visible in the northern part, only crests and hills, which have probably been parts of volcanic cones or lava-currents, partially destroyed by denudation. No fossils are found in that part of the island."

Cleve also devotes short paragraphs to recent species of molluscs found in the sugar-cane fields below Monkey Hill, St. Kitts, and to the limestone rocks, and their fossil contents, of Brimstone Hill on the same island (pp. 20—21).

Cleve's publication of 1882 (*Annals*) presents only an outline of the observations described in his previous work: (p. 192) "To the Post-pliocene time are to be referred the very important volcanic formations which extend from Saba through St. Eustatius, St. Kitts, Nevis, Redonda, Montserrat, Guadeloupe, etc."

It is interesting to note that A. A. Julien — a resident of Sombrero for four years — confirmed the accuracy of Cleve's petrographic distinctions of the rocks of St. Eustatius and Saba: cf. Discussion (*Transactions,* p. 23).

The Dutchman G. A. F. Molengraaff, who took part in the "Nederlandsche West-Indische Wetenschappelijke Expeditie 1884—1885", visited Saba and St. Eustatius in the period 10 April — 15 May 1885. Most of Molengraaff's time was spent on St. Eustatius, and his doctoral thesis is entirely devoted to this island (1886). Six chapters deal with: general data; physiography; geological observations; a more detailed survey of White Wall — Sugar Loaf; petrographic descriptions; and the geological position of St. Eustatius in the Lesser Antilles Arc. Molengraaff's survey is the first thorough contribution to the geology of the island. However, most of his observations are of a general character, and the sketch-map (scale 1 : 56,700) neither gives geological data (except in the case of the White Wall formation) nor shows the localities of the rock samples collected. These samples are being kept in the "Mijnbouwkunde" Section of the Mineralogical and Geological Museum, Technological University of Delft, Holland.

Notwithstanding the fact that Molengraaff's book was written in the Dutch language, his findings have received full recognition from his contemporaries and from younger geologists, of non-Dutch nationality.

Molengraaff's data on St. Eustatius are discussed more fully in Chapters VIII and IX.

Two years after publication of his thesis on St. Eustatius Molengraaff published a short article in German on the occurrence and crystallography of the volcanic sulphur of Saba (1888). Since the article contains his first general account of the geology of this island, a small excerpt from it is given: "Saba ist der obere Theil eines sehr stark denudirten Vulcans, welcher sich am östlichen Rande des Hauptkraters bis zu 850 m über den Meeresspiegel erhebt. — Der Boden der Insel besteht wesentlich aus Augit-Andesit, theilweise aus Hornblende-Andesit und deren Tuffen. Der mächtigste Lavastrom hat sich aus dem Hauptkrater in nördlicher Richtung ergossen, wo die erstarrte Lava eine im Meere hervorragende Halbinsel bildet, welche Flat-Point genannt wird." (It is surmised from this description that in 1888 Molengraaff considered the valley of The Bottom as the main crater. He thought that the Flat Point lava flow had been ejected from this crater).

Rocks from Saba and St. Eustatius, collected in 1841 by CH. SAINTE-CLAIRE DEVILLE, were subjected to petrographic and mineralogical examination by the Frenchman A. LACROIX (1890).

The monumental work by Lacroix on the inclusions of volcanic rocks (1893) contains a short note on quartz inclusions in Saba rocks (p. 48).

An interesting discovery was made by Lacroix (1893) concerning the metamorphic limestones found in the collection of Sainte-Claire Deville. These rocks are described as having been sampled from a loose block in one of the steep cliffs of Giles Quarter, on the south coast of Saba. Lacroix (V. Enclaves de calcaires) considers these rocks to be sedimentary limestones metamorphosed by volcanic agencies.

The description by the Englishman HENRY BENEST (1899) of a submarine outburst of fresh water off Saba, which was witnessed by Captain Lugar of the Central and South American Telegraph's Company, has little bearing on the geology of the island but is proof of possible artesian activity at a distance of one-third of a mile from the shore on the south-west side. Captain Lugar "saw the fresh water bubbling up in small circles. He sampled some, and found it brackish to the taste. The native who guided him to the spot averred that sloops and schooners frequently filled up their barecas from this submarine stream of artesian water."

The Canadian J. W. W. SPENCER made an overall study of the "Windward Islands". He visited some of these islands in 1896 and 1897. Although Sapper (1903) states that St. Eustatius and Saba "neuerdings auch von Prof. J. W. Spencer besucht worden waren", there is little indication that Spencer actually surveyed the two islands. His data on Saba and St. Eustatius are largely borrowed from Cleve.

Spencer (1901) submits general considerations on the Brimstone Hill limestone formation in St. Kitts, and on the White Wall formation in St. Eustatius which, according to fossil determinations and physical resemblances, may have been deposited at about the close of the Pliocene period. In St. Kitts the greatest volcanic activity — according to Spencer — appears to have been during the earlier part of the Pleistocene period, and it is concluded from the freshness of the mountain slopes that the eruptions have recurred nearly to the present day. Elevation of the adventitious dome of Brimstone Hill, thrusting up the limestone beds, is thought to have taken place in the Middle Pleistocene period, hence after the time of greatest volcanic activity. A correlation is made with White Wall "where the limestone-mantle has been carried up to a height of 900 feet, upon the flanks of the crater-cone, which . . . is still well preserved although composed only of cinders" (p. 536).

The remnants of the old volcanic foundation in the denuded Salt Pond peninsula of St. Kitts are compared by Spencer with the north-western hills of St. Eustatius.

In 1904 Spencer published another article on the "Windward Islands". Saba is described as being "simply an extinct volcanic cone, rising precipitously from the floor of the sunken Antillean ridge" (the latter lying at a depth of 2,250 feet or more). The following general account is given of the islands of St. Eustatius, St. Kitts and Nevis: (pp. 357, 358)

"Statia, St. Kitts and Nevis are all situated on a narrow submerged ridge. The north-western end of Statia and the south-eastern end of St. Kitts are the remains of the old

dissected and degraded mountains composed of the ancient trappean foundation of all the Antillean islands of the Windward chain, but the remaining portions of these two islands and Nevis are surmounted by volcanic ridges, belonging to geological days more recent than the early Pleistocene epoch, with the volcanic activity continuing down so recently that some of the craters are still preserved, . . ."
"The old eruptive foundation of these islands belonged to the very beginning of the Tertiary era, or to a little earlier geological time. During the Miocene, and until about the close of the Pliocene period, this region was a land surface, and no formations were accumulated beneath the sea. But in the Pleistocene period a most interesting phenomenon occurred. A volcanic upheaval raised Brimstone hill . . . to a height of about 700 feet, without having produced a crater." (The account concludes with a very short description of the upthrust limestone beds of Brimstone Hill and White Wall).

The American volcanologist E. O. HOVEY joined two expeditions which were sent out by the American Museum of Natural History, New York, to the volcanic islands of the Lesser Antilles in May — July 1902 and February — May 1903. Montserrat, Nevis, St. Kitts, St. Eustatius and Saba were visited on the second journey. Hovey's field studies led him to draw a comparison between the two active volcanoes of Mont Pelée (Martinique) and Soufrière (St. Vincent) and the supposedly extinct West Indian volcanoes. According to his article in *The American Journal of Science* (1903) "Nevis and Montserrat to-day stand as close analogues, on a smaller scale, of Mont Pelé before the eruptions" (p. 270). The peak of Saba is supposed to "have passed through the phases through which Mont Pelé is now passing, ... Bombs closely similar in appearance to those of Mont Pelé occur . . . on Saba" (p. 281).

The following is quoted from Hovey's publication in *The American Museum Journal* (1903): (pp. 53, 54)
"The great crater of Mt. Misery on the island of St. Christopher (St. Kitts) shows, on a smaller scale, just what the Soufrière was before May, 1902, and St. Eustatius (Statia) is another example of the same kind, though on a still smaller scale. Both are great open pits or calderas, entirely surrounded by walls of very irregular height. The crater of St. Eustatius contains no body of water; but that of Mt. Misery has within it a shallow lake, except toward the end of the dry season. The volcano of St. Eustatius is entirely extinct, but Mt. Misery has a considerable solfataric area (called a "sulphur" by the English West Indians) along the northeast wall of its crater. Bombs occur on the slopes of the St. Eustatius volcano which are closely similar to those thrown out by St. Vincent's Soufrière during the recent eruptions.
The island of Nevis culminates in a great volcanic cone containing a pitlike crater which has been cleft to its base on the northwest side. This cone, like those of Pelée and the Soufrière of St. Vincent, shows the remains of an older and larger crater-ring partly surrounding it, just as Monte Somma partly encircles Vesuvius."

Hovey's article on the volcanoes of Martinique, Guadeloupe and Saba (1905) contains a comprehensive comparison of the West Indian volcanoes, which are divided into two general groups: (p. 447)
"For the purposes of the present discussion the volcanoes of the islands may be divided into two groups — those whose eruptions have been like the recent outbreaks of Mont Pelée, and those whose eruptions have been like the outbreaks of the Soufrière of St. Vincent. In the first group may be placed Mont Pelée of Martinique, the Grande Soufrière of Guadeloupe, and Saba; in the second group, the Soufrière of St. Vincent, Mount Misery of St. Kitts, and Statia. Grenada probably belongs in the second group, while Montserrat and Nevis belong in the first, but data are not yet at hand for definite classification. The characteristics of the first, or Pelée group, are eruptions of the massive, solid kind, which leave no true crater, and produce typical "bread-crust" bombs of more or less pumiceous character from andesite of relatively high silica content. The second, or St. Vincent group, have true craters from which has come no solid extrusion similar to that which has made the present activity of Mont Pelée so remarkable. The volcanoes of Montserrat and Nevis are classed provisionally

with the Mont Pelée type because they seem to have very much the same shape as that of Mont Pelée before the eruptions of 1902 began; that is, each presents a great crater whose wall is breached on one side to the base by a cleft which continues into a gorge of erosion.
The volcanoes of the Caribbean date from early Tertiary time and seem to be mountains of accumulation."

A separate paragraph is devoted to Saba: (p. 451) "Saba is an island which seems likewise to lack a true crater. Its summits are formed of solid lava, which is andesite containing a relatively high percentage of silica. "Bread-crust" bombs of the Pelée type are abundant. Although there are three or four depressions between peaks there does not seem to be any true crater upon the island and it is referred provisionally to the Pelée type of volcano."

The second group of volcanoes is described in Hovey's article on St. Vincent, St. Kitts and St. Eustatius (1905, p. 454). This account is very similar to that quoted from the publication of 1903, with the exception of the statement that the walls of the craters of Mount Misery and the Quill volcano, as compared with those of the St. Vincent Soufrière, "show a similar alternation of lava with beds of tuff". The occurrence of lava beds in the Quill volcano is, however, extremely doubtful, and the same is probably true of Mount Misery.

Hovey's publication of 1925 is of minor importance; his statement that "recent elevation of the island chain ... is greatest at the north, beach conglomerates occurring at 1,500 feet on Statia" is evidently not based on critical examination of the beds in question.

Much attention has been devoted to the volcanic Lesser Antilles by the German volcanologist K. Sapper who in 1903 visited Saba (17 March), St. Eustatius (10—15 March), and the neighbouring islands further south. Sapper's publications (1903) will be discussed in Chapters III and VIII. His article on Nevis and St. Kitts (1903) compares the old volcanic centres of these two islands with north-western St. Eustatius. As far as Brimstone Hill is concerned, the author did not accept Spencer's theory of a volcanic dome thrusting up limestone beds on its flanks, but favoured the idea that the limestones had been deposited on a sloping substratum of much greater age.

A valuable contribution on the volcanic Lesser Antilles as a whole (including Saba and St. Eustatius) was published by Sapper in 1904. (This article was reprinted in a volume on the volcanic areas in Central America and the West Indies, 1905). Sapper's general account of phenomena such as *nuées ardentes* (glowing clouds) and volcanic domes, observed on Martinique's Mont Pelée and St. Vincent's Soufrière, is particularly important in view of the geology of Saba.

One of Sapper's conclusions is that in the Lesser Antilles lava flows played an important part in the volcanic formations until the end of the Quaternary, but appear to be entirely absent in historical eruptions; however, special mention is made of the recent lava plug of Mont Pelée. Other data from this publication are discussed in the following chapters.

The collection of rocks made by Cleve during his voyage of 1868—1869 was examined petrographically by the Swede A. G. Högbom (1905). The latter author stresses the fact that most of these rocks can be classed among the group of Andes granites and diorites, characterized by the occurrence of sodium-calcium feldspars and sometimes free quartz, and the almost complete absence of potash feldspars.

The Netherlands botanist I. Boldingh, who carried out a botanical survey in Saba in 1906, collected a number of andesitic rocks which were examined by C. E. A. Wichmann, Utrecht. Boldingh (1909) added but little valuable information on the geology of Saba. He noticed, however, (1) that the top of The Mountain lies approximately at the intersection of two diagonals, one SW-NE, the other NW-SE; (2) that the angle of inclination of the northern slopes of The Mountain is some 30 degrees in the higher altitudes, and distinctly less steep lower down; (3) that west, south and east of The Mountain, various "cones" occur which rise to 300—500 metres and seemingly rest "on the central part of the island at 200—300 m above the level of the sea"; and (4) that The Bottom "might easily be taken for the bottom of the crater". Boldingh's physiographic and geological description of St. Eustatius was borrowed largely from Molengraaff's thesis.

The investigations by the Netherlands mining engineer G. Duyfjes (1909, 1910), who was employed by the Government of Curaçao in the years 1908—1911, aimed in particular at development of the mining industry. His short reports in *Koloniaal Verslag* 1909 and 1910 list the publications of previous geologists and contain some data on the occurrence and mining prospects of minerals.

The American scientist T. W. Vaughan added greatly to palaeontological and geological knowledge of the West Indies. Apparently Vaughan paid no personal visits to Saba or St. Eustatius. According to Katharine Burdon (1920) he studied Brimstone Hill, St. Kitts, with some care, and found several species of coral in the upthrust limestone beds. Vaughan's publication of 1916 contains a short description of the ocean bottom off the shores of the Antilles. One type of profile "is that found off the volcanic islands, such as Saba and the members of the St. Christopher Chain, into the sides of which the sea has cut relatively narrow platforms. There are suggestions of submerged flats off the northwest end of St. Eustatius and southeast of Nevis" (pp. 53, 54).

Vaughan's lengthy contribution of 1919 is essentially a description of the fossil corals, and also contains extensive notes on coral reefs. On p. 303 the author refers to the description of the types of sublittoral profiles given in his publication of 1916.

Observations made during a voyage in the Lesser Antilles in October and November 1923, and a study of all available charts and published articles, have been presented by the American W. M. Davis in two publications (1924, 1926), which are largely devoted to geomorphology.

In his article of 1924 Davis describes Saba as a small, young island with a moderately cliffed volcanic cone, probably of Pleistocene eruption, with a bank less than a mile wide around it. Another type of bank, representing "reef-enclosed lagoon floors, formed according to Darwin's theory and modified by the processes of the Glacial-control theory", was observed by him in the St. Eustatius — St. Kitts — Nevis group: (pp. 209—210) "Statia consists of a deeply dissected cone on the north, in part overlapped by a young and loftier cone on the south; St. Kitts consists of several small volcanic residuals tied together by sand reefs and adjoined on the north by a group of lofty young cones; Nevis consists of three maturely dissected residuals, over and around which a loftier young cone has been built up; the bank 47 miles in length, above which these three composite islands rise, was probably formed as a barrier-reef lagoon floor on the flanks of the subsiding older elements of the group, and the newer cones were later built up on it. The occurrence of large slabs of limestone, some of them over a hundred feet across, on the flanks of the younger cone of Statia and of Brimstone hill, a small parasitic cone on a larger young cone of St. Kitts, supports this view."

Davis's classification of the Leeward Islands, as outlined in 1924, is much elaborated in his work on the Lesser Antilles published in 1926. The author divides the islands into first-cycle and second-cycle islands, which are of either simple or composite structure. Most of the first-cycle islands are of volcanic origin and belong to the Inner Arc. The second-cycle islands are situated mostly on the Outer Arc, and are older than the former group.

Saba — viewed by Davis only from passing steamers — is described as an example of a simple sequence of first-cycle development: (pp. 35—36) "Saba, the simplest island in the whole chain, represents an early stage: it is a young volcanic cone, ...

As yet it is little dissected by streams but rather sharply cliffed by waves around the shore and bordered by a narrow submarine shelf, hardly wide enough to be called a bank. It naturally shows no signs of subsidence in the way of embayments even if its subsidence has begun, for its little valleys all have hanging mouths in the cliff face, well above the sea level. Naturally it has no coral reefs, because, as has just been explained, they cannot be established on a detritus-covered, cliff-base shelf." *

St. Eustatius, St. Kitts and Nevis, situated on one single bank 47 miles in length, are considered by Davis to represent "a more advanced stage" of "more complicated first-cycle islands". Of these three islands, only St. Kitts was visited, the other two being merely seen from a distance. St. Eustatius was described as follows:** (pp. 50—51) "The last-named island is a volcanic doublet consisting of two cones of unlike age. A sketch made from St. Kitts through very hazy air is given too definite an expression in Figure 10. The older cone of Statia is now a well dissected mass, ... with a somewhat irregular and moderately cliffed shore line. It is overlapped on the southern side by the younger cone ...; the long concave slopes of this cone ... are less dissected and less cut back along their shore. According to Molengraaff, the younger cone bears on its southern side some huge monoclinal slabs of limestone, known as the "White Wall", containing shallow-water fossils and rising with strong inclination to a height of 900 feet [and appearing to have been lifted up from a preëxistent submarine bank when the volcano was formed]. From this as well as from the moderate inclination of its basal slopes, one may infer that the younger volcano was built up on a bank of calcareous deposits that had already been formed in association with the older volcano."

Davis's account of St. Kitts draws particular attention to the volcanic residuals of the older south-eastern part and to the large slabs of limestone cloaking the flanks of the parasitic cone of Mt. Brimstone. Here again, according to the author, it may be inferred, as in the case of St. Eustatius, that a bank had been formed in association with the older volcanic remnants before the younger volcanoes were built. "As the bank is continuous over the island-free stretch between the younger parts of Statia and St. Kitts, it is probable that it is there based on several completely submerged volcanic masses" (p. 55).

In 1926 the Frenchman A. Lacroix published a review of the lithological characteristics of the Lesser Antilles. For obvious reasons a large part of this publication is devoted to Martinique while the rocks of the other islands have been given less attention. In his Résumé Lacroix stresses: "le caractère calco-alcalin de l'ensemble de la remarquable province lithologique constituée par les Petites Antilles qui est à rapprocher de celle, plus vaste, de la région pacifique du continent américain."

The German geographer O. Winkler has written a thesis on the Netherlands West Indies, part of which was published in the *Mitteilungen der Gesellschaft für Erdkunde* (1926). Short paragraphs are included on the physiography and geology of Saba and St. Eustatius. It is clear that the author obtained his information from literature and not from his own observations. However, his short morphological sketch of the Saba volcano gives a fairly good impression of its outstanding features: (p. 98) "Die ganze Insel stellt sich als ein Vulkan dar, an dessen Hängen andere Gipfel peripher angeordnet sind und in steiler Neigung zur See hinabstürzen. Im Zentrum der Insel strebt

---

* It is clear from this description that Davis did not set foot on Saba: valleys with hanging mouths are exceptional, and coral reefs of small size do occur in places. His statement elsewhere about small boats being lowered down the cliffs to the harbourless shore is likewise not in accordance with the truth.

** Plate IV, with the erroneous title "The southern part of Statia, looking east by south. Orangetown lies at the foot of the volcano", is *not* a photograph of St. Eustatius.

der mächtige Mt. Peak gen Himmel und gipfelt scharf gezackt in einer Höhe von 880 m."

The jubilee volume dedicated in 1931 to Professor K. Martin of the University of Leyden, Holland, contains two articles devoted wholly or partly to the Lesser Antilles. The treatise by the Dutch geologist L. M. R. RUTTEN deals with the palaeontological knowledge of Surinam and the Netherlands Antilles in 1930. The list of fossils includes the molluscs found in the White Wall formation of St. Eustatius (cf. Molengraaff 1886). The other publication in this volume is that by G. A. F. MOLENGRAAFF on Saba, St. Eustatius and St. Martin. This valuable recapitulation of Molengraaff's previous work will be dealt with in detail in Chapters III—V and VIII; the article contains a few sketches, and a sketch-map of St. Eustatius, scale 1 : 60,000.

C. T. TRECHMANN's notes on Brimstone Hill, St. Kitts (1932), are important as regards the palaeontological correlation of its upturned limestones and the tilted White Wall formation of St. Eustatius. This Englishman gives a fine description of the stratigraphy, structure and molluscan fossils of Brimstone Hill, and refers briefly to the accounts of the White Wall by Cleve (1871) and Molengraaff (1886).* Trechmann's observations conflict at several points with the description of Brimstone Hill given by the Englishman K. W. EARLE (1922—1925, 1932). Reference may also be made to T. S. WESTOLL (1932).

The comprehensive study of volcanic domes published by the American H. WILLIAMS in 1932 is of particular interest for the understanding of this type of massive protrusion. In paragraph "Other West Indian Domes", he refers to E. O. Hovey (1903, 1905), who "considers that the central peak of the island of Saba is a craterless dome of acid andesite" (p. 63). In the list of domes grouped according to the nature of the lavas (p. 137), Saba is classed with Mont Pelée and several other volcanoes under the heading "pyroxene andesite".

A communication on an alleged eruption of the Saba volcano was made by the German G. HANTKE in Berlin (1936). This press item proved to be false, but it is interesting to refer to it: (p. 264) "Saba (Kleine Antillen). Vom Flugzeug aus wurde nach Meldung vom 25. April 1935 beobachtet dass grosse Steinmassen an der Nordseite dieser kleinen etwa halbwegs zwischen Puerto Rico und Guadeloupe gelegenen Vulkaninsel in die Luft geschleudert wurden und dann dampfend in die See stürzten. Dampf stieg auch aus andern Teilen der Insel auf. — Eine Bestätigung der Nachricht war bisher nicht zu erhalten. Die Insel besitzt eine Quellkuppe, und heisse Quellen sind von dort bekannt. Ein historischer Ausbruch hat sich bisher nicht ereignet. (D. Schriftl.) — (Mitteilung von Herrn G. Hantke, Berlin, nach Zeitungsmeldung)."

The phenomenon described above may have been the result of a landslide, while clouds may have been mistaken for ascending vapours. The fact that Saba is described as having a volcanic dome (Quellkuppe) is worth noting. It may be added here that K. Sapper, on p. 345 of his work *Vulkankunde*, remarks: "Falsch war die Nachricht eines Ausbruchs auf Saba 1867."

The treatises on Montserrat by the Scotchman A. G. MACGREGOR (1937, 1938) have no direct bearing on the geology of Saba and St. Eustatius. Nevertheless, the chapters on the island arcs of the Antilles and on the Caribbean volcanic arc in historic times (1938) offer valuable general data regarding the position of the northernmost volcanic islands. Likewise, the stratigraphy, tectonics and palaeontology of the beds of Roche Bluff and Landing Bay (Sweeny's Well) are important from the viewpoint of correlation

* In Trechmann's photograph No. 4 the north-western hills of St. Eustatius are erroneously described as the island of Saba.

with the sedimentary series of Brimstone Hill, St. Kitts, and White Wall, St. Eustatius, while the author's petrographic descriptions are useful for interpretation of the characteristics of the volcanic rocks of Saba and St. Eustatius. MacGregor includes the chemical analysis of Lacroix's dacitoïde of St. Eustatius (1926) in his table of rock analyses of Montserrat and Lesser Antilles (p. 74).

The little handbook on the Leeward Islands by the Netherlands Antillean S. J. Kruythoff (1939) contains short chapters on the geology of Saba (pp. 117—118) and St. Eustatius (pp. 129—130), but presents no new data.

The American volcanologist F. A. Perret (1942) makes a cursory remark on the two islands in his general notes on the volcanism of the Antilles: (p. 752) "This [volcanic activity] has, in any case, evolved farthest — and even to probable extinction in the northernmost islands, to which we can but briefly refer — Saba, with its inhabited crater "Bottom", and the beautiful little cone of St. Eustatius with an inclination of almost forty degrees." Perret's article also contains some general remarks on the *nuée ardente* phenomena and the building of domes which are helpful in understanding the geological features of Saba.

The British soil scientists F. Hardy and G. Rodrigues have published a treatise on the agricultural soils of St. Kitts and Nevis, with additional notes on St. Eustatius (1947). St. Eustatius was not visited by the authors, but laboratory data are given of surface soil samples collected by H. A. Ballou in 1933*, as well as some notes on the island's geology and agriculture supplied by C. A. S. Hynam, Government agriculturist of the Netherlands West Indies. The account of the geology of the three islands is further based on the report by K. W. Earle (1922—1925) and W. M. Davis's book on the Lesser Antilles (1926). The authors present a table of the geological history of St. Kitts, Nevis and Statia, partly taken from Earle's report and partly based on MacGregor's publication on Montserrat (1938). The data in this table pertaining to St. Eustatius are reproduced below.

Geological period and approximate age	*Volcanic and other events*
Late Cretaceous or Eocene (60 million years)	Eruptions that formed the basement rocks of the Statia — St. Kitts — Nevis bank
Late Miocene or Early Pliocene (10 million years)	Denudation of basement rocks. Eruption of the Northern Volcano
Pleistocene (2 million — 50 thousand years)	Deposition of White Wall. Eruptions of the South Volcano
Recent (20 thousand years)	Subaerial denudation of all volcanoes

The Dutchman J. H. Westermann published a survey of geology and mining in the Netherlands Antilles in 1949. The general descriptions of Saba and St. Eustatius are based largely on previous publications. His work contains an almost complete biblio-

* H. A. Ballou's publication of 1934 contains the erroneous statement (probably borrowed from Spencer 1904, and copied in 1954 by E. C. J. Mohr & F. A. van Baren in *Tropical Soils,* The Hague, p. 246) that St. Kitts, St. Eustatius and Saba "consist of a consolidated basement of old volcanic rocks, probably of Cretaceous or early Tertiary age".

graphy. An article by the same author, written in 1957 for the general public, deals with the geology of St. Martin, Saba and St. Eustatius, and their tectonic position within the Lesser Antillean Arc.

A survey of the soils was presented by the Dutchman J. S. VEENENBOS (1955). His work contains short geological descriptions, and some petrographic and mineralogical data, including analyses of the heavy and light mineral fractions of soil samples (by H. KIEL).

In 1956 Caribbean geology was admirably synthetized in two works: the volume by the Frenchman J. BUTTERLIN, and the *Lexique Stratigraphique International,* compiled under the direction of the Frenchman R. HOFSTETTER. Both publications contain short descriptions of the geology of Saba and St. Eustatius. The text of the chapters in the *Lexique* is based on data supplied by J. H. Westermann.

The Englishman F. H. S. WARNEFORD (1956 or 1957) gave very short but accurate descriptions of the two islands.

Reports on the geology of the Leeward Islands by the Government geologist of the Windward Islands, the Englishman P. H. A. MARTIN-KAYE, dated 1959, contain valuable data for general correlation of geological formations in the northern volcanic Caribbees. His manuscript, entitled "The Double Arc of the Lesser Antilles", has been accepted by London University as a doctoral thesis (1960); it will be printed by Overseas Geological Surveys, London, under the title *A summary of the geology of the Lesser Antilles.*

In 1961 Dutch publications came from the press by J. I. S. ZONNEVELD, on the geomorphology of St. Eustatius, and by C. O. VAN REGTEREN ALTENA on the molluscs, and H. ENGEL, on the echinids, of White Wall, St. Eustatius, and Brimstone Hill, St. Kitts.

For general information regarding the islands and their population, see Keur & Keur 1960.

SABA

(Appendices I, II and III)

CHAPTER II

PHYSIOGRAPHY – SUBMARINE CONTOURS – CLIMATE – VEGETATION AND AGRICULTURE – ROADS AND PATHS. ACCESSIBILITY – AERIAL PHOTOGRAPHS – MAPS – GEOLOGICAL SURVEY

Physiography (Figs. 3, 5, 6; Plates 1–14)

Saba, the northernmost island of the Lesser Antilles Volcanic (Inner) Arc, is situated 17° 37′ – 17° 39′ N and 63° 13′ – 63° 15′ W. It is a single composite volcano whose summit (The Mountain) has an altitude of 2,910 feet. The indented coast line has roughly the shape of a parallelogram, with the longer diagonal (slightly over 5 km or 3.3 miles) stretching approximately SW-NE, the shorter one (4¼ km or a little less than 3 miles) approximately NW-SE. The top of The Mountain lies approximately at the point of intersection of the two diagonals. The area of the island is about 12 sq. km (4.8 sq. miles).

The main peak, The Mountain, is surrounded by several smaller, more or less isolated peaks and (partly flat-topped) domes, of which the following are the most prominent: Great Hill (1,415′) flanked by Parish Hill (1,150′), Bunker Hill (1,265′), Fort Hill (430′), Thais Hill (1,305′), St. John's Hill (1,400′), Peter Simmonson's Hill (1,850′), Peak Hill (1,330′), Maskehorne Hill (1,820′), Booby Hill (1,490′), The Level (1,715′), Old Booby Hill (755′), Kelby's Ridge (510′), Troy (1,955′).

The slopes of the peaks and domes are steep, in places exceeding 60° or even nearly perpendicular.

Down the slopes of The Mountain run fairly straight to slightly curved, V- or U-shaped, steep-sided valleys or ravines, which are locally called "guts". Hanging valleys are rare, and most of the guts have a normal slope down to sea level. The steep-sided, deep and predominantly U-shaped guts of the northern, north-western and western slopes (between Island Gut in the north and Ladder Gut in the west) have been worn out in incoherent, agglomeratic and tuffaceous deposits, and consequently show conspicuous erosional features. The guts of the southern slopes (between Compagnie's Gut and Wash Gut) are of a more shallow, V-shaped type, and are separated by sharp, symmetrical divides fanning out near the coast. Well's Gut, running into Spring Bay, east coast, is the only gut which has developed into a normal valley system, with short and steep tributaries on both sides. Fort Gut in the south-west, and Curve Gut on the eastern slope, wind around and between some of the peripheral peaks and domes.

The guts have no permanent running water. They only carry water during and shortly after heavy rains.

Small, fairly level plateaux have either been formed by accumulation of erosional material, as is the case with the valley of The Bottom (650′ above sea level on an average) and the flats of Little and Big Rendez-Vous (1,650′), or are essentially remnants of watersheds, such as Windward Side (1,350′) and Spring Bay Field (780′).

The coastal features vary according to the local physiography and geology. The protruding portions of the coast in the south-west, south-east and east are due to the occurrence of lava domes, i.e. the Great Hill-Bunker Hill twin dome, Booby Hill, Old Booby Hill and Kelby's Ridge. In these places high, steeply sloping or practically perpendicular escarpments prevail, either sea-washed or with a very narrow pebbly beach at the foot of the cliff.

Torrens Point peninsula and the islets of Pilot Rock and Diamond Rock are the result of solidified lava flows, and the same applies to the protruding point just south of Green Island (north coast) and that of Booby Hole Ridge (east coast). A fine example of a fan-shaped lava flow having descended even below sea level is the peninsula of Flat Point, in the north-east. Great Point, on the north coast, consists largely of agglomerates and tuffs, overlain by a protective cover of solid lava rocks.

The more or less concave portions of the coast line are bound up with the agglomeratic and tuffaceous character of the local formation. This is particularly clear north of Ladder Bay; east of Torrens Point; in Round Bay, in the north; and at Giles Quarter, in the south. Pebbly beaches are prominent here.

Green Island is not a remnant of hard lava rocks – as might be thought from its advanced position – but consists of agglomerates and tuffs.

Ladder Bay, on the west coast, is sometimes used as a landing place, providing no heavy swell is running. The main landing place is at Fort Bay, on the south coast, where wind and sea conditions are, as a rule, more favourable than they are anywhere else.

Spring Bay, on the windward side, is the most beautiful bay of the island, hemmed in between the lava flow of Flat Point and the domes of Kelby's Ridge and Old Booby Hill. A wide, partly sandy beach has been formed where Well's Gut reaches this bay. Small fishing boats find shelter in The Cove, the northern inlet of Spring Bay.

Submarine contours (Fig. 2)

As described above, the coast line has been essentially shaped by physiographic and geological features. The 20-fathom (36 m) isobath is much less irregular, although it shows an outward bulge in front of Torrens Point and Diamond Rock, presumably as a result of a far advanced position of the lava formation. There is no such marked bulge in front of Flat Point, indicating that this lava flow does not extend very much beyond there.

The 100-fathom (180 m) line is roughly circular, except for its NW-trending portion, which is fairly straight. The possibility that this NW trend has a tectonic implication is discussed in Chapters III and XI.

The submarine slope of the island is steep in all directions. Its base may be supposed to lie at a depth of some 330 fathoms (600 m), which would mean that the volcano is roughly 5,000 feet high (over 1,500 m).

Saba is situated three miles north-east of the Saba Bank, and is separated from it by a passage over 300 fathoms in depth.

Climate

The climate of St. Martin, Saba and St. Eustatius has been described in some detail in Veenenbos 1955 (chapter III) and Stoffers 1956 (chapter V). In the following few paragraphs only the main climatological characteristics are given.

According to Köppen's system, the climate is intermediate between the savannah (Aw) and the monsoon forest (Am) types. The mean annual rainfall of Saba is 42-45 inches, with a variation from 32 to 55 inches over long periods. The "dry period", normally lasting from December to July but occasionally of a more prolonged character, has an average monthly rainfall that may be as low as 1.5 inches, at The Bottom.*

Precipitation varies with altitude and exposure to the (eastern) trade winds. Annual rainfall exceeds 80 inches on the higher windward slopes and the summit of The Mountain. The top of the latter is usually hidden by a cloud cap.

The average annual temperature is not exactly known, but that of the nearby island of St. Martin is 26.5° C. The months of July, August and September are the hottest (25.9° – 30.6°), January and February the coolest (22.7° – 27.4°). There is a distinct variation in temperature with the altitude above sea level.

The trade winds are predominantly easterly. The islands are situated in the hurricane region; the hurricane period comprises July, August, September, and occasionally October.

Vegetation and Agriculture

In early times the primary natural vegetation of Saba consisted of: montane formations on the top of The Mountain (palm brake and elfin woodland); rain forest on the higher slopes of The Mountain; and seasonal formations and dry evergreen woodland on the lower slopes of The Mountain, on the peripheral hills, and in the valleys separating the latter.

The primary cover has been transformed by man and live-stock over large areas. The primary montane formations have been preserved to a

---

* Veenenbos, p. 23, states: "It may be assumed that in the Pleistocene period, the rainfall was much higher than today, which would partly account for the present geomorphological features of the islands."

This statement has no justification in fact. It would seem that the geomorphological features of Saba (and the other two islands) can be rightly ascribed to erosional forces such as are largely the result of the present climatic conditions.

great extent, but the rain forest has disappeared almost entirely, and secondary rain forest and tree-fern brake have taken its place. The primary seasonal forest has also disappeared and has been replaced by secondary woodlands. The dry evergreen woodland is still widely present, but has been replaced by Croton-Lantana thickets in many areas.

The Mountain's eastern and southern slopes have been cleared for cultivation as high as 1,600 feet, whereas the less accessible western and northern slopes have retained their natural vegetation down to a much lower point. The higher situated level areas and some of the gentle slopes are under cultivation; examples of these are Booby Hill, The Level, Little and Big Rendez-Vous, Hell's Gate, Behind the Ridge and Sandy Cruz. White potatoes, sweet potatoes, yams, onions, vegetables and other subsistence crops are grown, in particular. Banana plantations occur in some of the higher guts and in the oval-shaped depression near the top of The Mountain. Fruit trees are found in the lower parts of the higher valleys.

The above data have been borrowed largely from Stoffers' excellent treatise on the vegetation of the Netherlands Antilles (1956), which contains particulars of the various types of plant cover and of cultivated and semi-cultivated areas. The distribution of these types is shown on vegetation maps.

Roads and paths. Accessibility

A winding concrete road which – as far as motor traffic is concerned – can be used only by jeeps and station cars, connects the main landing place at Fort Bay with the villages of The Bottom, St. John's, Windward Side, English Quarter, Upper and Lower Hell's Gate. The villages of The Bottom and Windward Side have a square system of narrow streets.

A flight of 528 steps leads from the pebbly beach of Ladder Bay to The Bottom.

For the rest, there are a number of footpaths, which make it possible to visit a good many places, including the summit of The Mountain and various hilltops. A fair portion of the island can therefore be reached without too much trouble. The massif of Great Hill – Parish Hill – Bunker Hill, the coastal cliffs and the northern and north-western slopes of The Mountain are, however, difficult of access or even inaccessible. They are steep and of a rough, rocky nature, and, in the case of The Mountain, covered with heavy forest growth.

Aerial photographs

The eastern portion of Saba has been photographed from the air by KLM Aerocarto, Holland. The photographed strip (axis: S 5° W – N 5° E) covers an area between the east coast and a line running from the south coast at the eastern corner of The Fans to a point just west of Green Island in the north.

The six photographs (Nos. 6985-6990) were taken on 7 July 1957, with a Wild RC 5a camera, on a scale of approximately 1 : 8,000.

On 27 April 1960 Saba was again photographed by KLM Aerocarto, on a scale of approximately 1 : 40,000 (two photographs, Nos. 5149 and 5150); Plate 1.

Maps

Until 1959 there was no dependable topographical map of Saba. A sketch-map on scale 1 : 25,000, without contour lines, was prepared by J. S. Veenenbos (1955) on the basis of a "Map of the Island of Saba (Dutch West Indies), lithographed from a copy sent by Governor M. L. Statius van Eps of said Island, January 1883", which was copied by the Cadastral Service of Curaçao in April 1950 (scale approximately 1 : 20,000). Veenenbos's map has been used for the present field survey.

In 1959 a contour map on a scale of approximately 1 : 20,000 became available, thanks to the initiative of KLM Aerocarto. This map was drawn on the Wild autograph from two aerial photographs taken in March 1959 on a scale of approximately 1 : 40,000; the drawing was done without terrestrial basis. Provided by the authors with local geographical names, it has been used for compilation of the map showing localities and survey routes and the geological map (Appendices I and II).

Geological survey

The fieldwork was carried out in the period 21 March - 9 April, 1958, with The Bottom and Windward Side as bases. Appendix I shows the survey routes. A boat trip on 24 March, made from Fort Bay to Well Bay and back, and a second boat trip round the island on 6 April, enabled the authors to get a view of the coastal outcrops and other geological features, which are difficult of approach from the land side.

In various places altitudes were measured with an altimeter, but these readings are by no means accurate. The magnetic deviation was 9° W.

KLM Aerocarto's aerial photographs of the eastern portion of the island were very helpful in the geological interpretation.

CHAPTER III

DESCRIPTION OF GEOLOGICAL AND VOLCANIC UNITS

General classification

Saba is a complex volcano whose upper three-fifths are above sea level. A number of natural units can be distinguished.

The basal formation of Saba's superstructure is largely built up of agglomeratic and tuffaceous strata. Andesitic beds (former lava flows) occur in various places, intercalated between the agglomerates and tuffs, but are definitely subordinate. This unit has been named the *basal unit of predominantly agglomerates and tuffs.*

The upper formation of the volcano appears to consist mainly of andesitic lava rocks, but agglomerates and tuffs are certainly not absent. Throughout large areas the solid rocks are covered by hillside waste, debris and soil, overgrown with dense vegetation. This unit has been named the *higher unit of predominantly andesites.*

Both the basal and the higher units have level or slightly sloping areas whose surface is formed chiefly by debris hiding the subsurface formation.

A third unit is formed by the *lava flows of Flat Point and Behind the Ridge,* in north-east Saba. These flows are definitely younger than the basal unit of predominantly agglomerates and tuffs, and in all likelihood contemporaneous with the higher unit of predominantly andesites.

The *summit dome of The Mountain* (roughly between the 2,700 feet contour and the two highest points at 2,910′) may be described as a separate unit.

The *volcanic domes, plug domes and isolated volcanic dikes surrounding The Mountain* constitute a fifth unit. They appear to have intruded into the basal and higher units, and are consequently comparatively young members of the volcanic sequence.*

The agglomeratic *nuée ardente deposits* of southern Saba probably belong to a very late phase of the volcano's history. The same is true of the *horizontal tuff deposits* encountered in the ravine connecting The Bottom and Fort Bay.

---

* Volcanic domes and plug domes may be generally and briefly described as protrusions of highly viscous lava forming a steep mound above their vent (*Geological Nomenclature* 1959, 4032). Howel Williams (1932, p. 54) suggests the following main types:
(a) *plug domes,* which represent upheaved (consolidated) conduit fillings;
(b) *endogenous domes,* which grow essentially by expansion from within;
(c) *exogenous domes,* built by surface effusion, usually from a central summit crater. He adds: "Manifestly, however, any individual dome may show all three types of growths; in most cases the distinctions will be difficult and in a few, even impossible to draw."

In the present treatise the term "volcanic dome" is generally used for types (b) and (c). See also Chapter VI.

Basal unit of predominantly agglomerates and tuffs

It is self-evident that this "basal unit" forms the base of Saba's superstructure, but not necessarily that of the submarine portion of the volcano, which reaches down to a depth of some 2,000 feet below sea level.

The formation appears to consist largely of volcanic agglomerates and tuffs, with alternating andesite beds here and there; the latter are most conspicuous where they form small peninsulas and capes. Accordingly, this basal unit has the structure of a normal strato-volcano, with ejectamenta prevailing over lava extrusions. In places, andesite dikes cut through the stratified beds. The ejectamenta of the southern slopes may be of the *nuée ardente* type.

Eastern Saba

In eastern Saba the basal unit is exposed in the valley system of Well's Gut; Curve Gut; the lower part of the watershed between these two valleys (the saddle between Spring Bay Field and Old Booby Hill); and the coastal strip east of and below The Level.* Since the formation of incoherent agglomerates and tuffs offers but little resistance to erosional forces it is only natural that extensive valley systems have developed here (Plate 1).

The contact of this unit with the overlying "higher unit of predominantly andesites" varies in altitude between 500′ (near Spring Bay Field, Plate 5[b]) and 1,400′ in the bend of the road between English Quarter and Hell's Gate. In the latter place (locality 100), coarse agglomerates are covered by hillside waste, whilst andesites outcrop nearby (101). Lower down in the Well's Gut valley system agglomerates and tuffs of reddish and whitish colours abound; as a rule they are strongly weathered and do not show bedding. In places, they are cut by andesite dikes; the basaltic (olivine-bearing) hornblende-andesite dike of locality 136 appears to be vertical, with an E-W strike.**

In Spring Bay Flat, bordering Spring Bay, Well's Gut and adjacent smaller guts cut through coarse and fine, little or non-stratified sediments a few feet thick, which may be considered to be deposits of debris laid down in a period when the base level of erosion was slightly higher than at present (133).

A fine section is disclosed at locality 131, in a branch of the gut west of Old Booby Hill. Here diverse strata of orange, grey and yellowish agglomerates alternate with one or more beds of weathered, pink-coloured andesite

---

* An outcrop at The Cove, the northern inlet of Spring Bay (locality 145), underlies the younger lava rocks of Flat Point. It is too small to be shown on the geological sketch-map. The following horizontal beds occur:
(from top to bottom)
1.5 feet of cemented coarse debris
1.5 feet of tuffaceous strata with a thin streak of agglomerate
5 feet of coarse agglomerate.

** For the names of the andesites, see Chapter V.

containing autolithic inclusions. No reliable measurement could be made of the strike and dip of these beds. The whole section is overlain by the andesite of Spring Bay Field (129).

In the west slope of the short gut just south of Old Booby Hill, whitish tuffs with rock fragments outcrop (127). At a higher level this slope is strewn with large andesite blocks which are presumably indicative of one or more andesite beds intercalated between the tuffs and agglomerates.

The agglomerates and tuffs of Curve Gut and the low, sloping Booby Hole Ridge south of it are underlain by basaltic lamprobolite-andesites, which form the perpendicular cape of this ridge (126). Andesites also outcrop at Booby Hole. They are consolidated lava flows which, to all appearance, were normal elements in the building-up of the old strato-volcano. The agglomerates of the steeply sloping coastal strip below the dome of The Level are well-stratified coarse and fine sediments. In the higher altitudes and nearer the dome, they have dips of possibly 40° towards the sea (125); lower down and farther away from the dome, the dips are approximately 30°. It would seem that this difference in dipping has resulted from intrusion of the dome of The Level into the older ejectamenta, lifting the agglomerates near its border in steeper dips (Plate 7^{b}). Since the material is of an incoherent, not very consolidated nature, erosional forces have shaped deep guts in these strata.

Near Wiba Hole andesite beds appear to be outcropping amidst agglomerates. It is a matter of conjecture whether these lava rocks form part of the older strato-volcano — as is probably the case with the andesites of Booby Hole Ridge — or belong to the intrusive body of the dome of The Level.

Southern Saba

The basal unit of predominantly agglomerates and tuffs, as outcropping along the lower, southern slopes of Saba — in particular in the area bounded by St. John's Flat and St. John's Hill in the west, the road between Crispine and Windward Side in the north, Booby Hill in the east, and the coast of Giles Quarter in the south — presents a geomorphological picture altogether different from that of eastern Saba: four parallel, straight to slightly curved, wide, V-shaped guts, separated by low but narrow-crested divides of simple construction, some of which fan out near the coast (Plates 2, 5^{a} and 13). This picture is complicated only by the occurrence of Peak Hill, a steep volcanic dike or plug (see below).

This broadly furrowed, smoothly sloping area is chiefly composed of more or less stratified, coarse, consolidated agglomerates rich in angular components and dipping about 15° towards the south (in Banana Gut, locality 149, fine to coarse agglomerates dip 25° towards S 35 E). In places, fine-grained, stratified tuffs occur between the agglomerates. Outcrops of lamprobolite-andesite appear to be subordinate (63, 64 and 65).

On the geological map the said southern slopes are uniformly coloured as "basal unit", but it is believed that in the lower extension of these slopes this unit is covered by younger *nuée ardente* deposits. The limits of the latter are not shown on the map; it is not feasible to outline their area. The stratified agglomerates and tuffs exposed in the western and eastern slopes of The Fans, dipping 15–20° southward, may belong to the one or to the other formation. The same applies to the white tuffaceous beds about 30 feet thick, dipping 20° towards S 10 E, in the eastern slope near the apex of the triangle of The Fans (locality 74). The *nuée ardente* deposits are described below.

South-western Saba

The agglomerate and tuff series of the area between Crispine, The Bottom and the south coast has been intruded by a number of volcanic dikes, domes and plugs (i.e. St. John's Hill, St. John's Flat – Thais Hill, Fort Hill, Great Hill – Bunker Hill). The beds differ from those of southern Saba, described in the previous section, and there is some variation in the types observed in several outcrops.

The horizontal beds encountered in a pit near Crispine (85) are described in the section "Volcanic domes, etc."

Along the road west of St. John's Hill (35) beds of purple, yellow, white and yellow-brown agglomerates and tuffs are exposed. The whole series, whose stratigraphic thickness is about 40 feet, dips 20° SW. From bottom to top, agglomerates, tuffs and coarse tuffs occur. The nearby locality 41 shows similar beds of fine agglomerates and tuffs, dipping 20° towards S 60 W.

Farther down the road and nearer the village of The Bottom (32) there is an outcrop of coarse agglomerates, passing into a yellowish, pinkish, brown and purple rock. This multicoloured rock is likely to have been subjected to solfataric action. At that spot a spring appears after a prolonged rainy period. At locality 44 reddish agglomerates occur.

The valley of The Bottom (Plate 10) is filled in with debris, the greater part of which has been transported down in the guts descending from The Mountain. The gut in front of the Administrator's house has cut into and exposes these debris deposits. It is thought that the agglomerate-tuff series forms the substratum of The Bottom valley, at least of most of it; the area has been coloured accordingly on the map. The dividing line drawn between the agglomerate-tuff series and the higher unit of predominantly andesites is, however, entirely tentative. The outcrop of large andesite blocks of locality 87 may be considered to represent an andesite bed in the agglomerate-tuff series.

Cleve (1871), Boldingh (1909) and Perret (1942) are of the opinion that the valley of The Bottom marks the place of the former crater of Saba's volcano, but Sapper (1903) and Molengraaff (1931) have rejected this view. Sapper noticed that the (SW) dips of the agglomerates and tuffs on the west slopes of St. John's Hill (cf. localities 35, 41) are "gegen den Thalkessel hin", and he concluded: "Die Tuffe sind jünger als die Hauptzüge der eigenthümlichen Oberflächengestaltung und sind nur als spätere Deckgebilde des Geländes, nicht aber als wesentliche Baumaterialien einer Kraterumwallung anzusehen." *

The present authors agree with Sapper and Molengraaff that there are no indications for believing that the valley of The Bottom is a former crater. The high hills bordering it to the west and south are volcanic domes and cannot be regarded as parts of a crater wall. The SW dips mentioned above, and the shape of the valley, also speak against such a supposition.

In the southern exit from the valley of The Bottom, and in the lower part of the ravine connecting this valley and Fort Bay, horizontal tuff deposits occur, data on which are given below.

In the ravine and the road connecting The Bottom and Fort Bay there are various outcrops of coarse agglomerates, some with bright, yellow to reddish colours. In places it is difficult to distinguish the agglomerates from the hillside waste.

Near Fort Bay (30), the road cuts through 25 feet of multicoloured, predominantly brown and pinkish, rather fine agglomerates with angular fragments, dipping 5° towards S 30 W. These agglomerates overlie strongly weathered and broken andesite which passes into a yellowish formation in the direction of the bay; the latter may have been andesite or tuff altered by solfataric action.

The spring of locality 31, occurring at an altitude of 30′ in the coastal cliff just west of Fort Bay landing place, appears to be on the contact between purple-coloured andesite and an underlying yellow-brown, clayey formation with grey and red spots, presumably weathered tuff. The water has a normal temperature; it is tapped and conducted through a narrow pipeline to a reservoir at the landing place (see also Chapter IV).

The substratum of the strongly undulating area between Fort Hill, Thais Hill, St. John's Flat and the coast consists of agglomerates, breccias and tuffs which alternate with andesite beds and have been intruded by andesite dikes. The ejectamenta are found in particular, but not exclusively, in the guts. The tuffs of localities 91 and 94 are white and contain large rock fragments; the breccias of the ridge at 92 strike N-S and dip steeply, and it seems that andesite dikes cut through them. The nearby lamprobolite-andesite dike of 93 has a similar strike and is practically perpendicular. The coast (95 a-b) is formed by E-W striking andesite dikes, bordered on the land side by agglomeratic and tuffaceous sediments.

It is difficult to ascertain how far uphill the agglomerate-tuff series extends. The boundary drawn between it and the domes of Thais Hill and St. John's Flat is therefore only tentative (see also section "Volcanic domes, etc.").

---

* Kruythoff's (1939) statements on p. 111, firstly that the Ladder Bay ravine "is beyond doubt a former outlet through which, at the time of eruption, molten volcanic matter ran from the overflowing crater to the sea" and, secondly, that the Fort Bay ravine "running from the crater floor upon which level 'The Bottom' or 'Leverocktown' is situated, . . . is also a former lava outlet", are romantic but decidedly erroneous.

Western and northern Saba

There is a marked difference between the coastal aspects of the agglomerate-tuff formation in eastern and southern Saba, on the one hand, and in the west and north, on the other hand. In the east and south the slopes of this formation either descend gradually to the level of the sea or are cut off by low cliffs (the long, vertical cliffs of Giles Quarter do not exceed about 80 feet in height), whereas along by far the greater part of the west and north coasts the agglomerate-tuff formation has high, exceedingly steep cliffs, at least 300 feet in altitude. The difference can be clearly seen in Plates 13^b, and 3^b and 12.

The agglomerates and tuffs of western and northern Saba are well-bedded and have, as a rule, slight dips towards the sea.

The southernmost agglomerates of the west coast can be seen outcropping near the beach at Ladder Point, at the foot of the Great Hill-Bunker Hill dome; the beds dip steeply towards the sea. From a boat other minor agglomeratic deposits can be observed on the steep west slope of Great Hill. It is somewhat doubtful whether the above-mentioned outcrops can be mapped as belonging to the basal unit, or actually form part of the volcanic dome.

North-west of and below Great Hill the agglomerates are better developed.

The high and very steep coastal cliff at locality 3 shows a rather complex section of nearly horizontal strata:

(from top to bottom)

? feet of coarse agglomerates

50 feet of basaltic lamprobolite-andesite with autoliths (cognate inclusions)

5 feet of coarse agglomerates

0—20 feet of brick-red tuffaceous beds (wedge-shaped)

25 feet of pinkish-white tuffaceous beds

20—0 feet of yellowish-white tuffaceous beds (wedge-shaped)

65 feet of coarse agglomerates.

The andesite may belong structurally to the dome of Great Hill (in which case it is intrusive into the series of ejectamenta), or it may be part of the basal unit of predominantly agglomerates and tuffs. It is noteworthy that this series does not seem to have been lifted up by the protruding lava of the dome.

The rather vague boundary between the basal unit of predominantly agglomerates and tuffs and the higher unit of predominantly andesites in western and northern Saba has nowhere been mapped in the field with any certainty except probably at one place in northern Saba: at the junction of the east and west branches of upper Island Gut, downstream from locality 108, where andesite overlies a thick series of grey agglomerates that dip slightly northward. Consequently, the boundary line has been sketched in only tentatively. Yet it appears that this line, i.e. the top of the basal unit, rises from south to north. At Ladder Bay the altitude of the top is estimated to be 500′ (Plate 3[b]), at Cow Pasture 600′, at Middle Island 700′, at Mary's Point 750′, south of Great Point 900′, in Island Gut (north coast) perhaps as high as 1,200′.

Between Ladder Bay and Torrens Point the coastal cliff consists of coarse agglomerates and, subordinately, thin beds (as a rule not exceeding 3 feet) of fine agglomerates. The whole series dips 10° to 25° westward, northwest in places. At locality 46, Middle Island, fine-grained whitish material has been found outcropping.

Well Gut is a deep and wide ravine, which has been eroded in the coarse agglomerates south of Mary's Point and reaches the coast just south of Well Bay. It is the confluence of three branches which cut deep into the hinterland.

Mary's Point, an abandoned settlement, is situated precariously above Great Gut, a deep ravine with almost perpendicular walls, cut into coarse agglomerates. At locality 51 a white tuff formation is intercalated between agglomeratic beds.

The authors did not traverse the agglomerate-tuff series of the north coast, with the exception of the area of the old sulphur mine. But some observations could be made from the footpath between Mary's Point and Sandy Cruz, as well as from the sea side during a boat trip. This whole coastal area consists of a heavily eroded, sloping landscape cut by exceedingly deep and wide ravines with steep sides. The strata have a northward dip of about 5°. At Great Point (Plate 12[b]) an andesite bed can be observed between coarse, bedded agglomerates, dipping 5° seaward, whilst a similar andesite occurs on the east slope of this peninsula. The cape east of Round Bay is formed by an andesite bed overlain by agglomerates.

It was possible to take a closer look at the agglomerates around the old sulphur mine. They are purple-grey rocks outcropping in a steep seaward slope below the lava escarpment of Behind the Ridge (Plate 9[a]). Over a large stretch these agglomerates have been altered by solfataric action into whitish-yellowish gypsum and sulphur deposits. There is a gradual transition from unaltered agglomerates to almost pure gypsum and sulphur minerals (Chapter IV).*

Green Island – which could not be visited – consists of agglomerates and tuffs that seem to be similar to those of the opposite slope of the main island, around the old sulphur mine. The name of the island would suggest that the rocks are green, but they are not. The southern half shows purple-grey rocks,

* Molengraaff (1888) mistook the agglomerates of the sulphur mine area for augite-andesites. In his publication of 1931 he wrote that "the andesite is bleached over a considerable distance and converted into a crumbling rock rich in sulphur, and in places in gypsum."

Cleve (1871) described the volcanic rocks of this particular place as both "tufa" and "trachyte".

whilst the northern part has yellow-brown to yellow-white strata, overlain and underlain by purple-grey rocks. Kruythoff's (1939) assertion that "the little key (north) known as 'Green Key' is a fallen boulder which once insecurely rode the Hell's Gate Heights" is extremely debatable. On the contrary, it may be assumed that Green Island, separated from the main island by a shallow channel, is an isolated remnant of a one-time peninsula of largely agglomeratic deposits.

Torrens Point, Pilot Rock, and the nearby islet of Diamond Rock (Plate 12) call for a separate description. Seen from a distance the southern part of Torrens Point is largely built up of alternating beds of agglomerates and tuffs:

(from top to bottom)

(a) pinkish agglomerates

(b) yellow-brown tuffs with beds of agglomerates

(c) dark-grey coarse agglomerates

(d) yellow tuffs and agglomerates.

Strangely enough, these beds dip 10° SE, hence landward. The deviation from the normal seaward dip may be connected with faulting. This assumption is supported by the occurrence of a local fault trough bordered by two minor faults (dipping 75° towards N 100 E, and 80° towards N 80 W).

The whole series of southern Torrens Point rests on an andesite, outcropping just above the water level, whose extension is found in a number of pinnacles, one of which is known as Pilot Rock.

The entire northern part of Torrens Point, with its pinnacles and the islets in front of it, seems to consist of andesites. This massif is probably connected with the andesite bed of Pilot Rock, but the geological relations are not quite clear. Pointed guano-clad Diamond Rock, and the low dark-coloured rock next to it, may be considered to be far advanced remnants of the former Torrens Point - Pilot Rock lava flow.

Higher unit of predominantly andesites

The basal unit of predominantly agglomerates and tuffs passes gradually into the higher unit of predominantly andesites as one climbs the slopes of The Mountain. The boundary line separating the two units on the sketch-map is therefore of a tentative character, as has already been said. It is by no means a contour line, because its height varies considerably: in the eastern region between 500′ and 1,400′, in the south between 1,100′ and 1,500′, in the south-west between 700′ and 1,500′, in the west between 500′ and 750′, and in the north between 750′ and 1,200′.

This higher unit is much less exposed than the agglomerate-tuff series. Hillside waste, a deeply weathered surface, and heavy plant and tree growth hide most of the solid rocks of the higher part of the volcano. The great majority of the outcrops which have been investigated and sampled belong to the andesite group. Ejectamenta are not altogether absent: loose fragments of agglomerates occur in the ravine north of The Bottom, and agglomerates are found outcropping here and there.

On the eastern slopes samples have been investigated from along the road between English Quarter and Hell's Gate, and in the neighbourhood of Spring Bay Field. At locality 101 a strongly weathered purple-brown andesite with autoliths (cognate inclusions) is cut by a wide fissure filled with debris. The low hill east of Spring Bay Field consists of basaltic (olivine-bearing) hornblende-andesite (129) which overlies strata of the agglomerate-tuff series. Similar rocks occur at the nearby localities 134a, b, and c: basaltic lamprobolite-andesites with autoliths. Spring Bay Field is a fairly flat area of andesitic debris, formerly in use as agricultural ground (Plate 5^b).

The south slope of The Mountain (Plate 4^b) has relatively few outcrops of strongly weathered basaltic lamprobolite-andesites with autoliths: localities 76—78. In certain rather flat areas, such as Little and Big Rendez-Vous, volcanic debris has accumulated; these areas are now used as agricultural land. The southern portion of Big Rendez-Vous is bordered by a low ridge (150) consisting partly of debris, partly of hornblende-andesite. Here pumice fragments are mixed with the ordinary debris. A hornblende-andesite occurs at 84. The slopes between Big Rendez-Vous and the Crispine-Windward Side road are largely composed of hillside waste, here and there mixed with pumice fragments (58); andesite outcrops are few (57: lamprobolite-andesite with autoliths).

The Windward Side village area (Plates 6^a and 8^b) is situated on the watershed between Plump Gut and Banana Gut, and forms the lower portion of the SE slope of The Mountain. Towards the east it is abruptly bounded by the steep slopes of Booby Hill, Kate's Hill and The Level. This saddle-shaped plateau is mainly composed of volcanic debris, which presumably rests on andesite rocks.

The west and north slopes of The Mountain have been scantily surveyed, largely because they are difficult of access. The outcrops of the slopes north of The Bottom and those along the footpath leading from this village to The Flat are all lamprobolite-andesites, some of them with autoliths: localities 15—19 and 43. The narrow ravine descending from a point east of Troy to The Bottom has been surveyed over a certain distance; its steep walls consist of either hillside waste or agglomerates, and the ravine itself is strewn with loose fragments of basaltic lamprobolite-andesites and hornblende-andesites with autoliths, and agglomerates (upstream and downstream from 42).

The lamprobolite-andesite outcrops above Mary's Point (52 = 55) may be connected with the andesite beds which can be observed high up in the tributaries of Well Gut (north of The Flat) as perpendicular escarpments. The rocks along the footpath leading eastward from Mary's Point are largely andesite blocks (basaltic lamprobolite-andesite at 53, hornblende-andesite at 54), but agglomerates are also found.

In the Sandy Cruz area basaltic lamprobolite-andesites with autoliths were found at localities 108 and 111. A perpendicular wall of andesitic rocks can be observed high up in the east branch of upper Island Gut, SE of 112. The western slope at the junction of the east and west branches of upper Island Gut, just downstream from 108, shows a perpendicular wall of andesite, overlying grey agglomerates that extend far down and towards the north. At this place the contact between the higher andesite unit and the basal agglomerate-tuff unit is indicated (see also p. 31).

Bottom Hill, Troy and the elevation north of Troy were not visited by the authors, on account of the dense vegetation, and their geological significance can only be conjectured (see also section "Volcanic domes, etc.").

Lava flows of Flat Point and Behind the Ridge

North-eastern Saba differs from the other regions of the island in the presence of extensive sheets and flows of consolidated andesitic lava, which overlie the basal unit of predominantly agglomerates and tuffs. There is no clear connection between these sheets and flows and the higher unit of predominantly andesites, but it is very probable that they are contemporaneous.

Slightly concave block fields above Hell's Gate, bordered by N 50–60 E trending ridges, are assumed to be the remains of an old lava flow, descending from a point possibly as high as 1,800′ on the north-east slope of The Mountain down to the projecting Flat Point peninsula (Plates 1 and 9[a]). From Lower Hell's Gate downward the upper surface of this flow is not hollow but shows as a slightly arched tongue with curved transversal "flow lines", as expressed in the topography and the vegetation. It clearly fans out where it reaches the sea, and the curiously upturned lava blocks at the coast give the impression of a sudden chilling of the lava in the water.

This Flat Point lava flow – according to Molengraaff (1931) "the most copious flow of lava" in all Saba – may be only slightly less than one mile in length.

A ravine runs along the southern rim of the Flat Point flow. Near The Cove, the northern inlet of Spring Bay, this ravine cuts lengthwise into the flow and separates its main body from a narrow and steep andesite ridge, the latter being apparently the upturned southern border – a typical lava levee. Another ravine separates this Flat Point border ridge from the volcanic dome of Kelby's Ridge.

The rocks of the Flat Point flow are basaltic lamprobolite-andesites (with or without autoliths), some of which are scoriaceous: localities 118, 119, 143, 144, 146, 147.

The lower portion of the Flat Point flow rests on the agglomerates and tuffs of the basal unit. At the beach of The Cove (145) the lava rocks overlie some horizontal beds of this series (see p. 27, footnote).

The upper portion of the Flat Point flow rests partly on the sloping lava sheet of Behind the Ridge, which may be considered an earlier extrusion. At 113 a basaltic lamprobolite-andesite, with autoliths, was sampled. This lava sheet of Behind the Ridge ends abruptly in the west and north, where it overlies agglomerates and tuffs. The northern border is an almost perpendicular lava wall some 150 feet high at its maximum, towering above the agglomerates and tuffs of the old sulphur mine (Plate 9[a]); its height diminishes eastward, in the direction of Flat Point. Prismatic jointing and flow structures can be noticed in many places. Where this lava wall approaches the coast, agglomeratic beds alternate with sheets of lava rocks. The rock sampled at 117 is a basaltic lamprobolite-andesite with autoliths.

The degree to which the andesite sheet of Behind the Ridge extends below the Flat Point lava flow is a matter of conjecture. It is unlikely that it extends very far towards the SE, and the lava rocks occurring between Upper Hell's Gate dome and Kelby's Ridge probably form no part of it.

Summit dome of The Mountain

The summit of The Mountain, rising as high as 2,910′, looks rather different from various angles. When viewed from WNW and NW or from the south-east (Windward Side; Plate 6[a]), it has the appearance of a smooth, slightly pointed cone. Seen from the south it presents itself as a long crest, above a smooth, easily scalable slope (Plates 4[b] and 5[a]).

The views from the east and north-east present yet another picture: seen from there the summit is also a long crest, but consisting of several unscalable, sheer-sided peaks, separated by deep, W-E and approximately WNW-ESE trending clefts. It looks as if these peaks have been shaped essentially by perpendicular lava spines or dikes. This jagged and broken appearance of the northern summit is very clear in Plate 6[b]. The views from Old Booby Hill and Windward Side (Plates 5[b] and 6[a]) show the contrast between the smooth southern slope and the broken northern portion of the summit.

The difference between the southern and northern slopes of The Mountain's summit is also evident when one climbs to the top. The approach on the south flank, from Big Rendez-Vous, is an easy one. At about 2,790′ a rim is reached which borders a shallow, elongated depression; the length of its long axis, trending N 40 W-N 140 E, is estimated to be 650 feet, and that of the short axis 350 feet. The bottom of the depression lies at an altitude of about 2,700′. In the north-west corner it seems to be closed by an andesite spine (2,875′), but in reality it ends in a deep cleft north of this spine. The lower portion of the depression is occupied by a banana plantation, whilst the rims are overgrown with a dense stand of palm brake and elfin woodland. The north-eastern rim lies at an altitude of some 2,800′. A lava block collected inside the depression (locality 81) is a basaltic lamprobolite-andesite, with autoliths.

By crossing the depression one arrives at the broken northern portion of the summit. Two elevated points – the highest points on the Saba volcano – can be reached fairly easily: locality 79 (2,910′), overlooking Windward Side; and 80, farther north and equally high (2,910′), looking down on Hell's Gate and the north coast. Both tops may be considered to be perpendicular andesite spines or dikes with sheer walls in three directions; the rocks are basaltic lamprobolite-andesites.

In the older literature there is some discussion of the elongated depression of The Mountain's summit. Sapper (1903) and Molengraaff (1931) found it not possible to form an opinion on its nature; anyhow, they were not inclined to consider it a crater. Hovey (1903, 1905) expressed a rather definite view regarding this main peak, which he thought to be a craterless volcano of the Mont Pelée type* (Chapters I, VI). His theory is supported by the present authors, who are inclined to describe the summit of The Mountain as a dome**, whose horizontal section is roughly oval in shape with the long axis trending approximately NW-SE. This dome seems to be characterized in particular by vertical lava protrusions now visible as perpendicular andesite spines and dikes. It is thought that erosive forces have given the summit its jagged appearance: the spine-shaped andesite bodies are now separated by deep clefts. The N 40 W-trending elongated depression may be considered to be of a nature similar to that of the clefts north of it. The main difference is that the depression is less deep and is filled in with debris to a much higher level than is the case with the northern clefts.

Generally speaking, the domal structure of the summit of The Mountain need not be doubted. However, the limits of the dome are difficult to determine owing to the deep weathering of the slopes and the presence on them of hillside waste and dense vegetation. Since the dome is thought to include, in particular, the broken and clefted formation at the summit, it is tentatively indicated on the geological map as the roughly elliptical area inside the 825 m (2,700′) contour. An ideal section of it is given in Appendix III.

Volcanic domes, plug domes and isolated volcanic dikes surrounding The Mountain

The volcanic domes, plug domes and isolated volcanic dikes, apparently confined to the region south-east of the line Great Hill – The Mountain – Upper Hell's Gate – Kelby's Ridge, are a very conspicuous feature of

---

* Sapper (1904, pp. 64, 65) supported Hovey's comparison of the peculiar summit portion of Saba's Mountain with the recent volcanic dome of Mont Pelée: "Wie der Staukegel des Mont Pelé den Étang sec mehr und mehr auszufüllen droht, so ist nach Hovey (1903) und Lacroix (1903) auch die eigenthümliche Gestaltung der Gipfelpartien des Vulcans von Saba und der Soufrière von Guadeloupe durch ähnliche Vorgänge zu erklären. Nach den bisherigen Stand unserer Kenntniss muss in der That diese Erklärung als die wahrscheinlich richtige angesehen werden."

See also Von Wolff 1914 (p. 492).

** Hantke (1936) briefly described Saba as a volcano with a "Quellkuppe" (volcanic dome or plug dome), but this definition was probably borrowed from Hovey.

Saba. It may be assumed that they constitute comparatively young members of the volcanic sequence, which have forced their way through the rocks of the older formations.

The botanist Boldingh (1909) was the first scientist to describe the various "cones" rising to 300–500 metres west, south and east of The Mountain, and seemingly resting "on the central part of the island at 200–300 m above the level of the sea". Molengraaff (1931) gave the following general description: "On the flanks of the main volcanic mountain there are found scattered here and there minor, more or less conical hills"; but he did not indicate the true nature of these hills.

The northernmost dome is that of Kelby's Ridge. It is a volcanic dome of small dimensions, not exceeding 510′ in altitude. At its seaward side the jointed interior has been laid bare by the action of the surf. The land slopes show very little of the dome's structure. The rocks collected are strongly weathered andesites containing autoliths. The rock of locality 141 is a basaltic lamprobolite-andesite. Nothing can be said of the age relationship between Kelby's Ridge and the lava flow of Flat Point. On the other hand it is very likely that this dome has protruded through the basal unit of predominantly agglomerates and tuffs outcropping south of it.

The tremendous escarpment below Upper Hell's Gate, measuring some 500 feet from top to bottom, appears to be the exposed eastern and southern flanks of a volcanic dome (Plate 5[b]). Vertical prismatic jointing is a notable feature of this almost perpendicular wall, which is found to consist of basaltic (lamprobolite-)andesite (102). The western and north-western parts of the dome would seem to be hidden by the deposits of The Mountain's north-eastern slope. At the foot of the escarpment, in Well's Gut valley, agglomerates and tuffs of the basal unit are found, and the conclusion may be drawn that the lava of the Upper Hell's Gate dome has pierced through the latter formation.

Old Booby Hill (755′) is the peculiar remnant of a volcanic dome, rising high above the agglomerates and tuffs to the west of it (Plates 7[a, b]). This steep, conical hill is strewn with loose andesite blocks. Not far to the south-east of the summit, a minor dome-shaped elevation of broken andesite plates occurs. The battered and indented coastal cliffs show bent jointing planes, revealing something of the interior structure. The contact between this dome and the presumably older basal unit of predominantly agglomerates and tuffs can nowhere be studied. The rocks of localities 130 and 132 are hornblende-andesite with autoliths, and basaltic lamprobolite-andesite, respectively.

The massif of The Level - Booby Hill (Plates 2, 5[a] and 8[b]) may be considered a twin volcanic dome. The Level (1,715′) has a fairly regular dome shape. Booby Hill (1,490′) trends NW-SE.

The Level is a huge truncated cone with very steep slopes, except where it borders on Booby Hill. Its eastern side (Plate 7[b]) is almost perpendicular in places, showing nearly vertical jointing planes and, here and there, slightly bent plates of andesite. It would seem to have protruded through the agglomerates and tuffs of the east coast, dragging up those nearby, which appear to have a steeper dip than the strata nearer the coast (see p. 28). The top of The Level has an oval, shallow depression, with the long axis of 650 feet trending N 60 E; the short axis measures about 400 feet. Its SW end is lower than the NE end, and opens towards Booby Hill. The cultivated fields in this depression are strewn with small fragments of pumice and andesitic material. This was also noticed by Veenenbos 1955, p. 78. At localities 122 and 124 basaltic lamprobolite-andesites with autoliths have been collected.

Booby Hill has two NW-SE trending, dike-shaped elevations. One of these, Kate's Hill (Plate 8[b]), facing Windward Side, is a vertical dike of basaltic lamprobolite-andesite (103). The interior of Booby Hill has been exposed by the action of the surf at Abraham's Hole and South-East Point, where oblique and distinctly bent jointing planes of the andesites can be seen (Plate 7[c]). The following andesite types have been sampled and investigated: basaltic (lamprobolite-)andesite (72) and basaltic lamprobolite-andesite (120). Autoliths can be observed in most of the outcrops.

Peak Hill (1,330′; Plate 13[b]) lies just SW of Booby Hill, but is separated from it by the formation of predominantly agglomerates and tuffs. It is a steep, isolated volcanic dike or plug dome, consisting of basaltic lamprobolite-andesite with autoliths (59).

The south slope of The Mountain has several steep-sided, dike- and plug-shaped elevations, roughly arranged in straight lines, i.e. Maskehorne Hill (1,820′), Little Diamond (1,820′), Peter Simmonson's Hill (1,850′), St. John's Hill (1,400′), and a few smaller ones. They consist of (hornblende-) andesites (56, 83), hornblende-andesites (82) and basaltic lamprobolite-andesite (61).

St. John's Hill is essentially a vertical, N 60 E striking andesite dike or plug dome, largely concealed by hillside waste and beds of pumice (40); cf. Veenenbos 1955, p. 78. It is entirely surrounded by the basal unit of predominantly agglomerates and tuffs into which it has intruded. However, the nearby horizontal strata encountered in a pit at Crispine (85) are probably connected with the formation of domes:

(from top to bottom)

3 feet of fine-grained, grey-coloured agglomerate, containing breadcrust bombs of various sizes

2.5 feet of grey, tuffaceous material

3 feet of light-coloured, pinkish-brown, tuffaceous material.

Thais Hill and St. John's Flat constitute a twin volcanic dome (Plates 2, 3[a], 4[a] and 8[a]).

Thais Hill (1,305′) has very steep north, west and south sides, exposing andesite with columnar, prismatic jointing and, in places, bent jointing planes. Its eastern side, however, is a remarkable dip slope, dipping towards N 75 E, with outcrops of pumice agglomerates (cf. Veenenbos 1955, p. 78); at locality 36 the agglomerate consists of pyroxene-hornblende-pumice. The flat top of Thais Hill has only small dimensions (60×30 feet), and has presumably been levelled off by man; it is strewn with small rock fragments among which pumice is dominant. Block heaps of andesite occur on the N and SE sides of this small plateau; the rock of 37 is a lamprobolite-andesite with autoliths. At 34 a basaltic lamprobolite-andesite has been collected.

The lower western and southern slopes of Thais Hill are less steep, and consist partly of hillside waste, partly of massive andesite rocks; they may perhaps be considered to form part of the Thais Hill dome. At locality 96, on the top of a ridge, a series of hornblende-andesite beds or dikes (N 40 E, 43 E) clearly determine the direction of this ridge. At 26 another hornblende-andesite occurs. Along the road at 25, strongly weathered and broken andesite passes upwards into a pinkish and yellow formation with gypsum deposits, apparently the result of former solfatara action.

St. John's Flat (1,075′) has – as its name indicates – an extensive flat top, bordering St. John's Hill to the north and Thais Hill to the north-west. The steep sides on the west, south and east expose andesites with vertical, prismatic jointing. The rock of locality 39 is lamprobolite-andesite with autoliths. A small pit, dug in the strata covering the top of St. John's Flat (38), shows practically horizontal beds, a favourite dwelling place of bees:

(from top to bottom)
3 feet of pumice agglomerate
1.5 feet of tuff
1.5 feet of coarse tuff
1 foot of tuff
? of agglomeratic tuff.

It may be assumed that the south foot of St. John's Flat dome reaches down to the coast. The basaltic lamprobolite-andesite (with autoliths) of locality 66, affected by former solfatara action nearby is probably part of it.

Fort Hill (430′; Plate 3ª) is a volcanic dome or plug dome of small dimensions. The hornblende-andesite rocks containing autoliths at locality 27 are strongly broken, and show bent jointing planes whose strike and dip could be measured in a few instances: N 65 E, 60 NNW; N 20 E, 60 WNW. A lamprobolite-andesite, with autoliths, occurs at 90.

Practically the whole south-west corner of Saba may be mapped as a twin volcanic dome, towering high above the sea and the valley of The Bottom. It culminates in Great Hill (1,415′) and Bunker Hill (1,265′), the latter also bearing the name of St. Patrick (Plates 2, 3, 4ª and 10).

Earlier visitors have paid some attention to this dome-shaped massif. Sapper (1903) noticed tuffs below a lava flow west of the road to Fort Bay, and cautiously suggested that "der recht unregelmässig geformte Hügel südwestlich von Bottom der Ueberrest eines kleineren Stratovulkans sei, der dem grossen Hauptvulkan parasitisch aufsass." Molengraaff (1931) wrote: "The remnants of one of the more important subordinate cones now constitute a group of hills, the highest of which is known as Great

Hill, which reaches an altitude of 408 m. The greater portion of this subordinate cone has apparently been destroyed by the action of the waves." The layman Kruythoff (1939) described the semi-hemispherical peak of Great Hill (named by him "Paris") as a "dome-shaped peak (that) seems to have been sawed in twain; the western portion having tumbled into the sea at some unknown period, has left behind a rugged circular wall, standing upright."

The entire massif dips steeply to all sides; it is believed to consist predominantly of andesites (see also p. 31). The andesites abound in rounded autoliths. In many places the rocks are strongly weathered, to such an extent that – on account of the autoliths – they may resemble agglomerates.

Bunker Hill is largely dome-shaped, but vertical andesite dikes, striking N 20 W, are conspicuous. The following rock types have been collected and investigated: lamprobolite-andesite (12, 13), hornblende-andesite (23) and basaltic lamprobolite-andesite with autoliths (29).

Parish Hill (1,150′) is the name of the plateau directly below and east of Great Hill. At locality 6 a dike of lamprobolite-andesite, with autoliths, strikes N 35 W and dips 35 SW. The other rocks investigated are lamprobolite-andesites with autoliths (5, 11), and basaltic lamprobolite-andesite (89).

Great Hill is a very peculiar semi-hemispherical summit spine, rising above the Parish Hill plateau, with the convex side towards the east and south; it is broken off sharply at the western side. The surface rocks of the domed side have an imbricate arrangement, and the loose slabs have slid down here and there (Plate 11). The rocks sampled at localities 7–8 and 9 are lamprobolite-andesites with autoliths. Another lamprobolite-andesite has been collected at the base of the rockfall stretching down from the perpendicular western side of the spine (14).

South of Great Hill a small but typical andesite spine, called Little Hill by some people, can be observed.

The west or seaward slope of the Great Hill – Bunker Hill massif is exceedingly steep. This feature, together with the practically straight S-N trending coastline, may suggest the presence of a fault plane. The hot-water spring on the narrow pebbly beach north of Ladder Point may be another indication (Chapter IV).

It is doubtful whether the elevations south-west (Bottom Hill), west (Troy) and north-west of The Mountain's summit should be classed as domes. They are too densely wooded for proper geological investigation.

"Nuée ardente" deposits of the lower slopes of southern Saba

A field study was made of the lower, down-sweeping slopes of southern Saba, terminating in fans and coastal cliffs which are separated by guts (see also the description at p. 28); this study was followed by macro- and microscopic examination of the rocks collected. The results have convinced the authors that true *nuée ardente* deposits crop out in this area. The exact extent of the deposits could not be determined and their limits are not indicated on the geological map. The *nuée ardente* deposits rest on the basal unit of predominantly agglomerates and tuffs, and have been dissected by guts (Plates 2, 5[a] and 13).

The triangular area called The Flat, between Compagnie's Gut and Tom's Gut, ends abruptly at the coast in a long, vertical cliff about 80 feet high. The upper strata of this cliff consist largely of loose debris, whilst the lower part is a formation of slightly consolidated agglomerates. A pebbly beach separates the cliff from the sea; this beach stretches from the southern extension of St. John's Flat dome in the west as far as the escarpment near South-East Point.

The triangular area further east called The Fans, between Tom's Gut and Swanna Gut, is similar in appearance to The Flat. Southward dips of 15–20° can be measured in the stratified agglomerates and tuffs exposed in the western and eastern slopes of The Fans. The stratification of the agglomeratic layers in the long, vertical coastal cliff, 80 feet high, is also rather distinct (Plate 13[b]).

Still further eastward along this coast, generally called Giles Quarter, the narrow dividing ridge between Swanna Gut and Wash Gut abuts in a sloping triangular cliff some 120 feet in height (locality 70). The upper part of the cliff abounds in large angular blocks of andesite, some with flow structure, whilst the lower portion consists of coarse agglomerates.

The coastal cliff east of the mouth of Wash Gut stretches as far as the escarpment near South-East Point (andesite dome of Booby Hill). The composition of the cliff deposits is, in part, chaotic and tumultuous, with very big andesite blocks occurring amidst finer material. In the upper portions, probably as high as 180′, horizontal stratification is manifest (Plate 14).

On the whole, these gently dipping deposits of the coast of Giles Quarter are unconsolidated to very slightly consolidated agglomeratic beds consisting of angular, subangular and roundish fragments and blocks of andesites, of various sizes, in a matrix of volcanic sand and tuff.* Bedding, generally of a regular character, is indicated by the alternation of layers differing in the average size of the rock fragments and blocks composing them, or in the proportion of those fragments and blocks to the finer material. Thin layers consisting only of finer material occur in places, but their horizontal dimensions are small. The thick, white tuffaceous bed of locality 74 (p. 29) may belong to the basal unit, or may be an intercalation in the *nuée ardente* deposits representing a normal ash eruption.

A comparatively large number of the andesite fragments collected, particularly those from the cliffs east of Swanna Gut, show a rough, sugary and porous surface when examined with a pocket lens or under a binocular microscope. The surface of other fragments is partly smooth and non-

---

* Rittmann (1960, p. 90) describes chaotic tuffs as deposits of glowing clouds or mudflows.

porous, partly rough and porous, while a third category has only compact, smooth surfaces. Some of the rocks are roundish volcanic bombs. Autoliths can be detected in several of the andesites. The colours of the rocks vary from light- or yellowish-grey to dark- and brown-grey; pinkish and reddish-brown fragments also occur.

The petrographic and mineralogical composition of the rock fragments and the matrix is described in Chapter V.

The *nuée ardente* deposits of Saba's south coast cover the older basal unit, and are probably also younger than the nearby volcanic domes of St. John's Flat and Booby Hill. They very much resemble the *nuée ardente* deposits of the northern slope of Soufrière Hills in Montserrat (Plate 15[a]), as described by MacGregor (1937, 1938). Similar beds are known from Mont Pelée, Martinique (Lacroix 1904, 1908). In Chapter VI the character, origin and comparative age of the *nuée ardente* eruptions are discussed.

In the ejectamenta of one of the coastal cliffs of Giles Quarter, Ch. Sainte-Claire Deville found a loose block which is supposed to be a limestone metamorphosed by volcanic agencies (Lacroix 1893; for petrographic data, see Chapter V). It is difficult to evaluate Sainte-Claire Deville's find, since there are no further data on the locality and occurrence of this rock. It may indicate that Saba's volcano broke through a formation of limestone and subsequently ejected metamorphosed fragments of the rock, mixed with ordinary volcanic ejectamenta, during one or more of the eruptions of the *nuée ardente* type. However, the evidence for this is weak.

Horizontal tuff deposits in the ravine connecting The Bottom and Fort Bay

Peculiar beds of horizontal tuffs occur in the southern exit from the valley of The Bottom, on both sides of the road and the ravine leading to Fort Bay. The upper surface of the series forms a narrow terrace at an altitude of approximately 600′. The western outcrop (locality 20) lies a few feet below the top of the terrace, and shows the following horizontal strata:*

(from top to bottom)
3 feet of fine yellow tuff
1.5 feet of brown-grey tuff with rock fragments of max. 4 inches diameter
0.3 feet of yellow tuff with rock fragments
0.5 feet of brown-grey tuff with rock fragments (perhaps a lens)
3 feet of yellow-brown to brown-yellow tuff with rock fragments, in horizontal streaks.

---

* Cf. Sapper (1903): "Am südlichen Ausgang des Kesselthals von Bottom bemerkt man ca 6 m mächtige gelbe, feinkörnige Aschen von lössartigem Aussehen, aber mit deutlicher horizontaler Schichtung, angedeutet durch unvollständige Lagen kleiner Steinchen." — "Tuffe, wie sie am Osthang des Kesselthals vorkommen, fehlen an dieser Stelle völlig."

A comparable outcrop, at the same level, is found on the east side of the road and the ravine: 88. Below a talus of max. 6 feet in thickness, about 13 feet of stratified tuffaceous sediments occur:

(from top to bottom)

1 foot of yellow-brown to brown-grey tuff with small rock fragments

0.5 feet of brown-grey gravel of small rock fragments and fine tuffaceous matter

12 feet of yellow-brown to brown-yellow tuff with small rock fragments.

Both localities are favoured by swarms of bees as a place for brooding.

The authors are somewhat dubious as to the origin of the horizontal tuffs described above. The position of the strata may suggest that they have been deposited in a former closed basin which was part of the old valley of The Bottom, before the Fort Bay ravine breached the southern edge of this basin and cut itself into the tuffs. There are no indications that the beds have been deposited in a former lake.

Somewhat similar horizontal tuffs are found in the lower part of the Fort Bay ravine, at 28. Here, a white tuff layer 3–5 feet thick overlies brown, bedded tuff.

As is the case with the horizontal tuffs near The Bottom, questions arise as to their origin. Superficially they resemble the young products of the Quill volcano of St. Eustatius; in fact, possible deposition of ashes after strong eruptions of this volcano need not be excluded if the eastern trade winds are taken into account. However, the heavy mineral content of the beds of locality 28, and of 20 and 88 (near The Bottom), in particular the occurrence of lamprobolite, contradicts the assumption that they are Quill tuffs (see Chapter V). These horizontal tuffs may, therefore, be products of late ash eruptions of the main volcanic centre of Saba (The Mountain) which have been partly preserved in some hidden corners. Further exploration will no doubt lead to the discovery of more horizontal tuff outcrops.

CHAPTER IV

SULPHUR DEPOSITS. HOT SPRINGS

Saba has several places where previous solfataric action on andesites, agglomerates or tuffs is apparent (see Chapter III). There is only one limited area, however, where this activity of sulphur-bearing gases has led to the forming of fairly extensive deposits of sulphur and gypsum, i.e. the north slope of Behind the Ridge, facing Green Island (Plate 9). The sulphur deposits of Behind the Ridge, discovered probably in 1869 by two Americans, have been mined only for short periods, especially in the years 1875–1876 and 1904–1907, and with little success.*

P. T. Cleve (1871) gave the following description: "Near Hell's Gate there occurs in the tufa a sulphur deposit with gypsum and alum-stone. The sulphur is evidently a remnant of an old fumarol." — "Near the sulphur-mines of Saba the trachyte is changed to a kind of alum-stone. Such an altered trachyte has been analysed by Mr. Th. Fiebelkorn who has found it to contain: Si 34.10 S 32.00 Al 17.82 Al_2Cl_3 5.47 KCl 0.10 H 12.00. Sum. 101.49. Thus by action of vapours containing sulphuretted hydrogen the rock has been deprived of its iron, lime, sodium, and a part of the silica, the former having been transformed to soluble sulphates and swept away."

G. A. F. Molengraaff (1888) published an article on the occurrence and crystallography of the sulphur of Saba, part of which is reproduced here:
"Etwas nördlicher, unter der kleinen Ortschaft Hell's Gate, findet man ein Schwefellager, das im Anfang der achtziger Jahre mit geringem Erfolg ausgebeutet wurde. Dieses Lager befindet sich ca. 110 m über dem Meeresspiegel an dem steilen Abhange, welcher Hell's Gate vom Meere trennt. Der bauwürdige Theil ist durchschnittlich 4 bis 6 Meter mächtig; die horizontale Ausdehnung kann man wegen der Unzugänglichkeit des Terrains und der vielen Abstürze nur schwierig genau beurtheilen; die innere Ausdehnung des Lagers ist unbekannt, weil die Abbauversuche nur bis zu geringer Tiefe fortgesetzt sind. In einer Breite von ca. 100 m ist das Schwefellager durch Tagesbau bearbeitet; Stollen sind nur stellenweise und in geringe Tiefe getrieben.
Wenn man von Hell's Gate die sehr steile Böschung nach dem Meere hinuntergeht, so sieht man allmählich die braunröthliche Farbe des Augit-Andesites, aus welchem der Boden besteht, blasser und endlich vollständig weiss werden, indem zugleich das Gestein seine feste Beschaffenheit verliert und in eine leicht zerreibbare, pulverige Substanz übergeht. Bald begegnet man den ersten gelben Streifen, welche mit Schwefel gefüllte Spalten sind, und noch etwas weiter abwärts ist das Gestein ganz von Schwefeladern durchsetzt, die sich in allen Richtungen durchkreuzen. Wo Spalten nicht ganz gefüllt sind, ist der derbe Schwefel mit einer Kruste der prächtigsten Krystalle überzogen; in sehr schmalen Spalten sitzen die letzteren oft unmittelbar auf dem weissen, zersetzten Augit-Andesit.

---

* Facts concerning the history of the discovery and mining of these deposits, and data on the chemical analysis of sulphur and gypsum samples, can be found in Westermann 1949 (pp. 76—77, 93—96). The latter publication also contains a practically complete bibliography on sulphur and gypsum in Saba. Literature on this subject has therefore not been included in the Bibliography of the present treatise.

Offenbar hat man hier eine erloschene Solfatare vor sich. Schwefligesäure- und Schwefelwasserstoff-haltende Dämpfe haben den Augit-Andesit zersetzt, wobei sich Schwefel abschied. Dieser ist durch die Hitze stellenweise wieder verdampft und aus dem schwefelhaltigen Dampfe sind die Schwefelkrystalle durch Sublimation entstanden."

K. Sapper (1903) did not visit the area of Behind the Ridge.

G. A. F. Molengraaff (1931) wrote: "In the northeastern portion of the island near Hell's Gate the andesite is bleached over a considerable distance and converted into a crumbling rock rich in sulphur, and in places in gypsum. Evidently solfataras have been active here. The numerous cracks in the strongly decomposed rock which intersect one another in all directions are filled with pure sulphur, and where the cracks are not quite closed they are lined with a crust of well developed crystals. The crystals of sulphur of this deposit are small (1—3 mm in diameter) but exceptionally rich in forms."

The present authors visited the spot. Their opinion as to the nature of the rock which was subjected to solfataric action differs from that of Cleve and Molengraaff. This rock was found to be andesitic agglomerate of a purple-grey colour, not andesite. There is a gradual transition from unaltered agglomerate to almost pure yellow sulphur and white gypsum. A number of samples were collected in order to demonstrate this transition. However, no analyses were made, since the process of transition is not considered to have any significant bearing on the geological problems of the island.

The sulphur crystals in fissures have been formed as a result of sublimation from sulphurous gases, whereas the major portion of the sulphur and gypsum deposit is thought to be the product of these gases on reaction with the minerals of the agglomerates. It is likely that the gases emanated from a lava intruded into the agglomerate series, and not from the lava flow which is now visible as the high perpendicular wall above the sulphur-mine slope.

The sulphur-bearing beds of this north coast slope are irregular or more or less lens-shaped. They vary in thickness between 12 and 20 feet and have lengths of up to 300 feet. Tunnels and shafts have been dug as deep as 150 feet into the slope.

The other localities of Saba's former solfataras are less spectacular. They are usually characterized by a multicoloured appearance, with yellow, brown and reddish colours prevailing. In 1950 J. H. Westermann visited an old "sulphur mine" situated in the lower part of the east slope of The Bottom valley, at the side of Crispine, dug some 30 feet into the volcanic rock.

Saba's solfataras were manifestations of late or rather post-volcanic activity. Nowadays there are no active solfataras left. The only place where hot air, apparently without sulphurous gases, is believed to escape from fissures in the rock, is locality 62, in a bend of the road between Crispine and Windward Side. However, since the road was widened and rocks were removed at this place, a number of years ago, this "hot hole" – as it is called locally – has become difficult to trace. At any rate, the authors hardly noticed that the temperature at the spot was any higher than the normal temperature of the air.

The only recent and conspicuous manifestation of post-volcanic activity is the hot water spring on the narrow, pebbly beach between Ladder Point and Ladder Bay. It is situated slightly over one-quarter of a mile north of Ladder Point and below the almost perpendicular west slope of the Great Hill – Bunker Hill massif.

K. Sapper (1903) wrote about this spring: "Die Spuren noch fortdauernder vulkanischer Thätigkeit sind auf Saba äusserst geringfügig. Ich besuchte eine kleine warme Quelle am Südwestrande der Insel; dieselbe war aber von grobem Steingerölle überdeckt und bei dem hohen Wasserstand des Meeres mischte sich Meerwasser der warmen Quelle bei, so dass sie nur eine Temperatur von 54,2° C zeigte. Einige weitere warme Quellen befinden sich am Nordende der Insel."

According to S. J. Kruythoff (1939) the hot springs at Well Bay — apparently the springs in northern Saba referred to by Sapper — have disappeared as a result of heavy billows which broke through the barrier separating them from the sea: "Waters which ran from them hot enough to poach an egg have been replenished and chilled by the sea."

In 1906 the military dispenser T. Buys made a chemical analysis of the water of the spring north of Ladder Point, which he described as "salinic-alcalic mineral water".

J. H. Westermann visited this spot on 15 March, 1950. The spring, hidden by beach pebbles, was excavated at two places. Just above sea level the water was found to flow over a bed of sand, while it appeared to be actually welling up some ten feet away, higher up the slightly sloping beach. Its temperature was 55—57° C. The samples were investigated by E. D. A. Sindram (Laboratory for Public Health, Curaçao): Cl′ 2,084—2,180 mg/l, total hardness 102—115 D°. On the basis of this incomplete analysis the water was described by the Department of Tropical Products of the Royal Tropical Institute, Amsterdam, as being probably of hypotonic and muriatic, sulphatic character (reports of 8 and 25 September, 1950).*

In 1867 and 1935 there were press reports of eruptions of the Saba volcano, which proved to be false (Chapter I). The lack of active solfataras and the rare occurrence of hot water springs indicate that the volcano is now extinct. "Nobody now-a-days ever speaks or even thinks 'volcano'" (Kruythoff 1939, p. 116).

---

* J. S. Veenenbos (1955, pp. 17—20) has published some data on the water of Saba. The Fort Bay spring (Chapter III), sampled by P. Wagenaar Hummelinck in July 1949 and analyzed by F. W. Kleve, Aruba, is reported in table 2 to have a chlorine content of 2,000—3,000 Cl′ mg/l and a pH of 8.

The reader's attention is also drawn to the statement in Chapter I, on the bubbling-up of fresh water at a distance of one-third of a mile from the south-west shore of Saba (Benest 1899). Whether this alleged "submarine stream of artesian water" has any relation to post-volcanic activity is conjectural.

CHAPTER V

PETROGRAPHY

Previous petrographic descriptions

P. T. Cleve's (1871) macroscopic descriptions of the Saba rocks are only of a general nature: (pp. 38—39, 40)
"11. *Trachyte* is the ruling rock in the volcanic islands as Saba, S:t Eustatius, S:t Kitts, Montserrat etc. The rock of Saba is composed of a dirty-red porous mass in which are imbedded numerous white crystals of glassy feldspar (easily melted by the blow-pipes), some needles of hornblend and also very few small greenish crystals of augite. The Sp. Gr. is 2,71. The rock of Saba has been analysed by Dr. Th. Nordström. The small quantity of potash as well as the presence of much lime and sodium prove that the rock is chiefly composed of oligoclase (andesine?) or microtinite, and as the low quantity of silica indicates the absence of quartz, this trachyte may be classed as microtinite without quartz.
20. *Trachytic tufas,* composed of small quantities of feldspathic and often pumiceous ashes, occur in the volcanic islands, as in Saba, S:t Eustatius, S:t Kitts, etc."

A. G. Högbom (1905) gives a more detailed account of one of the andesites collected by Cleve (locality not known): (pp. 228—229)
"51. *Andesit* (Trachyt, Cl.); Saba. Die Insel ist nach Cleve ein erloschener Vulkan und wird von diesem Gestein und begleitenden Tuffen aufgebaut. In dem hell grauen Gestein werden makroskopisch weisse Körner von Plagioklas und schwarze Amphibolstengel gesehen. Der mikrotinartige Plagioklas ist ein prachtvoll zonalstruierter Labrador-Oligoklas mit zonal angeordneten Interpositionen und verästelten Grundmasse-einschlüssen. Die Amfiboleinsprenglinge, welche spärlicher und kleiner sind, zeigen tief braune bis braungelbe Absorbtionsfarben und geringe Auslöschungsschiefe. Kleinere Körner von einem blassgrünen bis gelblichen Augit sind in etwa gleicher Menge wie die Hornblende vorhanden. Die Hornblendeindividuen sind öfters mit einer orientierten Umrandung von diesem Augit versehen. In der isotropen Grundmasse liegen reichlich kleine Plagioklasleisten, Augit- und Magnetitkörner. Analyse S. 231, j."
(For the chemical analysis of this rock, published previously by Cleve, and again by Högbom, see below).

A. Lacroix (1890) describes the rocks collected in 1841 by Ch. Sainte-Claire Deville as "labradorites" of varying mineralogical composition: (pp. 72, 73)
"Les roches volcaniques de *l'île Saba* sont encore des *labradorites* différant surtout les unes des autres par la nature de leurs grands cristaux: 1. labradorites à labrador, pyroxène et amphibole (hornblende brun jaune très polychroïque et très biréfringente, analogue à celle de la Martinique); 2. labradorites à labrador et pyroxène (ce pyroxène est incolore; il devient jaune d'or sur les bords, les microlites sont en général entièrement jaunes, ils rappellent la variété de pyroxène jaune des roches à leucite du Latium); 3. labradorites à labrador et à olivine; ce dernier minéral, parfois très abondant, est accompagné soit de pyroxène, soit, mais plus rarement, d'amphibole en grands cristaux. Ces roches sont peu ou pas augitiques, elle renferment parfois en très grande quantité des grains de *quartz* arrondis, atteignant un demi-millimètre, qui sont tantôt entourés de la zone vitreuse incolore et de la couronne de microlites de pyroxène (incolore, vert clair ou jaune) et qui, tantôt, au contraire, en sont dépourvus. Ces labradorites à olivine et à enclaves de quartz présentent une très grande analogie avec les roches de Californie et de la Névada décrites par Hague et Diller sous le nom de

quartz basalt. Ces savants considèrent ce quartz comme primaire; celui des roches de Saba me semble d'origine étrangère au magma initial de la roche. J'ai retrouvé des enclaves analogues dans les labradorites de l'île Saint-Eustache."

The quartz inclusions in Saba rocks are mentioned again by Lacroix in his work on the inclusions of volcanic rocks (1893): (p. 48) "Parmi les roches recueillies à l'île de Saba par Ch. Sainte-Claire Deville, j'ai trouvé (*C. Rendus,* CXI, 71, 1890) des *labradorites à hornblende,* riches en enclaves de grains de quartz. Les couronnes augitiques manquent souvent."

This same volume by Lacroix (1893) contains a lengthy description of two metamorphic limestones, found in the collection of Sainte-Claire Deville and said to have come from a loose block in one of the steep cliffs of Giles Quarter: (pp. 156—157) "La collection des roches des Antilles, recueillie autrefois par M. Ch. Sainte-Claire Deville et conservée au Collège de France, contient deux échantillons, indiqués comme ayant été détachés d'un bloc d'environ 1 mètre cube, trouvé par ce savant dans les tufs de *labradorites* de l'île de Saba (grande falaise verticale de Giles-Quartier, Est de l'île). D'après les notes de M. Deville, ce bloc est constitué par une roche étrangère au sol de l'île. Il est impregné de divers minéraux cuprifères et ferrugineux (magnétite, hématite, chessylite), que l'on doit évidemment considérer comme des produits de fumerolles.
L'examen microscopique m'a fait voir que ces échantillons sont constitués par des calcaires métamorphiques. L'un d'eux, très riche en calcite, renferme des grains clairsemés d'augite et de grenat; ces deux minéraux y sont de formation contemporaine, ils possèdent la même couleur jaune d'or. L'autre est beaucoup plus silicaté, le pyroxène en gros grains vert jaunâtre, devenant par places jaune d'or, comme dans l'échantillon précédent, forme dans la roche des nids irréguliers; il est soit seul, soit accompagné d'anorthite et de grenat jaune brun très pâle en lames minces. Dans certaines parties, l'anorthite devient assez abondante et la roche ressemble à quelques-unes des enclaves d'Aubenas, étudiées plus haut. L'anorthite peut même localement dominer; elle renferme alors, en grande abondance, une multitude de petits grains de grenat. Quant au calcaire, il a, par places, complètement disparu, tandis que dans d'autres points, il sert en quelque sorte de ciment au nids silicatés qui viennent d'être décrits.
Ces deux roches sont très riches en produits ferrugineux brunâtres qui représentent peut-être les restes de matière volcanique introduite dans le calcaire. Ils sont d'ailleurs trop altérés pour qu'il soit possible de préciser davantage. Beaucoup des éléments de la roche renferment de petites inclusions microscopiques qui sont en général des inclusions vitreuses.
L'origine de ces calcaires, que je n'ai pas vus en place, ne me paraît pas douteuse; je les considère comme des calcaires sédimentaires, modifiés par la roche volcanique au milieu de laquelle ils ont été recueillis."

The evaluation of these "accidental xenocrysts" is a difficult matter, as we know practically nothing about their locality and mode of occurrence (see Chapter III, section "*Nuée ardente* deposits").

Lacroix's review of the lithological characteristics of the Lesser Antilles (1926) gives analyses of two andesitic types from Saba, taken either from lava flows or from blocks in agglomerates, in which the intermediate feldspar contains less than 50% anorthite. One of these types is Cleve's "trachyte" (Högbom 1905: andesite), described by Lacroix as "une andésite oligoclasique, dans laquelle on relève la même pauvreté en potasse". The other analysis refers to a "dacite à hornblende et hypersthène" (See section "Chemical analyses").

One of the chapters of K. Sapper's publication of 1904 is devoted to the chemical composition of the volcanic rocks of the Lesser Antilles. It contains the statement that in the southernmost islands (Grenada, St. Vincent) only the more basic rocks are found; farther north, basic rocks are supposed to be less prominent and to occur together with intermediate and acid rocks, while they are lacking entirely in St. Eustatius and Saba. This statement is illustrated by a list of rocks and a table of chemical analyses. As far as Saba is concerned, the list contains an augite-andesite, with tridymite, from Hot Springs, and a hornblende-andesite, locality not indicated; both rocks were collected by Sapper and microscopically determined by A. Bergeat. Nordström's analysis of an andesite, sampled by Cleve, is added.

G. A. F. MOLENGRAAFF (1931) listed amphibole-pyroxene-andesite, amphibole-andesite and pyroxene-andesite. He microscopically examined rocks from four localities; agreed with Högbom's description of the amphibole-augite-andesite (locality unknown); and added the following remarks: (p. 718) "The andesites of Saba, which I have seen, all contain both amphibole and pyroxene; in the majority of them amphibole predominates over pyroxene. The andesite of Corner Ridge, a hill in the eastern portion of the island between Windward Side and Hell's Gate, is dark-coloured and very rich in ferric constituents. The brown hornblende in this rock has uncommonly broad opacite-rims. In the valley which leads from the Bottom to Fort Landing I found an andesite, in which under the microscope a few irregular, obviously xenolithic, grains of quartz were observed. At Fort Landing a somewhat scoriaceous andesitic lava occurs with much glass in its groundmass."

PETROGRAPHY OF THE MAGMATIC ROCKS

General classification

Microscopic examination of 85 magmatic rock samples from Saba has made it possible to establish four main groups:

I. Andesites with green or brown hornblende, or its pseudomorphs, augite, and (mostly) some hypersthene: hornblende-pyroxene-andesites, briefly named *hornblende-andesites.*

II. Andesites with lamprobolite, or its pseudomorphs, augite, and (mostly) some hypersthene: lamprobolite-pyroxene-andesites, briefly named *lamprobolite-andesites.*

III. Andesites with green or brown hornblende, or its pseudomorphs, augite, mostly some hypersthene, and olivine: basaltic (olivine-bearing) hornblende-pyroxene-andesites, briefly named *basaltic (olivine-bearing) hornblende-andesites.*

IV. Andesites with lamprobolite, or its pseudomorphs, augite, mostly some hypersthene, and olivine: basaltic (olivine-bearing) lamprobolite-pyroxene-andesites, briefly named *basaltic (olivine-bearing) lamprobolite-andesites.*

Some remarks on the nomenclature

Before chemical and petrographic descriptions of the said rocks are given, some general remarks may be made regarding the nomenclature adopted.

HÖGBOM (1905) described the Saba rock collected by CLEVE as an "andesite", apparently belonging to Group II mentioned above. LACROIX (1890) used the name "labradorite" for the Saba rocks collected by Ch. Sainte Claire Deville. He made a distinction between "labradorites à labrador, pyroxene et amphibole" (probably belonging to Group II, according to the description of the hornblende), "labradorites à labrador et pyroxène" (Group I) and "labradorites à labrador et à olivine" (probably Group III). In the later publication by LACROIX (1926), Cleve's rock was named "andésite oligoclasique"; an analysis was also given of a "dacite à hornblende et hypersthène" (Group I). From MOLENGRAAFF's descriptions (1931) it is impossible to ascertain whether his "amphibole-pyroxene-andesites", "amphibole-andesites" and "pyroxene-andesites" of Saba belong to Group I or to Group II, since he does not give details of the hornblendes.

The nomenclature of the magmatic rocks of the Volcanic Lesser Antilles has been discussed rather elaborately by LACROIX (1926) and by MACGREGOR (1938), and some consideration may be given to these authors' classification.

LACROIX distinguished the following main types, largely on chemical analyses:

"(a) des dacites, ... caractérisées, au point de vue chimico-minéralogique, par la constance de la silice libre dont la teneur est indépendante de la présence ou de l'absence du quartz exprimé;

(b) des dacites cryptomorphes, des dacitoïdes; dans celles-ci, le quartz ne se trouve qu'à l'état de phénocristaux et encore ceux-ci sont-ils peu abondants et assez irrégulièrement distribués;

(c) des andésites et labradorites *a*, voisines des dacitoïdes, qui constituent exclusivement ou essentiellement les laves actuellement connues;

(d) des basaltes."

"En résumé, la caractéristique lithologique des Petites Antilles est la prédominance d'une série *dacitique* (andésitique ou labradorique), aboutissant à des *andésites* ou à des *labradorites a*, contenant toujours, au moins une petite quantité de silice libre, et enfin à des laves parfaitement saturées et des *basaltes*.
Malgré la haute teneur en silice libre (exprimée ou non) qui peut dépasser 20% dans cette série dacitique, la proportion globale de la silice est rarement plus élevée que 63%; elle ne descend guère au-dessous de 52% et cette particularité est due à la teneur peu élevée en alcalis, parmi lesquels la soude domine beaucoup sur la potasse, et à la richesse assez grande en chaux. Comme, d'autre part, le magma est assez alumineux, il en résulte que les feldspaths abondent; ils sont exclusivement constitués par des plagioclases très zonés, avec zones fort basiques; en même temps, comme conséquence de cette abondance de l'alumine, il reste peu de chaux non feldspathisée, ce qui entraîne la presque constance des pyroxènes rhombiques. Enfin, ces roches des Antilles fournissent de multiples exemples d'olivine, associée ou non à du quartz, dans des roches à excès de silice."

MACGREGOR based the nomenclature adopted for the rocks of Montserrat partly on their mineral content and partly on seven new chemical analyses representing the various rock types.
"With regard to the two most basic rocks, olivine-bearing lavas with basic plagioclase phenocrysts and a silica percentage of about 52, there is no difficulty; they are clearly olivine-basalts. The other five analysed rocks, on the other hand, present a problem of considerable complexity. Their silica percentage ranges from 56.75 to 64.21; all contain abundant phenocrysts of basic plagioclase, along with some of hypersthene or augite. The three most siliceous rocks have phenocrysts of hornblende, and sparse porphyritic quartz."
"The Montserrat rocks, like Lacroix's dacites and dacitoïdes, are very different from the dacites of Rosenbusch, being, for example, richer in magnesia and lime and poorer in potash (Rosenbusch 1923). To such labradorite-bearing andesitic rocks, including the West Indian dacites and dacitoïdes of Lacroix, the name "bandaite (= labradorite-dacite)" was given by Iddings twenty-four years ago (Iddings 1913). The name was derived from the volcano Bandai San in Japan."

"The writer defines the rock-names used in this paper as follows. The equivalent terms "labradorite-dacite" or "bandaite" describe andesitic rocks characterized by modal labradorite and silica, and agreeing closely with Niggli's peléeitic magma type. Similar rocks without modal silica should preferably be called labradorite-andesites. A labradorite-andesite passes into a basalt when it contains less than 10% of normative quartz; the majority of basalts defined in this way have a silica percentage below 55. The rocks of Montserrat are almost all labradorite-dacites and olivine-basalts; the former include hornblende-pyroxene-bandaites and hypersthene-bandaites, in either of which traces of olivine are occasionally found. In practically every Montserrat rock, other than olivine-basalts, modal silica is present either as sparse quartz phenocrysts, or as primary tridymite (or cristobalite) in the groundmass."

In his chapter on the geology of Montserrat, MARTIN-KAYE (1959) has given a brief account of MacGregor's publication. It is noteworthy that he entirely ignores the bandaite nomenclature of MacGregor and refers only to labradorite-dacite and hornblende-labradorite-dacite!

One of the lava rocks of Nevis has been described as a "dacite à hornblende, augite et hypersthène" (LACROIX 1926). MARTIN-KAYE (1959) described porphyritic andesites with pyroxenes and lamprobolite.

EARLE (1922) lists the magmatic rocks of the Basal Series of St. Kitts as augite-hypersthene-andesites. WESTOLL (1932) has published descriptions of hypersthene-andesites with infrequent hornblende from Brimstone Hill; pyroxene-andesites from near Brimstone Hill; and olivine-basalt from Black Rocks, which was called "labradorite a à hypersthène et olivine" by LACROIX (1926) and olivine-bearing andesitic basalt by WESTERMANN & KIEL. MARTIN-KAYE (1959) mentions pyroxene-andesites, dacites (evidently of minor development), and the olivine-basalt of Black Rocks.

The rocks of St. Eustatius are classed as andesites by MOLENGRAAFF (1886): augite-andesites, hypersthene-augite-andesites and, subordinately, hornblende-augite-andesites.

After evaluating the nomenclatures applied by various authors to the rocks of the Volcanic Lesser Antilles, and in particular the islands north-west of Guadeloupe, the present authors feel justified in deciding not to follow the nomenclatures of Lacroix and MacGregor but to adhere to the general terminology of "andesites" for Saba.* It is clear, however, from both the chemical and the mineralogical composition, that the Saba rocks are closely allied to the "dacites" and "dacitoïdes" of Lacroix and the "bandaites" of MacGregor.

The Saba rocks have been classed as andesites and basaltic (olivine-bearing) andesites, *not* as basalts. This classification is admittedly somewhat arbitrary, but careful consultation of a number of textbooks* has led the authors to accept the name "andesite" rather than "basalt", on account of both the petrographic criteria and the chemical analyses.

The motivation for naming the Saba rocks andesites and basaltic andesites is based in particular on the data presented in Williams, Turner & Gilbert's *Petrography* (1955; pp. 39, 43, 93—96), reproduced and summarized below.

Texture. Most andesites are porphyritic rocks with a pilotaxitic or hyalopilitic groundmass, though some are vitrophyric. Intergranular, intersertal, and ophitic textures

---

* F. H. Hatch & A. K. Wells, *The Petrology of the Igneous Rocks,* London 1937, p. 193.
G. W. Tyrrell, *The Principles of Petrology,* London 1955, p. 126.
E. E. Wahlstrom, *Igneous Minerals and Rocks,* New York 1955, p. 309.
H. Williams, F. J. Turner & C. M. Gilbert, *Petrography,* San Francisco, 1955, pp. 39, 43, 93, 95.

occur in varieties transitional to basalts. Among basalts the most usual texture is intergranular.

Mineral composition. SiO_2-percentage. The presence or absence of olivine is not diagnostic, but olivine-rich lavas are much more likely to be basalts than andesites. Generally speaking, the average composition of the plagioclase in andesites is more sodic than $Ab_1\ An_1$ (about An_{40}), while that in basalts is more calcic (about An_{55}); but the porphyritic plagioclase in most andesites is labradorite more calcic than An_{55}. The groundmass plagioclase, however, is usually much more sodic in andesites than in basalts. Moreover, the interstitial glass or cryptocrystalline matrix of many andesites has the composition of a mixture of quartz and alkali feldspar.
If the silica percentage of the rock is less than 52, it is usually permissible to call the lava basalt. But if there is doubt on this point, such terms as "basaltic andesite" and "andesitic basalt" may be employed.

Hornblende-andesites generally form thick, short flows, steep-sided domical protrusions, or intrusive plugs and dikes. Their hornblendes are seldom fresh and green except in quickly chilled, glass-rich types; otherwise they are brownish or reddish oxyhornblendes, or are partly or completely replaced by granular mixtures of augite and magnetite. Fresh pyroxenes almost always accompany the hornblende, and occasionally a little olivine is to be seen. The plagioclase of these rocks tends to be somewhat more sodic than that of olivine-andesites and pyroxene-andesites.

Chemical analyses (Table 1)

Table 1 gives the chemical analyses (in percentages by weight) of lava rocks of Saba, St. Eustatius and other Volcanic Caribbees. Most of the analyses are taken from literature. New ones have been added for Saba (two complete analyses and two SiO_2 determinations: Nos. 3–6), St. Eustatius (two SiO_2 determinations: Nos. 11, 12), and St. Kitts (one complete analysis: No. 14); they were produced by the "Chemisch-Technisch Laboratorium Dr. Lobry de Bruyn", Amsterdam.

The figures for the Saba rocks (collected on volcanic domes, Flat Point lava flow and some unknown localities) are typical of andesites, i.e. "intermediate" rocks. Their silica content varies between 53 and 61%. The Flat Point lava, a basaltic andesite relatively rich in olivine, has the lowest SiO_2 percentage (analysis No. 6); it is comparable with that of the andesitic basalt lava flow of Black Rocks, St. Kitts (No. 13) and the basalt of O'Garra's, Montserrat (No. 18). The lavas of the volcanic domes of Saba (Nos. 3–5) differ but little in composition from those of St. Kitts (No. 14), Montserrat (No. 17), Guadeloupe, Martinique and St. Lucia.

Contrary to what might be expected, the basaltic andesite of The Mountain (No. 5) appears to be very similar in composition to the olivine-free andesite of Great Hill (No. 3). The occurrence of (secondary) tridymite and cristobalite may be responsible for this.

The Saba analyses corroborate Lacroix's (1926) conclusions regarding the Lesser Antilles lavas, viz. that the silica percentages vary predominantly between 52 and 63; that the rocks are relatively rich in calcium; that natron and potash occur in smaller quantities; and that the content of potash is in fact extremely poor (see also Van Tongeren 1934, who lists average analyses of Lesser Antilles lava rocks).

	Saba						St. Eustatius					
	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	60.80	58.56	57.97	59.79	57.63	53.57	55.72	53.23	69.54	57.38	60.50	57.48
Al_2O_3	16.34	17.00	18.81		18.78		16.01		12.68	18.20		
Fe_2O_3	0.68	2.63	3.01		3.17		7.41		4.01	4.21		
FeO	5.14	3.57	2.37		2.62					3.12		
MgO	1.47	3.45	3.47		3.94		2.81		3.52	2.23		
CaO	6.92	8.32	7.16		6.11		8.59		4.41	8.22		
Na_2O	6.71	3.89	3.00		3.08		4.79		3.71	4.04		
K_2O	1.12	1.36	1.01		1.18		3.30		1.43	0.80		
TiO_2		0.72	0.65		0.58				trace	0.78		
P_2O_5		0.06	0.153		0.168					0.12		
H_2O+	0.37	0.84	1.79		1.74					0.81		
H_2O-		0.08	0.51		1.43					0.54		
MnO		trace	0.134		0.146					0.09		
Total	99.55	100.48	100.037		100.574		98.63		99.30	100.54		
An %	16	43								46		
SiO_2 libre	1.6	10.4								12.1		

Table 1. Chemical analyses of rocks of Saba, St. Eustatius

St. Kitts		Nevis	Montserrat			Guade-loupe	Martinique			St. Lucia
13	14	15	16	17	18	19	20	21	22	23
53.74	61.02	61.42	64.21	59.68	52.00	56.00	60.12	62.90	63.53	62.04
18.55	19.61	17.09	16.83	18.23	19.22	17.53	17.02	17.20	17.02	17.97
3.19	4.45	2.95	3.74	2.44	2.73	5.49	1.35	1.28	2.80	3.31
6.35	2.09	2.65	1.77	4.37	5.61	2.69	4.09	4.20	3.25	2.08
3.81	1.72	1.73	2.22	2.82	5.54	3.24	2.16	2.52	2.08	2.95
9.06	5.70	6.66	6.03	7.52	10.58	10.12	8.86	6.76	5.83	6.22
2.97	3.51	4.59	3.40	3.07	2.53	2.19	2.78	3.18	3.59	2.24
0.72	0.44	1.28	1.09	0.65	0.76	0.59	1.14	1.32	1.05	1.57
1.19	0.47	0.74	0.34	0.46	0.63	1.16	0.96	0.33	0.47	0.59
0.07	0.200	0.17	0.09	0.11	0.11	0.37	0.23	0.14	0.16	0.09
0.27	0.59	0.39	0.17	0.14	0.20	0.49	1.80	0.24	0.16	1.09
0.34	0.24	0.29	0.20	0.12	0.15	0.14			0.09	0.28
0.08	0.211	0.23	0.11	0.17	0.11	0.17	0.11	0.10	0.14	0.05
100.34	100.161	100.10	100.20	99.78	100.17	100.18	100.62	100.18	100.17	100.48
58		36				62	56	51		61
7.8		14.7				18.2	17.9	19.2		25.5

nd other Volcanic Caribbees (see also p. 56)

LIST OF ROCKS WHOSE ANALYSES ARE GIVEN IN TABLE 1

(arranged geographically)

The rock names are those applied by the authors mentioned between brackets.

1. "Trachyte" (Cleve 1871)
   "Andesit" (Högbom 1905)
   "Andésite oligoclasique" (Lacroix 1926) } *Saba;* locality unknown
2. "Dacite à hornblende et hypersthène" (Lacroix 1926), *Saba;* locality unknown
3. "Lamprobolite-pyroxene-andesite" (Westermann & Kiel), *Saba;* spine of the volcanic dome of Great Hill, locality 7
4. "Lamprobolite-pyroxene-andesite" (Westermann & Kiel), *Saba;* volcanic dome of Bunker Hill, locality 13
5. "Basaltic (olivine-bearing) lamprobolite-pyroxene-andesite" (Westermann & Kiel), *Saba;* summit dome of The Mountain, locality 81
6. "Basaltic (olivine-bearing) lamprobolite-pyroxene-andesite" (Westermann & Kiel), *Saba;* lava flow of Flat Point, locality 146
7. "Hornblende-augite-andesite" (Molengraaff 1886), *St. Eustatius;* volcanic dike of Signal Hill
8. "Augite-andesite" (Molengraaff 1886), *St. Eustatius;* crater rim of the Quill volcano
9. "Dacite-pumice" (Molengraaff 1886), *St. Eustatius;* Sugar Loaf, bed 4
10. "Dacitoïde" (Lacroix 1926), *St. Eustatius;* locality unknown
11. "Pyroxene-andesite" (Westermann & Kiel), *St. Eustatius;* volcanic neck, Bergje, locality 104
12. "Pyroxene-andesite" (Westermann & Kiel), *St. Eustatius;* lava flow of Gilboa Hill, locality 92
13. "Labradorite *a* à hypersthène et olivine" (Lacroix 1926), *St. Kitts;* lava flow of Black Rocks
14. "Lamprobolite-hypersthene-andesite" (Westermann & Kiel), *St. Kitts;* volcanic dome of Brimstone Hill, MK 5631 (Martin-Kaye 1959)
15. "Dacite à hornblende, augite et hypersthène" (Lacroix 1926), *Nevis;* locality unknown
16. "Labradorite-dacite (hornblende-pyroxene-bandaite)" (MacGregor 1938), *Montserrat;* intrusion, coast south-west of Landing Bay
17. "Labradorite-dacite (hornblende-pyroxene-bandaite)" (MacGregor 1938), *Montserrat;* crater dome, Castles Peak
18. "Olivine-basalt" (MacGregor 1938), *Montserrat;* lava flow, South Soufrière Hill, at O'Garra's
19. "Dacitoïde à pyroxène" (Lacroix 1926), *Guadeloupe;* volcanic dome, Soufrière
20. "Dacite à hornblende et hypersthène" (Lacroix 1926), *Martinique;* volcanic dome, piton du Massif du Carbet (l'Alma)
21. "Dacite à hypersthène" (Lacroix 1926), *Martinique;* dome de 1903, Mont Pelée
22. "Hypersthene-andesite" (Shepherd & Merwin 1927, in MacGregor 1938), *Martinique;* spine of 1902—1903, Mont Pelée
23. "Dacite à hypersthène" (Lacroix 1926), *St. Lucia;* volcanic dome, Petit Piton

General petrographic characteristics of the andesites

The andesites of Saba, although they vary in mineral contents and texture, have many characteristics in common. It is therefore justified to begin by giving a general description of them.

Texture

The texture of nearly all andesites is porphyritic or, more frequently, glomeroporphyritic.* Naturally the proportion of the volume occupied by phenocrysts to that occupied by the groundmass varies considerably.

The very coarse hornblende-andesite of locality 42c resembles a hornblende-diorite but differs from it in containing glass.

Porous and vesicular rocks occur notably in the *nuée ardente* deposits of the south coast: 69a, 70c, 71a, 71b, 71d. The breadcrust bomb 85a of Crispine is locally vesicular.

Phenocrysts

Feldspar

Feldspar is present only as plagioclases which, as a rule, are more abundant than the ferromagnesian minerals. The plagioclase phenocrysts have rectangular to equidimensional, tabular forms or are lath-shaped; they vary in size between some mm to a fraction of 1 mm. Most crystals show the normal oscillatory zoning.

Many plagioclases have smoothly rounded, corroded edges and spongy cores, or at least internal sponginess in some of the zones. This sponginess is due to the presence of minute cavities filled with colourless to brownish glass. Larger, isolated cavities are also found to contain glass.

Sponginess was found by the authors to be a common feature in the andesite-plagioclases of the northern Volcanic Caribbees: cf. Molengraaff 1886, chapter V, St. Eustatius; Westoll 1932, St. Kitts; Martin-Kaye 1959, p. 63, Nevis; MacGregor 1938, p. 50, Montserrat. The latter author believes that sponginess is largely due to magmatic corrosion caused by a change in physico-chemical conditions.

Several plagioclases also contain minute inclusions of pyroxenes, hornblende, lamprobolite and iron ore.

The composition of the plagioclase phenocrysts, found approximately by measuring extinction angles, appears to vary little and may, on the whole, be classed as intermediate: andesine-labradorite. The average anorthite content of the phenocrysts in twenty-seven olivine-free andesites was 52%; in the same number of olivine-bearing andesites this percentage was found to be 50. In a basaltic (lamprobolite-)andesite of the Flat Point lava flow (locality 119) the average percentage proved to be 62%, some plagioclases having as much as 76% An (bytownite).

* The term "glomeroporphyritic" is used for the texture of rocks in which phenocrysts of plagioclase form clusters, often along with the pyroxenes, hornblendes, lamprobolites and iron ores. The name was introduced by J. W. Judd (1886).

A u g i t e

Augite is present in practically all andesites. In about 25% of the number of rocks examined it was the only pyroxene observed. The augite phenocrysts are usually smaller than the plagioclases, and less abundant. In some rocks they are subordinate. Their colour is yellowish green. Twinning can occasionally be observed. Many crystals show a black or reddish-brown rim of iron oxide.

H y p e r s t h e n e

Where augite and hypersthene phenocrysts are both present (which is the case in about 75% of the number of rocks examined), the latter are much less common and, in many instances, subordinate. Pleochroism, from pale green to pinkish, is not very distinctive. Twinning can be observed in some sections.

Since hypersthene is a mineral formed under high pressure in a gas-rich magma, it is bound to react with the remaining magma when pressure and gas content are much lower. Cores of hypersthene surrounded by augite have been observed in the thin sections of Nos. 17, 26, 70b, 71c and 141; some of the hypersthene crystals have black rims of iron oxide.

H o r n b l e n d e   a n d   l a m p r o b o l i t e

The phenocrysts of this mineral group are either brown or green hornblendes, or orange-brown lamprobolites.

The *brown and green hornblendes* often show twinning and have marked pleochroism from dark brown to yellow or yellow green, and dark green to green or pale green, respectively. In rock Nos. 23, 26, 84 and 96 brown and green hornblendes occur together.

The majority of the andesites are characterized by a content of orange-brown hornblende, known under the name of *basaltic hornblende, oxyhornblende* or *lamprobolite.** The extinction angle of this type of hornblende is much smaller than that of the other hornblendes, and often approaches 0°. Consequently, twinning is practically absent. Pleochroism is very

* The name "oxyhornblende" was introduced by A. N. Winchell (*Amer. Mineral. 17*, 1932, pp. 472—477).

The name "lamprobolite" was proposed by A. F. Rogers (*Amer. Mineral.* 25, 1940, pp. 826—828) for the mineral usually called "basaltic hornblende".

A. N. Winchell (*Elements of Optical Mineralogy*, Part II, New York 1951, pp. 437—439) has stated that natural oxyhornblendes are usually oxidized only partially, rather than completely, and that, therefore, their properties are intermediate between those of ordinary hornblendes and those of completely oxidized hornblende. According to this author the size of the extinction angle is an approximate guide to the amount of oxidation, but natural oxyhornblendes with an extinction angle of 0° are usually not completely oxidized. Winchell is also of the opinion that the oxidation which transforms the hornblende is probably a process of loss of hydrogen: "Oxyhornblende is found in volcanic rocks such as basalt under conditions which suggest that it was formed, not as a primary mineral, but as an alteration product of common hornblende. The alteration involves no introduction of oxygen, but only loss of hydrogen."

marked, and ranges from a vivid ruddy or orange brown to pale yellow. Many lamprobolite phenocrysts have an elongated, somewhat ragged appearance.

Lamprobolites are practically absent in the andesites of St. Eustatius. In those of St. Kitts the pyroxene-andesites of the Older Volcanics carry "occasionally a little basaltic hornblende" (Martin-Kaye 1959, p. 50), while the present authors determined rocks of Monkey Hill and Brimstone Hill (Martin-Kaye 5631) as pyroxene-lamprobolite-andesites. For Nevis, Martin-Kaye (1959) mentions andesites with pyroxenes and lamprobolite; the rocks collected by the authors on The Peak are lamprobolite-pyroxene-andesites. In Montserrat lamprobolite is a common mineral in bandaites; it is described by MacGregor (1938) as "a deep but brilliant ruddy brown" amphibole.

The latter author has devoted a lengthy discussion to the occurrence and origin of this "red-brown hornblende" (pp. 51—53). According to him it "occurs only in rocks that are reddened and oxidized", and whose analysis "reflects the oxidation, in the excess of ferric over ferrous iron". After describing experiments carried out by various investigators on the production of reddish brown hornblende, MacGregor states that in Montserrat "the red-brown type of hornblende results from some change affecting either green or brown hornblende". He also notes "that the red-brown amphibole occurs only in rocks that show clear signs of oxidation from external sources (for instance the production of iron oxide rims around pyroxenes)." MacGregor adds that "it is probable that under volcanic conditions oxidation by air plays a part in the change. .... Lacroix (1904, p. 532) attributed the formation of red-brown hornblende (occurring in Martinique rocks reddened by superficial volcanic oxidation) to the effects of volcanic oxidation on green and brown hornblende; he produced a similar result by heating such amphiboles in air."

It is difficult to say whether or not the lamprobolites of Saba should be considered as green or brown hornblendes altered by oxidizing agencies under volcanic conditions, either internal or external. The fact that, in contrast to the conditions in Montserrat, the Saba lamprobolites do not occur "only in rocks that are reddened and oxidized" suggests that oxidation from external sources has hardly played a part in their formation. It is also characteristic that lamprobolite-bearing andesites and hornblende-bearing andesites occur in the same volcanic formations, while in most of these formations a few andesites have been met with which contain lamprobolite besides brown hornblende (3, 48a, 70a, 79, 80, 81, 103, 134b, 141). These facts would indicate that the alteration of green and brown hornblende into lamprobolite by oxidizing agencies has been restricted to certain zones and parts of the volcanic units of Saba. The conclusion can probably be drawn that formation of the Saba lamprobolites should not be considered to be due to a process of oxidation from external sources, but rather to a locally active process of oxidation (or only of loss of hydrogen?) during consolidation of the magma.

The hornblende and lamprobolite phenocrysts formed at great depth in a gas-rich magma under conditions of high pressure. They became unstable nearer the surface, where the magma was poorer in gas and the pressure was lower. This instability is revealed by resorption phenomena in several of the hornblendes and lamprobolites, which show black or brown "opacite" rims*. Some of the hornblendes have a rim of augite, while in No. 84 the green hornblende is found to have been partly altered into chlorite. The *pseudomorphs,* described as either "pyroxenic" type or "black" type, are, however, the most conspicuous resorption features (cf. MacGregor 1938, pp. 54, 55). In the "pyroxenic" type the amphiboles are largely or wholly replaced by an aggregate of augite and hypersthene, with some plagioclase and iron ore. In the "black" type an almost opaque, fine-grained aggregate of iron ore and pyroxene has taken the place of the amphibole crystals. "Black" types seldom occur without the "pyroxenic" type being present, but the latter is often found without the "black" type.

There are several rocks which lack hornblende or lamprobolite but contain pseudomorphs of the "pyroxenic" type or of the "pyroxenic" and "black" types (see the List of andesite rocks and Table 2). It may be assumed that here all amphiboles have been completely transformed.

In his description of the resorption phenomena in amphiboles of Montserrat rocks MacGregor discusses the origin of the two types of pseudomorphs. According to H. S. Washington (1896) the "black" type of alteration "is not due to reaction with the magma, but takes place when the mineral becomes unstable under conditions of diminished pressure, and slow cooling from a relatively high temperature." However, experiments carried out in Japan (1927) may suggest "that under magmatic conditions "black" pseudomorphs are produced by a change in concentration of the magma, or by rising temperature, or by both." MacGregor believes that the "pyroxenic" pseudomorphs are probably formed at greater depths than the "black" type. "The pyroxenic type of alteration was apparently very prevalent in the rocks of the Mt Pelé eruption of 1902, in which porphyritic hornblendes were rarely intact. Lacroix inferred that the change is of deep-seated origin as compared with that which produced "black" pseudomorphs, and is due to reaction with the magma."

It is interesting to quote F. J. Turner & J. Verhoogen (*Igneous and Metamorphic Petrology,* New York 1951), pp. 216–217: "Resorption of hornblende .... to give pseudomorphous aggregates of iron ore, pyroxene, and plagioclase – a process involving oxidation of iron to the ferric condition – is favored by near-surface conditions, including loss of water from the magma. Much of this resorption occurred after eruption of the enclosing magma as lava." (See also Rittmann 1960, pp. 105, 114).

If the above conclusions of MacGregor are accepted, the prevalence of "pyroxenic" pseudomorphs in the Saba andesites would suggest that

* Opacite (Vogelsang 1872) is a noncommittal description for aggregates of black, opaque grains which may be iron ores but are, in general, too small for individual determination by optical methods.

the majority of the amphiboles have been subjected to resorption at comparatively great depths. However, the pseudomorphs may also have formed during or after the eruptive stage, hence nearer the surface; *vide* Turner & Verhoogen.

Olivine

Olivine phenocrysts are present in a number of andesites which have accordingly been named "basaltic andesites". Most of the olivines are corroded, partly resorbed and show rounded shapes. Reaction rims are common features: usually they consist of pyroxene (predominantly augite); rims of hornblende (42 d) or lamprobolite (59, 79, 80) are rare. The olivines may also have reddish-brown iddingsite (?) or black "opacite" rims. In some rocks the olivine crystals have been totally altered into secondary minerals. The fresh olivines look colourless to very pale yellow.

It is clear that the olivines were generally not in equilibrium with the magma in the final stages, perhaps on account of the alteration of the basaltic magma into an andesitic magma (partly due to the absorption of quartz material?). Similar corrosion and resorption features have been observed by MacGregor in the basalts and olivine-bearing bandaites of Montserrat.

Iron ore

All Saba andesites contain small phenocrysts of black iron ore in greatly varying amounts. It is thought that most of the iron is magnetite. The grains have frequently been oxidized into a reddish-brown iron oxide.

Apatite

Small apatite prisms have been noticed sporadically, in comparatively few andesites (5, 8, 16, 19, 53, 57, 69b, 82, 126, 141, 144).

Quartz

Quartz crystals have been found in small numbers in andesites belonging to all four groups. They are mostly small (max. diameter 0.5 mm), rounded and embayed, hence partly resorbed, crystals, which often have reaction rims of small prisms and microlites of pyroxene (in most cases augite). Quartzes with and without rims may occur in one rock. The quartzes occasionally have holes containing glass (57, 70, 85a).

Lacroix (1890, 1893) held the opinion that the rounded quartz grains in the Saba andesites are "enclaves" foreign to the andesitic magma. Molengraaff (1931) found "a few irregular, obviously xenolithic, grains of quartz" in an andesite of the valley leading from The Bottom to Fort Bay. Quartzes appear to be entirely absent in the lava rocks of St. Eustatius, although Lacroix (1890) wrote: "J'ai retrouvé des enclaves analogues dans les labradorites de l'île Saint-Eustache." The authors found quartzes in some of the magmatic rocks of St. Kitts and Nevis, while MacGregor (1938) described "porphyritic quartz" in several of the bandaites of Montserrat; apparently these quartzes, defined as rounded or embayed, corroded relics with and without reaction rims, were considered by MacGregor as normal phenocrysts and not as foreign elements.

It is a matter of conjecture whether the quartzes in the Saba rocks are phenocrysts or xenocrysts. It is generally believed that, where quartzes accompany olivine in basalts, they are almost invariably xenocrysts, picked up from older lavas or from metamorphic or sedimentary rocks, and, being out of harmony with the enclosing basaltic magma, are rounded and embayed by magmatic corrosion and enveloped by reaction rims (Hatch & Wells, 1937, p. 214; Williams, Turner & Gilbert, 1955, pp. 41–42; Tyrrell, 1955, p. 93).

However, the Saba rocks, although several of them contain olivine, cannot be classed as true basalts; they are all andesites. Moreover, the fact that the quartzes occur widespread in the four main andesite groups, and also in all volcanic formations of the island, would suggest that they are phenocrysts which were normally formed in the andesitic magma and were partly corroded and resorbed at a later stage.

The phenocrystal or xenocrystal character of the quartzes has some bearing on the type and evolution of the magma. If the quartzes may be considered phenocrysts, the original magma probably had an andesitic character. Owing to crystallization of the quartzes this andesitic magma became more basaltic, and subsequently corroded and resorbed the quartz crystals, some of which, however, protected themselves with an armour of pyroxenes. If the quartzes are xenocrysts, it is likely that the original magma was basaltic, and became more andesitic as a result of assimilation of the unprotected quartzes.

The absence of quartzes in the numerous autoliths — which are presumably fragments of the conduit walls (see below) — may possibly indicate that the quartzes in the main rock are xenocrysts. Our knowledge of the volcanic structure of Saba is, however, insufficient for a proper evaluation of this criterion.

Whatever the origin of the quartzes may be, they have been called phenocrysts in the list of andesitic rocks (see below).

Groundmass

The texture of the rocks with a microcrystalline groundmass is predominantly intergranular to pilotaxitic, rarely (39 (1), 84, 143) intersertal.*

---

* (Tyrrell 1955, p. 90)
Intergranular. The framework of plagioclase laths or tablets is so arranged that triangular or polygonal interspaces are left between the crystals; these interspaces may be entirely filled with granules of augite, olivine, and iron oxides.
Intersertal. The interspaces of the framework, described under "intergranular", are filled with glassy, cryptocrystalline, chloritic or serpentinous materials.

(Williams, Turner & Gilbert 1955, p. 23)
Pilotaxitic. The crowded laths and microlites of feldspar are disposed in a sub-parallel manner as a result of flow, and their interstices are occupied by micro or cryptocrystalline material.

In the intergranular to pilotaxitic groundmass minute laths and microlites of plagioclase are usually predominant. The composition of the plagioclase microlites in some of the thin sections has been found approximately by measuring extinction angles. It appears that the average anorthite content of the groundmass plagioclases is slightly lower than that of the phenocrysts: in olivine-free andesites it is 46–47% (compared with 52%), in olivine-bearing andesites 48% (50%).

Among the ferromagnesian minerals, present as granules, augite occurs most frequently, whereas hypersthene, hornblende and lamprobolite are subordinated or absent, even if these minerals are present as phenocrysts. Iron ore (magnetite) is common as small, scattered grains; in some rocks it occurs in great abundance.

The few andesites with an intersertal groundmass contain colourless to brownish glass.

A number of rocks have a micro to cryptocrystalline or predominantly cryptocrystalline groundmass of microlites in which no definite texture can be seen (felsophyric texture). The hornblende-andesites 70 and 70c have a partly glassy (vitrophyric) and thready groundmass with microlites of plagioclase, ferromagnesian minerals and iron ore. The groundmass of the vitrophyric and partly vesicular breadcrust bomb of Crispine (85a) consists of colourless to brownish glass with a few, small crystals of plagioclase, pyroxene and green hornblende.

In several andesites the groundmass crystals are coated with reddish-brown iron oxide. Calcite, as a secondary mineral, has been observed in 48a and 82. In other rocks the groundmass has a dusty look.

Cristobalite – a metastable substitute for quartz, especially where crystallization of the groundmass has been rapid – is found in varying amounts in the groundmass of several of the Saba andesites. It is not quite certain whether tridymite is also present.

MacGregor (1938) described tridymite and cristobalite as being abundant in many of the rocks of Montserrat. He was of the opinion that much of the tridymite is of primary magmatic origin, and that its crystallization took place as an ordinary groundmass constituent, before the glass solidified. Some of it, occurring in pore cavities, may have been formed as a secondary mineral. The cristobalite – which is not so widespread as tridymite – may possibly replace original tridymite in all cases.

The present authors have no definite opinion on the origin of these minerals in the Saba rocks. Perhaps the gaseous circulation and transfer of silica has been largely responsible for the deposition of cristobalite and tridymite in vesicles after the groundmass had been completely solidified, or perhaps these minerals have been produced by transformation of glass as a result of reheating or the action of water vapour (cf. Lacroix 1904, p. 519; 1908, p. 56).

Autoliths (cognate inclusions)*

Autoliths or cognate inclusions are commonly seen in the andesites of the four main groups, and they appear to occur in volcanic domes, plugs and lava flows alike. They may be most frequent in the domes and plugs, but this is difficult to ascertain.

Macroscopically the autoliths can easily be recognized in the rocks as rounded or ovate inclusions of various sizes, usually not exceeding three or four inches in diameter. They are somewhat darker in colour, and look finer-grained than the enclosing rock. In reality the autoliths have a coarser texture: MacGregor (1938) has pointed out, with reference to the Montserrat rocks, that the optical illusion of a finer-grained texture is produced by the greater abundance of phenocrysts in the main rock.

The coarser texture of the autoliths, as compared with that of the groundmass of the enclosing andesites, is apparent under the microscope. Although there is a fairly abrupt transition between the two rocks – which can be noticed from the change in texture – the boundary is never sharp, and the crystals of both dovetail together.

The autoliths may be either non-porphyritic or porphyritic (glomero-porphyritic); the latter are less common. The phenocrysts in the porphyritic autoliths are the same as those in the main rock: plagioclase of intermediate composition (several with internal sponginess, cavities filled with glass, and inclusions of ferromagnesian minerals and iron ore), augite, hypersthene (less common), hornblende (rare), lamprobolite, olivine, and black iron ore. The hornblende or lamprobolite has often been altered into pseudomorphs, usually of the "pyroxenic" type but also, less commonly, of the "black" type. The ferromagnesian minerals occasionally have black or brown rims of iron oxide. It is noteworthy that quartzes have not been observed.

The texture of the non-porphyritic autoliths and of the groundmass of the porphyritic autoliths is either intergranular or intersertal; the intersertal types are far more abundant than the intergranular types. In the intergranular autoliths laths and tabular crystals of plagioclase predominate over ferromagnesian minerals; black iron ore is always present as small grains. The intersertal autoliths and those with an intersertal groundmass contain much grey to brownish glass.

* The name autolith (or cognate inclusion) was introduced by T. H. Holland in 1900 for "a fragment of igneous rock enclosed in another igneous rock of later consolidation, each being regarded as a derivative from a common parent magma" (*Geological Nomenclature* 1959, 5114).

Autoliths have been called by Lacroix (1893) "enclaves homoeogènes" *i.e.* "enclaves de roches en rapport de composition et d'origine avec le magma de la roche englobante". The same name was used by this author in his publications of 1904 (p. 536) and 1908 (p. 51) on the Mt. Pelée of Martinique, and in his treatise of 1926 (p. 398) on the Lesser Antilles.

Tyrrell, 1955 (p. 95) — using the name "xenoliths" — has given the following characterization: "Xenoliths are called *cognate* when they represent fragments of rocks which are genetically related to the enclosing rock, and which, in most cases, have been formed at an early stage of crystallisation."

Although practically all autoliths can be classed as "cognate inclusions", i.e. inclusions genetically related to the enclosing rock, they differ from it in various respects. The groundmass of the enclosing rock is predominantly free of glass (intergranular to pilotaxitic), whereas by far the greater part of the enclosed autoliths are rich in glass and have an intersertal texture. The autoliths in hornblende-bearing andesites often lack hornblende, but the majority of the autoliths in lamprobolite-bearing andesites also contain lamprobolite. In a few cases lamprobolite-bearing andesites have hornblende-bearing autoliths (48a, 77, 141 (1)). Roughly half the number of autoliths in basaltic (olivine-bearing) andesites contain olivine. None of the autoliths appear to have quartz crystals, whereas quartzes occur in many of the enclosing andesites, albeit only in relatively small numbers.

The autoliths in Nos. 29 and 42a have coarse dioritic textures; hornblende and lamprobolite are absent, but pseudomorphs ("pyroxenic" type) are present.

The list of andesitic rocks (see below) contains specific petrographic data on autoliths and the enclosing rocks.

Autoliths do not occur very frequently in the rocks of St. Eustatius, St. Kitts and Nevis, but they have been observed in many of the lava rocks of other volcanic Caribbees. Lacroix (1904, 1908, 1926) and MacGregor (1938), in particular, have made careful studies of their composition, occurrence and origin in Martinique and Montserrat respectively.

As regards Martinique, reference is made to Lacroix's publication of 1926 (pp. 398–399). The dacites of this island appear to contain abundant "*enclaves homoeogènes*", named "*enclaves synmorphes*" "parce que leur structure se rapproche de celle de la lave englobante sans lui être identique". They contain much glass in the feldspar interstices. Brown, automorphous hornblende elongated along the vertical axis, is the predominant element among the coloured minerals; it may be accompanied by hypersthene or augite. By way of exception, the xenoliths of the dacite of the Pitons du Carbet (ancient domes) contain quartz phenocrysts. Lacroix believed that these "enclaves" are crystallization differentiates of the magma itself, apparently consolidated at the same time as the enclosing rock: "Ces enclaves constituent un type de ségrégation (différenciation) effectuée par cristallisation dans le magma même et formant comme des glaçons de cristaux qui ont été fragmentés au cours de l'épanchement et charriés sous forme de masses, généralement arrondies, dont le diamètre, à la Martinique, dépasse rarement un décimètre."

The chemical analysis of these cognate xenoliths proves that they contain less SiO_2 than the enclosing rocks, and more CaO, MgO and Fe_2O_3.

In Montserrat MacGregor recognized three main types of autoliths, termed by him "cognate xenoliths". The type which would seem to be more or less identical with the autoliths of Saba is represented by autoliths in the rock of the dome of Castles Peak (pp. 63–67). The Castles Peak autoliths are not markedly porphyritic; they consist mainly of zoned labradorite along with dark-brown hornblende or pyroxenic pseudomorphs representing original hornblende, pyroxenes, apatites and iron ores. Abundant wide interspaces between the feldspars and hornblendes are largely occupied by brownish spherulitic material, accompanied by brown glass. There is also much cristobalite in the interspaces; it is of earlier formation than the spherulites or the glass. The autoliths are porous in varying degrees. The enclosing rocks (hornblende-bandaite) have a very fine-grained but non-glassy, holocrystalline groundmass. MacGregor suggested that these Montserrat xenoliths "represent partly crystallized bandaite magma that once lined the walls of the magma conduit. During renewal of upward movement of similar magma, pieces of semi-crystallized wall-rock were torn from the conduit sides and incorporated as xenoliths in ascending magma, while still under great pressure. The hornblende of the xenoliths is brown, and sometimes shows partial or complete resorption of the "pyroxenic" type. From these facts we may make the further inference that the wall-rock from which the xenoliths were derived came from a moderate depth in the conduit, ... Before their "birth" the xenoliths are to be regarded as being composed of a crystal mesh with a little residual magma entangled in it. Apparently the magmatic residuum and its mineralizers were somehow trapped along with the enclosed xenolith, and these volatile fluxes were retained until the period of final consolidation of the xenolith, when the minutely vesicular glassy residuum was formed. How otherwise can we account for the presence of glassy vesicular xenoliths in the holocrystalline and very slightly porous rock of the dome?"

Brouwer (1921–1922) described "enclaves homoeogènes" in the lava-dome rocks of the Ruang volcano, north of Celebes, which are somewhat similar to the autoliths of Saba. He considered these inclusions to represent fragments of the semi-crystallized higher parts of the conduit, enveloped and carried upwards by fresh magma rising from greater depth during a volcanic eruption. According to him the glassy material in the autoliths proves that crystallization of the higher parts was not yet completed when the eruption of the deeper magma took place.

The authors of the present treatise adhere to the theories on the origin and formation of autoliths postulated by MacGregor and Brouwer. The autoliths of the Saba domes, plugs and lava flows are considered to be fragments of partly crystallized andesite magma from the conduit walls or from the higher parts of the conduits, carried up by ascending magma as rounded fragments which finally consolidated simultaneously with this younger magma. In most cases the residual magma in the semi-solid fragments (autoliths) consolidated as irregular pools of glass in the interstices of the crystals which had been formed earlier. The fact that the boundary between the autoliths and the enclosing rock is never sharp also proves that the final consolidation of both rocks took place simultaneously. Pseudomorphs of the hornblendes and lamprobolites in the autoliths may have formed as a result of the high temperature and low pressure of the incorporating magma, which made these amphiboles unstable.

List of microscopically examined andesitic rocks, arranged according to petrographic groups and volcanic formations

The four main petrographic groups have been named:

I. Hornblende-andesites
II. Lamprobolite-andesites
III. Basaltic (olivine-bearing) hornblende-andesites
IV. Basaltic (olivine-bearing) lamprobolite-andesites

All of these contain pyroxenes: augite, and mostly also hypersthene.

In each petrographic group the rocks have been classed under the volcanic formation to which they belong:

Lava beds of the basal unit of predominantly agglomerates and tuffs — *Basal unit*
Lava beds of the higher unit of predominantly andesites — *Higher unit*
Lava flows of Flat Point and Behind the Ridge — *Lava flows*
Summit dome of The Mountain — *The Mountain*
Volcanic domes, plug domes and isolated volcanic dikes, surrounding The Mountain — *Volcanic domes, plug domes and dikes*
Loose blocks in agglomerates or debris, basal unit — ditto
Loose blocks in agglomerates or debris, higher unit — ditto
Loose blocks in nuée ardente deposits — ditto.

Since a general description of the andesites, their minerals and textures has been given in the preceding pages, the petrographic data on the individual samples have been limited to a few "key" minerals, such as hornblende and lamprobolite and their pseudomorphs, olivine and quartz; the rocks with an intersertal groundmass are specially mentioned. A very short description has also been added of the *autoliths*, their characteristic minerals, such as hornblende, lamprobolite and olivine, and their texture; the autoliths containing olivine are designated as "basaltic".

I Hornblende-andesites

Basal unit — no samples

Higher unit

54 Brown hornblende phenocrysts and (rarely) ? olivine.

84 Brown and green hornblende phenocrysts; the groundmass contains some glass.

150 Green hornblende and quartz phenocrysts.

Lava flows — no samples

The Mountain — no samples

Volcanic domes

23 (Bunker Hill). Brown and (rarely) green hornblende phenocrysts. Contains *autolith* with intersertal texture, without hornblende.

26, 96 (presumably belonging to Thais Hill dome). Brown and green hornblende phenocrysts.

130 (top Old Booby Hill). Brown hornblende and quartz phenocrysts. Contains *autolith* with intersertal texture, without hornblende.

Plug domes and dikes

27 (Fort Hill). Brown hornblende phenocrysts. Contains *autolith* with intergranular texture, without hornblende.

56 (Peter Simmonson's Hill). Hornblende is lacking; presumably it has been entirely altered into pseudomorphs ("pyroxenic" type). Quartz phenocrysts. Owing to the proximity of locality 82 (see below) this andesite is tentatively classed as a (hornblende-)andesite.

82 (Small top NNE of Little Diamond). Brown hornblende and quartz phenocrysts.

83 (Little Diamond). Hornblende is lacking; presumably it has been entirely altered into pseudomorphs ("pyroxenic" and "black" types). Tentatively classed as a (hornblende-)andesite.

Loose blocks in agglomerates or debris, higher unit

42c (in gut north-east of The Bottom). Very coarse hornblende-andesite, consisting of large crystals of intermediate plagioclase, brown hornblende and iron ore, and with much glass in the interstices. Apart from the glass, this rock resembles a hornblende-diorite.

Loose blocks in nuée ardente deposits

70 (coastal cliff between Swanna Gut and Wash Gut). Green hornblende and quartz phenocrysts. Groundmass rich in glass, partly vitrophyric, non-porous; without hornblende.

70c (coastal cliff between Swanna Gut and Wash Gut). Vesicular rock with abundant green hornblende and several quartz phenocrysts. Groundmass partly vitrophyric.

71a (coastal cliff east of Wash Gut). Porous rock with green hornblende phenocrysts. *Autolith* with abundant green hornblende and intersertal texture.

71b (coastal cliff east of Wash Gut). Andesite with porphyritic and locally vesicular texture. Many of the plagioclase phenocrysts are partly albitized and epidotized. Ferromagnesian minerals are absent: clusters of iron ore grains probably indicate that pyroxenes (and hornblendes) were originally present. The groundmass is rich in very small, probably secondary quartz grains. The rock is tentatively classed as a (hornblende-)andesite.

71c (coastal cliff east of Wash Gut). Brown to brownish green hornblende phenocrysts are abundant. *Autolith* with abundant brown to brownish green hornblende and intersertal texture.

85a (Crispine). Breadcrust bomb (Plate 16). Locally vesicular andesite with green hornblende and quartz phenocrysts in a vitrophyric groundmass. Tentatively classed as *nuée ardente* rock.

II Lamprobolite-andesites

Basal unit

63 Lamprobolite and quartz phenocrysts.

64 Lamprobolite phenocrysts.

93 Lamprobolite phenocrysts are rare, but pseudomorphs ("pyroxenic" and "black" types) are common; quartz phenocrysts.

Higher unit

15, 16, 17, 18, 19 In the andesites of localities 15 and 19 lamprobolite has not been observed; presumably this mineral has been entirely altered into pseudomorphs ("pyroxenic" and "black" types). The two rocks are tentatively classed as (lamprobolite-)andesites. In the andesites of 16, 17 and 18 lamprobolite is very rare, and occurs in places as a core in "pyroxenic" types. No. 19 contains quartz phenocrysts. *Autoliths* with intersertal texture occur in 16 and 17, and with intergranular texture in 18; none of them contain lamprobolites.

43, 52 Lamprobolite phenocrysts.

53(1) Lamprobolite phenocrysts. Contains *autolith* of porphyritic basaltic lamprobolite-andesite with intersertal groundmass.
57 Lamprobolite and quartz phenocrysts. Contains *autolith* with intersertal texture, without lamprobolite.

Lava flows — no samples

The Mountain — no samples

Volcanic domes

5 (Parish Hill), 12, 13 (Bunker Hill), 14 (Great Hill). Lamprobolite and quartz phenocrysts.
6, 11 (Parish Hill), 7 (Great Hill). Lamprobolite and (in 7 and 11) quartz phenocrysts. Contain *autoliths* of porphyritic texture with lamprobolite and an intersertal groundmass.
9 (Great Hill) is an *autolith* of porphyritic texture with lamprobolite and an intersertal groundmass.
37b (Thais Hill). Lamprobolite phenocrysts. Contains *autolith* of porphyritic basaltic lamprobolite-andesite with intersertal groundmass.
39(2) (St. John's Flat). Lamprobolite and quartz phenocrysts.

Plug domes and dikes

90 (Fort Hill). Lamprobolite and quartz phenocrysts. Contains *autolith* with lamprobolite and intersertal texture.

Loose blocks in agglomerates or debris, basal unit

48a (coastal cliff Well Bay). Lamprobolite and (rare) brown hornblende phenocrysts. Contains *autolith* of coarse hornblende-andesite with brown-green hornblende and with an intersertal texture.

Loose blocks in nuée ardente deposits

69a, b (coastal cliff of The Fans). Lamprobolite and quartz phenocrysts; 69a is porous in places.

III Basaltic (olivine-bearing) hornblende-andesites

Basal unit

136a Green hornblende and quartz phenocrysts.

Higher unit

129 Brown hornblende and quartz phenocrysts.

Lava flows — for the rocks with pseudomorphs only, see: IV Basaltic lamprobolite-andesites

The Mountain — no samples

Volcanic domes — see also: IV Basaltic lamprobolite-andesites

39(1) (St. John's Flat). Green hornblende phenocrysts. The groundmass has an intersertal texture. The rock resembles an *autolith* with hornblende instead of lamprobolite.

Plug domes and dikes — no samples

Loose blocks in agglomerates or debris, higher unit

42d (in gut north-east of The Bottom). Brown hornblende and quartz phenocrysts. Contains *autolith* of olivine-bearing hornblende-andesite with intergranular texture.

Loose blocks in nuée ardente deposits

70b (coastal cliff between Swanna Gut and Wash Gut). Abundant brown hornblende and several quartz phenocrysts.

71d (coastal cliff east of Wash Gut). Porous rock with abundant brown hornblende phenocrysts. *Autolith* with brown hornblende and intersertal texture.

IV Basaltic (olivine-bearing) lamprobolite-andesites

Basal unit

3 Lamprobolite, brown hornblende (rare) and quartz phenocrysts. Contains *autolith* of porphyritic texture with lamprobolite and an intersertal groundmass.

126 Lamprobolite and quartz phenocrysts.

Higher unit

53(2), 77, 78 Lamprobolite and quartz phenocrysts. No. 77 contains *autolith* of coarse hornblende-andesite with brown hornblende and an intersertal texture.

108 Rare lamprobolite phenocrysts. Contains *autolith* of porphyritic lamprobolite-andesite whose groundmass has an intersertal texture.

111 Lamprobolite (rare) and quartz phenocrysts. Contains *autolith* of pyroxene-andesite (without hornblende or lamprobolite) with an intergranular to intersertal texture.

134b Lamprobolite, brown hornblende (rare) and quartz phenocrysts. Contains *autolith* of basaltic pyroxene-andesite (without hornblende or lamprobolite) with an intersertal texture.

Lava flows

113, 117 (Behind the Ridge). Lamprobolite and quartz phenocrysts. No. 117 has little lamprobolite and contains *autolith* of porphyritic basaltic andesite, with "pyroxenic" pseudomorphs (but without hornblende or lamprobolite) and an intersertal groundmass.

118, 119 (upper portion Flat Point lava flow). Basic plagioclase and quartz phenocrysts. Hornblende and lamprobolite are lacking; pseudomorphs ("pyroxenic" and "black" types) have taken their place. Since lamprobolite-bearing andesites occur in the same lava flow (146, 147), the rocks of 118 and 119 are tentatively classed as basaltic (lamprobolite-)andesites.

143 (lower portion Flat Point lava flow). Rich in olivine phenocrysts, and contains infrequent quartzes; the groundmass contains some glass. Pseudomorphs ("pyroxenic" types) may be altered lamprobolite phenocrysts. Like 118 and 119, this andesite is tentatively classed as a basaltic (lamprobolite-)andesite.

144 (lower portion Flat Point lava flow). Pseudomorphs ("pyroxenic" type) may be altered lamprobolite phenocrysts. Like 143, this andesite is tentatively classed as a basaltic (lamprobolite-)andesite.

146, 147 (lower portion Flat Point lava flow). Lamprobolite (rare) and quartz phenocrysts. The majority of the lamprobolites may have been entirely altered into pseudomorphs ("pyroxenic" and "black" types). Both rocks contain *autoliths* of porphyritic texture, with olivine phenocrysts but without lamprobolite; the groundmass has an intersertal texture.

The Mountain

79, 80, 81 Lamprobolite, brown hornblende (rare) and quartz phenocrysts. Nos. 79 and 80 contain *autoliths* of basaltic lamprobolite-andesite. No. 81 contains an *autolith* of lamprobolite-andesite with intersertal texture.

Volcanic domes

8 (Great Hill), 89 (Parish Hill). These are the only samples from this dome that contain olivine phenocrysts besides lamprobolite and quartz phenocrysts. The other rocks from the dome are lamprobolite-andesites.

29 (Bunker Hill). Lamprobolite is rare, but pseudomorphs ("pyroxenic" and "black" types) are common. Quartz phenocrysts. Contains *autolith* with a dioritic texture; lamprobolites absent but "pyroxenic" type common.

34 (Thais Hill). Lamprobolite (partly altered into "pyroxenic" and "black" types) and quartz phenocrysts.

66 (foot of St. John's Flat). Lamprobolite phenocrysts. Contains *autolith* of lamprobolite-andesite with intersertal texture.

72 (foot of Booby Hill). This quartz-phenocrysts-bearing basaltic andesite lacks both hornblende and lamprobolite but contains pseudomorphs ("pyroxenic" and (rare) "black" types). Since No. 120 from the same dome contains lamprobolite, the andesite of 72 is tentatively classed as basaltic (lamprobolite-) andesite.

102 (Hell's Gate dome). The rock is tentatively classed as basaltic (lamprobolite-) andesite: lamprobolite is lacking; pseudomorphs are of the "pyroxenic" type.

103 (Kate's Hill). Lamprobolite, brown hornblende (rare) and quartz phenocrysts. Contains *autolith* of porphyritic lamprobolite-andesite whose groundmass has an intersertal texture.

120 (Booby Hill). Lamprobolite and quartz phenocrysts.

122 (The Level). Lamprobolite (rare) and quartz phenocrysts. Many of the lamprobolite phenocrysts have apparently been altered into pseudomorphs ("pyroxenic" type), which are common. Contains *autolith* with an intersertal texture; no lamprobolites, but with "pyroxenic" types.

124 (The Level). Quartz phenocrysts. Pseudomorphs ("pyroxenic" type) may be altered lamprobolites, and the rock is tentatively classed as basaltic (lamprobolite-)andesite; cf. No. 122.

132 (foot Old Booby Hill). Lamprobolite (rare) and quartz phenocrysts. Pseudomorphs ("pyroxenic" and "black" types) may be altered lamprobolites. Contains rounded *autolith* of pyroxenite (augitite).

141 (Kelby's Ridge). Lamprobolite (rare), hornblende and quartz phenocrysts. Contains *autoliths* of porphyritic basaltic lamprobolite-andesite with intersertal groundmass, and of porphyritic olivine-bearing hornblende-andesite with intersertal groundmass.

Plug domes and dikes

59 (Peak Hill). Lamprobolite and quartz phenocrysts. Contains *autolith* of basaltic lamprobolite-andesite.

61 (Maskehorne Hill). Lamprobolite and quartz phenocrysts. Several of the lamprobolites altered into pseudomorphs ("pyroxenic" and "black" types).

Loose blocks in agglomerates or debris, higher unit

42a (in gut north-east of The Bottom). Lamprobolite (rare) and quartz phenocrysts. The majority of the lamprobolites appear to have been entirely altered into pseudomorphs ("pyroxenic" and "black" types). Contains *autolith* with a coarse dioritic texture, without hornblende or lamprobolite but with pseudomorphs ("pyroxenic" type).

Loose blocks in nuée ardente deposits

70a (coastal cliff between Swanna Gut and Wash Gut). Abundant lamprobolite, rare brown hornblende and several quartz phenocrysts.

Petrographic conclusions

The microscopically examined andesite rocks have been arranged in Table 2.

	Hornblende-andesites	Lamprobolite-andesites	Basaltic (olivine-bearing) hornblende-andesites	Basaltic (olivine-bearing) lamprobolite-andesites
Loose blocks in *nuée ardente* deposits	6 (1)	2	2	1
Loose blocks in agglomerates or debris, higher unit	1	—	1	1
Loose blocks in agglomerates or debris, basal unit	—	1	—	—
Plug domes and dikes	4 (2)	1	—	2
Volcanic domes	4	9	1	13 (3)
The Mountain	—	—	—	3
Lava flows	—	—	—	8 (4)
Higher unit	3	9 (2)	1	6
Basal unit	—	3	1	2
all formations	18 (3)	25 (2)	6	36 (7)

Table 2. Distribution of andesite types in the volcanic formations of Saba (85 samples)

The number of rocks shown in Table 2 is too small to allow of statistical conclusions. Nevertheless, some tentative statements may be made.

(a) Each of the main andesite groups is found in more than one formation.

(b) The andesites without lamprobolite (24 samples) are much less numerous than the lamprobolite-bearing andesites (61).* In some of the

* The few (10) andesites containing both hornblende and lamprobolite have been classed as lamprobolite-andesites or basaltic lamprobolite-andesites.

rocks the hornblende and lamprobolite have been altered completely into pseudomorphs; these rocks are classed tentatively as (hornblende-) or (lamprobolite-)andesites: numbers between brackets.

(c) The olivine-free andesites (43) are about equal in number to the olivine-bearing andesites (42), but the proportions differ greatly in each of the formations.

(d) The basaltic (olivine-bearing) hornblende-andesites appear to be much less common than the andesites of the other groups. The group of basaltic (olivine-bearing) lamprobolite-andesites is the most prominent.

(e) The andesites of The Mountain's summit and those of the lava flows of Flat Point and Behind the Ridge seem to be restricted to the group of basaltic lamprobolite-andesites. If more samples were to be examined this statement might prove to be untenable.

It appears from the list of andesites that quartz phenocrysts and autoliths occur equally in all four andesite groups and all volcanic formations. The vesicular and porous rocks seem to be restricted to the *nuée ardente* deposits.

Petrography of some pyroclastic rocks

Only a few agglomerates and tuffs have been examined under the microscope. The majority of the pyroclastic samples proved to be too weathered and fractured to permit thin sections to be made.

Short descriptions of three rocks are given below.

36. Andesitic pumice-agglomerate (E slope of Thais Hill). Lapilli of pumice, and small fragments of glassy to cryptocrystalline andesitic rocks, are embedded in a cement of brown-yellowish, cryptocrystalline material with larger crystals and crystal fragments of green and brown hornblende, pyroxene and iron ore. The lapilli have a colourless glassy groundmass with a vitrophyric texture and a fluidal and vesicular structure; this groundmass contains phenocrysts of zoned, intermediate plagioclase, green hornblende, brown hornblende (rare), pyroxene and black iron ore.

38a. Pumice-agglomerate (St. John's Flat). The lapilli of pumice have a spongy, vesicular groundmass and some phenocrysts of intermediate plagioclase, green hornblende, augite, hypersthene (rare) and black iron ore.

42b. Andesitic crystal tuff (gut NE of The Bottom). A strongly weathered rock with fragments of plagioclase, "pyroxenic" pseudomorphs and partly resorbed quartz crystals in an isotropic matrix.

Mineralogical analysis of agglomerates and tuffs

A number of agglomerates and tuffs have been investigated with a view to obtaining proportional figures of their heavy mineral contents.

The fraction between 30 and 500 micron was boiled in concentrated HCl (removal of limonite and carbonates) and subsequently treated with hot HNO_3 (removal of sulphides). This process also eliminates some heavy minerals such as apatite.

The dried residue consisting of rock fragments and light and heavy minerals, was investigated in clove oil (refractive index 1.54). The count included 100 heavy-mineral grains, but excluded opaque minerals. Of the light minerals, only quartzes were recorded, without being actually counted.

Sample Nos.	Locality	Rock
Horizontal tuff deposits in the ravine connecting The Bottom and Fort Bay		
20a (top)	near The Bottom	brown-grey tuff
b (bottom)	,,	yellow-brown tuff
88c (top)	,,	yellow-brown tuff
b	,,	brown-grey gravel and tuff
a (bottom)	,,	yellow-brown tuff
28b (top)	near Fort Bay	white tuff
a (bottom)	,,	brown tuff
(average sample)		
Horizontal deposits on top of volcanic domes or in their immediate vicinity		
38b (top)	St. John's Flat	tuff
c	,,	coarse tuff
d	,,	tuff
e (bottom)	,,	agglomeratic tuff
85a (top)	Crispine	grey, fine agglomerate
b	,,	grey tuffaceous material
c	,,	pinkish-brown tuffaceous material
123	The Level	andesitic and pumice fragments
(average sample)		
Basal unit of predominantly agglomerates and tuffs		
30	Fort Bay	multicoloured fine agglomerate
35c (top)	road St. John's Hill	coarse tuff
b	,,	tuff
a (bottom)	,,	agglomerate
46	Middle Island	fine whitish tuffaceous material
51	Mary's Point	white tuff
74*	The Fans	white tuff
91	near Fort Hill	white tuff
97	near Peak Hill	agglomeratic tuff
98	,,	talus
116a	Sulphur Mine	agglomerate
137	Well's Gut	agglomerate
145	The Cove, Flat Point	tuff, agglomerate
(average sample)		

Table 3.

* The tuffaceous bed of 74 may perhaps belong to the *nuée ardente* deposits; it is largely composed of glass shreds.

Thickness in feet	Sample treated with HCl and HNO_3					
	Hornblende, green	Hornblende, brown	Lamprobolite	Augite	Hypersthene	Quartz (X = present)
0.5	.	.	1	97	2	.
3	18	4	9	66	3	X
1	10	5	16	61	8	X
0.5	11	.	19	60	10	X
12	21	9	15	40	15	X
3—5	36	.	.	40	24	.
	26	6	20	36	12	X
	(18)	(3)	(12)	(57)	(10)	
1.5	40	5	29	14	12	X
1.5	36	4	11	34	15	X
1	18	5	22	44	11	X
	41	3	1	40	15	X
3	91	.	.	7	2	X
2.5	89	1	.	1	9	X
3	67	4	4	22	3	.
	56	.	.	34	10	X
	(55)	(3)	(8)	(24)	(10)	
25	11	.	15	67	7	X
	97	.	1	1	1	.
	61	12	20	7	.	X
	90	.	5	5	.	.
	86	2	3	6	3	?
	17	11	29	41	2	X
	96	2	.	1	1	.
	.	2	.	91	7	X
	78	1	1	11	9	X
	25	.	6	64	5	X
	.	.	5	93	2	.
	87	2	.	9	2	X
	1	5	52	37	5	X
	(50)	(3)	(11)	(33)	(3)	

Mineralogical analysis of agglomerates and tuffs of Saba

Table 3 shows the frequency of hornblende (green and brown), lamprobolite, augite and hypersthene, in pyroclastic rocks of three volcanic units. Augite appears to be present in all samples, but its percentages vary considerably in the three units. Hypersthene is much less frequent than augite. Green hornblende outnumbers brown hornblende and lamprobolite.

The averages of the three volcanic units show that augite is the most abundant mineral in the horizontal tuff deposits (57%), whereas green hornblende is the most frequent one in the deposits on top of volcanic domes (55%) and in the basal unit (50%). The figures for brown hornblende are low in all three units (3%), those for lamprobolite vary between 12, 8 and 11%. The amount of hypersthene is lowest in the basal unit (3%).

Obviously, it is not permissible to draw specific petrographic conclusions from the distribution of the heavy minerals. There is no doubt, however, that Saba's pyroclastic rocks belong to the same petrographic group as the island's magmatic rocks.

The heavy mineral analyses of Saba *soils* derived from extrusive rocks, as published by H. Kiel (in Veenenbos 1955), also show relatively high percentages of hornblende as compared with those of the pyroxenes.*

* In table 26 of Veenenbos (1955) the names "hypersthene" and "enstatite" should be reversed; enstatite is absent in the Saba rocks and soils.

CHAPTER VI

VOLCANIC HISTORY AND GENERAL REMARKS ON THE VOLCANIC STRUCTURE OF SABA, WITH NOTES ON OTHER ISLANDS OF THE VOLCANIC LESSER ANTILLES

(Appendix III, Ideal sections)

VOLCANIC HISTORY

Table 4 shows the presumed stratigraphic position of the units of the composite Saba volcano, as correlated with comparable formations of the nearby Volcanic Caribbees, viz. St. Eustatius, St. Kitts, Nevis and Montserrat (MacGregor 1938, Martin-Kaye 1959).

It may be surmised that the first eruptions which initiated the submarine phase of Saba's volcano date back to Middle or Upper Pleistocene, while the last volcanic processes may have continued until the middle of the Holocene period.

Data on the submarine portion of Saba island are lacking, for obvious reasons. The lower portion of Saba's superstructure, named here the *basal unit of predominantly agglomerates and tuffs,* is essentially a strato-volcano, with pyroclastic material predominating over andesitic lava flows.

In the higher parts of the volcano the pyroclastic beds appear to be less prominent, while andesitic lava beds become more numerous: *higher unit of predominantly andesites.* Among the lava eruptions of this younger phase two copious flank outflows occurred which are outstanding features of north-west Saba: *lava flows of Flat Point and Behind the Ridge.* They are either contemporaneous with the higher unit or slightly more recent.

The *summit dome of The Mountain,* probably extruded in the one-time crater of the strato-volcano, and the *volcanic domes, plug domes and isolated volcanic dikes surrounding The Mountain,* are thought to be the youngest members of the volcanic sequence. It is impossible to define the relative ages of the various extrusions and protrusions, but their topographic arrangement would suggest that all of them were formed in the same period. The pyroclastic strata outcropping in the cliffs of the south coast are described as *nuée ardente deposits* laid down by Peléan explosions that issued from the summit dome of The Mountain. A very recent age must also be ascribed to the *horizontal tuff deposits* of which remnants are found in a few places in the ravine connecting The Bottom and Fort Bay; it is thought that they are the products of late ash eruptions of the normal vulcanian type.

As has been noticed in other volcanoes (Williams 1932, p. 146) the development of domes, forming permanent seals to the conduits, marked the decrease and eventually the close of volcanic activity. This period of decadence and extinction of the Saba volcano may be tentatively placed

Absolute Chronology in years	Geological Chronology	SABA		ST. EUSTATIUS
		Hot water spring Solfataric activity		Solfataric activity of White Wall
	HOLOCENE	Summit dome, *nuée ardente* explosions	Peripheral volcanic domes	Upthrust White Wall — Sugar Loaf
				Main eruptions of Quill volcano
— 10,000	———	Higher unit	Lava flows of Flat Point, etc.	
		Basal unit		Sedimentation of White Wall — Sugar Loaf strata (70,000—20,000 years)
	PLEISTOCENE	Initial submarine eruptions		Initial submarine eruptions of Quill volcano
— 1,000,000	———			Eruptions of the North-western volcanic centre
	PLIOCENE			

Table 4. Stratigraphy of the northern Volcanic Lesser Antilles

ST. KITTS *	NEVIS *	MONTSERRAT **
Fumaroles	Fumaroles	Fumaroles
Upthrust Brimstone Hill and other domes		Upthrust Roche Bluff, etc., strata Castles Peak dome, *nuée ardente* explosions
Main eruptions of Mount Misery volcano		Main eruptions of Soufrière Hills, St. George's Hill, South Soufrière Hill
Sedimentation of Brimstone Hill and Godwin Gut limestones (approx. 45,000 years)		Sedimentation of Roche Bluff and Landing Bay strata
Initial eruptions of Mount Misery volcano	Eruptions of Nevis Peak volcano	Initial eruptions of Soufrière Hills, St. George's Hill, South Soufrière Hill
Eruptions of Middle Range and South-east Range	Eruptions of Madden's Mountain	Eruptions of Garibaldi Hill Eruptions of Centre Hills
Eruptions of the Older Volcanics	Eruptions of Round Hill and Saddle Hill	Eruptions of Silver Hill

* partly after Martin-Kaye 1959

** partly after MacGregor 1938 and Martin-Kaye 1959 in the middle of the Holocene. The younger Holocene has witnessed only post-volcanic solfatara activity and the *formation of sulphur deposits*. The sole recent manifestations of post-volcanic action are the *hot water spring* north of Ladder Point and the questionable "hot hole" along the road between Crispine and Windward Side.

Some of Saba's volcanic features are worthy of general discussion, in particular since identical phenomena are found in other Volcanic Caribbees. In the following pages special attention is given to (a) the lava flows of Flat Point and Behind the Ridge, (b) the summit dome of The Mountain, (c) the volcanic domes, plug domes and isolated volcanic dikes surrounding The Mountain, (d) the *nuée ardente* deposits of the south coast, and (e) the horizontal tuff deposits in the ravine connecting The Bottom and Fort Bay.

Lava flows of Flat Point and Behind the Ridge

The exact sites of the vents which fed these flank outflows are unknown. It is believed that the upper parts of the lava flows are relatively thin and the lower ends much thicker, a common feature in flows of similar andesitic character. The maximum vertical thickness of the flow of Behind the Ridge is 150 feet at its lower end, while in the middle of the peninsula of Flat Point the thickness of the lava is estimated as slightly more than 100 feet. The features of the Flat Point flow are remarkable for their good state of preservation.

In type, the surface lava may be described as "block lava" which, in places, has a markedly scoriaceous appearance.

The two lava flows seem to have no genetic relation to the nearby summit dome of The Mountain, Hell's Gate dome or the dome of Kelby's Ridge, but petrographically the rocks of flows and domes are very similar. Apparently it was the physical rather than the chemical properties which caused the basaltic andesite magma to extrude and consolidate as domes in some places, and in others to flow down the slope of The Mountain, forming true lava sheets and tongues almost one mile in length at the maximum.

During formation of Saba's basal unit of predominantly agglomerates and tuffs several lava outflows took place. These are now exposed as lava beds near the sea level, where they form promontories and capes.

The volcanic landscape of north-west St. Eustatius shows many lava flows which have been exposed as a result of denudation of the old north-western volcano. No flows are known in the case of the younger Quill volcano. The andesitic basalt* of Black Rocks, north-east coast of

---

* Described as olivine-rich feldspar-basalt (Bergeat, in Sapper 1904), "labradorite" with olivine but no hypersthene (Lacroix 1904), augite-olivine-basalt with a glassy base (Westoll 1932). The sample collected by the authors in 1958 (No. 28) has been determined as a non-glassy andesitic augite-olivine-basalt rich in iron ore and with infrequent quartz phenocrysts.

St. Kitts, probably represents one of the younger lava flows of the Mount Misery volcano; it is visible over only a short distance as "rugged cliffs of dark, partly scoriaceous and oxidised rocks" (Martin-Kaye 1959, p. 51).

Summit dome of The Mountain

The summit of The Mountain is characterized in Chapter III as a volcanic dome. Hovey (1903, 1905) was the first volcanologist to describe Saba's main peak as a volcano of the Mont Pelée type. The present survey has corroborated his views. There are, indeed, some resemblances between the features of the summit of The Mountain and those of the recent crater dome of Mont Pelée (*vide* the photographs and figures in Lacroix 1904, 1908; Williams 1932). Similar characteristics are found in the crater domes of the Soufrière, Guadeloupe (Lacroix 1908), and of Castles Peak, Montserrat (MacGregor 1938), which are much older than the Mont Pelée dome and possibly of about the same age as The Mountain's summit dome.

A major difference is that the domes of Castle Peak, Soufrière and Mont Pelée are crater domes (the latter volcano had an open crater prior to the eruption of 1902: Étang sec), whereas The Mountain lacks all remnants of a crater. It may probably be assumed that the summit dome, and its debris, have completely filled in the former crater of the strato-volcano, at the same time breaching and entirely covering the crater rim, and in places even spilling over it. Something similar has happened with the southern portion of the Mont Pelée dome, which completely covers the southern rim of the old crater. A fine example of a volcano which is craterless at times is the still active Merapi of Central Java. For many years, andesitic summit domes have been developing there – some of them entirely filling-in the crater – and subsequently been exploded and destroyed. Drawings and photographs of Merapi in publications by Van Bemmelen, Brouwer, Escher, Rittmann and Williams (Bibliography) are perhaps suggestive of the eruptive phase through which the Saba volcano passed, long ago.

The jagged appearance of the summit dome of The Mountain – as in the case of the other West Indian domes, previously mentioned – is due to the occurrence of perpendicular lava dikes and pinnacles separated by deep clefts. These features have been accentuated by the erosive forces, which have been active in particular since the total extinction of the Saba volcano.

The morphology of the summit dome is probably the result of such processes as have been described by Lacroix (1904) in the case of the Mont Pelée dome. His description is summarized by Williams (1932) as follows: (p. 57) "Throughout its growth, the surface of the dome was largely concealed by débris and appeared superficially as a fragmentary pile through which projected vertical-sided, fissured pinnacles of "solid" rock (fig. 2; after Lacroix 1904, fig. 27, p. 120). It seems that the whole of the dome was traversed by deep fissures, between which the solid crags and spines were upthrust, their sides being striated and polished in the process. Usually, the extruded parts were at first polyhedral, ... In addition to the slickensiding of the fissure walls, friction breccias were produced on a large scale by movements of the solid parts, while "igneous breccias" resulted from the welling up of fresh magma between blocks that were already cooled."

To this description, Williams adds the comment that domes of Peléan type show little internal structure: (p. 145) "Growing largely by expansion from within, they are intensely fissured and brecciated, and the flow-planes, while rudely concentric with the surface, are obscure and much distorted. During protrusion, irregular dikes are continually intruded between the solid parts and serve as feeders to surface flows, but on cooling these dikes resemble the wall rocks so closely as to be indistinguishable."

The summit dome of The Mountain is believed to have grown in the way postulated by Lacroix (1904; 1908, p. 31) for the Mont Pelée dome. Williams (1932) presents this development in the following words: (pp. 57–58) "Lacroix has stressed the fact that the dome grew by two distinct processes, namely, by the emission of viscous magma and by extrusion in the solid state. Its growth was partly by endogenous and partly by exogenous accretion. Once the conduit had been cleared, the magma spread over the floor of the Étang sec, issuing through one or more vents whence only water vapor and cinders had previously been erupted. Owing to its high viscosity and to the form of the crater, the magma was unable to flow beyond the rim, but immediately piled around the source to form a dome." — "The dome was thus essentially a viscous body, enclosed within an intensely fissured, solid crust, itself mantled by piles of angular blocks, ..."

It may therefore perhaps be assumed that Saba's summit dome was formed primarily by endogenous action, i.e. by expansion from within, while the upheaving of consolidated rocks in the central conduit by ascending gases (Williams 1932, pp. 54, 143; plug dome) may also have played a rôle in the process. No traces have been noticed of former surface effusions from the top part of the dome, but the possibility that the dome is partly exogenous should not be entirely excluded. As has been remarked before, the main difference between Saba's summit dome and the Mont Pelée dome is that the latter has been observed to grow in a crater of which remnants have been visible down to the present day, whereas in the case of Saba no traces of a crater are left.*

---

* The pinnacles of Saba's summit dome do not exceed a height of some 80 feet. It is possible that, during the eruptive phase, protrusive spines like the well-known "aiguille" of the Mont Pelée dome developed. The latter first appeared toward the end of October 1902; attained a height of almost 1,000 feet above the dome by the beginning of July 1903; and ultimately collapsed because of continued eruptions. The semi-hemispherical spine of Great Hill (see below) was probably formed in the same way as the Mont Pelée "aiguille."

The general structure of the Saba volcano shows that formation of the summit dome was preceded by phases of pyroclastic activity alternating with lava effusions. Apparently this building-up of a strato-volcano reached its final phase in the vertical extrusion of gas-poor, relatively cool and viscous lava, and the upheaving of solid rocks under great pressure, forming a summit dome in the central crater and closing its conduit. This was the last major eruptive activity of the main volcano.

There are indications that formation of the summit dome was accompanied by periodic explosions, comparable to those observed at Mont Pelée and Merapi, which deposited ejecta – mostly pumice lapilli and fine tuff – along the slopes of the volcano. *Nuée ardente* explosions took place mainly or exclusively in a southerly direction (see below). After each explosive eruption – due to periodically high gas pressure at the top of the magma column in the conduit – the gas content of the remaining magma decreased considerably, the viscosity became higher, and the explosive phase was followed in turn by an extrusive phase.

As regards the propelling force in such domical protrusions, reference is made to Williams 1932, p. 146. MacGregor (1938, p. 66), describing the formation of Castles Peak dome, Montserrat, suggests that "the magma that was eventually to make the dome was gradually pushed upwards to form a hot, but more or less solid, plug below which enormous gas pressure accumulated."

The andesite dikes and pinnacles of the summit dome show indistinct columnar jointing here and there. The petrographic composition of these basaltic lamprobolite-andesites is very similar to that of the domes surrounding The Mountain (see below).

Volcanic domes, plug domes, and isolated volcanic dikes surrounding The Mountain

The various domes and dike-shaped protrusions rising conspicuously from the slopes of the main volcano's superstructure add much to the complex picture and the volcanological attractiveness of the island of Saba (Figs. 5, 6).*

For practical reasons a somewhat arbitrary attempt has been made to classify these lava extrusions in four types (Table 5).

Several of the above-named lava extrusions appear to be situated in roughly linear arrangements, indicating that they were built up from vents spaced at varying distances along fissures. The map shows the following linear arrangements:

Great Hill – Bunker Hill – Fort Hill
Thais Hill – St. John's Hill – Peter Simmonson's Hill – Maskehorne Hill

* An analogous picture is presented by drawings and a photograph published by Kuenen (1935) and Umbgrove (1949) of the extinct but probably somewhat younger Penanggungan volcano, south of Surabaya (Java), with eight basaltic and andesitic lava domes or plugs protruding along its slopes (Fig. 7).

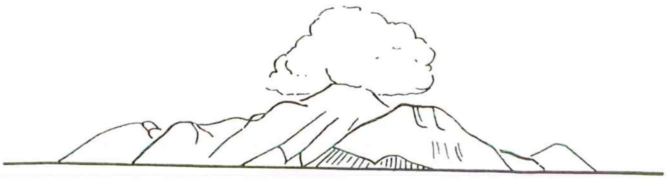


Fig. 5. Sketch of Saba, seen from the south-east. Mountain tops, from left to right: twin volcanic dome of Bunker Hill — Great Hill — Parish Hill; ditto of Thais Hill — St. John's Flat; Peter Simmonson's Hill; The Mountain (the summit, 2,910′, in clouds); twin volcanic dome of Booby Hill — The Level; Old Booby Hill.

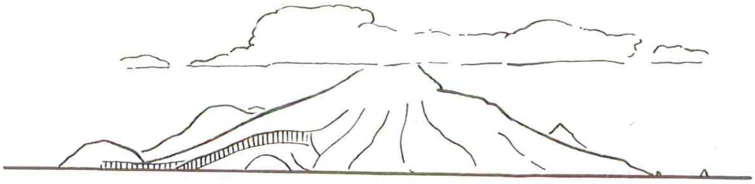


Fig. 6. Sketch of Saba, seen from the north. Mountain tops, from left to right: Old Booby Hill; The Level; The Mountain (the summit, 2,910′, in clouds); Great Hill. The lava flows of Behind the Ridge and Flat Point are seen on the left. Far to the right, the tiny islet of Diamand Rock.

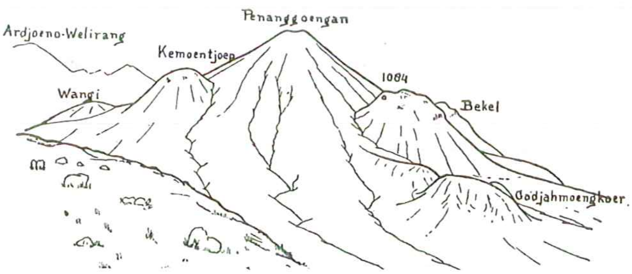


Fig. 7. The Penanggungan volcano, Java, seen to the south-west from the P. Prahu (after Ph. H. Kuenen, 1935).

Peter Simmonson's Hill – Little Diamond Hill – small top NNE of Little Diamond

Peak Hill – Maskehorne Hill – summit dome of The Mountain

Great Hill – summit dome of The Mountain – Hell's Gate dome – Kelby's Ridge

	Type of Rock			
			Basaltic (olivine-bearing)	
	Hornblende-andesite	Lamprobolite-andesite	hornblende-andesite	lamprobolite-andesite
Volcanic domes				
Parish Hill		X		X
Great Hill summit spine		X		X
Bunker Hill	X	X		X
Thais Hill	X	X		X
St. John's Flat		X	X	X
Booby Hill				X
The Level				X
Old Booby Hill	X			X
Hell's Gate dome				X *
Kelby's Ridge				X
Volcanic domes or plug domes				
Fort Hill	X	X		
Peter Simmonson's Hill	X *			
Plug domes				
Little Diamond	X *			
Small top NNE of Little Diamond	X			
Maskehorne Hill				X
Plug domes or volcanic dikes				
St. John's Hill (no sample)				
Peak Hill				X

* The hornblendes and lamprobolites have been completely altered into pseudomorphs.

Table 5. Dome- and plug-shaped lava extrusions in Saba, and their andesite types

In the following, it is mainly the volcanic domes proper which will be considered. Only a little space is devoted to the plug domes and volcanic dikes.

The *morphology of the volcanic domes* varies greatly. They are steep-sided, approximately symmetrical or elliptical, dome-, cone- or pyramid-shaped elevations, some of which are truncated. They usually have aprons of talus which, to a large extent, conceal the solid core, and are covered on top by piles of angular blocks. In an earlier stage, the cone-shaped Kelby's Ridge and Old Booby Hill may have had the form of roundish domes which were subsequently eroded, but it is equally possible that the present shape of these and other domes is primarily due to their mode of formation. Hell's Gate dome, The Level and Great Hill — Parish Hill have a true dome-shape.

The larger volcanic domes are typical twin domes: Great Hill — Parish Hill — Bunker Hill, Thais Hill — St. John's Flat, Booby Hill — The Level. Such twin domes must have started to grow as two or more separate domes, which, since their vents were relatively close together, eventually joined.*

Some domes, in particular The Level and St. John's Flat, have a flat or slightly hollow summit. According to Williams 1932, pp. 109, 131, these flat tops or axial depressions may be due to thermal contraction during consolidation, and/or the withdrawal of magma at great depth, and/or the reduction of gas pressure during the closing stages. The Saba domes have no remnants of summit craters.

Although piles of blocks and talus hide large parts of the domes, there are several places where either their steep to almost vertical, solid flanks or the interior are visible. The shore cliffs, in particular, make it possible to study the compact interior structure. Jointing is developed to a great extent, in some places in a vertical columnar (prismatic) fashion and in several other places as distinctly bent jointing planes. Most of this prismatic and platy jointing is thought to be due to contraction during the process of consolidation of the magma, but the platy joints near the surface of the domes may have been caused by weathering.

"The growth of many domes is accompanied by the protrusion from their upper surfaces of tall, obelisk-like pinnacles of lava which are usually short-lived and are destroyed either by explosion or by collapse." (Williams 1932, p. 53). It is likely that all the Saba domes possessed such pinnacles in their earlier stages. At present only three of the domes surrounding The Mountain show conspicuous remnants of spine- and dike-shaped protrusions, i.e. Booby Hill, Bunker Hill and Great Hill.

The summit of Booby Hill carries two dike-shaped elevations, one of which, Kate's Hill, is particularly conspicuous. Bunker Hill's top is characterized by vertical andesite dikes.

---

* cf. "Dômes jumeaux", a term used by G. C. Georgalas in *Bulletin Volcanologique II, tome 21,* 1959 (pp. 3—64) for the twin domes Triton A and B in the caldera of the Santorin volcano, Aegean Sea.

The southern portion of the dome of Great Hill — Parish Hill has a few bizarre pinnacles whose height nowhere exceeds 60 feet. These pinnacles resemble the spikes which previously existed on the dome of Mont Pelée as well as those found on the Soufrière of Guadeloupe and the Santa Maria, Guatemala (Lacroix 1904, 1908*; Williams 1932). Great Hill proper is a semi-hemispherical summit spine rising 260 feet above the Parish Hill plateau. This spine's convex side — whose loose rock slabs at the surface have an imbricate arrangement — is directed towards the east and south; the western side looks like a perpendicular fault scarp. The impression is gained that the summit spine has been thrust, in a more or less solid state, from the underlying dome, probably in the fashion of the famous Mont Pelée "aiguille", already referred to.**

It may be assumed that the summit spine of Great Hill at one time also rose higher above the dome than it does at present, and that it has suffered from partial destruction by collapse and erosion.

Petrographically, there is little variation between the different domes of Saba. Basaltic (olivine-bearing) lamprobolite-andesites are typical of all of them, while the domes of south-west Saba consist also of olivine-free lamprobolite- and hornblende-andesites. It is unlikely that a more detailed classification would result from petrographic investigation of further samples.

Williams (1932, p. 136) remarks that domes are composed chiefly of viscous, acid and intermediate rocks, and that perhaps the most abundant rock type is pyroxene-andesite, which greatly predominates over hornblendic andesites. The Saba domes are largely hornblendic pyroxene-andesites, with augite more common than hypersthene. Their porphyritic texture and the large size of the phenocrysts point to a slow crystallization before actual extrusion took place. Most of the rocks examined from the Saba domes have a glass-free groundmass. Williams (p. 135) states that glassiness is a typical feature of domical lavas and "is certainly to be expected in the crusts of all domes". He adds that "usually, however, the glassy crusts pass inward to a crypto- or micro-granular core". It is possible that the majority of the Saba samples, although collected from the flanks and summits, actually belong to a zone inside the crust which has been partly removed by erosion.

Analyses of domical rocks of Saba and other islands have been compared with those of other rock types (Chapter V, Table 1). There appears to be little difference between them. This corroborates Williams's statement on

* The rapid demolition by erosion of the large and smaller "aiguilles" of the Mont Pelée dome, as compared with the partial preservation of the spikes of the much older Soufrière dome, has been commented upon by Lacroix 1908 (pp. 43, 62—63). His considerations should be taken into account before a relatively recent age is assigned to Great Hill as compared with the other Saba domes.

** "Staukuppe" is the term used by Rittmann (1960, pp. 30—31) for volcanic domes. "Stosskuppe" is Rittmann's name for spines such as are described in the above text: "Bei sehr hoher Viskosität der Schmelze können massige Lavasäulen aus dem Förderschlot durch die Staukuppe hindurch in die Höhe geschoben werden."

p. 136: "A study of analyses of domical lavas has failed to reveal any feature which is even approximately characteristic. Analyses appear entirely haphazard, from which it must be concluded that the primary causes of domical eruption, as distinct from other types of volcanic activity, are chiefly physical and are also connected with the content and nature of the volatile constituents."

The petrographic similarity of the Saban domes and lava flows, which belong to different volcanic units, is also in accordance with the statement by Lacroix (1908, p. 87) on the variations in activity of one volcano with a consistent chemical composition of the magma: "L'histoire de nombre de volcans, dans lesquels la composition chimique du magma n'a pas changé sensiblement avec le temps, offre des exemples de variations tout à fait remarquables dans le mode d'activité." (See also Brouwer 1921–1922).

Rounded autoliths (cognate inclusions) are very common in the domical rocks of Saba. The same holds good for the lavas of many other domes in the world, and – according to Williams, p. 61 – "seems, indeed, to be an almost characteristic feature of massive volcanic protrusions". However, the rocks of Saba's lava beds and flows also contain autoliths.

In Table 6 the dimensions and rock types of the Saba domes and some domes in other islands of the Volcanic Caribbees are listed. *

A paragraph may be added here regarding the probable *mode of growth* of the domes surrounding The Mountain.

All these domes have developed as lateral cones on the flanks of the main volcano, but none of them has formed inside a crater. The larger domes were presumably built up by expansion from within (endogenous growth) and by repeated surface effusion of lava (exogenous growth), but it is impossible to indicate what portions were formed in the one or the other way, or whether one process prevailed over the other. The authors are inclined to accept for the Saba domes the view expressed by Williams, 1932: (pp. 142–143) "In other cases, the first expressed lava hardens to form a solid crust which is then forced upwards by the accession of fresh material beneath. Under such stresses, the solid crust inevitably fractures, and from time to time new magma pours through the fissures onto the surface of the dome. The growth of the dome is thus partly exogenous and partly endogenous, and it is likely that in most of the domes of which we have detailed knowledge this double process is continually in operation."

It is also interesting to refer to the descriptions by Trechmann (1932) and Martin-Kaye (1959) of the Brimstone Hill dome of St. Kitts (Plate 32[b]), a structure which shows great similarity to the Saba domes. Trechmann considers it to be a plug extruded comparatively recently, which has

* Martin-Kaye (1959; pp. 49, 54—55) suggests that Ottley's Mountain, Sandy Point Hill and possibly Monkey Hill, St. Kitts, may have been of similar mode of emplacement to Brimstone Hill, although they are larger and have no uplifted flanking deposits.

partly carried up sedimentary beds on its sticky flanks and shoulders, and has partly broken through the beds.

Martin-Kaye writes as follows: (p. 53) "That the andesite must have been solidified and rigid, although probably still hot and steaming at the time of its extrusion is suggested by the abrupt form of the hill, the absence of any interfingering into the sediments or inclusion of any caught up blocks of the latter within it, and the absence of drag and flow structures in the rock. Moreover thermal metamorphism or hardening of the dragged up flanking rocks is not marked."

Obviously, Trechmann and Martin-Kaye are of the opinion that Brimstone Hill has formed largely or exclusively by expansion from within, hence by endogenous growth.

In Chapter III it has been pointed out that, to all appearance, the agglomeratic and tuffaceous beds at the east foot of The Level have been lifted somewhat by the intruding dome. Accordingly, at the time of the uplift, this dome, or at least its carapace, must have been in a solid or semi-solid state, so as to be capable of dragging up the sediments. Perhaps the other Saba domes were also pushed up through the older volcanic strata in the same fashion, their magma being relatively cool, highly viscous and, at any rate on the surface (carapace), near the point of complete consolidation. At the same time the gas pressure must have been at its maximum, forcing up the dome. This upheaval must have been accompanied by the partial break-up and crumbling of the crust into piles of angular and subangular blocks; part of this blocky cover slid down along the flanks and built up a talus at the foot of the dome.

The mode of growth of Great Hill's semi-hemispherical summit spine has been briefly indicated above. It is very probable that this spine was thrust in a solid or semi-solid state through the carapace of the dome of Parish Hill, very much as the one-time Mont Pelée "aiguille" protruded from the underlying dome. Nevertheless, there is a difference in that the "aiguille" was of glassy andesite whereas the andesite of the Great Hill spine is non-glassy.

According to Lacroix 1908 (pp. 33–34) the "aiguille" was the extension of the conduit of the Mont Pelée volcano. Its glassy, quickly chilled andesite was thought to be formed of magma which rose in a viscous state, either directly from the depths of the volcano or from the central part of the dome. It was pushed through the resisting carapace of the dome, slowly enough to become solid before reaching the surface and quickly enough to prevent any notable crystallization of the groundmass of the andesite. Sapper (1904, p. 20) wrote concerning the Mont Pelée spine that it was pushed up from the dome in a solid, rather fixed state, owing to the pressure exerted by the fluid magma inside the dome, whose volume increased on account of continuous accretion from below.

The sketches published by Williams (1932) show the various domes with relatively narrow conduits through which the magma is supposed

Islands	Horizontal and vertical dimensions		
	average diameter at base of dome in metres	approximate height of dome, from visible base to top, in metres	proportion height: diameter
Saba			
Great Hill - Parish Hill	700	150(230)	1 : 4.7(1 : 3)
Bunker Hill	700	190	1 : 3.7
Thais Hill	300	150	1 : 2
The Level	750	250	1 : 3
Old Booby Hill	700	230	1 : 3
Hell's Gate dome	500	150	1 : 3.3
Kelby's Ridge	350	150	1 : 2.3
Summit dome of The Mountain (crater dome)	350—400	60	1 : 6
St. Eustatius			
Hypothetical dome below White Wall	?	?	
St. Kitts			
Sandy Point Hill	800	260	1 : 3
Brimstone Hill	650	240	1 : 2.7
Ottley's Mountain	1,300	250	1 : 5
Monkey Hill (?)	1,000	180	1 : 5.5
Montserrat			
Castles Peak (crater dome)	500	170	1 : 3
Guadeloupe			
dome of Soufrière (crater dome)	950	300	1 : 3
Martinique			
Mont Pelée (crater dome Sept. 1903, without spine)	800	400	1 : 2
Pitons du Carbet	(dimensions considerably larger than those of Mont Pelée dome)		
St. Lucia			
Gros Piton	1,600 (at sea level)	800	1 : 2
Petit Piton	1,100 (at sea level)	750	1 : 1.5

Table 6. Data on some of the

Constituent rock	SiO_2 %	Literature
(basaltic) lamprobolite-pyroxene-andesite	57.97	
(basaltic) hornblende/lamprobolite-pyroxene-andesite	59.79	
(basaltic) hornblende/lamprobolite-pyroxene-andesite		
basaltic lamprobolite-pyroxene-andesite		
(basaltic) hornblende/lamprobolite-pyroxene-andesite		
basaltic lamprobolite-pyroxene-andesite		
basaltic lamprobolite-pyroxene-andesite		
basaltic lamprobolite-pyroxene-andesite	57.63	
?		
pyroxene-andesite		Martin-Kaye 1959
(hornblende-)lamprobolite-hypersthene-andesite		Westoll 1932; Westermann & Kiel 1961
pyroxene-andesite		Martin-Kaye 1959
lamprobolite-pyroxene-andesite		Westermann & Kiel 1961
labradorite-dacite (hornblende-pyroxene-bandaite)	59.68	MacGregor 1938
trachydolerite	57.95	Sapper 1904
dacitoïde à pyroxene	56.00	Lacroix 1926
hypersthène-andesite		Lacroix 1904, 1908; Williams 1932
dacite à hypersthène	62.90	Lacroix 1926
dacite à hornblende et hypersthène	60.12	Lacroix 1908, 1926
quartz-andesite or dacite		Earle 1924; Trechmann 1935
quartz-andesite or dacite		Earle 1924; Trechmann 1935
Rhyolith gegen Dacit neigend		Sapper 1904
dacite à hypersthène	62.04	Lacroix 1926

olcanic domes of the Lesser Antilles

to have been extruded. Contrary to this view the present authors have tentatively drawn the Saban domes as inverted cones, hence with very wide conduits. However this may be, it would seem that narrow and wide conduits both offer conditions suitable for the pushing up and extrusion of highly viscous or semi-solid magma, a mode of growth believed to be typical of most domes, including those of Saba.

It might perhaps be more correct to call some of the Saban protrusive bodies *plug domes* or *volcanic dikes* rather than volcanic domes: Fort Hill (?), Peter Simmonson's Hill (?), Little Diamond, small hilltop NNE of Little Diamond, Maskehorne Hill, St. John's Hill and Peak Hill (Table 5). These elevations are steep hills with a comparatively narrow, circular or elongated base, partly eroded and enveloped by debris. They may be essentially bodies of lava, consolidated in the conduit and subsequently forced upward by gas pressure. Petrographically they are not a separate group, although it would seem that olivine-bearing andesites are less common in them than is the case with the volcanic domes.

Some of the Saba domes and other protrusions are covered with layers of tuff, pumice lapilli and, rarely, breadcrust bombs*, or have such deposits in their immediate neighbourhood: Thais Hill, St. John's Flat, St. John's Hill (Crispine), The Level and maybe others. These deposits are described in Chapter III.

It is difficult to say whether these ejecta are late-volcanic eruptive products of the main volcano, connected with the rise of its summit dome, or whether they were erupted by the flank domes. However that may be, it is likely that explosive phases have accompanied the extrusion and upheaval of the flank domes.

Williams (1932, p. 141) has expressed the opinion that – since most of the active gases are expelled with the pumice before dome formation commences, and also during the dome-building period – intense solfatara action is seldom conspicuous during and after upheaval and that, consequently, important solfataras are rarely found in the vicinity of domes. This is also true of the Saban domes; the only solfatara field of importance, now extinct, is found along the north coast, apparently unconnected with a dome. However, solfataras or their deposits are found connected with the Mont Pelée dome, the Soufrière dome of Guadeloupe, and the hypothetical dome beneath White Wall, St. Eustatius.

---

* A beautiful polygonal breadcrust bomb is shown in Plate 16 (Crispine). Sapper (1904, p. 24) described similar bombs from the summit area of Mont Pelée as "losgelöste Stücke noch flüssigen Magmas, die während ihrer Luftreise oberflächlich erstarrten, beim Auffallen auf den festen Grund die kantigen Formen annahmen und die charakteristischen Oberflächenrisse erhielten."

Rittmann (1960, p. 89) explains the polygonal breadcrust bomb as follows: "Bei explodierenden Bomben werden Bruchstücke der bereits dicken Erstarrungskruste weggesprengt, so dass ein polygonaler Kern, manchmal mit treppenförmig absetzenden, tiefen Rissen, übrigbleibt, der sich nachträglich noch aufbläht und zu einer polygonalen Brotkrustenbombe wird."

"Nuée ardente" deposits

In the preceding pages mention has been made of the *nuée ardente* character of the volcanic strata which are exposed in the cliffs along the south coast (Giles Quarter). The general type of these deposits has been described in Chapter III. Their mode of occurrence, and also the porous structure of a great number of the andesite fragments, have made the present authors believe that in the main these deposits have been formed by *nuées ardentes* (glowing clouds) or more or less similar volcanic avalanches.

Several authors have given descriptions of *nuées ardentes.* Glowing clouds may have different modes of origin, but they can be characterized by the following general definition: an exceedingly hot, heavily gas-charged and gas-emitting, self-explosive, very mobile suspension of incandescent lava material, rushing down the slope of a volcano at great speed, practically frictionless and noiseless, the solid particles being separated from one another by a cushion of compressed gas; these avalanches usually carry along with them a multitude of blocks and fragments of unexploded rock, and the whole mass accumulates and is deposited as a volcanic breccia.

It is not feasible to exactly define the limits of these *nuée ardente* deposits. The surface layers of the lower sloping area between St. John's Flat dome in the west and Booby Hill dome in the east can be decidedly classed as such. They rest on the beds of the basal unit of predominantly agglomerates and tuffs, and are probably also younger than the domes mentioned. The *nuée ardente* strata are best exposed in the coastal cliffs.

The authors have also studied the *nuée ardente* deposits on the northern slopes of Soufrière Hills, Montserrat (Plate 15^{a}), which have been described by MacGregor (1938, pp. 30–34). The latter geologist emphasized the porous character of many of the rock fragments: "The recognition of the prevalence of porosity of varying kinds and degrees and in rock-fragments of all sizes, is, I believe, of great importance, because of its bearing on the mechanism of *nuées ardentes.*" According to him a very considerable number of lava blocks and fragments containing highly compressed gas in their pores emitted this gas in descending as constituents of the *nuées ardentes* of Montserrat, and thus became markedly porous. These blocks and fragments are believed to have been blown up during one or more great explosions which accompanied or preceded formation of the dome of Castles Peak.

MacGregor compared the Montserrat deposits, in particular their volcanic dusts, with similar beds formed by the glowing clouds of Mont Pelée (Avalanche Valley), and found them to be of exactly the same character.

The *nuée ardente* deposits of Saba are of the same nature as those of Montserrat, and it is believed that the explosive eruptions with which they were connected accompanied formation of the summit dome of The Mountain (see above). It is therefore most likely that the *nuée ardente* eruptions of Saba and Montserrat were either "directed domal avalanches" of the Peléan type, i.e. lateral discharges by violent explosions from exposed flank of dome in volcanic crater, or "discharged domal avalanches" of the Peléan type, i.e. lateral discharges by mild explosions from exposed flank of dome in volcanic crater (*Geological Nomenclature* 1959).

However, as far as Saba and Montserrat are concerned two other possible types of *nuée ardente* should not be left out of consideration: the "Pelée vertical type", i.e. vertical explosive discharge from domal area of the volcanic crater, and the "Merapi type", i.e. lateral disintegration of exposed flank of dome on volcano top.

In this respect the nature of the *nuée ardente* deposits is of some importance. Lacroix (1908) has expressed the opinion that the more or less stratified deposits are the result of vertical explosions of his "type vulcanien", whereas the non-stratified deposits are the outcome of explosions of the "type péléen": (p. 82)

"Toutes ces propriétés spéciales aux nuées vulcaniennes et aux nuées péléennes entraînent comme conséquence des différences capitales dans la nature des dépôts qu'elles édifient les unes et les autres. Ceux des blocs projetés verticalement par les premières, qui ne retombent pas dans le cratère pour être rejetés par l'explosion suivante, roulent individuellement sur les flancs du volcan, les plus gros restant concentrés près de l'orifice éruptif. Les matériaux de moindres dimensions subissent aussi un classement par ordre de grosseur; ils constituent des dépôts plus ou moins stratifiés: leur distribution dans l'espace peut être soumise à de grandes perturbations sous l'influence des vents constants (alizés) ou variables. Dans le cas des nuées péléennes au contraire, c'est la totalité des matériaux projetés qui se déplace, sans qu'il s'y produise aucun classement; ainsi s'accumulent des brèches non stratifiées, dans lesquelles on constate la plus extraordinaire disproportion de taille entre les éléments trouvés côte à côte."

Lacroix divided the Peléan type into: (a) vertical explosions whose "cloud", instead of dissipating largely in the atmosphere as is the case with the vulcanian explosions, fell heavily back on to the flanks of the volcano and subsequently rolled down the slopes (cf. Pelée vertical type!); and (b) oblique explosions. The eruptions of the Soufrière volcano of St. Vincent and some eruptions of Mont Pelée were classed by Lacroix under (a); most of the other Mont Pelée avalanches under (b).

According to R. W. van Bemmelen (University of Utrecht) – who made observations on the eruptions of Merapi, Central Java, in 1942 and 1943 – the *nuée ardente* strata of that volcano are the outcome of a great many glowing clouds in sequence, each depositing a lower bed of a largely chaotic character and a much thinner upper layer consisting predominantly of ash. Thus, a series was formed which showed a distinct though somewhat ill-defined stratification (verbal communication).

Van Bemmelen's observations contradict Lacroix's thesis that the more or less stratified *nuée ardente* deposits are the result of vertical explosions of the vulcanian type only. It may therefore be safely assumed that the fairly regularly bedded *nuée ardente* beds of Saba and Montserrat have been formed by Peléan explosions, either "directed" or "discharged". This theory would also be supported by the circumstance that their deposition does not seem to have been appreciably influenced by the eastern trade winds.

The well-stratified *nuée ardente* deposits of the Soufrière volcano of St. Vincent in the Rabaca Dry River (Plate 15^{b}) and the Wallibou River – visited by the first author in 1958 – may be described, on the basis of the present classification, as the result of vertical discharges from the open, domeless crater (St. Vincent vertical type; cf. Anderson & Flett 1903, 1908). The St. Vincent glowing clouds, which deposited these stratified (!) volcanic sediments, were classed by Lacroix (1908) as "type péléen" whose "jet de l'explosion est vertical".

Rittmann (1960, pp. 32–34) discusses the various types of glowing clouds. He prefers the terminology of "descending" and "falling-back" glowing clouds ("absteigenden und zurückfallenden Glutwolken") to Pelée type and St. Vincent type, since the latter has been observed in both the Mont Pelée of Martinique and the Soufrière of St. Vincent. A third category is named by Rittmann "overflowing" glowing cloud ("überquellende Glutwolke"), and is not known to have occurred in the Lesser Antilles.

Horizontal tuff deposits

The few remaining outcrops of horizontal tuff deposits in the ravine which connects the valley of The Bottom and Fort Bay indicate that not all the late eruptions of the main volcano were of the Peléan or Merapi type, as described in the preceding section. It may be assumed that these tuffs were deposited in the course of normal vulcanian outbursts. Their resemblance to the young Quill tuffs of St. Eustatius is contradicted by the difference in heavy mineral content.

ST. EUSTATIUS

(Appendices IV, V and VI)

CHAPTER VII

PHYSIOGRAPHY – SUBMARINE CONTOURS – CLIMATE – VEGETATION AND AGRICULTURE – ROADS AND PATHS. ACCESSIBILITY – AERIAL PHOTOGRAPHS – MAPS – GEOLOGICAL SURVEY

PHYSIOGRAPHY (Figs. 4, 8; Plates 17–30, 33a)

St. Eustatius, situated 17°28′–17°32′ N and 62°56′–63°0′ W, is approximately 21 sq. km (8.2 sq. miles) in area. It is oblong in shape, with the axis running NW–SE. Its length is 7.9 km or almost 5 miles; its greatest width is 4 km or 2.5 miles.

The island's topography is characterized by three main elements: (1) the hilly north-western portion (approximately one-fourth of the total area), the remains of an old and strongly denuded volcanic landscape; (2) the young Quill volcano in the south; and (3) the almost horizontal to gently sloping plain between (1) and (2), which in fact forms the foot of The Quill – the "Cultuur vlakte" (agricultural plain), covering an area of some 1,400 acres.

The rough topography of the *North-western region* is largely a feature of the geological formations and their resistance to erosional forces. The rounded tops of Boven (964′), Gilboa Hill (574–586′), Bergje (732′), Signal Hill (769′) and other high hills consist of hard lava rocks which have withstood denudation with more success than the softer rocks of agglomeratic and tuffaceous character now found in the saddles between the hills and in the valleys. Even so, some of the smaller and lower hills appear to consist entirely of agglomerates and tuffs.

This north-western portion of the island has two well-developed valley systems, which reach the sea: Venus Bay valley and Tumble Down Dick Bay valley. These two valleys, and also those not running into the sea, are dry except during and shortly after heavy rainfall.

Venus Bay valley is formed by three main tributaries which cut deep into the hills. The northern tributary, running west-east, has its headwaters only a short distance from the west coast, the watershed being situated just above Jenkins Bay. The middle tributary begins west of Bergje and curves northwards and round this lava neck, forming a peculiar circular valley whose outer slope resembles a somma wall. The third tributary has its source on the Little Mountains plateau, just south of Bergje, and runs NNE.

The east-west-running Tumble Down Dick Bay valley is fairly straight, and has several short side-valleys coming down from the steep slopes to the north and south. The valleys of Wash Gut, Zeelandia, Concordia and Billy Gut run south-east or south into the "Cultuur vlakte".

There is a significant difference between the west coast and the east coast. The west coast is characterized by straight lines and by high, very steep cliffs, largely made up of agglomeratic and tuffaceous deposits. It is possibly partly determined by faulting (see Chapter VIII). Pebbly beaches occur at Tumble Down Dick Bay and Jenkins Bay.

The east coast is of an irregular nature, showing promontories of old lava flows alternating with bays where agglomerates and tuffs prevail. Venus Bay is of a pebbly and sandy character.

The Quill * (1,973′) is a regularly-built volcano whose sloping glacis covers the southern portion of the island. It is perhaps the finest example of its kind in the Antilles, with a beautiful, truncated cone, regular, concave sides and a wide, deep crater, almost circular in shape, with exceedingly steep inner slopes. The narrow crater rim varies in altitude between 1,240′ (a depression in the western section, where a footpath gives access to the crater) and 1,973′ (the highest point, on the eastern part of the rim **). The lowest point on the crater bottom is 895′ above sea level. The E—W diameter of the crater rim measures approximately 2,400 feet, the N—S diameter about 2,600 feet; the diameter of the crater bottom is somewhat less than 1,200 feet.

The Quill volcano has two irregular features. One is Round Hill (500′), a small dome-shaped elevation rising from the lower part of the north-western slope. The regularity of the south slope is broken by the White Wall formation, a slab consisting mainly of marine (limestone) sediments, which is probably some 650 feet thick and rests in a sloping position of about 45° S against the volcano. The foot of this formation is washed by the sea; the top lies at about 880 feet.

Narrow ravines (guts), formed by rainwater, are found on all the outer slopes of The Quill; they have developed, in particular, on the southern slopes. The deep Big Gut and Soldier's Gut bound the main body of White Wall.

The lower glacis of the Quill volcano is cut off at the coast by a perpendicular cliff, on an average 100′ high. There is a narrow pebbly beach at the foot of this cliff.

The almost flat north-western portion of the glacis of the Quill volcano bears the name "*Cultuur vlakte*" (agricultural plain). It varies in altitude between some 100 and 250′ above sea level. This plain abuts on the spurs of the north-western hills, and is bordered on the sea side by steep cliffs (60—150′ high), except near Billy Gut on the leeward coast and in the northern part of Concordia Bay, where the plain merges into sandy beaches. The cliffs on the leeward coast are somewhat higher than those on the windward coast. In places they are cut by short, narrow ravines.

---

* The Dutch inhabitants in the eighteenth century called the crater the "kuil", which means pit or hollow. Later on, the name "kuil" became corrupted into "quill".

** On the highest point of the crater rim, marked on the topographical map of 1915 as 601.5 m, a concrete triangulation stone has been erected, with the inscription: Inter-American Geodetic Survey — "Do not disturb" — R.M. 1 — Quill — 1954.

The capital of St. Eustatius, Oranjestad, is built on top of the leeward cliffs. The ruins of the eighteenth century quarter "Down town" can be found on the sandy beach at the foot of these cliffs; the front row of ruined houses is washed by the surf.

Submarine contours (Fig. 2)

The 10-fathom (18 m) isobath is roughly parallel to the coast line, but the 20-fathom (36 m) isobath has a peculiar bulge west of Oranjestad.

The island's submarine "platform", bordered by the 20-fathom line, is separated from a similar "platform" surrounding St. Kitts – Nevis by depths not exceeding 28 fathoms. The 100-fathom (180 m) line surrounds all three islands.

Climate

The general climate of St. Eustatius is described in Chapter II.

Mean annual rainfall, as measured at five different places on the "Cultuur vlakte", varies between 37 and 48 inches. But it is definitely higher on the slopes of the Quill volcano: 60–80 inches. The mean monthly rainfall in the "dry period" may be as low as 1.2 inches (Oranjestad).

Vegetation and agriculture

The primary natural vegetation of St. Eustatius has been preserved to some extent on the higher slopes and in the crater of the Quill volcano, where it varies between montane thicket, elfin woodland, dry evergreen forest, evergreen bushland and several kinds of seasonal forest. Parts of the seasonal forest have changed into secondary woodland as a result of human interference. The lower slopes of The Quill are covered with thorny woodland and Croton-Lantana thicket, also derived from seasonal formations.

The vegetation of the North-western hills consists largely of secondary woodland derived from forest intermediate between seasonal and dry evergreen, as a result of cultivation, cutting, charcoal burning and foraging by goats.

The "Cultuur vlakte" is semi-cultivated. When rainfall permits, subsistence crops such as sweet potatoes and yams are grown, while some cattle are also kept.

Reference: Stoffers (1956).

Roads and paths. Accessibility

The "Cultuur vlakte" has a fairly good road system. Generally speaking, these roads are not paved, but they can be used without difficulty by jeeps, ordinary cars and trucks. Two dirt roads lead round the Quill volcano; one runs from Oranjestad almost as far as Fort de Windt, opposite Sugar Loaf, and the other runs a fair way south-east from English Quarter to Behind the Mountain. The most northerly place that can be reached by a motor vehicle is the mouth of Wash Gut, near Zeelandia. The road to Zeelandia runs across Golden Rock airfield.

There are two main footpaths on the slopes of The Quill. One footpath leads up the western slope to the lowest point of the crater rim, and then branches into a steep path down to the crater bottom and another path over the southern crater rim to triangulation point 601.5. The other footpath climbs from a place near The Farm to the top of White Wall, and from there descends to the motor road of Behind the Mountain.

The upper slopes of The Quill are densely wooded and difficult of access. The inner crater wall is almost perpendicular and cannot be climbed.

The greater portion of the North-western hills can be surveyed without difficulty by means of a network of footpaths which extend to the various hilltops. However, some of the slopes, in particular those facing the sea side, are extremely steep, and difficult or even dangerous to climb. The west coast cliffs are unscalable.

Aerial photographs

The whole island was photographed from the air by KLM Aerocarto, Holland, on 21 and 29 June 1957, on a scale of 1 : 8,000 (Wild RC 5a camera); Plates 18, 19 and 28. The 46 photographs (Nos. 6789–6816, 6826–6827, 6869–6875, 6886–6894) are arranged in 7 strips, with directions varying between N 25 E and N 50 E.

On 26 April 1960 St. Eustatius was again photographed by KLM Aerocarto, on a scale of approximately 1 : 40,000 (three photographs, Nos. 5101, 5102 and 5103); Plate 17.

Maps

The "Topographische Kaart van Sint Eustatius", scale 1 : 20,000 (J. Smulders & Co., The Hague, 1915) is a good map for surveying purposes. The map of Appendix IV has been drawn from it, with 25-m instead of 10-m contour lines, and with minor corrections of the coast line, the road system and some guts, as indicated by the aerial photographs.

The sketch-maps, scale 1 : 25,000, of the soil survey by Veenenbos (1955) were also drawn from the topographical map of 1915, but show no contour lines.

In Molengraaff's map of 1886, scale 1 : 56,700, drawn from a map made by G. B. Laurence in 1850, the topography is indicated by shading. Molengraaff's sketch-map, scale 1 : 60,000, published in 1931, was copied from the topographical map of 1915; it has contour lines.

Geological survey

The fieldwork was carried out in the period 8–21 March 1958, with Oranjestad as basis. Appendix IV shows the survey routes. A boat trip was made on 16 March from Oranjestad (Down town) to Jenkins Bay and back, with a view to studying the steep, inaccessible cliffs of the west coast. – The aerial photographs have been of great help in locating outcrops and in interpreting geological structure.

The magnetic deviation was 9° W.

CHAPTER VIII

DESCRIPTION OF GEOLOGICAL AND VOLCANIC UNITS

General classification

St. Eustatius consists of three main geological and volcanic units, which can be easily distinguished.

The *north-western volcanic hills,* occupying about one-fourth of the island's total area, appear to be the remnants of one old strato-volcano of fairly simple structure.

Approximately three-fourths of the island's area is taken up by the young, though extinct, *Quill volcano.*

The third unit is by far the smallest: *White Wall formation,* a peculiar series of largely sedimentary strata resting in a tilted position against the south slope of the Quill volcano.

North-western volcanic hills

Data from previous publications *

Since G. A. F. Molengraaff (1886, 1931) has studied St. Eustatius in some detail, it is proper to give a fairly lengthy account of his findings.

In his doctoral thesis (1886) Molengraaff described the hills of the north-western portion of the island as the remains of old volcanoes whose original shape had been strongly affected by erosion and denudation — so much so, in fact, that their relationship and the sites of the original craters can only be indicated with difficulty. According to Molengraaff, only the more solid parts of these volcanoes had been preserved, whilst the loose ejecta were presumed to have been removed entirely.

He considered the top of the hill named Boven as a point from which enormous lava flows descended northward and eastward into the sea. Gilboa Hill was described as consisting partly of debris, partly of solid volcanic rock, with steep escarpments along the east coast. The curved ridge of Bergje (with the concave side towards the north-west) would have been one of the youngest craters.

The whole area north of Tumble Down Dick valley was thought by Molengraaff to represent the remains of an old volcano that had very probably been much higher and narrower in earlier times; he called it the "North volcano". The original crater rim of this volcano was breached at two places in particular, i.e. at Venus Bay and Concordia Bay. A second and smaller crater was formed inside the main one; Bergje would be one remnant of the rim of this smaller crater. Molengraaff also maintained that lava flows descended from the crater of Bergje into Venus Bay valley (now visible north of Venus Bay?) and in the direction of Concordia Bay (perhaps he had in mind the ridge between Wash Gut and Zeelandia).

The horseshoe-shaped ridge of Panga and Signal Hill, with its open side towards SSE, was believed by Molengraaff to be the northern remnant of the rim of a parasitic crater of the great "North volcano". The core of the crater rim at Signal Hill and Battery Amsterdam was found to consist of lava rocks (andesites), and the coastal cliff section of Panga of alternating beds of debris, andesites and tuffs.

Pilot Hill and the steep cliff coast between Tumble Down Dick Bay and Jenkins Bay were described as consisting of an irregularly stratified formation of agglomerates

* For the observations of W. Maclure (1817) and P. T. Cleve (1871), the reader is referred to Chapter I.

and tuffs, without any indication of lava flows. Former solfatara action near Jenkins Bay has transformed this formation into brittle, yellow or whitish material, with gypsum in fissures. Further north, at "Noordkaap" on Molengraaff's map, an old lava flow only a few feet wide was observed to have reached the sea. Agglomeratic deposits occur between "Noordkaap" and the lava rocks of 63.4, i.e. Molengraaff's "Heiligenbaai".

The rocks collected by Molengraaff were described by him predominantly as "augite-andesites". "Hornblende-augite-andesites" were found as dikes in the south-eastern part of Signal Hill.

K. Sapper (1903) has added little to Molengraaff's general description of the north-western volcanic hills. However, at Sugarhole (coastal cliff of Panga), he saw lava apophyses in agglomerates which Molengraaff described as alternating beds of andesites and tuffs. Sapper likewise considered the north-western portion of the island to be a complex of strongly denuded strato-volcanoes: "Ihre äussere Form ist aber so stark zerstört, dass man nur in wenigen Fällen, so bei dem Hügelrücken, der im Signal Hill gipfelt, noch eine Andeutung derselben wahrnimmt, sonst aber auf genaue Localisirung der alten Eruptionscentren verzichten muss."

In Sapper's publication of 1904 it was stated that in the north-western portion "die Eruptionscentren ziemlich zerstreut (sind) über das Inselareal". The author added: (pp. 49—50) "Da die rasch wirkende Abtragung die vorhandenen topographischen Gebilde sehr bald angreift und unter theilweiser Zerstörung umgestaltet, so ist man selbst in jenen Gebieten, wo entzückend schöne Aufschlüsse den Bau einzelner Inseltheile klarlegen (Westküste von S. Vincent, Nordwestküste von Statia), nicht im Stande, die Lage der Eruptionscentren genau festzulegen, sondern muss zufrieden sein, wenn man eine begründete Vermuthung für die ungefähre Lage aussprechen kann."

In another chapter of this publication ("Die Form der Antillen-vulcane") Sapper considered Signal Hill to be the only recognizable eruptive centre of the older volcanic formation.

Many years after publication of his doctoral thesis G. A. F. Molengraaff (1931) summarized his views as follows: (p. 720)

"The northwestern group consists of several strongly denuded hills of volcanic origin, of which the highest, called Boven, rises 294 m above sea-level.

The former centres of volcanic activity cannot with certainty be verified; an exception is made by the horseshoe-shaped ridge Panga, the southeastern part of which is called Signal Hill (234 m), which may be considered the remnant of a former active crater. These northwestern hills are built up by coarse ejectamenta alternating in several places with flows of andesitic lava, which are clearly visible in the precipitous wave-cut coast-cliffs. The prevailing rock is augite-andesite but in the lava of Signal Hill hornblende is as frequent a mineral as augite. At Sugarhole*, according to Sapper (1903) intrusions of andesite cut through the agglomerates."

Here, Molengraaff was clearly less certain about the location of the volcanic centres than he was in 1886, but he maintained his theory regarding the Panga ridge.

The short geological description of N.W. St. Eustatius by F. Hardy & G. Rodrigues (1947) reads as follows: "Basement rocks seem not to be represented nor exposed anywhere in Statia. The shape of the much-denuded old northern volcano can easily be reconstructed from the present topographical outlines. The remains of its crater are recognisable at Gilboa Hill and in the West-coast ridge. Two large lava flows emerge from North Hill; the first is directed northwards and the second eastwards. Other small cones of different ages, each having emergent lava flows, may also be traced in the north of Statia. The age of these volcanoes may tentatively be assigned to Pliocene."

---

* Molengraaff's publication erroneously calls this "Signal Hill".

Hardy & Rodrigues's statement that the original northern volcano can easily be reconstructed from the present features is, to a certain extent, true. Such a reconstruction, however, also encounters several difficulties.

The recent survey has indeed made it probable that the north-western hill complex is essentially the asymmetric remnant of one large strato-volcano whose crater was situated somewhere above the present hill of Bergje. The original volcano may have reached as high as 2,000′ (610 m) above sea level. In the course of centuries this volcano has been strongly denuded, and the authors believe that the more or less isolated hills, plateaux and ridges – Bergje, Boven, Gilboa Hill, Game Bow, Pisga, Mary Glory, Fory, Pilot Hill, Signal Hill, Panga and several smaller ones – are merely the remains of this volcano's lower portion. Its western extension appears to have been carried away entirely, hence its asymmetric shape (Plate 17).

Agglomerates and tuffs prevail over lava beds, but the solid lava rocks can be mapped in the field and on the aerial photographs more easily than the softer ejectamenta, since they are better preserved. Accordingly, the lava beds and intrusive bodies shown on the map probably constitute the majority of those actually outcropping. Over large areas the ejectamenta are hidden below hillside waste, products of weathering, and ash deposits from the Quill volcano. The outcrops of agglomerates and tuffs which could be mapped are shown on the map with figures and strike and dip symbols.

The tectonic position of some of the agglomerates and tuffs is not quite in accordance with the assumption that north-western St. Eustatius represents the remains of one huge volcano; their strikes and dips show, in fact, a marked deviation from the position they would be expected to have. Further data will be given below.

Bergje (732′; Plates 18 and 20) is presumed to be the remnant of the crater pipe of this north-western volcano. It has the characteristics of a composite volcanic neck, composed largely of pyroxene-andesites (localities 82, 103, 104) and to a lesser extent of agglomeratic deposits. The andesites show vertical prismatic jointing along the slopes of Bergje, and more or less horizontal and locally distinctly bent jointing near the top. Softer agglomeratic material among the andesites is indicated by the occurrence of some caves in the perpendicular north slope, and perhaps also by the depression on the hilltop.

Bergje is surrounded on its western side by a somma-shaped wall. At first sight one would be inclined to consider this to be an older crater wall within which a younger volcanic structure had been built up. Closer examination, however, reveals that this "somma" and the semicircular V-shaped valley separating it from the volcanic neck of Bergje are only the result of erosional forces.

The somma-shaped wall – whose inner side slopes 40° – consists largely of consolidated andesitic agglomerates (86) and tuffs. A few beds or dikes of pyroxene-andesite (76) alternate with or cut through the ejectamenta.

The strikes and dips of the tuffs and agglomerates in this area are little consistent with the assumed central position of the volcanic neck of Bergje. At locality 74 the beds strike N 40 E and dip 40° SE; the agglomerates of 77 dip steeply in a westward direction; the alternating agglomerates and andesite beds of 86 strike N 125 E and dip 30° NE; the coarse agglomerates of hill 139.1 have a dip of 20°–30° towards ENE.

The outer side of the somma-shaped wall is formed by the exceedingly steep and strongly eroded coastal cliff south of Jenkins Bay (Plates 18 and 22[a]).

The hill of Boven – the highest summit of the north-western hills: 964′ (Plates 19 and 21[a]) – shows several S–N to SW–NE trending andesite beds whose dips vary between N and NNE. They are supposed to be old lava flows which have descended in a northern and north-north-easterly direction from the former central crater (of whose pipe Bergje is thought to be the remnant). The banked pyroxene-andesite of the summit of Boven (locality 46) is 60 feet thick and dips 10° N. The rocks of 47, 49 and 50 are also andesites. The pyroxene-andesite bed of 87 (in the coastal cliff of Jenkins Bay) alternates with agglomerates; the whole series strikes N 130 E and dips slightly towards the east.

The fairly straight west coast of Boven has not been surveyed north of locality 87. It may be surmised from Molengraaff's description, and also from the aerial photographs, that here too agglomerates prevail over lava rocks, as is the case south of 87. Boven's east coast is characterized by several capes, bordering Boven Bay, Fontaan Bay and Venus Bay (Plates 19 and 21[b]). These capes consist of hard lava rocks, with prismatic jointing in places, and are former lava flows; agglomerates are found outcropping between them. The fine-grained agglomerates exposed north of Venus Bay have striking yellow and red colours, presumably as a result of former solfataric action.

The few outcrops noticed in the valley of Venus Bay are of pyroxene-hornblende-andesite (51), pyroxene-andesite (52) or agglomerates.

Gilboa Hill (574′–586′) has a structure which is somewhat similar to that of Boven. Beds of pyroxene-andesite (41, 91–94) follow directions varying between NNE and ENE, and it may be assumed that they are solidified lava flows which have descended from the former central crater in NE to ENE directions. Perhaps the outcrops of 41a, 42 and 93 belong to andesite dikes which cut squarely (N–S, NNE–SSW) through the older strata. The seaward bulge of Gilboa Hill consists of high cliffs of andesite with prominent vertical prismatic jointing. At locality 94 the lava rock shows a typical honeycomb structure owing to weathering. The andesite outcrops at point 38.9 have dips of 30° E and 60° NE; they are flanked on the west by agglomerates.

The divide between Venus Bay valley and Wash Gut is built up entirely of ejectamenta. At locality 43 coarse andesitic agglomerates with a reddish cement (N 50 E, steep) alternate with grey agglomerates; a steeply dipping, yellowish bed of consolidated tuff, less than one foot thick, cuts N–S through these grey agglomerates. Purple-grey andesitic agglomerates, alternating with thin, 8″-wide beds of yellow consolidated tuff, crop out at 44; the whole series appears to be sharply folded (strikes of N 40 E and N 30 W could be measured), while the axis of this miniature fold was found to be vertical! Somewhat similar, steeply dipping tuffs, striking N 30 W, are found nearby (45).

The steep, compressed appearance of these agglomerates and tuffs, which stratigraphically underlie the andesite beds of Gilboa Hill, may be explained by assuming that they belong to an older volcanic series.

The ridge immediately south of this series consists almost entirely of agglomerates. At locality 106, the highest point, a peculiar perpendicular wall is formed of coarse andesitic agglomeratic material. Somewhat lower down, coarse and fine agglomerates were found striking N–S, with a steep eastward dip (107). Farther east this ridge has outcrops of andesite beds alternating with agglomerates; the pyroxene-andesite at 109, overlying agglomerates, is estimated to be 75 feet thick.

Game Bow (105) consists of basaltic pyroxene-andesite in the form of either a lava bed or a dike. South-east of this elevation, basaltic pyroxene-andesite beds (98) and agglomeratic beds (97) were found outcropping.

The plateau of Little Mountains, south of Bergje, has but few outcrops. It would seem that this plateau consists largely of ejectamenta intruded by a number of lava dikes (pyroxene-andesite at 71, basaltic pyroxene-andesite at 102). Pisga (68), the low hill behind the house of Little Mountains, is probably also a dike (pyroxene-andesite).

The western part of the Little Mountains plateau is bounded by a steep slope down to the coast. The section of this coastal slope between Tumble Down Dick Bay and Negropath presents a very irregular profile of largely agglomerates and tuffs, with reddish-coloured spots here and there, and a few intercalated lava beds. Between Negropath and Jenkins Bay the almost perpendicular cliff consists practically entirely of agglomerates and tuffs; a dip of 30° southward could be measured in places. This cliff is the tangential section of the somma-shaped wall of Bergje. Westward lava flows appear to have been absent or rare in the early periods of the north-western volcano.

The west coast of northern St. Eustatius may in fact be largely coincident with a N–S fault zone. The portion of the old volcano to the west of this fault zone would seem to have been removed entirely by marine erosion (see also Chapters X and XI).

The southern rim of the Little Mountains Plateau is probably indicated by an andesite bed of great extent. A less prominent andesite flow has been observed from the sea; it outcrops somewhat lower down the slope to Tumble Down Dick Bay.

The hills of Mary Glory, Solitude, and Fory, stretching eastward into the "Cultuur vlakte", are also composed of alternating tuffs, agglomerates and andesite beds and dikes. Steep dips and strikes of agglomerates and tuffs can be noticed that do not seem to have any relationship with the presumed centre of early volcanism. At locality 67, for instance, the steeply dipping strata strike N 20 W. The nearby agglomerates along the path leading downslope and north-eastward (101) also have steep dips, and a possible strike of N 40 W. On the other hand, the steeply dipping andesitic crystal-tuff and agglomerates of 96 have a "normal" strike of N 30 E. The rocks of the culmination of Fory (100), mistaken in the field for sheet-jointed agglomerates, proved to be andesite when examined under the microscope.

The lava rocks of this area were determined as pyroxene-andesites (65, 67, 95, 100) and basaltic pyroxene-andesites (23, 84, 85).

The authors' survey of the horseshoe-shaped hill complex of Signal Hill – Cul de Sac – Panga – Pilot Hill has not convinced them of the correctness of Molengraaff's conception of a parasitic crater breached towards the south. Their objections will be set out below.

The strikes and dips of the agglomeratic, tuffaceous and andesitic beds are not consistent with the radial structure to be expected in such a small-sized local crater. The outcrops of ejectamenta have yielded the following measurements. Locality 63 shows reddish, consolidated andesitic agglomerates and tuffs* dipping 45° towards N 120 E, and agglomeratic beds of Panga's north slope dip 75° towards N 100 W. The coastal cliff section of Pilot Hill (26; Plate 22^{b}) consists of a series of alternating strata of semi-consolidated yellow tuff, partly containing rock fragments, and coarse andesitic agglomerates (with a yellow tuffaceous cement), dipping 10° towards N 100 W; the cliff is topped by a thick bed of andesite. The coastal cliff directly south of Pilot Hill consists largely of banked, irregular dipping, coarse agglomerates with some intercalated lava beds. At one point a dip of 25° SE has been measured. No dip could be measured for the andesitic crystal-tuff of locality 17.

As far as the lavas of the horseshoe complex are concerned, it may be remarked that the long, narrow, steep andesitic outcrops of Signal Hill do not seem to be normal outflows of a parasitic crater but rather are dike-shaped intrusions, comparable with Rittmann's "Radialgänge" (1960, pp. 146–149). Most of the rocks prove to be pyroxene-andesites (12–15, 19–22); one was found to be a basaltic pyroxene-andesite (11).** It is possible that the andesite of 21 (at the site of an old battery) has, or had, some connection with the andesite of 22 (top Signal Hill).

The culmination of Panga (59, 61) consists essentially of a roughly N–S directed pyroxene-andesite flow which can probably be followed as far south as and even beyond Fort Royale. The southern foot of Panga (Plate 23) is entirely built up of andesitic rocks showing prismatic jointing. This

---

* Molengraaff (1886, p. 18) describes this outcrop as "laterite" a few metres thick.

** The dikes in the SE portion of Signal Hill are described by Molengraaff (1886, p. 40) as "hornblende-augite-andesites": see Chapter IX.

lava flow may have originated near the centre of the old north-western volcano.

No particular conclusion can be drawn with respect to the outcrops of jointed pyroxene-andesite of localities 18 and 19 in the Panga valley, and those of the pyroxene-andesites (25, 27, 30) and basaltic pyroxene-andesites (29) further north-west.

Summarizing, it may be stated that the horseshoe-shaped Panga-Signal Hill complex is not a parasitic crater but the remnant of the southern foot of the great north-western volcano. Admittedly, this view is supported more convincingly by the position of the lava beds than by the dips of the agglomerates and tuffs.

The Quill volcano

Data from previous publications *

G. A. F. Molengraaff (1886, 1931) described the Quill volcano as one famous in the Caribbean area for its beautiful, regular, symmetrically shaped, truncated cone.

The narrow crater rim is almost circular, with a cross-section of approximately 2,400 feet in the direction E 8 N—W 8 S and a slightly longer cross-section in the direction N 2 W—S 2 E. The inner wall is very steep everywhere, nearly perpendicular in places, except in the western part, where a footpath descends from the lowest point of the rim into the crater (the slope here was measured as 34°—36°). The crater bottom is fairly level, but very uneven on account of the numerous blocks that have tumbled down from the crater wall. It may be assumed that earthquakes — which are a regular occurrence in St. Eustatius — are playing a great part in the gradual demolition of the crater rim. This is corroborated by Bisschop Grevelink's description of the earthquake of 8 February 1843, which apparently caused large pieces of rock to fall down into the crater from the eastern wall: (1846, p. 138) "... dat terwijl de schuddingen zeer nabij hunne grootste hevigheid genaderd waren, eensklaps een donderend geluid werd gehoord, komende van den rand des kraters, welke zich tegelijkertijd in een' wolk van stof hulde, veroorzaakt, zooals later bleek, door het afscheuren van verbazende rotsblokken, welke van den Oostelijken binnenwand in de diepte wentelden; ..."

Molengraaff (1886) described the crater rim as built up of apophyses and "brokwerk", i.e. piled-up blocks and fragments, cemented by loose agglomerates, largely consisting of "augite-andesite" and to a minor extent of "hornblende-augite-andesite". The latter rock has been found here and there as loose blocks in the tuffs of the eastern slope of the volcano. Molengraaff added that this hornblende-augite-andesite may be assumed to form dikes in the crater, although he did not observe them, perhaps on account of the inaccessibility of the inner wall and the dense vegetation (pp. 20, 40).

The numerous fissures in the inner wall of the crater were found to contain gypsum and occasionally some calcite, formed by solfataric action.

In Molengraaff's publication of 1931 the crater formation has been described very briefly: "The main crater consists of coarse ejectamenta; these are very large near the rim, where the crater wall consists of huge ejected blocks of augite-andesite, here and there also of hornblende-augite-andesite, but on the outside of the cone they quickly decrease in size."

---

* The general descriptions by W. Maclure (1817) and P. T. Cleve (1871) are referred to in Chapter I.

The outside of the volcano has the slope theoretically to be expected in the case of a cone built up of loose ejectamenta. Near the crater rim the slope — strewn with big blocks — varies between 35° and 40°, except at the lowest point of the rim (30°). Farther down, the angle decreases gradually and the ejectamenta become finer and finer. At a height of approximately 525′ the slope changes rather abruptly from 35°—30° to 20°—19°; this flexure coincides with the transition of lapilli into fine tuffs. In the east and west the slope decreases to 9°—7° and is cut off by a perpendicular coastal cliff, on an average 100 feet high. In the north-west, where the foot of the volcano merges into the agricultural plain, practically horizontal tuff layers are encountered.

Round Hill (500′), a small, slightly arched, semi-spherical "parasitical cone", is situated N 53°W of the centre of The Quill's crater, on the slope of the volcano. Round Hill's north-western slope lies at an angle of 21.5°, its south-eastern slope (opposite the volcano) at an angle of 8°. The underlying rocks are entirely covered by tuff and debris.

The south slope of the main volcano is interrupted by the gypsum-limestone slab of White Wall.

The tuff layers of the foot of the Quill volcano are built up principally of volcanic ash and, in addition, of bombs (both autoliths and xenoliths), lapilli and pumice. Molengraaff's views on the composition and origin of these strata are given here in his own words: (1931; pp. 728—729)

"The tuffs of the main volcano can be best studied in the steep cliffs near the coast. Near Oranjestad this cliff is about 42 m high. It is well stratified, thick horizontal layers of tuff being piled one on the other in very regular succession. Going from below upwards the layers decrease in thickness. Near the beach the average thickness is not less than 1.50 m and some of the layers there attain 2 m whereas in the upper portion of the cliff no layer is found thicker than 60—80 cm.

In each of the layers the component parts are arranged according to their specific gravity (stricto sensu the velocity they attained in the air falling down after having been violently ejected by the volcano); near the bottom more or less sharp-edged blocks of lava and rounded bombs are found with little ash in between, higher the blocks are of smaller size and the percentage of ash increases, still higher the layer consists almost solely of ash, whereas the top-portion of each layer again contains besides ash numerous smaller and larger pieces of pumice. In the lower layers exposed in the cliff exclusively white dacitic pumice is found apparently identical to that of Sugar Loaf and the White Wall: higher up dark-coloured pumice predominates over the white pumice.

In several of the layers near Oranjestad, principally in those occurring 4—15 m above sea level, ejected blocks of limestone are not rare. They contain remains of corals and shells which appeared to me to be identical with those found in the White Wall formation. If so, they are probably ejected by the main volcano during the eruption (or eruptions) which destroyed the submarine bank, a tilted portion of which now forms the White Wall.

The arrangement of the ejected material which is found repeated in several of the successive layers which I have examined might be explained in two ways.

(1) Each of the layers of tuff now visible in the coast-cliffs might represent a result of one total eruption of the main volcano; the arrangement might then be explained if we accept that each eruption commenced with the ejection of smaller and larger blocks of lava, bombs, and some xenoliths of limestone, besides ash; and terminated with the ejection of abundant fragments of pumice, and of ash. In this case the apparent arrangement after the specific gravity would be in reality a time-arrangement, the pumice indicating the final stage of the eruption.

(2) Each of the layers of tuff now visible in the coast-cliffs might represent the result of one single explosion during an eruptive period. In this case all the different fragments now found in one layer should have been ejected at the same time and should have been sorted by the differences in their velocities in the air.

This second explanation, although it would explain the very neat arrangement in the layers satisfactorily, is probably not permissible because the total amount of ejectamenta thrown out by one single explosion in that case would have been too enormous to be readily acceptable. From this explanation would also follow, that the main volcano with all its ejectamenta originated as the result of one single period of volcanic activity, during which also the submarine bank was destroyed, a tilted portion of which now forms the White Wall.
Doubtless a renewed study of the tuffs deposited by the main volcano will be of great interest and may give a clue to the solution of some still dubious points in the geological history of St. Eustatius."

K. Sapper (1903) made only a few remarks on the Quill volcano. He stated that the steep inner wall of the crater of this strato-volcano consists partly of coarse agglomerates, partly of solid rock ("theils aus festem Fels"). He appeared to be rather doubtful regarding Cleve's and Molengraaff's conception of Round Hill as a "parasitical cone", since it is entirely covered with younger debris.

In his publication of 1904 Sapper described The Quill as the Lesser Antilles' most regularly-built strato-volcano, with a well-preserved crater formerly called the Punch-bowl. He added the following data to Molengraaff's description of 1886: (p. 60) "So viel ist aber deutlich zu erkennen, dass auf der NO.-Seite die Böschung sanfter ist als auf der SW.-Seite und dass der eigentliche Vulcankegel sich noch ziemlich weithin gleichmässig unter dem Meeresniveau fortsetzt, bezw. sanft abflacht, dass also die relative Höhe des Berges am mindestens 200 m höher angesetzt werden muss, als seine Erhebung über dem Meeresspiegel angiebt."

The short description of The Quill by F. Hardy & G. Rodrigues (1947) offers no new viewpoints.

Recent field survey

The present authors largely agree with the data presented in the preceding paragraphs. Nevertheless, additional statements may be made, to correct certain descriptions and views given by Molengraaff (1886, 1931) and Sapper (1903, 1904), and complete the geological and geomorphological picture.

The crater of The Quill is densely wooded; its perpendicular inner walls cannot be studied at close range. No stratification is visible in these walls; it may be assumed that lava beds are absent there, notwithstanding Sapper's (rather vague) statement regarding the occurrence of solid rock. Although in Appendix VI (ideal section G—H) a single lava bed is tentatively indicated in the central portion of the volcano, the authors believe that the top, including the crater, the slopes and the foot of The Quill consist entirely of loose products, and consequently represent the ejectamenta stage (Plates 17, 24 and 25).

Several samples have been collected of the rocks outcropping on the crater rim and of the huge blocks which have tumbled down into the crater. The majority of these samples are pyroxene-andesites (Nos. 1, 4, 7, 121, 124) and basaltic pyroxene-andesites (9). Other blocks in the crater consist of andesitic tuff (4) or andesitic agglomerate (6).

These large blocks, presumably ejected by powerful eruptions in the later stages of the volcano's activity, were deposited on and near the crater rim. The finer material — small bombs, lapilli and ashes — settled mainly along the slopes and at the foot of the volcano. There is, however, a difference between the predominantly coarser type of ejectamenta in the southern, eastern and northern foot and the predominantly finer type in the western foot (see the descriptions below). No doubt this difference in material should be ascribed to the sorting effect of the eastern trade winds, which blew the finer products westward and north-westward.

Quill tuffs also occur in the north-western hills. Molengraaff (1886, p. 18) found that practically the whole north-western portion of St. Eustatius was covered with a fine and good soil derived from volcanic ash, mostly mixed with small lapilli and fragments of pumice, which he described as ejectamenta of the Quill volcano. The present authors observed a fine, whitish, non-consolidated Quill tuff to be widely distributed over the Little Mountains plateau, the area of Mary Glory, the low hill of locality 85 and the slopes of Signal Hill and Panga. Samples were collected at localities 16, 58, 60 (with lapilli) and 62. A possibility that these tuff pockets may be outcrops of older strata, such as the yellow, semi-consolidated tuffs of Pilot Hill (26), is contradicted by their heavy-mineral assemblage, which differs from that of the older strata but conforms very closely with the mineralogical picture of the tuffs of the Oranjestad cliff (Chapter IX).

The volcanic strata of The Quill have been examined in some detail in the following localities.

South slope of the Quill volcano (Plate 30b). Outcrops on the south slope show coarse agglomerates, dipping about 12° southward (Toby Gut; 53 and higher). A multicoloured series of light-brown, reddish-brown, light-grey and dark-grey agglomerates and other ejectamenta, some 250 feet thick, has been exposed by the landslide in the higher part of Big Gut. This series overlies White Wall sediments. Agglomerates can also be observed above the isolated patches of the White Wall formation at 33.

Coastal cliff of Compagnie's Bay (Plate 26a). The vertical section at 40 consists of the following, almost horizontal strata:
(from top to bottom)
6 feet of very coarse agglomerates, grey with a reddish tinge, containing breadcrust bombs (40g)
3 feet of red, fine agglomerate (40f)
13 feet of grey, fine agglomerate (40e)
13 feet of agglomerates containing breadcrust bombs (40d, c), alternating with three tuff layers (40b) not exceeding 1 foot in thickness
6 feet of coarse agglomerate, containing breadcrust bombs (40a).

Coastal cliff of eastern Schildpadden Bay. The strata of Schildpadden Bay are believed to be younger than those described from Compagnie's Bay. The beds of 116 and 117 dip 2°N, and their combined stratigraphic column may be roughly described as follows:
(from top to bottom)
10 feet of coarse agglomerate, containing breadcrust bombs (117a)
1,5 feet of tuff with lapilli (117b)
7 feet of medium-grained tuff, lapilli and bombs, including breadcrust bombs (117c, 116a)
1,5 feet of medium-grained tuff with thin layers (about 1 inch) of lapilli (116b)
5 feet of medium-grained tuff, lapilli and breadcrust bombs, some of which were estimated to have a volume of 35 cubic feet (116c).

Locality 118 is a cliff 10 feet in height, consisting of a coarse agglomerate with many breadcrust bombs. At 119 the cliff section, about 20 feet in thickness, is composed largely of tuffs with bombs.

Coastal cliff of western Schildpadden Bay (cf. Plate 27, Concordia Bay). It is quite likely that the practically horizontal series exposed at the cliff of 120 is slightly younger than the beds encountered in the eastern part of Schildpadden Bay. The agglomerate of 117a can perhaps be correlated with the agglomeratic bed between 120a and 120b. The following strata are briefly described:
(from top to bottom)
33 feet of a bedded series of tuffs with bombs and four intercalated thin layers of fine tuff
6 feet of well-bedded tuffs, alternating with thin layers of lapilli (120a)
6 feet of agglomerate, thinning out towards NW
10 feet of well-bedded tuffs, alternating with thin layers of lapilli (120b).

Outcrops at the roadside near Para Mira, north of Oranjestad. The total thickness of the horizontal strata at 113, 114 and 115, outcropping at the roadside, is approximately 12 feet:
(from top to bottom)
1,5 feet of coarse lapilli (113a)
1 foot of coarse tuff with fine lapilli (113b)
0,3 feet of lapilli (113c)
1 foot of coarse tuff with fine lapilli (113d)
3 feet of coarse lapilli (113e)
1 foot of coarse tuff with fine lapilli (113f)
1,5 feet of coarse lapilli (113g)
1,5 feet of fine and coarse, well-stratified tuffs (115h)
? feet of lapilli (115i).

Coastal cliff north-east of Oranjestad (Plate 23). A more or less continuous section has been measured and sampled at localities 111 and 112, in the curve of the road leading from Upper Town to Down Town on the beach. The strata are practically horizontal:
(from top to bottom)
1,5 feet of alternating beds of coarse lapilli and of small bombs; most of the bombs are pumice, others are andesites (111a)
1,5 feet of white, fine tuff with a coarser top layer of 4 inches (111b)
4 inches of tuff with lapilli (111c)
1 foot of white, coarse tuff with lapilli and small bombs (111d)
20 feet of well-bedded white tuff with lenses and thin layers (4 to 20 inches thick) of lapilli (111e)
30 feet of fine tuff layers alternating with strata and lenses chiefly of lapilli; the lapilli beds, particularly in the lower portion of the series, may be up to 6 feet in thickness (111f)
3,5 feet of coarse tuffaceous material, lapilli, and volcanic bombs with a maximum diameter of 2,5 feet (111g).

The authors did not succeed in finding fragments of limestone such as are described by Molengraaff as occurring in the beds of the Oranjestad cliff between 4 and 15 m above sea level and which he believed to have been ejected by the volcano after the partial destruction of the submarine bank now exposed as White Wall – Sugar Loaf. Fragments in the Molengraaff-collections at Delft have been re-examined (see section "White Wall formation") and were found to be more or less metamorphosed limestones in some of which fossils can be recognized. These limestone fragments may indeed be considered as identical with those found in the White Wall formation, which proves that eruptions of The Quill breached these sedimentary beds. *

Molengraaff has also drawn attention to the occurrence in the lower layers of the Oranjestad cliff of white dacitic pumice fragments apparently identical with the pumice of Sugar Loaf. The authors have examined pumice samples collected by Molengraaff in Sugar Loaf beds 4 (KB 4295) and 9 (KB 4284), and two pumice fragments from the said cliff (KB 4205 – M 223 and KB 4206 – M 229). There is some variance in the quantities of plagioclase, green hornblende and hypersthene minerals, and the Sugar Loaf samples are much richer in calcite (!) than the cliff fragments, but the identity need not be doubted. It is another argument for the breaching of the White Wall formation by Quill eruptions.

Examination of the various sections of Quill ejectamenta allows two statements to be made:

(a) The sorting effect of the eastern trade winds, mentioned in the first paragraph of p. 112, is very clearly illustrated by the ratio of coarser and finer ejectamenta in each section. The strata of the southern slope of the Quill volcano and those of Compagnie's Bay, north of the crater, consists of predominantly coarse and fine agglomerates, with tuff intercalations playing only a minor rôle. In the coastal cliff of Schildpadden Bay, further north-west, tuff and lapilli are much more prominent than at Compagnie's Bay, but agglomerates are also of common occurrence. The coastal section of Oranjestad, west of the crater, is built up mainly of tuffs and lapilli, while coarser material is subordinate.

(b) It is impossible to adopt Molengraaff's views on the succession of the strata and the arrangement of the component parts. Here and there, the Oranjestad cliff may give the impression that, going upwards in the section, the layers decrease in thickness, and that in some layers the coarser elements occur chiefly in the lower parts. In other localities of the cliff, however, the succession is different, while beds of coarse material are often found to be lens-shaped and therefore of limited extent (Plates 26^{b} and 27). Molengraaff's theories are likewise not supported by the sequence of beds in the sections along the north-east coast.

In conclusion it may be stated that Molengraaff's deductions on the decreasing activity of The Quill's eruptions (1886, p. 23), and his ideas on

---

* cf. Martin-Kaye's description of the low cliff on the shore below Brimstone Hill, St. Kitts (1959, p. 54): "The cliff exposures contain fragments of limestones very similar to those encountered on the flanks of Brimstone Hill." Martin-Kaye suggests that these cliff deposits "must have been laid down after the extrusion of the hill (by normal detrital processes) unless they were formed by some initial explosion before the piton was upthrust." There would seem to be another, more acceptable explanation, i.e. that the cliff section was built up by eruptions of Mt. Misery, which ejected normal volcanic products as well as fragments of the breached limestone formation part of which is now exposed on the flanks of Brimstone Hill. This explanation would also follow from Martin-Kaye's maps showing the coastal area near Brimstone Hill as "later tuffs, etc., of Mt. Misery" and "Mt. Misery pyroclastics".

the sorting of the ejectamenta during each eruption (1931, pp. 728–729), are debatable.

The Quill volcano has ejected a much greater number of breadcrust bombs than the north-western volcano and the Saba volcano. The single St. Eustatius specimen which has been petrographically examined differs from the type described from Martinique and Montserrat in that the interior groundmass is but only slightly porous (Lacroix 1904, p. 523; MacGregor 1938, p. 61; see also A. Lacroix, Remarques sur les matériaux de projection des volcans et sur la génèse des roches pyroclastiques qu'ils constituent, *Livre Jubilaire publié à l'occasion du Centenaire de la Société Géologique de France 1830–1930,* pp. 448–9).

The loose surface material of the typically dome-shaped Round Hill, on the north-west slope of The Quill, does not reveal the nature of this elevation (Plate 24; locality 10); fragments were found to be pyroxene-andesite, basaltic pyroxene-andesite and scoria. Round Hill is probably formed of slightly arched tuff layers pushed up by a relatively young volcanic plug which has not quite reached the surface (cf. the volcanic dome which is thought to occur below White Wall).

A most interesting rock fragment was found on the lower part of the east slope of The Quill, at 39a. It is a fairly coarse hornblende-diorite. A similar rock was found by Molengraaff (1886, p. 44) as a volcanic bomb on the south-east slope of Signal Hill; this "hornblende-andesite" appears to consist of fragments of hornblende-diorite cemented by pumice. These rocks, ejected by The Quill, suggest the existence of a dioritic body in the subsurface of St. Eustatius.

It is practically certain that no eruption has taken place in post-Columbian times since there are no active fumaroles and the crater bottom and crater rim carry a dense stand of fair- and large-sized trees. Nevertheless, the volcano is very young. It is true that the crater rim shows definite signs of demolition and collapse, probably largely owing to earthquakes; but the general shape of the volcano is beautifully preserved, and erosion gullies have not developed to any great extent. Judging from the state of preservation, the last eruption may perhaps be dated as post-Middle Holocene.

White Wall formation and its fossil contents, with notes on the Godwin Gut and Brimstone Hill limestones (St. Kitts) and the fossiliferous strata at Roche Bluff and Landing Bay (Montserrat)

Data from previous publications on the White Wall formation

In G. A. F. Molengraaff's doctoral thesis (1886) a separate chapter is devoted to White Wall (pp. 27—34). Molengraaff's findings were published in English in his treatise of 1931, with additional notes. Since the latter description is considered by the present authors to be fundamentally right, the text is reprinted below, practically unabridged and only slightly remodelled; a single footnote has been added.

The White Wall
(after G. A. F. Molengraaff 1931, pp. 722—728)

"On the south side of the island the regular form of the main volcano is interrupted by a high, dazzling white wall of limestone rising from the seashore at a steep angle and being visible miles and miles away. As early as the 18th century it was named on Dutch charts and plates the "Witte Hoek" (White Wall). This wall is cut off, as well on the east as on the west side, by a ravine and separated from the tuffs, which do not contain limestone. At a height of 212—270 m the wall of limestone terminates and on top of it at a height of about 320 m the same tuffs reappear, which are found all round the volcano. So this limestone formation is quite local and strictly limited to a small section in the southern slope of the main volcano. The peculiar and conspicuous position of the White Wall with regard to the main volcano of Statia is excellently shown in a sketch made by Davis in the year 1926, which is reproduced here in Fig. 8.

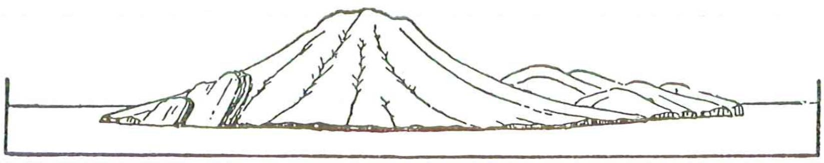


Fig. 8. A rough outline of St. Eustatius, as seen through hazy air from the north-west end of St. Kitts (after W. M. Davis 1926).
Sugar Loaf and White Wall rest in a sloping position against the south slope of the Quill volcano. On the right: the older, denuded volcanic landscape of north-west St. Eustatius.

On the west side of the White Wall stands at the shore a picturesque rock, 73 m high, possibly a faulted portion of the White Wall itself, named Sugar Loaf, which is connected with the White Wall by a narrow saddle (51 m). The stratification of the Sugar Loaf may be easily studied on its east side where an excellent section (Fig. 9) is exposed.

The strike of the strata of the Sugar Loaf is W 5 S, their dip is 42° south. The strike of the White Wall is near the Sugar Loaf also W 5 S, but going eastward deviates a little more towards the north. The dip of the lowest part of the White Wall coincides with that of the Sugar Loaf.

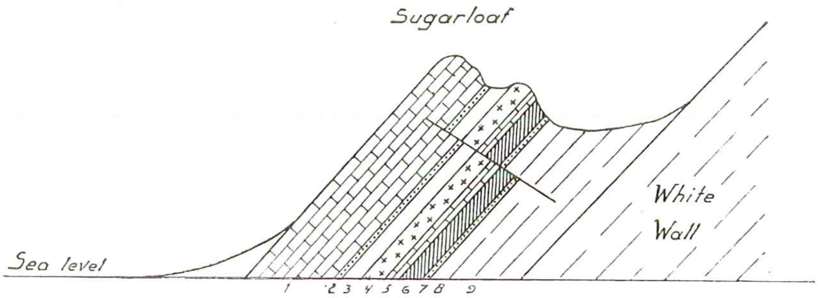


Fig. 9. Sketch of the strata visible in the eastern slope of Sugar Loaf 1885: 1. Coralrock; 2. Conglomerate with corals and shells; 3. Pumice tuff; 4. Dacite-pumice; 5. Coralrock; 6. Soft limestone with corals and shells; 7. Conglomerate with some shells and corals; 8. Yellowish tuff; 9. Whitish tuff.

In the before-mentioned section on the east side of Sugar Loaf the sequence of the strata from top to bottom is:

1. Coralrock with many shells.
2. Conglomerate, made of fragments of lava, tuff-breccia, and numerous corals and shells, with a partly calcareous, partly tufaceous cement.
3. White pumice tuff.
4. Pure dacitic pumice; this layer is 4 m thick.
5. Coralrock containing, besides corals, some shells.
6. Soft limestone, rich in corals and shells.
7. Conglomerate containing a few shells and corals.
8. Yellowish tuff with numerous small fragments of lava and pumice.
9. Whitish andesite-tuff rich in fragments of glass (vitric tuff); this tuff passes gradually into the overlying tuff 8.

The strata below 9 are not well exposed but for certain between layer 9 and the White Wall one more layer rich in corals occurs.

The upper stratum of the White Wall consists of a sheer wall of superficially black-stained coralrock dipping about 43° south. From 130 m upwards the coral-limestone is covered with some volcanic sand and ash.

Above Sugar Loaf the upper end of the sheer wall of coralrock, the proper White Wall (Fig. 8), is reached at a height of 212 m; towards the east this height becomes greater.

Above that altitude the dip diminishes and the formation is much faulted, tuff being exposed in most places underneath the cover of limestone (Sapper 1903, p. 317, fig. 2). At an altitude of about 270 m a broad saddle dipping southward is reached, which forms the divide between the two ravines, indicated on the topographical map as Big Gut and Soldier Gut, which limit the White Wall respectively to the west and the east. This saddle connects the White Wall with the southern slope of the main volcano. A stratified deposit of gypsum is formed here near the upper end of Big Gut and its origin is probably due to the action of a now extinct solfatara on the calcareous tuff and limestone of the White Wall formation.

In the ravine at the eastern end of the White Wall fossiliferous tuffs and coralrock are again found in abundance, but at the time of my visit the effects of mudflows caused by heavy rains, many huge blocks having slid down from above, prevented me from obtaining a clear insight into the stratigraphy.

The interior of the White Wall being then nowhere well exposed and accessible, the true relation between the White Wall and Sugar Loaf is still uncertain. Possibly Sugar Loaf is a portion of the White Wall itself, being pushed forward by faulting, or having slid downwards, as I have accepted formerly. If so the top-stratum of Sugar Loaf should be identical to the outer stratum of the White Wall. The complete conformability of the strata of Sugar Loaf to those of the White Wall is not favourable to this surmise, and it is equally possible that the strata exposed in Sugar Loaf must be regarded as belonging to a higher horizon than that of the White Wall, now almost entirely removed by erosion; in that case a section through the White Wall and Sugar Loaf should be a continuous one, the White Wall representing the lower portion and the Sugar Loaf the upper portion of the same continuous succession of strata.

This question must be regarded as an open one at present. At all events the attitude and structure of the entire formation as well as the position (Fig. 10) of the individual coral-colonies and the shells prove clearly that the strata have been originally laid down in a horizontal position and that later, after the deposition of the uppermost stratum of coralrock No. 1 in Sugar Loaf, the entire formation has been tilted as one huge slab to its present position, and at the same time has been disturbed, as is shown by the well marked small fault in Sugar Loaf and by the numerous faults found in the upper portion of the White Wall.

The direction of the present dip pointing away from the crater of the main volcano gives support to the surmise that the tilting was caused by one, or possibly more than one, eruption of the volcano.

The geological history of this part of the island would in that case have been the following.

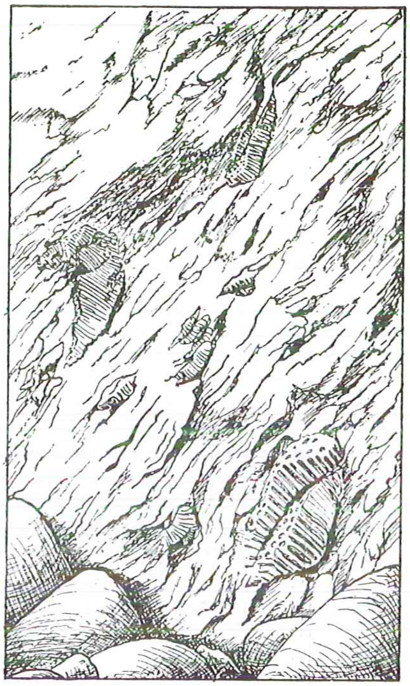


Fig. 10. Plate-like colonies of Montastrea which have been tilted from their original horizontal position together with the entire formation of Sugar Loaf.

A certain time after the northwestern group of volcanic hills had been formed and most probably its volcanic activity had come to an end, there existed to the south-east of this island a submarine shoal on which, in the shallow sea, mollusca and corals flourished. This shoal probably might be compared to the shoal on which corals and mollusca now prosper, which extends on the present day from the main volcano a certain distance towards the east. Every now and then the organic life on this submarine bank was temporarily destroyed by volcanic eruptions which covered the shoal with their ejectamenta which is clearly to be seen in the section at Sugar Loaf. Fragments of andesite, ash and dacite-pumice were nearly exclusively thrown out by these eruptions. The fact that in the tuff of the main volcano elsewhere on the island a similar pumice is of common occurrence, justifies the supposition, that the volcanic products of which the White Wall and Sugar Loaf are partly composed, have been thrown out by the main volcano. In this way a stratified formation was laid down, consisting partly of ejectamenta alone, partly of ejectamenta and limestone with shells and corals. The upper portion of this formation is now visible in the White Wall and Sugar Loaf. The entire formation originated probably during a period of slow subsidence, because it is reasonable to suppose, that the successive layers of coralrock in Sugar Loaf which now, in the stratigraphical column, are found at distances apart up to 48 m have been formed at about the same slight depth below sea level. Finally a violent paroxysmal eruption must have taken place, which probably gave rise to the greater part of the main volcano and its tuffs, at the same time lifting and tilting a gigantic slab of the above described, then still horizontal submarine White Wall formation to its present position.

Howsoever this may be, the existence of limestone and tuffs with corals and shells to the height of about 300 m above sea level in the White Wall must be considered a local phenomenon. It is erroneous to draw the conclusion that the whole island of Statia should have been uplifted in post-Pliocene time (Cleve and later Sapper and also Hovey came to this conclusion).

First of all upheaval of the entire island could not possibly explain the strong tilt of the strata of the White Wall and Sugar Loaf. Further, nowhere else on the island traces of upheaval of any importance are found. Some facts to which Sapper (1903, p. 318) and myself (1886, p. 31) have drawn the attention point to slight recent subsidence.

The first record about the White Wall appears to have been given by Maclure (1817). He evidently has visited the spot and his description is quoted by Cleve (1871) as follows: 'The whole of this marine deposition dips to the south-west, at an angle of upward of 45 degrees from the horizon, resting upon a bed of cinders, full of pumice and other volcanic rocks, and is immediately covered by a bed of madrepore, sand and cinders, mixed together, with blocks of volcanic rocks so disseminated that there can be no doubt of the volcanic origin of the substance above and below the madrepore rock, which may be from five to six hundred yards thick.'

Cleve, on his visit to Statia in 1869, has not studied the White Wall.

After my visit to the island in the year 1885 only one geologist, K. Sapper, has, as far as I know, visited the White Wall; this happened in the year 1903. Sapper then came to the conclusion that the sedimentary formation which forms the White Wall and Sugar Loaf had been deposited on a sloping substratum and that these layers from their very origin had been strongly inclined and that they were lifted to their present position by a general upheaval of the island. In the year 1905 Sapper explains this opinion more fully. The way in which the shells lie and the individual coral-colonies stand in the layers pleads against this conception. *

At my request, in the year 1917, Mr. G. J. van Grol, then governor of the island, had photographs taken showing distinctly the position of individual colonies of corals (Astraeidae) with plate-like growth parallel to the present attitude of the layers. Fig. 10 is a copy of a pen-drawing made by Professor Umbgrove at Delft from one of these photographs. After Sapper had seen these photographs he withdrew his opinion which differed from mine: 'Auf die Hebung eines Vulkansektors in junger geologischer Vorzeit hat G. A. F. Molengraaff hingewiesen. Es betrifft den White Wall am Vulkan The Quill am Südende der Insel Statia. Ich selbst hatte allerdings angenommen, dass in dem zwischen 2 tiefen radialen Barrancos gelegenen Gebiet Absatz des Gesteins auf steil geneigter Unterlage stattgefunden hätte; aber van Grols Nachweis, dass die Korallen senkrecht auf den jetzt geneigten Kalksteinen stehen, hat Molengraaff Recht gegeben.' (1927, p. 217).

---

* In his publication of 1905, pp. 184—190, Sapper maintains his view regarding the primary deposition of the steep limestone beds of Brimstone Hill and White Wall on a dipping substratum, contrary to the opinion of Spencer and Molengraaff: "Ich ... möchte deshalb auch das thatsächlich vorhandene ziemlich steile Einfallen nicht auf Rechnung einer plötzlichen Aufrichtung durch eine local wirkende vulkanische Kraft setzen, sondern sehe sie als natürliche Folge des Absatzes auf einer geneigten Unterlage an."

However, Sapper mentions a letter from Molengraaff (24 July 1903) in which the latter stated that, as far as he remembered, "einzelne Korallenstöcke der White Wall-Schichten, wo sie ganz waren, nicht vertical standen, sondern senkrecht zu den Schichtflächen."

In the year 1901 Spencer who, as far as I know, has not visited the White Wall himself, in his paper on the physical development of St. Kitts etc., compared the limestone formation of the White Wall with that of Brimstone Hill on St. Kitts. His opinion is that both Brimstone Hill and the White Wall originated from a local upheaval caused by volcanic activity. He concludes on p. 537: 'Owing to these two volcanic uplifts, the limestones which underlie the submerged coastal plains may be seen, for they appear nowhere else on these islands.'

Davis (1926), in his study on the Lesser Antilles, accepts my explanation and gives on page 58 the sketch reproduced in Fig. 8. He concludes: 'The huge inclined slabs of limestone, known as the "White Wall", in the shore of the cone, appear to have been lifted up from a preexistent submarine bank when the volcano was formed.'

Hovey (1925) states: 'Recent elevation of the island chain (of the Volcanic Caribbees) is evident. It is greatest at the north, beach conglomerates occurring at 1,500 feet on Statia, 1,000 feet on Guadeloupe, and at less elevation as one goes southward', without mentioning the facts on which this interpretation is based.

According to my opinion this view is not correct; recent elevation of the entire island of Statia has not taken place at all. Only local elevation, probably in Pleistocene time or possibly still later, took place at the White Wall, as a result of volcanic action of the main volcano.

The strata of the White Wall and Sugar Loaf are very rich in fossils. The state of conservation both of the corals and the mollusca is perfect and some of the shells found in the tuffs still show traces of their natural colours. I have given in 1886 a list of the mollusca (48 species) which I had collected compared with those (40 species) which Cleve had collected at Brimstone Hill on St. Kitts in the year 1869. There is an almost complete identity between the two faunas. All the species are still found living in the Caribbean Sea. Cleve (1871, p. 21) mentions one exception, a *Modiolaria* closely related to a northern, still living species. The corals have not yet been determined, and, my collection being small, the list gives only a faint idea of the richness of the fauna which is here preserved.

As to the age of this formation Cleve is of opinion that it is newest Pliocene, or post-Pliocene.

According to Spencer (1901, p. 537) the formation exposed in Brimstone Hill on St. Kitts (and in the White Wall on Statia) appears to correspond to the surface-marls of Sombrero, the upper marls of Anguilla, and those at the Usine of Pointe à Pitre in Guadeloupe. These have about the same thickness, contain a similar fauna, and are regarded as the equivalent of the Lafayette formation of the American continent belonging to the time about the close of the Pliocene Period.

I have taken the age to be post-Pliocene and the state of conservation of the fossils makes me incline to believe that a determination as late-Pleistocene or sub-Recent might be permissible.

The problem of the White Wall is not yet solved and fully deserves closer examination."

* * *

K. Sapper (1903) was the first to notice that the White Wall formation extends for a considerable distance west of White Wall proper: (pp. 317—318) "Unrichtig ist jedenfalls die Ansicht, dass der White Wall wie ein Sektor des Vulkankegels zwischen 2 tiefe Schluchten eingeschlossen wäre, denn man kann von unten aus die Kalkauflagerungen weit über die westliche Grenzschlucht nach Westen hin in ansehnlicher Höhe überm Meer (ca. 150 m) noch verfolgen."

Sapper also pointed out that the volcanic activity of the Quill volcano persisted after the (supposedly sloping) deposition of the White Wall beds, the faulting of the limestone and tuff beds, and the alleged sliding down of Sugar Loaf: "Dass die Abrutschung des Sugarloaf zu einer Zeit stattgefunden hatte, als die vulkanischen Ausbrüche noch lange fortdauerten, bemerkt man deutlich an den ziemlich mächtigen, von Molengraaff nicht besonders erwähnten Auflagerungen junger Tuffe am Südende des Sugarloaf."

In the eastern section of White Wall the dips vary considerably and are quite irregular, apparently — according to Sapper — largely owing to local movements; he observed minor folds and faults here. His sketch of the western section illustrates the many small faults which occur at about 150 m and complicate the southern dip.

Recent field survey. Stratigraphy, tectonics and lithology of the White Wall formation

White Wall and Sugar Loaf proper (Plates 17, 28–30)

Sections along the west side of White Wall (Big Gut), and along the western foot and the crest of Sugar Loaf, have been surveyed and sampled. Table 7 shows the simplified stratigraphy, in which samples from previous surveys (Molengraaff 1886, Westermann 1950) are also incorporated.

Field observations and examination of samples have convinced the authors that the strata of White Wall and Sugar Loaf form one continuous, conformable series. Sugar Loaf cannot therefore be considered as a portion of White Wall which was pushed forward by faulting and subsequently slid downwards (an assumption made by Molengraaff in 1886 but abandoned in 1931); it is merely the stratigraphically higher portion of the formation, reduced considerably by marine erosion owing to its exposed position.

The authors also agree with Molengraaff that the present position of the individual coral colonies in the limestone beds proves that the dip of the latter, in fact of the whole series of strata, is not a primary but a secondary one, caused by tilting.

The stratigraphic thickness is estimated at 150 m (500 feet) for White Wall, and at almost 50 m (150 feet) for Sugar Loaf, making a total of approximately 200 m (650 feet) for the whole uptilted formation. Its tectonic position is defined by the following strikes and dips:

White Wall, basal bed (No. 54 m)	N 70 E	50 S
ditto, upper layer (54 a)	N 85 E	45 S
ditto, top of hill (35)	N 90 E	40 S
Sugar Loaf	N 85 E	42–45 S

The photograph republished from Molengraaff's thesis (Plate 29) shows that the strike of the White Wall strata becomes more north-easterly at the eastern foot, near Soldier's Gut. Faulting has locally complicated the regular dip (Molengraaff 1886, 1931; Sapper 1903). Big Gut in the west and Soldier's Gut in the east roughly mark the N–S faults laterally bounding the upthrust slabs.

The top of White Wall (Nos. 35–38) consists of beds of limestone and fossiliferous tuff, alternating with dense masses of stratified gypsum. The boundary between the White Wall formation and the Quill agglomerates cannot be clearly defined here; in any case the sediments do not reach much higher than 270 m (880′).

		Nos. Molengraaff 1886, 1931	Nos. Westermann coll. 1950	Nos. Westermann & Kiel coll. 1958	Approximate position; stratigraphic thickness (3) or distance (—3) in metres		Lithology
SUGAR	↑		E 5		foot of outer slope		tuff, fossiliferous
	Wes-			31a	3		coquina
	tern	1	E 6	b	6		coral limestone
	foot		E 7	c	1		coquina and other limestone
			E 8, 9	d	4		coral limestone
	↓		E 10	e	5		coral limestone
	↑	2	E 11	55d	1½		conglomerate of volcanic material and fossil fragments
		3	E 12	c	3	max.	very fine-grained limestone
LOAF		4	E 13	b	4	50 m	pumice
		5	E 14	-	2		coral limestone
	crest	6		a	5		limestone
		7	E 15	31f	2		conglomeratic tuff, fossiliferous
		8		g	7		tuff with pumice fragments, without fossils
		9		h	7		calcareous and brecciated tuff, without fossils
	↓	'below 9'			—		tuff ?
on top of	saddle with			32	upper stratum		coral limestone
below	Sugar Loaf			56	upper stratum		coral limestone
	↑		E 17	54a	— 3		lithothamnium limestone
				b	—10		,,
WHITE				c	—13		,,
				d	—13		,,
				e	— 9		,,
	Big			f	— 1		,,
	Gut			g	— 7	max.	,,
WALL				h	— 7	150 m	,,
				i	—18		,,
				j	— 3		,,
			E 16*	k	—18		coquina
				l	—18		lithothamnium limestone
	↓			m	—30		tuff, without fossils

* A loose coquina sample in Big Gut possibly identical with 54k.

Outcrops west of White Wall

The observation by Sapper (1903), that the White Wall formation extends for a considerable distance west of White Wall proper, has been corroborated by the present authors. In the landslide section of the upper part of Big Gut, at a height of approximately 100 m (325′), calcareous strata can be observed below agglomerates of The Quill. Farther westward two outcrops can be seen in the slope of the volcano, at a height of 150–200 m (490–650′), where whitish, calcareous, bedded sediments underlie agglomeratic, volcanic strata (locality 33); their dip is estimated at 16° towards the south-east (Plates 28 and 30b). This locality has not been visited, but loose, transported limestone blocks of the outcrops were collected in Toby Gut (57).

Lithology

The lithology of the majority of the samples has been examined in thin sections by P. H. de Buisonjé, Geological Institute of the University of Amsterdam. In the following paragraphs the samples of the surveyed sections of White Wall and Sugar Loaf are listed in stratigraphic order (from top to bottom). The list also contains some scattered samples of the formation, including the metamorphosed and non-metamorphosed limestones found by Molengraaff in the tuffs of the coastal cliff near Oranjestad and believed to have been ejected by the Quill volcano.

Description

Subdivision by Molengraaff 1886, 1931	Survey by Westermann & Kiel 1958 Description by de Buisonjé
	Sugar Loaf
	31a White limestone (coquina) with many molluscs, calcareous algae* and Archaias; the texture is granular, the grains are equidimensional. In places, barite aggregates in cavities.
bed 1 — "Coral rock with many shells"	31b Coral limestone.
	31c Dark-spotted yellow limestone (partly coquina) with molluscs, calcareous algae, fragments of echinids, and Amphistegina. Volcanic fragments and magnetite.
	31d Coral limestone.
	31e Coral limestone.

* Although it is quite likely that *Lithothamnium* is the most important of the calcareous algae, the latter name is preferred. They are found as thin, long branches; incrustations; or rounded fragments. For the sake of simplicity, however, the name "Lithothamnium limestone" is used in Table 7.

bed 2 — "Conglomerate, made of fragments of lava, tuff-breccia, and numerous corals and shells, with a partly calcareous, partly tufaceous cement"	55d Dark-spotted, light-coloured conglomerate of volcanic material with fragments up to 1½ inches in diameter; calcareous cement. Many calcareous algae (rounded); fragments and spines of echinids, fragments of molluscs; many Amphistegina.
bed 3 — "White pumice tuff"	55c Dark-spotted, white, very fine-grained limestone, irregularly bedded; without recognizable fossils. Andesitic fragments and minerals (feldspar, pyroxene, magnetite) are common.
bed 4 — "Pure dacitic pumice"	55b Pumice, with vesicular and fluidal structure. Mainly volcanic glass; phenocrysts of labradorite, green hornblende and magnetite.
bed 5 — "Coral rock containing besides corals, some shells"	Coral limestone.
bed 6 — "Soft limestone, rich in corals and shells"	55a White limestone with fragments of coral, calcareous algae (incrustations), echinids and molluscs; Amphistegina, Homotrema and small foraminifera. Some volcanic rock fragments and minerals.
bed 7 — "Conglomerate containing a few shells and corals"	31f Dark-spotted yellow tuff with rounded rock fragments, feldspar, pyroxene and magnetite. Rich in fragments of calcareous algae; Amphistegina, Archaias.
bed 8 — "Yellowish tuff with numerous small fragments of lava and pumice"	31g Light-grey tuff with fragments of pumice (plagioclases, green hornblende, hypersthene, augite and magnetite in a groundmass of glass with vesicular and fluidal structure).
bed 9 — "Whitish andesite-tuff rich in fragments of glass (vitric tuff); this tuff passes gradually into the overlying tuff 8"	31h Grey, very fine-grained, thin-bedded, calcareous and tuffaceous sediment with plagioclase, hornblende and augite; rock fragments similar to those described under 31g. No fossils can be recognized.
below bed 9 — "not well exposed but for certain one more layer rich in corals occurs"	

White Wall
(upper stratum near saddle of Sugar Loaf)

"a sheer wall of superficially black-stained coral rock"	32 White dense limestone with corals, fragments of calcareous algae and molluscs, some spines of echinids; Homotrema, Amphistegina and small foraminifera.

White Wall
(Big Gut section)

54a White fine-grained limestone with fragments of calcareous algae, echinids and molluscs; Amphistegina, Archaias. In places, volcanic material and magnetite.

54b Grey-white, very fine-grained limestone with fragments of calcareous algae, molluscs and echinids; Archaias.

54c Black-spotted white limestone with fragments of calcareous algae and echinids; some Amphistegina. In places, volcanic material.

54d Black-spotted yellow to grey-white limestone with fragments of calcareous algae and echinids; Homotrema, Amphistegina, Globigerina and other small foraminifera.

54e Black-spotted yellow-white limestone with fragments of calcareous algae, molluscs and echinids; Homotrema, Amphistegina and Globigerina.

54f Black-spotted, yellow-white limestone with fragments of calcareous algae, molluscs and echinids; Homotrema, Amphistegina.

54g White granular limestone with fragments of calcareous algae, molluscs and echinids; Homotrema, Amphistegina.

54h Yellow-white, fine-grained limestone with fragments of calcareous algae, molluscs and echinids; Homotrema, Amphistegina, Archaias, and other small foraminifera.

54i Black-spotted granular limestone with fragments of calcareous algae and molluscs; Homotrema, Amphistegina. Much volcanic material, andesitic fragments.

54j Black-spotted, white, fine-grained limestone with fragments of calcareous algae; no other fossils. Volcanic material.

54k Grey coquina. Apart from the bivalves (in the case of some of which both valves have been preserved) there are fragments of calcareous algae and echinids; Homotrema, Amphistegina. Some volcanic material.

541 Grey-white, fine-grained limestone with fragments of calcareous algae and molluscs; a few Amphistegina. Some volcanic material.

54m Very fine-grained tuff with plagioclase, augite, hypersthene, green hornblende and magnetite crystals, a fair amount of quartz fragments, and some secondary calcite.

White Wall
(top of hill)

35 Yellow-white, very fine-grained and crumbly limestone with long (?) sponge needles; some feldspar and magnetite.
36 Gypsum.
37 Gypsum with very fine-grained limestone in the interstices.
38 Grey, very fine-grained tuff with a few fragments of echinids (spines) and molluscs. Very small fragments of feldspar, grains of magnetite and other minerals.

White Wall formation
(loose fragments in Toby Gut, transported from locality 33)

57 Brown dense limestone with fragments of calcareous algae and echinids; Homotrema, Amphistegina, small foraminifera. Some fragments of feldspar.

Coastal cliff near Oranjestad

5.7 m above sea level	Mol. 4209 4211 4212	Fine detrital limestone with fragments of calcareous algae, echinids and molluscs; Amphistegina common, Homotrema and smaller foraminifera. Volcanic material is absent.
ditto	Mol. 4213 4217 4219 4226 4227	Very hard, uneven-grained, mosaic-textured, recrystallized limestones (calcite-marbles). The outlines of Amphistegina and echinid spines can be noticed in 4217. Most of the samples contain some grains of magnetite.

Fossiliferous formations of St. Kitts and Montserrat

Lithologically and palaeontologically, the strata of White Wall and Sugar Loaf are very similar to the limestones outcropping in Godwin Gut and those thrust up by the dome of Brimstone Hill, St. Kitts (Trechmann 1932, Martin-Kaye 1959). There is also good evidence that they can be correlated with the fossiliferous strata found in a sloping position at Roche

Bluff and Landing Bay, Montserrat (MacGregor 1938). All three outcrops were visited by the authors in February–March 1958, and samples were collected. The lithology of these samples has been described by P. H. de Buisonjé.

In the following paragraphs the descriptions by Trechmann, Martin-Kaye and MacGregor are summarized, while the recently found data are added.

Limestones of Godwin Gut, St. Kitts

Martin-Kaye (1959, p. 52) has reported as follows on this formation: "The Godwin Gut limestone is nowhere particularly well exposed and its relations with the adjacent rocks cannot be seen. It appears to outcrop for some distance along the south-western side of the Middle Range at about 1,150 ft. above sea level. It is best exposed in Godwin itself where it is found in blocky masses of relatively soft, whitish or yellowish limestone containing occasional rather poorly preserved fossils including corals (*Montastrea annularis*). Associated with the limestones are massive white and grey streaked, tough silicified blocks."

The few samples (Nos. 38, 38a) collected by the present authors in March 1958 are grey-white limestones with many incrustations of calcareous algae, fragments and spines of echinids, Homotrema, Amphistegina and Globigerina. No. 38a contains the coral *Montastrea annularis*. See also Tables 8 and 9.

It is likely that the Godwin Gut limestones are of about the same age as those of Brimstone Hill, i.e. late Pleistocene. Their tectonic position is indistinct, but it may be surmised that the present occurrence on the flanks of the Middle Range, at an altitude of 1,150 feet, is due to volcanic uplift.

Limestones of Brimstone Hill, St. Kitts

Trechmann (1932) summarized the accounts of Brimstone Hill given by Cleve (1871), Spencer (1901), Sapper (1903) and Earle (1922, 1925). He also gave a rather detailed description of the dome and the various layers of upturned sedimentary rocks which occur around it on all sides except the north-east. From his long report, we would mention only that the series of limestone and ashy marl on the west side is estimated to be as much as 200 feet thick.

Trechmann's examination of the mollusc fauna led him to believe that their age would be Pliocene, possibly late Pliocene.

Martin-Kaye (1959, pp. 53–54) published the following characterization of the Brimstone Hill sediments:
"At points where suitable sections can be seen, particularly above the middle of the cane railway cutting, the succession in the upthrust beds consists of shaly ashes overlain by coarser-block volcanic breccias in turn overlain by limestone. At other points limestone appears to rest more or less directly on the andesite. – The shaly ashes are grey or red, apparently rather thinly bedded pulverent rocks inclined to be slightly fissile. –

Locally fossils may be collected from them. The thickness is uncertain. Most prominent of the flanking rocks and forming white scars round parts of the base and sides of the hill are the limestones. These have been broken into great blocky masses, sometimes almost on end and forming pinnacles a hundred feet or so in height. Generally, however, they possess radial dips in accord with the slopes of the hillside and at about 30°—40°. In the sections above the cane railway track the thickness is shown to be about 15 to 25 ft. Locally there is the appearance of considerably greater thickness, perhaps a hundred feet or more, particularly at the north-west part where the road to the top approaches the hill. The greater thickness here is probably due to repetition by faulting during uplift and/or gravity sliding back of higher over lower blocks after or during the uplift.
The limestones are typically white and marly or chalky, sometimes rather granular perhaps due to foraminifera. Fossils are abundant, often in a good state of preservation although fragile. Lamellibranchs with the two valves in position are commonly found, and apart from the foraminifera, molluscs form the most abundant fossils, although corals are locally frequent.
The age of the limestones has been placed by Trechmann as Pliocene, possibly late Pliocene, and by others as late Pliocene or early Pleistocene. The date of extrusion of the plug thus lies probably in the Pleistocene or possibly later."

Samples were collected by the authors in March 1958. The relative stratigraphic position of these samples in the steeply dipping limestone beds (Plate 32[a]) could not be ascertained. Stratigraphically they cannot be far apart, since the total thickness of the strata probably does not exceed 100 feet. Accordingly, the samples are listed in numerical and geographical order. Their localities are indicated on the basis of Martin-Kaye's map of Brimstone Hill (1959).

D e s c r i p t i o n

40 (NW part, 200 feet north of "quarries"). White limestone with some foraminifera and corals, and fragments of calcareous algae and echinids. Feldspar fragments.

41 (NW part, 150 feet south-east of "quarries"; strata striking S 30 E, dipping 72° W). White limestones with many fragments of calcareous algae and some fragments of corals, echinids and molluscs; few foraminifera.

42, 42b (W part, at point ← 33°; 42b probably underlies 42; strata striking approximately N—S, dipping 35° W). White to yellow limestones with foraminifera and some corals, fragments of calcareous algae, echinids and molluscs; well-preserved echinids in 42 have been determined by H. Engel as *Clypeaster rosaceus* and *C. subdepressus* (?). Some feldspar fragments in 42b.

42a (same locality as 42; position uncertain). Grey pumice with phenocrysts of plagioclase, augite, hypersthene and magnetite in a glassy, vesicular groundmass with fluidal structure.

43 (W part, at "uptilted & fractured white fossiliferous limestones"). Greyish-yellow limestones with foraminifera, corals, and fragments of calcareous algae, echinids and molluscs. Some rocks contain a few plagioclase fragments.

44 (SW part, just north of and inside triangular area marked "Agglom. & volc. ss."). A westward-dipping series (13 feet thick) of coral limestone with foraminifera overlies a series (13 feet) of volcanic agglomerates and breccia; the latter covers beds of reddish ash containing fragments of reddish, weathered pumice (phenocrysts of plagioclase, augite, hypersthene and magnetite in a vesicular glassy groundmass).

Fossiliferous strata at Roche Bluff and Landing Bay, Montserrat

The fossiliferous strata in the coastal cliffs 195 yards north-east of Sweeny's Well, Landing Bay, and north-north-westwards of Roche Bluff Point have been described by MacGregor (1938, pp. 22–23). The beds are uptilted and broken. Fossils were only found by him near Landing Bay and at the northern end of the outcrop beyond Roche Bluff Point; there were "broken masses of coral limestone, and highly tuffaceous limestones containing algae, foraminifera, spines of echinoderms, serpulae, lamellibranchs and ostracods".

The foraminifera and corals listed in MacGregor's publication have been included in Tables 8 and 9. Their age is believed to be not earlier than Pleistocene, on account of both the specific identifications and the state of preservation. All species are known as common forms now living in the shallow-water and coastal environments of the Caribbean area.

The first of the present two authors visited the coastal cliff of Landing Bay, north-east of Sweeny's Well (Plate 31) and collected a few samples (February 1958). The cliff appeared to consist of an uptilted series of yellow-white tuffaceous and agglomeratic limestones (Nos. 7–10) with a stratigraphic thickness of approximately 250 feet (striking N 115 E and dipping 60° north-eastward), overlain towards the north-east by strata of brown, coarse volcanic agglomerates and underlain towards the south-west by reddish-brown agglomerates. According to MacGregor (p. 23) the agglomerates of the north-eastern section were deposited by the South Soufrière Hill volcano after the upthrust of the limestones, and consequently cover them unconformably; the agglomerates immediately to the south-west, with a southerly dip of 75°, are thought by MacGregor to be separated from the limestones by a fault.

The samples of the fossiliferous series are listed here in stratigraphic order, from top to bottom.

Description

10 (north-east part of the cliff; highest bed; thickness 20 feet). Grey, calcareous agglomerate; fragments of pyroxene-hornblende-andesite with a glassy groundmass.

9 (bed 16 feet thick, stratigraphically directly below 10). Dark-spotted, yellow, fine-grained limestone with fragments of calcareous algae; Amphistegina, Archaias, Globigerina. Some magnetites.

8 (middle part of the cliff). Dark-spotted, yellow, fine-grained limestones with fragments of calcareous algae and echinids; Amphistegina and Globigerina. Magnetite grains are present in varying quantities.

7 (south-west part of the cliff; lowermost bed). Dark-spotted, yellowish limestone with many Amphistegina and some Globigerina. Magnetite grains.

Palaeontology, facies and chronology of the fossiliferous formations of St. Eustatius, St. Kitts and Montserrat

Palaeontology

The foraminifera have been studied by C. W. Drooger, Mineralogical and Geological Institute of the University of Utrecht; the corals by P. H. de Buisonjé and M. van den Boogaard, Geological Institute of the University of Amsterdam; the echinids by H. Engel (1961), Zoological Museum of the University of Amsterdam; and the molluscs by C. O. van Regteren Altena (1961), National Museum of Natural History, Leiden.

Reference is also made to the determinations of Montserrat foraminifera by C. D. Ovey, and corals by H. Dighton Thomas (MacGregor 1938).

The faunas of the three islands are, of course, not quite identical, but they are very closely related.

Foraminifera (Table 8a, b). Drooger has characterized the faunas as follows. Foraminifera are absent in several rock samples. When they occur, their state of preservation is mostly poor, which makes the smaller species difficult to recognize. The best preserved faunas are found in Sugar Loaf 31 f and 55 c and Brimstone Hill 43 II. *Amphistegina lessonii* is the dominant species and very characteristic in the high percentage of specimens, usually more than 50%, of the high, plano-convex variety (*mamillata* d'Orbigny). It may be assumed that *Amphistegina radiata,* as determined by Ovey for Montserrat, is a synonym of *A. lessonii.* In many samples *Archaias compressus,* often accompanied by other Peneroplidae, is also a prominent species; *A. aduncus,* as mentioned for Montserrat, is probably a variety of *A. compressus. Homotrema* sp. was found in several of the thin sections (De Buisonjé).

The foraminiferal faunas of the three islands have much in common. The associations are indicative of shallow tropical waters among coral reefs, or near such reefs, in which reef debris was deposited. Globigerinidae and more varied faunas would suggest an environment in the neighbourhood of open water. The unusually high frequency of the conical *Amphistegina* variety indicates uniformity of facies and perhaps synchronous deposition.

The age of the foraminiferal associations cannot be fixed with certainty, but their recent character suggests Quaternary, possibly latest Tertiary.

Ovey (in MacGregor 1938) gave the following characterization of the Montserrat fauna: "The assemblage, in which *Amphistegina radiata* is the predominating species, is typically of a tropical shallow-water nature. The fauna compares well with other records, both from Tertiary and recent rocks, of other authors from the West Indies and neighbourhood. It is not earlier than Miocene in age, and is in accord with a Pleistocene or Recent date for the containing deposits. Calcareous algae are also abundant."

O s t r a c o d s. Drooger found ostracods, including representatives of the genera *Bairdia*, *Loxoconcha* and *Cythereis* s.l., in samples Sugar Loaf 31 b, c, f and 55 c.

C o r a l s (Table 9). De Buisonjé and Van den Boogaard make the following remarks on the coral faunas of St. Eustatius and St. Kitts.

Acropora muricata (*cervicornis*) and *Manicina areolata* are quiet-water species. *Agaricia agaricitis* var. *purpurea*, *Dichocoenia stokesi* and *Meandrina maeandrites* are represented by specimens that grew in quiet water. The specimens of all five species have almost sound coralla. *Montastrea annularis*, *M. cavernosa* and *Diploria strigosa* are robust species that live in the surf zone on the outside of the reefs; of these three species the collection contains only coralla fragments. *

Sedimentation probably took place in quiet water, either in the deeper zones outside the reef, or in the lagoon inside the reef. The quiet-water corals have hardly been transported at all, or may even be "in situ", whereas the robust corals of the surf zone (of which only fragments are found) have been transported into the quiet-water environment.

All species are forms still living today in the Caribbean Sea.

The coral fauna of Montserrat is described by Dighton Thomas, in MacGregor 1938 **: "None of the broken coralla shows any indication of an area of attachment; but it is clear that, even if, before fossilization, they had become detached from their original position of growth, they could not have drifted far. All the species thus known as fossils from the island are common forms now living in the shallow water of the West Indies. The specimens from Montserrat would indicate that similar conditions prevailed during the formation of the coral-bearing limestones, the age of which, both from the specific identifications and the state of preservation of the fossils, would appear to be not earlier than Pleistocene."

E c h i n i d s. Well-preserved specimens of *Clypeaster rosaceus* and *C. subdepressus* (?) occur in sample 42 of the Brimstone Hill limestones; fragments in the collection of Molengraaff were probably found in the Sugar Loaf series (1885). *Paraster eustatii* nov. spec. was described from a coquina of the upper layer of Sugar Loaf: 31 a or c (Engel 1961).

The occurrence of the *Clypeaster* species does not contradict the Pleistocene age indicated by the other faunas.

---

* The specimen of *Acropora palmata* from Molengraaff's collection has a sound coralla, although the species is typical of the surf zone of the reef. It may be that this specimen is not fossil but recent.

** Dighton Thomas also mentions the few coral species collected by K. W. Earle in 1923 "at Sweeny's Bay, Roche's"; among them were found *Diploria clivosa* (Ellis & Solander), as well as *Montastrea annularis* and *M. cavernosa* (syn. *Phyllocoenia* (*Orbicella*) *annularis* and *P.* (*O.*) *cavernosa*). They have not been incorporated in the table, since their locality is uncertain.

Determinations by C. W. Drooger

Nos. E: collection Westermann, 1950

Nos. 31a, etc.: collection Westermann & Kiel, 1958

• = few specimens

● = frequent or abundant

Locality	No. E	No.	*Amphistegina lessonii* d'Orbigny	*Archaias compressus* (d'Orbigny)	*Asterigerina carinata* d'Orbigny	*Cibicides cora* (d'Orbigny)	*Cibicides pseudoungerianus* (Cushman)	*Discorbis floridana* Cushman	*Elphidium owenianum* (d'Orbigny)	*Eponides antillarum* (d'Orbigny)	*Eponides repandus* (Fichtel & Moll)	*Globigerina* sp.
St. Eustatius, *Sugar Loaf*												
	E 5		•									
		31a		•								
		b	●	•								
		c	●							•	•	
	E 8	d-e	●	•					•			
	E 11	55d	●	•								
		c	●									
	E 14		•						•			
		a	•									•
	E 15	31f	●	●	●	•	•	•		•	•	•
White Wall												
		32	•									
		54a	●	•								
		b		•								
		c	●									
		d, e	•									•
		f, g	•									
		h	•	•								•
		i, k	•									
		l	•									
White Wall formation above Toby Gut												
		57	•									

Table 8a. Distribution of foraminifera

						●					*Globigerinoides conglobata* (Brady)
						●					*Globigerinoides cyclostoma* (Galloway & Wissler)
						●					*Globigerinoides triloba* (Reuss)
						●					*Globorotalia menardii* (d'Orbigny)
						●					*Gypsina vesicularis* (Parker & Jones)
						●					*Hanzawaia concentrica* (Cushman)
						●					*Heterostegina antillarum* d'Orbigny
●	●	●	●	●	●		●				*Homotrema* sp.
		●					●				*Miliolidae*
						●					*Miliolinella fichteliana* (d'Orbigny)
						●					*Nonion formosum* (Seguenza)
						●					*Planulina ariminensis* d'Orbigny
						⬤			●		*Quinqueloculina lamarckiana* d'Orbigny
						●					*Quinqueloculina tricarinata* d'Orbigny
										●	*Rotalia rosea* d'Orbigny
						●		●			*Siphonina reticulata* (Czjzek)
						●					*Textularia candeiana* d'Orbigny
						●					*Triloculina tricarinata* d'Orbigny
										●	*Valvulineria bradyi* Brotzen

in the sediments of St. Eustatius

Determinations by C. W. Drooger, and C. D. Ovey (in MacGregor 1938)

Nos. K: collection Westermann, 1950

Nos. M: MacGregor (1938)

Nos. 38, etc.: collection Westermann & Kiel, 1958

● = few specimens

⬤ = frequent or abundant

Locality	Sample	*Amphistegina lessonii* d'Orbigny	*Amphistegina radiata* (Fichtel & Moll)	*Anomalina* cf. *ammonoides* (Reuss)	*Archaias aduncus* (Fichtel & Moll)	*Archaias compressus* (d'Orbigny)	*Archaias* sp.	*Asterigerina carinata* d'Orbigny	*Biloculina* cf. *subsphaerica* d'Orbigny	*Bolivina pulchella* (d'Orbigny)	*Cassidulina laevigata* d'Orbigny
ST. KITTS, *Godwin Gut*	38, 38a	●									
Brimstone Hill	40										
	K 1,2 41	●						●		●	
	42	●				●		●			
	b	●				⬤					
	43	●									
	43(I)	⬤									
	(II)	●				⬤		●			
	44	●				●					
MONTSERRAT, *Cliff 195 yards NE of Sweeny's Well, Landing Bay*	10	●									
	9	●					●				
	8a	⬤									
	b	⬤									
	7	⬤									●
	M 149		⬤				●		●		
	M 150		⬤	●			●				
	M 151						●				
Cliff 1500 yards NW along coast from Roche Bluff	M 162		⬤					●			
	M 165		⬤								
	M 194		⬤		●						
	M 196		⬤				●				

Table 8b. Distribution of foraminifera

Dentalina cf. *communis* (d'Orbigny)							●											
Elphidium discoidale (d'Orbigny)											●	●						
Elphidium poeyanum (d'Orbigny)											●	●						
Globigerina dubia Egger			●															
Globigerina bulloides d'Orbigny				●	●	●												
Globigerina sp.		●				●	●		●	●			●			●	●	●
Globigerinoides triloba (Reuss)								●			●							
Globorotalia sp.				●		●												
Gypsina vesicularis (Parker & Jones)													●					
Homotrema sp.																		●
Miliolidae				●		●		●			●		●	●	●			
Nonion cf. *depressulus* (Walker & Jacob)						●												
Operculina venosa (Fichtel & Moll)	●			●		●	●											
Peneroplis sp.						●									●			
Planorbulina mediterranensis d'Orbigny						●												
Quinqueloculina lamarckiana d'Orbigny												●						
Quinqueloculina seminula (Linnaeus)							●											
Textularia sagittula Defrance		●				●												
Triloculina tricarinata d'Orbigny						●												
Tretomphalus bulloides (d'Orbigny)																●		

in the sediments of St. Kitts and Montserrat

Determinations by P. H. de Buisonjé & M. van den Boogaard, and H. Dighton Thomas (in MacGregor 1938) Nos. 31b, etc.: collection Westermann & Kiel, 1958 Mol. bed 1, 5: Molengraaff 1886, 1931 Nos. M. 161, etc.: Lit. MacGregor 1938 Earle & Spencer: Lit. Earle 1922, 1925 (locality unknown)	*Acropora muricata* (Linnaeus) (*cervicornis*)	*Acropora palmata* (Lamarck)	*Agaricia agaricites* (L.) var. *purpurea* Le Sueur	*Colpophyllia natans* (Müller)	*Dichocoenia stokesi* (M. Edwards & Haime)	*Diploria labyrinthiformis* (Linnaeus)	*Diploria strigosa* (Dana)	*Isophyllia sinuosa* (Ellis & Solander)	*Madracis decactis* (Lyman)	*Manicina areolata* (Linnaeus)	*Meandrina maeandrites* (Linnaeus)	*Montastrea annularis* (Ellis & Solander)	*Montastrea cavernosa* (Linnaeus)	*Porites astreoides* Lamarck	*Siderastrea siderea* (Ellis & Solander)	*Solenastraea hyades* (Dana)	*Stephanocoenia intersepta* (Esper)	*Stephanocoenia michelini* (M. Edwards & Haime)
St. Eustatius, *Sugar Loaf*																		
Mol. bed 1	X	X			X					X		X	X		X			
31b					X				X		X	X	X					
c								X										X
d—e					X		X			X	X	X						X
Mol. bed 5											X							X
55a			X		X							X	X		X			X
White Wall																		
32			X				X					X						
56			X		X		X					X			X			
St. Kitts, *Godwin Gut*																		
38a												X						
Brimstone Hill																		
Earle & Spencer												X	X		X		X	
40												X						
42												X						
43				X	X					X		X	X					X
44												X		X				
Montserrat, *Cliff 1,500 yards NW along coast from Roche Bluff*																		
M 161					X													
163																	X	
164																X		
192						X												
193													X					
195												X						

Table 9. Distribution of corals in the sediments of St. Eustatius, St. Kitts and Montserrat

M o l l u s c s. Van Regteren Altena's publication (1961) gives a detailed account of the mollusc fauna of the White Wall formation and the Brimstone Hill limestones. According to him there can be no doubt that the molluscs lived in shallow water, probably near the coast.

The fauna of the upper beds of Sugar Loaf is believed by Van Regteren Altena to be probably of Pleistocene age, but nothing can be said about Molengraaff's layer 3 and older strata, including White Wall. The molluscs of Brimstone Hill are also probably Pleistocene, though possibly somewhat older than the upper beds of Sugar Loaf.

F a c i e s

Lithology and fossil faunas of the four sediment series are clearly indicative of a tropical shallow-water environment, near the coast, presumably in the relatively quiet zone just outside the coral reefs or in the reef lagoon. It may be assumed that these coastal environments were connected with the Pleistocene island volcanoes of St. Eustatius, St. Kitts and Montserrat, and, therefore, were separated by stretches of deeper water.

G e o l o g i c a l a n d a b s o l u t e c h r o n o l o g y

All faunas point towards a Pleistocene age of the sediments. This is corroborated by the radiocarbon dating of coral specimens, in the Physical Laboratory, University of Groningen:

Sugar Loaf	31b :	21,850 ± 100	years
Sugar Loaf	55a :	>49,000	years
White Wall	32 :	32,640 ± 300	years
Brimstone Hill	42 :	44,400 ± 1,200	years.

The datings of Sugar Loaf 31b and the top layer of White Wall (32) are quite acceptable, if it is borne in mind that these beds are separated by a sediment series almost 50 metres (some 150 feet) thick. However, the dating of Sugar Loaf 55a, situated between the two other samples, is anomalous. It may be that the coral specimen of 55a has been redeposited from older beds, but White Wall appears to be almost coral-free.

If it is assumed that a series 150 feet thick was deposited at Sugar Loaf between approximately 33,000 and 22,000 years ago, hence over a period of about 11,000 years (an average rate of sedimentation of one foot in slightly more than 70 years), the whole White Wall — Sugar Loaf complex of about 200 metres (650 feet) thickness may have been formed in some 45,000—50,000 years. From this it would follow that sedimentation of the entire White Wall formation took place between approximately 70,000 and 21,000 years ago.

The Brimstone Hill coral sample is somewhat older than those of Sugar Loaf, and is comparable in age to the middle section of the White Wall formation.

Since the Pleistocene period extends from not more than 1,000,000 to about 10,000 years ago, it is clear that the White Wall formation, the Brimstone Hill limestones, and probably also the Godwin Gut limestones and the fossiliferous strata in Montserrat, all belong to the late Pleistocene.

Origin, deposition and uplift of the White Wall formation

The largely organogenic sediments of the uptilted beds of White Wall and Sugar Loaf, and in nearby smaller outcrops, are believed to have been deposited in the shallow sea bordering the partly denuded north-western volcano, either in a lagoon fringed by coral reefs or just outside these reefs.

The fairly monotonous Lithothamnium-limestone series of *White Wall proper* (stratigraphic thickness of about 150 m i.e. almost 500 feet) has been formed in a marine environment too deep for coral growth; fragments of calcareous algae, echinids and molluscs are common, besides Amphistegina, Archaias, Homotrema and other foraminifera. Most of the samples contain some volcanic rock fragments and angular minerals, among which green hornblende is conspicuous (Table 10). Since hornblende is very rare in the rocks of the north-western volcano but occurs regularly in the ejectamenta of The Quill, it may be assumed that deposition of the limestones took place simultaneously with eruptions of the latter volcano. The tuff outcrop of 54 m, underlying the limestone series, is also thought to be a Quill product. *

The above assumption raises the question whether the distance between the site of White Wall and the vent of The Quill is too small for an undisturbed sedimentation of limestones in the immediate neighbourhood of this active volcano. ** It would seem that deposition of organic sediments could have taken place only during very early, probably submarine, activity of the volcano, when the volcanic material was ejected partly in the air, partly in the water. The finer fragments and, in particular, the minerals must have been suspended in the water for a considerable time before settling on the bottom, together with the organic material. However, the possibility should not be excluded that part of the volcanic material in the White Wall limestones (but not the hornblendes!) are erosion products from the older, already extinct north-western volcano. Accordingly, the White Wall formation is supposed to have been deposited after the north-western volcano ceased its activity and during the initial submarine volcanism of The Quill. In 1926 Davis expressed

* Quartz fragments, although very subordinate, occur throughout the series but have not been found in the Quill tuffs. Their origin is questionable.

** There is a possibility, of course, that the centre of the early submarine eruptions lay at some distance from the present crater pipe and further away from White Wall.

a somewhat similar view, stating that probably "the younger volcano was built up on a bank of calcareous deposits that had already been formed in association with the older volcano" (p. 51).

An analogous conclusion has been drawn by Davis (1926, p. 55) and Trechmann (1932, p. 245) with regard to the age relations between the Brimstone Hill limestones and the volcanic formations of St. Kitts.

Davis remarked that, as in the case of St. Eustatius, a bank had been formed in association with the older volcanic remnants before the younger volcanoes were built; as the bank is continuous over the island-free stretch between the younger parts of St. Eustatius and St. Kitts, he thought it probable that it is based there on several completely submerged volcanic masses.

Trechmann's opinion was as follows: "The view that the sedimentaries (of Brimstone Hill) are a late beach formation does not appeal to me; they seem to be older even than the main volcano of the island, but probably newer than the old volcanic accumulations at the south end of St. Kitts. It is difficult to imagine the massive white chalks and limestones to have been deposited round the edges of a very active volcano, but volcanic activity had already commenced, as the calcareous tuffs near the intrusion, and also to a less extent the white chalks, contain broken chips of glassy and other volcanic fragments." (It may be added that De Buisonjé found plagioclases in the limestones).

The stratigraphically highest bed of White Wall (32, 56) is very similar to the underlying Lithothamnium limestones except that it also contains corals. This proves that – either because of accumulation of sediments or because of a relative lowering of the sea level with regard to the land – the coastal environment had become sufficiently shallow for coral growth.

The *Sugar Loaf series* – about 50 m or 150 feet thick – is a normal succession on top of the White Wall strata and shows a great diversity in lithology (Table 7). There is a conspicuous alternation of volcanic beds, both fossiliferous and non-fossiliferous (tuffs, conglomerates, pumice), and various kinds of limestones, including coral limestones and coquinas. In the lower part of the series the volcanic beds prevail over the organic sediments, whereas in the upper strata the reverse condition obtains.

Most of the organogenic sediments contain volcanic rock fragments and minerals. Table 10 shows that green hornblende is dominant amongst the ferromagnesian minerals, proving that eruptions of the young Quill volcano proceeded simultaneously with sedimentation of the limestones, the latter taking place in a shallow-water environment (coral growth).

The deposition of the various kinds of tuffs must have been largely submarine, in view of the fact that several of them contain fossils. The deposition of the non-fossiliferous volcanic beds may have been either subaerial or submarine, but it should be borne in mind that the lack of fossils does not necessarily exclude submarine sedimentation, since strong eruptions could easily have destroyed marine life. Hence, it is difficult to draw conclusions pertaining to relative sea level movements on the basis of lithology.

There is, however, one layer in Sugar Loaf which indicates that subaerial deposition took place at any rate for a short period: the solid and homogeneous pumice bed, some 4 m (13 feet) thick, in the middle of the series. Since hornblende is the predominant ferromagnesian mineral, it may be assumed that the pumice is a Quill product. Molengraaff (1886) came to the conclusion that this pumice is a true lava bed of the Quill volcano and not an accumulation of pumice ejectamenta. However, in 1931 Molengraaff had abandoned the idea of a pumice lava, and wrote only of ejectamenta of dacite-pumice. The present authors are of the opinion that the solid character of the pumice bed is strongly suggestive of a lava flow, rather than of an accumulation of pumice fragments subsequently cemented together. The low specific gravity of the pumice excludes submarine deposition, and it is assumed that a gas-rich lava has flowed over strata temporarily emergent above sea level. At that time the top of the young Quill volcano must also have been above sea level. This emergent stage of the volcano did not last long, as is proved by the organic sediments overlying the pumice.

According to De Buisonjé, the coquina of sample 31a may have been deposited at about sea level. The tuff containing Amphistegina, found at the foot of Sugar Loaf, is the youngest outcropping bed of the series.

Molengraaff (1931) was of the opinion that the entire White Wall formation originated during a period of slow subsidence. However, the nature of the sediments gives no indication of a relative rise of the sea level with regard to the land throughout the period of deposition. Probably this deposition was largely a gradual filling-up of a coastal environment.

Nevertheless, it would seem inevitable that the sedimentation of the White Wall formation should have been accompanied by sea level oscillations which occurred repeatedly in late Pleistocene time, chiefly on account of the variations in glaciation during the last Glacial stage. The tentative correlations presented by Flint (1957) in his table 23-B (stratigraphic units and events in Europe and Central North America since the last major Interglacial) suggest a glaciation period between approximately 60,000 and 40,000 years ago, an interstadial between 40,000 and 30,000, and another glacial maximum (the "last major glaciation") after about 30,000 years and before 18,000 years ago. * As the deposition of the White Wall formation is thought to have taken place between 70,000 and 21,000 years ago, it is reasonable to assume that at least two major falls and one rise of the sea level occurred during this period.

---

* In this respect it is interesting that results obtained from pollen analyses and radiocarbon datings of lake and peat-bog sections in the Eastern Cordillera of Colombia led to the conclusion that the climatic phases of the Holocene and the Würm glaciation of equatorial South America and of Europe are perfectly synchronous (Th. van der Hammen & E. Gonzalez in *Leidse Geol. Meded. 25,* 1960, p. 261, and *Geologie en Mijnbouw 39,* 1960, p. 737).

After deposition of the youngest stratum of Sugar Loaf, some 21,000 years ago, the eruptions of the Quill volcano appear to have become more voluminous, interrupting the sedimentation of limestone beds and rapidly building up a cone above sea level, covering the horizontal, organogenic series with agglomeratic and tuffaceous beds. The rise of a volcanic plug or dome, presumably in the middle of the Holocene, has subsequently lifted a fault-bounded portion of the White Wall formation and the overlying volcanic strata; it is probable that the latter, being of an incoherent nature, slid down the tilted limestone largely through gravitational force, while the remaining material was subsequently washed into the sea by rainwater. * Hence, the original White Wall formation has become exposed as two dip-sloping slabs the larger of which rests against the present south slope of The Quill. A few isolated outcrops are also found in the slope of this volcano some distance towards the west (see also Chapter X).

* Molengraaff (1886, 1931) noticed that, from 130 m upwards, the upper stratum of White Wall proper is covered by some volcanic sand and ash. It is likely that this is erosion material from the higher parts of The Quill.

CHAPTER IX

PETROGRAPHY

PREVIOUS PETROGRAPHIC DESCRIPTIONS

G. A. F. MOLENGRAAFF (1886) has given detailed petrographic descriptions of the rocks collected by him. Some of his data will be referred to in the following sections. He has also published some chemical analyses (see below).

The rocks collected in 1841 by CH. SAINTE-CLAIRE DEVILLE were called "labradorites" by A. LACROIX (1890, p. 73). The latter found "enclaves" of quartz in these rocks, similar to the quartzes in the Saba rocks. * Lacroix's publication of 1926 contains the chemical analysis of a "dacitoïde" whose locality is not indicated.

K. SAPPER (1904) has listed the following rocks of St. Eustatius:

Augite-andesite	White Wall, Signal Hill	A. Bergeat and G. A. F. Molengraaff
Augite-andesite (rich in tridymite, and olivine-bearing)	The Quill	Bergeat
Hornblende-andesite	Signal Hill	Molengraaff
Hypersthene-augite-andesite	loose rocks on the beach; fragments in the tuff of The Quill	Molengraaff
Hornblende-pyroxene-andesite (with chemical analysis)	Signal Hill	Molengraaff
Dacite-pumice (with chemical analysis)	Sugar Loaf	Molengraaff

PETROGRAPHY OF THE MAGMATIC ROCKS

General classification

Microscopic examination of magmatic rocks of St. Eustatius by Molengraaff and the present authors has led to the establishment of the following groups:

MOLENGRAAFF (1886)	WESTERMANN & KIEL
Augite-andesites and hypersthene-augite-andesites	Pyroxene-andesites and basaltic (olivine-bearing) pyroxene-andesites
Hornblende-augite-andesites	Pyroxene-hornblende-andesite and basaltic (olivine-bearing) pyroxene-hornblende-andesites
Hornblende-andesite	Hornblende-diorite
	Scoriae
Pumice	Pumice

* Neither Molengraaff nor the present authors have noticed quartz phenocrysts or xenocrysts in the rocks of St. Eustatius.

Some remarks on the nomenclature

In Chapter V it was concluded that the name "andesite" appears to be more appropriate for the rocks of Saba than the terminology used by, for instance, Lacroix (1890, 1926). The majority of the St. Eustatius lava rocks are also described as "andesites", following Molengraaff (1886).

Chemical analyses (Table 1)

The andesites of St. Eustatius have silica percentages varying between 53 and 60.5, hence within the range established for the Lesser Antilles by Lacroix (1926). The Quill andesite was found to have the lowest content, that of the volcanic neck of Bergje the highest. The calcium figures of the andesites are relatively high; the Na_2O and K_2O percentages are much lower.

The composition of the dacite pumice of Sugar Loaf (analysis No. 9), with almost 70% SiO_2 and a low calcium content, differs notably from that of the andesites.

General petrographic characteristics of the andesites

The andesites of St. Eustatius have many characteristics in common; these are briefly described below. The petrographic terminology is the same as that used in the chapter on the petrography of Saba.

Texture

All andesites have a porphyritic or glomeroporphyritic texture.

Phenocrysts

Feldspar

Feldspar is the dominant phenocryst; it occurs only as plagioclase. The shape varies between rectangular and equidimensional; lath-shaped crystals are common. Oscillatory zoning is frequently found.

Several plagioclases in each thin section have rounded edges and spongy cores; the internal sponginess in due to minute glass inclusions and is often bound to certain zones (see also Molengraaff 1886, pp. 36 *, 43). Many phenocrysts also contain isolated cavities with colourless or brownish glass and small inclusions of pyroxenes and iron ore.

The composition of the plagioclase phenocrysts, estimated approximately by measuring extinction angles, proved to be intermediate: andesite-labradorite. The average anorthite content of the phenocrysts in about forty pyroxene-andesites without olivine is 51; the same percentage was found in eight olivine-bearing pyroxene-andesites. Molengraaff (pp. 35, 40) con-

* Molengraaff considered the extraordinary richness in glass inclusions to be a typical feature of the plagioclases of the St. Eustatius andesites. We know now that plagioclases with spongy cores are also very common in lava rocks of nearby islands: Saba, St. Kitts, Nevis, Montserrat.

cluded that oligoclase and labradorite were most common. According to him, anorthite is not rare but plays an important rôle only in an "augite-andesite" which outcrops near the entrance of the Quill crater; albite was not encountered.

A u g i t e

Augite phenocrysts are present in practically all andesites. Several crystals show twinning. In the thin section of an olivine-bearing pyroxene-andesite bomb from the coastal cliff of Compagnie's Bay (40a III), augite occurs as a core with a rim of hypersthene. Many augites are surrounded by a black or brownish rim of very small iron oxide grains, or have been partly or completely altered into a black opacite mass (Molengraaff, plate III, figs. 4, 5 and 6).

H y p e r s t h e n e

Hypersthene phenocrysts occur in most of the andesites in numbers about equal to or smaller than those of the augites. Hence, the name "pyroxene-andesites" is preferred to "augite-andesites". *

In a number of rocks hypersthenes can be seen that show oblique extinction, with angles of about 10°. The oblique extinction is found in sections whose normal on the slide is in the vicinity of one or both optic axes; these sections show a lower birefrigence than those with straight extinction.

Pleochroism of the hypersthenes is not very distinctive: in the sections with straight extinction the colours change from pale green to yellow or pinkish. Twinning has been noticed in several crystals. As is also the case with augites the hypersthenes often have black, brown and reddish-brown rims of iron oxide.

In several rocks hypersthenes can be observed as cores surrounded by augite; here the hypersthene (which is known to be a high-pressure mineral) reacted with the magma and was transformed along the periphery into augite (a low-pressure mineral).

H o r n b l e n d e

Hornblende has been noticed in very few andesites: by Molengraaff in what he called "hornblende-augite-andesites", and by the present authors in a pyroxene-hornblende-andesite collected at locality 51 (outcrop near Venus Bay), a volcanic bomb in the coastal cliff of Compagnie's Bay, and a breadcrust bomb in the coastal cliff of Oranjestad (40a III and 111: basaltic (olivine-bearing) pyroxene-hornblende-andesites). No. 40a II, a

* It is not clear why Molengraaff found no hypersthene in the majority of the andesites which he classed as "augite-andesites" and considered to be the most common lava rock of St. Eustatius. Hypersthene has been described by Molengraaff only in the "hypersthene-augite-andesites" found as loose fragments in the tuffs of the Quill volcano, particularly on the north-western slopes.

pyroxene-andesite bomb from the same cliff, should probably also be placed in this group (see below).

The hornblende is brown-green or green hornblende, with a distinctive but not very strong pleochroism from brown-green to pale green. Several crystals show twinning.

The phenocrysts are often surrounded by a narrow, black rim of "opacite".

"Pyroxenic" and (rare) "black" types, alteration products of hornblende, occur in the andesites of 40a III and 111; some of the "pyroxenic" pseudomorphs contain remnants of hornblende. Similar pseudomorphs, but without remnants of hornblende, are found in the andesite bomb 40a II; consequently, this rock is tentatively classed as a pyroxene-hornblende-andesite.

Olivine

Olivine phenocrysts occur in a number of pyroxene-andesites, which accordingly have been named basaltic pyroxene-andesites. The olivines are usually corroded and altered into secondary minerals (serpentinized). In some rocks a brown alteration mineral, probably iddingsite, has been noticed. Coronas of minute pyroxene crystals, and rims of iron ore, are common features.

Iron ore

Grains and crystals of black iron ore (magnetite, titano-magnetite) are present in all andesites. Where oxidation has taken place, brownish colours have replaced black.

Apatite

Apatite can be seen in some andesites as inclusions in plagioclases and augites.

Groundmass

In the andesites with a microcrystalline groundmass the texture is predominantly intergranular to pilotaxitic. Intersertal textures (i.e. with glassy material in the interspaces) are less commonly found, and often in conjunction with the above-mentioned textures: pyroxene-andesites of localities 6, 7, 21, 39b; olivine-bearing pyroxene-andesites of 98 and 102. A vitrophyric groundmass of brown glass, spotted with minute plagioclases, ferromagnesian minerals and iron ore, occurs in the olivine-bearing pyroxene-hornblende-andesite found as a volcanic bomb in the coastal cliff of Compagnie's Bay (40a III). In a breadcrust bomb of the Oranjestad cliff (111) the groundmass is intersertal to vitrophyric, and slightly vesicular.

The type of groundmass with intergranular to pilotaxitic texture consists of minute plagioclase laths or microlites (anorthite percentage slightly lower than that of the phenocrysts), granular or prismatic pyroxenes (mostly augites, less frequently hypersthene), and black grains and crystals of iron ore; the iron ore specks may occur in great abundance. In some andesites the groundmass has a dusty appearance.

Some andesites have a cryptocrystalline groundmass in which plagioclases, pyroxenes and iron ore can be recognized.

Secondary minerals, such as iron oxide, calcite, chalcedony, chlorite, zeolite and titanium-bearing minerals, occur in places. Tridymite has been noticed as a secondary mineral in cavities and fissures in several olivine-bearing and olivine-free andesites.

Autoliths (cognate inclusions)

Autoliths are rare in the St. Eustatius andesites. The inclusion found in a pyroxene-andesite bomb from the coastal cliff of Compagnie's Bay (40a II) is very similar to the enclosing rock, except that it is finer-grained. The autolith in the olivine-bearing pyroxene-hornblende-andesite bomb from the same locality (40a III) is an olivine-bearing augite-andesite with intersertal groundmass.

List of microscopically examined magmatic rocks, arranged according to petrographic groups and volcanic formations

The five main petrographic groups are

I	Pyroxene-andesites, including Molengraaff's augite-andesites and hypersthene-augite-andesites.
II	Basaltic (olivine-bearing) pyroxene-andesites, including Molengraaff's augite-andesites.
III	Pyroxene-hornblende-andesite, basaltic (olivine-bearing) pyroxene-hornblende-andesite, and Molengraaff's hornblende-augite-andesites.
IV	Hornblende-diorite and Molengraaff's hornblende-andesite.
V	Scoriae.
VI	Pumice.

In each petrographic group the rocks have been classed under the volcanic formation to which they belong:

North-western volcanic hills,
The Quill volcano,
White Wall formation.

I Pyroxene-andesites

Molengraaff's "augite-andesites" have been described as the commonest magmatic rocks of the island: the proper element of all formations except White Wall and part of Signal Hill. The "hypersthene-augite-andesites" were found by him as loose fragments in the tuffs of the Quill volcano, particularly on the south-western slopes.

North-western volcanic hills

All the following andesites probably belong to lava flows and dikes:
Nos. 12—15, 19—22, 25, 27, 30, 41, 42, 46, 49, 52, 59, 61, 65, 67, 68, 71, 76, 87, 91, 92, 94, 95, 100, 103, 104, 109.

In the field some of these andesites have been mistaken for sheet-jointed, consolidated agglomerates: 20, near Signal Hill; 67, near Mary Glory; 100, Fory.

The two rocks examined from locality 100 have a porphyritic texture, and are very rich in plagioclase phenocrysts, several of which are merely crystal fragments and splinters. The pyroxenes have reddish brown rims; the cryptocrystalline groundmass, showing many microlites, is also reddish brown, and turbid.

The Quill volcano

There are no characteristic differences between the pyroxene-andesites of the north-western volcanic hills and those of the Quill volcano, notwithstanding the fact that the latter are loose fragments and blocks, or bombs, in volcanic agglomerates.

Nos. 1, 4, 7, 121 and 124 have been collected in the bottom and on the rim of the crater; 10 at Round Hill, and 39b on the eastern slope of the volcano.

II Basaltic (olivine-bearing) pyroxene-andesites

North-western volcanic hills

The olivine-bearing pyroxene-andesites have been collected from lava flows and dikes: 11, 23, 29, 84, 85, 98, 102, 105. They occur less frequently than the olivine-free pyroxene-andesites.

The Quill volcano

The olivine-bearing pyroxene-andesites of the Quill volcano are very similar to those of the north-western volcanic hills. They have been collected as loose fragments or bombs on the crater rim (9) and at Round Hill (10).

III Pyroxene-hornblende-andesite and basaltic (olivine-bearing) pyroxene-hornblende-andesite

Hornblende-bearing andesites are very rare in St. Eustatius, and the establishment of a separate group would not seem justified if Molengraaff had not distinguished a group of "hornblende-augite-andesites" among the rocks collected by him.

North-western volcanic hills

The authors collected only one andesite that can be called a pyroxene-hornblende andesite: 51, an outcrop of lava blocks near Venus Bay. The brown-green, slightly pleochroic hornblende phenocrysts are subordinate; the groundmass is pilotaxitic.

North-western volcanic hills and the Quill volcano

The presence of "hornblende-augite-andesites" (without olivine) has been described by Molengraaff as follows (translated from the Dutch text, p. 40): The hornblende-bearing augite-andesites occur on St. Eustatius only subordinately. Rock formations of these andesites are found only in the eastern part of the horseshoe-shaped Signal Hill crater, where wide, massive dikes of it cut through the augite-andesite mass. Loose fragments of this rock are also found here and there in the tuff of the main volcano, in particular along the eastern slope. It is probable that this andesite forms dikes in the crater of the main volcano, but they have not been observed.

Molengraaff also published a chemical analysis of the Signal Hill andesite.

The present authors did not succeed in obtaining thin sections of Molengraaff's "hornblende-augite-andesites". But they have examined nine andesites occurring as dikes in the Signal Hill massif (11—15 and 19—22), and also three andesites collected by Molengraaff on the south-east slope of Signal Hill. In none of these was hornblende encountered; hence, Molengraaff's determinations may not be correct.

The Quill volcano

There are two volcanic bombs collected in the coastal cliff at Compagnie's Bay (40a II, 40a III), and a breadcrust bomb from the coastal cliff of Oranjestad (111), which can be assigned to Group III.

No. 40a III is a basaltic pyroxene-hornblende-andesite. It contains olivine, subordinate green hornblende, and pseudomorphs of the latter mineral; the groundmass is vitrophyric. The olivine-bearing autolith in this andesite has an intersertal texture.

No. 40a II lacks olivine and hornblende, but the "black" types and the, less common, "pyroxenic" types are probably pseudomorphs of hornblende.

No. 111 is a basaltic pyroxene-hornblende-andesite. It contains olivine, (rarely) green hornblende, and pseudomorphs; the groundmass is partly microcrystalline, partly glassy. Macroscopically there is a clear distinction between the dark-grey crust with radial cracks and the light-coloured, somewhat porous-looking interior. Under the microscope the groundmass of the crust portion appears to contain brown glass, whereas the interior has colourless glass. Vesicles are rare in both portions; they can be observed more easily in the crust than in the interior.

IV Hornblende-diorite

Some volcanic bombs and fragments, presumably ejected by *the Quill volcano*, have proved to be diorites.

Molengraaff collected such a bomb on the south-eastern slope of Signal Hill; he called it a "hornblende-andesite" (p. 44). A second thin section was made from this bomb and examined by the authors. The rock consists almost wholly of large crystals of plagioclase, green hornblende, augite and magnetite; it has a holocrystalline, hypidiomorphic texture, except for a matrix occurring here and there in thin zones and interstices between the large crystals.

The plagioclases contain glass inclusions and hornblende fragments. The hornblendes, often twinned, are strongly pleochroic from pale yellow-green to dark olive-green. Augite crystals and grains are less abundant and occur partly as inclusions in hornblende.

The matrix, consisting of a yellowish or brownish glass with microlites of plagioclase and small hornblende prisms, is partly porous and — according to Molengraaff — has a pumiceous appearance.

On the eastern slope of The Quill (39a) the present authors found a rock fragment which in many ways resembles Molengraaff's "hornblende-andesite" bomb from Signal Hill. It is a true hornblende-diorite with a hypidiomorphic-granular texture, consisting of large subhedral crystals of intermediate plagioclase; euhedral or subhedral crystals of green, pleochroic hornblende; and some grains and crystals of black iron ore.

It may perhaps be assumed that Molengraaff's "hornblende-andesite" and the hornblende-diorite are essentially the same rocks, except for the thin zones of matrix in the former. The "hornblende-andesite" consists of diorite fragments ejected by the Quill volcano and cemented by lava which, during and after the eruption, consolidated into a semi-glassy matrix.

The diorite fragments may be considered parts of an older, deep-seated rock formation. The gabbroic inclusions in scoriae from Round Hill (locality 10) probably have the same origin.

V Scoriae

Two types of scoriae have been found: a basaltic (olivine-bearing) hornblende-pyroxene-scoria, and a scoria with gabbroic inclusions.

The basaltic (olivine-bearing) hornblende-pyroxene-scoria has been collected as a volcanic bomb in the coastal cliff at Compagnie's Bay (40a I). Its phenocrysts are intermediate plagioclase, green, twinned hornblende, augite, hypersthene with and without rim of augite, subordinate olivine with rim of pyroxene, and black iron ore. The groundmass is an extremely vesicular, brown glass with microlites of plagioclase, ferromagnesian minerals and iron ore. The rock contains an autolith of augite-hornblende-andesite with an intersertal texture.

The scoria 10(3) from Round Hill is an extremely vesicular, brown to black volcanic glass with microlites of plagioclase; this groundmass encloses fragments of a gabbroic rock consisting of basic plagioclase, augite, olivine and, subordinately, green hornblende.

VI Pumice

Molengraaff described the following kinds of pumice (translated from the Dutch text, p. 47):

Pumice occurs throughout the whole island, but is much more abundant in the tuffs of the main volcano than in the northern hill country. Two types can be clearly distinguished.

A. Augite-andesite pumice.

The chemical composition is the same as that of the augite-andesites. It is found both in the northern hilly country and in the upper tuff strata of the main volcano. The colour is light brown. The pumice is rich in preformed crystals of augite, plagioclase and magnetite. In the tuff, many transitional types between this pumice and the augite-andesite lava proper were found.

B. Dacite pumice.

The chemical composition of a fragment of the dacite pumice of the White Wall formation is given in Table 1. This type of pumice is restricted to the tuff strata of the main volcano which are situated more than 15 metres below the surface, and to a compact bed in Sugar Loaf approximately 4 metres thick. It is pure white in colour, has a finely fibrous structure and can be easily distinguished macroscopically from the andesite pumice.

Microscopically, this pumice is an almost colourless glass with numerous large and small gas bubbles, all of which extend in the same direction. Porphyritic crystals of plagioclase, hornblende and augite are subordinate.

Petrographic conclusions

The lava rocks of the older north-western volcanic hills and the younger Quill volcano are very similar. The majority of them can be classed as olivine-free or olivine-bearing pyroxene-andesites. The andesites with olivine occur less frequently than those without olivine.

Hornblende has been found by the present authors in only one thin section of rock (51) from the north-western volcanic hills. The description by Molengraaff of "hornblende-augite-andesite" dikes in Signal Hill could not be corroborated.

In the rocks of the Quill volcano hornblende has been found only in a few volcanic bombs; it is of the green variety.

Hornblende appears to be a common mineral in an older diorite and gabbroic formation underlying the Quill volcano, as is indicated by the fragments ejected by one or more eruptions of this volcano.

Lamprobolites are absent in the thin sections examined microscopically. The same is true of quartz phenocrysts or xenocrysts. Autoliths have rarely been noticed.

The andesites of Saba and St. Eustatius differ mainly in the occurrence and frequency of the following minerals and inclusions:

	Saba	St. Eustatius
hornblende	very common	rare
lamprobolite	very common	absent
pseudomorphs of hornblende	very common	rare
quartz phenocrysts (or xenocrysts)	common	absent
autoliths	common	rare

Petrography of some pyroclastic rocks

A small number of pyroclastic rocks have been examined in thin sections under the microscope.

North-western volcanic hills

17. Andesitic crystal-tuff, SW slope of Signal Hill, consisting of crystals and fragments of plagioclase, augite, and iron ore, and glass fragments.

96. Andesitic crystal-tuff, W of Zeelandia, consisting of plagioclases and pyroxenes in a glassy matrix; secondary lamelliform ilmenite crystals.

26, 43, 44 (1, 2), 63, 83, 86, 106. Andesitic agglomerates, consisting of varicoloured, strongly weathered and decomposed, angular and subangular fragments of porphyritic pyroxene-andesites, cemented by a glassy matrix containing crystals of plagioclase, pyroxene (mostly augite) and iron ore, and locally weathered and chloritized (26).

The Quill volcano

4 (1). Andesitic tuff, crater bottom, consisting of a very fine, dusty matrix of plagioclase, augite, glass fragments and iron ore, more or less in parallel arrangement.

6. Andesitic agglomerate, western inner slope of the crater, consisting of weathered fragments of pyroxene-andesites, cemented by a matrix of brownish and reddish-brown, fine glass tuff.

For the sake of completeness an English translation of Molengraaff's description of the Quill tuff is added (1886, p. 48): It consists mainly of glass splinters, small fragments of feldspar and augite crystals, and magnetite grains. Hornblende and hypersthene fragments are rare. The material is very fine-grained, and all crystals are incomplete. The colour of the tuffs varies between light and dark grey; the light-grey tuff is richest in glass splinters and fragments of pumice.

Mineralogical analysis

The samples were treated and counted in the same way as those of Saba. Table 10 shows the frequency of hornblende (green and brown), augite and hypersthene in pyroclastic rocks and organogenic sediments of the three geological and volcanic units.

Agglomerates and tuffs of the north-western volcano. With the exception of Cul de Sac sample No. 63 hornblendes are lacking, the heavy mineral content consisting practically entirely of augites and hypersthenes. The steeply dipping strata from the upper Wash Gut are characterized by a predominance of augite; this may or may not indicate that they belong to a separate and older (?) volcanic unit. No. 63 shows no hornblende in thin section; nevertheless, this mineral was found to be more frequent than pyroxenes. Secondary epidote is another mineral of this strongly weathered rock. Small percentages of green and "basaltic" hornblende were found in *soil* samples (H. Kiel, in Veenenbos 1955, table 17).

Tuffs and organic sediments of White Wall – Sugar Loaf. High percentages of green hornblende, and the occurrence of some quartzes, are characteristic of this formation. The percentages of the pyroxenes vary greatly; in the pumice of 55b pyroxenes appear to be absent.

Agglomerates and tuffs of the Quill volcano. The heavy mineral assemblages of the Quill pyroclastics resemble those of White Wall – Sugar Loaf. But the hornblende figures are much lower, the pyroxene percentages accordingly higher, and quartzes are practically absent. There is little variation in the pyroxene percentages. Epidote, a secondary mineral, has been noticed in 117c and 120a, b. In 120a heavy minerals are rare; the rock fragments consist of nearly colourless volcanic glass with some microlites. In *soil* samples from the Quill volcano green, brown and "basaltic" hornblende occur in small percentages, the green variety being more frequent than the other two.

Sand beaches of Oranjestad and Concordia Bay. These beaches are conspicuous for their locally high content of black titaniferous magnetite and ilmenite. A rough sand analysis made in 1933 gave the following figures: magnetite 25%; ilmenite 11%; pyroxene and hornblende 49%; feldspar, quartz, etc. 10.5%; calcite (shells, etc.) 3.5% (*Med. Afd. Handelsmuseum Kolon. Inst., Amsterdam 14,* 1934, pp. 64–67; see also Westermann 1949, p. 92).

Sands collected by J. I. S. Zonneveld in 1956 were analyzed at the Technological University of Delft, Holland. These sands were found to contain the following minerals: heavy fraction (in decreasing order of frequency) – hypersthene, magnetite, ilmenite and martite, diopsidic pyroxene, olivine, bronze-green hornblende, oxy-hornblende, apatite, zircon, organisms with ore inclusions; light fraction – intermediary plagioclase (45–50% An), organogenic carbonates, sanidine (trace), quartz (trace).

The heavy iron minerals of the andesitic tuffs have obviously been sorted and concentrated by surf action.

Sample Nos.	Locality	Rock	Thick-ness in feet	Sample treated with HCl and HNO_3: Hornblende, green	Hornblende, brown	Lamprobolite	Augite	Hypersthene	Quartz (X = present)
Agglomerates and Tuffs of the Quill Volcano									
16	South slope Signal Hill	tuff		15	.	.	37	48	.
58	Panga ridge	tuff		14	.	.	42	44	X
60	,,	lapilli		13	1	.	45	41	.
111a	Coastal cliff north-west of Oranjestad	lapilli	57	1	.	.	50	49	.
b	,,	tuff		14	2	.	41	43	.
c	,,	tuff and lapilli		22	.	.	32	46	.
d	,,	tuff and lapilli		13	.	.	47	40	.
e	,,	tuff and lapilli		10	.	.	43	47	.
f	,,	tuff and lapilli		12	1	.	43	44	.
g	,,	lapilli		20	.	.	46	34	.
112b	Coastal cliff near Oranjestad	tuff		13	.	.	42	45	.
120a	Schildpadden Bay	tuff and lapilli	23	18	.	.	39	43	.
b	,,	tuff and lapilli		17	1	.	41	41	.
117a	,,	agglomerate	13	.	.	.	47	53	.
b	,,	tuff and lapilli		3	.	.	45	52	.
c	,,	agglomerate		5	.	.	40	55	.
116a	,,	tuff and lapilli	13	3	.	.	44	52	.
b	,,	tuff and lapilli		2	.	.	40	58	.
c	,,	tuff and lapilli		4	.	.	43	53	.
40e	Compagnie's Bay	agglomerate	27	2	.	.	40	58	.
d	,,	agglomerate and tuff		10	.	.	54	36	.
c	,,	agglomerate and tuff		9	.	.	44	47	.
b	,,	tuff		10	.	.	47	43	.

Tuffs and Organic Sediments of Sugar Loaf and White Wall

31a	Sugar Loaf	coquina		60	2	·	18	20	X
c	”	coquina and other limestone		9	·	·	28	63	·
55c	”	limestone		98	·	·	·	2	X
b	”	pumice		100	·	·	·	·	X
a	”	limestone	160	92	1	·	2	5	X
31f	”	conglomeratic tuff		81	·	·	·	19	X
g	”	tuff with pumice fragments		92	·	·	·	8	X
h	”	calcareous and brecciated tuff		90	·	·	1	9	X
32	White Wall, Big Gut	limestone		83	·	·	7	10	X
54a	”	limestone		48	·	·	20	32	X
b	”	limestone		56	·	·	20	24	X
c	”	limestone		67	1	·	19	13	X
f	”	limestone		41	·	·	21	38	X
g	”	limestone		48	1	·	12	39	X
h	”	limestone	500	31	·	·	34	35	X
i	”	limestone		40	·	·	60	·	X
j	”	limestone		96	·	·	4	·	X
k	”	coquina		94	·	·	6	·	X
l	”	limestone		35	·	·	45	20	X
m	”	tuff		5	·	·	39	56	X
35	White Wall, top	limestone		43	·	·	31	26	X
38	”	tuff		39	·	·	33	28	·

Agglomerates and Tuffs of the North-western Volcano

26a	Pilot Hill	agglomerate	20	·	·	·	52	48	·
26	”	tuff and agglomerate	10	·	·	·	48	52	·
43	upper Wash Gut	agglomerate and tuff		·	·	·	99	1	·
44	”	agglomerate and tuff		·	·	·	93	7	·
48	Boven	agglomerate		·	·	·	49	51	·
63	Cul de Sac	agglomerate and tuff		52	10	·	37	1	·
96	north of Solitude	agglomerate		·	·	·	17	83	·

Table 10. Mineralogical analysis of agglomerates, tuffs and organic sediments of St. Eustatius

CHAPTER X

VOLCANIC HISTORY AND GENERAL REMARKS ON THE VOLCANIC STRUCTURE OF ST. EUSTATIUS, WITH NOTES ON OTHER ISLANDS OF THE VOLCANIC LESSER ANTILLES

(Appendix VI, Ideal sections)

Table 4 shows the tentative stratigraphic position of the geological and volcanic units of St. Eustatius, as correlated with those of nearby Volcanic Caribbees, viz. Saba, St. Kitts, Nevis, and Montserrat. This table is rather different from those published by MacGregor 1938, Hardy & Rodrigues 1947 (Chapter I), and Martin-Kaye 1959.

The first eruptions of the old *north-western volcano* may date back to late Pliocene. Since the greater portion of the superstructure has been eroded, volcanic activity presumably ceased in the early Pleistocene period.

The basement of the north-western volcano has not been found. However, steeply dipping agglomerates and tuffs – whose strikes and dips are abnormal in the general scheme of this volcano's structure – may indicate that it was built up on the ruins of an older one. Whether or not these steep dips are proof of orogenic movements prior to formation of the volcano is also a matter of conjecture (cf. the Andean orogenesis at the end of the Miocene and the beginning of the Pliocene; see table Martin-Kaye 1959). The mineral content of a few steeply dipping agglomerates and tuffs, as compared with that of other ejectamenta in the north-western hills, may perhaps support the idea that there are at least two volcanic units of different age. The data are, however, too scanty to enable conclusions to be drawn.

The north-western volcano is largely of the strato-volcanic type; it has been built up by alternating eruptions of lava and ejectamenta. The mapping of lava flows and dikes has been facilitated by aerial photographs. Bergje is thought to be the remnant of the central crater pipe, a typical volcanic neck. Since the western portion of the volcano has disappeared (presumably in connection with faulting), the north-western portion of St. Eustatius has an asymmetric shape. Volcano-tectonic troughs may or may not have played a rôle in shaping the valleys of Venus Bay and Zeelandia.

The lava rocks are predominantly pyroxene-andesites, less frequently basaltic (olivine-bearing) pyroxene-andesites; pyroxene-hornblende-andesites are rare. With the exception of one sample the agglomerates and tuffs of this area lack hornblende.

A long time after the north-western volcano ceased its activity and had become partly denuded, a series of largely organic sediments were deposited in the surrounding shallow coastal sea: the *White Wall formation*. Their facies and fossil contents indicate that sedimentation took place either in a lagoon fringed by coral reefs, or outside these reefs, and possibly in both environments. The lower section of the series, now exposed in White Wall proper, lacks corals, probably owing to the fact that the water was too deep for coral growth. Corals are, however, abundant in some of the younger beds found in Sugar Loaf, which proves that in this later period shallow-water conditions prevailed.

Throughout the series the organic sediments are found to contain some volcanic material, while in the Sugar Loaf beds several strata are entirely composed of volcanic material; the latter strata may indicate temporary emergence above sea level (this is particularly true as regards the solid pumice lava in the middle of Sugar Loaf).

Green hornblende is a conspicuous mineral in both organic and volcanic beds, and it is therefore likely that the volcanic material originated largely from early eruptions of *the Quill volcano*, which had formed as a new centre of activity south-west of the older north-western volcano. Since the distance between the location of the early vent of The Quill and the strata now exposed in White Wall and Sugar Loaf was very small, it may be assumed that at that time the volcano was in its infancy and largely submarine. However, deposition of the volcanic ejecta of Sugar Loaf, and in particular the outflow of the pumice lava, took place when the volcano was temporarily emergent above sea level.

Radiocarbon datings of corals from White Wall and Sugar Loaf have determined the beginning and the end of the sedimentation period of the White Wall formation as approximately 70,000 and 21,000 years ago, i.e. during late Pleistocene. These datings corroborate the age deduced from palaeontological evidence.

Sedimentary formations similar to the White Wall – Sugar Loaf series of St. Eustatius occur in St. Kitts (Godwin Gut and Brimstone Hill limestones) and Montserrat (fossiliferous strata at Roche Bluff and Landing Bay). Their fossil contents and the radiocarbon dating of a coral from the Brimstone Hill limestones indicate that they also formed during late Pleistocene, in analogous shallow-water environments.

Since the deposition of the youngest stratum of the White Wall – Sugar Loaf series, some 21,000 years ago, *the Quill volcano* appears to have rapidly built up its cone, covering the White Wall formation with agglomeratic and tuffaceous ejectamenta. Limestone and pumice fragments, torn from the White Wall formation, were expelled together with the volcanic ejectamenta, and are now found in the coastal cliff near Oranjestad; some of these limestone fragments have been metamorphosed into very hard calcite-marbles.

The Quill is not a strato-volcano, because visible lava flows are absent (except for the pumice lava in Sugar Loaf). Its activity was largely of the Vulcanian type, with explosive eruptions from a central, wide, deep and circular crater predominating. The volcano is essentially built up of ejectamenta ranging from very large blocks and bombs to lapilli and fine ashes. The big blocks are found, in particular, on and near the crater rim. Smaller blocks and bombs occur lower down the slopes. The influence of the eastern trade winds on the distribution of the ejectamenta is indicated by the fact that in the southern and eastern coastal cliffs coarser material prevails over finer products, whereas the western cliffs consist largely of tuffs and lapilli. Fine Quill ashes are also found in pockets in the western part of the north-western hilly country.

Petrographically the andesites of The Quill are very similar to those of the north-western volcano. The agglomerates and tuffs are characterized by the presence of green hornblende. Fragments of hornblende-diorite, ejected by the volcano, indicate the presence of a plutonic body in the subsurface.

The eruptive activity of The Quill would seem to have continued until only a few thousand years ago, judging from its young appearance and regular conical shape; the well-preserved, deep and steeply walled crater; and the absence of advanced, deep erosion gullies (with the exception of those on both sides of White Wall).* It is almost certain that the volcano is now extinct, because historical eruptions are not known and fumaroles are lacking. The heavy woody vegetation in the crater and on the slopes is another indication that activity has ceased.

It has been argued above that the volcano's initial and submarine eruptions took place simultaneously with sedimentation of the White Wall formation, and that this sedimentation was interrupted about 21,000 years ago by intensified volcanic activity, resulting in the rapid building up of a cone above sea level. A span of somewhat less than 20,000 years for the formation of a comparatively small volcano such as The Quill would seem to be ample time, if compared with volcanic data from other parts of the world.

For comparison the sizes are given of various contemporaneous Lesser Antilles volcanoes:

	Approximate diameter at sea level in miles	Height in feet
The Quill, St. Eustatius	2.5	1,973
Mount Misery, St. Kitts	5	3,711
Peak of Nevis	5.5	3,596
Soufrière Hills, Montserrat	4	3,002
Mont Pelée, Martinique	8	4,584
Soufrière, St. Vincent	6	4,048

These bigger volcanoes either may have had a longer history than The Quill or they have ejected more material in the same time span.

There are several examples of volcanoes in, for instance, Central America and Indonesia which have grown to large size in less than one thousand

* A. J. Pannekoek (1949, p. 276) judged the age of volcanoes from the stage reached by erosion: "The youngest volcanoes still present their original conical surface, and the radial gullies which have come into being after an eruption are not yet so deep as to remove the original surface between them."

years or even in a few years, e.g. Izalco, west of San Salvador (since 1770); Parícutin, Mexico (since 1943); Barcena, on the island of San Benedicto, west of Mexico (since 1952); Anak Krakatau, between Sumatra and Java (since 1927); Tangkuban Prahu, Merapi and Sundoro, Java (largely within 1,000 years).

It is likely that volcanic intrusions played a rôle in The Quill's evolution, albeit only a minor one by comparison with Saba. One example is the dome-shaped *Round Hill*, thought to be formed by a lava plug intruded north-west of the central vent.

The second indication of a volcanic dome is given by the *upthrust slab of White Wall – Sugar Loaf*, dipping steeply towards the south and bounded by two faults, roughly coinciding with Big Gut and Soldier's Gut. Molengraaff has only vaguely explained the mechanism of this tilting. In his thesis he postulated that the volcanic force proper, exerting itself very locally, had been responsible for the uplift. In his publication of 1931 he surmised "that the tilting was caused by one, or possibly more than one, eruption of the volcano"; he also referred to "a violent paroxysmal eruption . . . which probably gave rise to the greater part of the main volcano and its tuffs, at the same time lifting and tilting a gigantic slab of the then still horizontal submarine White Wall formation to its present position."

The present authors are not in favour of Molengraaff's idea of a paroxysmal eruption as the acting force. It is more likely that the slabs of White Wall and Sugar Loaf have been lifted and tilted by the intrusion of a volcanic dome or plug in a late phase of The Quill's history, probably not long before the final extinction of the volcano (5,000–3,000 years ago ?). It is thought that this lava intrusion pushed up the originally horizontal sedimentary strata and, as a matter of course, the overlying beds of younger Quill ejectamenta. The ejectamenta have slid down the steeply tilted White Wall and Sugar Loaf slabs, as a result partly of mere gravitational force, partly of downflowing rainwater. The uptilting of the slabs and the removal of the overlying ejectamenta account for the fact that the southern coast line shows a marked inward bend.

In the case of Round Hill there is no indication of a volcanic intrusion other than the faint dome-shaped elevation at the surface. The volcanic dome below White Wall and Sugar Loaf has not come to the surface either, but it has left two traces: firstly, the tilting of the said beds, and secondly, the thick gypsum deposits on top of White Wall. The gypsum is supposedly a product of the interaction between the calcareous sediments of White Wall and sulphur-bearing gases (solfataras) ascending from the intruded lava plug, at that time not quite consolidated. *

---

* According to Williams (1932, p. 141), intense solfataric action is seldom conspicuous during and after the upheaval of domes (see also Chapter VI): "... important solfataras are rarely found in the vicinity of domes and such as do occur are relatively cool and chiefly emit steam, sulphur compounds, and carbon dioxide." The thick beds of gypsum at White Wall are, however, suggestive of fairly strong solfataric action.

The hypothesis of a volcanic dome below White Wall is strongly supported by the *andesitic dome of Brimstone Hill, St. Kitts,* which has thrust up limestone beds similar in age and character to those in St. Eustatius (Chapter VIII; Plate 32). The dome structure of the intruding andesite of Brimstone Hill has been established beyond doubt.

Trechmann (1932, pp. 241–242) gave the following description: "Brimstone Hill is obviously a plug extruded comparatively recently, and has carried up on its sticky flanks and shoulders the curious upturned sedimentary beds which occur around it on all sides except the north-easterly and which on the east side rise nearly to the level of the summit. The plug has not merely raised, but has broken through the various layers of sedimentary rocks, so that there has been considerable complication and smashing up of the beds."

Martin-Kaye (1959, p. 53) observed that "the hill is a prominent isolated feature of obviously volcanic origin. In general geology it consists of a core of igneous rock coated on portions of its flanks by limestones and pyroclastic rocks which dip radially outwards. Clearly the core has been upthrust, perhaps in somewhat analogous fashion to the spine of Mont Pelée and the Pitons of St. Lucia, and in the process previously overlying rocks were split open and part dragged up on the sides. – Some of the limestones appear to have been heat hardened, and some ashy beds have been ocherished, but this is quite likely to have been caused by fumarolic action which is still in minor evidence in the vicinity." ("Brimstone" is, of course, an old name for sulphur).

Fossil contents of the limestones and the radiocarbon dating of a coral (44,400 ± 1,200 years) prove that the Brimstone Hill dome was extruded in late Pleistocene time or even during the Holocene. This agrees with Trechmann's theory that the extrusion of Brimstone Hill is a much later event than the formation of the cone of Mount Misery, near whose foot Brimstone Hill is situated. It is, however, quite possible that the eruptive activity of Mount Misery continued after the extrusion of the dome. In Table 4 the upthrust of the White Wall formation and that of the Brimstone Hill limestones are indicated as being synchronous: middle Holocene.

Similarly, the *tilting of the Pleistocene fossiliferous strata at Roche Bluff and Landing Bay, Montserrat* (Plate 31), is tentatively dated as middle Holocene. According to MacGregor (1938, pp. 20, 23) "these tuffs are believed to have been upraised and tilted by volcanic upheaval almost contemporaneous with their formation. It seems probable that explosions more or less contemporaneous with the consolidation of the dacite [outcropping south-west of Landing Bay], which I regard as intrusive, caused the uptilting and breaking up of the pale tuffs of Roche Bluff, not very long after their formation."

Martin-Kaye (1959, p. 85) remarked that "the rather steep and varying dips and general brecciation suggests that this centre [at Roche Bluff and Landing Bay] may possibly be of similar upthrust nature to that of Brimstone Hill, but more complex."

It is likely that the dome of Brimstone Hill and the hypothetical intrusions of St. Eustatius and Montserrat formed in a very short time.

The relatively small *outcrops of the White Wall formation in the slope of the Quill volcano west of White Wall* present a special problem. Their position cannot be explained by an uplift due to a volcanic dome. Most likely they are large portions torn from the limestone beds and ejected by powerful eruptions. Owing to their size they were deposited not far from the crater, whereas smaller limestone fragments came down at a much greater distance away, for instance in the tuff layers now exposed in the Oranjestad cliff.

The *geological history of St. Eustatius during the last few thousand years* has mainly been characterized by a process of denudation brought about by rainwater and marine erosion. The effect of the latter has been aggravated by a relative rise of the sea level with regard to the island. Molengraaff (1886, pp. 31, 53) early drew attention to this phenomenon. He stated that the whole island, and in particular the older north-western portion, had been much larger in former times, the area being decreased by surf action probably assisted by subsidence. Sapper (1903, p. 318) illustrated the apparent subsidence of the island in the following words: "Die Thatsache, dass die Ueberreste der alten, Ende des 18. Jahrhunderts aufgelassenen Hafenstadt von Statia gegenwärtig zum Theil im Wasser stehen, spricht dafür, dass seit jenem Zeitraum eine nicht unwesentliche Senkung der Insel stattgehabt hat, und wenn man hört, dass noch vor wenigen Jahrzehnten ein Sandstrand längs der Nordküste der Insel bestand, der das Bereisen desselben zu Pferde gestattete, so muss man schliessen, dass die Senkung in jüngster Zeit noch Fortschritte gemacht hatte. Leider sind mir aus der Zeit des 18. Jahrhunderts keine genauen Pläne der Insel oder zuverlässige Abbildungen der Stadt bekannt geworden, so dass eine Feststellung des genauen Betrags der Senkung nicht möglich ist. Auch sind die Häuser der Altstadt zu stark zerstört, um in dem vom Wasser bespülten Theil noch die Lage des Fussbodens mit Sicherheit erkennen zu lassen; aber schätzungsweise wird man den Betrag wohl auf etwa 2 m angeben dürfen. Dass es sich um eine Senkung, und nicht blos um ein locales Eindringen des Meeres handelt, scheint mir aber nach dem Thatbestand zweifellos zu sein."

Hovey (1925, p. 837) also referred to a "very recent depression ... indicated at Statia, where the foundations of some old buildings may be seen submerged beneath the sea at low tide." (Plate 23).

It is difficult to decide whether the recent submergence of St. Eustatius is due to subsidence of the island or to a rise in sea level. According to Flint (1957, pp. 260–261) a recent, somewhat variable rise in the level of the sea is suggested by measurements at and near Boston (Massachusetts): submergence at a rate of 2.5–3.0 mm per year between A.D. 1650 and 1950, and of 1.5 mm per year between 4500 B.C. and A.D. 1620. These figures would roughly account for the situation of the lower town of Oranjestad.

The decrease in area of the north-western hills is thought to be partly due to *downthrow faulting* and the subsequent entire removal of a western segment of the old volcano. The dislocation may have occurred either in Pleistocene or Holocene time. In this connection it may be remarked that St. Eustatius and the other Volcanic Caribbees have occupied an unstable tectonic position down to the present day, as is indicated by the earthquakes which still occur periodically.

Similar downthrow faulting is suggested for the western segment of *Salt Pond peninsula, St. Kitts* (Fig. 11, Plate 33[b]). The authors paid a short visit to the peninsula on 21 February 1958, and they are inclined to believe that this strongly dissected landscape of "Older Volcanics" (Martin-Kaye 1959) is the remnant of a denuded and partly submerged late Pliocene or early Pleistocene strato-volcano, somewhat larger than and perhaps of about the same age as Statia's north-western volcano. The roughly circular, central depression of Great Salt Pond probably indicates the site of the former crater (cf. Martin-Kaye p. 50), while the strikes and dips of outcrops of lavas, agglomerates and tuffs surrounding it seem to support this hypothesis. The wide, low valleys between the hills, connecting the central depression with the bays, may or may not have been formed by previous volcano-tectonic troughs. The supposed fault zone along the west coast – giving the old volcano its asymmetric shape – is marked in places by friable, multicoloured rocks containing gypsum and sulphur and altered by solfataric activity (Guana Point).

Similar tectonic processes may have affected the second main eruptive centre of "Older Volcanics", situated in the *Basseterre region.* Of this old strato-volcano, only an eastern arcuate portion, formed by the Canada, Conaree and Morne Hills (with outward-dipping beds of lavas, agglomerates and tuffs), has been preserved, the western section having disappeared entirely.

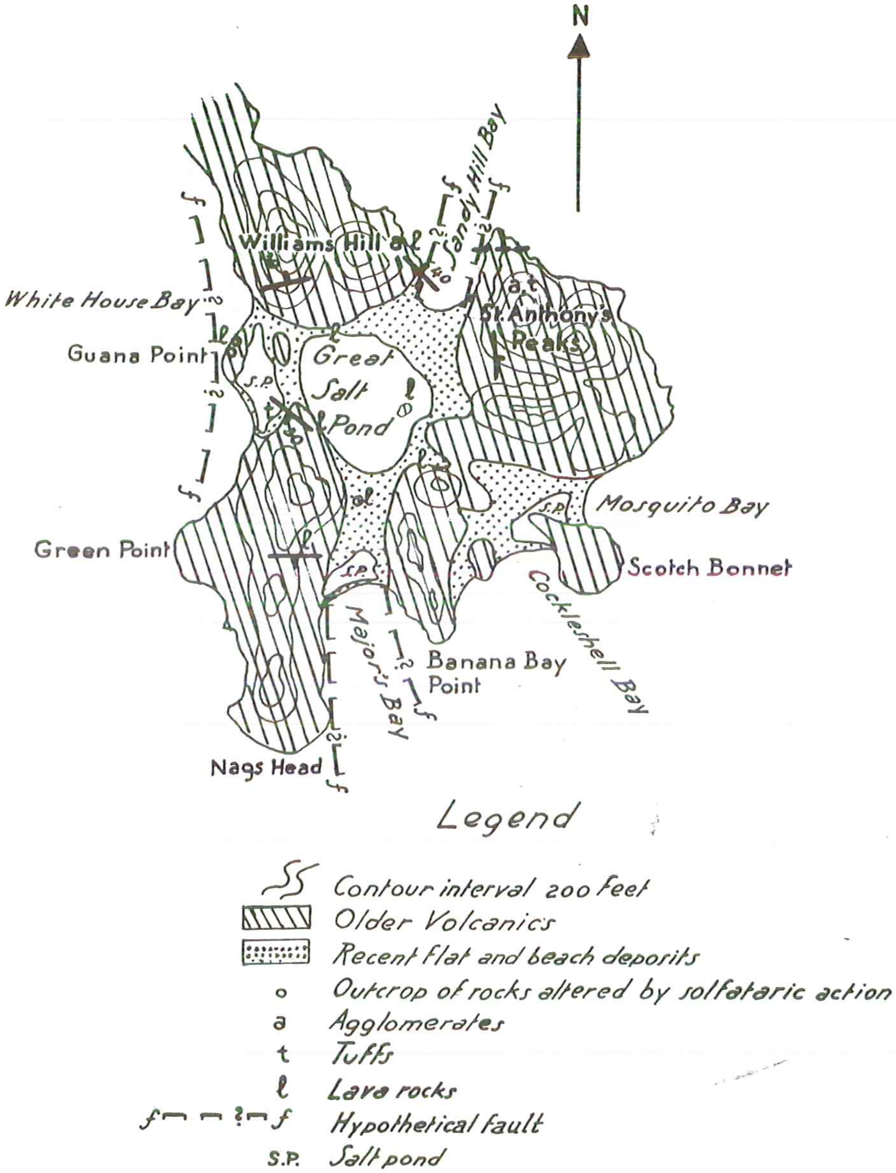


Fig. 11. Sketch map of Salt Pond Peninsula, St. Kitts, scale approximately 1 : 64,000, showing strikes and dips, and hypothetical faults (partly after Burdon, 1920, and Martin-Kaye, 1959).

SABA AND ST. EUSTATIUS
AS PART OF
THE CARIBBEAN VOLCANIC ARC

* * *

BIBLIOGRAPHY

CHAPTER XI

SABA AND ST. EUSTATIUS AS PART OF THE CARIBBEAN VOLCANIC ARC, WITH NOTES ON THE SABA BANK

Figs. 1 & 2

It is beyond the scope of this treatise to give a survey of the various theories on the origin of the Lesser Antilles Arc, such as those postulated by, for instance, Hess (1938, 1950, 1953), Barrabé (1942), De Bruyn (1951*), Ewing et al. (1954), Woodring (1954), Butterlin (1956), Officer et al. (1957), Barr (1958), Van Bemmelen (1958), Hospers (1958), Vening Meinesz (1960) and Martin-Kaye (as yet unpublished). An exception may be made only in the case of one aspect of Hess's hypothesis in so far as it has been elaborated by Christman (1953); it deals with the position of Saba.

Hess explained the tectonic, volcanic and seismic relations in the Caribbean area on the basis of F. A. Vening Meinesz's theory pertaining to gravity anomalies and the associated island arc structures. According to Hess and Christman the "active volcanic arc" of the Volcanic Caribbees, being a zone of tension fissures, has been situated at a fixed distance of 160—120 km inside the zone of downbuckling since at least Eocene times. Both the Eocene volcanism of St. Bartholomew and the Oligocene volcanism of St. Martin are supposed to have occurred at the site of this zone of tension fissures, which corresponds with the present line connecting Saba and St. Eustatius, and extends beyond those islands. Hence the apparent shift of the site of volcanic activity from St. Bartholomew (middle to late Eocene) to St. Martin (post late-Eocene), and finally to Saba (Quaternary), would in fact be due to the eastward movement of the earth's crust towards the downbuckle: "If the geanticlinal axis and the axis along which the centers of volcanic activity occurred maintained a given distance from the axis of the downbuckle, as the crust moved eastward into the buckle, the two axes would appear to move westward in regard to any given point on the crust. Thus, the westward shift of volcanoes from east of St. Barts to the island of St. Barts, to the island of St. Martin, and finally to Saba, sheds additional light on the continued maintenance and development of the downbuckle during the Tertiary." (Christman 1953, p. 95). Considering the distance of 60 km between Saba and St. Martin — St. Bartholomew the rate of the crust's movement since middle or late Oligocene (some 36 million years ago) would have been about 1 metre in 600 years (Westermann 1957, p. 163). It is noteworthy that as far back as 1926 Davis suggested "that the line of volcanic activity

* In the bathymetric chart of De Bruyn the "active volcano" (?) of Mount Misery in St. Kitts is erroneously named "Saba".

has migrated westward from an earlier position on the outer curve to a later position on the inner curve" (p. 177).

The Hess-Christman hypothesis looks attractive but the position and enormous extent of the Saba Bank do not appear to fit in with it.

The Saba Bank has been given attention by Spencer (1901, 1904), Vaughan (1916, 1919), Davis (1926) and others. A "Chart of San Saba Bank" based on U.S. Hydrographic Chart No. 2318 is published in Vaughan 1919, p. 316. The Bank is also drawn on the marine chart of the Hydrographic Department of the Netherlands Ministry of the Navy, 1956.

It is situated south-west of Saba, from which it is separated by a channel three miles wide with a maximum depth of about 380 fathoms (700 m). The submarine plateau of Saba Bank enclosed by the 100 fathom (180 m) isobathic contour has an area of approximately 890 sq. miles (2,300 sq. km); its greatest length, in the direction N 70 E – S 70 W, is 40 miles, its breadth in the direction N 30 W – S 30 E is 27 miles. The upper surface of by far the greater portion of the Bank lies between 9 and 30 fathoms below sea level.

A submerged, curved barrier reef, from 7 to 10 fathoms below sea level, extends along the south-eastern and eastern border for 35 miles; coral and coral sand are clearly visible from a ship.

According to Vaughan (1919, p. 304) the bank is a submarine plateau, "leveled by planation agencies, which almost certainly were both subaerial and submarine"; submergence has taken place in geologically recent time. Davis (1926, pp. 137–138) explained the bank as "an atoll-lagoon floor, deprived of its original reef and probably somewhat planed down by low-level abrasion in the last Glacial epoch. The main reason for assuming that a composite volcanic island is buried under this bank is that its size is much greater than it should be if it were based only on a single cone like that of Saba island."

The physical characteristics of the surface and erosion features of the Caribbean islands and their submerged shelves, including the Saba Bank, have been used by Spencer (1901) as arguments for his theory of considerable vertical movements in the Miocene-Pliocene-Pleistocene periods. His views as to changes of level of land and sea are, however, not based on proper observations (Sapper 1904; Rutten 1934, 1935).

According to Hess's theory the island arc structure should be accompanied by extensive fault lines, largely in a radial direction, i.e. perpendicular to the arc. The Pleistocene or post-Pleistocene NS faults which the present authors believe to border the west coast of Saba, the old north-western portion of St. Eustatius, and the old eruption centres of the Basseterre region and Salt Pond Peninsula of St. Kitts, cannot be easily explained by this theory.

Apparently the volcanic arc manifests itself beyond Saba in a west-north-west direction. Sheet 210 of the Netherlands marine chart of the West Indies (1956) shows small-sized shallows of only 84 m, 87 m and 82–128 m depth at distances of approximately 20 km, 24 km and 30 km

WNW of Saba (Fig. 2). These shallows, indicated by a circular dotted line and the additional note "stones, coral and coral sand", are separated by depths of maximum 859 m. Since St. Eustatius, Saba and the shallows occur along a slightly curved axis, it is thought that the latter are the tops of submarine volcanoes of Pleistocene or perhaps Holocene age. However, there is also the possibility that they are in some way connected with the nearby Saba Bank, whose northernmost corner almost touches the said axis between Saba and the shallows.

Saba (4.8 sq. miles or 12 sq. km) is surrounded by a narrow submarine shelf (cf. Vaughan 1916, Davis 1926). The submarine area around Saba within the 100-fathom isobathic contour measures 6.2 sq. miles or 16 sq. km. Saba is separated from St. Eustatius by a distance of some 26 km and by sea depths of maximum 780 m.

St. Eustatius, St. Kitts and Nevis rise from a roughly N 40 W – S 40 E trending submarine plateau whose length is 55 miles and whose breadth varies from 3.8 (near St. Eustatius) to 10.8 miles (near Nevis). The area enclosed by the 100-fathom isobathic contour amounts to approximately 405 sq. miles (1,050 sq. km), of which the three islands occupy 126 sq. miles (326 sq. km). Davis (1926, pp. 57–58) described the area as follows: "The bank is thought to have been built up as a reef-enclosed lagoon floor in association with a subsiding series of earlier volcanic islands, some of which appear to be wholly submerged in the island-free stretch between Statia and St. Kitts and in the southern end of the bank beyond Nevis; and . . . the bank here is believed to have recently lost its enclosing reef by low-level abrasion [during the Glacial epochs]. The younger volcanoes appear to have been piled up on the bank in Glacial or Post-glacial time. Discontinuous reefs are charted on the bank near some of the islands . . ."

Perhaps Davis was right in assuming that the basis of the entire St. Eustatius – St. Kitts – Nevis bank is formed by older and younger volcanics. We cannot trace this basis between St. Eustatius and St. Kitts, and south of Nevis, but the small andesitic rock of Booby Island, situated between St. Kitts and Nevis, clearly connects the older volcanics of the two islands.

There is a notable alternation of older (Plio-Pleistocene) and younger (Pleisto-Holocene) volcanics in the Lesser Antillean Arc.

The following scheme obtains in the northern portion (Saba – Montserrat):

Saba	The Mountain	– young
St. Eustatius	NW volcano	– old
	The Quill	– young
St. Kitts	Mount Misery, Middle and SE Range	– young
	Basseterre and Salt Pond Peninsula "Older Volcanics"	– old

Booby Island		– old
Nevis	Round Hill centre	– old
	Madden's Mountain and Nevis Peak	– young
	Saddle Hill centre	– old
Redonda		– old
Montserrat	Silver Hill, Centre Hills, Garibaldi Hill and St. Georges Hill	– old
	Soufrière Hills and South Soufrière Hill	– young

However, it is difficult to evaluate this alternation of volcanic centres, the more so since we know very little of the deeper stretches of the sea separating Saba and St. Eustatius, Nevis and Redonda, and Redonda and Montserrat. Palaeomagnetic measurements in rocks of the various volcanic units may prove to be a great help in determining their relative ages.

The earthquake maps of Rutten & Van Raadshooven (1940), Barr (1958), and Robson (1958) indicate the epicentres found in the neighbourhood of Saba and St. Eustatius, as well as those elsewhere along the Lesser Antillean Arc. The epicentres may be partly of tectonic, partly of volcanic origin.

Volcanically and petrographically the islands of Saba and St. Eustatius show the same general characteristics as the other Volcanic Caribbees. Young crater domes and peripheral domes, formed by andesitic to dacitic lavas, are found in Saba, probably in St. Eustatius, in St. Kitts, Montserrat, Guadeloupe, Martinique, St. Lucia, and perhaps other islands. *Nuée ardente* deposits associated with crater domes occur in Saba (The Mountain), Montserrat (Soufrière Hills) and Martinique (Mont Pelée). Deep and wide, more or less circular young craters are typical of The Quill of St. Eustatius, Mount Misery of St. Kitts, and the Soufrière of St. Vincent. Breadcrust bombs are found in Saba, St. Eustatius, Montserrat and Martinique. The rocks of all the Volcanic Caribbees, both lavas and pyroclastics, belong to the same petrological group.

Most of the young volcanoes of the Lesser Antilles have ejected fragments of older formations, notably of the plutonic and metamorphic subvolcanic basement. In the case of Saba metamorphic limestone has been described which is perhaps comparable to the metamorphic White Wall limestones thrown out by Statia's Quill volcano. Diorite fragments have been found as blocks in the ejectamenta, or as boulders, in St. Eustatius, St. Kitts (Wingfield River; Earle 1925), Guadeloupe (Lacroix 1904), Dominica, Martinique, St. Lucia, St. Vincent and Grenada (Mitchell 1953), indicating that the volcanoes are built partly on a dioritic foundation. Fels (1903) described an "anorthite" fragment, assumed to have been ejected by Mount Misery volcano, St. Kitts. Lacroix (1904) noted blocks of gabbro, quartz-diorite and micaceous schists in the volcanic tuffs of

Martinique. Earle (1928) mentioned “anorthite-olivine rocks”, “norites” and “calc-silicate-hornfels” (metamorphosed siliceous or argillaceous limestones?) as xenoliths thrown out by the Soufrière of St. Vincent; some of these plutonic rocks and metasediments were also collected by Westermann when he climbed the volcano on 16 February 1958.

CHAPTER XII

BIBLIOGRAPHY

Anderson, T. & J. S. Flett, 1903. Report on the eruptions of the Soufrière, in St. Vincent, in 1902, and on a visit to Montagne Pelée, in Martinique. Part I. *Phil. Trans. of the Roy. Soc. of London. A. 200,* pp. 353—553.

Anderson, T. & J. S. Flett, 1908. Report on the eruptions of the Soufrière, in St. Vincent, in 1902, and on a visit to Montagne Pelée, in Martinique. Part II. *Phil. Trans. of the Roy. Soc. of London. A. 208,* pp. 275—332.

Ballou, H. A., 1934. The Dutch Leeward Islands. *Tropical Agriculture, Trinidad, 11,* pp. 317—320.
(Saba, St. Eustatius)

Barr, K. W., 1958. The structural framework of the Caribbean region (Abstract and maps). *Caribbean Geological Conference, Report of the first meeting held at Antigua, B.W.I., December 1955,* pp. 30—33.

Barrabé, L., 1942. La signification structurale de l'Arc des Petites Antilles. *Bull. de la Société Géologique de France, Notes et Mémoires* (5) *12,* pp. 147—159.

Bemmelen, R. W. van, 1956. The influence of geologic events on human history (an example from Central Java). *Verhandelingen van het Koninklijk Nederlandsch Geologisch-Mijnbouwkundig Genootschap, Geologische Serie XVI (Gedenkboek H. A. Brouwer),* pp. 20—36.
(Merapi volcano)

Bemmelen, R. W. van, 1958. Stromingsstelsels in de silicaatmantel. *Geologie en Mijnbouw (Nieuwe serie) 20,* pp. 1—17.
(Caribbean region, pp. 11—17)

Benest, H., 1899. Submarine gullies, river outlets, and fresh-water escapes beneath the sea level. *The Geographical J. 14,* pp. 394—413.
(Saba, p. 400)

Bergeat, A., 1907. Staukuppen. *Neues Jahrbuch für Mineralogie, Geologie und Paläontologie. Festband,* pp. 310—329.

Bisschop Grevelink, A. H., 1846. Beschrijving van het eiland Sint Eustatius. *Bijdragen tot de kennis der Nederlandsche en vreemde koloniën 3, Utrecht.*

Boldingh, I., 1909. *The flora of the Dutch West Indian Islands. 1. The flora of St. Eustatius, Saba and St. Martin.* Leiden.
(Saba, pp. 239—241; St. Eustatius, pp. 237—239)

Brouwer, H. A., 1921—1922. Sur les dômes volcaniques des volcans actifs de l'archipel malais. *Zeitschr. für Vulkanologie 6,* pp. 37—46.

Brouwer, H. A., 1925. *The geology of the Netherlands East Indies.* New York.

Bruyn, J. W. de, 1951. Isogam maps of Caribbean Sea and surroundings and of Southeast Asia. *Proc. Third World Petroleum Congress, The Hague 1951, Section I,* pp. 598—612.

Burdon, Katharine J., 1920. *A handbook of St. Kitts — Nevis, a Presidency of the Leeward Islands Colony, containing information for residents and visitors concerning the islands of St. Christopher or St. Kitts, Nevis and Anguilla.* The West India Committee, London. (Chapter VII. Geology, pp. 93—96).

Butterlin, J., 1956. *La constitution géologique et la structure des Antilles.* Centre National de la Recherche Scientifique, Paris.
(Saba, St. Eustatius, pp. 283—288)

Christman, R. A., 1953. Geology of St. Bartholomew, St. Martin, and Anguilla, Lesser Antilles. *Bull. of the Geol. Soc. of America 64,* pp. 65—96.

Cleve, P. T., 1871. On the geology of the North-eastern West India Islands. *Kongl. Svenska Vetenskaps-Akademiens Handlingar 9, 12* (1870), Stockholm, 48 pp. (Saba, p. 18, 3 figs.; St. Eustatius, pp. 19—20, 3 figs.)

Cleve, P. T., 1882. Outline(s) of the geology of the Northeastern West India Islands. *Ann. New York Academy of Sciences 2 (1881),* pp. 185—192. Abstract: *Trans. New York Academy of Sciences 1,* 1881—1882, pp. 21—24.

Cotton, C. A., 1944. *Volcanoes as landscape forms.* London.

Davis, W. M., 1924. The formation of the Lesser Antilles. *Proc. of the National Academy of Sciences (U.S.A., Washington) 10, 6,* pp. 205—211.
(Saba, St. Eustatius)

Davis, W. M., 1926. *The Lesser Antilles.* American Geographical Society. Map of Hispanic America. Publication no. 2.
(Saba, pp. 35—36; St. Eustatius, pp. 48—51, 55; Saba Bank, pp. 137—138)

Deville, Ch. Sainte-Claire, 1847. *Voyage géologique aux Antilles et aux îles de Ténériffe et de Fogo.* Vol. II, Fasc. 1, Paris.

Deville, Ch. Sainte-Claire, 1864. *Hypsométrie des Antilles. Extrait du Voyage géologique aux Antilles,* etc. Paris.

Duyfjes, G., 1909. Het mijnbouwkundig-geologisch onderzoek van de kolonie Curaçao. *Koloniaal Verslag 1909. III. Curaçao. Bijlage Q.* 's-Gravenhage, pp. 41—43.

Duyfjes, G., 1910. Het mijnbouwkundig-geologisch onderzoek van de kolonie Curaçao in 1909. *Koloniaal Verslag 1910. III. Curaçao. Bijlage S.* 's-Gravenhage, p. 37.

Earle, K. W., (1922—)1925. *Reports on the geology of St. Kitts-Nevis, B.W.I., and the geology of Anguilla, B.W.I.,* published by the Crown Agents for the Colonies (50 pp.).

Earle, K. W., 1923. *Report on the geology of Montserrat* (type-written report by the Government geologist of the Windward and Leeward Islands, September 6th, 1923, with comments by A. G. MacGregor, Edinburgh, January 14th, 1952; 4 pp.).

Earle, K. W., 1924. The geology of St. Lucia. *Supplement to St. Lucia Gazette,* Government Printing Office, Castries, pp. 107—111.

Earle, K. W., 1928. *Report on the geology of Saint Vincent and the neighbouring Grenadines.* Printed at the Government Printing Office, Kingstown, St. Vincent (8 pp.).

Earle, K. W., 1932. Brimstone Hill, St. Kitts. *The Geol. Magazine 69,* pp. 335.

Engel, H., 1961. Some fossil Clypeastrids (Echinoidea) from Brimstone Hill (St. Kitts) and Sugar Loaf (St. Eustatius), Lesser Antilles. *Beaufortia, Zoological Museum Amsterdam, 9, 94,* pp. 1—6.

Escher, B. G., 1948. *Grondslagen der algemene geologie.* Amsterdam.

Ewing, M. & J. L. Worzel, 1954. Gravity anomalies and structure of the West Indies, parts I & II. *Bull. of the Geol. Soc. of America 65,* pp. 165—173, 195—200.

Fels, G., 1903. Ein Anorthitauswürfling von der Insel St. Christopher. *Zeitschr. für Krystallographie und Mineralogie 37,* pp. 450—460.

Flint, R. F., 1957. *Glacial and Pleistocene geology.* New York.

Geological Nomenclature of the Royal Geological and Mining Society of the Netherlands, edited by A. A. G. Schieferdecker, Gorinchem, 1959.

Gravity expeditions 1948—1958. Volume V, edited by G. J. Bruins. Publication of the Netherlands Geodetic Commission, Delft, 1960.
(Caribbean region, interpretation by F. A. Vening Meinesz, pp. 33—34)

(H a n t k e, G.), 1936. Nachrichtendienst über vulkanische Ereignisse. 1934/35. Amerika, Saba (Kleine Antillen). *Zeitschr. für Vulkanologie 16,* p. 264.

H a r d y, F. & G. R o d r i g u e s, 1947. The agricultural soils of St. Kitts — Nevis with notes on Statia (Dutch). *Studies in West Indian Soils 13,* The Imperial College of Tropical Agriculture, Trinidad (45 pp.).
(St. Eustatius, pp. 4—10, provisional soil map)

H e s s, H. H., 1938. Gravity anomalies and island arc structure with particular reference to the West Indies. *Proc. of the Amer. Phil. Soc. 79, 1,* pp. 71—96.

H e s s, H. H., 1950. Investigaciones geofísicas y geológicas en la región del Caribe. *Boletín de la Asociación Venezolana de Geología, Minería y Petróleo 2, 1,* pp. 5—22.

H e s s, H. H., & J. C. M a x w e l l, 1953. Caribbean research project. *Bull. of the Geol. Soc. of America 64,* pp. 1—6.

H ö g b o m, A. G., 1905. Zur Petrographie der kleinen Antillen. *Bull. of the Geol. Institution of the Univ. of Upsala 6* (1902—1903), pp. 214—233.
(Saba, pp. 228—231)

H o s p e r s, J., 1958. The gravity field of northern South America and the West Indies. *Geologie en Mijnbouw (Nieuwe serie) 20,* pp. 358—365.

H o v e y, E. O., 1903. Martinique and St. Vincent revisited. *The Amer. Museum J. 3, 4,* pp. 41—54.
(St. Eustatius, p. 53)

H o v e y, E. O., 1903. The new cone of Mont Pelé and the gorge of the Rivière Blanche, Martinique. *The Amer. J. of Science (4), 16,* pp. 269—281.
(Saba, p. 281)

H o v e y, E. O., 1905. Volcanoes of Martinique, Guadeloupe, and Saba. *Rep. Eighth International Geographic Congress, Washington 1904,* pp. 447—451.
(Saba, pp. 447, 451; St. Eustatius, p. 447)

H o v e y, E. O., 1905. Volcanoes of St. Vincent, St. Kitts, and Statia. *Rep. Eighth International Geographic Congress, Washington 1904,* pp. 452—454.
(St. Eustatius, p. 454)

H o v e y, E. O., 1925. The volcanic Caribbees. *Proc. Pan-Pacific Science Congress Australia, 1923, 1,* pp. 836—837.
(Saba, St. Eustatius)

(Kaart van) *West Indië, St. Maarten, Saba, St. Eustatius en omliggende eilanden.* (Blad) 210, 1 : 250.000, samengesteld uit Nederlandse en buitenlandse gegevens. 's-Gravenhage — Uitgegeven in nov. 1903 door het Ministerie van Marine, Afdeling Hydrografie. Hernieuwde uitgave dec. 1956.

(Kaart van) Nederlandse Antillen. *Plannen Bovenwindse Eilanden.* 's-Gravenhage — Uitgegeven in maart 1960 door de Chef der Hydrografie.

J o h n Y. K e u r & D o r o t h y L. K e u r, 1960. *Windward children. A study in human ecology of the three Dutch Windward Islands in the Caribbean.* Assen.

K r u y t h o f f, S. J., 1939. *The Netherlands Windward Islands, and a few interesting items on French St. Martin. A handbook of useful information for visitor as well as resident,* Antigua.
(Saba, pp. 110—124; St. Eustatius, pp. 125—137)

K u e n e n, P h. H., 1935. Contributions to the geology of the East Indies from the Snellius expedition. Part I Volcanoes. *Leidsche Geologische Mededeelingen 7,* pp. 274—283 (The Penanggoengan).

L a c r o i x, A., 1890. Sur la composition minéralogique des roches volcaniques de la Martinique et de l'île Saba. *Comptes Rendus hebdomadaires des séances de l'Acad. des Sciences, Paris, 111,* pp. 71—73.

L a c r o i x, A., 1893. *Les enclaves des roches volcaniques.* Macon.
(Saba, pp. 48, 156—157)

Lacroix, A., 1904. *La Montagne Pelée et ses éruptions.* Paris.

Lacroix, A., 1908. *La Montagne Pelée après ses éruptions.* Paris.

Lacroix, A., 1926. Les caractéristiques lithologiques des Petites Antilles. *Livre Jubilaire publié à l'occasion du Cinquantenaire de la fondation de la Société Géologique de Belgique.* Liège, pp. 387—405.
(Saba, St. Eustatius, pp. 401—402)

Lexique stratigraphique international. Volume V. Amérique Latine (Sous la direction de R. Hoffstetter). Fascicule 2b. Antilles (sauf Cuba et Antilles Vénézuéliennes). (Congrès Géologique International 1956). Centre National de la Recherche Scientifique, Paris, 1956.
(Saba, pp. 261—263; St. Eustatius, pp. 257—260)

MacGregor, A. G., 1937. Royal Society expedition to Montserrat, B.W.I.: Preliminary report on the geology of Montserrat. *Proc. of the Roy. Soc. of London. B. Biol. Sciences 121,* pp. 232—252.

MacGregor, A. G., 1938. The Royal Society expedition to Montserrat, B.W.I.: The volcanic history and petrology of Montserrat, with observations on Mt. Pelé, in Martinique. *Phil. Trans. of the Roy. Soc. of London. B. Biol. Sciences 229,* pp. 1—90.
(St. Eustatius, pp. 74, 76)

Maclure, W., 1817. Observations on the geology of the West India Islands, from Barbadoes to Santa Cruz, inclusive. (read Oct. 28, 1817). *J. of the Academy of Natural Sciences of Philadelphia 1, 1,* pp. 134—149.
(Saba, p. 148; St. Eustatius, pp. 147—148)

Martin-Kaye, P. H. A., 1959. *Reports on the geology of the Leeward and British Virgin Islands,* Castries, St. Lucia. (117 pp.).

Martin-Kaye, P. H. A., (in the press). *A summary of the geology of the Lesser Antilles.* Overseas Geological Surveys, London.

Mitchell, R. C., 1953. New data regarding the dioritic rocks of the West Indies. *Geologie en Mijnbouw (Nieuwe serie) 15,* pp. 285—295.

Molengraaff, G. A. F., 1886. *De geologie van het eiland St. Eustatius. Eene bijdrage tot de kennis der Nederlandsche koloniën.* Ac. Thesis Utrecht, Leiden (62 pp.).

Molengraaff, G. A. F., 1888. Ueber vulkanischen Schwefel aus Westindien. *Zeitschr. für Krystallographie und Mineralogie 14,* pp. 43—48.
(Saba)

Molengraaff, G. A. F., 1931. Saba, St. Eustatius (Statia) and St. Martin. *Leidsche Geologische Mededeelingen 5 (Feestbundel K. Martin),* pp. 715—739.
(Saba, pp. 715—718; St. Eustatius, pp. 718—729)

Officer, C. B., Ewing, J. I., Edwards, R. S. & H. R. Johnson, 1957. Geophysical investigations in the eastern Caribbean: Venezuelan Basin, Antilles Island Arc, and Puerto Rico Trench. *Bull. of the Geol. Soc. of America 68,* pp. 359—378.

Pannekoek, A. J., 1949. Outline of the geomorphology of Java. *Tijdschrift van het Koninklijk Nederlandsch Aardrijkskundig Genootschap (2), 66,* pp. 270—326.

Perret, F. A., 1942. Notes on the volcanism of the West Indies. *Proc. of the Eighth American Scientific Congress, Washington 1940, 4, Geological Sciences,* Washington, pp. 751—756.
(Saba, St. Eustatius, p. 752)

Regteren Altena, C. O. van, 1961. The mollusca from the limestone of Brimstone Hill, St. Kitts, and Sugar Loaf and White Wall, St. Eustatius, Lesser Antilles. *Proc. Koninklijke Nederlandse Akademie van Wetenschappen, Amsterdam, B, 64, 2,* pp. 288—304.

Regteren Altena, C. O. van, 1961. Note on the type locality of Trigoniocardia panis-sacchari v. R. Altena. *Basteria 25,* pp. 52—53.
(St. Eustatius)

Rittmann, A. 1960. *Vulkane und ihre Tätigkeit.* Stuttgart.

Robson, G. R., 1958. Seismological and volcanological work in the eastern Caribbean 1952—1955 (Abstract and map). *Caribbean Geological Conference, Report of the first meeting held at Antigua, B.W.I., December 1955,* p. 26.

Rutten, L. M. R., 1931. Our palaeontological knowledge of the Netherlands West Indies in 1930. *Leidsche Geologische Mededeelingen 5 (Feestbundel K. Martin),* pp. 651—672.
(St. Eustatius)

Rutten, L., 1934. Oude land- en zee-verbindingen in Midden-Amerika en West-Indië. *Tijdschrift van het Koninklijk Nederlandsch Aardrijkskundig Genootschap* (2) *51,* pp. 551—600.

Rutten, L., 1935. Alte Land- und Meeresverbindungen in Westindien und Zentralamerika. *Geol. Rundschau 26,* pp. 65—94.

Rutten, L. & B. van Raadshooven, 1940. On earthquake epicentres and earthquake shocks between 1913 and 1938 in the region between 0° and 30° N and 56° and 120° W. *Verhandelingen der Nederlandsche Akademie van Wetenschappen, afdeeling Natuurkunde II, 39, 4,* pp. 1—44.
(Caribbean region, pp. 7—13, 38)

Sapper, K., 1903. Ein Besuch der Insel Montserrat (Westindien). *Centralblatt für Mineralogie etc.,* pp. 279—283.

Sapper, K., 1903. Ein Besuch der Inseln Nevis und St. Kitts (S. Christopher). *Centralblatt für Mineralogie etc.,* pp. 284—287.

Sapper, K., 1903. Ein Besuch von S. Eustatius und Saba. *Centralblatt für Mineralogie etc.,* pp. 314—318.

Sapper, K., 1904. Die vulcanischen Kleinen Antillen und die Ausbrüche der Jahre 1902 und 1903. *Neues Jahrbuch für Mineralogie etc. 2,* pp. 1—70.
(Saba, pp. 37, 39, 41, 45, 50, 64, 65; St. Eustatius, pp. 31, 33—36, 39, 41—43, 45, 49—52, 59, 60)
(cf. 'Dritter Theil' in: Sapper, K., 1905. *In den Vulcangebieten Mittelamerikas und Westindiens,* Stuttgart, pp. 154—225).

Sapper, K., 1927. *Vulkankunde.* Stuttgart.
(Saba, p. 345; St. Eustatius, p. 217)

Spencer, J. W. W., 1901. On the geological and physical development of the St. Christopher Chain and Saba Banks. *The Quart. J. of the Geol. Soc. of London 57,* pp. 534—544.
(Saba, Saba Bank, St. Eustatius)

Spencer, J. W., 1904. The Windward islands of the West Indies (read 2nd Nov. 1901). *Trans. of the Canadian Institute 7 (1901—1902),* pp. 351—370.
(Saba, Saba Bank, pp. 356, 357; St. Eustatius, pp. 357, 358)

Stoffers, A. L., 1956. Studies on the flora of Curaçao and other Caribbean Islands. Volume I. The vegetation of the Netherlands Antilles. *Publ. of the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht, 15* (142 pp.).

Tongeren, W. van, 1934. Chemical analyses of some rocks from Aruba (with some remarks on the magmatic province of the Lesser Antilles). *Proc. Koninklijke Akademie van Wetenschappen, Amsterdam, 37,* pp. 162—167.
(Saba, p. 167)

Trechmann, C. T., 1932. Notes on Brimstone Hill, St. Kitts. *The Geol. Magazine 69,* pp. 241—258.
(St. Eustatius, p. 247)

Trechmann, C. T., 1932. Brimstone Hill, St. Kitts. *The Geol. Magazine 69,* p. 430.

Trechmann, C. T., 1935. The Pitons of St. Lucia, British West Indies. *Natural History Magazine* (London) 5 (35), pp. 134—135.

Umbgrove, J. H. F., 1949. *Structural history of the East Indies.* Cambridge.

Vaughan, T. W., 1916. Some littoral and sublittoral physiographic features of the Virgin and northern Leeward Islands and their bearing on the coral reef problem. *J. of the Washington Academy of Sciences 6, 3,* pp. 53—66.
(Saba, Saba Bank, St. Eustatius, pp. 53, 54, 57)

Vaughan, T. W., 1919. Fossil corals from Central America, Cuba, and Porto Rico, with an account of the American Tertiary, Pleistocene, and Recent coral reefs. *Smithsonian Institution U.S. National Museum Bull. 103,* pp. 189—524.
(Saba, Saba Bank, pp. 303, 304, 316)

Veenenbos, J. S., 1955. A soil and land capability survey of St. Maarten, St. Eustatius, and Saba (Netherlands Antilles). *Publ. of the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht, 11* (94 pp.).
(Saba, pp. 78—81; St. Eustatius, pp. 63—68)

Warneford, F. H. S., (1956 or 1957). *An introduction to the history of volcanic and seismic activity in the West Indies, with special reference to the Lesser Antilles.* St. John's, Antigua.
(Saba, St. Eustatius, pp. 4—5)

Westermann, J. H., 1949. Overzicht van de geologische en mijnbouwkundige kennis der Nederlandse Antillen, benevens voorstellen voor verdere exploratie. *Mededeling Koninklijke Vereeniging Indisch Instituut, Amsterdam, 85* (168 pp.).
(Saba, St. Eustatius, pp. 17—18, 50—54)

Westermann, J. H., 1957. De geologische geschiedenis der drie Bovenwindse eilanden St. Martin, Saba en St. Eustatius. *De West-Indische Gids 37,* pp. 127—168.
(Saba, pp. 143—146; St. Eustatius, pp. 146—154)

Westoll, T. S., 1932. Description of rock specimens from Brimstone Hill and three other localities in St. Kitts, B.W.I. *The Geol. Magazine 69,* pp. 259—264.

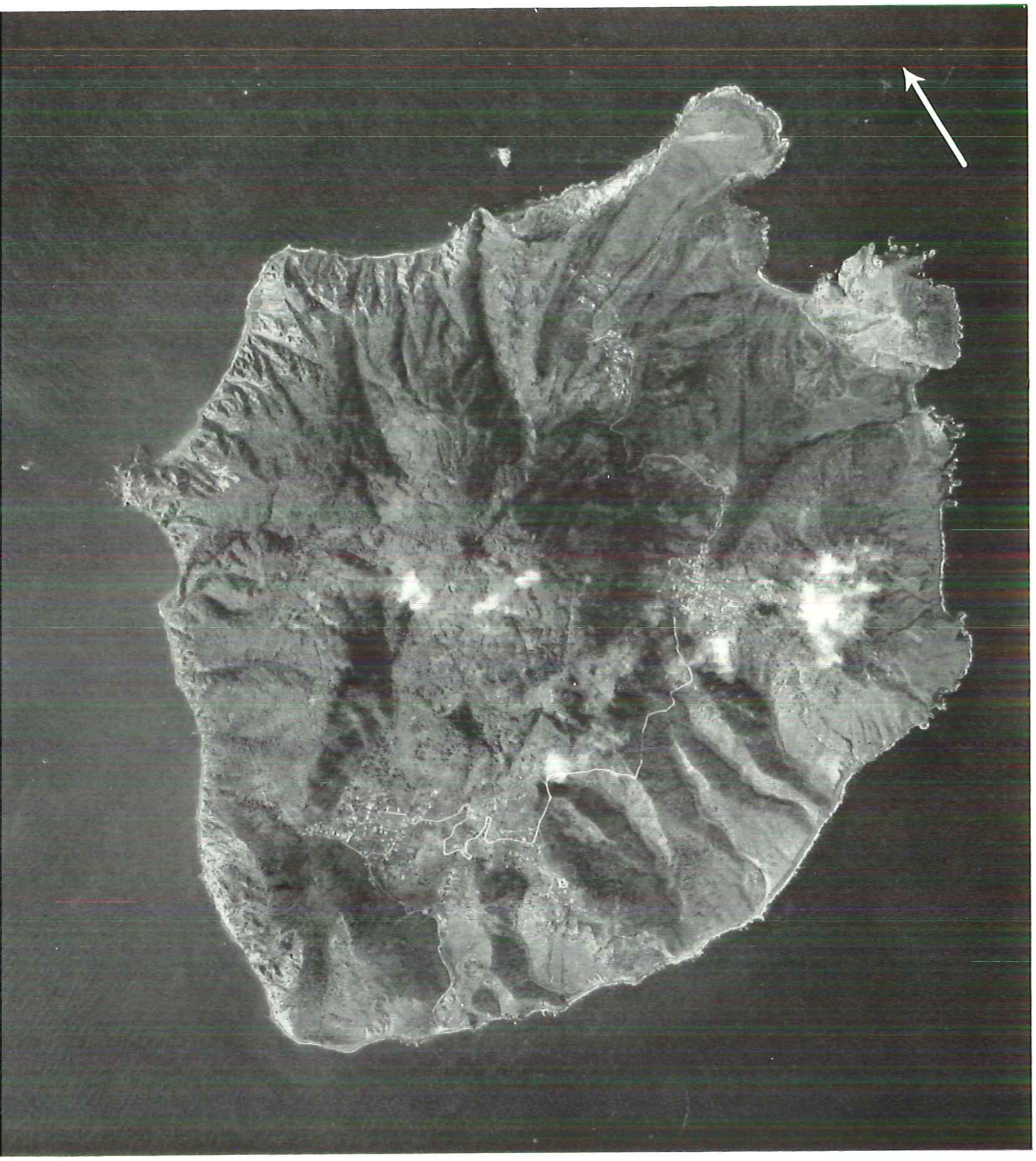
Williams, H., 1932. The history and character of volcanic domes. *University of California Publ. Bull. of the Department of Geol. Sciences 21, 5,* pp. 51—146.
(Saba, pp. 63, 137)

Winkler, O., 1926. Niederländisch-Westindien (Eine länderkundliche Skizze). *Mitt. der Gesellschaft für Erdkunde zu Leipzig für 1923 bis 1925,* pp. 87—137.
(Saba, pp. 98, 104—105; St. Eustatius, pp. 97—98, 104)

Wolff, F. von, 1914. *Der Vulkanismus 1.* Stuttgart.
(Saba, p. 492)

Woodring, W. P., 1954. Caribbean land and sea through the ages. *Bull. of the Geol. Soc. of America 65,* pp. 719—732.

Zonneveld, J. I. S., 1961. Aardrijkskunde uit de lucht. St. Eustatius. *Tijdschrift van het Koninklijk Nederlandsch Aardrijkskundig Genootschap 78,* pp. 53—56.

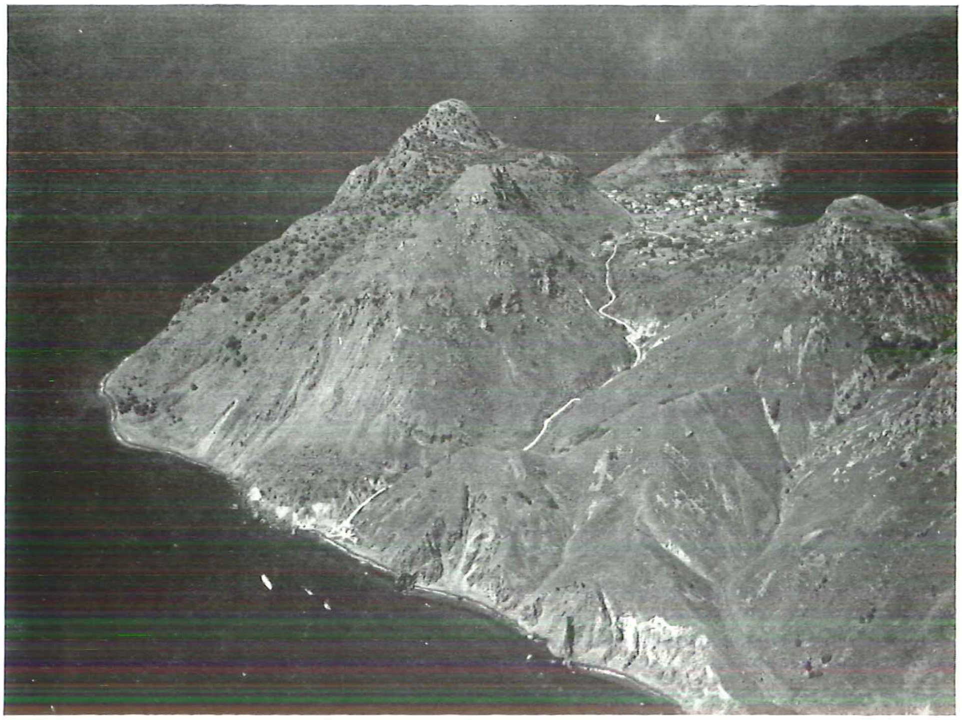


1. Aerial photograph of Saba, 1960 (scale 1 : 36,000).

e winding road connecting Fort Bay, The Bottom, Windward Side and Hell's Gate is clearly visible. e white streak across Flat Point is a primitive airstrip. Diamond Rock and Green Island can be seen north-west and north of the main island.

2. Saba seen from the air, towards the north-east.

The Mountain is cloud-covered. The south-western corner of the island is formed by the twin dome of Bunker Hill — Great Hill (1,415′). In the middle of the picture, separated from Bunker Hill — Great Hill by the narrow, winding Fort Bay ravine, is the twin dome of St. John's Flat — Thais Hill (1,305′). The twin dome of Booby Hill — The Level (1,715′) forms the south-east corner of the island. The wide, sloping area sweeping down between St. John's Flat and Booby Hill is thought to consist largely of *nuée ardente* deposits.



3a. South-western corner of Saba, seen towards NNW.
The twin volcanic dome of Bunker Hill — Great Hill (left) is separated from Thais Hill (right) by the ravine, with concrete road, connecting the village of The Bottom with Fort Bay. Fort Hill dome lies east of the landing place.

3b. Ladder Bay, west coast of Saba.
The "ladder" connects the landing place with The Bottom. Great Hill (1,415') is part of a twin volcanic dome. The coastal cliff consists of seaward-dipping agglomerates.

4a. South-western Saba, seen from the south-east.
On the left: the twin volcanic dome of Bunker Hill — Great Hill (1,415′). On the right: the twin volcanic dome of St. John's Flat — Thais Hill (1,305′). On the right in the background: the slope of The Mountain.

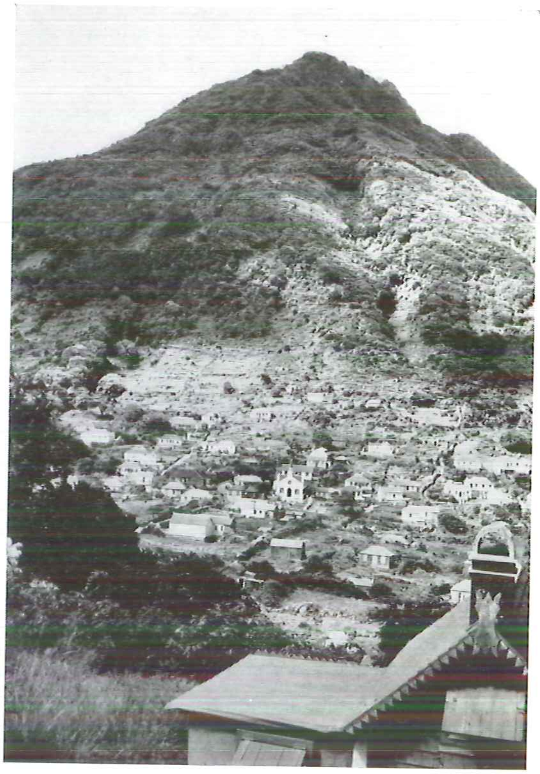
4b. South slope of The Mountain (2,910′), Saba, seen from Big Rendez-Vous.
The summit dome has the appearance of a long crest. On the left: the entrance to the oval depression near the top.

5a. South-eastern Saba, seen from the south.

On the right: the twin volcanic dome of The Level (1,715′) and Booby Hill (1,490′). The sloping area sweeping down west of Booby Hill, traversed by wide V-shaped guts, is thought to consist largely of *nuée ardente* deposits. On the left, in the background: The Mountain (2,910′).

5b. The Mountain (2,910′), Saba, seen from the east (slope of Old Booby Hill).

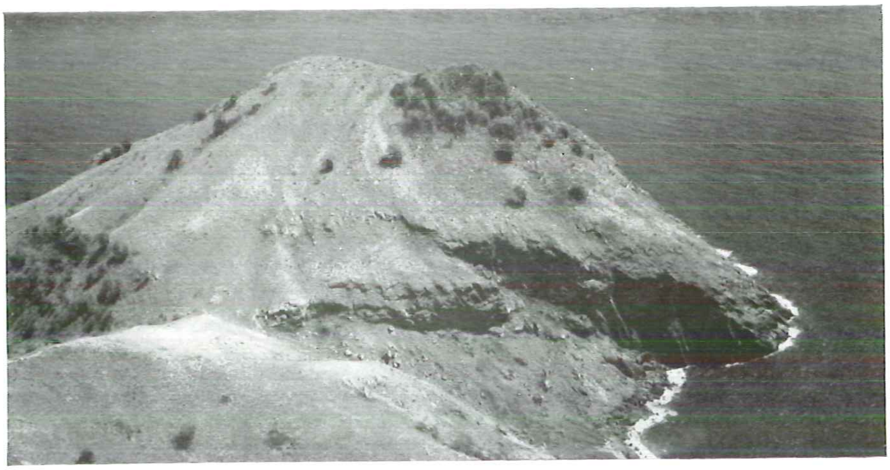
The broken, jagged shape of the summit dome is apparent. On the left: the plateau of Spring Bay Field (780′), an andesite bed overlying the light-coloured formation of predominantly agglomerates and tuffs. On the right: the volcanic (andesite) dome of Upper Hell's Gate (1,500′), piercing through the agglomerates and tuffs of Well's Gut valley. Well's Gut can be seen high up the slopes of The Mountain: two branches.



6a. Windward Side (1,350′) and The Mountain (2,910′), Saba, seen from the west slope of The Level.

The southern slope of The Mountain is smooth and has a distinct flexure. The jagged-looking north side of the summit dome is very steep. A deep, narrow ravine descends along the eastern slope.

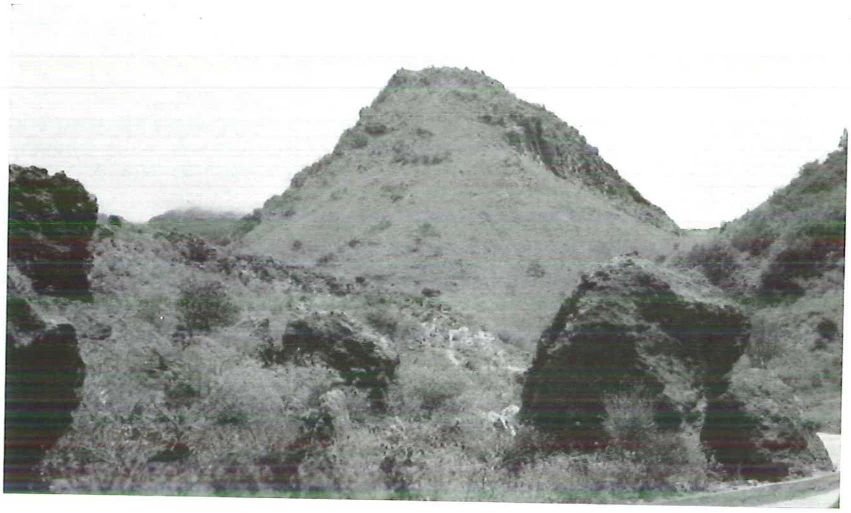
6b. The jagged appearance of the summit dome of The Mountain, Saba, as seen from the north-east (Upper Hell's Gate).



7a. The volcanic dome of Old Booby Hill (755′), Saba, as seen from The Level.

7b. The volcanic dome of The Level, east coast of Saba, seen from the south.

7c. The volcanic dome of Booby Hill at South-East Point, Saba.
The oblique and bent jointing planes of the andesite can be clearly seen.



8a. Volcanic dome of Thais Hill (1,305′), Saba, seen from the road near Fort Bay. The Mountain (behind Thais Hill) is hidden by clouds.

8b. Twin volcanic dome of The Level (1,715′) and Booby Hill (1,490′), Saba, seen from the slope towards Big Rendez-Vous.

The village is Windward Side. The vertical andesite dike of Kate's Hill can be seen to the right of the road leading up Booby Hill.

9a. North coast of Saba seen towards the east.

The Flat Point lava flow in the background overlies the older lava flow of Behind the Ridge, the latter standing out as a steep wall above the agglomerates and tuffs in the vicinity of the old sulphur mine. The sulphur mine itself is not shown in the picture; the white spots on the slope are the remnants of other solfataras nearby.

9b. Entrance of old sulphur mine of Behind the Ridge, Saba (Edmund Hassell).

PLATE 10

10. View of The Bottom, from the west slope of St. John's Hill, Saba.

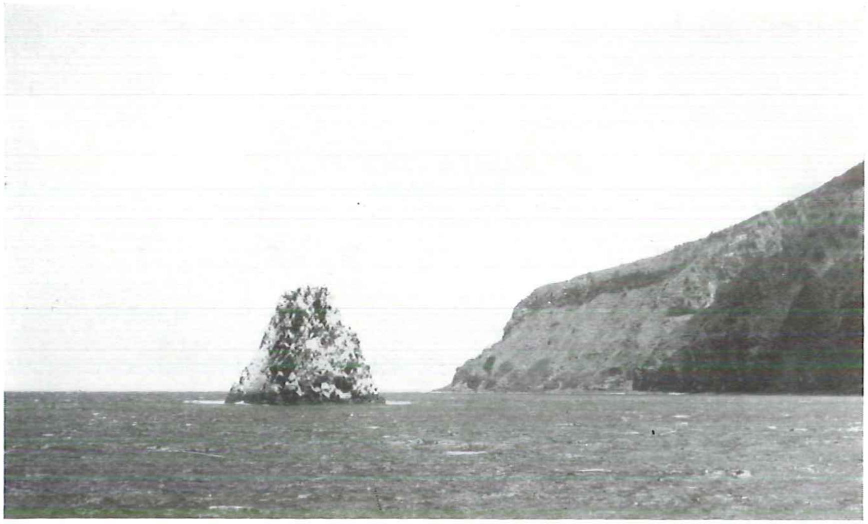
The village (650′) is dominated by the twin volcanic dome of Great Hill (1,415′) whose semi-hemispherical summit spine rises clearly above the plateau called Parish Hill (1,150′). The sloping ridge to the right belongs to the higher unit of predominantly andesites. The valley of The Bottom is filled in with debris.

11a. Semi-hemispherical summit spine of Great Hill (1,415′), Saba, seen from Parish Hill. The andesite slabs have an imbricate arrangement.

11b. Top of the semi-hemispherical summit spine of Great Hill, Saba. Andesite slabs with an imbricate arrangement.

12a. Pilot Rock and Torrens Point, north-west Saba, seen from Well Bay.

The larger part of the peninsula consists of agglomeratic and tuffaceous beds, dipping south-east (landward). A fault trough can be noticed. Further to the right the agglomerates show a normal seaward dip. The low, dark-coloured rock pinnacles to the left (Pilot Rock) belong to an andesite bed.



12b. Guano-clad Diamond Rock and peninsula of Great Point, north coast of Saba. Great Point shows a (dark-shaded) andesite bed between slightly northward-dipping strata of agglomerates.

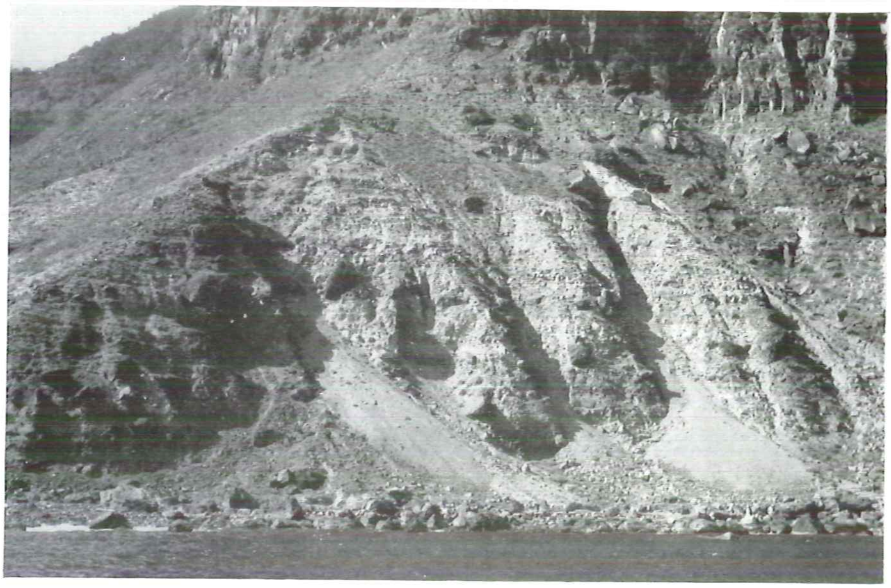
13a. Swanna Gut, south coast of Saba (1906).

Typical sloping landscape with wide V-shaped ravines separated by sharp divides. The divide on the right broadens into The Fans: *nuée ardente* deposits.

13b. Coastal cliff of The Fans, Giles Quarter, south coast of Saba.

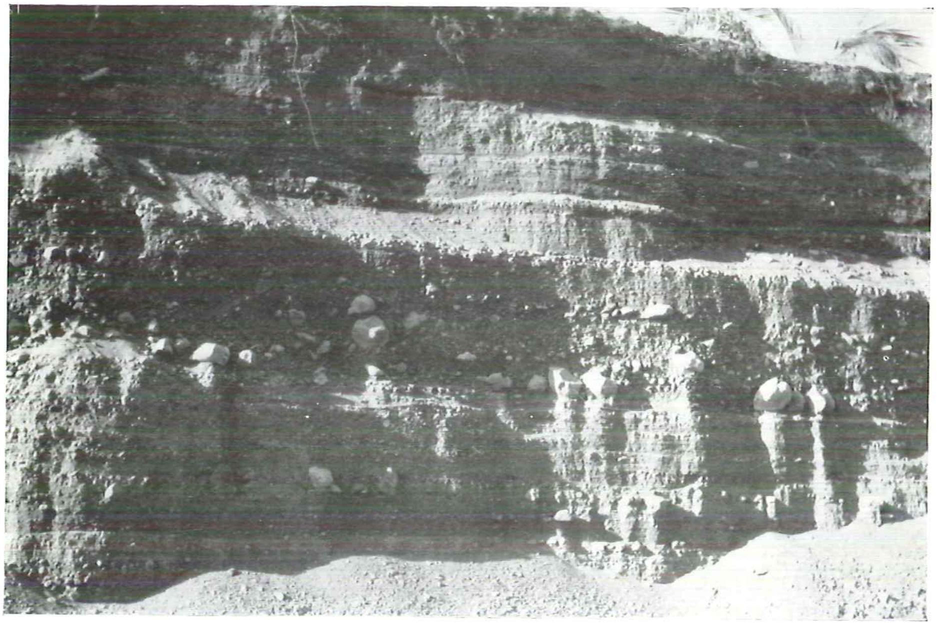
The stratified agglomerates exposed in the cliff (80′) at the lower end of the smooth slope may be classed as *nuée ardente* deposits. The steep, cone-shaped Peak Hill (1,330′) is a volcanic plug or dike. To the right, the volcanic dome of Booby Hill.

14a. A close-up of the chaotic *nuée ardente* deposits between Wash Gut and the foot of Booby Hill dome, south coast of Saba (height of the cliff approximately 60 feet).

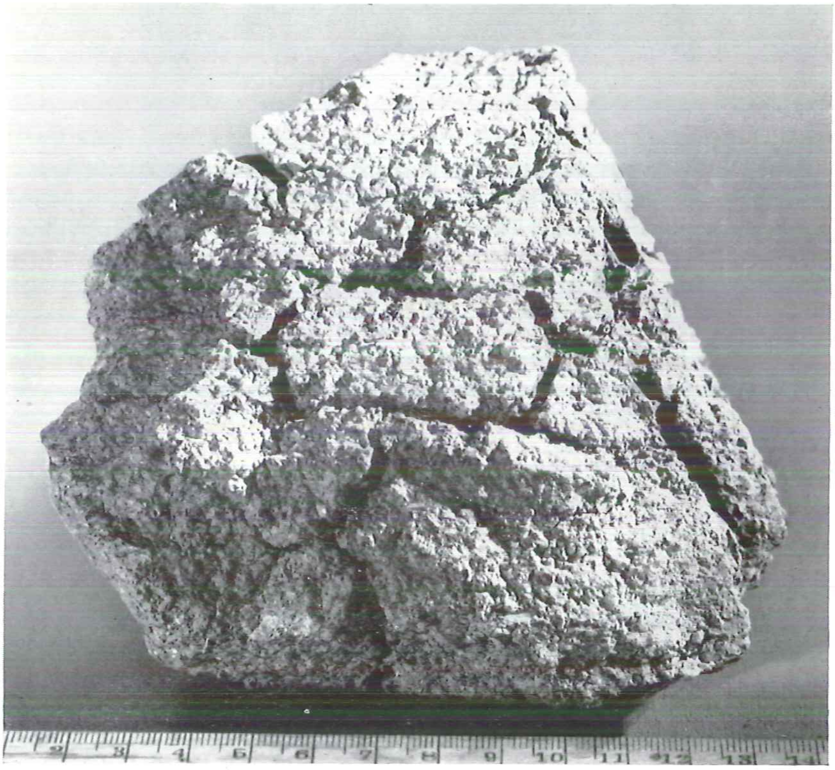


14b. *Nuée ardente* deposits, probably reaching as high as 180′, between Wash Gut and the foot of Booby Hill dome, south coast of Saba.
These partly stratified, partly chaotic agglomerates may be younger than the dome, whose vertically jointed andesite wall is clearly visible above the agglomerates.

15a. *Nuée ardente* deposit in the northern glacis of Soufrière Hills, near Paradise, Montserrat.



15b. *Nuée ardente* deposits from the eruptions in 1902 of the Soufrière volcano, St. Vincent, near the mouth of Rabaca Dry River, east coast. The height of the section is about 20 feet.



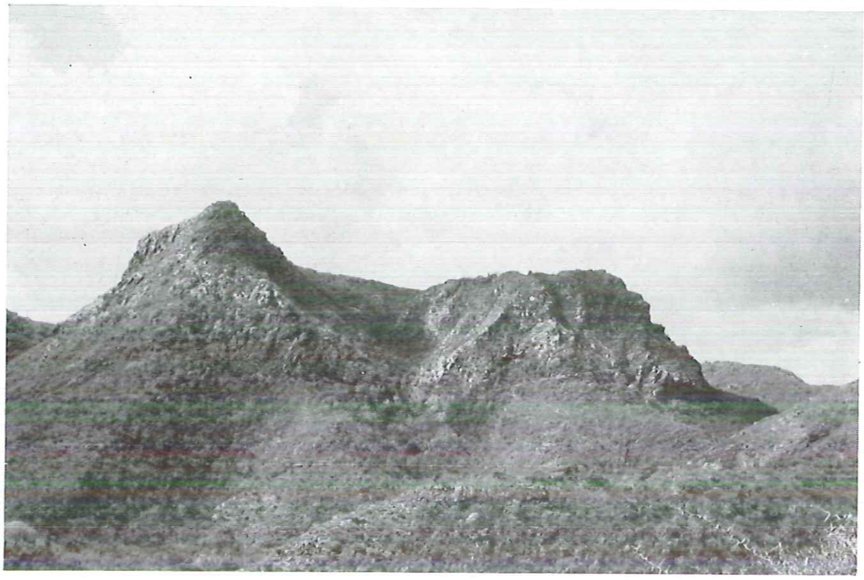
16. Andesitic breadcrust bomb, Crispine, Saba.

17. Aerial photograph of St. Eustatius, 1960 (scale 1 : 40,000).

The asymmetric, old and denuded volcano in the north-west is very different from the young Quill volcano. The white patches south of The Quill's crater belong to the tilted White Wall. Round Hill, probably a volcanic plug, is visible east of Oranjestad.

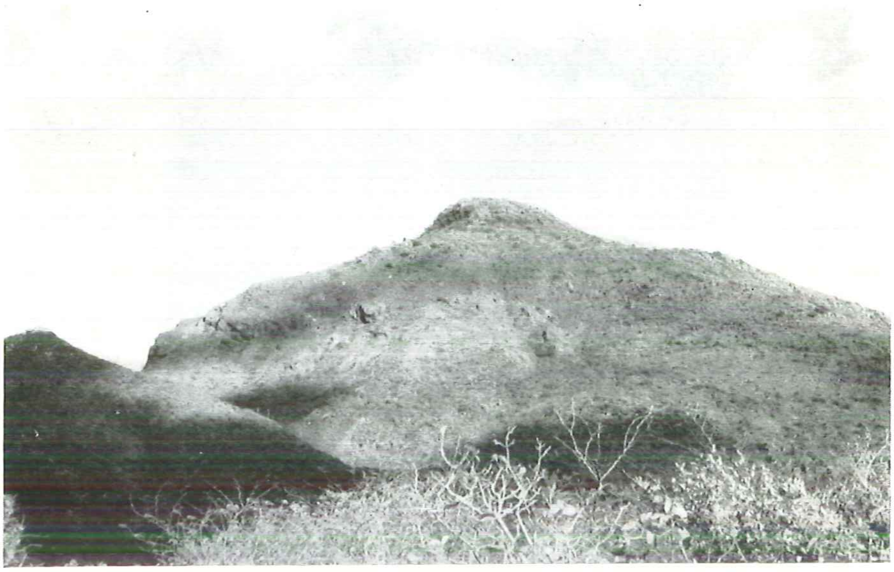
18. Aerial photograph of Bergje and Jenkins Bay, St. Eustatius, 1957 (scale 1 : 10,000). Bergje (732′) is thought to be the remnant of the main crater pipe of the old north-western volcano; it is an andesitic volcanic neck. It is partly surrounded by a somma-shaped wall, the result of erosional forces. Faulting may have been responsible for shaping the coast line.

19. Aerial photograph of Boven, St. Eustatius, 1957 (scale 1 : 10,000).
The top of Boven (964′) consists of an old lava flow, stretching NNE. The east coast is marked by several lava flows forming peculiar capes; softer agglomeratic rocks are found outcropping between them. Venus Bay (south-east) has a pebbly to sandy beach.



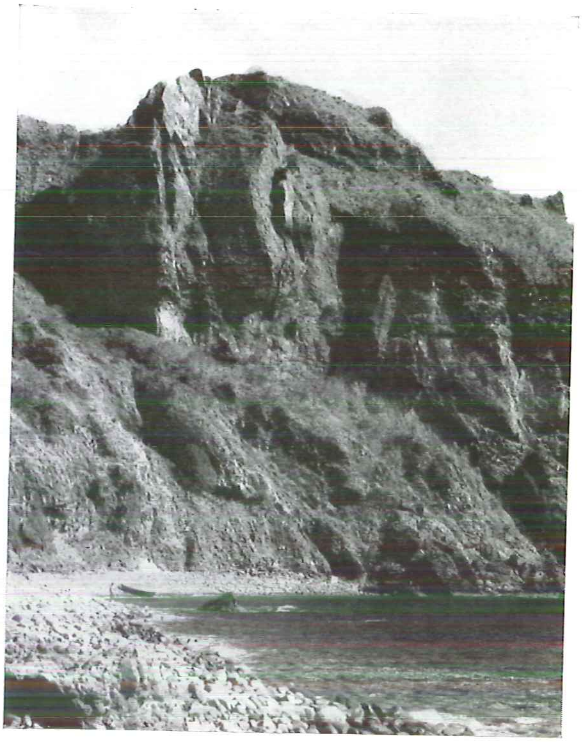
20a. Bergje (732′), St. Eustatius, seen from the south slope of Boven.

20b. Bergje, St. Eustatius, seen from the south slope of Boven.
It is a volcanic neck, surrounded on the western side by a somma-shaped wall.



21a. Boven (964′), St. Eustatius, seen towards the north-west; it is topped by an andesite bed. On the left: summit 139.1.

21b. Promontory of old lava flow, north of Venus Bay, St. Eustatius.



22a. Jenkins Bay, St. Eustatius, seen from the north. The high wall forms part of the "somma" of Bergje (compare Plate 18).

22b. Pilot Hill (374′), seen from Tumble Down Dick Bay, St. Eustatius. Seaward-dipping strata of tuffs and agglomerates, topped by an andesite bed.

23. "Down town", Oranjestad, St. Eustatius, with ruins of eighteenth century buildings in the surf. On the right, the steep coastal cliff (before removal of the vegetation). In the background, Panga ridge and the island of Saba.

24. The Quill volcano, Round Hill (left) and Oranjestad, St. Eustatius.

25a. The Quill volcano, St. Eustatius, as seen from the beach of Concordia Bay. The beach sand is rich in black titaniferous iron ore.

25b. The Quill volcano and Oranjestad, St. Eustatius, as seen from Fortress Amsterdam (Panga).

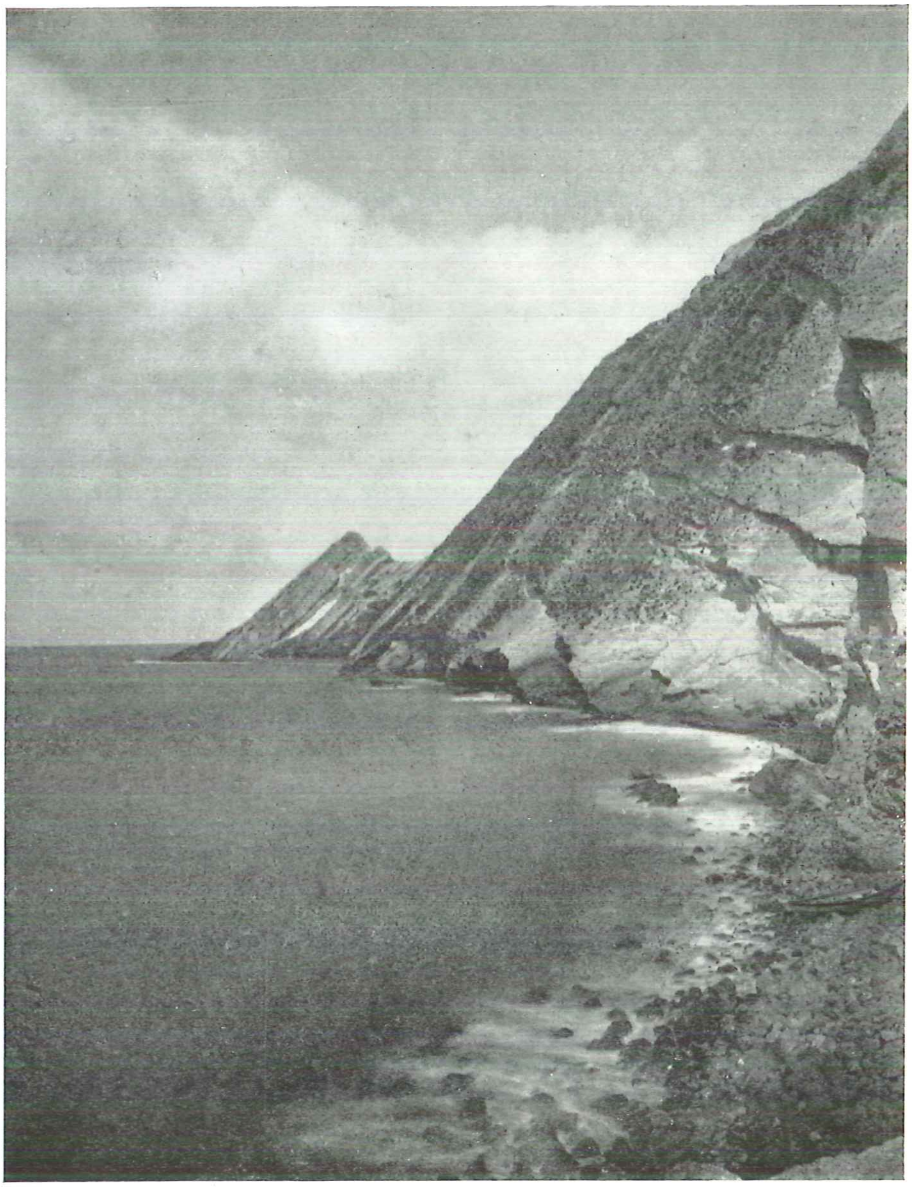
26a. Coastal cliff of Compagnie's Bay, St. Eustatius, with a well-bedded series of agglomerates and tuffs.

26b. Coastal cliff of Oranjestad, St. Eustatius. Agglomeratic beds wedging out between tuff layers.

27. Coastal cliff of Concordia Bay, St. Eustatius, with horizontal beds of volcanic tuff.

28. Aerial photograph of White Wall formation and the southern slope of the Quill volcano, St. Eustatius, 1957 (scale 1 : 7,200).

White Wall is bounded by Big Gut (left) and Soldier's Gut (right). Its seaward dip-slope shows almost horizontal stripes and some fault lines. The much smaller limestone slab of Sugar Loaf is seen near the mouth of Big Gut. Isolated outcrops of the White Wall formation occur in the headwater tributaries of Toby Gut, west of Big Gut.



29. Sugar Loaf (left) and White Wall, St. Eustatius, seen to the west from the mouth of Soldier's Gut (1885).

30a. Sugar Loaf (240′) and, on the left, the lower portion of White Wall, St. Eustatius, seen to the east from near Fortress de Windt.

30b. Panorama of the south slope of the Quill volcano and White Wall, St. Eustatius, seen from nea Fortress de Windt.
Left: isolated white outcrops of the White Wall formation in the slope of the volcano; strata of tuffs an agglomerates on both sides of the western branch of Big Gut. Centre: eastern branch of Big Gut wit landslide. Right: White Wall.

31a. Coastal cliff east of Landing Bay, Montserrat, seen towards the north-east. An uptilted, steeply dipping series of yellow-white tuffaceous and agglomeratic limestones between brown volcanic agglomerates (right) and reddish-brown agglomerates (left).

31b. Landing Bay, Montserrat, seen towards the north-east. Uptilted fossiliferous strata occur in the coastal cliff washed by the white surf.

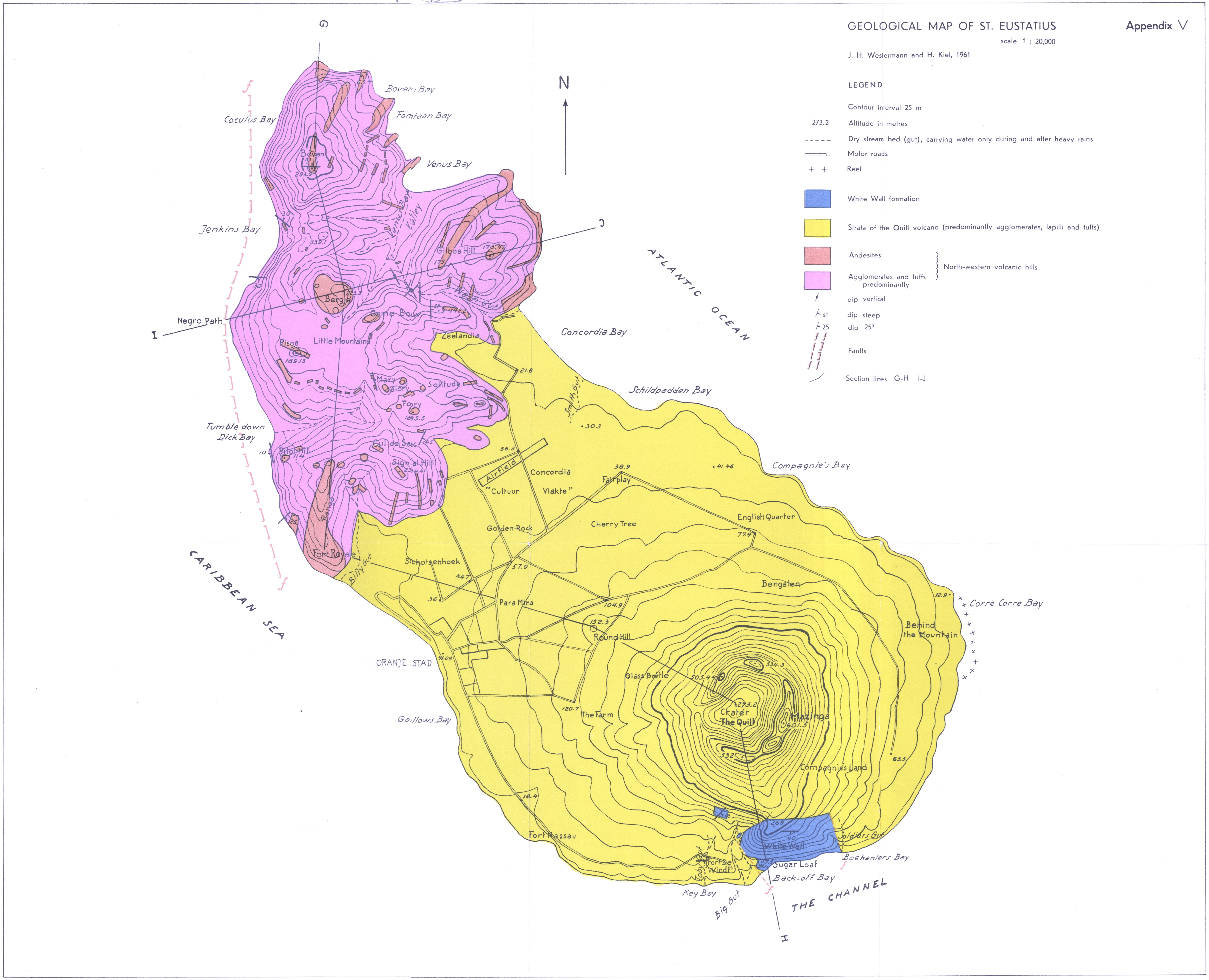
32a. Steep, upturned limestone slabs, NW Brimstone Hill, seen from the north-west.

32b. Brimstone Hill, St. Kitts, seen towards the north-west. On the top: the fortress, "the Gibraltar of the West Indies". To the right: Mount Misery.

33a. Silhouette of St. Eustatius, seen from Belmont Estate, St. Kitts.

33b. Salt Pond Peninsula, St. Kitts. View from Simson's house across Great Salt Pond towards Nevis (Peak of Nevis in the background).

Publication of the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht, No. 24



Publication of the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht, No. 24

TOPOGRAPHICAL MAP OF ST. EUSTATIUS

Appendix IV

scale 1 : 20,000

showing rock-sample localities (in red) and survey routes (in red)

J. H. Westermann and H. Kiel, 1961

Topography based on Topographical Map 1915, and on aerial photographs taken by KLM Aerocarto in 1957 on a scale of approximately 1 : 8,000

LEGEND

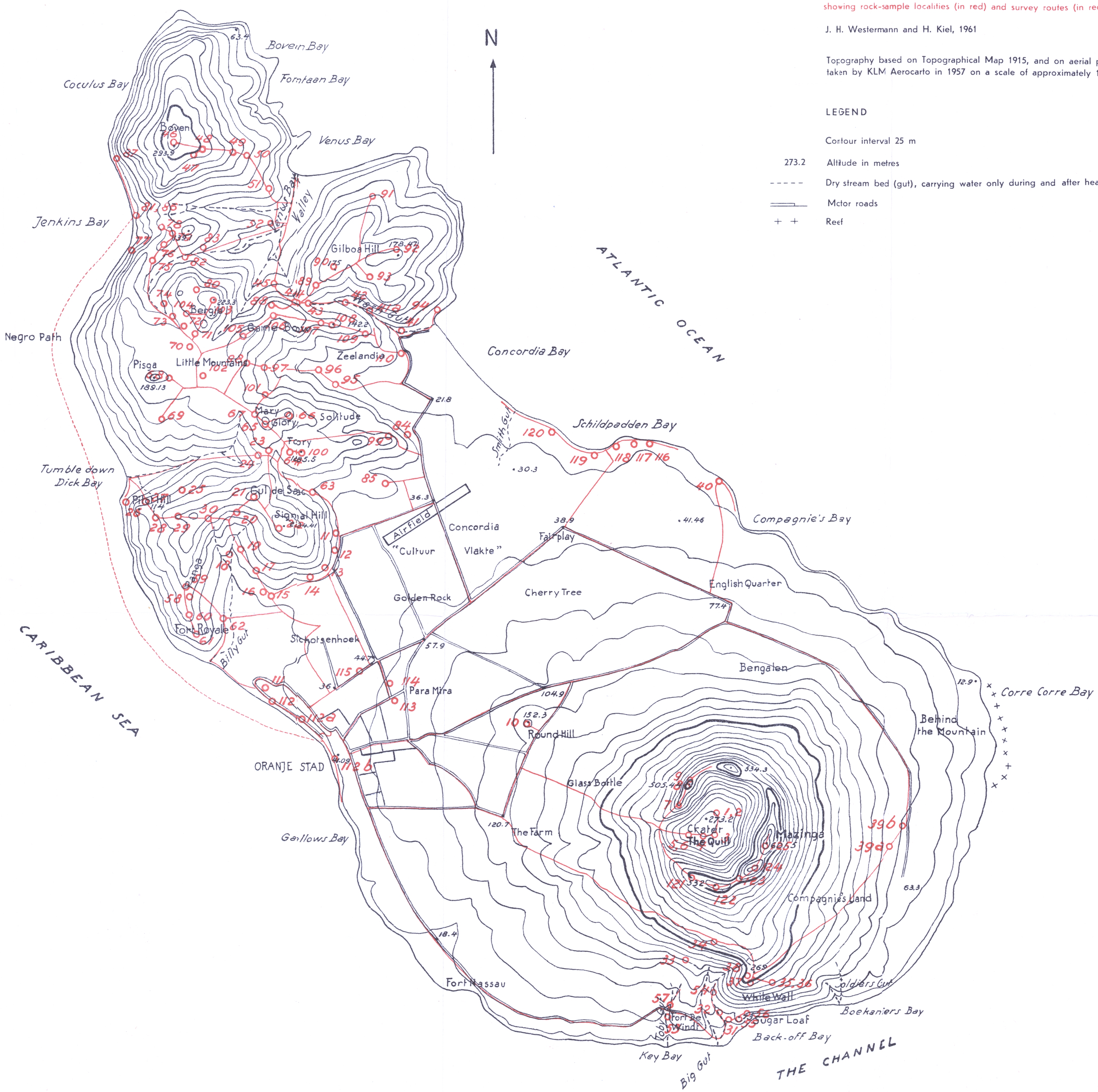
Contour interval 25 m

273.2 Altitude in metres

- - - - Dry stream bed (gut), carrying water only during and after heavy rains

═ Motor roads

+ + Reef



Publication of the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht, No. 24

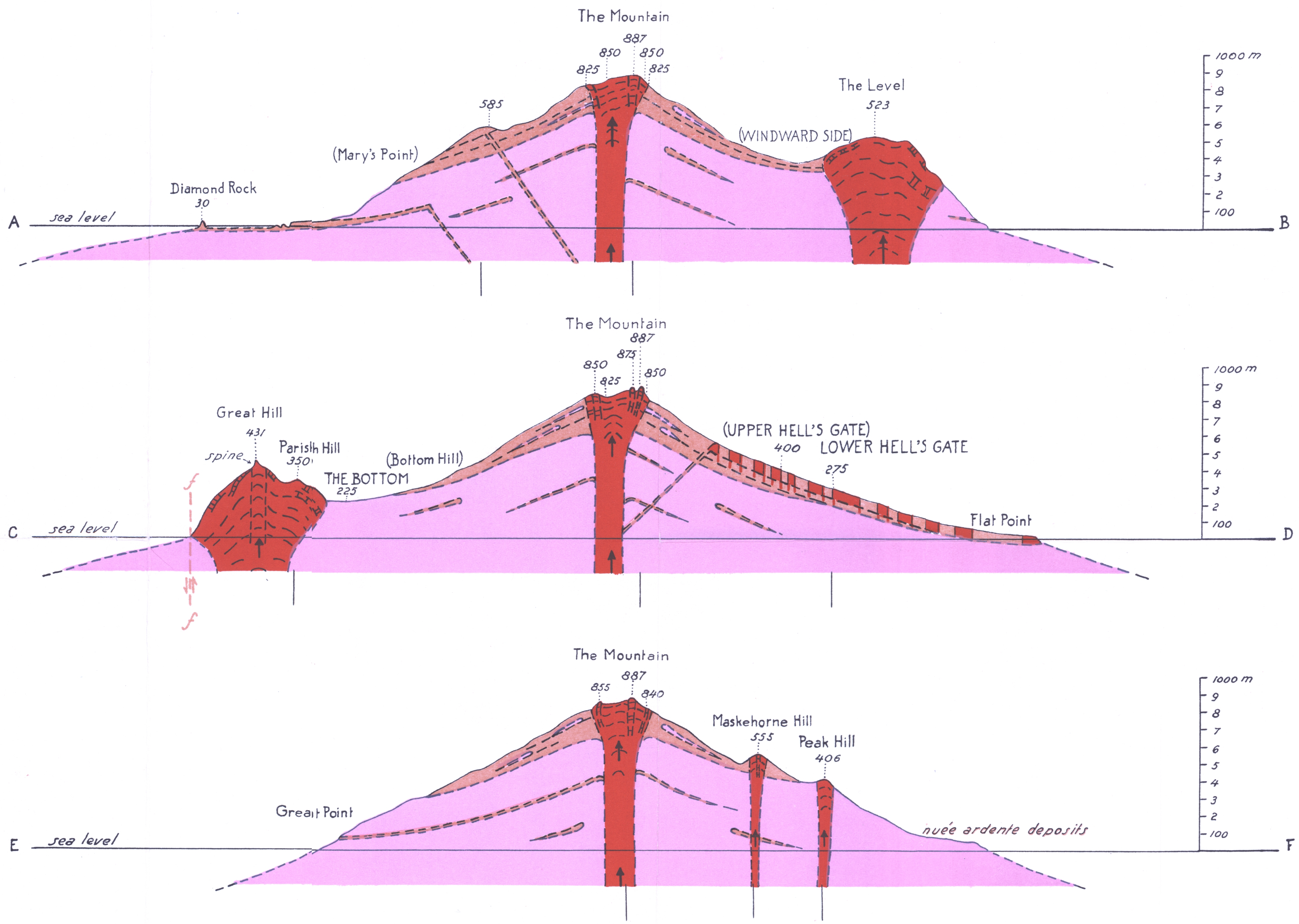
2828-3 62x42

Appendix III

IDEAL SECTIONS OF SABA

scale approximately 1 : 20,000

J. H. Westermann and H. Kiel, 1961



LEGEND

Nuée ardente deposits (indicated in Section E-F)

Volcanic domes, plug domes and isolated volcanic dikes

Lava flows of Flat Point / Behind The Ridge

Higher unit of predominantly andesites

Basal unit of predominantly agglomerates and tuffs

Fault

Deflection point of section line

Publication of the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht, No. 24

GEOLOGICAL MAP OF SABA

Appendix II

scale approximately 1 : 20,000

J. H. Westermann and H. Kiel, 1961

LEGEND

Contour interval 25 m

821 Altitude in metres

- - - - - Dry stream bed (gut), carrying water only during and after heavy rains

Jeep road

Path

not indicated on map — Horizontal tuff deposits (in the ravine connecting The Bottom and Fort Bay)

limits not indicated on map — *Nuee ardente* deposits (south coast between St. John's Flat and Booby Hill domes)

Volcanic domes, plug domes and isolated volcanic dikes

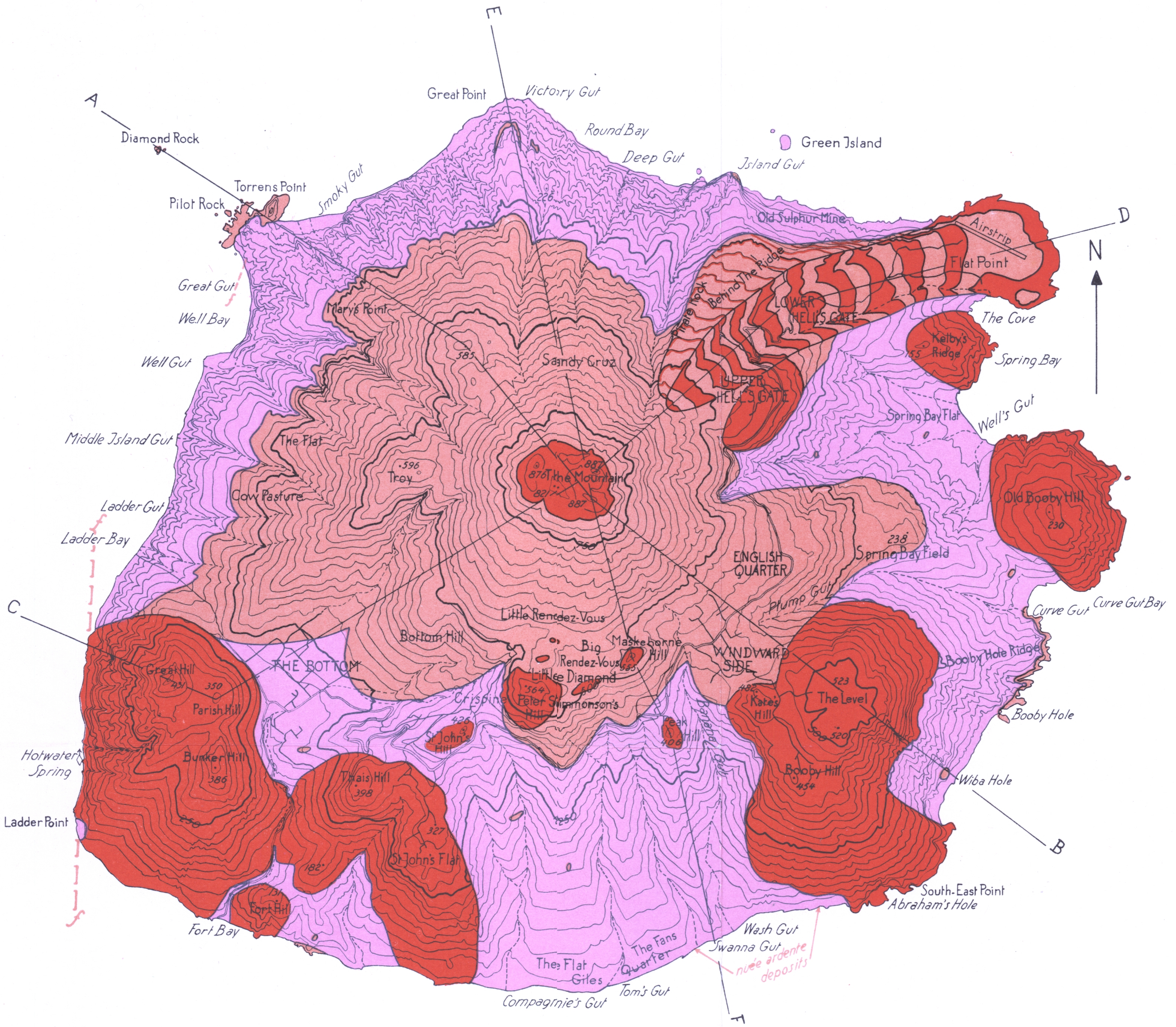
Lava flows of Flat Point / Behind The Ridge

Higher unit of predominantly andesites

Basal unit of predominantly agglomerates and tuffs

Faults

Section lines A-B C-D E-F



raubbes 2828-1 40x36 pdf

Publication of the Foundation for Scientific Research in Surinam and the Netherlands Antilles, Utrecht, No. 24

TOPOGRAPHICAL MAP OF SABA

Appendix I

scale approximately 1 : 20,000

showing rock-sample localities (in red) and survey routes (in red)

J. H. Westermann and H. Kiel, 1961

Topography based on map drawn by KLM Aerocarto from two aerial photographs taken in 1959 on a scale of approximately 1 : 40,000 (without terrestrial basis)

LEGEND

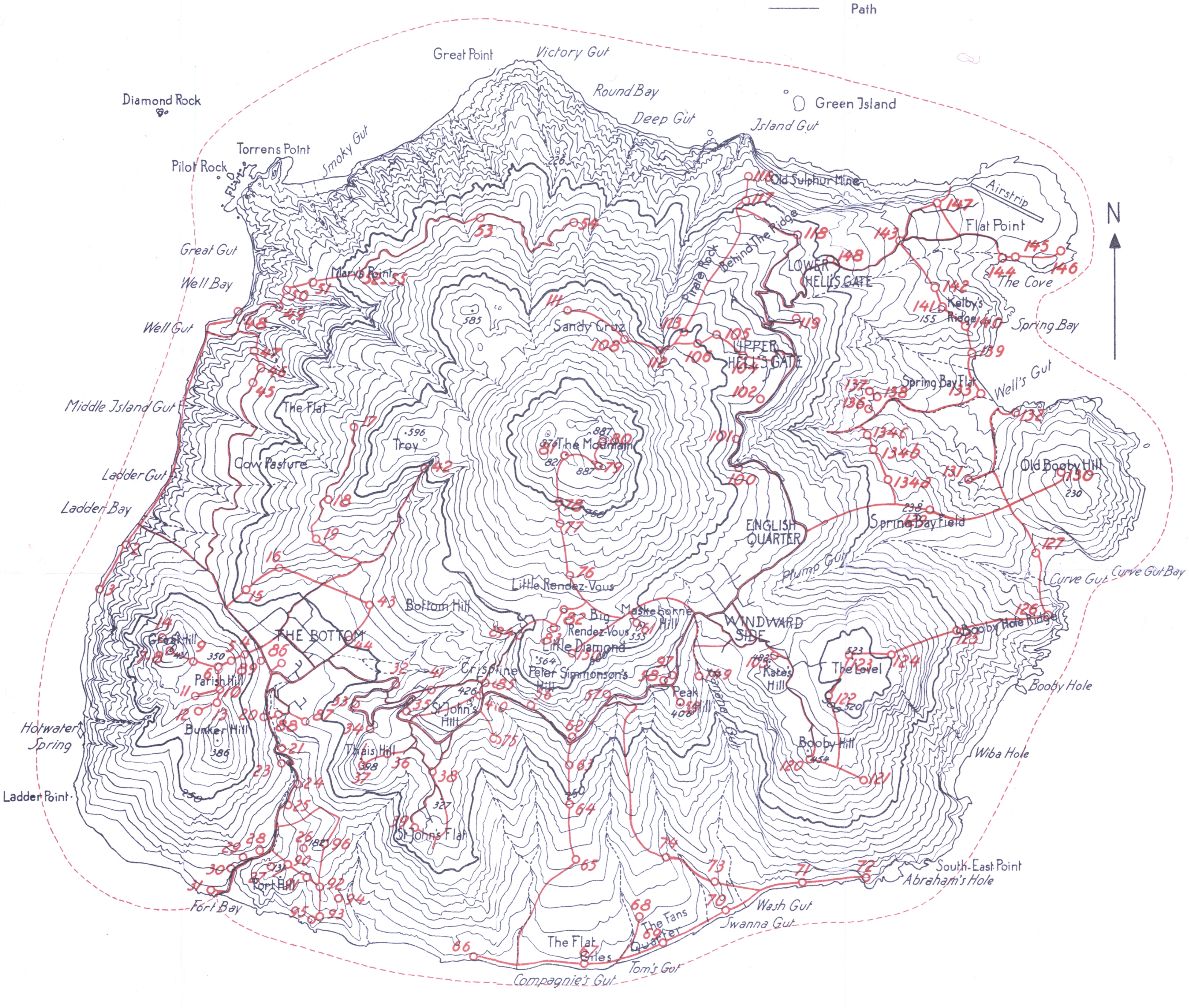
Contour interval 25 m

821 Altitude in metres

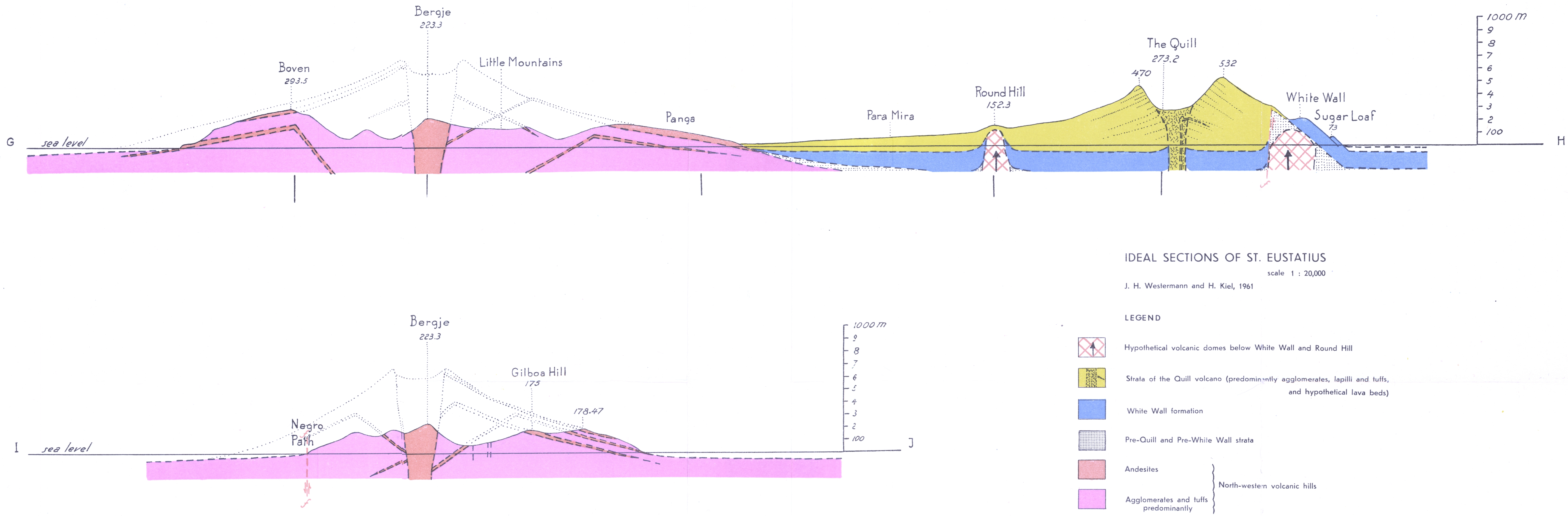
- - - - Dry stream bed (gut), carrying water only during and after heavy rains

═══ Jeep road

—— Path



Appendix VI



IDEAL SECTIONS OF ST. EUSTATIUS

scale 1 : 20,000

J. H. Westermann and H. Kiel, 1961

LEGEND

- Hypothetical volcanic domes below White Wall and Round Hill
- Strata of the Quill volcano (predominantly agglomerates, lapilli and tuffs, and hypothetical lava beds)
- White Wall formation
- Pre-Quill and Pre-White Wall strata
- Andesites } North-western volcanic hills
- Agglomerates and tuffs predominantly } North-western volcanic hills
- Vertical beds of agglomerates and tuffs
- Fault
- Reconstruction of North-western volcano
- Deflection point of section line