

Thesis submitted for the degree of Doctor of Philosophy  
in the University of Oxford

**THE VOLCANIC HISTORY AND PETROLOGY OF THE  
SOUFRIÈRE REGION, ST. LUCIA**

by  
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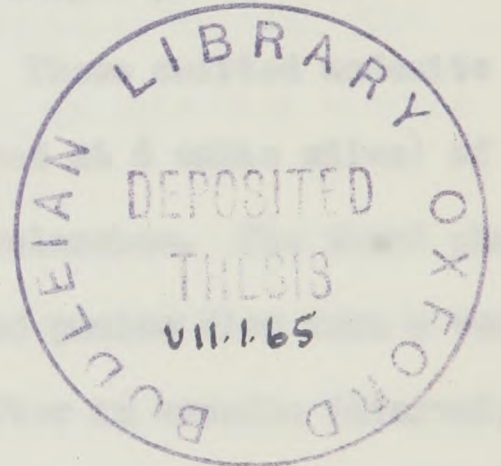
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## ABSTRACT

The Soufrière region, which includes the most recently active volcanic centre on the island of St. Lucia in the West Indies, is the site of a relatively ancient volcanic caldera. This structure, with a diameter of approximately 4 miles, has an age of definitely more than 50,000 years and probably of several times this age. Apart from continuous solfataric activity, there have been no historic eruptions, and the morphology of the caldera has been considerably modified by erosion since the time of its formation. The history of volcanic events in the Soufrière region may be divided into four principal phases: the first involved the effusion of basalt lava from vents both within and to the east of the site of the ultimate caldera. During the second phase, following what was probably a long time-interval, a group of andesitic strato-volcanoes developed in an area slightly to the northeast of the ultimate caldera. These emitted andesite flows and, apparently, a very large volume (estimated at 6 cubic miles) of pyroclastic material, probably mainly as glowing avalanches. The third phase opened with the emission of andesite pumice fall and pumice flow from a vent which probably lay within the ultimate caldera. After an erosion interval, activity was renewed on a more violent scale, in a series of ultravulcanian explosions, and these were followed by a second period of voluminous, andesite pumice flows which immediately preceded caldera subsidence. The fourth and final phase has occupied the relatively long period since collapse, during which fifteen volcanic domes and seven craters have developed within the caldera: initially of andesitic composition, around the margin of the caldera, and subsequently of dacite lava, towards the centre of the collapsed area. The effusion of these lavas was accompanied by pyroclastic eruptions

of pumice fall (with an estimated volume of 1.23 cu. miles) and pumice flows (with an estimated volume of 0.27 cu. mile). The youngest large pumice flow, dated by the radiocarbon method, occurred 39,050 years ago.

The mineralogy of the St. Lucian lavas compares closely with that of typical, calcium-rich, island-arc suites. All rocks contain calcic plagioclase phenocrysts, the cores of which generally consist of bytownite while the rims, especially in the andesites and dacites, include oscillatory zones in which the calcium content commonly decreases to a minimum of about  $An_{40}$ . The mafic minerals in the basalts include augitic clinopyroxene, with or without orthopyroxene and olivine, whilst in the andesites, orthopyroxene (hypersthene or ferrohypersthene) predominates. The dacites are characterized by amphibole (common hornblende, oxyhornblende, or cussingtonite) and biotite, with subordinate orthopyroxene and occasional olivine phenocrysts, accompanied by 5 - 15% of large, rounded or bipyramidal phenocrysts of quartz. The youngest dacites of the Soufrière region are unusual in that they contain phenocrysts of calcium-poor, cussingtonitic amphibole.

Twenty new analyses of whole rocks from St. Lucia are presented, and these extend over a silica range from 50% in the earliest to 66% in the most recent products. The suite is relatively rich in alumina (15 - 19%) and poor in alkalis ( $Na_2O$  up to 3.5%,  $K_2O$  up to 1.5%), although by West Indian standards the potash content is high. The rocks as a whole are members of the calc-alkaline, "Pacific" series, characteristic of mobile structural belts. The silica variation diagram for St. Lucia illustrates the compositional heterogeneity of the basalts, and the gap (from 53 - 59%) in silica content, which also corresponds to the gap in time between the eruption of the basalts (phase 1) and the andesites (phase 2). The andesites,

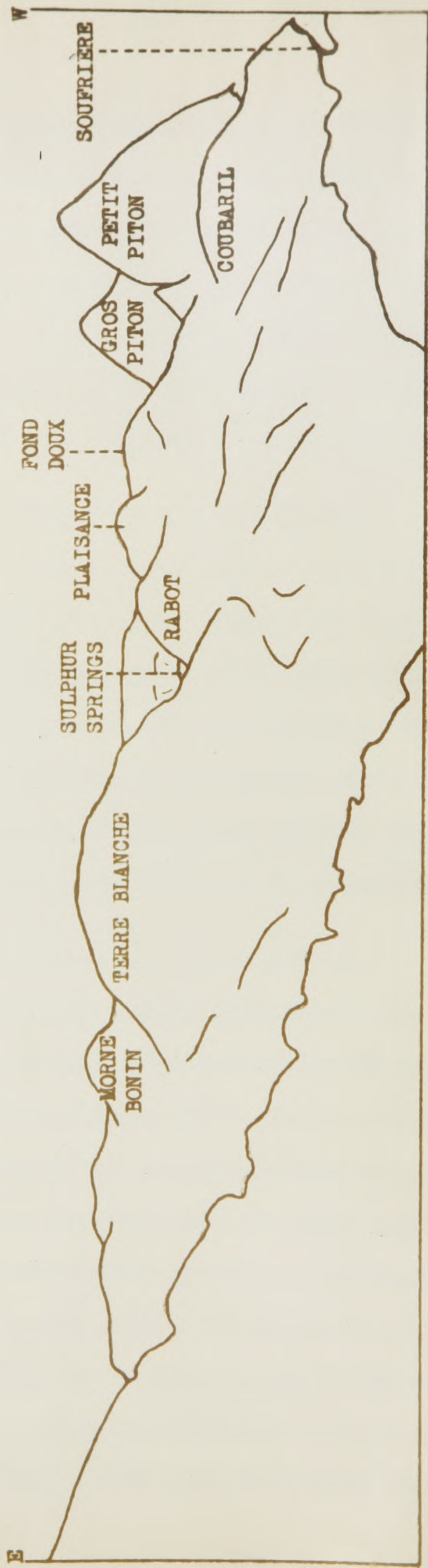
on the other hand, appear to be closely related to the dacites, forming a single, continuous series. A comparison of the Fe : Mg : Na+K ratios reveals the close chemical similarity of the andesites and dacites of St. Lucia to those of Crater Lake, Oregon, and to the "hypersthenoic" series of Hakone volcano, Japan. The Ca : Na : K ratios show that the rocks of St. Lucia contain a higher proportion of potash relative to soda and lime than most other suites of the orogenic regions.

The distribution of the minor elements in ten rocks from St. Lucia conforms closely to that found in other West Indian and orogenic volcanic suites, with the notable exception of rubidium, which is much more abundant in the acid rocks of St. Lucia than in those of other suites from the Lesser Antilles. A co-variance plot of seven minor elements in the analysed samples from St. Lucia provides an arrangement of specimens along the abscissa which is closely parallel to the order according to silica content, and this in turn corresponds to the chronologic sequence of eruption.

The basalts of St. Lucia are believed to have crystallized from essentially unmodified, primary magma. The occurrence in the Soufrière region of two basalt varieties, namely porphyritic and aphyric, is explicable either as the result of the accumulation at depth of plagioclase feldspar crystals, or alternatively may be attributed to the independent development two primary magmas, of tholeiitic and alumina-rich types. There is no support in the Soufrière region for differentiation of basalt, or assimilation by primary basalt magma, on a sufficiently extensive scale to produce the observed volume and sequence of the more acid lavas. It is, therefore, proposed that the andesites and dacites of St. Lucia were derived largely by partial melting of local crustal material.

# FRONTISPIECE.

Panorama of the Soufrière region from the north. Terre Blanche (1,900 ft. a.s.l.) represents a morphologically intact dome, contrasting in shape with the Petit Piton (2,400 ft. a.s.l.) from which almost all of the marginal talus appears to have been removed. Fond Doux (1,663 ft. a.s.l.) is believed to represent the stump of an even earlier dome. Gases from the Sulphur Springs are the cause of the stunted vegetation on the western flanks of Terre Blanche Hill.



**FRONTISPIECE**





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## 1. INTRODUCTION

The subject of this thesis is the geology of the most recently active volcanic centre on the island of St. Lucia. The field geology, petrography, mineralogy and chemical composition of the erupted materials are described and likely genetic processes are discussed.

Field work was carried out in the early months (the West Indian dry season) of 1962 and 1963. A total of 16 weeks was spent on St. Lucia, and an additional 3 weeks on other islands of the Antillean arc between St. Vincent and St. Kitts. A further week was spent at the University of the West Indies Seismic Research Unit, Trinidad. For field mapping, the 1:25,000 topographic sheets published by the Directorate of Overseas Surveys (D.O.S. No.345, 1958) were reproduced on a scale of 1:10,560. These were used in conjunction with vertical air photographs of scale 1:15,200. A geological map was produced of an area of 65 sq. miles around Soufrière (the southwestern quarter of the island) and a reconnaissance survey was made of the whole island.

779 rock and ash specimens were shipped to Oxford, where laboratory work included petrographic study of 246 thin sections, chemical analysis of 22, and partial chemical analysis of a further 12 samples. 10 of these rocks were analysed spectrographically for minor elements. Modal compositions of all analysed rocks were determined by point counter,

and the constituent minerals were separated for refractive index measurement. 65 samples of unconsolidated pyroclastic material were analysed granulometrically.

This investigation forms the second regional study in a programme of volcanological research in the Windward and Leeward Islands, financed by a Special Grant from D.S.I.R., and directed by Professor L. R. Wager and Dr. G. M. Brown at Oxford University, with the active collaboration of Dr. G. R. Robson of the Seismic Research Unit, University of the West Indies, Trinidad. The project was initiated by Professor Wager and Dr. Robson, who made a reconnaissance survey of the Lesser Antilles in October and November, 1959. The first regional study, on the geology of Mt. Misery volcano, St. Kitts, was submitted as a D.Phil. thesis at Oxford by Dr. P. E. Baker (1963). The project as a whole is concerned with the active or potentially active volcanic centres in the Lesser Antilles. It seeks to provide a detailed account of their past eruptive habits, petrology and petrochemistry, and thereby to explain more fully the evolution of the Antillean islands, in terms of the types and sequence of magmas which have risen to the surface in this part of the globe. A detailed investigation of the geology of this part of the world seemed particularly desirable in view of the large amount of geophysical and seismological data obtained in the region during the past decade.

## 2. THE LESSER ANTILLES: A VOLCANIC ISLAND ARC

FIG. 1

MAP OF THE LESSER ANTILLES

### 2. 1. PHYSIOGRAPHY OF THE ISLAND ARC

The Lesser Antilles (Fig.1) are a chain of islands linking the northeastern corner of South America with Puerto Rico and the Greater Antilles. They extend more or less north-south for a distance of 450 miles, and mark the highest points along a series of arcuate ridges, convex toward the Atlantic Ocean.

The main ridge describes a smooth curve from Grenada in the south to Saba in the north: these islands consist of Tertiary and Quaternary volcanic material, locally flanked by thin lenticles of marine calcareous sediments. It is noteworthy that the crest of this ridge lies at about 2,000 feet below sea level between all the more widely separated islands north of St. Lucia (see bathymetric map, Fig.2). On the islands, the highest peaks stand 3,000 to 5,000 feet above sea level, so that each volcanic pile rises 5,000 to 7,000 feet above the general level of the ridge.

An external arc, composed of lower-lying limestone islands with subordinate volcanics, diverges from the main volcanic arc in Guadeloupe, and includes the eastern half (Grande Terre) of Guadeloupe, Desirade, Antigua, Barbuda and the Anguilla group. These "limestone Caribbees" are separated from the volcanic Leeward Islands by water not deeper than 6,000 ft. and most of them stand on broad submarine banks

FIG. 1

MAP OF THE LESSER ANTILLES

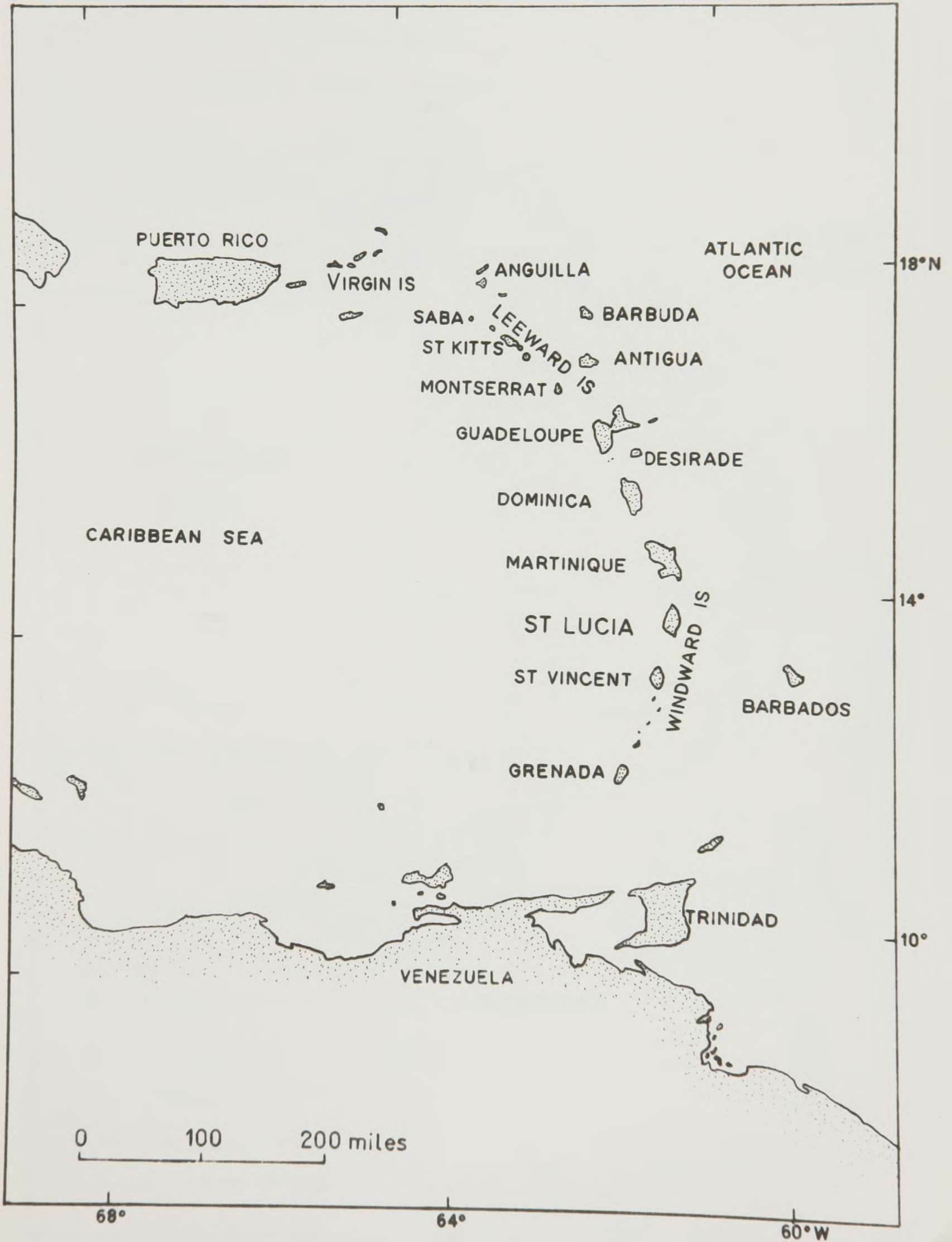
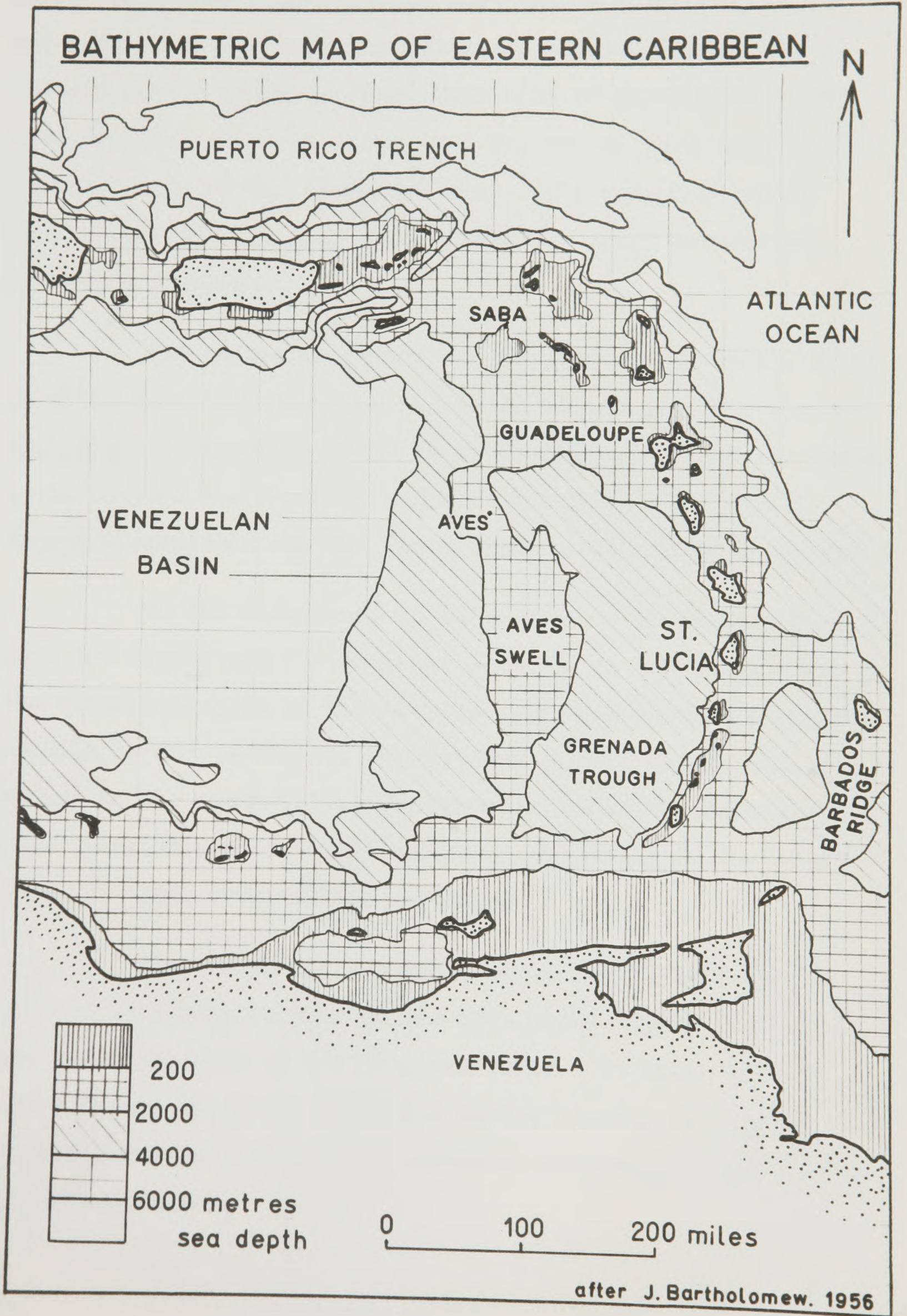


FIG. 2



which are nowhere submerged by more than 600 ft. To the north and east of these banks, by contrast, the sea floor plunges steeply into a south-eastward extension of the Puerto Rico deep, so that there is water over 18,000 ft. deep outside the entire length of the limestone arc. This external trench shoals southward to less than 12,000 ft. depth between St. Lucia and Barbados.

The outermost feature in the arc system is the ridge on which lies the limestone island of Barbados. This has been explained by several authors (e.g. Woodring, 1928) as an extension, through the Northern Range of Trinidad, of the fold system responsible for the Venezuelan Cordillera de la Costa.

On the Caribbean, or inner side of the main volcanic arc, sea depths are the converse of those on the outer side: the western margins of the southern (Windward) islands descend rapidly to over 6,000 ft. to form the Grenada Trough (Fig.3), whilst to the southwest of the northern (Leeward) islands the water remains comparatively shallow, especially in the area south of Saba, known as the Saba Bank.

The fourth and innermost north-south ridge in the eastern Caribbean is that of the Aves Swell, lying parallel to and 150 miles west of the Windward Isles. It rises to within 6,000 ft. of sea level along its entire length, but only protrudes above sea level at its northern extremity in the small island of Aves.

FIG. 3

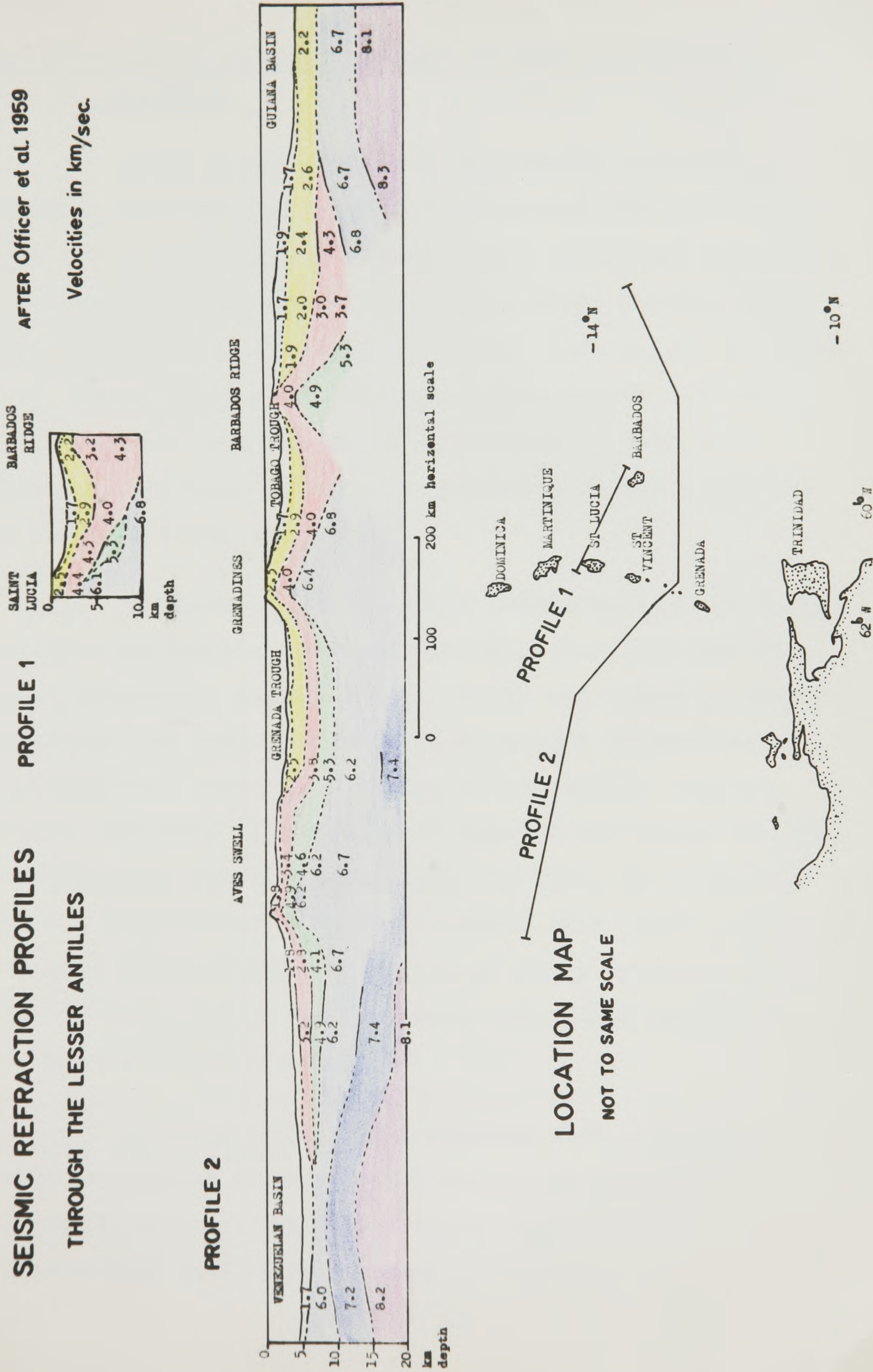
SEISMIC REFRACTION PROFILES

PROFILE 1

AFTER Officer et al. 1959

THROUGH THE LESSER ANTILLES

Velocities in km/sec.



## 2. 2. THEORIES ON THE STRUCTURAL EVOLUTION OF THE EASTERN CARIBBEAN

Rocks at the surface in the Greater Antilles and northern Venezuela are largely of Cretaceous age, and represent a thick geosynclinal sequence (with volcanics) which has undergone low grade metamorphism, large-scale folding, and igneous intrusion. Those of the Lesser Antilles, on the other hand, are of Tertiary and Quaternary age, largely volcanic, unmetamorphosed and relatively undisturbed by folding or faulting. No rocks older than Tertiary have been identified in the Lesser Antilles.

Theories on the structural development of the Lesser Antilles are notable for their variety. They fall into two broad categories, dependent upon whether the author in question considered the Caribbean crust to be oceanic or continental. Opposing views were stated by two of the earliest writers, Spencer and Hill. Spencer (1895) regarded the Lesser Antilles as relics of a formerly widespread land area, the valleys of which made the present-day ocean deeps. Hill (1905, p.276), on the contrary, regarded the islands as simple volcanoes built up from the ocean floor, "as oceanic in origin and relations as the islands of the Pacific".

Woodring (1928, 1954) supposed that a submarine ridge below the present islands formed during the late Cretaceous (Laramide) orogeny. He believed that there must have been a volcanic land area in the present Venezuelan Basin, from which

the thick Cretaceous geosynclinal deposits of the Greater Antilles were derived.

Schuchert (1935, p.393) appears to support the view that tectonic processes were responsible for formation of the arc, on which the volcanoes subsequently grew as "young volcanic islands parasitic upon the folded formations making the much older basement of the (Greater) Antillean and Venezuelan mountain chains".

Theories up to this time had not been influenced by geophysical considerations, which have been quoted as important evidence by all subsequent writers. The earliest geophysical work (Hess, 1938) consisted of gravity measurements, and revealed a belt of negative anomalies along a line connecting the Puerto Rico Trench with the Barbados Ridge, and a belt of positive anomalies running along the volcanic island chain.

To account for the negative anomaly, Vening Meinesz (1954) suggested that the Puerto Rico Trench marked the site of a descending convection current, causing downbuckling of the crust and a "topographic deficiency of matter". Ewing and Worzel (1954), without offering any explanation of its manner of formation, suggested that the Puerto Rico Trench contained a great thickness of sediment which alone could account for the negative gravity anomalies.

The most recent phase of geophysical research in the Caribbean region has concentrated upon the measurement of seismic

velocities in the crust (Fig.3) and a large number of these velocity profiles have been produced by Ewing, Officer et al. (1957), and Officer, Ewing et al.(1959). They found that beneath the Caribbean Sea no sharp change in seismic velocities existed between the mantle and overlying lower velocity layers, and stated (Officer, Ewing et al. 1959, p.107): "a major difference in an oceanic section and a Caribbean section is that in the former there appears to be an abrupt change in velocity from about 6.5 to 8.1 km/sec. at the crust-mantle boundary, whereas in the latter we usually find material whose velocity is 7.1 - 7.7 km/sec. between the mantle and the 6.5 km/sec. crustal material". The average Caribbean crust was also found to be thicker, with lower velocities in the upper part, than a typical oceanic section, and this they tentatively explained (1959, p.107) as the result of extensive intrusion "by a differentiate migrating upward from deep in the mantle". They concluded that the Caribbean was not a drowned continental area, but an altered oceanic region in the process of becoming an addition to the continent, and that the outer deep-sea trench had been depressed by overthrusting of the expanded Caribbean crust. Beneath the volcanic islands the intermediate velocity layers were found to be thicker and to rise closer to the surface.

Hess (1960a) maintained that island arcs developed in regions of oceanic crust. He emphasised the significance of serpentinitised peridotite in the cores of Puerto Rico anticlines, and that no granitic basement had been found in all the Greater

Antilles, in contrast to the granitic basement of the Venezuelan Cordillera de la Costa. He suggested that 40% serpentinitised peridotite below the Caribbean might be responsible for anomalous seismic wave velocities in the lower part of the crust. Elsewhere, however, he has suggested (1960b, p.180) that "most calc-alkaline magmas are derived from partial fusion of the continental crust", from which he seemingly infers that even if the lower crust beneath the Caribbean sea consists largely of serpentinitized peridotite, there is an abundant supply of continental material capable of yielding acid calc-alkaline lavas beneath the present volcanic arc.

In this context, the existence of a dioritic to granodioritic batholith in the Virgin Islands (Helsley, 1960) and quartz-diorites on St. Martin and St. Barthelmy, in the Anguilla group (Christman, 1953) and on Désirade, near Guadeloupe (Barrabé, 1942, p.148-52), must be regarded as significant.

In spite of the large amount of geophysical information recently compiled, which has led to a relatively detailed knowledge of the physical properties of the crust in the eastern Caribbean region, the composition of this crust in terms of rock types is still not well understood. The reason is that seismic velocity data are open to a variety of interpretations, and cannot be translated into definite rock types. Values of between 6-8 km/sec., for example, can be explained either by serpentinitized peridotite (Hess, 1960a, p.237), or by a relatively dense

sialic rock. It is, however, conclusively established that:

- 1) The crust beneath the Caribbean sea is not typically oceanic.
- 2) There is a definite thickening beneath the island arc-complex, relative to the sub-Caribbean and Atlantic oceanic crust, of crustal layers with a velocity of less than 5.5 km/sec. corresponding to sialic material and not to normal or hydrated mantle material.

From the geophysical evidence it can be concluded that the Lesser Antilles are neither simple volcanic piles rising from an oceanic-type crust, nor do they simply represent upstanding relics of an extensive submerged continent, although continental material is definitely concentrated beneath the island arc.

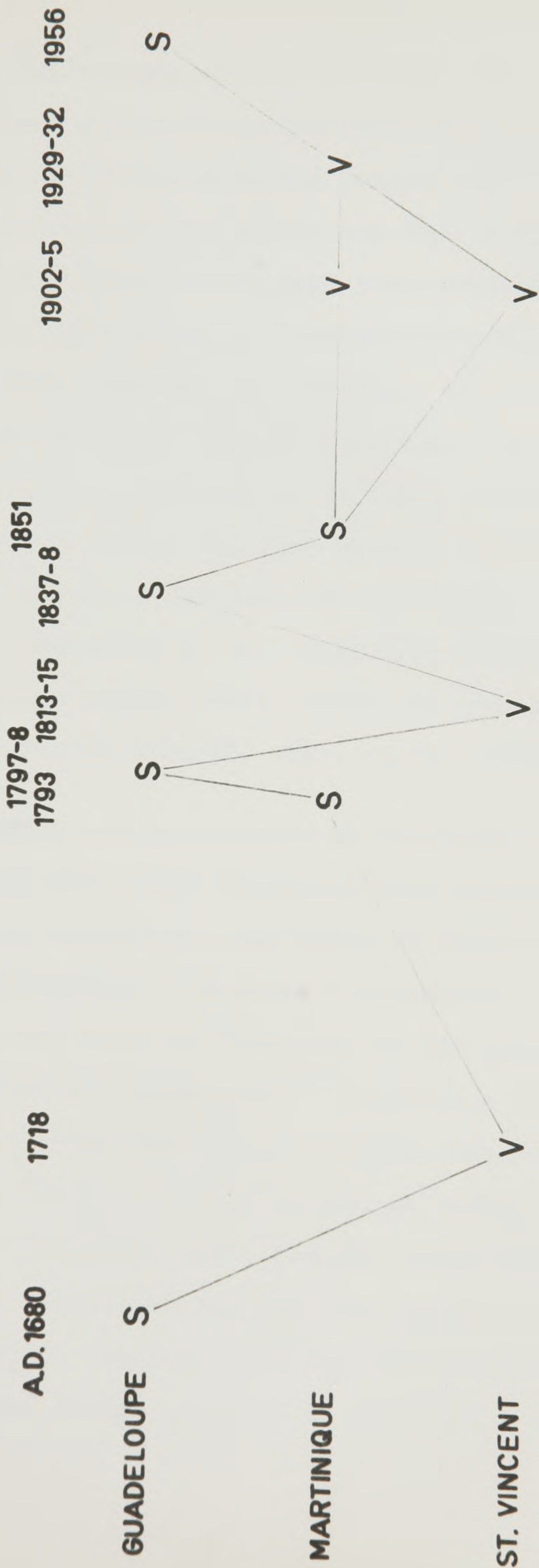
## 2. 3. RECORDED VOLCANIC AND SEISMIC ACTIVITY

### Eruptions

Records of volcanic and seismic events on the islands began with continuous colonization by Europeans in the late seventeenth century, though the accuracy of reports dating before 1800 is often in doubt. Of the eight islands from St. Kitts to St. Vincent on which historic activity of some kind is reported, (MacGregor, 1938, p.7), only three, St. Vincent, Martinique and Guadeloupe, are definitely known to have had eruptions involving fresh incandescent lava. The distribution and dates of these eruptions are shown in Fig.4.

FIG. 4

HISTORIC ERUPTIONS IN THE LESSER ANTILLES INVOLVING FRESH INCANDESCENT LAVA



V VIOLENTLY EXPLOSIVE (VULCANIAN-PELEAN) ACTIVITY  
S MILDLY EXPLOSIVE (STROMBOLIAN) ACTIVITY

On Guadeloupe, none of the four recorded eruptions of the Soufrière volcano involved more than mildly explosive ash and scoria emission or lasted longer than a few weeks. It is only on St. Vincent and Martinique that violent historic eruptions of Vulcanian-Peléan type have occurred. Three such eruptions have taken place at the Soufrière volcano of St. Vincent, in 1718, 1812-14, and 1902-03. On Martinique, Mt. Pelée produced two small lateral eruptions, in 1792 and 1851, prior to the violent outburst of 1902-05, accompanied by glowing avalanches, which became the type-example of Peléan activity. A second phase of Pelean activity occurred from 1929-32. Both 1902 and 1929 eruptions of Mt. Pelée were accompanied by the growth of a large summit dome: these are the only two examples of dome formation in historic times in the West Indies.

Despite the uncertainty of the early record, it is clear that only five major eruptions have occurred in the Lesser Antilles since 1700, and three of these have taken place in the present century. It seems a reasonable supposition that this has been the order of frequency of Vulcanian-Peléan eruptions throughout the Quaternary. Radiocarbon dating shows that a large glowing avalanche occurred on Guadeloupe about 1400 A.D. (Bruet, 1953, p.106), and this method of dating, together with archaeological evidence, show that Mt. Pelée has a record of numerous large eruptions over the last 10,000 years (Grunevald, 1961, p.8). It is unlikely that the occurrence of three major eruptions in the Lesser Antilles in the twentieth century,

after only one each in the eighteenth and nineteenth centuries, has any significance, particularly since the Soufrière of St. Vincent, responsible for three of the five, has erupted at regular intervals spaced by about 100 years. The relatively brief historical record of volcanoes with so long an eruptive cycle does not justify generalizations of this kind.

In addition to the major eruptions, the occurrence of six minor historic eruptions, including four summit eruptions from La Soufrière volcano of Guadeloupe and two flank eruptions from Mt. Pelée, show that activity in the West Indies does not always follow the same pattern of extreme violence. The most recent of these minor eruptions, which occurred on Guadeloupe in October 1956 (Barrabé and Jolivet, 1958), involved the emission of cinders over a period of four days, from a fissure on the flank of the summit dome. The thickness of these cinders reached 18 inches near the source, whilst fine ash, carried westward by the wind, fell over a narrow sector extending  $7\frac{1}{2}$  miles, as far as the coast.

Although magmatic activity has been restricted to three islands in historic times, there is evidence that all ten of the larger islands of the volcanic arc, from Saba to St. Vincent, have been violently active in the Quaternary era. Glowing avalanche deposits have been reported on each of these islands, and most exhibit youthful landforms in areas which must be considered still to be potentially active volcanic centres. It is worthy of note that St. Lucia, situated in the part of the

arc which has been most violently active in historic time, and between two islands which erupted almost simultaneously in 1902, has shown no sign of magmatic activity in the historic past.

### Soufrières

Present-day soufrière activity is most conspicuous on the islands St. Lucia, Dominica, and Guadeloupe. On all three islands, large-sized soufrières, with boiling pools and fumaroles, have been active throughout historic time. On Guadeloupe the solfatara-field is near the summit of La Soufrière volcano, and the intensity of activity has varied greatly. Activity on the other two islands has shown little variation with the exception of a small phreatic eruption in Dominica in 1880. Robson and Willmore (1955, p.38) have calculated that the mean heat output from each of these soufrières is of the order of  $1.5 \times 10^7$  cal/sec. (A similar value is calculated for heat loss through the crater lake of the Soufrière volcano, St. Vincent). This figure is about half that quoted (Robson and Willmore, 1955, p.39) for the equivalent of one major eruption per century, which corresponds to a continuous rate of  $3 \times 10^7$  cal/sec. It is possible that the continuous release of heat energy at the soufrières on Guadeloupe, Dominica and St. Lucia has some casual connexion with the absence of major eruptions on these islands in historic time.

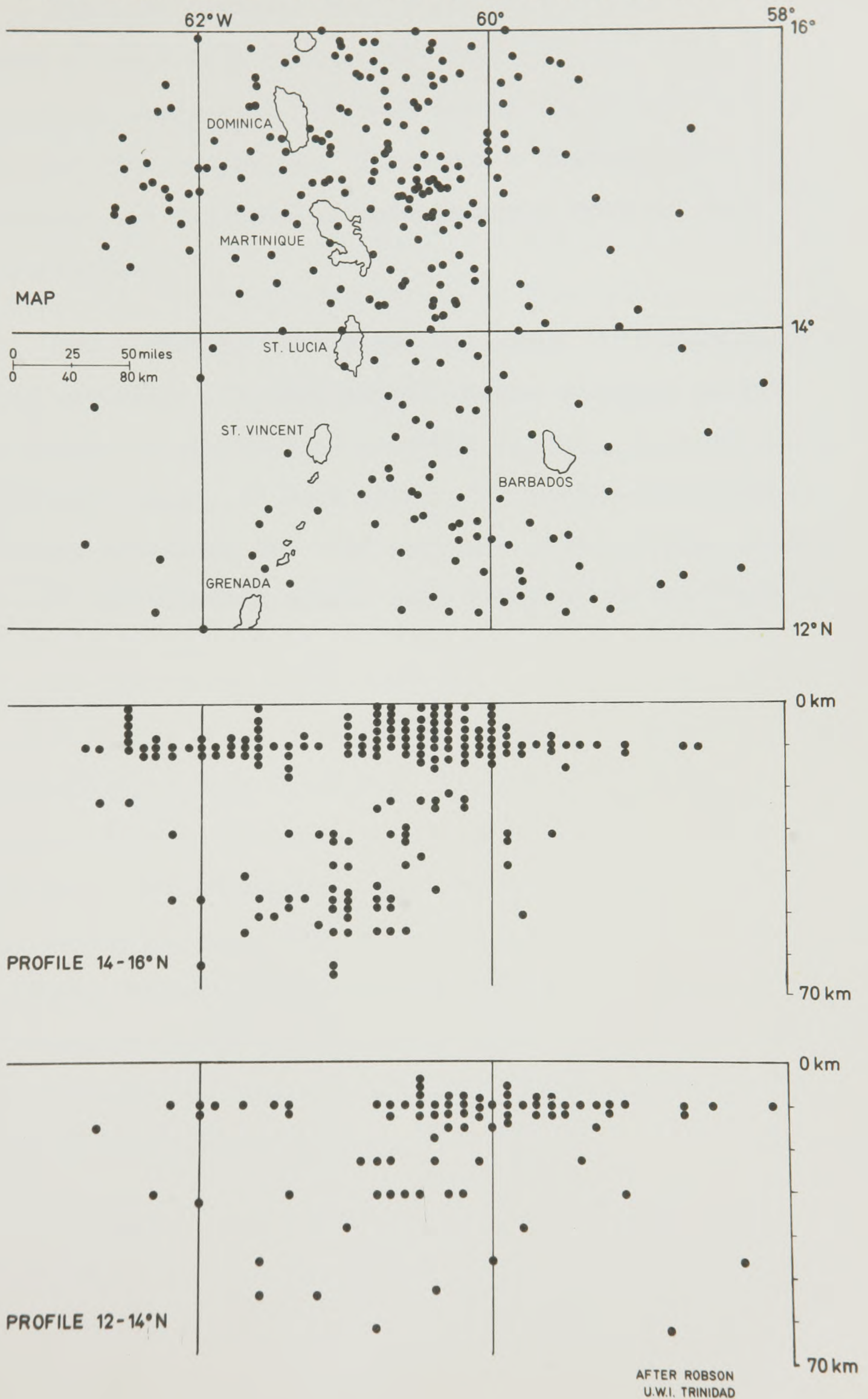
Less vigorous fumarolic or thermal spring activity occurs on most of the other islands of the volcanic arc.

FIG. 5. EARTHQUAKE FOCI IN THE CARIBBEAN

Seismic activity

Earthquakes of sufficient strength to be noticed by the inhabitants are relatively frequent in the islands: several per year are felt on St. Lucia. More severe shocks, of intensity up to VI or VII, most commonly occur during "seismic crises", when earthquakes may be recorded at the rate of several per day over a period of months. A typical crisis occurred in Montserrat between 1934-36 (Powell, 1938), in which the more intense tremors caused rock-falls and damage to buildings. Similar crises affected St. Kitts and Nevis in 1950-51 (Willmore 1952) and in 1961-62 (Robson and others, 1962). In the later stages of the 1961-62 series, a large number of earthquake foci were concentrated below Nevis peak at 1-10 km. depth, which suggested that a body of magma was in movement. Tremors of this type commonly precede volcanic eruptions, providing a means of prediction, and to this end "the Seismic Research Unit was set up in 1952 with headquarters in Trinidad and equipped with a network of vertical component Willmore-Watts seismographs, one instrument being installed in each of the larger British Islands in the Eastern Caribbean" (Robson, 1962). The epicentres and depths of earthquakes recorded in the vicinity of the Windward Islands between 1953 and 1960 are shown in Fig. 5. This demonstrates a concentration of shallow foci in a submarine north-south belt 50 miles wide immediately to the east of the volcanic arc, and a transverse belt of slightly deeper foci passing between Dominica and Martinique.

FIG. 5. EARTHQUAKE FOCI IN THE WINDWARD ISLANDS, 1953-1960



Historic accounts show that seismic crises are likely to precede a large West Indian eruption. In St. Vincent, mild tremors became abnormally frequent during the year preceding the 1812 and 1902 eruptions. There was a further increase in the frequency and violence of earthquakes a week or two before the 1902 eruption.

Mont Pelée in Martinique has given less warning of impending activity: in 1902 slight shocks occurred on the western flanks of the volcano at about the same time as explosive phenomena began, 12 days before the destructive climax. In the month preceding the 1929 eruption of Mt. Pelée, ground tremors and subterranean sounds were reported at the summit.

### 3. ST. LUCIA: GENERAL GEOLOGICAL BACKGROUND

#### 3. 1. PHYSICAL GEOGRAPHY

##### Physiography

St. Lucia lies in latitude  $14^{\circ}\text{N}$ , longitude  $61^{\circ}\text{W}$ . It is separated from Martinique to the north by a channel 20 miles wide and 4,500 ft. deep, and from St. Vincent to the south by a channel 24 miles wide and 2,000 ft. deep. The island has a maximum length of 27 miles and a maximum width of 14 miles. Its area is approximately 233 sq. miles.

The island rises from a submarine bank extending three miles from land on all sides except to the west: here, deep water is less than half a mile offshore. Depths of up to 200 ft. are recorded at the seaward edge of the bank, beyond which they descend abruptly to over 1,000 ft. The contrast between submarine depths off the eastern and western coasts is reflected in the shape of the coastline: the eastern (windward) coast has long, low-lying spits and deep embayments, whilst along the western shore, especially the central section, the land surface descends rapidly toward the Caribbean sea. The contrast between this and the lower and more even relief of the eastern half of the island is illustrated in Plate 1.

The axial region of the island is mountainous and deeply dissected, so that ridges and peaks rising to 2,000 - 3,000 ft. overlook valleys at less than 1,000 ft. above sea

PLATE 1.

Panorama of St. Lucia from the southern extremity. The photograph shows the contrast between the gently shelving, eastern part of the island to the right, and the more rugged outline of the younger volcanic hills in the western half of the island (left of the picture), where the Gros Piton (larger and closer) and Petit Piton (beyond, to the right) form conspicuous landmarks. The middle ground is occupied by marine deposits around Vieux Fort, now lying c. 10 ft. a.s.l.

**PLATE 1**



level. The predominance of sub-parallel longitudinal ridges has left a complex river system in which several of the main rivers run parallel to the length of the island (subsequently) for a large part of their course. The northern and southern extremities of the island are composed of lower lying hills representing worn-down volcanic remnants. Broad terraces of marine deposits north of Réduit and near Vieux Fort, at not more than 10 ft. above sea level, indicate that the most recent change at each end of the island involved a slight uplift of the land.

#### Climate

From April to November, afternoon shade temperatures are in the middle and upper 80's (°F), though heat is generally moderated by easterly trade winds which average 6 m.p.h. (less in Soufriere, and more on the windward coast). Evening, night and early morning temperatures are in the 70's or low 80's, and cool season midday temperatures are similar.

Rainfall is subject to orographic control. The lower-lying north and south ends of the island are relatively dry, with about 50 inches per year, whereas the high central ridge receives over 100 inches. In Castries the mean annual precipitation is 78 inches, with rain falling on an average of 279 days in the year. The drier months are February to April, with an average of 3 inches per month, when rain falls as brief showers on two days in three. The wettest months are July and August, each with an average of 10 inches of rain on 26 days,

falling generally as several heavy showers a day. Humidity is often close to 100% at dawn, and averages 79% over the year.

### Vegetation

The natural vegetation of St. Lucia consists of dense tropical rain forest in wetter areas and deciduous scrub forest at the drier extremities of the island. At lower altitudes, most of the forest has been cleared for crops, so that rain forest remains intact only on the higher central ranges. Trees include bois blanc, balata, bois pain marron, bois tan rouge, gommier, laurier, merise and some red cedar. These are commonly draped by lianes and colonized by Spanish moss and tree pine-apples. In places where the original forest has been cleared, it has sometimes been replaced by a secondary growth of tree ferns and cabbage palms. On the lower rocky slopes of the Pitons where trees are sparse, the undergrowth consists of a dense tangle of briars and cacti.

### Agriculture

Agriculture is mixed: bananas are grown ubiquitously, and stems are hauled by truck to Castries or Vieux Fort, where they are carried on board the weekly greenboats by the women. Sugar cane is grown only in the broad alluvial valleys south of Castries, where it is processed at a single factory. Coconuts, cocoa and coffee are cultivated especially in the wet and fertile valleys of the Soufrière region, where the products are dried on the estates. Much of the copra is processed at a local factory in Soufrière. Small areas of pasture land exist at the

northern and southern ends of the island. Minor agricultural products include citrus fruits, breadfruit, nutmeg, cloves, pawpaw, avocado, mangoes, maize, rice, sea-island cotton, yams, sweet potatoes and manioc.

### 3. 2. ISLAND HISTORY

The earliest settlement of St. Lucia is believed to have been by Arawak Indians migrating from South America via Trinidad, probably near the beginning of the Christian era. At a later date, Carib Indians followed and replaced the Arawaks, killing the menfolk and marrying the women. The Caribs had apparently established themselves in the Lesser Antilles only shortly before the arrival of the first Europeans. Relics of both Carib and Arawak cultures have been identified by Rouse (1964).

St. Lucia was possibly sighted by Columbus on his fourth voyage in 1502. French tradition, however, relates that shipwrecked seamen of their nation found the island in a subsequent year, on St. Lucy's day (13th December) and named it after the virgin-martyr of Syracuse. The earliest record of the name Santa Lucia occurs on a Vatican globe of 1520 (Jesse, 1962, p.14).

In the course of the seventeenth century both British and French made numerous attempts to occupy the island, but no permanent settlement was made until 1744 when the French established a garrison. In 1765 the first sugar plantation was

established near Vieux Fort, and by 1772 the total population, including African slaves, was reported to be over 15,000. In 1803, after more than a century of dispute and skirmishing between the British and French, the island was finally attached to the British Crown. The populace, however, continued to speak French and kept in close contact with French Martinique, so that today St. Lucia is still characterised by French place and personal names, French patois, and by many Creole customs.

Up to the late 1800's, sugar, coffee, and cocoa in that order were the main agricultural products. By the turn of the century, a British military base had been established at Castries, which had also become the principal coaling station for ships in the Eastern Caribbean. The value of coal traded in 1900 amounted to 54% of total exports from the island. By 1920, however, the coaling trade had virtually ended, and a period of economic depression ensued. Sugar remained the principal export, though coconuts and bananas began to be significant. In the past 10 years, bananas have become increasingly important, and in 1958 overtook sugar both in quantity and value of exports. It seems likely that in the near future the export of sugar will virtually cease.

### 3. 3. RECORDS OF VOLCANIC ACTIVITY

The only site of historic activity on St. Lucia is at the Sulphur Springs. All descriptions of this area indicate that solfataric and fumarolic activity has continued at a fairly constant level throughout historic time. Only one episode of

greater violence has been recorded: this was first mentioned by the Surveyor-General to the French Government, Lefort de Latour, who stated in a report in 1789 that "these pools from time to time are the site of minor explosions. It is about 20 years since the last one which spread a thin layer of cinders far and wide." This explosion seems to have been only a small phreatic eruption, involving no fresh incandescent matter, since he adds: "there is absolutely no truth in the popular belief that there is subterranean fire which one sees sometimes issuing from the fumaroles. Never, neither by day nor by night have the inhabitants of the neighbourhood of the crater seen sparks or flames."

### 3. 4. PREVIOUS GEOLOGICAL WORK

Published geological descriptions of St. Lucia consist almost entirely of brief accounts of field observations, in which attention has been focussed principally on the Sulphur Springs.

The earliest writings on the natural phenomena of the island were by men who visited it primarily for other professional work, and who were not geologists. Lefort de Latour (1787) and a Swedish physician named Cassan (1790), however, both gave descriptions of the Sulphur Springs showing that activity then was much as today.

On the basis of an eight-day visit made in January and February of 1903, Sapper (1903) gave the first accurate

account of the general geology of the island. He commented on the mature stage of development of the island, and on the fact that there was no recent stratovolcano of the type found on St. Vincent and Martinique. He rejected the views of Hill and Spencer that the Pitons were relics of an old crater. Sapper explained the unusual shape of these masses to be the result of landslips. He also rejected the popular belief that the Sulphur Springs occupied the site of a former volcanic crater. He included with his report a sketch-map of the Sulphur Springs, together with temperature measurements made in this area. He correctly identified dacite as the most important rock type at the surface of the Soufrière region, and andesite as the predominant rock on the island as a whole. He described outcrops of coral limestone in the Soufrière region, on Coubaril, at 450 ft. above sea level, and marine terraces at Malgrétoute at 90-120 ft. above sea level.

Lacroix (1904, p.591) gives a brief petrographic description of rocks from St. Lucia. He points out that the range of rock-types is similar to that in Martinique, including dacite, andesite and basalt, and he compares dacite from the Petit Piton on St. Lucia to that of the Pitons du Carbet on Martinique.

Hovey (1905) recorded a visit to the Sulphur Springs in March 1903. His photograph of the area (1905, Plate 93) closely resembles Plate 16a in this report. He concluded, apparently independently of Sapper, that: "The sulphur springs

area.....seems not to be the remains of or connected in any way with an ancient crater."

Earle (1923), as Government Geologist to the Windward and Leeward Islands, gave a cursory description of St. Lucia, containing few original comments. He did, however, describe "a small pocket of limestone situated at about 100-150 ft. a.s.l." near Malgrétoute. He stated (1923, p.3) that "In this the only common fossil is Orbicella annularis, Ellis and Sol., which is everywhere characteristic of Pleistocene and Recent coral reefs in the West Indies, and there is little doubt that the deposit is a raised coral limestone of Pleistocene age."

The American volcanologist Perret visited the island in 1939 and again in 1940. In the correspondence column of a local newspaper (Perret, 1940) he expressed his views on the structure of the Sulphur Springs, which he considered to have "formed in the crater of a true volcano." He also put forward the hypothesis that the Pitons were "like the famous but ephemeral spine of Mt. Pelée, a form of monolithic extrusion or giant 'aiguille'."

Temperature measurements and estimates of heat flow at the Sulphur Springs were made by Robson and Willmore (1955). Their map (p.23) shows the distribution of the heated pools, which remained virtually unchanged in 1963. Robson and Willmore briefly described rock-types in the vicinity of the Sulphur Springs and the extent of alteration caused by fumarolic gases. Like Sapper and Hovey, they rejected the belief that the Sulphur

Springs occupied the site of a former volcanic crater.

A series of unpublished Progress Reports on the Geological Survey of the Windward Islands by Martin-Kaye, made when Government Geologist to the Windward and Leeward Islands between 1951 and 1961, includes several references to the geology of St. Lucia. The present author had access to these reports at the Seismic Research Unit, Trinidad. In report No.11 (1961), Martin-Kaye described for the first time the caldera structure of the Soufrière region: "A caldera-type hollow behind the town of Soufrière contains not only the two well-known Pitons of St. Lucia but a number of other domes, spines and craterlets." In report No.10 (1960), he recorded an attempt to date fossil charcoal from Fond St. Jacques. Determinations made on this sample (R.545/1) by Dr. T. A. Rafter, of the Division of Nuclear Sciences, Lower Hutt, New Zealand, gave an age of greater than 50,000 years (i.e. beyond the range of the method).

From air photographs of the Soufrière region, Robson prepared a topographic feature map, copies of which are held in the Department of Geology and Mineralogy, Oxford, and in the Seismic Research Unit, Trinidad.

No geological map and few petrographic descriptions of the rocks of St. Lucia existed before the present investigation. There were two earlier chemical analyses: one, of the Petit Piton dacite, is given in Lacroix (1926, p.403); the second, of Belfond dacite, was made for Martin-Kaye at the Geological Survey Department, British Guiana.

### 3. 5. GRAVITY AND MAGNETIC ANOMALIES

A gravity and magnetic survey of St. Lucia was undertaken by Masson-Smith and Andrew, of the Overseas Geological Surveys (Department of Technical Co-operation) from 12-17 February, 1963. Their provisional results are reproduced in Figures 6 and 7.

With reference to the gravity anomaly map (Fig.6), Dr. Masson-Smith stated (personal communication, October 1963): "The gravity picture is similar in all the islands (of the Lesser Antilles). A positive N-S ridge with steep flanking gradients is intersected by E-W negative troughs. I think that the interpretation will show that the major structure is a string of N-S blocks of high-density rock dipping steeply on all sides, separated by narrow E-W belts of lower density rock. It has been suggested that the anomaly changes may be due to rapidly changing thicknesses of ash cover since the ash is very much less dense than the consolidated surface material, but topographic correlation suggests that the ash cover is fairly thin and uniform on land, at least."

The present author adds the following comments with regard to St. Lucia:

- 1) The high positive anomalies of over 180 mgals correspond approximately to the surface outcrop of basaltic rocks (see geological sketch-map, Fig.8).
- 2) The lowest anomalies (of less than 160 mgals) occur mid-way along the western margin of St. Lucia, north of the caldera

FIG. 6

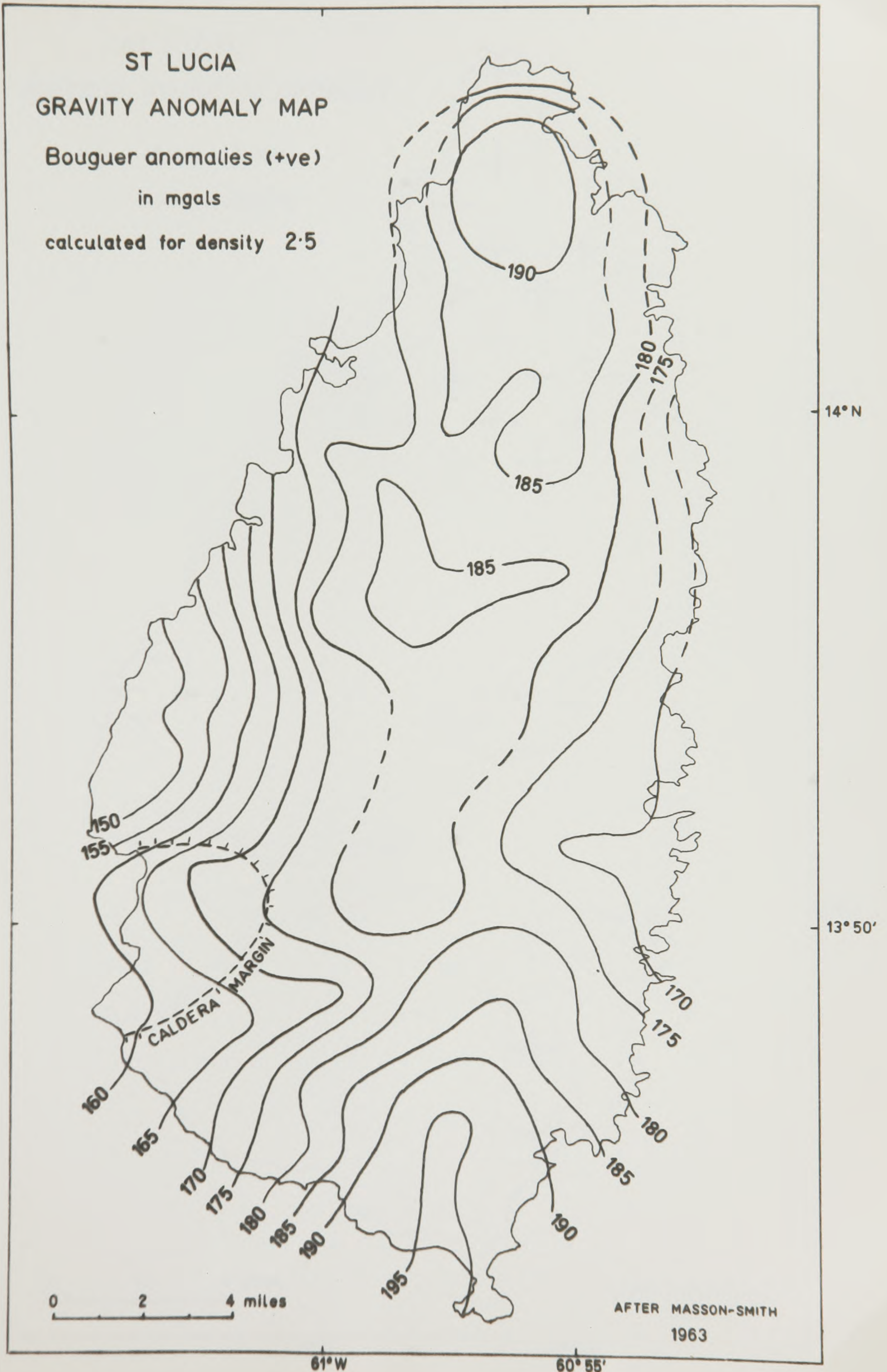


FIG. 7

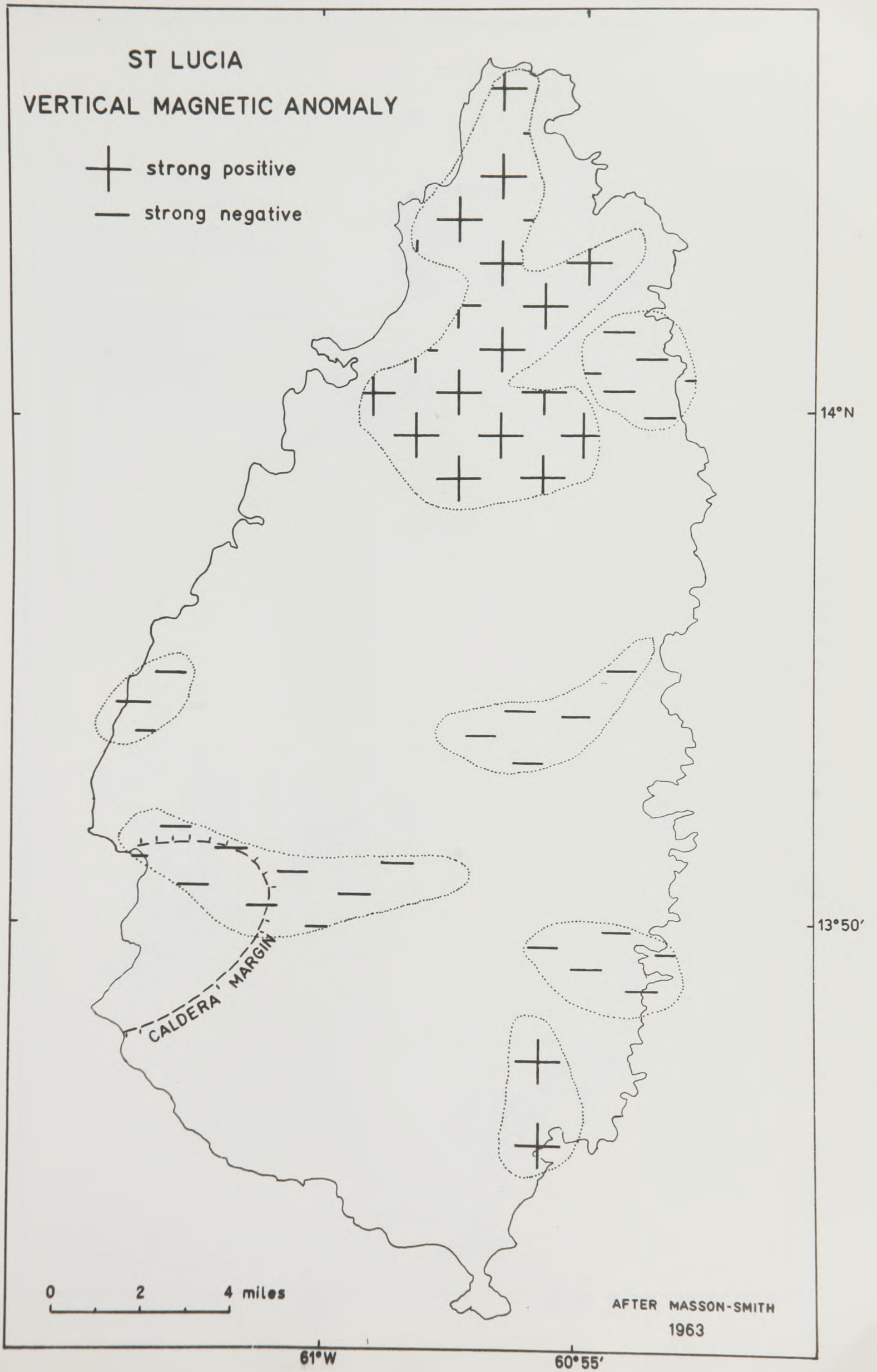
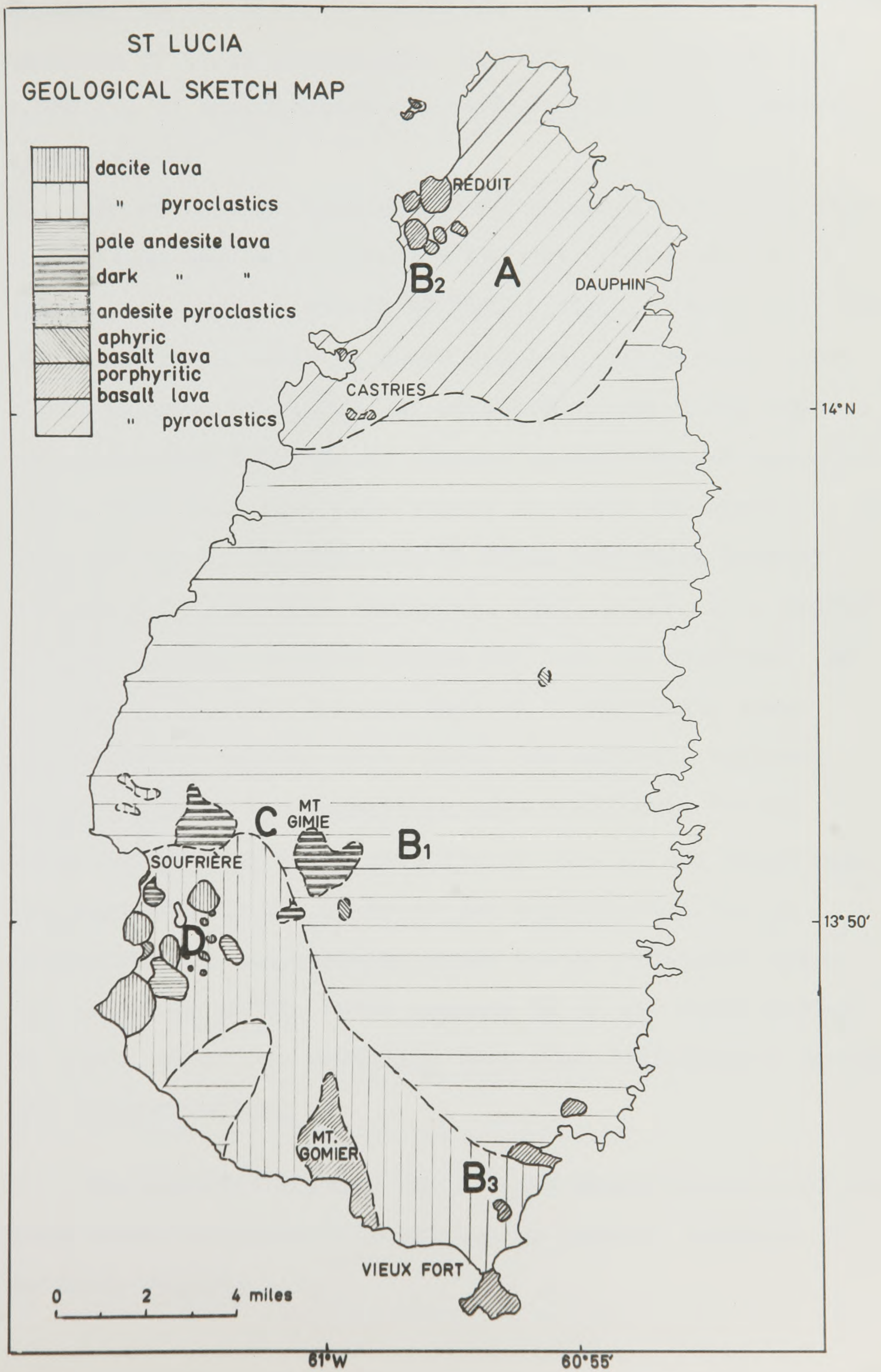


FIG. 8



region. It is in this part of the island that the thickest sections of pyroclastics are exposed, consisting of over 1,000 ft. of consolidated and semi-consolidated andesite agglomerates.

- 3) The area of caldera collapse shows slightly higher gravity values than the adjacent areas to north and south, so that the isogals swing westward to form a small salient over the collapsed area. This at first sight is unexpected, since the foundering of higher and presumably less dense layers, and subsequent mantling by thicker unconsolidated pyroclastics, would have been more likely to lower the anomaly. In only one out of six calderas in Japan for which gravity surveys have been made (Yokoyama, 1963, p.70), is a higher gravity anomaly recorded within the area of collapse. In St. Lucia, however, the presence of a relatively large proportion of massive lava within the caldera, extruded subsequently to its formation, must contribute to the increased gravity value relative to that of the thick agglomerate-tuff to the north of the caldera, and of the unconsolidated ash deposits south of the collapsed area.
- 4) The ash cover on St. Lucia appears to be not very uniform on land. There has certainly been much differential erosion and redistribution.

The magnetic anomaly map (Fig.7) shows strong positive anomalies which correspond closely to the surface outcrops of basalts (c.f. Fig.8).

### 3. 6. GENERAL GEOLOGY OF THE ISLAND

A geological sketch map, based on a reconnaissance survey of the whole island, is shown in Fig.8. The oldest rocks at the surface are probably the deeply weathered basaltic agglomerates in the northern quarter of the island, the source of which has not been identified. Occasional limestone lenses in these agglomerates have been classed as Lower Miocene by Martin-Kaye (1961), who states that "amongst the foraminifera is Operculinoides cojimarensis". The basalt agglomerates are intruded by plagioclase-pyroxene(-olivine)-phyric basalt in the Castries region, and similar lavas form a cluster of conical hills at Reduit. At the southern extremity of the island, near Vieux Fort, a group of hills composed of similar plagioclase-pyroxene (-olivine)-phyric basalt lava occurs, and these resemble the Réduit cones also in their morphology. A large lava flow extending into the sea from Mt. Gomer is similar in appearance to lavas of the Vieux Fort centre.

At isolated localities along the central ridge of the island, deeply altered aphyric basalt lava flows and breccia are exposed, and similar lavas outcrop south of Soufrière. The time-relationship of these to the porphyritic lavas at the northern and southern ends of the island is not clear, although a small exposure of plagioclase-phyric basalt outcrops adjacent to aphyric lava south of Soufrière, suggesting that these two at least may have been nearly contemporaneous.

Dark andesite lavas outcrop on the flanks of Mt. Gimie

and neighbouring mountains, and overlie aphyric basalts south of Soufrière. These peaks probably mark the source of most of the thick andesite pyroclastics occupying the central section of the island.

The youngest rocks of St. Lucia outcrop in the southwest and include massive pale andesite and dacite lavas, and related pyroclastics.

The approximate location of eruptive centres and their chronological sequence is indicated on the map by the letters A, B, C, and D. It is worthy of note that these show a progressive westward shift with time, a feature to which Grunevald (1961, pp.25-6) has drawn attention on the island of Martinique. On Dominica, also, the youngest centres apparently lie near the western margin of the island.

FIG. 9

4. THE SOUFRIERE REGION : GEOMORPHOLOGY

In contrast to the remainder of the island, the Soufrière region is an area of relatively youthful volcanic landforms. It can be divided into three morphological units:

4. 1. OLDER VOLCANIC REMNANTS IN THE NORTHEASTERN PART

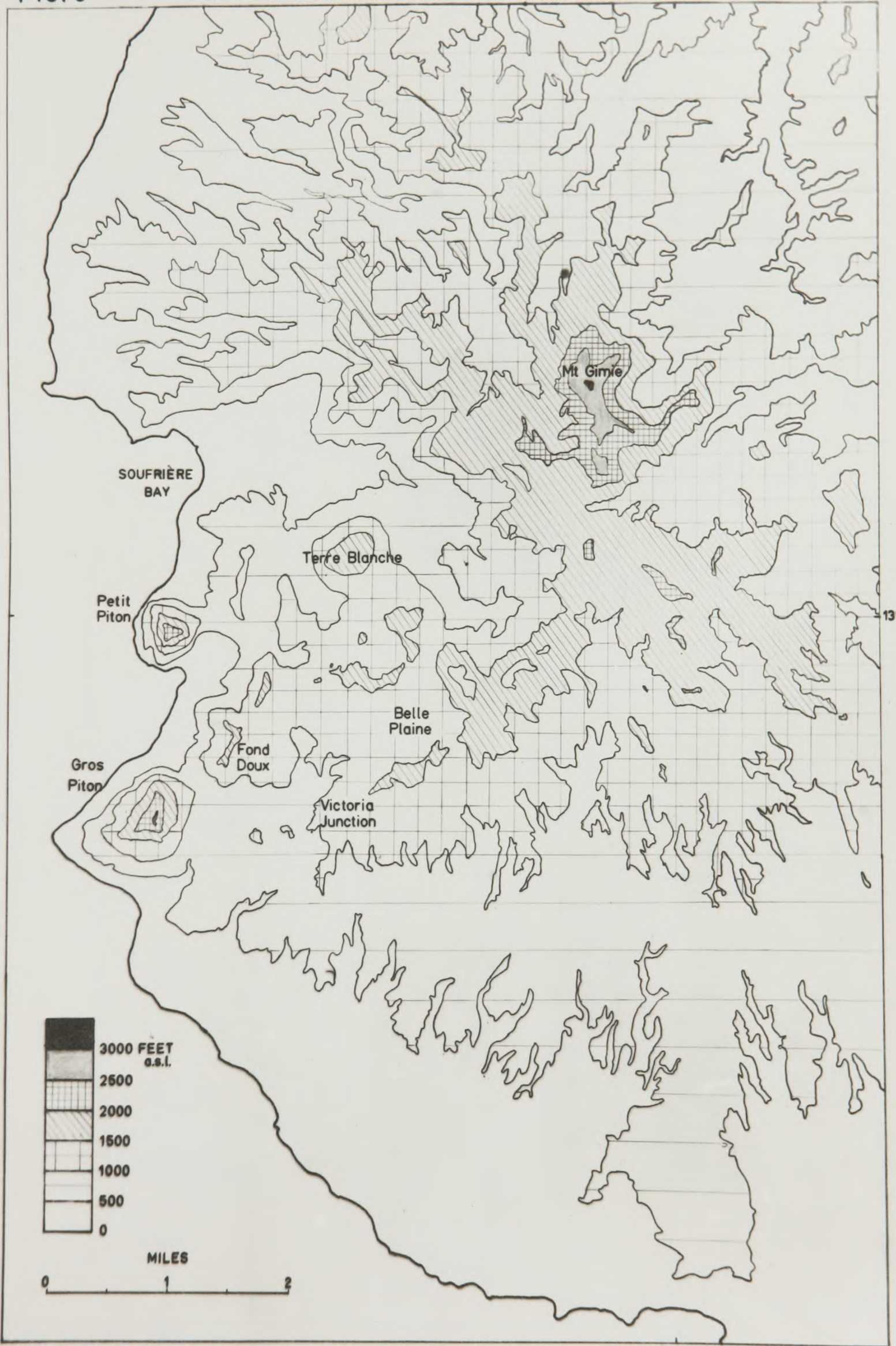
The topographic map of the Soufrière region (Fig.9) shows an area of deeply dissected, older volcanic remnants in the north and east, encompassing Mt. Gimie, Piton Canaries, Mt. Tabac and the prominent hills east of Migny. Rising to over 3,000 ft. a.s.l., this includes the highest peaks of the island. The irregular drainage pattern in this area (see Fig.10), reflects the more mature morphological development of this part of the Soufrière region.

4. 2. THE CALDERA

This occupies the central part, and forms the most important structure of the Soufrière region. It consists of a steep wall to the north and east, up to 1,000 ft. high (Plate 2a), which becomes less conspicuous on the southern side, from Victoria Junction westward. If the caldera was once a complete, circular feature, its western margin must since have foundered beneath the sea. The structure seen at the present is, therefore, by no means a clear-cut example of a caldera. Yet other features contribute to the impression that collapse of the area within the wall has taken place. Among these are the occurrence of

FIG. 9

SOUFRIÈRE REGION: TOPOGRAPHIC MAP

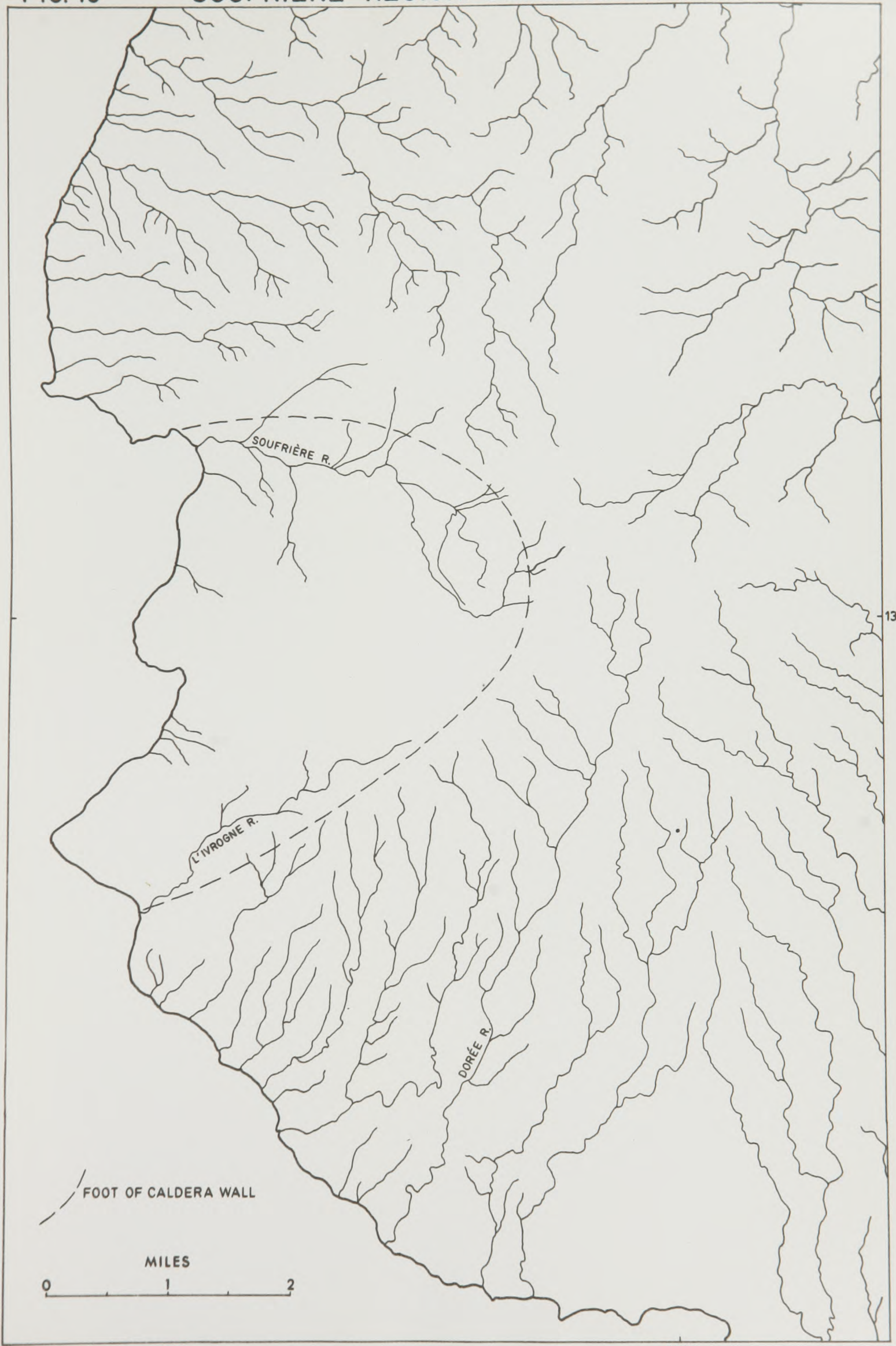


FROM D.O.S. 345, 1958.

61°W

FIG. 10

SOUFRIÈRE REGION: DRAINAGE MAP



FROM D.O.S. 345. 1958.

61° W

PLATE 2.

- a) Panorama showing the eastern part of the caldera, seen from Pond Doux summit. The rim forms a prominent level feature at 2,000 ft. a.s.l. in the northeastern sector (left of the picture), behind which rises Mt. Gimie (3,117 ft. a.s.l.). Horne Bonin, in the centre background, has twin peaks rising to 2,200 ft. a.s.l., which protrude from the caldera-wall. From Horne Bonin to Victoria Junction (extreme right) the caldera rim drops from 2,000 to 1,350 ft., and becomes less conspicuous.
- b) Panorama showing the central part of the caldera, seen from the Petit Piton summit. A labelled sketch of this picture is given in Fig. 12.

PLATE 2



unexpectedly flat areas on top of the wall southwest of Mt. Gimie, at 2,000 ft. a.s.l. (Plate 2), and in Belle Plaine at the foot of the eastern wall, lying 1,200 ft. a.s.l. If these two levels are taken to represent parts of a former, relatively even land surface, it must be concluded that collapse of the area within the wall involved a vertical downward movement of about 800 ft. That this wall has some genuine significance is also suggested by the positions of the Soufrière and Ivrogne rivers, the only two large streams within the depressed area (see drainage map, Fig.10), whose courses run around the foot of the wall, and may possibly have exploited a more easily eroded marginal fault zone.

The existence of a submarine extension of the caldera wall on the western side remains uncertain. The Admiralty chart (No.1273, 1888) does not give soundings in the area where a relic feature might be expected, and no opportunity for making such a survey offered itself during the present investigation. Furthermore, accepting that some kind of ridge did once form the western margin, it would be possible to account for its absence today by two alternatives:

- 1) North-south vertical faulting, or a flexure with its axis along the present coastline, since the time of caldera collapse. This would also account for the steeply shelving shoreline along the most westerly section of the island.
- 2) Simple marine erosion during the long time interval since the caldera was formed.

In view of the fact that the water depth reaches 600 feet only

$\frac{1}{4}$  mile offshore in Soufrière Bay, equivalent to a submarine slope of  $25^{\circ}$ , the first explanation seems not unlikely.

Williams (1941, p.242) gives the following definition:

"Calderas are large volcanic depressions, more or less circular or cirque-like in form, the diameters of which are many times greater than those of the included vent or vents, no matter what the steepness of the walls or form of the floor".

In the Soufrière region of St. Lucia, a large topographic depression exists on the present land, and is at least cirque-like in form. It also includes a cluster of craters and domes. This structure is therefore considered to correspond sufficiently well to the accepted definition of a caldera to warrant the name.

Features within the caldera include a number of more or less independent dome-shaped hills or ridges, whose flanks are composed of either solid lava or large loose boulders. They are interpreted as viscous lava protrusions or volcanic domes in various stages of morphological decay. This sequence of disintegration is believed to be represented by 1) Terre Blanche (one of the younger features), 2) the Pitons, and 3) Fond Doux (one of the older protrusions within the caldera. Evidence for this will be examined in detail at a later stage (sections 5.2.3., 5.2.5., 5.2.6.)). Between the cluster of smaller hills to the south of Terre Blanche lie seven volcanic craters, of which the five surrounding Belfond hill appear to be morphologically intact and therefore recently formed.

#### 4. 3. THE SOUTHERN GLACIS (Plate 3)

The third morphological unit in the Soufrière region occupies the southern area, and will be referred to as the southern glacis. This is a tabular surface which slopes gently southward from an elevation of 1,350 ft. at Victoria Junction to sea level between the Gros Piton and Laborie. It consists largely of pumice flow (glowing avalanche) deposits, which in their characteristic manner have accumulated to form a smooth and gentle slope. Since the deposition of the most recent avalanche material, this surface has been dissected by a series of parallel rivers flowing southward, which have eroded gorges up to 150 ft. deep (e.g. Rivière Dorée, east of Sauzay).

#### 4. 4. ROCK WEATHERING AND SOIL FORMATION

The humid tropical climate of St. Lucia leads to rapid rock weathering, especially in the higher regions where rain falls more frequently. Almost all material above 1,200 ft. which has been exposed long at the surface is deeply altered, and often a ferruginous clay containing quartz crystals is all that remains.

On the southern glacis, by contrast, rainfall is much lower, and most exposures are fresh, though sometimes capped by a hard pan up to 2 ft. thick. Soils, where present, are of the terras type, consisting of sticky, yellowish-grey clay.

To the northwest of Soufrière town, less weathered bouldery material, or lithosol, covers a large part of the surface.

PLATE 3.

The southern glacier from Choiseul, looking northeast. In the background are the Gros Piton (centre), Petit Piton (right) and Fond Doux (partly concealed behind the palm trunk). The glacier, built up mainly from glowing avalanche (pumice flow) and mudflow deposits, descends from 1,350 ft. at Victoria Junction on the extreme right of the picture, to sea level between the Gros Piton and Choiseul, with a slope of  $7^{\circ}$ .

**PLATE 3**



## 5. THE SOUFRIÈRE REGION: GEOLOGY

### 5. 1. BASIS OF RECONSTRUCTION OF THE VOLCANIC HISTORY

Attention is drawn briefly to problems encountered in attempting to reconstruct the geological history of the Soufrière region. Two parallel sequences exist: that of lava units situated mainly within the caldera, and that of the pyroclastic stratigraphy exposed best in and beyond the caldera rim.

#### Lavas

Lava units seldom display clear time relationships; contacts between neighbouring bodies are rarely seen, due either to geographical separation, or to blanketing by more recent pyroclastics. Thus, in order to establish the chronological sequence of extrusion of the lavas, recourse must be had to other kinds of evidence, of a less direct and less reliable nature. These include:

- 1) The depth of weathering of lavas.
- 2) The morphology of the major structures.
- 3) The stratigraphic sequence of petrographically similar pyroclastics.

The depth of weathering varies appreciably with altitude, which must therefore be taken into account. Present morphology is the outcome of two factors: original form, and extent of subsequent modification by erosion. The rate of weathering, and consequent morphological change, also vary according to the texture of the original material. Thus, for example, aphyric basalts are old,

but are hard and relatively fresh in shoreline exposures, whilst much more recent vesicular dacite and dacitic ash found above 1,500 ft. altitude, is profoundly altered to a depth of two to five feet.

#### Pyroclastic stratigraphy

Pyroclastics form the bulk of the material exposed outside the caldera, and six major units have been distinguished. None of these, however, could be subdivided and correlated in detail, so that it was not possible to establish a detailed stratigraphy of the type described by Baker (1963) on St. Kitts. The succession is also complicated by the recurrence of similar formations, e.g. andesite pumice flows, which characteristically form structureless deposits showing great lateral variation in thickness. Erosion between successive eruptions has caused redistribution of unconsolidated pyroclastics, leaving mudflow and fluviatile material. Thus are developed different facies of the same original deposit. There is little doubt that there have been more units of pyroclastic deposits in the Soufrière region than the number recognised, and of greater total thickness than given here. During a single historic eruption in Martinique from 1929-32, for example, Perret (1937, p.86) recorded several hundred small pyroclastic flows, and it is likely that eruptions of a similar kind have taken place in St. Lucia.

#### Correlation of pyroclastics with lava units

For the most recent pyroclastics, correlation with

the lava sequence can be established without difficulty. For earlier pyroclastics, however, equivalent lavas in many cases have not been identified with certainty. It is probable that some vents either were buried or disintegrated explosively, whilst others ultimately may have been blocked by domes whose composition differed from earlier emitted clastic material. It is, therefore, not reasonable to expect to find a massive lava equivalent to each pyroclastic unit, and the further back in time the reconstruction is projected, the less likely will this become. The Soufriere region has had a long history as an eruptive centre, and the pyroclastic sequence itself either has not been completely preserved or is not exposed in present-day outcrops.

The field characteristics of units consisting of lava will first be described, and the evidence for their relationships in time will be examined (section 5.2.). This will be followed by a detailed account of the pyroclastic stratigraphy (section 5.3.), in which the mode of eruption of these units and their possible relationships to structures composed of lava will be discussed. All field localities in the Soufriere region, to which reference is made, are shown on the Geological Map (end pocket). In all geological nomenclature, the author has attempted to conform with the definitions given by Schieferdecker (1959).

## 5. 2. LAVA FLOWS, CONES AND DOMES

### 5. 2. 1. BASALT FLOWS

#### Aphyric basalt

Aphyric basalt lavas are exposed in only a small part of the area mapped. They outcrop along the shore to the north and south of the Petit Piton, and were also found at 2,000 ft. a.s.l. on the island watershed, east of Migny. The latter locality is outside the caldera, whilst the shoreline outcrops are inside the area of collapse (see Geological Map).

The rock in all three localities is fine-grained, hard and dark. Flow-banding is visible in the shoreline outcrops as layers or lenticles up to 1 cm. wide of rock of slightly paler and darker colour, while calcite veinlets up to 2 mm. wide, containing scattered pyrite crystals, are relatively common. Outcrops are frequently shattered, sometimes so strongly that it is impossible to remove whole fragments larger than one or two inches across. This applies particularly to exposures along the coast north of the Petit Piton (Plate 4a). In the latter area, the attitude of the flow-banding is visible, in cliffs about 60 ft. high, between sea level and the road. By the shore due west of Coubaril, dips are vertical over a zone 30 ft. across, and to the north and south of this locality can be seen to flatten fan-wise over a lateral distance of about 70 ft. to an almost horizontal attitude (Fig. 11). It is possible that the vertical flow-banding marks the site of a fissure through which

PLATE 4.

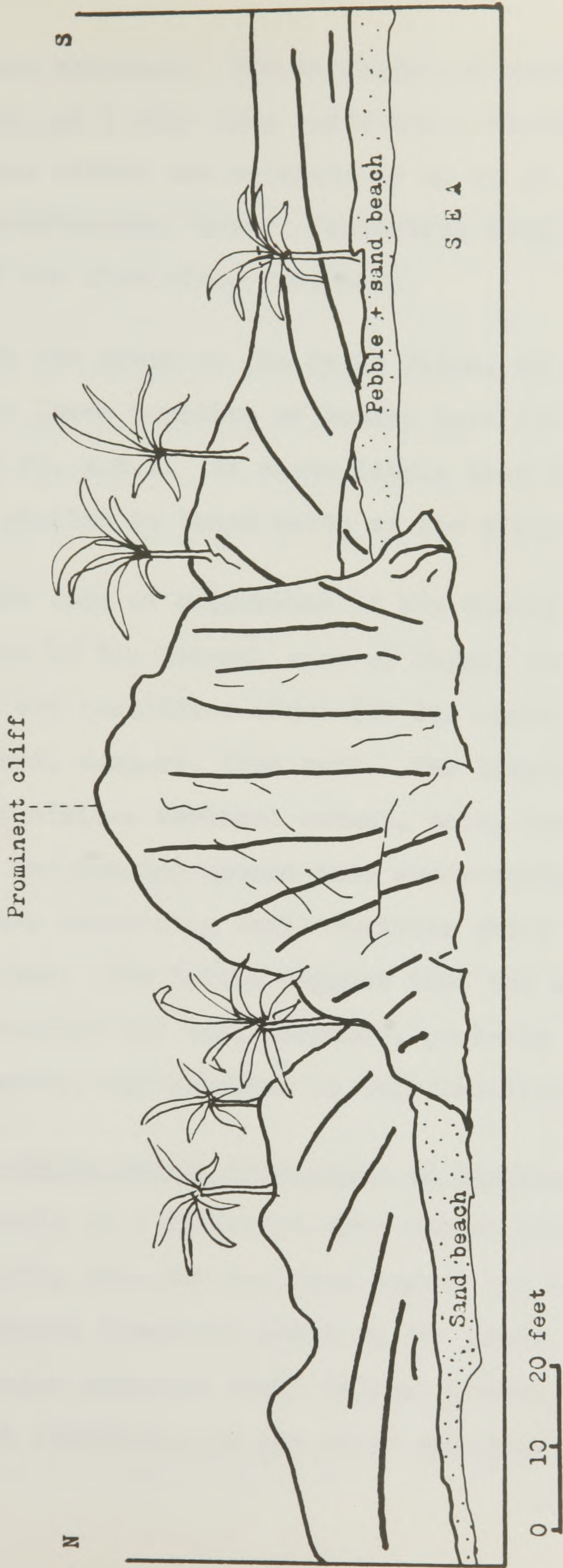
a) Aphyric basalt lava flow. Roadside exposure between Soufrière and Kalgrétoute, 75 ft. a.s.l. The lava, which has been strongly shattered, is part of an apparently single, homogeneous flow 80 ft. thick. Traces of flow banding, dipping gently to the left (northward) can be seen in the darker-coloured face near the bottom right, and above the cutlass.

( Length of cutlass: 20 in. )

b) Dark andesite conglomerate, breccia and fine agglomerate. Roadside exposure on the northwest flank of Coubaril, 200 ft. a.s.l. Large rounded boulders up to 18 in. across in a matrix of finer consolidated material form the lowest unit (lower right). This passes upward into breccia, composed of angular dark andesite fragments up to 6 in. across. A sharp break, with slightly irregular surface, separates this from the overlying indurated fine agglomerate. The pyroclastics dip northwest at  $30^{\circ}$ , parallel to the present slope of the hillside, off the flanks of Coubaril, which is believed to represent a former cone and the source of this material.



FIG. 11. SKETCH SHOWING ATTITUDE OF FLOW-BANDING IN APHYRIC BASALT CLIFFS BY THE SHORE DUE WEST OF COUBARIL.



The dark lines show, diagrammatically, the attitude of the flow-banding, which is vertical in the prominent cliff and flattens fan-wise both to the north and to the south.

the magma was extruded. The existence of massive cliffs up to 75 ft. thick and  $\frac{1}{2}$  mile long indicates a copious supply of magma. These cliffs are overlain by up to 30 ft. of deeply reddened, scoriaceous "bole", indicating long sub-aerial exposure of the flow after extrusion.

To the south of the Petit Piton, no basalt was found in situ, but loose boulders of banded lava (L.424) occurred as high as 400 ft. a.s.l. It seems likely that they have come from flows similar to those north of the Piton.

The mode of occurrence of the basalt lava on the central ridge of the island, east of Migny, is less clear. It outcrops in two localities about 400 ft. apart in a region of deeply altered, compact, fine tuff. The larger outcrop is 12 ft. wide, and of similar vertical extent, being fresh in its lower part (L.34) but passing upward into sandy-coloured, tuff-like, weathered lava containing small cavities which look like old vesicles (L.36). The latter suggest that the material was extruded at the surface and was, therefore, probably a flow. No flow-banding, however, was observed at this locality.

#### Plagioclase-phyric basalt flow south of Soufrière

Basalt of a different type occurs locally to form low cliffs extending into the sea just beyond the northern end of exposures already described north of the Petit Piton. This rock (L.251) contains numerous small felspar phenocrysts, but apart from these it resembles, in its field occurrence, exposures of

aphyric basalt to which it is closely related both in space and, apparently, time.

Plagioclase-pyroxene(-olivine)-phyric basalt flow of Mt. Gomer

In the southeastern part of the area mapped, a large, apparently single flow of basalt extends from La Haut southward to the coast at Laborie, creating a north-south ridge, on which the highest eminence is named Mt. Gomer. This lava (L.570) contains, in addition to feldspar, numerous pyroxene phenocrysts. It is similar in appearance to the older porphyritic basalts of the Vieux Fort and Castries centres (see Fig.8), and probably belongs to an early period in the volcanic history of the Soufrière region. It is overlapped by the andesite and dacite pumice flows, and is therefore certainly older than both of these.

5. 2. 2. DARK ANDESITE CONES

Masses composed of dark-coloured andesite lava and consolidated agglomerate are responsible for the main topographic features to the northeast of the caldera, including Mt. Gimie, 3,117 ft. a.s.l. (Plate 2), Mt. Tabac, 2,224 ft. a.s.l., and the high ground east of Migny. Inside the caldera, the hill of Coubaril is made of similar material. The high elevation of the area north-east of the caldera (Fig.9) is responsible for heavy rainfall, thick forest cover, and consequent intense alteration of all material which has long been within 10 ft. of the surface. Useful exposures therefore occur only in stream sections or road

cuts, or steep slopes exposed by recent landslides. Gentler slopes, moreover, are usually mantled by younger pyroclastic material from the Soufrière centre.

Massive rock is exposed alongside the road northeast of Migny, where dark greenish-grey lava can be obtained from the cores of the larger, jointed blocks. Similar material is exposed in stream sections on the flanks of Mt. Gimie. Samples from Mt. Tabac and Coubaril are of slightly paler, greenish-grey colour, and contain rare, large quartz crystals. In this respect they differ from rocks from the Gimie and Migny area. The state of weathering, however, is closely comparable, and it seems likely that all four masses belonged to the same period of volcanic activity.

Prolonged erosion has deeply modified the shape of these mountains, so that their original structure can only be guessed. However, their prominent shape and geographic isolation from one another suggests that they probably grew from separate eruptive vents, and the occasional patches of lava found around their present flanks are interpreted as relics of flows. Road-cut exposures on the northwest flank of Coubaril reveal, in addition to massive lava, beds of dark andesite breccia and indurated agglomerate (Plate 4b) dipping at  $30^{\circ}$  off the slopes of the hill, conformably with the present topography. These are interpreted as pyroclastic fragments ejected from a central vent and deposited on the slopes of a growing cone. The present morphology of the upper part of Coubaril hill consists of a horse-

shoe-shaped ridge (see Frontispiece) opening to the north, which may represent an old, partly disintegrated crater rim.

These dark andesite masses, at the time of their active growth, are envisaged as having formed small strato-volcanoes composed of lava flows interbedded with pyroclastics, each broadly comparable in structure to the cone of Mt. Misery on St. Kitts (Baker, 1963, p.26). It is probable that the dark andesite cones on St. Lucia, like Mt. Misery, were built up by a series of alternating effusive and explosive phases.

Dark andesite units outside the caldera underlie the earliest known post-caldera pyroclastics. By analogy, it is supposed that Coubraril also existed prior to formation of the caldera. It must, therefore, have subsided bodily at the time of caldera collapse.

### 5. 2. 3. PALE ANDESITE DOMES

Fond Doux and Morne Bonin are two large hills lying near the margin of the caldera (see Frontispiece and Geological Map), composed of pale-grey andesite lava. Fond Doux is situated near the southern rim of the caldera, and rises to 1,663 ft. a.s.l. Sparse outcrops of massive pale andesite are exposed, especially on the south-eastern flank at about 1,000 ft. a.s.l., in vertical cliffs up to 50 ft. high. The hill as a whole is fairly deeply dissected, and slopes are not greater than 30°. Occasional outcrops of blocky agglomerate composed of similar lava occur on the hill, and also to the south of the Ivrogne

river near its mouth. These are made up almost entirely of angular lava fragments from  $\frac{1}{2}$  to 6 in. across, with little or no fine matrix. On two small circular hills to the south, rising to 1,100 and 900 ft. a.s.l., boulders identical in appearance to the Fond Doux rock are common, and from this evidence the hills are believed to be satellites to the Fond Doux extrusion.

Morne Bonin is an elongate hill with twin summits, 2,200 ft. a.s.l., which projects from the eastern wall of the caldera. On its southwestern side, it overlooks Belle Plaine which lies at 1,200 ft. altitude, so that its relative height is 1,000 ft. The northwestern and southwestern flanks consist largely of talus, in which loose blocks up to 6 ft. across are common. Some of these show cooling cracks of the type common in breadcrust bombs. Identical blocks were also found on the caldera rim south of Belle Plaine. Broad banding, on a scale 1 - 3 in. wide, of slightly paler and slightly darker lava, is present in several of the blocks (e.g. L.5). No lava was found in situ on Morne Bonin hill, on the higher parts of which dense undergrowth made access very difficult.

The occurrence of steep slopes of blocky talus forming the flanks of Morne Bonin, and the morphology of this hill and the Fond Doux group, suggest that these masses probably had an original dome-like structure, and were extrusions which, judged by their considerably modified morphology, are relatively old and probably developed at an early stage after caldera formation. It is not unlikely that the rising magma took advantage of the

fractures along which caldera collapse had occurred, being the easiest route to the surface. Williams (1942, p.336, diagram 5) demonstrates how the earliest activity after collapse of Krakatau-type calderas is most likely to occur near the rim.

#### 5. 2. 4. ST. PHILLIP QUARTZ-POOR DACITE

A small outcrop of massive lava is seen in a tributary of the Migny river in the northeastern part of the caldera. This rock is dark grey in colour, slightly vesicular, and contains a relatively small number of large quartz phenocrysts, as well as plagioclase and hornblende. It has therefore been named a quartz-poor dacite. Though the amount of massive rock exposed is not large, much of the surrounding area consists of agglomerate containing blocks of similar appearance up to 6 in. across, in a lightly-consolidated, crystal-tuff matrix. Sections in Ravine Claire show this to be up to 60 ft. thick. Elsewhere, exposures are much confused by recent, landslipped debris from the northern wall: this applies particularly to roadside outcrops between Soufrière and Fond St. Jacques.

There is no definite indication of where or how these rocks originated. It seems probable, however, that the massive lava represents a small, independent extrusion from a vent below its present site. The pyroclastics may have been emitted earlier from this same vent.

Time relationships of this material to other intra-caldera units were not clear. The semi-consolidated state of

the pyroclastics suggests that they were probably among the earlier of the dacitic rocks. The location of the St. Phillip quartz-poor dacite near the border of the caldera implies that it may, like the pale andesites, have been emitted through the fractures along which caldera collapse took place.

### 5. 2. 5. PITON-TYPE DACITE DOMES

The two Pitons are steep-sided, conical masses composed largely of dacite lava. Both lie inside the caldera. The Petit Piton (Plate 5a) rises abruptly from the sea to 2,400 ft. altitude, with an average slope of  $55^\circ$  and an apical angle of  $70^\circ$ . The Gros Piton (Plate 5b), with a maximum elevation of 2,550 ft., is taller but less steep. The southwest flank, in particular, has a relatively gentle ( $30^\circ$ ) slope, the lower part of which is strewn with large boulders: some of these are over 20 ft. across, and the average size is 2 - 3 ft. (Plate 6a). Flaisance is an elongate hill which is less steep-sided than the Pitons, and no solid outcrops are seen on its flanks. The abundance of rather weathered blocks (e.g. L.284), of a variety closely similar to the Piton lava, suggests that massive rock of this type is present not far below the surface. The Rabot ridge is a north-south trending structure, similar to Flaisance.

Bare rock exposed on the steeper faces of both Pitons is often deeply weathered and not easily accessible, and fresh exposures are more readily seen along the coast west of the Petit Piton. Here, in addition to massive lava, relatively small areas

PLATE 5.

a) Petit Piton, seen from the south. The photograph, taken from the summit of Fond Doux (1,663 ft. a.s.l.), shows in true perspective the steepness of the flanks, which are composed almost entirely of massive dacite lava, and clad by rain forest which is scanty on the lower part but becomes denser towards the summit. The latter is 2,400 ft. a.s.l.

b) View of the Gros Piton from the east (south of Victoria Junction). Massive dacite forms the core of the mountain, but the apron round the southwestern flank, to the left of the picture, consists of loose boulders (see Plate 6a), believed to be the remnant of a formerly more extensive talus which collected around the flanks of the growing protrusion.

To the right of the picture, the southern half of Fond Doux is visible, with its summit on the extreme right: this is a more deeply dissected, pale andesite mass.



PLATE 6.

a) Talus at the southern foot of the Gros Piton, exposed in the gully of L'Ivrogne river. In this exposure, angular blocks are up to 3 ft. across, and the spaces between them are filled by smaller fragments of Piton dacite. This material is believed to represent the original, blocky scree which developed around the flanks of the protrusion during active growth.

b) Horizontal flow-banding in Petit Piton dacite: an exposure of massive lava a few feet above sea level on the western flank of the mountain. Paler-coloured margins mark the separate bands, which are up to 7 in. thick, sub-parallel to one another and lenticular, with tongues or lobes protruding into adjacent bands. This structure appears to have resulted from the lateral movement of adjacent, viscous layers, in a kind of sluggish laminar flow.

( Length of hammer head: 7 in. )



of strongly sheared dacite are seen. Irregular flow-banding, visible locally in fresh dacite (Plate 6b), dips approximately northeast (inward) at angles of up to  $20^{\circ}$ . Similar, gentle dips were observed in vertical faces at between 500 - 1,000 ft. a.s.l. on the western flanks of the Petit Piton. The Piton dacite lava contains angular inclusions of aphyric basalt up to 5 ft. across (Plate 7a) as well as smaller, rounded inclusions of dolerite and gabbro up to 2 ft. across (Plate 7b). A single, small inclusion of pale-grey, quartzitic hornfels (L.724) was found.

There have been a number of conflicting views on the origin of the Pitons. Spencer and Hill are reported by Sapper (1903, p.274) to have described them as remnants of a former crater, the western part of which had been removed by the sea. This opinion was reiterated by Earle (1923, p.1). Sapper (1903, p.274), however, rejected Spencer's and Hill's explanation, and stated\*: "the enormous dacite masses which form these mountains show no bench-like arrangement or any other signs of their formerly belonging to a crater, so that I like to think of them as stock-shaped masses of rock, whose remarkable form (like a sugar loaf in the case of the Petit Piton) was created by subsequent transformation, mostly by landslips." Perret (1940) put forward the hypothesis that the Pitons were examples of massive, solid protrusions comparable to the spine which grew from Mt. Pelée on Martinique in 1902-3.

The present author agrees with Sapper that there is no definite evidence that the region between the Pitons resembles

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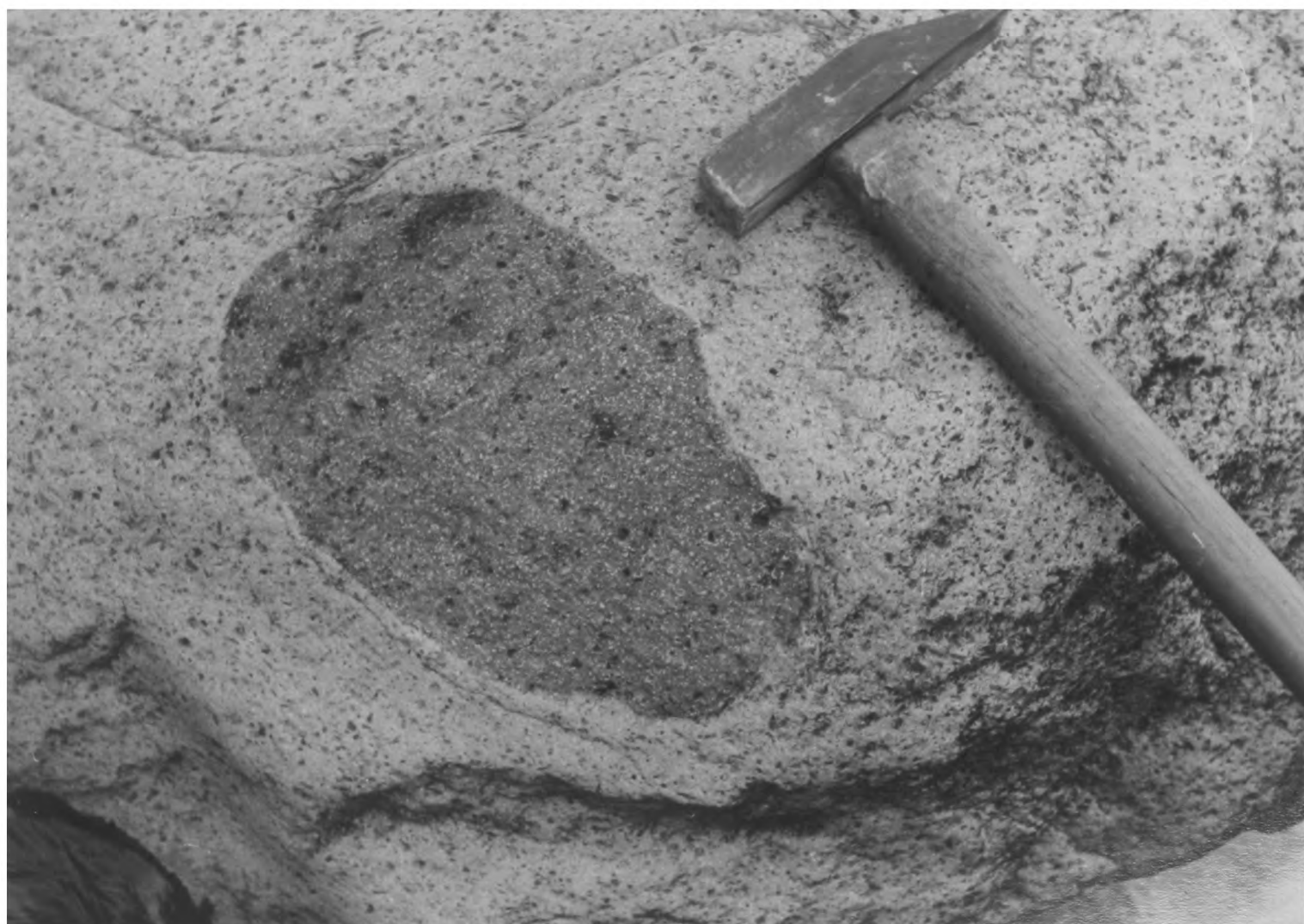
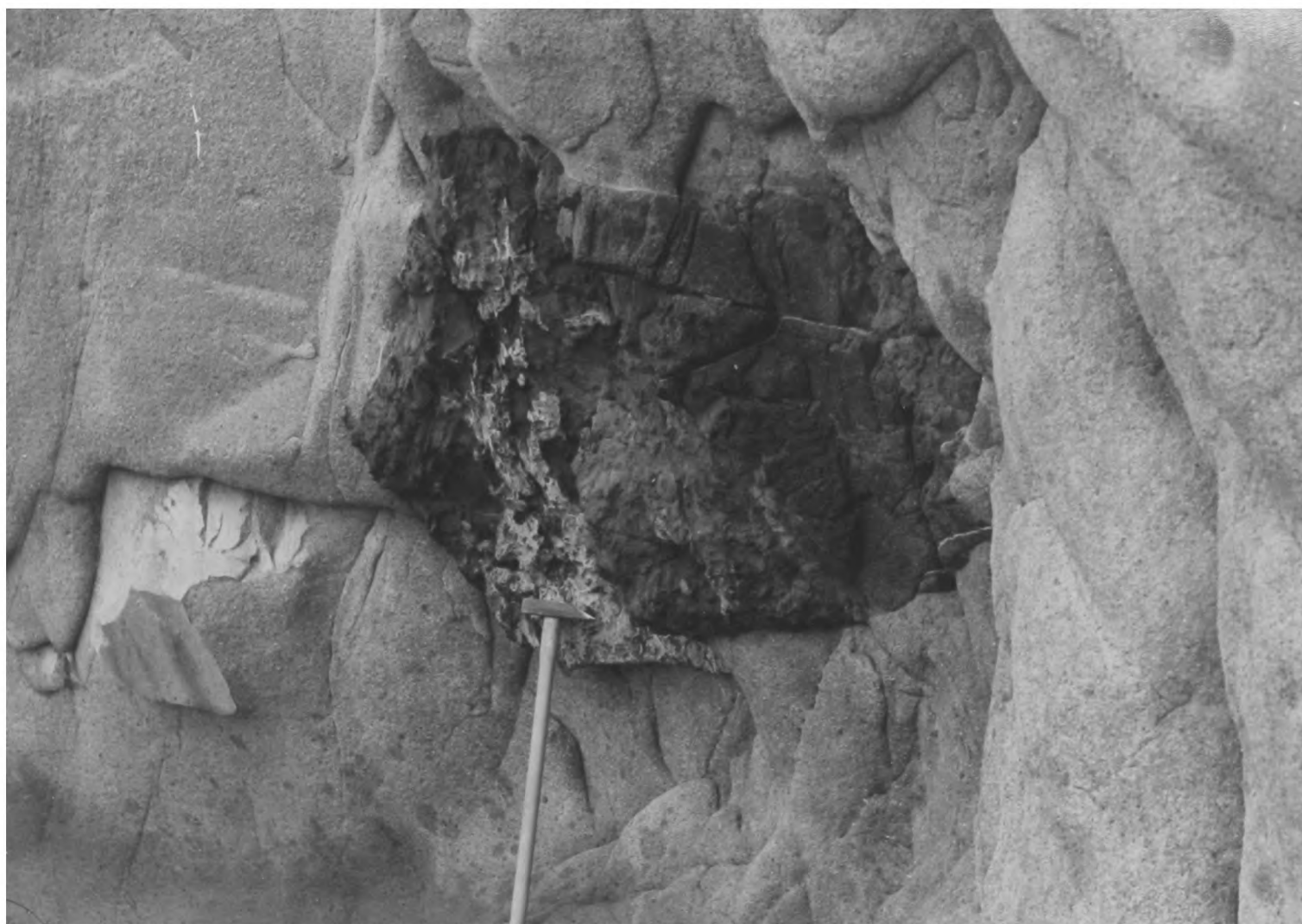
\*Translated from the German by the present author.

PLATE 7.

a) Xenolith of aphyric basalt in Petit Piton dacite, exposed 5 ft. above sea level on the western flank of the Piton. The xenolith is 6 ft. across, angular, and has sharp contacts with the dacite, but shows no visible effects of thermal metamorphism. Dacite lava has filled small cracks in the basalt, indicating that the latter remained solid although enclosed in liquid dacite.

b) Xenolith of "lamprophyric" hornblende-dolerite (similar to L.717) in Gros Piton dacite, exposed in L'Ivrogne river. The inclusion is 1 ft. long. Phenocrysts in both dacite and dolerite include shattered quartz crystals up to 10 mm. across, some of which have fallen out leaving small pits in the surface.

This is the commonest type of inclusion in Gros and Petit Piton dacite.



the eastern half of a former crater. The high proportion and variety of rock-types surrounding this area are not typical of a crater-structure, and no bedded pyroclastics are seen in the supposed eastern rim, formed by Pond Doux and Plaisance.

Sapper is undoubtedly correct in his statement that the present steepness of the Pitons is due to landslips. He did not, however, state how he believed the Pitons were initially emplaced. Though he compared their shape to that of stocks, he did not state that they were intrusive rather than extrusive.

Perret's analogy to the historic spine of Mt. Pelée is difficult to accept, principally because of the relative sizes of the phenomena. Whilst the Martinique spine, with a maximum height of 1,000 ft. and basal diameter of 450 ft., had a volume of 0.002 cubic miles, the Petit Piton rises to more than twice the height, and has a calculated present volume above sea level of 0.061 cubic miles, i.e. 30 times greater than the Mt. Pelée spine. It is, therefore, a phenomenon of a different order of magnitude. Moreover, the spine of Mt. Pelée grew on the summit of a newly formed dome, and is the largest undoubted example of this kind of feature in the geological record. Other spines, for example those formed in 1924 on the dome of Santa Maria in Guatemala (Sapper, 1926), were very much smaller, with a maximum height of 218 ft. Yet numerous examples of viscous, expanding protrusions, or volcanic domes, have formed in historic time, and several of these have reached a comparable size: e.g. Santa Maria in Guatemala, on the flank of which a dome grew

between 1922-25 to a height of about 1,500 ft. with a basal diameter of 3,000 ft. (Sapper, 1926), i.e. with a volume of approximately 0.057 cu. mile. In the Soufrière region of St. Lucia, Terre Blanche Hill, rising 1,400 ft. above the surrounding topography and with an estimated volume of 0.076 cu. mile, is believed morphologically, to be an intact example of such a feature, and is composed of dacite lava closely similar to that of the Pitons.

Definitions of dome-types were given by Williams (1932, pp.52-4), who distinguished:

- 1) Plug domes, representing upheaved conduit fillings;
- 2) Endogenous domes, growing essentially by expansion from within;
- 3) Exogenous domes, built by surface effusion, usually from a central summit crater.

Williams also defined spines, as slender, obelisk-like protrusions from the upper surface of a dome.

As has been indicated, it is believed that the Pitons, like the younger dacite domes on St. Lucia, formed as viscous extrusions which grew largely by endogenous growth at the surface to form more or less hemispherical hills. The core consisted of viscous lava, and from the flanks, as they cooled, boulders of solidified material broke and fell to form an apron of scree (c.f. Lacroix, 1904, p.134, with reference to the 1902-03 dome of Mt. Pelée), of which only a small proportion, on the western and southern flanks of the Gros Piton (Plate 5b), has survived

subsequent erosion. In the case of the Petit Piton, almost all talus has disappeared and the massive core is at present being reduced, and its profile sharpened, by large-scale landslipping of massive segments.

When discussing the identification of dome types, Williams (1932, p.53) comments on the relative rarity of plug domes, compared with endogenous domes, and states: "...if there be good reason to regard a protrusion as due to the upheaval of an actual plug....., and if the mass then rises distinctly above the crater floor, it may with reason be referred to as a plug dome.....". Though this remains a possible alternative explanation for the origin of the Pitons, it is considered by the present author less likely than the mechanism of endogenous growth.

The occurrence of fewer blocks on the landward than on the seaward side of the Gros Piton suggests that there was less original talus here, since no satisfactory explanation can be given of why removal should have been more effective on the landward side. The presence of a Piton dacite boulder in limestone north of Malgrétoute, however, indicates that the sea was once at least 100 ft. higher at a time subsequent to Piton formation, and if Sapper's observations (1903, p.278, and section 5.4. of this thesis) are correct, and involved the same limestone, it seems that the sea must once have washed the flanks of the Pitons at a level 450 ft. higher than today.

5. 2. 6. TERRE BLANCHE AND ADJACENT DACITE DOMES AND CRATERS

Domes in this group include the hill of Terre Blanche, and four smaller protrusions, of similar lava-type, lying immediately to the south and south-east (Fig.12 and Plate 2b).

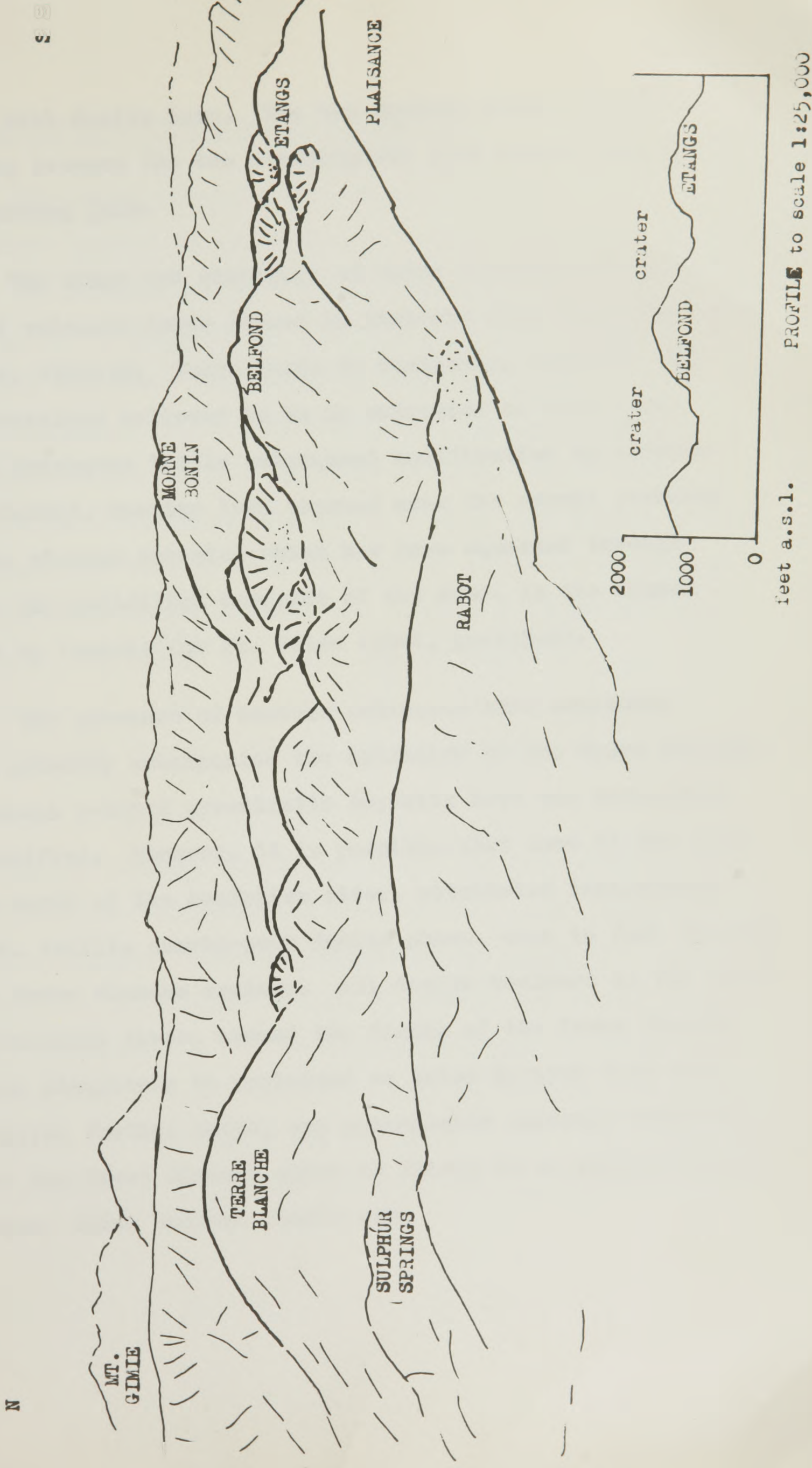
Terre Blanche hill is almost hemispherical in shape, and rises to 2,000 ft. a.s.l. from a surrounding topographic level of about 600 ft. Its volume, calculated as a cone of radius 0.4 mile, and height 0.3 mile, is 0.076 cu.mile. The flanks of the hill are composed of loose blocks, up to 6 ft. in diameter, of pink, slaggy dacite which is occasionally inter-banded with dark grey dacite. Only at the summit of the hill is massive lava seen: this rock (L.245) outcrops within an area of about 100 x 40 ft. at the western side of the summit of the hill. It is less slaggy, having a pink or grey/<sup>colour and</sup>compact texture, with irregular darker and paler flow-bands up to  $\frac{1}{2}$  in. wide, and fewer large phenocrysts than in the talus lava.

Smaller domes to the south of Terre Blanche are composed of similar, pink dacite lava, and on account of this and their proximity to Terre Blanche hill, are attributed to the same period of extrusion.

Three craters lie adjacent to the Terre Blanche domes: these are basin-shaped depressions, about  $\frac{1}{2}$  mile in diameter from rim to rim, and up to 300 ft. deep. They have flat bottoms, filled with alluvial crystal ash, which are intensively cultivated and very fertile. The inner walls are composed of loose

FIG. 12. SKETCH SHOWING THE TERRE BLANCHE AND BELFOND DOMES AND CRATERS,

seen from the Petit Piton summit, looking east.



blocks of pink dacite lava. The two craters north of Belfond hill, lying between the two southernmost pink dacite domes, form an intersecting pair.

The shape and structure of Terre Blanche is similar to that of volcanic domes formed in historic time (e.g. Mt. Pelée, Martinique, 1929-32; Santa Maria in Guatemala, 1922-5). The hill is therefore believed to be an extrusion of this type, which has undergone little subsequent modification by erosion. The flow-banded, massive lava exposed near the summit probably represents viscous material which has been squeezed through cracks in the solidified carapace of the dome, in the manner described by Lacroix for Mt. Pelée (1904, pp.135-6).

The presence of craters indicates that explosive activity probably accompanied the extrusion of the Terre Blanche domes, though related pyroclastic deposits have not definitely been identified. However, it is possible that some of the pyroclastics north of the Soufrière river, attributed tentatively to the St. Phillip quartz-poor dacite phase, were in fact ejected from the Terre Blanche craters. All dacite boulders to the south of the Soufrière river, around the flanks of the Terre Blanche domes, can adequately be explained as talus derived from the domes, whilst further south, any pyroclastic material which may belong to the Terre Blanche phase is likely to be buried beneath the younger, thick Belfond pumice ash.

5. 2. 7. BELFOND DACITE DOMES AND CRATERS

This group consists of a cluster of five domes and three craters located in the southern-central part of the caldera (Fig.12), and is named after the most prominent hill. The domes are composed of a distinctive, very pale-grey dacite lava with large, fresh amphibole phenocrysts. These protrusions are up to  $\frac{1}{4}$  mile in diameter, with a relative height of approximately 400 ft. Their surfaces consist almost entirely of loose lava blocks, though outcrops of massive lava occur rarely. The shapes of some of the domes seem to have been modified by explosive eruptions from the adjacent craters, which are similar in shape and size (see profile, Fig.12) to the Terre Blanche craters. Their inner slopes consist of loose, pale-grey dacite blocks, commonly between one and four feet across. Two of the craters form an intersecting pair.

The Belfond craters are believed to have been formed around vents emitting ash and pumiceous lava blocks. Lava fragments found in the youngest pyroclastic unit of the Soufrière region are identical in appearance to blocks forming the crater sides and flanks of the domes. It seems possible that the domes have grown on the site of former craters, thereby blocking the conduit and leading to the opening of new adjacent vents. Extrusive and explosive activity in this area may have been in part contemporaneous.

### 5. 3. PYROCLASTIC DEPOSITS, IN SEQUENCE

#### 5. 3. 1. TERMINOLOGY OF THE PYROCLASTIC DEPOSITS

Two types of pyroclastic deposit are of particular importance in the Soufrière region: these are called pumice fall and pumice flow. The terms were first used by Kōzu in 1934, to describe the two types of deposit formed during the Vulcanian-Peléan eruption of Komagatake in Japan in 1929. Kōzu (1934, p.136) stated:

"In this great activity, the volcano ejected a tremendous quantity of dacite pumice newly derived from magma. The pumice may be classified into two varieties: one of which is what we call the 'pumice fall' and the second the 'pumice flow'. They differ in the manner of ejection from the craters, opened on the summit, not in their essential mineralogical composition. The former was ejected straight up as high as 12 km. above sea level and fell over a vast area east of the volcano on sea and land, influenced by the wind from the west, reaching to a distance of more than 200 km. The latter was ejected in large columns from the crater in an enormous quantity, but not so high as the former, and fell straight down on to the summit, then rushed down along the valleys of the mountain in different directions."

The importance of the manner of ejection was particularly emphasized by Kōzu. Sedimentary features and size characteristics of the deposits from eruptions of these two

types were pointed out by Kuno (1941), who described the stratified nature of fall deposits and the manner in which they characteristically mantle the older topography, in contrast to the structureless appearance of flows, which are typically concentrated in topographic depressions. Kōzu's terminology was adopted by Williams (1942, p.68) in his description of the youngest deposits around the caldera of Crater Lake, Oregon.

The occurrence of blocks of non-vesicular or vesicle-poor lava instead of pumice, in deposits formed by the two types of eruption described by Kōzu, appreciably alters their character. The actual formation of deposits of this type has been observed in the large historic eruptions of Martinique and St. Vincent in the West Indies, and these deposits have been subdivided in detail according to the type of structure from which they were ejected and their precise mode of emission, (Lacroix, 1930, MacGregor 1952). However, as stated by MacGregor (1952, p.72), such variety cannot be recognised in ancient deposits, which on St. Lucia are described by the terms block-plus-ash fall (corresponding broadly in mode of origin to pumice fall), and block-plus-ash flow (corresponding to pumice flow). The relationships of these four types of pyroclastic deposit are summarized in Table 1.

Secondary pyroclastic deposits in the Soufrière region have developed by re-distribution of the primary material already described. These include four principal types:

**Table 1. TYPES OF PRIMARY PYROCLASTIC DEPOSIT OCCURRING IN THE SOUFRIÈRE REGION, ST. LUCIA**

MODE OF ERUPTION	FALL	FLOW
NAME and constituents	PUMICE FALL ash + pumice blocks	PUMICE FLOW ash + pumice blocks
	BLOCK + ASH FALL ash + non-vesicular lava blocks	BLOCK + ASH FLOW ash + non-vesicular lava blocks
FIELD CHARACTERISTICS	1) Stratified (vertical size grading) 2) Particle size increases towards source 3) Evenly mantles pre-existing topography 4) Thickness increases towards source	Unstratified  No regular particle size variation  Concentrated in pre-existing valleys  Thickness often increases away from source

1) Mudflow or laharic deposits, composed of unsorted material closely resembling, both in lithology and in distribution, the primary block-plus-ash flow material. Re-mobilisation of the latter through the agency of torrential rain, or floods of water escaping from a lake, leads to thick flows of viscous mud, capable of carrying along even the largest boulders. Deposits of this type were observed to form during the eruption of the Soufrière volcano of St. Vincent in 1902 (Anderson and Flett 1903, p.423). Mudflow deposits obviously may form by re-mobilisation of any incoherent material at the surface, i.e. from any of the primary pyroclastic deposits shown in Table 1.

- 2) Fluviatile material, although also transported by water, differs in mode of transport from that of the mudflow in that a large amount of water carries only a small amount of detritus, and the finest or, given equality in size, the least dense fractions are transported farthest. The maximum size of material transported varies according to the velocity of the water. Thus the deposits are stratified, with alternating sandy and pebbly layers (e.g. Plate 15b).
- 3) Shoreline conglomerates are formed by rolling of boulders on the contemporary sea shore, and mixing with finer sandy material. As with fluviatile deposits, the finest, dust-size fractions tend to be completely removed. The coarser boulders are often completely rounded, and the deposit usually acquires a crude stratification (e.g. Plate 10b).
- 4) Landslipped, or hill-creep material, displays a variety of facies: on the flanks of a dome, it is normally composed of large, loose blocks of the dome-forming lava (e.g. Plate 6a). Elsewhere, it may consist of a heterogeneous mixture of tuff, lava and recent soil. Older material with such an origin is likely to be almost indistinguishable from mudflow and primary block-plus-ash flow.

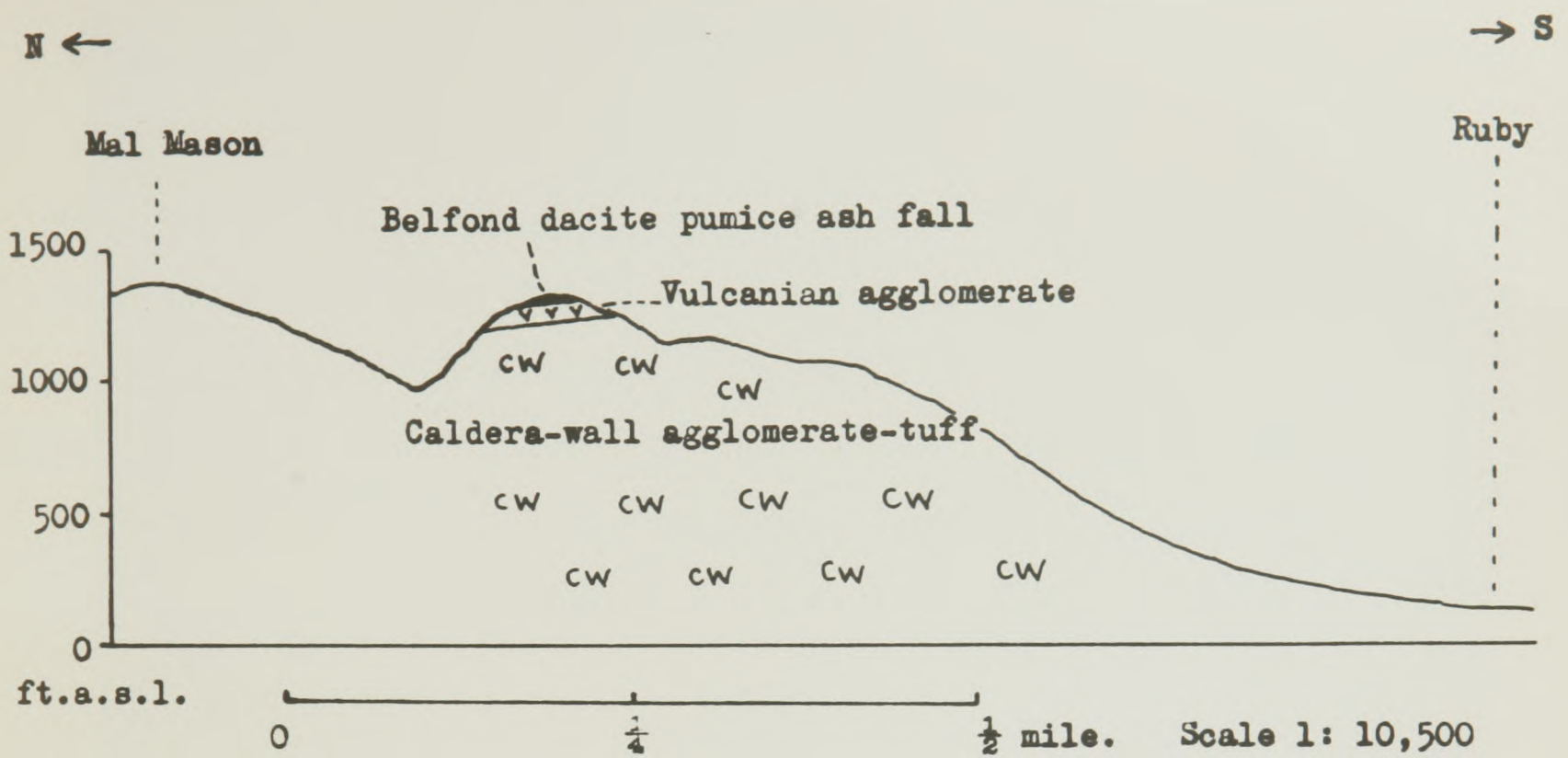
### 5. 3. 2. CALDERA WALL ANDESITE AGGLOMERATE-TUFF

The largest vertical section across the caldera-wall is that exposed along the main road north from Soufrière. Road-cuttings made only a few years ago expose relatively fresh material in more or less continuous outcrops, though in places

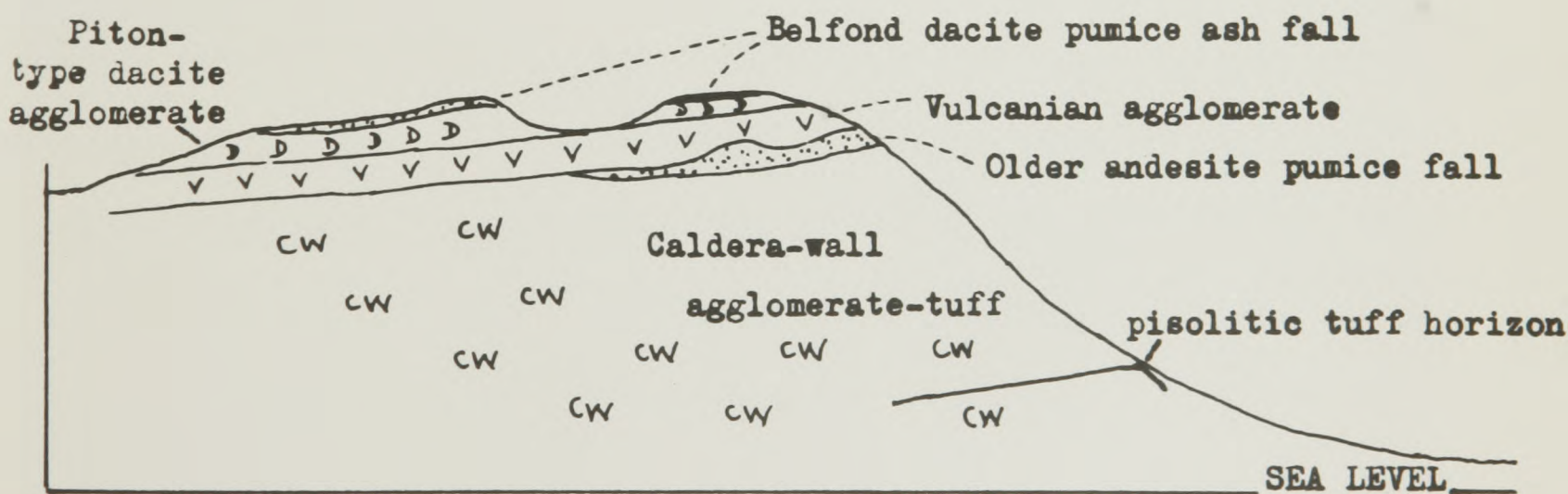
large-scale landslips have obscured or modified the original facies. A vertical thickness of about 1,000 ft. of consolidated agglomerate is exposed (Fig. 13a) consisting essentially of angular blocks of andesite lava up to 6 ft. across in a cream-coloured, tuffaceous matrix.

Lava types are notably varied in colour, from almost white to pink and dark grey: the rock texture varies from non-vesicular to mildly vesicular, being more frequently the latter. Banding is visible in numerous of the included fragments, and consists of parallel zones  $\frac{1}{2}$  - 4 inches wide of different colour. All sizes of blocks are found from 6 ft. in diameter down to fragments so small that they grade into the matrix of dust and crystal tuff. The average proportion of blocks greater than  $\frac{1}{2}$  inch across varies between 30 and 70% (Plate 8b). Throughout most of its vertical thickness of 1,000 ft., the agglomerate is completely without stratification, grading, or systematic variation in structure, and no difference was observed between lava types from the lower and upper parts of the mass. One notable exception, however, was found by the roadside due north of Soufrière at about 140 ft. a.s.l., where a bedded, fine, cream tuff horizon 2 ft. thick, with pisolitic layers (L.240) was observed to dip southward at  $43^\circ$ . That this represents an original dip seems most unlikely in an ash fall deposit of even thickness. This implies that the whole outcrop represents part of a large, shifted mass which was tilted either at the time of caldera collapse or by subsequent large-scale landslip. A similar tuff, without pisolites, was found at

FIG. 13. CROSS-SECTIONS THROUGH THE NORTHERN WALL OF THE CALDERA.



a) Cross-section through the northern wall of the caldera.



b) Diagrammatic cross-section through the northern wall of the caldera, showing the full pyroclastic sequence.

(To approximately the same scale as Fig. 13a.)

PLATE 8.

a) Caldera-wall andesite agglomerate-tuff, exposed in a roadside section immediately north of Victoria Junction. The deposit contains angular blocks of andesite up to 3 ft. across, and lava fragments from this size down to  $\frac{1}{2}$  in. across form about 50% of the agglomerate. The matrix consists of crystals, glassy dust and fine lava fragments which are firmly consolidated to form a cream to grey-coloured, compact tuff. The deposit is without definite stratification, although finer and coarser material occurs in irregular, ill-defined patches.

( The vertical stripes are due to superficial staining by water. )

b) Closer view of typical Caldera-wall andesite agglomerate-tuff. The exposure is at Derrière Horne, beside the road. The largest block is 4 ft. high, though most range in size from 3 - 12 in. Almost all are composed of andesite lava which varies in texture from mildly vesicular to non-vesicular, and in colour from very pale grey to charcoal-grey, pink, or cream-coloured rocks.



100 ft. a.s.l. above Rachette Point, dipping northward at 4°.

Andesite agglomerate-tuff of similar appearance outcrops in the southern wall of the caldera, and is well exposed just north of Victoria Junction (Plate 8a). The material is similar in every respect to that exposed north of Soufrière, though nowhere in the southern area is a vertical thickness of more than 150 ft. visible. From Victoria Junction southward, over the upper part of the glacis, this agglomerate is frequently seen at the surface or beneath a superficial mantle of more recent pumice flow deposits. Where it outcrops, weathered-out boulders up to several feet across characteristically litter the surface, which is often barren of vegetation.

In the highland area north and east of the caldera, similar agglomerate is seen to form the lowest exposed deposit of many of the steeper slopes and sections, from which unconsolidated, younger pyroclastics have been removed by erosion. At higher altitudes, where weathering is deeper and more intense, and outcrops rarer, the recognition of this material becomes increasingly difficult. Consolidated agglomerates and conglomerates containing similar lava types outcrop northward from Soufrière almost to Castries, and also occur on the eastern side of the island (see Fig. 8).

Relationships of the andesite agglomerate-tuff to the dark andesite masses composed of lava and pyroclastics (e.g. Gimie, Tabac) are nowhere clearly revealed. Indeed, the distinction between weathered Caldera-wall agglomerate-tuff and the

deeply altered pyroclastics of which the flanks of Mt. Gimie appear to consist in part, was not satisfactorily established. It is possible that the two are closely related in time and place of origin.

The fact that the agglomerate-tuff forms the caldera-wall shows that it must have existed and been well-consolidated before caldera-collapse. Stratified horizons are rare and in one case, north of Soufrière, the dip is probably anomalous. The thickness observed in the north wall indicates the vast volume erupted. Moreover, the base is nowhere visible.

The absence of bedded structures invites the supposition that the material was pyroclastic flow rather than fall. It is probable that redistribution by mudflow and other agencies has affected some of the sequence. The absence of conspicuous erosion surfaces or soil horizons suggests that it came from eruptions which were not separated by long time-intervals, though recognition of such breaks in material so old and structureless might expectably be difficult.

The greater thickness observed to the north side of the caldera (1,000 ft.), by comparison with the maximum visible thickness of 150 ft. in the south, is undoubtedly to some extent due to the higher elevation and deeper dissection of the northern region. This higher elevation, however, is probably due to the fact that the original sequence of Caldera-wall agglomerate-tuff was thicker. From this it is concluded that

the area to the north of the present caldera was nearer than the southern side to the source. It seems likely, then, that the agglomerate-tuff originated from this highland area, and may have issued from eruptive centres connected with the dark andesites of the Gimie-Tabac group.

### 5. 3. 3. OLDER ANDESITE PUMICE FALL AND PUMICE FLOW

#### Pumice fall in coastal exposures near Grand Caille Point

Exposures on the north side of Soufrière Bay reveal a maximum of 18 ft. of consolidated, bedded, andesite pumice (Plate 9a), made up of eight units which show inverted grading, overlying finely stratified tuff at the base. Each graded unit is between 2 and 4 ft. thick, and exhibits a passage upward from fine ash, composed of pumice fragments and crystals, at the clearly defined base, into sub-angular pumice lumps with a maximum size of 3 inches at the top. The eight graded units are all of similar thickness, and overlie finely stratified material at the base of the formation. The pumice beds lie on an eroded, reddened surface of Caldera-wall agglomerate, and dip gently northwest at 5°. Stratified pumice with similar characteristics was found on the north side of Grand Caille Point, only 700 ft. distant from the first locality: this is almost certainly a northward extension of the same deposit.

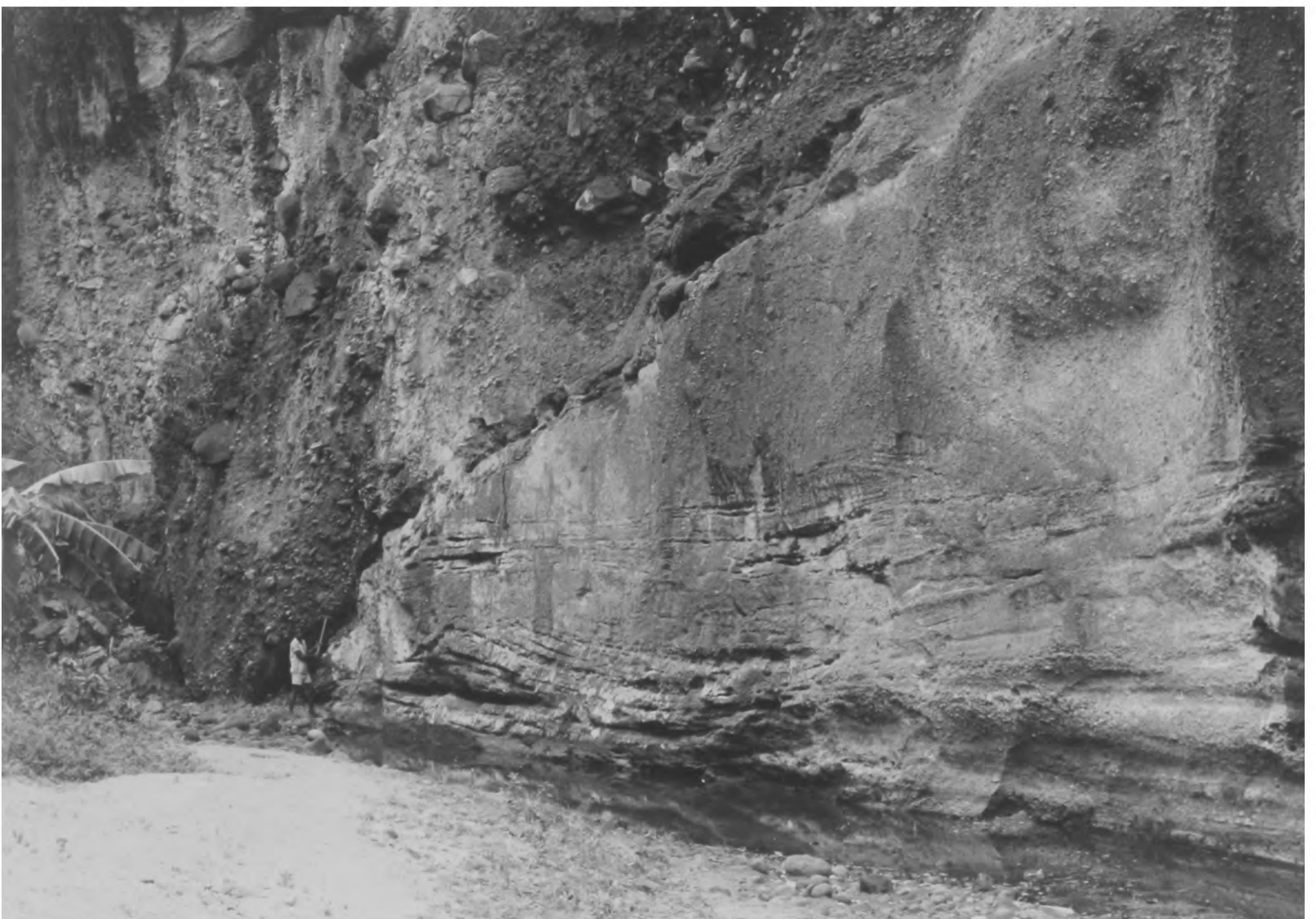
The fine stratification of the lower part of the deposit, and even thickness and grading of higher units,

PLATE 9.

a) Older andesite pumice-fall units showing inverted grading, east of Grand Caille Point, on the north side of Soufrière Bay. The pumice units disconformably overlie Caldera-wall andesite agglomerate-tuff with a reddened surface. The pumice layers have been deeply eroded, and are overlain by a conglomerate facies of the Vulcanian andesite agglomerate (see Fig. 13), forming a less steep face which supports vegetation.

The andesite pumice at this locality has a maximum thickness of 18 ft., and consists of up to eight reverse-graded units, each between one and four feet thick, overlying finely-stratified material at the base. The grain size of a graded unit increases upward, from crystal-tuff containing  $\frac{1}{2}$  in. lapilli at the base, to pumice fragments of average size 2 - 3 in. at the top.

b) Older andesite pumice deposits in Trou Barbet river gorge, showing an irregular erosion surface overlain by a structureless, mudflow facies of the Vulcanian andesite agglomerate, which contains blocks up to 2 ft. across. The andesite pumice exposed here consists of 10 ft. of stratified, strongly cross-bedded agglomerate, overlain without visible discordance by 12 ft. of structureless andesite pumice which is interpreted as flow. The size of the pumice fragments rarely exceeds one inch.



indicate almost certainly that the material represents pumice fall. The inverted grading may be explained by two possibilities: either as the product of a series of eruptions which threw up progressively coarser material, or as the result of some form of mechanical sorting after deposition, e.g. floating of the lighter pumice lumps in water until, first in the case of the smaller fragments, they became waterlogged. The reddened surface of the underlying agglomerate-tuff, however, indicates probable sub-aerial exposure of this deposit prior to the pumice eruptions. Hence it is believed that the pumice fell on land, not in water, and that the grading is the result of a steady increase in the size of material ejected during each explosive phase.

Trou Barbet River: pumice fall and pumice flow

Stratified andesite pumice, overlain by similar unstratified material, was also found at the foot of the southern glacis. In the Trou Barbet river valley, in the vertical-sided gorge just upstream of the point where it is crossed by the minor road northwest of Choiseul, 10 ft. of irregularly bedded pumice are overlain by 12 ft. of similar, though unstratified material (Plate 9b). The lower, stratified portion consists of mildly cross-bedded, fine layers, in two of which there is slight inverted grading. Lumps of pumice reach a maximum size of 1 inch, being smaller than in the exposures north of Soufrière. Unlike the latter, the stratified material in the Trou Barbet valley shows marked cross-bedding, suggesting partial reworking by water or wind. However, on the evidence of the composition

of the material and the structure of the deposit, in addition to its stratigraphic relationships to the Vulcanian agglomerate, it is tentatively correlated with the stratified andesite pumice north of Soufrière.

The stratified pumice in the Trou Barbet river is overlain by 12 ft. of unstratified material, which is interpreted as pumice flow. In all other respects, it appears identical to the underlying stratified pumice. The level at which banding disappears undulates gently, but shows no evidence of a significant time-interval.

#### Source of the older andesite pumice fall and flow

No specific source for the andesite pumice has been identified. Since the size of fragments in the fall deposits is larger in the exposures north of Soufrière, it is tentatively concluded that these were closer to the eruptive centre. It is presumed that this lay within, or close to the site of the present caldera, and that the vent from which the material was erupted no longer exists. The gentle northward dips visible in exposures near Grand Caille Point suggest that the source of the material probably lay to the south, i.e. within the caldera.

#### 5. 3. 4. VULCANIAN ANDESITE AGGLOMERATE

##### Graded facies

This deposit is most clearly exposed on the northern rim of the caldera, along the main road northeast of Colombette. Thirty-three crudely graded units occur, each 2 - 4 ft. in

thickness and composed of steel-grey, angular, quartz-andesite lava blocks in a semi-consolidated ash matrix of similar colour (Plate 10a). The maximum size of blocks decreases from 1 ft. at the base of a unit to 1 inch at the top. Junctions between successive units are not distinct, and the large blocks at the base of the higher layer seem sometimes to have embedded themselves in the fine, upper part of the underlying unit. Blocks vary in texture from solid, grey, crystalline lava to glassy and mildly vesicular types, some of which show flow banding. Breadcrust bombs also occur.

No evidence of erosion or weathering is seen between any of the units, which are strikingly similar throughout the whole sequence of about 100 ft. The lateral persistence and planar attitude of the units is revealed by outcrops up to  $\frac{1}{2}$  mile further north along the road. The graded beds dip consistently northwest at  $7 - 10^\circ$ , indicating that they were deposited on an even, gently sloping surface.

Similarly graded units are found in road sections north of Canaries, where the average thickness tends to be less (1 - 3 ft.) and the material is finer, with a maximum size of 6 inches. Outcrops in this area expose only 6 consecutive units.

To the south of the caldera, crudely graded agglomerate of similar lithology to the Colombette deposit is seen in the deep gully of the Trou Marc river, where 11 units form the upper 40 ft. of a vertical section. The material includes occasional breadcrust bombs.

PLATE 10.

a) Crudely graded Vulcanian andesite agglomerate. This roadside exposure, northeast of Colombette, shows 6 of the sequence of 33 Vulcanian block-plus-ash fall units visible near the top of the northern wall of the caldera. Each unit has a thickness of approximately 3 ft., and contains blocks of grey quartz-andesite lava whose maximum size decreases from 1 ft. at the base to 1 in. at the top. Junctions between successive units are not sharp. The layers dip northwest at  $7 - 10^\circ$ .

b) Conglomerate facies of the Vulcanian andesite agglomerate, exposed in coastal cliffs south of Anse Mahaut. The photograph shows a section 40 ft. high, composed of layers and lenses of boulders up to 4 ft. across in a loosely compacted, grey tuff matrix. The rounded shape of the boulders and crude stratification suggest that this represents a shoreline facies, uplifted relative to present sea level.



### Conglomeratic and structureless facies

In numerous localities, semi-consolidated agglomerate containing lava blocks identical to those in the graded units, including glassy and vesicular quartz-andesites, banded andesite blocks, and breadcrust bombs (Plate 11a), is seen in completely unstratified, or stratified conglomeratic deposits. The latter type are well exposed along the coastal cliffs of Grand Caille Point, and are the predominant type outcropping from here northward to Canaries (see Plate 10b). Rudely bedded, lenticular horizons of subangular to rounded boulders up to 1 ft. across (and occasionally larger) interfinger with beds of finer, largely sand-size material. The lateral impersistence of these beds contrasts greatly with the planar nature of the graded units, and this, together with the rounding of the boulders, indicates some form of redistribution in an aqueous, probably shoreline environment.

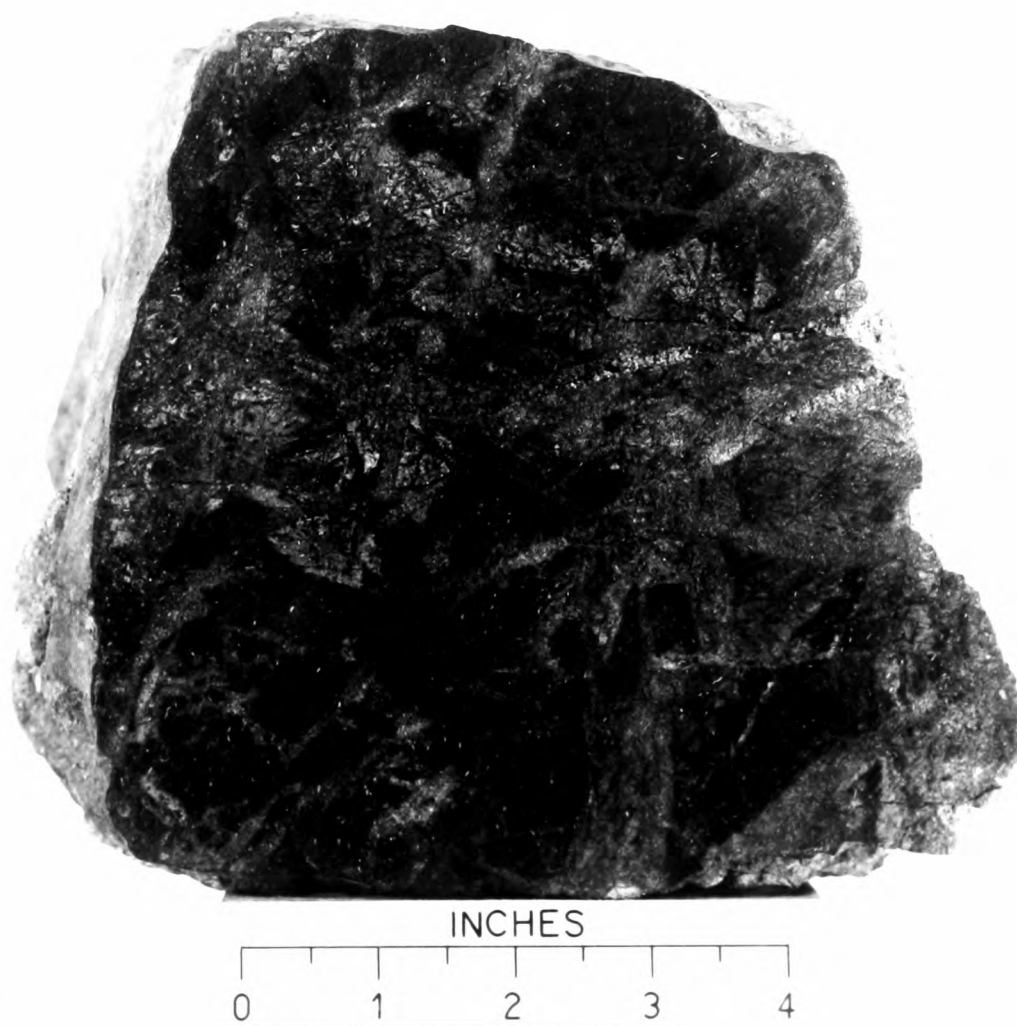
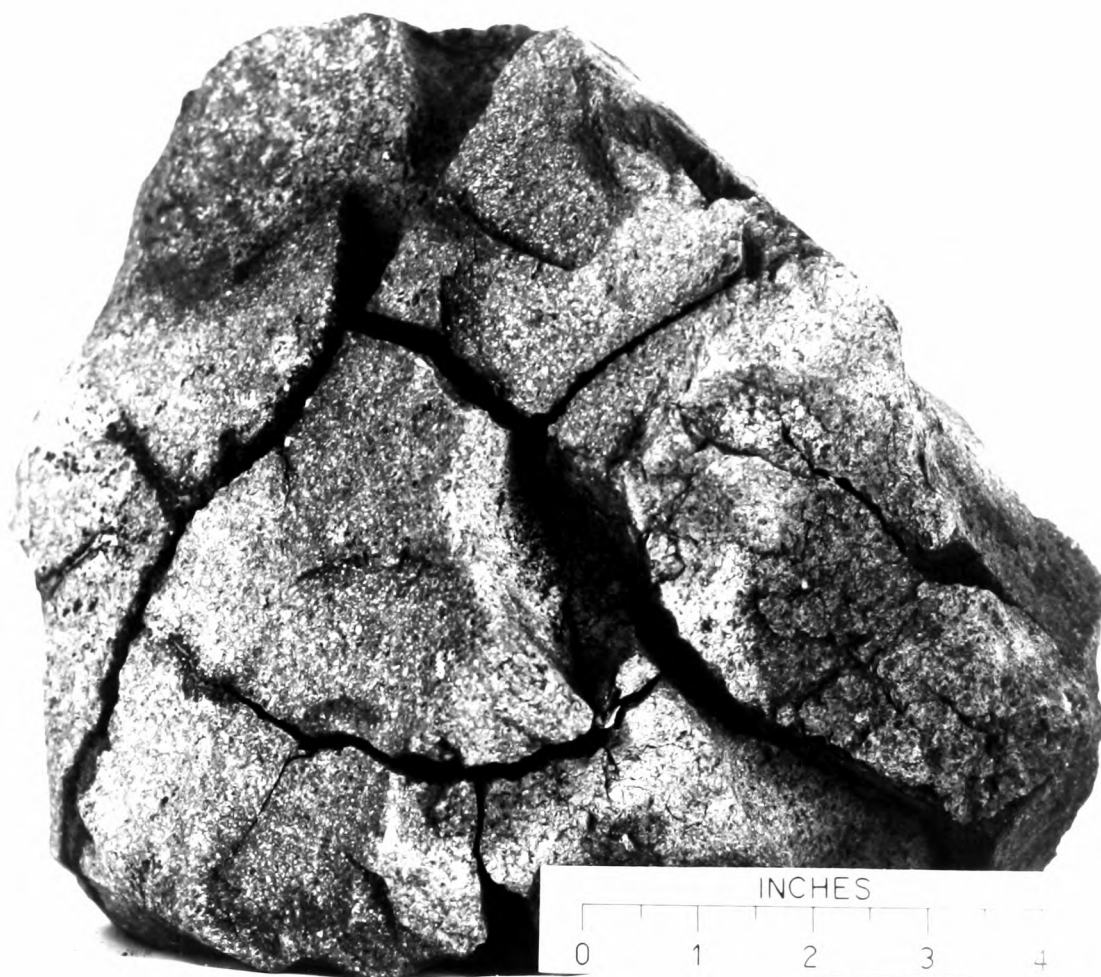
Similar deposits are also found along the coast northwest of Choiseul. Here there is commonly no form of stratification present (c.f. Plate 9b) and the material is interpreted as the product of redistribution by mudflows. In some of these deposits, banded blocks are particularly conspicuous.

The graded facies of this semi-consolidated andesite agglomerate is too planar and laterally extensive to be the product of pyroclastic flows. It is, therefore, believed to have been formed by a series of repeated vertical eruptions of great violence. The occurrence of breadcrust bombs supports

PLATE 11.

a) Breadcrust bomb L.767, from the Vulcanian agglomerate north of Anse Mamin. The bomb is angular, with a surface traversed by irregular cracks up to  $\frac{1}{2}$  in. wide and 1 in. deep. The outermost layer of the bomb is  $\frac{1}{2}$  in. thick and composed of glassy, grey andesite. Beneath this "crust" the andesite is vesicular and paler grey. This structure, common in andesitic bombs, results from rapid cooling of the outer shell on contact with the air, and subsequent expansion of the interior due to vesiculation.

b) Brecciated metasedimentary block L.572, included in a Younger andesite pumice flow east of Choiseul. The block is 6 in. across, and contains angular patches of finely granular, white quartzite and of black, mafic-rich material. These are traversed by a network of intersecting veins of coarsely granular quartz up to  $\frac{1}{4}$  in. wide, visible in the photograph as finely mottled, pale grey lines. This type of block is relatively common in the lowest Younger andesite pumice flow, but was found at no other horizon in the Soufrière region.



this hypothesis that the material was ejected high into the air, whilst the banded blocks invite the conclusion that a massive structure, possibly a dome, was disrupted to contribute ejecta of this type. These banded blocks have not, however, been identified with any lava structure existing at present.

The graded Vulcanian units appear to be evenly distributed around the present caldera, and dip regularly away from this centre. It is, therefore, concluded that they were erupted from this area. They are, moreover, the youngest deposit in the Soufrière region which cannot satisfactorily be correlated with massive structures within the caldera, and for these reasons it is tentatively suggested that this agglomerate represents the deposits of the last pre-caldera eruptive phase: a sequence of at least 33 repeated Vulcanian eruptions of great violence which removed an estimated 1.8 cubic miles of surface and sub-surface material from their source.

5. 3. 5. YOUNGER ANDESITE PUMICE FLOWS

Thick deposits of white, andesite pumice occur in the Soufrière region, principally in the lower part of the southern glacis. These are well exposed east of Choiseul, and in numerous sections alongside the main road between Choiseul and Victoria Junction. An aggregate thickness of 136 ft. was recorded in the area southeast of Choiseul, composed of at least two flow units separated by a block-rich horizon 15 feet thick.

Typical material is semi-consolidated, containing up to 60% of almost white pumice blocks from  $\frac{1}{4}$  in. to 3 in. across, in a pale, powdery to tuffaceous matrix. (Plate 12a). Stratification and vertical variation is completely lacking, except in a few localities where fine tuff beds not more than 9 in. thick intervene, e.g. beside the main road north of Choiseul, at 350 ft. above sea level.

Characteristics of the deposit closely resemble those of typical pumice flows (see Table 1), in the absence of size-sorting and the existence of lateral variation in thickness, with concentration in pre-existing topographic depressions. The intercalated, fine tuff horizons probably represent material ejected to a greater altitude during a pumice flow eruption, which landed slightly later, on top of the main flow deposit; alternatively the fine material may represent wind-blown dust, redistributed during the interval between successive pumice flows.

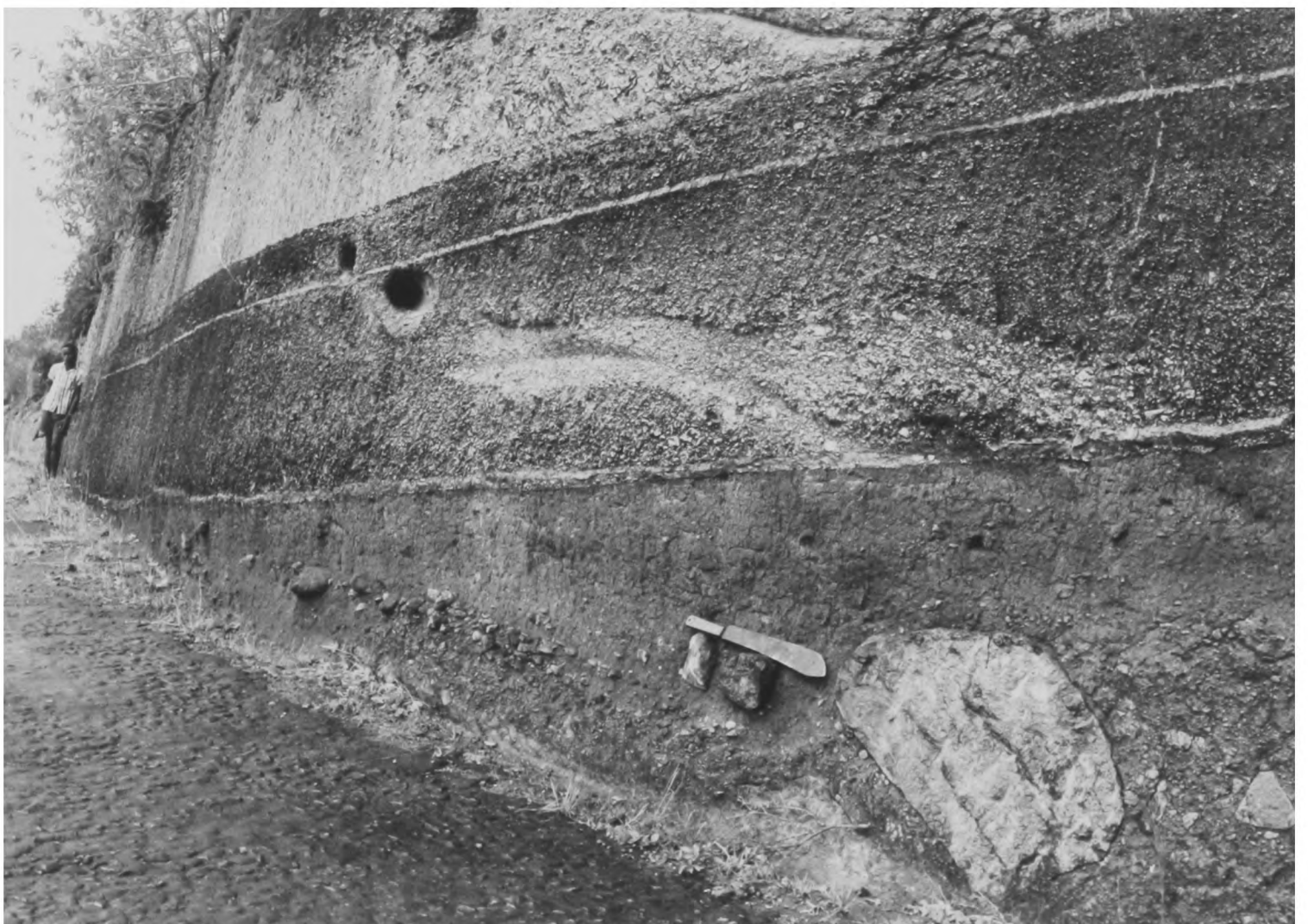
PLATE 12.

a) Younger andesite pumice flow, exposed beside the main road north from Choiseul, at 840 ft. a.s.l. The material is completely structureless, and composed of angular lumps of white pumice up to  $2\frac{1}{2}$  in. across, in a lightly consolidated, pale, powdery matrix.

( Length of hammer head: 7 in. )

b) Diagonal facies of Younger andesite pumice, overlying a weathered surface of the Caldera-wall agglomerate. The section is exposed beside the road, on the west side of the Portalesse Carpet river valley, at 75 - 100 ft. a.s.l. At the base, the Caldera-wall agglomerate contains angular andesite boulders up to 3 ft. across, and has a reddened, earthy surface to a depth of 2 ft. The overlying units of semi-consolidated andesite pumice are structureless, and believed to represent flows. The dark circle at the top of the lowest pumice unit is a cylindrical hole over 3 ft. long, in which a few small fragments of charcoal were found. This is believed to be the cavity left by a carbonized log which, on being carried into the water by the glowing avalanche, floated to the top of the deposit. N.B. Carbonised remains of vegetation are normally found at the base of glowing avalanche deposits.

( Length of outlass: 20 in. )



On the western side of the Portalese Carpet river valley, beside the road, a sequence of three units of andesite pumice is exposed (Plate 12b). The units vary in thickness from 1 - 6 ft. There is no stratification, and the material is identical to typical andesite pumice flow. Between each unit, however, a thin white tuff layer occurs, and each of these is perfectly horizontal. It is suggested that the tuff layers represent fine ash showers which fell before and between the flows. These tuff layers and the two intervening pumice units all maintain a strikingly constant thickness, lying perfectly horizontal, and these features are unusual in a sequence of pyroclastic flows deposited subaerially. For this reason, it seems possible that the material may have been deposited in a quiet, aqueous environment, possibly an inshore lagoon. There is, on the other hand, no grading present in the thicker units, which might have been expected in subaqueous deposits, due to floating of the less dense pumice fragments. The precise environment of deposition of these deposits is therefore not definitely established. If the interpretation of these beds as lagoonal deposits is correct, the fact that they are now 100 ft. a.s.l. indicates a relative uplift by this amount since their formation.

#### Identification of Older and Younger andesite pumice deposits

In appearance and composition, the andesite pumice deposits described as "Younger" closely resemble the Older andesite pumice flows, and in outcrops where relationships to

overlying and underlying formations are not visible, the two could not be differentiated with certainty. That two separate periods of andesite pumice eruptions did occur, however, is revealed by the relationships of this material to the Vulcanian agglomerate, which it both overlies and underlies (Fig.14, Plate 9b).

Exposures of andesite pumice flow at other localities in the southern part of St. Lucia

A notable feature of the structureless andesite pumice is that similar material is exposed at widely separated localities throughout the southern half of St. Lucia, on the eastern as well as the western side of the island. Fig.15 shows the principal outcrops and thicknesses. Exposures commonly lie on the sides of present-day valleys, and appear to be the relics of flows which have come to rest in contemporary topographic depressions. In most cases, it could not be ascertained whether a particular deposit represented Older or Younger andesite pumice. However, since the younger deposits in the Choiseul region are thicker and appear to be entirely the products of pumice flows, with no stratified ash fall units, it seems more likely that these are the equivalent of the pumice flows which reached the eastern side of the island.

The wide distribution of the andesite pumice, in contrast to that of the younger dacite pumice which is almost entirely restricted to the southern glacis, indicates that the eruptions responsible for it produced a large volume of material,

FIG. 14a.

SKETCH OF SECTION SHOWING STRATIGRAPHIC RELATIONSHIPS OF THE YOUNGER ANDESITE PUMICE, in a roadside exposure on the north side of Canaries valley, 100 ft. a.s.l. Younger andesite pumice flow overlies an eroded surface of graded Vulcanian agglomerate.

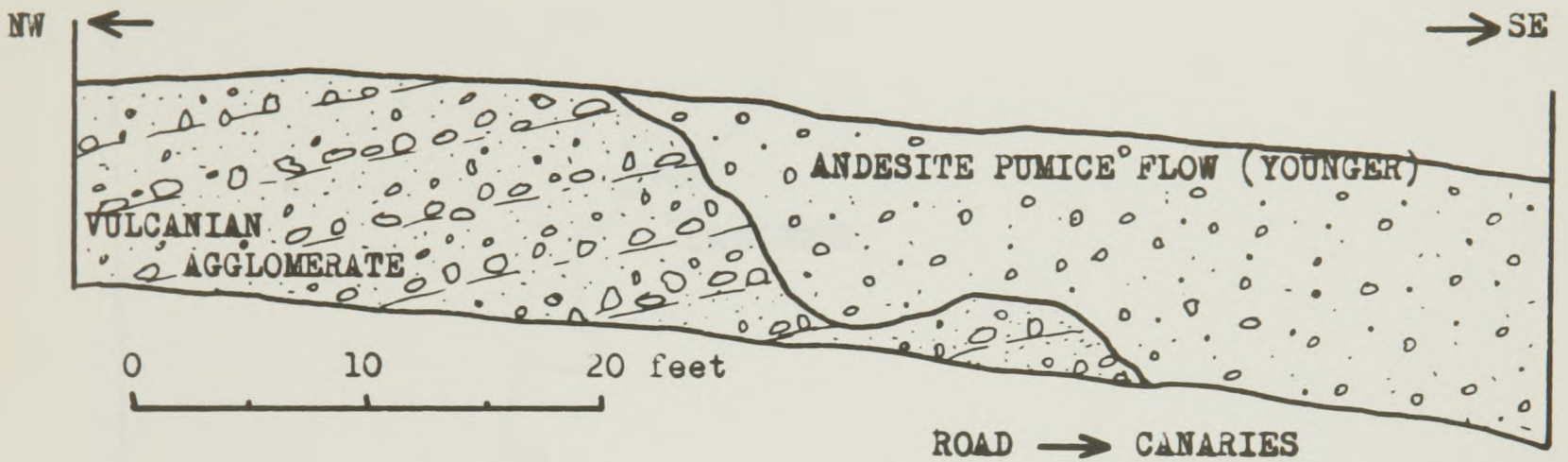
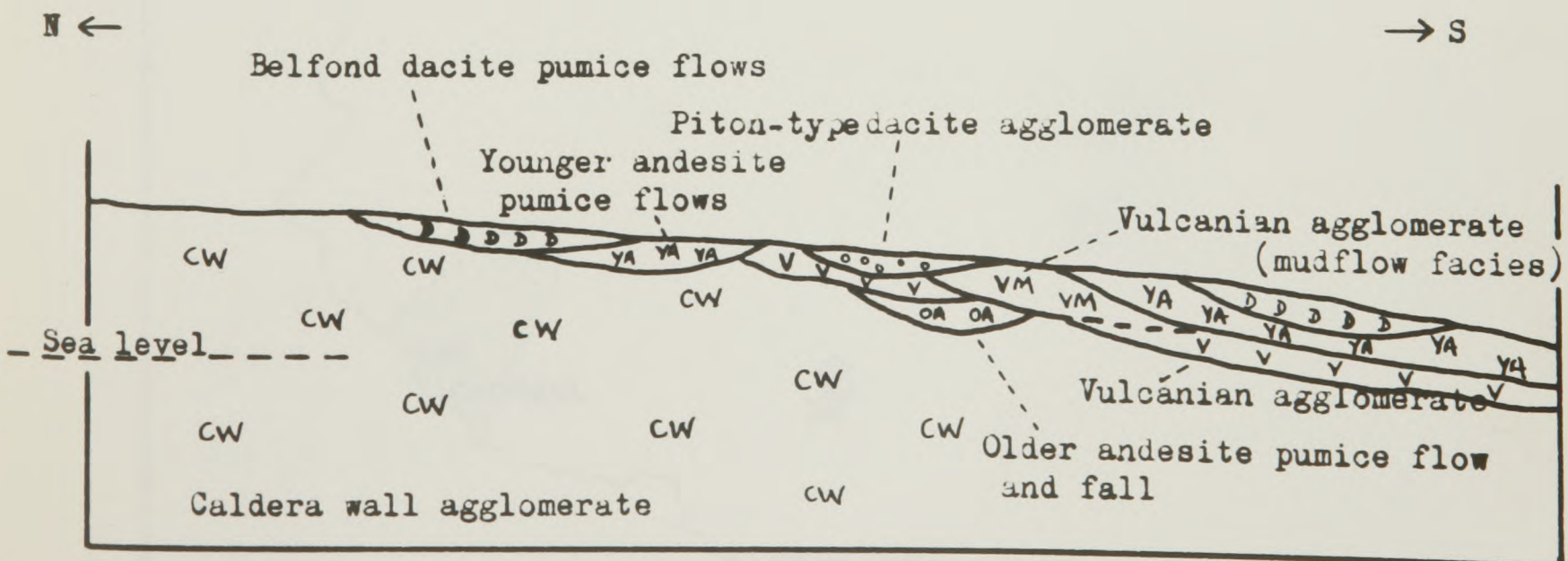


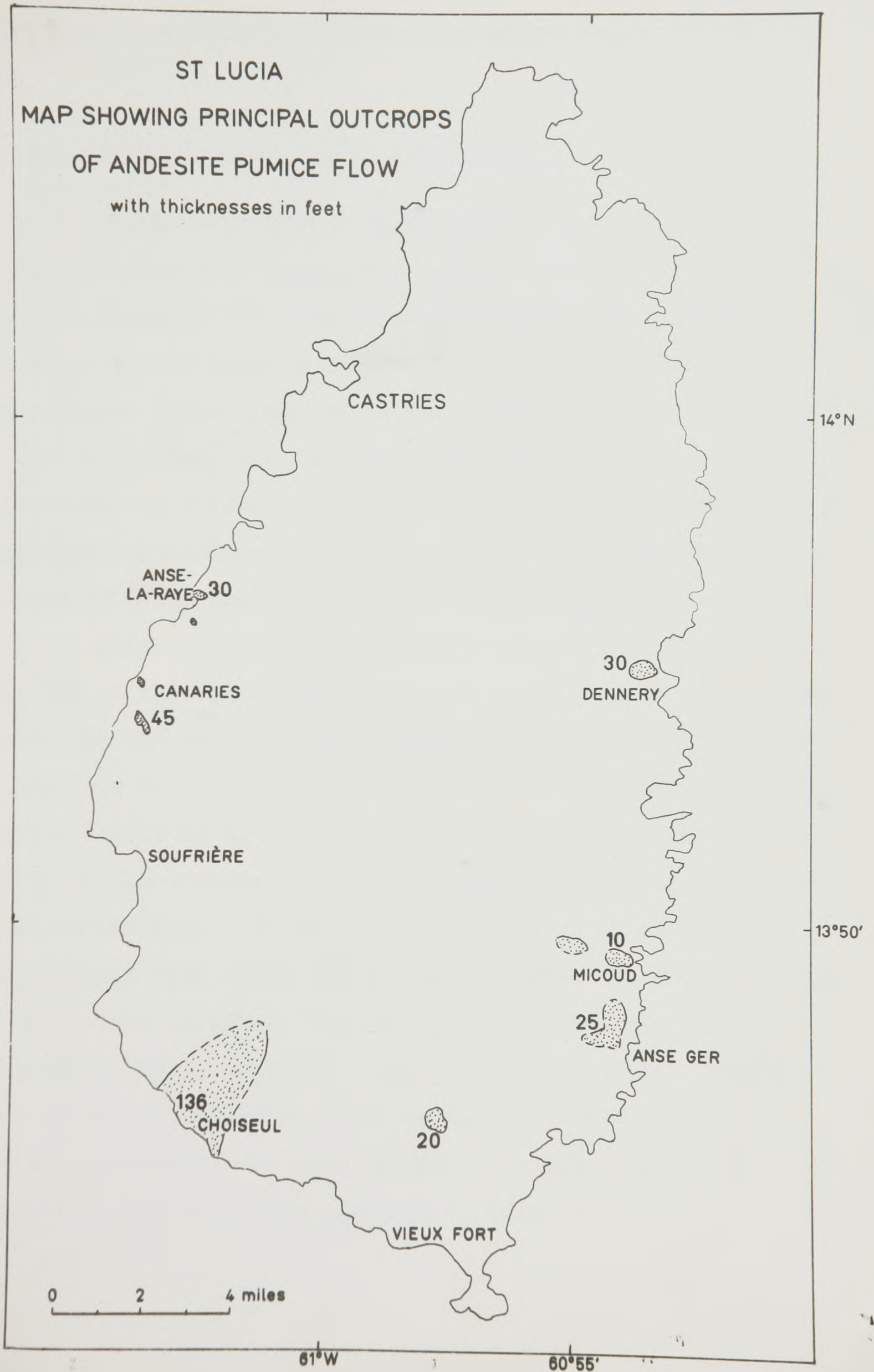
FIG. 14b.

DIAGRAMMATIC SECTION ACROSS THE SOUTHERN GLACIS, showing the relationships of pyroclastic units.



(Length of section is approximately  $\frac{1}{2}$  mile)

FIG. 15



which was carried long distances and across the island watershed.

### 5. 3. 6. PITON-TYPE DACITE AGGLOMERATES

Semi-consolidated agglomerates, containing boulders of dacite similar in appearance to that forming the Pitons, are seen south of the Gros Piton (La Pointe and Morne Sion), and along a belt about  $\frac{1}{2}$  mile wide around the present rim of the caldera, between northeast and southeast. Exposures south of the Gros Piton, and in particular along the coast at La Pointe, are of material which varies from lightly consolidated agglomerate containing about 70% of subangular blocks up to a maximum of 6 ft. across, to stratified crystal tuff bands up to 1 ft. wide. Elsewhere, blocks of grey or pink dacite form only 30% of the whole deposit and lie in a more or less consolidated ash and crystal tuff. Further north, in the vicinity of Derrière Morne, deposits of dacite breccia containing highly angular blocks up to 12 in. across lie in a semi-consolidated matrix of fine debris which represents no more than 20% of the whole (Plate 13a). At Saltibus and north of Migny, dacite agglomerates with about 50% of angular or subangular blocks up to 18 in. across (Plate 13b) are seen in exposures with a maximum thickness of 15 ft. Finally, on top of the northern part of the caldera rim, south of Quatre Chemin, 30 ft. of dacite agglomerate are seen to overlie unconformably an eroded surface of the Vulcanian agglomerate (Fig.16).

PLATE 13.

a) Piton-type dacite breccia at Berrière Morne. Angular blocks of grey dacite up to 1 ft. across lie in a matrix of semi-consolidated, ashy debris. Material finer than 4 mm. in grain size forms only about 20% of the deposit, which is believed to have formed from a block-rich pyroclastic flow.

b) Piton-type dacite agglomerate at Saltibus. This roadside exposure shows sub-angular blocks of pink and grey dacite up to 18 in. across, in a consolidated tuff matrix. The whole deposit is considerably weathered: the tuff is partially converted to clay, and the feldspar phenocrysts in the lava are kaolinized. Numerous, large quartz crystals remain intact. The more intensive weathering at Saltibus than at Berrière Morne (Plate 13a) can be explained by the geographical location (see section 4.4).



Although there is great variety in the structure of different outcrops of the early dacite pyroclastics, the lava types all appear to be similar. At La Pointe, blocks are fresh and seem identical to the dacite of the Gros Piton. Specimens from other localities resemble the Piton type more closely than any other lavas seen in situ in the Soufrière region. It is, however, by no means certain that all were ejected from vents now sealed by the Pitons, and it seems likely that they represent the products of several independent eruptions of varying character.

Material from within a mile of the Pitons, and particularly that to the south of the Gros Piton, probably represents, to a large extent, talus fans from the Piton domes. It is possible that incandescent block-plus-ash flows issuing from the flanks of the growing domes also contributed to these deposits. The breccia deposit of Derrière Morne (Plate 13a) must represent either talus material which, since it is highly angular, appears not to have been transported far, or alternatively, it may be material from block-rich pyroclastic flows of a type similar to some of those which were emitted from the 1929-32 dome of Mt. Pelée, described by Ferret (1937, Fig.40). If the former was the case, the original talus slopes of the Gros Piton must have extended farther eastward than the present height of the solid core would lead one to suppose. For this reason, the second explanation is preferred.

The agglomerates which lie on the eastern and north-eastern rim of the caldera are unlikely to have been deposited in this position by pyroclastic flows. It seems, therefore, that these represent the products of vertical, Vulcanian eruptions, though no grading was observed in the deposits.

#### 5. 3. 7. BELFOND DACITE PUMICE FALL AND PUMICE FLOWS

Unconsolidated ash deposits containing blocks of very pale grey, dacite pumice are of two distinct types: lithic, and completely structureless. These correspond, respectively, to ash fall and ash flow deposits (see Table 1). In addition, local deposits of highly sorted pumice pebbles occur, which represent secondary, fluviatile material.

#### Belfond dacite pumice fall

Stratified deposits, composed of dacite pumice lapilli and ash, are seen especially in the southern part of the caldera, east of Fond Doux. The St. Rémy river has cut deeply into the unconsolidated ash, exposing over 100 ft. of this material (Plate 14a) in the canyon-like river valley sides. Dips of up to 20° are visible, and the attitude of the bedding frequently conforms with the present land surface.\* The stratification consists of alternating lapilli and ash horizons of 1 - 12 in. thickness. Irregularities of bedding include inconsistently thick and lenticular horizons, and some mild cross-stratification. Lava blocks are up to 4 in. across, angular, and consist of

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\*In his description of dacite pumice ash fall deposits in southern El Salvador, Williams (1955, p.27) aptly refers to this phenomenon as "mantle bedding".

PLATE 14.

a) Belfond dacite pumice fall. Part of a section exposed in the St. Rémy river. The stream has cut deeply into the unconsolidated ash to form a vertical-sided ravine 100 ft. deep, whose walls are composed entirely of stratified Belfond dacite pumice ash. The stratification is made up of alternating coarser (lapilli) and finer (ash) horizons of 1 - 12 in. in thickness. Dips usually conform with the present land surface, suggesting that the pumice fell as an even deposit mantling the pre-existing topography. Slight cross-bedding indicates that some re-distribution, probably by torrential rain as well as wind, has taken place.

b) Belfond dacite pumice fall, northeast of Colombette. This roadside exposure, at 1,300 ft. a.s.l., consists of irregularly stratified pumice lapilli alternating with pumice-plus-crystal ash. It forms the highest (i.e. most recent) deposit on the caldera-rim. Individual layers are between  $\frac{1}{2}$  and 2 in. thick, and some show mild cross-bedding.  
( Length of outlass: 20 in. )



finely vesicular pale-grey dacite containing large, fresh amphiboles, identical to that forming the Belfond domes (section 5.2.7.). Smaller fragments of pumice in this deposit are relatively dense: although vesicular, they contain a high proportion of phenocrysts.

Belfond dacite pumice fall deposits extend southward to east of La Pointe, where observed thicknesses are greatly reduced. The eastern margin of the same sheet outcrops at Victoria Junction, where 15 ft. of slightly finer, lithic ash of pinkish colour form the topmost layer on the caldera rim.

37 ft. of stratified white dacite ash are seen to lie horizontally on top of the ridge east of Malgrétoute. On the northern rim of the caldera, northeast of Colombette, 30 ft. thickness of similar lithic ash (Plate 14b) dip northwestward at  $6^\circ$ . Northwest from here, 10 ft. thickness are seen at Bouton. Finally, beyond the eastern margin of the caldera, 1 mile northeast of Migny, 40 ft. of deeply weathered stratified dacite ash containing white pumice blocks are believed to belong to the same eruptive phase. Natural carbon from this locality has been submitted for age measurement (Martin-Kaye, 1960), and proved to be older than 50,000 years. The dating of the Belfond dacite pumice deposits is discussed in full on p.73.

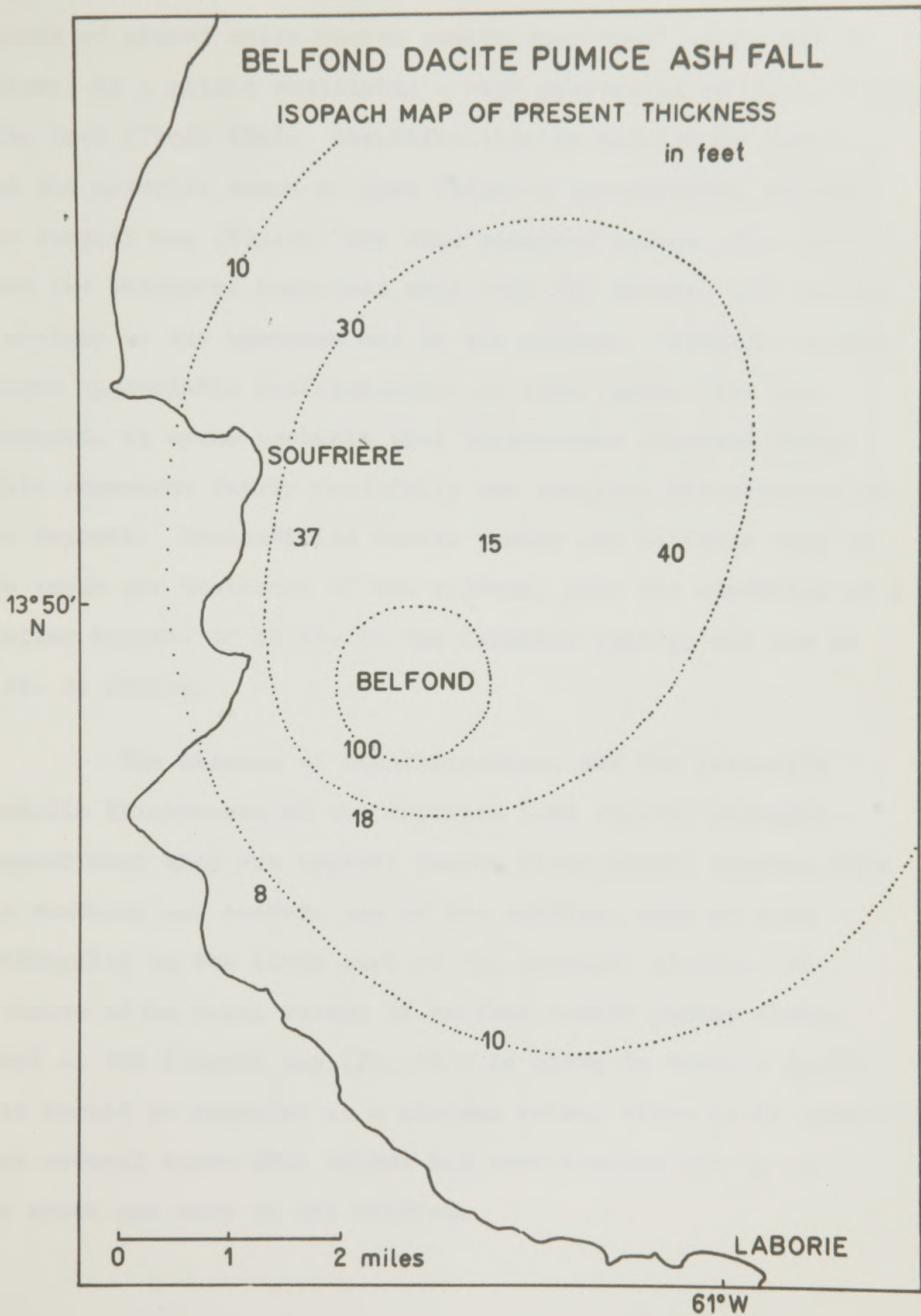
Blocks of white, vesicular dacite, which occur abundantly in the stratified ash, are identical to the lava of the Belfond-Étangs region, and there seems little doubt that it was

erupted from this southern group of craters. The presence of well-defined stratification indicates that the material fell as ash showers, during or between which slight redistribution (probably by torrential rain as well as by wind) has caused the mild cross-bedding observed. In addition to the clear stratification of this deposit, the fact that it appears to have evenly mantled the pre-existing topography may also be cited as strong evidence in favour of its formation from vertical ash eruptions. Wide variation in the grain size of individual layers and the absence of distinctive, laterally correlatable horizons, made it impossible usefully to compare samples collected at different distances from the eruptive centre. The present distribution of the Belfond ash fall is shown in Fig.17. The northeasterly extension of the 30 ft. and 10 ft. isopachs is not considered to be specially significant, in particular because the area to the south and southwest of the caldera is known to have been crossed by glowing avalanches, which are likely to have scoured incoherent material from the surface in the initial part of their course, in the manner described by Williams (1942, p.79) with reference to the glowing avalanches of Mt. Mazama.

#### Belfond dacite pumice flows

Unstratified dacite pumice ash, containing pale grey dacite pumice blocks, was found in thick deposits in the lower part of the southern glacis, between Choiseul and Laborie. Four individual units were identified, each separated by a soil layer (Fig.19). The highest of these units forms a single

FIG. 17



deposit up to 80 ft. thick at Choiseul, in which subangular blocks of almost white dacite pumice represent about 50% by volume, in a matrix containing a high proportion of fine, flour-like dust (Plate 15a). Stratification is completely lacking, and the material seems to have filled a pre-existing valley. The isopach map (Fig.18) for this youngest pumice flow shows that the thickness increases away from the source, and reaches a maximum at the southern end of the glacis. Although in some places appreciable redistribution of this pumice flow has occurred, it seems probable that thicknesses observed today still represent fairly faithfully the original distribution of the deposit. Unstratified dacite pumice ash is found only to the south and southeast of the caldera, with the exception of a similar deposit of 15 ft. in the Canaries valley, and one of 7 ft. at Bouton.

The absence of stratification, and the laterally variable thicknesses of the deposits (see Fig.19) strongly suggest that they are typical pumice flows which, pouring over the southern and eastern rim of the caldera, came to rest principally on the lower part of the southern glacis. An estimate of the total volume of Belfond dacite pumice flows, based on the isopach map (Fig.18), is given in Table 2 (p.72). This should be regarded as a minimum value, since it is possible that several times this volume has been carried out to sea to the south and west of the caldera.

PLATE 15.

a) Belfond dacite pumice flow on the southern glacis, at Londonderry, 490 ft. a.s.l. Rounded to subangular blocks up to 1 ft. across, of white dacite pumice, lie in a matrix composed of crystals and a high proportion of fine, white powder consisting of comminuted pumice.

( Length of hammer head: 7 in. The dark shadows are pick-marks. )

b) Fluvial dacite pumice ash and lapilli, on the west side of the Piave river valley, in a roadside exposure. Formed by fluvial redistribution of dacite pumice flow, this deposit consists of crystal ash and rounded pumice lumps up to 3 in. across, in extremely well size-sorted layers, some of which contain a conspicuous admixture of darker, foreign material. Material of the finest grade, abundant in the pumice flow, is completely absent in the fluvial, secondary deposit.



FIG. 18

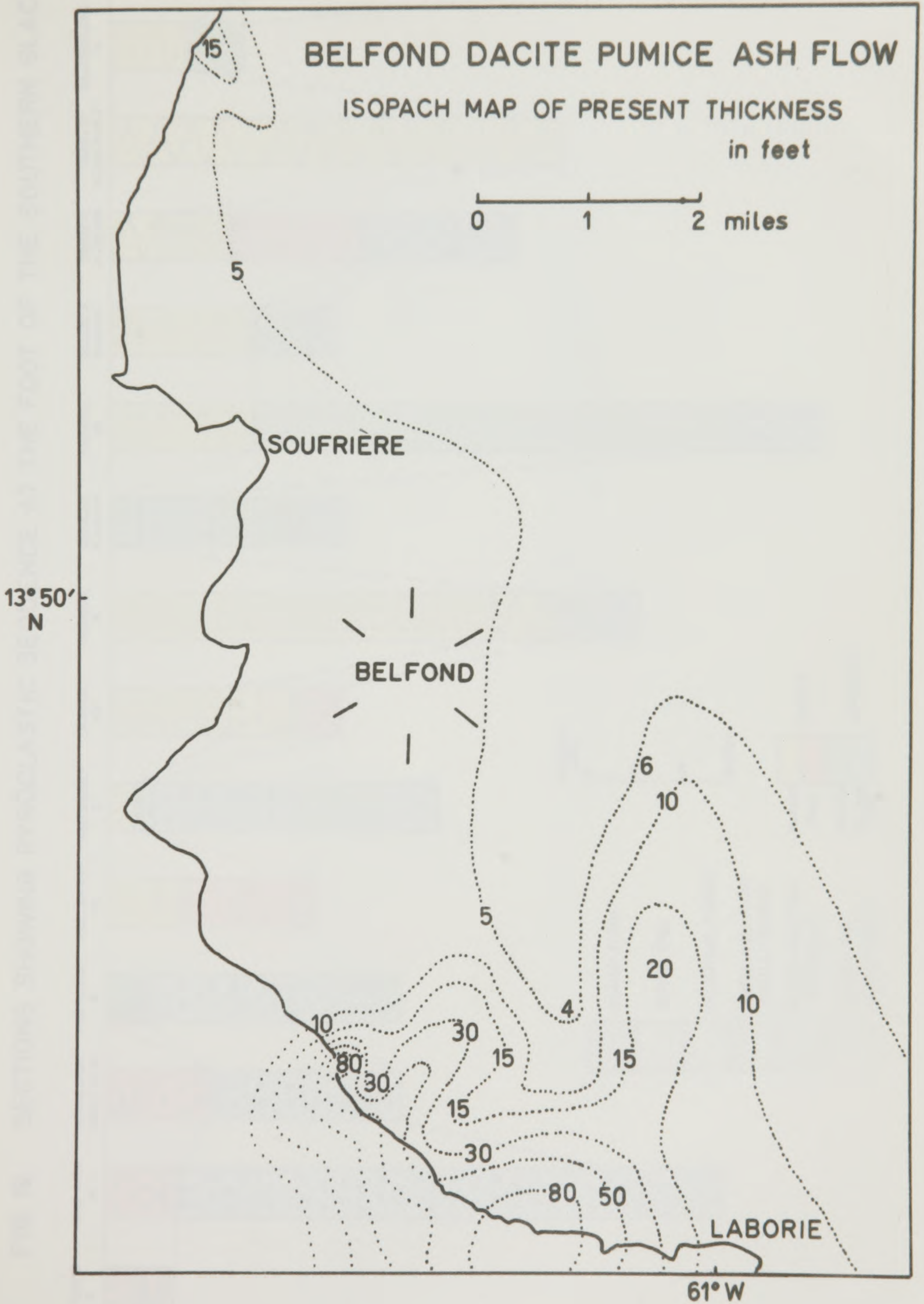


FIG. 19. SECTIONS SHOWING PYROCLASTIC SEQUENCE AT THE FOOT OF THE SOUTHERN GLACIS

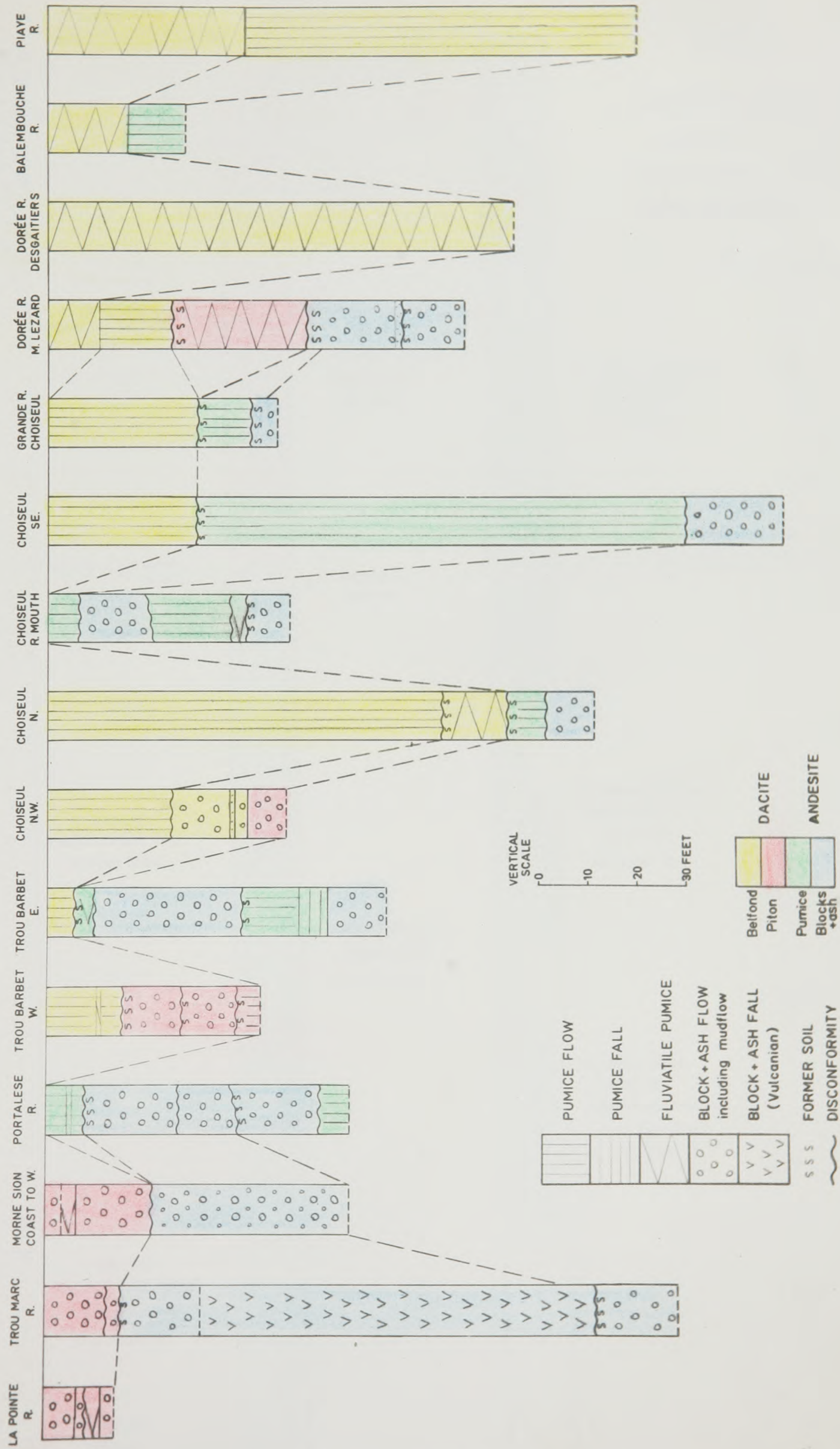


FIG. 20

COMPOSITE SECTION  
SHOWING THE FULL  
PYROCLASTIC SEQUENCE  
IN THE SOUFRIÈRE REGION

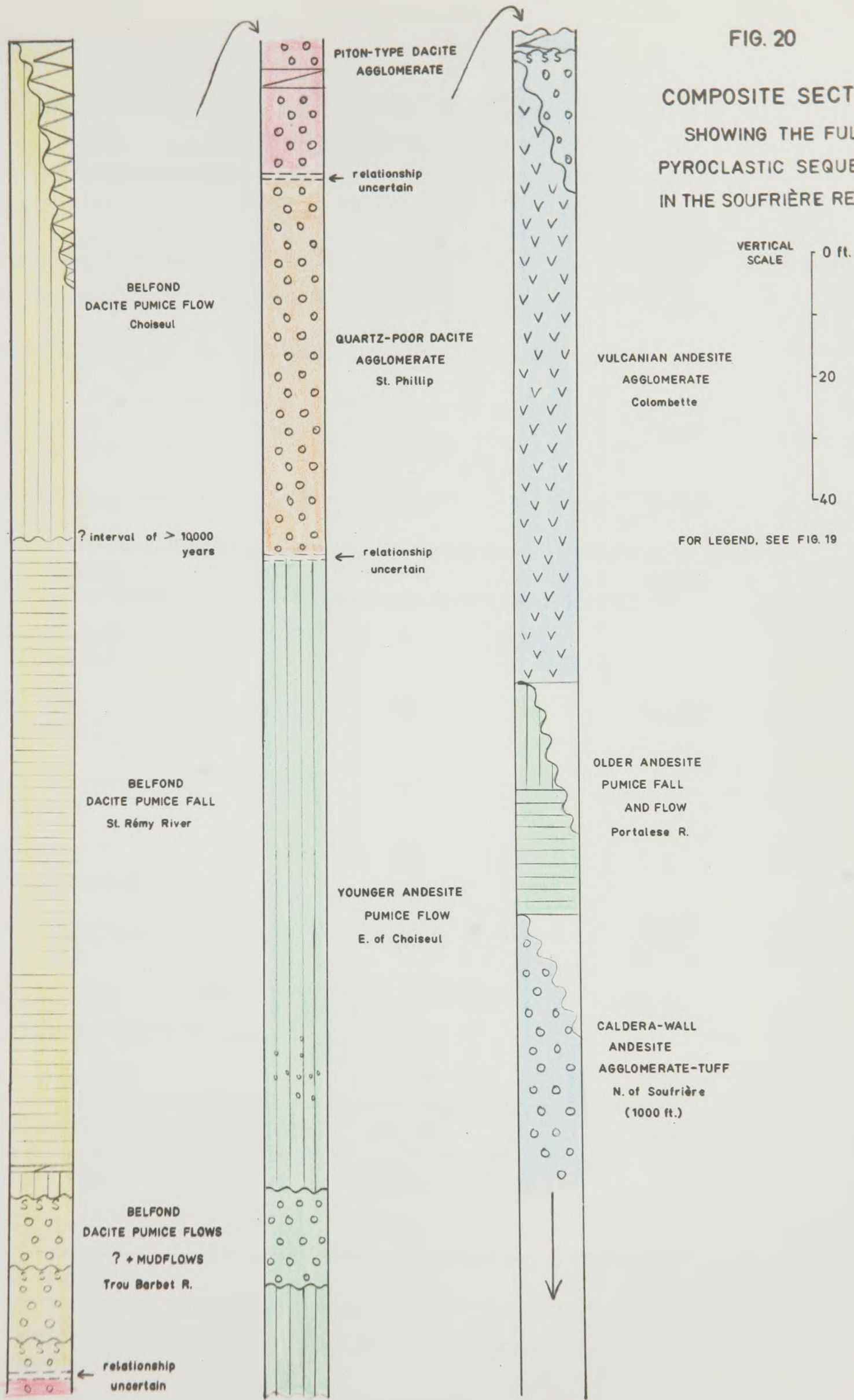


TABLE 2

## ESTIMATED VOLUMES OF LAVA AND PYROCLASTIC TYPES IN THE SOUPRIERE REGION

All volumes are in cubic miles

Type	Lava (dome)	Lava (flow)	Pyroclastics (fall)	Pyroclastics (flow)	Total
Belfond dacite	0.015	-	1.232	0.229	1.476
Terre Blanche dacite	0.082	-	?	?	0.082
Piton-type dacite	0.243	-	?	0.021	0.264
St. Phillip dacite	0.007	-	-	0.016	0.023
<b>TOTAL DACITE</b>	<b>0.347</b>	<b>-</b>	<b>1.232</b>	<b>0.266</b>	<b>1.845</b>
Morne Bonin andesite	0.021	-	0.003	-	0.024
Fond Doux andesite	0.038	-	-	0.006	0.044
Younger andesite pumice	-	-	-	?1.0	?1.0
Vulcanian agglomerate	-	-	1.8	-	1.8
Older andesite pumice	-	-	0.67	some	0.67
Calders-wall agglomerate-tuff	-	-	-	6.0	6.0
Dark andesite	-	0.315	?	-	0.315
<b>TOTAL ANDESITE</b>	<b>0.059</b>	<b>0.315</b>	<b>2.50</b>	<b>7.006</b>	<b>9.183</b>
Aphyric basalt	-	0.002	-	-	0.002
Porphyritic basalt	-	0.77	-	-	0.77
<b>TOTAL BASALT</b>	<b>-</b>	<b>0.772</b>	<b>-</b>	<b>-</b>	<b>0.772</b>

N.B. Belfond and Terre Blanche dacites are believed to represent original quantities.

All others represent the volume estimated on the basis of present-day outcrops.

Time-relationships of Belfond pumice flows to pumice fall

At Bouton, and above the Dorée river southwest of Mt. Lézard, Belfond pumice ash fall overlies pumice flow. It is thus clear that some pumice showers fell subsequently to glowing avalanche eruptions, though it seems likely that contemporaneous eruptions of fall and flow also occurred, as observed in the historic eruption of Komagatake in Japan (Kōzu, 1929). The existence of three soil horizons separating Belfond dacite pumice flows indicates that eruptions from the Belfond vents occurred at intervals spread over a long period of time. This fact is corroborated by radiocarbon dating evidence: whilst the youngest Belfond dacite pumice flow has an estimated age of 39,050 ( $\pm$  1,500) years (Appendix A), charcoal from a similar pumice fall deposit exposed east of Migny gave an age of more than 50,000 years (Martin-Kaye, 1960). The Belfond dacite pumice fall at this latter locality, moreover, is 40 ft. thick, suggesting that it may well be equivalent to the thick, fall deposits in the St. Rémy river gorge. Thus the Belfond dacite phase has occupied the last 50,000 years at least, and a period of ash fall eruptions occurred at least 10,000 years before the most recent pumice flow.

Fluviatile dacite pumice

Overlying the most recent pumice flow deposits in numerous localities, especially between the Dorée and Piaye rivers, beds of well-sorted ash and rounded pumice lapilli (Plate 15b), containing a small proportion of foreign pebbles,

differ greatly in appearance from the stratified pumice ash fall exposed in the southern part of the caldera. At Desgaitiers, the whole succession of 95 ft. consists of material of this type. Elsewhere, 10-15 ft. typically overlie unstratified pumice flow. Lens-shaped beds are common. Stratification seldom diverges from the horizontal by more than  $5^{\circ}$ , and often is not parallel to the present land surface. In both of these features, as well as in the higher proportion of foreign fragments, the fluviatile material differs from normal dacite pumice fall.

The rounded shape of the larger pumice lumps, efficient size sorting, and almost complete absence of the finest, dust-sized fractions, are all characteristic of fluviatile deposits, examples of which have been described by Williams (1955, p.29) in southern El Salvador. It is probable that most deposits of this type in the lower part of the southern glacis represent the redistributed upper portion of the youngest dacite pumice flow, which was originally thickest in this area.

#### 5. 4. CORAL LIMESTONE BLOCKS

The only rock of non-volcanic origin in the Soufrière region is coral limestone, which was found in one locality as boulders up to 6 ft. across, at between 75 and 125 ft. a.s.l., alongside and above the road to Malgrétoute. One block measuring 5 ft. across, on the present shore below these outcrops, contained dacite boulders of Piton type.

The occurrence of limestone north of Malgrétoute, on top of one of the highest hills in this region, was first described by Lefort de Latour (1787) and subsequently by Sapper (1903, p.278). Sapper reported an outcrop of coral limestone and limestone conglomerate overlying massive rock on Coubaril, at up to 450 ft. above sea level, (i.e. near the summit). Earle (1923) reported "a small pocket of limestone situated at about 100 - 150 ft. a.s.l. near the main road at Malgrétoute", which is believed to be the same outcrop as that found by the present author. A thorough search, however, failed to reveal the exposure at the higher altitude described by Sapper.

The discovery of boulders of Piton dacite in the limestone is important, since it indicates that the limestone was formed subsequently to the Pitons and that sea level, at the time when the limestone was formed, must have been at least 125 ft. higher than at present. Thus, if Sapper's observation is correct, a relative uplift in this area of over 450 ft. must have occurred since the formation of the Pitons. There are no dome lavas younger than the Pitons, in the immediate vicinity, which might have been responsible for the local uplift of the limestone as on Brimstone Hill, St. Kitts (Baker, 1963, p.36).

#### 5. 5. THE SULPHUR SPRINGS

The Sulphur Springs (Plate 16a) occupy an area of about 300 x 450 ft. in the valley southwest of Terre Blanche hill (see Frontispiece), and present one of the largest and

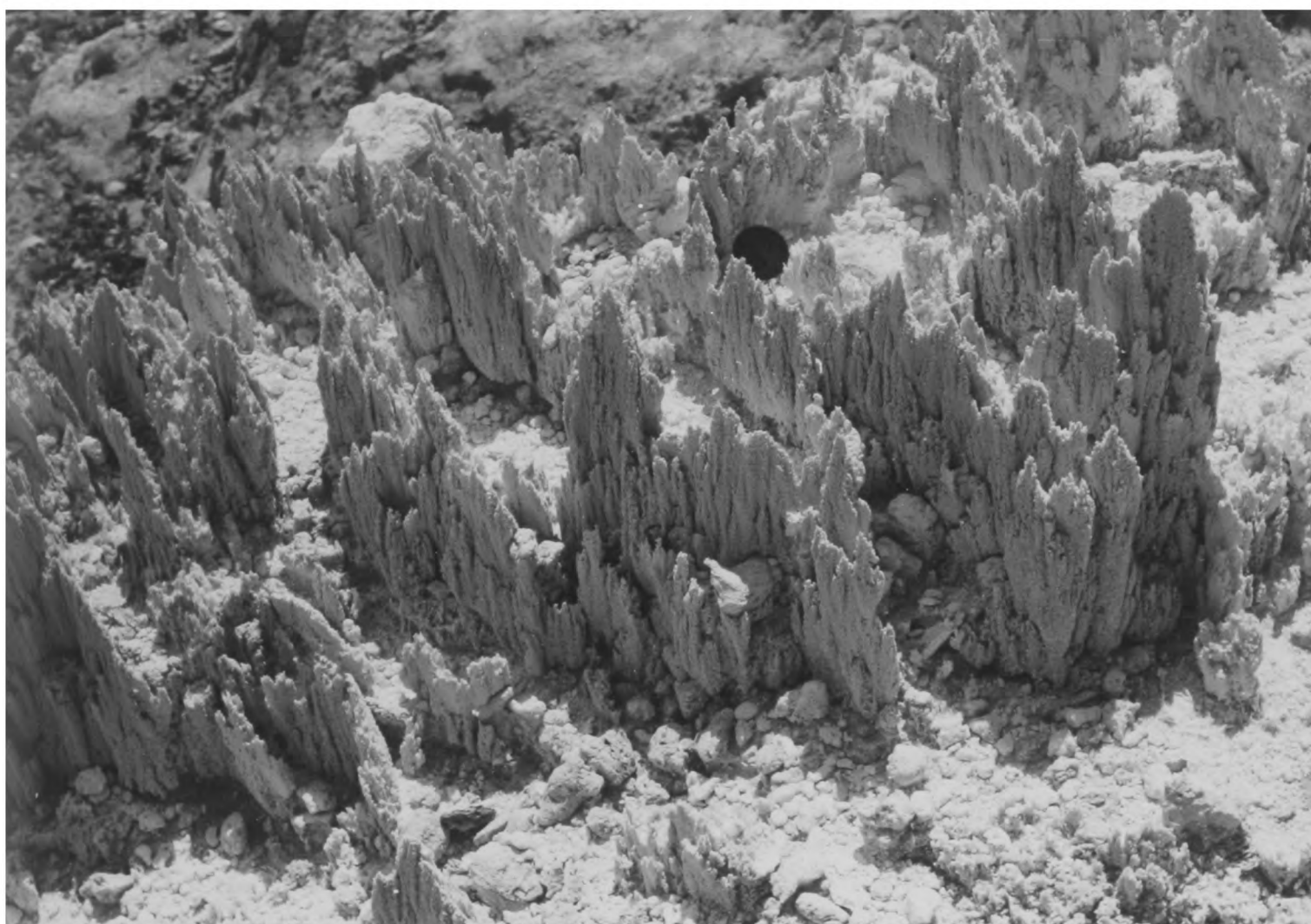
PLATE 16.

a) The Sulphur Springs, viewed from the east. Four of the cooler pools ( 70 - 80°C ) are visible in the foreground. Small rivulets connect these, flowing from left to right of the picture, down the valley. Behind them, "boiling" pools, containing water at a higher temperature, are concealed by steam. On the mound to the right of the area obscured by steam there are many small fumaroles, around which encrustations of crystalline sulphur are being deposited. In the background, stunted vegetation descends almost to the foot of the southwestern side of the valley. The rocks in the area are of altered dacite ash (see Geological Map).

( A man in the foreground provides the scale. )

b) Close-up of rain-erosion in rotted ash at the Sulphur Springs. The material was formerly dacitic ash containing lava blocks, but has been altered to a white friable substance consisting largely of kaolin which is lightly consolidated due to encrusting fumarolic sublimates. Quartz is the only mineral which has not decomposed.

( The black circle is a coin, 1½ in. across. )



most impressive spectacles of self-tararic activity in the West Indies. In the southern part of this area, eleven large pools up to 30 ft. in diameter contain water at temperatures close to boiling. The impression of boiling is given in several of these pools, due to steam which blasts through the water and causes jets to rise 3 - 4 ft. high (Plate 17a). The pools are supplied with water by springs on the southern and western flanks of the valley, and rivulets connect adjacent pools and finally lead into a larger stream flowing down the eastern side of the valley. In several of the smaller pools, steam bubbles through thick black mud, keeping it continually stirred and throwing clots a few inches across up to 2 ft. into the air (Plate 17b).

In the whole of the area, dacite ash and blocks have been strongly altered by the steam and sulphurous gases, from which encrustations of crystalline sulphur, gypsum and other minerals have been deposited. Of the original minerals in the ash, only quartz remains as scattered crystals in a white kaolinised residue (Plate 16b). Numerous small, dry fumaroles, emitting steam quietly from vents 1 - 4 inches in diameter, occur on the surface of a mound 60 ft. high in the northern half of the area. Vegetation is absent from the whole area described, and stunted on the adjacent valley sides.

Measurements of temperature and heat flow at the Sulphur Springs were made by Robson and Willmore (1955), and no additional work of this type was done during the present

PLATE 17.

a) "Boiling" pool, Sulphur Springs. This pool, one of the most vigorously active in 1963, is about 20 ft. across and fed by a rivalet entering from the upper right. Its temperature, measured by Robson and Willmore (1955, pool no. 9), was  $91^{\circ}\text{C}$ . Some of the steam forcing through the water fails to condense, causing fountains up to 3 ft. high. Rotted dacite ash and boulders surround the pool

b) "Boiling" mud pot, Sulphur Springs. Steam blasts noisily through the thick mud, throwing clots 2 ft. into the air. The photograph shows an area about 8 ft. across. The temperature in this pool, measured by Robson and Willmore (1955, p.27, pool no.10) was  $93^{\circ}\text{C}$ .



investigation. There seemed to have been little change in the general character of activity between 1955 and 1963. The Sulphur Springs, in fact, appear to have maintained a more or less constant level of activity throughout their recorded history.

It was suggested originally by Cassan (1790) that the Sulphur Springs occupied a former volcanic crater, and this view was repeated by Perret (1940), and is firmly held today by many local residents.\* The present author, however, fully concurs with the opinion expressed by Sapper (1903, p.275) who denied that the Sulphur Springs occupied the site of a former explosive vent.

#### 5. 6. VOLCANIC HISTORY OF THE SOUFRIÈRE REGION

The history of volcanic events in the Soufrière region is divisible into four major phases (see Table 3, p.83 and Fig.21), involving:

- 1) Effusion of basalt lavas.
- 2) Growth of andesitic strato-volcanoes around a centre slightly northeast of the future caldera.
- 3) The first eruptions of andesitic pyroclastics from the site of the future caldera, building up to violent activity and terminating with caldera collapse.
- 4) Effusion and eruption from within the caldera of acid andesite and dacite lavas and pyroclastics.

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\* A leaflet about the Sulphur Springs, entitled "St. Lucia's Drive-in Volcano", was presented to the author, as to all visitors to the island, by the St. Lucia Tourist Board.

FIG. 21a BIRD'S EYE VIEWS SHOWING THE POSSIBLE EVOLUTION OF THE SOUFRIÈRE REGION.

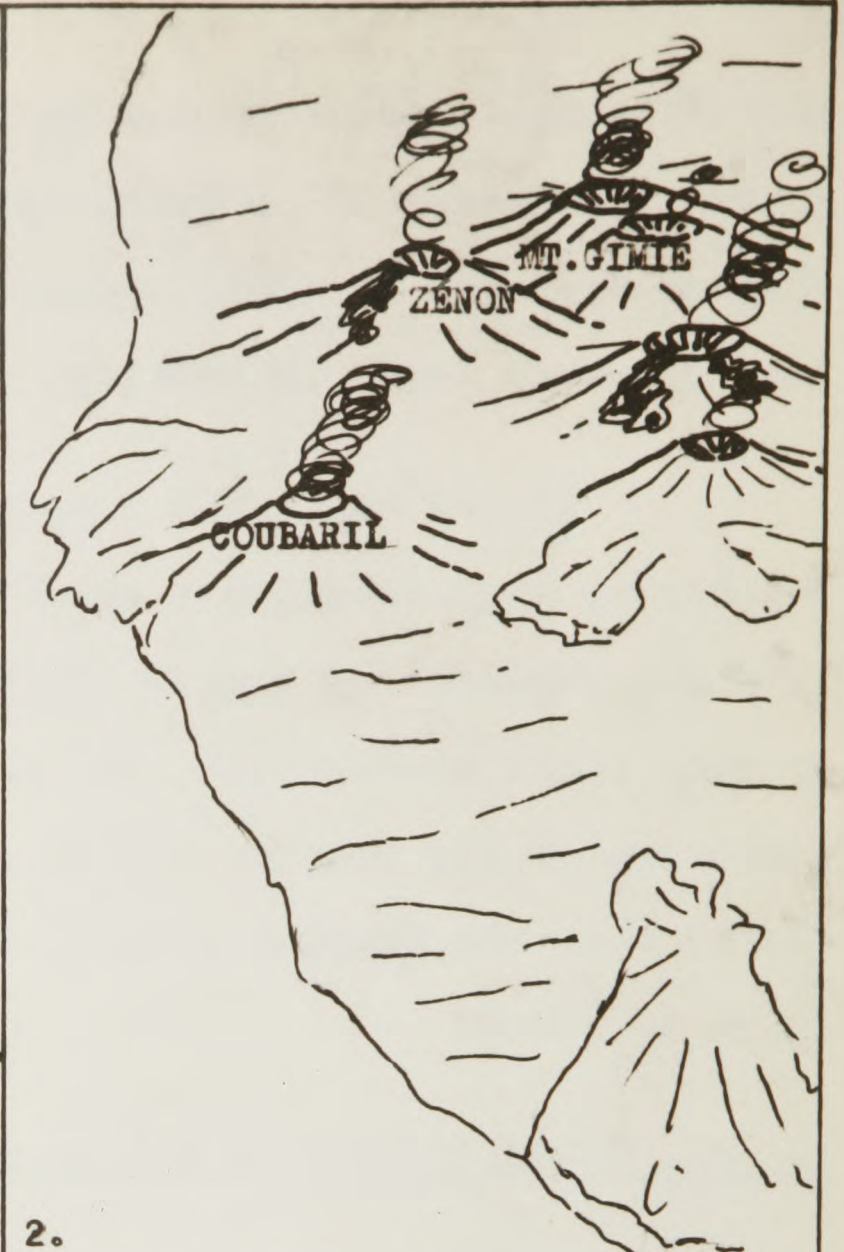
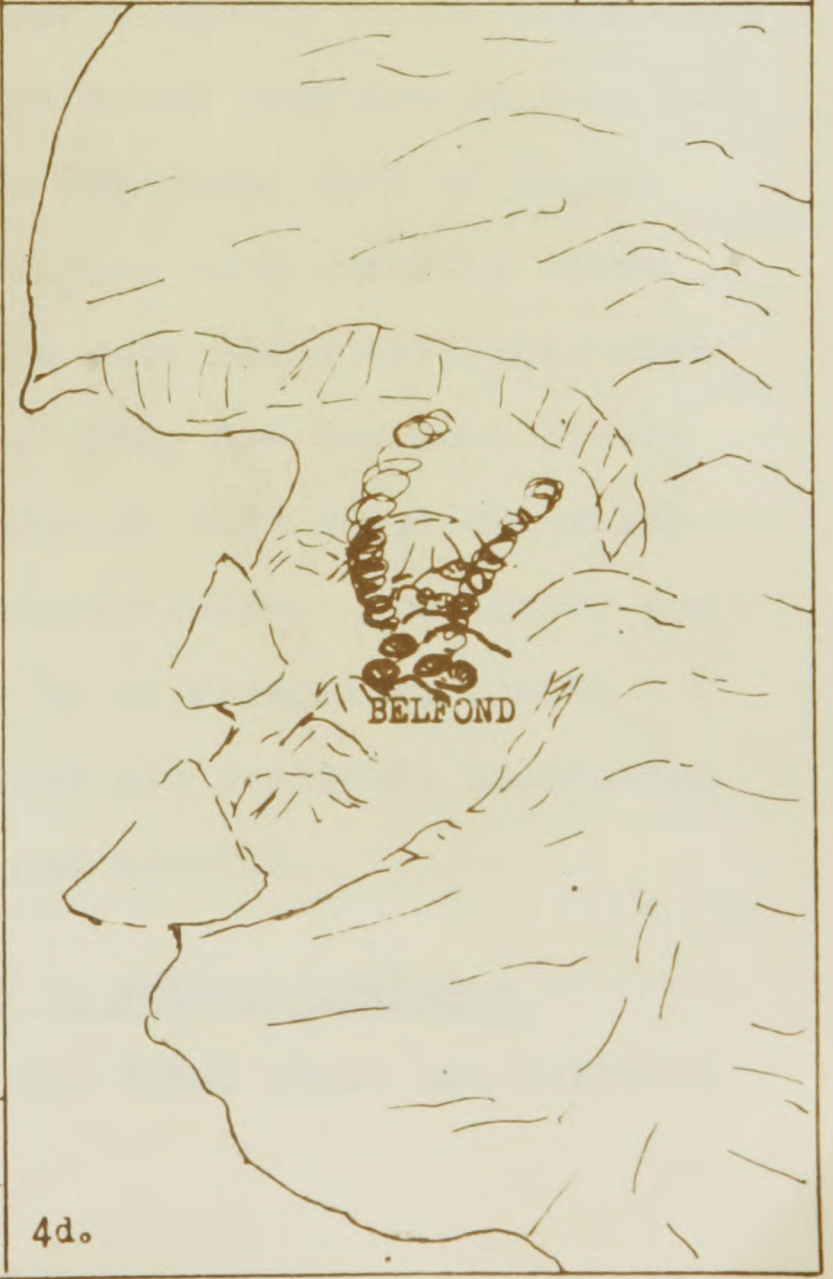
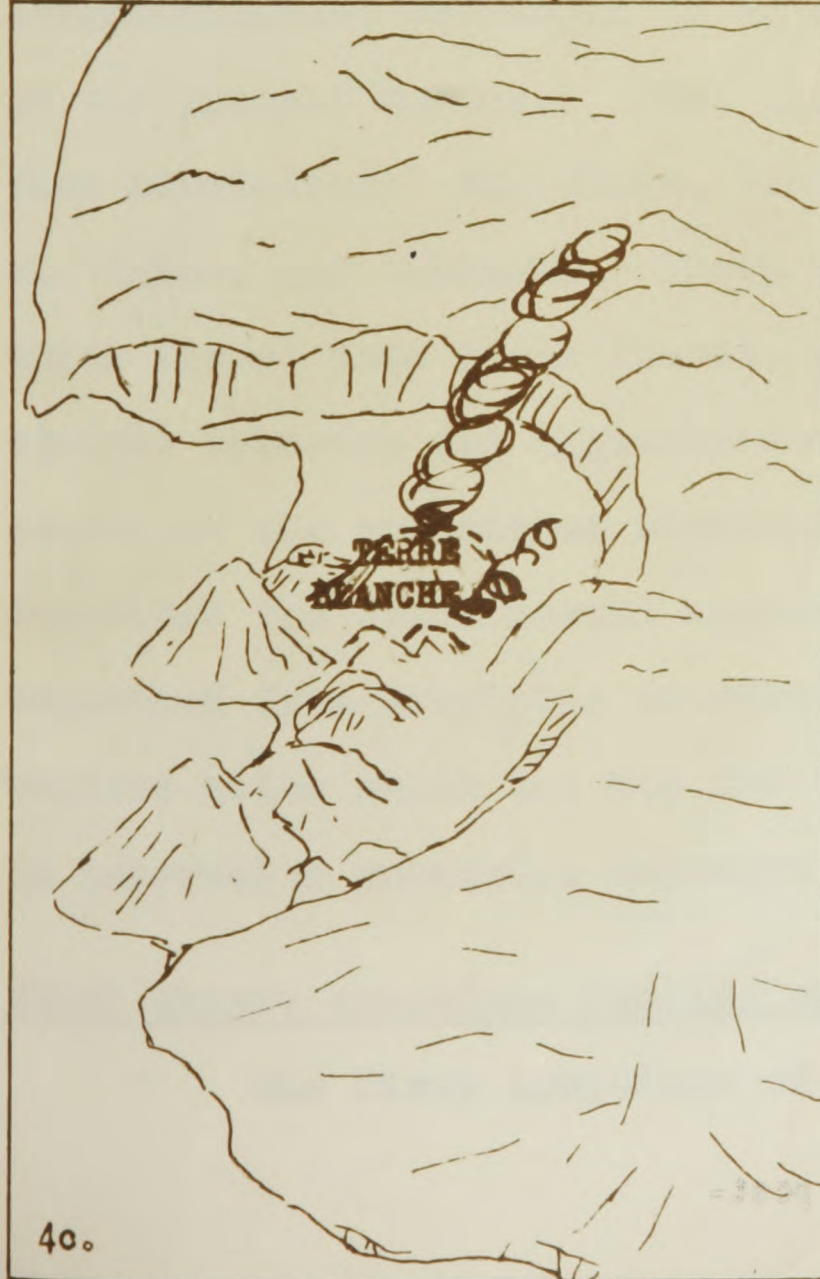
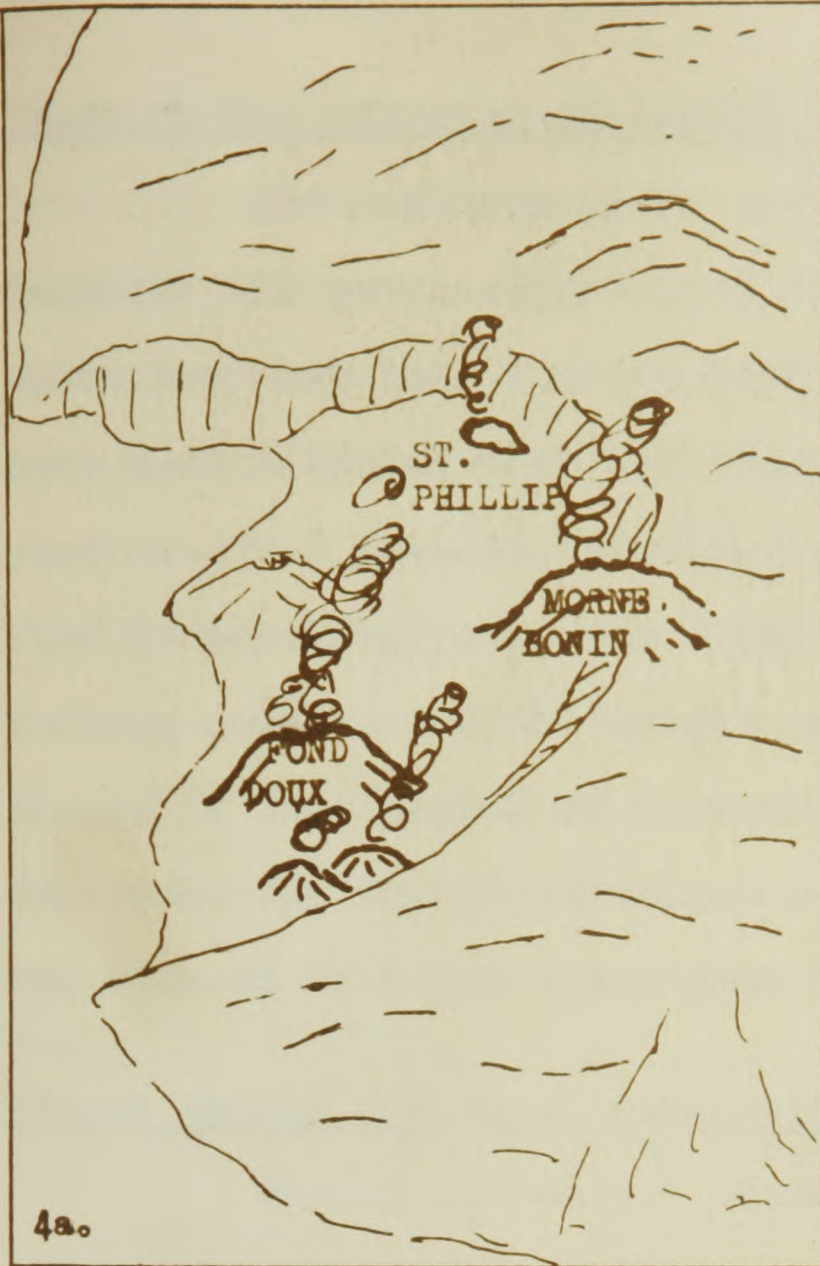


FIG.21b BIRD'S EYE VIEWS SHOWING THE POSSIBLE EVOLUTION OF THE SOUFRIÈRE REGION.



### First phase: effusion of basalt lavas

The earliest known events in the Soufrière region involved the quiet effusion of aphyric basalt lavas, from vents which have not been located with certainty but which appear to have been situated near the central ridge of the island, and also near the present shoreline south of Soufrière. A large flow of porphyritic basalt forming the Mt. Gomier ridge and flowing southward past Laborie probably belonged also to this phase. A long period of subaerial denudation appears to have followed, for basalt exposures south of Soufrière are reddened and altered in their upper part to a depth of 30 ft.

### Second phase: growth of andesitic strato-volcanoes

During the second phase, a number of small andesitic strato-volcanoes developed in an area slightly to the north-east of the present caldera. Five independent eruptive centres have been identified: Mt. Gimie, Piton Canaries, east of Migny, Mt. Tabac, and Coubaril. These emitted dark andesite lavas which flowed down their flanks, and were interstratified with ejected breccias and agglomerates. They are the most likely source of the voluminous block-plus-ash flow eruptions which deposited the Caldera-wall agglomerate-tuffs. The latter are separated from overlying deposits by an irregular, eroded surface below which the top few feet are reddened, indicating an interval of subaerial exposure and erosion.

### Third phase: eruptions leading up to caldera collapse

The first eruptions of the third phase are believed

to have involved vertical ejection of andesite pumice. This Older andesite pumice fell both to the north and south of the present caldera, from initial eruptions of fine crystal-plus-pumice ash, followed by at least eight cycles of increasing violence, each of which deposited up to 3 ft. of lump pumice near the source. This pumice was a new rock type in the Soufrière region, and may have come from a new vent within the site of the future caldera. These pumice showers appear to have been followed directly by relatively small pumice flow eruptions. Much of this Older andesite pumice was removed by subsequent erosion, as shown by exposures on the north side of Soufrière Bay (Plate 9a). At some time during this erosion interval, a structure composed of banded dark and pale grey andesite is believed to have formed at the surface. This was possibly a dome, which blocked the vent from which the andesite pumice was previously ejected. Blocks of this banded lava are found as inclusions in the next pyroclastic formation, the Vulcanian agglomerate, which is interpreted as the product of at least 33 consecutive Vulcanian eruptions of extreme violence, each one of which left a deposit about 3 ft. thick, consisting of coarse blocks and ash, covering the entire area within a mile or two of the source. These eruptions removed an estimated 1.8 cubic miles of material, consisting largely of fresh magma, from a subsurface reservoir beneath the future caldera. Extensive redistribution of this Vulcanian agglomerate, as mudflows, suggests that torrential rains accompanied or followed these eruptions.

The next eruptive activity, apparently following after no detectable time-interval, consisted of at least two large pumice flows which, near the foot of the southern glacis, reach a thickness of 136 ft. Andesite pumice is believed to have flowed down all the major topographic depressions in the southern half of St. Lucia at this period (Fig.15), indicating that an enormous quantity of material was emitted, for which it is impossible to give an accurate estimate, but which possibly amounted to more than one cubic mile. These are believed to have been the final eruptions before caldera collapse.

#### Fourth phase: post-caldera effusions and eruptions

The fourth and final phase of activity in the Soufrière region includes the growth of acid andesite and dacite domes within the caldera, and eruption of related pyroclastics. The earliest post-caldera extrusions appear to have been of acid andesite, forming the domes of Fond Doux and Morne Bonin. Breadcrust bombs found to the west and south of Morne Bonin indicate that minor pyroclastic eruptions preceded, or accompanied the growth of this dome. The St. Phillip quartz-poor dacite probably belongs also to this early period of post-caldera activity. These eruptions seem to have been concentrated around the margin of the caldera. The next events within the caldera involved the extrusion of the Pitons, Plaisance, and Rabet as dacite domes. It is believed that dome growth was preceded, or accompanied by vertical Vulcanian eruptions which deposited the blocks and ash (Piton dacite agglomerate) which outcrop in

numerous places around the rim of the caldera. Some of this material may be possibly related to the later, Terre Blanche stage.

Terre Blanche dome is, morphologically, much younger-looking than the Pitons and, together with adjacent smaller domes to the south, probably developed at a considerably later date. In addition to Terre Blanche and four smaller dome-like protrusions, three adjacent craters indicate that explosive eruptions accompanied extrusive activity.

The latest activity in the Soufrière region took place in the southern-central part of the caldera, and involved the opening of several vents between Belfond and Étangs, emission of pale grey dacite ash and blocks, and extrusion of five domes of similar material. The greater proportion of the pyroclastics appear to have been erupted vertically, falling as pumice ash showers, though pumice flows were also emitted during at least four periods, which were separated by intervals long enough for soil formation. These flows welled over the southern rim of the caldera and poured down the southern glacis, accumulating to form the thickest deposits towards the bottom of this slope, near Choiseul. An unknown quantity of pumice flow material must also have travelled southward and westward, out to sea. The most recent of these dacite pumice flows occurred 39,050 years ago, according to measurements made on carbonized remains of vegetation from the base of this deposit (Appendix A).

Present-day activity involves the relatively quiet emission of steam and sulphurous gases at the Sulphur Springs (see section 5.5.), and this type of activity is often quoted as characterizing the dying stages of a volcanic cycle. It is, however, equally common during periods of dormancy at a volcanic centre, and there is no reason to suppose that activity involving fresh lava has ended in the Soufrière region.



TABLE 3. VOLCANIC HISTORY OF THE SOUFRIÈRE REGION: POSSIBLE RELATIONSHIPS OF PYROCLASTIC SEQUENCE TO MASSIVE LAVAS

PHASE	FALL	- PYROCLASTICS -	FLOW	MASSIVE LAVAS	COMMENTS
4d. BELFOND	Pumice + ash fall, maximum exposure 100 ft.		Pumice + ash flow, estimated aggregate 136 ft. 4 major units.	Belfond DOMES (5) + craters. Pale grey dacite.	Last large flow eruption 39,050 years ago.
	? DISCONFORMITY?		( EROSION SURFACE )		
4c. TERRE BLANCHE				Terre Blanche and adjacent DOMES + craters. Pink dacite	
4b. PITON	Piton-type agglomerate		2 ash + block flow units separated by thin tuff horizon. Total 24 ft.	2 Piton DOMES + Plaisance + Rabot. Grey dacite.	MALGRÉTOUTE CORAL LST. (younger than Piton dacite) 150 ft. a.s.l.
	OVERLAIN BY			(St. Phillip dacite)	
4a. PALE ANDESITE DOMES	local breadcrust bombs S. of Morne Bonin		?	Morne Bonin DOME. Fond Dour DOME.	
* * * * * CALDERA * * * * * COLLAPSE * * * * *					
3c. ANDESITE PUMICE (YOUNGER)			136 ft. at Choiseul. At least 2 units, separated by 15 ft. of block + ash flow.		
	DISCONFORMITY		( EROSION SURFACE )		
3b. VULCANIAN	100 ft. 33 crudely graded units, each 2 - 4 ft. thick.		mudflow facies (also CONGLOMERATIC facies).		Derived in part by destruction of banded andesite structure (? DOME).
	DISCONFORMITY		( EROSION SURFACE )		
3a. ANDESITE PUMICE (OLDER)	36 ft. Semi-consolidated white andesite pumice <u>flow</u> fall				
	DISCONFORMITY		( EROSION SURFACE )		
2b. CALDERA-WALL AGGLOMERATE-TUFF	One pisolitic tuff layer.		Vertical thickness c. 1,000 ft. in N. wall. Pyroclastic flows + mudflows.		Source possibly high ground to N.E. (? Dark andesite cones)
	?	?	?	?	?
2a. DARK ANDESITE	Local dark andesite agglomerates (dipping off flanks of cones)			Gimie, Migny, Zenon, Coubaril, Gomier FLOWS (?)	
	( EROSION SURFACE )				
1. BASALT LAVA				porphyritic lava flow of Mt. Gomier (? 200 ft. thick) aphyric lava flows (up to 60 ft. thick)	

## 6. GRAIN SIZE DISTRIBUTION IN PYROCLASTIC DEPOSITS

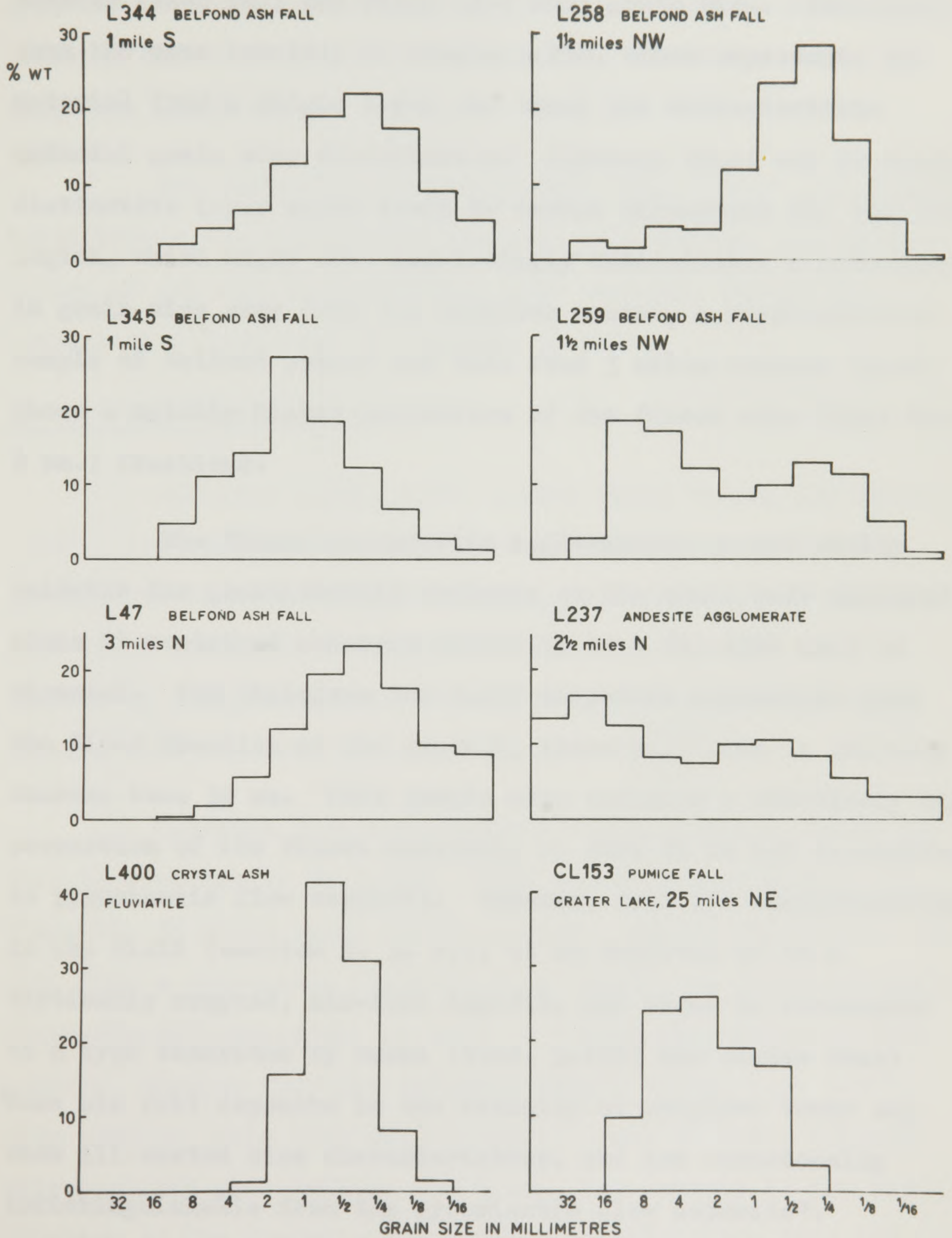
FIG. 22. GRAIN SIZE DISTRIBUTION IN PYROCLASTIC FALL DEPOSITS

Sixty-five samples of unconsolidated pyroclastic material, including Vulcanian andesite agglomerate and younger deposits, were mechanically analysed for particle size distribution, using a method described in Appendix B. Histograms were drawn for each sample, and these show the distinct characteristics of ash fall, ash flow, and fluviatile material recognised as such in the field.

### 6. 1. PYROCLASTIC FALL

Histograms of pyroclastic fall deposits (Fig. 22) are characterised by moderately good size-sorting, due to the combined effects of explosive force, which transports the largest lumps only short distances from the eruptive centre, and eolian differentiation (Williams 1957, p.62) which removes the finest particles to great distances. This paucity of very coarse and very fine material is well displayed by the Belfond pumice ash fall deposits (L.258, L.345). Decrease in maximum and average size of particles in this deposit away from the eruptive centre cannot, however, be demonstrated for this material, since it is composed of finely stratified particles of pumice and crystals whose average size alternates between  $\frac{1}{4}$ - $\frac{1}{2}$  and 1-2 mm. from layer to layer. This is demonstrated in samples L.344 and L.345, from horizons 16 ins. vertically apart at the same locality. Fine-scale alternations, involving different grain size in layers one inch or less in thickness, can also produce a bimodal

FIG. 22. GRAIN SIZE DISTRIBUTION IN PYROCLASTIC FALL DEPOSITS



histogram resulting from the superimposition of two modes. An example of this is provided by L.259, which includes layers of coarser (16-2 mm.) and finer ( $\frac{1}{2}$ - $\frac{1}{4}$  mm.) grain size. This comes from the same locality as sample L.258, which represents the material from a single layer and shows the characteristic unimodal grain size distribution. Although there was no single distinctive layer which could be traced throughout the Soufrière region, which might have convincingly demonstrated a reduction in grain size away from the eruptive centre, a representative sample of Belfond pumice ash fall from 3 miles distant (L.47) shows a notably higher proportion of the finest size (less than  $\frac{1}{8}$  mm.) fractions.

The Vulcanian andesite agglomerate was not wholly suitable for granulometric analysis on the scale here employed, since it contained numerous blocks up to 1 ft. (300 mm.) in diameter. The histogram for L.237 therefore represents only the finer fraction of the deposit, whose real mode is probably coarser than 32 mm. This sample also contains a relatively high proportion of the finest material, so that it is not dissimilar to pyroclastic flow deposits. However, from its characteristics in the field (section 5. 3. 4.), it is believed to be a vertically erupted, air-fall deposit, and seems to correspond to a type described by Murai (1961, p.199) who states that: "Some air fall deposits in the vicinity of eruptive vents may show ill-sorted size characteristics, and are occasionally indistinguishable from the pyroclastic flow deposits".

Reworking of ash fall deposits by fluvial action leads to further concentration of the intermediate fractions, with the result shown in L.400. In this material, the finest fraction has been removed in suspension, and the coarsest fragments isolated.

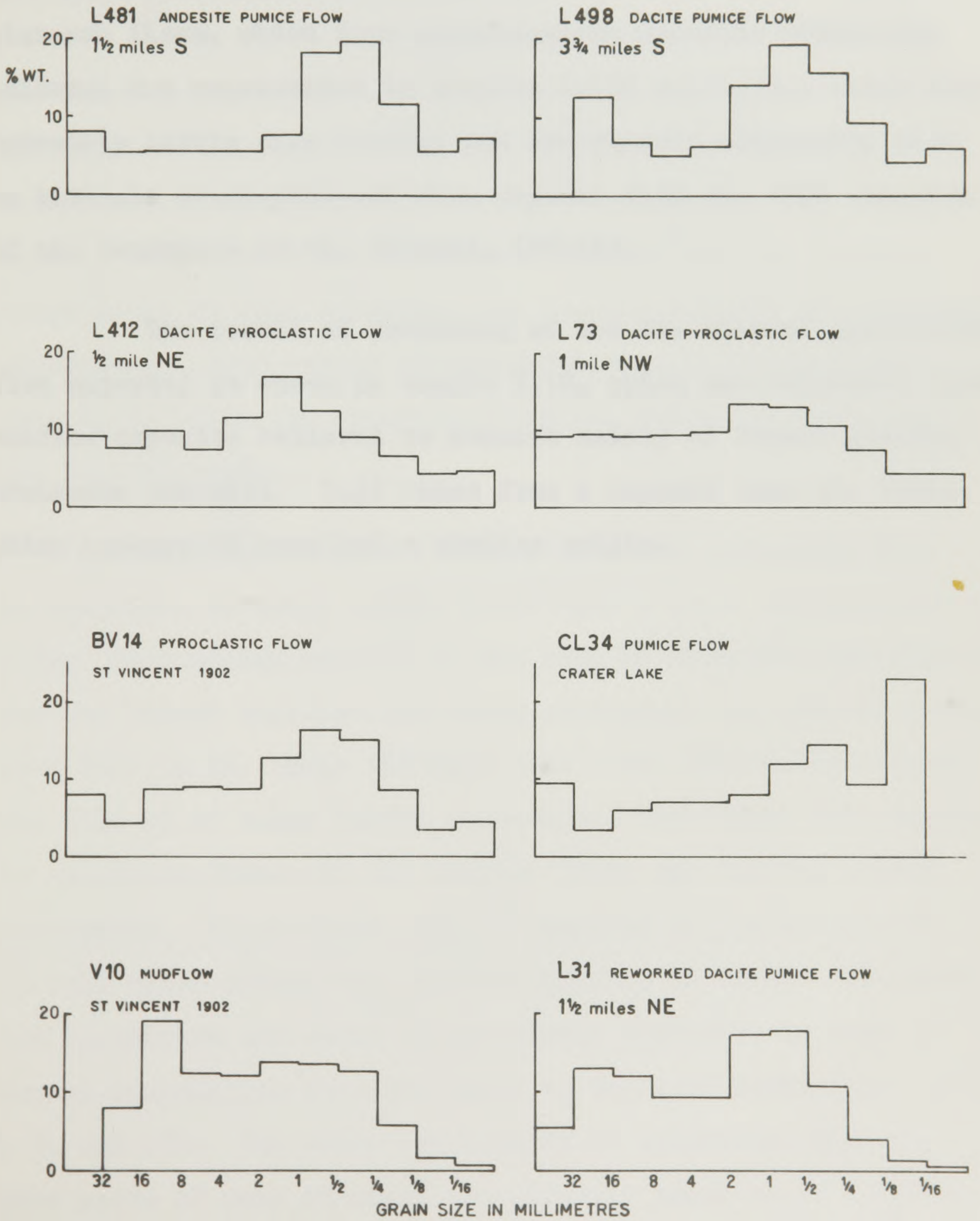
The histogram for pumice fall from Crater Lake (CL.153) demonstrates the essentially similar, well sorted, unimodal nature of ash fall deposits from this volcano, though the average size (1-8 mm.) is slightly coarser.

## 6. 2. PYROCLASTIC FLOW

Williams (1957, p.61) states that: "Among the features which characterize almost all Pelean deposits, none is more distinctive than the chaotic mingling of fragments of all sizes, from dusty particles to gigantic blocks and bombs." This absence of size sorting is evident in the histograms of pyroclastic flow deposits shown in Fig.23.

Material from the youngest Belfond dacite pumice ash flow is represented by L.498. This sample was collected at Choiseul,  $3\frac{1}{2}$  miles south of its source: unlike the Belfond ash fall from a comparable distance (e.g. L.47), it still contains fragments of large size, as well as a high proportion of fine powder. Samples from the andesite pumice flows (e.g. L.481) show similar grain size distribution. Both of these deposits show a slight mode between  $\frac{1}{2}$  - 1 mm., due largely to the crystal fraction of the deposits which falls mainly within this range.

FIG. 23. GRAIN SIZE DISTRIBUTION IN PYROCLASTIC FLOW DEPOSITS



Neither contains the extremely high concentration of the finest, comminuted pumice characteristic of the dacite pumice flows of Crater Lake, a feature which may be the result of the greater distance traversed by the Crater Lake flows. Dacite block-plus-ash flows, which form structureless deposits within the caldera, are represented by samples L.412 and L.73., which show extremely little size-sorting and are closely comparable with an historic block-plus-ash flow deposit from the 1902 eruption of the Soufrière of St. Vincent, (BV.14).

The result of reworking of the St. Vincent pyroclastic flow material is shown in sample V.10, which was collected from mudflow deposits believed to consist mainly of former glowing avalanche material. L.31 comes from a deposit from St. Lucia which appears to have had a similar origin.

The abundance of total quartz varies only a broad range from the total silica content of the lava. In addition, and as shown from the lower Antilles and other provinces, the general pattern found that in St. Lucia the most acid rocks (especially those with more than 75% of large quartz phenocrysts (see Table III), which the analyses (Table 6) all contain fewer and smaller quartz phenocrysts. Plagioclase, though abundant as phenocrysts in all rock types except the aphyric basalts, is always relatively rich in calcium and shows no systematic variation in average composition from the basic to the acid rocks (see Tables 7, 9, and 11). The cores and rims of hornblende, and the outer parts of many crystals are strongly altered to an actinolite

## 7. PETROGRAPHY

### 7. 1. ROCK CLASSIFICATION AND NOMENCLATURE

#### Classification used in this account

Lavas of the Soufrière region have been classified into three principal groups: basalts, andesites, and dacites. The divisions are based primarily on ferromagnesian phenocryst mineral assemblages, and also on the abundance of quartz phenocrysts. These and related textural differences are usually recognisable in hand specimen, and largely reflect the chemical composition. This scheme of classification is outlined in Table 4, in which the approximate silica range for each rock type is also shown.

Although Lacroix (1926, p.394) has emphasized that the abundance of modal quartz bears only a broad relationship to the total silica content of the lava in andesites and dacites from the Lesser Antilles and other provinces, the present author found that in St. Lucia the most acid rocks invariably contain more than 5% of large quartz phenocrysts (see Table 10), whilst the andesites (Table 8) all contain fewer and smaller quartz phenocrysts. Plagioclase, though abundant as phenocrysts in all rock types except the aphyric basalts, is always relatively rich in calcium and shows no systematic variation in core or average composition from the basic to the acid rocks (see Tables 7, 9, and 11). The cores are usually of bytownite, and the outer parts of many crystals are strongly zoned in an oscilla-

TABLE 4. Classification of volcanic rocks of the Soufrière region,  
St. Lucia

Rock type	Colour	Characteristic ferromagnesian mineral assemblage	SiO <sub>2</sub> % approx. range
BASALT	melanocratic	<u>Clinopyroxene</u> most abundant. Olivine sometimes present (always subsidiary). Orthopyroxene absent or rare. Magnetite relatively abundant.	50 - 54
ANDESITE	melanocratic	<u>Orthopyroxene</u> most abundant. Hornblende frequently present (always subsidiary).	59
	leucocratic	Clinopyroxene } Olivine } rarely present.	60 - 63
DACITE	leucocratic	<u>Amphibole</u> most abundant* <u>Biotite</u> } Orthopyroxene } always present. <u>Clinopyroxene</u> } Olivine } rarely present.	63 - 66

\*In dacites from the Pitons, amphibole is less abundant than pyroxene, by which it has largely been replaced.

TABLE 5. CLASSIFICATION OF THE BASALT-ANDESITE-DACITE SERIES BY VARIOUS AUTHORS

	LESSER ANTILLES			U.S.A.	JAPAN
68	MARTINIQUE Lacroix 1926, p. 394	MONTSERRAT MacGregor 1938, p. 48	ST. KITTS Baker 1963, p. 100	CRATER LAKE Williams 1942, p. 130	HAKONE Kuno 1950, p. 958
	DACITE	DACITE	DACITE	DACITE	(not present)
65	DACITE	BANNAITE	ANDESITE	ANDESITE	ANDESITE
	DACITOIDE (no modal quartz)	= labradorite dacite	PALE ANDESITE	(not present)	(not present)
60	DACITE	LABRADORITE ANDESITE (not present)	ANDESITE	BASALTIC ANDESITE	ANDESITE
	LABRADORITE	BASALT	BASALTIC ANDESITE (few present)	BASALT	BASALT
56	DACITE	BASALT	BASALT	BASALT	BASALT
	BASALT	BASALT	(not present)	BASALT	BASALT
52	DACITE	BASALT	BASALT	BASALT	BASALT
	BASALT	BASALT	(not present)	BASALT	BASALT
CHI- TERIA	1) Presence of modal quartz 2) Normative quartz presence distinguish- shes labradorite/ basalt	1) Presence of modal quartz Normative quartz basalt < 10% < andesite	Ferromagnesian mineral assemblage 1) Ferromagnesian mineral assemblage 2) Abundance of modal quartz	SiO <sub>2</sub> %	Colour index of groundmass

tory fashion. The mineral is, therefore, of no value as a means of differentiating between rocks from St. Lucia.

#### Classifications used by other authors

Rocks of St. Lucia belong to the basalt-andesite-rhyolite association of Turner and Verhoogen (1960, p.272) and to the calcic series of Peacock (1931). This group has proved particularly difficult to classify, and the use of different criteria by various authors has led to substantially different divisions, sometimes even in the same magmatic province. This is illustrated in Table 5, which attempts to equate some of the more important systems of classification.

Lacroix (1904) initially subdivided the lavas of Martinique on a mineralogical basis into basalts, andesites and dacites. In 1926, however, he reclassified them according to their chemical characteristics, paying particular attention to the abundance of normative and modal quartz. The meaning of the term dacite was extended to include an extremely wide range, being defined as any lava containing plagioclase as the predominant feldspar and modal quartz, whilst the term "dacitoïde" was introduced for one of similar chemical composition but without modal quartz, i.e. with free silica expressed in the norm, but present only in the glassy or cryptocrystalline matrix of the rock. "Labradorite" was the name applied to rocks of a more basic character, approximately equivalent to basalts of the present classification, whilst Lacroix used the term basalt only for rocks without normative silica, which are extremely rare

in the West Indies.

MacGregor (1938, p.48), in his classification of lavas of Montserrat, revived the term "bandaite" (Iddings, 1913, vol.2, p.111) for labradorite-bearing andesites containing modal silica\*. Like Lacroix (1926), he defined the boundary between labradorite-andesite and basalt by the criterion of normative quartz: he classified rocks with less than 10% of the latter as basalts, and stated that these were generally found to have a silica percentage of less than 55. MacGregor, therefore, like Lacroix, used criteria involving a combination of modal and chemical compositions, yet distinguished only two effective groups: bandaites (labradorite dacites), and olivine basalts.

Rocks of Crater Lake region were classified by Williams (1942, p.130) largely on the basis of chemical analysis. The rock names and silica percentages correspond closely with the divisions adopted by Baker (1963, p.100) and the present writer with reference to the Lesser Antilles, though in the Crater Lake series dacites are clearly separated from andesites by a gap from 62% to 68%  $\text{SiO}_2$ .

In his account of the petrology of Hakone volcano, Japan, Kuno (1950, p.958) classified the rocks according to the colour index of the groundmass. He stated that: "This is based on the idea that the bulk composition of the porphyritic

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\* Iddings (1913, vol.2, p.112) introduced the term bandaite for "labradorite-dacites, whether with modal quartz or occult quartz."

rocks may be affected by crystal sorting, while the groundmass compositions represent those of possible magmatic liquids". In St. Lucia, however, many of the rocks have a glassy or cryptocrystalline groundmass, rendering such a classification impossible. Kuno (1950, p.984) also introduced a new, detailed classification based on the ferromagnesian silicate mineral assemblage, with major divisions according to phenocryst minerals present, and subdivisions based on groundmass. This was adopted and extended by Katsui (1961, p.7). St. Lucian basalts fall into categories c, IVc and Vc, andesites chiefly into classes Ie, V, Ve, VI and VIe, whilst dacites almost all fall into class XVII.

## 7. 2. OPTICAL METHODS

Plagioclase composition was estimated by universal stage measurement of the maximum extinction angle in the zone perpendicular to (010), using the determinative curve of Winchell (1951, p.262). Results are believed to be accurate to  $\pm 5\%$  An, although the relative accuracy (e.g. the range of zoning in one crystal) is probably accurate to  $\pm 2\%$  An. For crystals with such extensive and fine-scale oscillatory zoning as those in most of the St. Lucian rocks, this proved the only practicable method.

An estimate of the average composition of the plagioclase in a rock was made by selecting 10 representative crystals (e.g. large and small, zoned and unzoned, in approximate proportion to their abundance in the rock section), estimating their

composition by measuring maximum extinction in the zone normal to (010), and making a correction for the area and compositional range of zoning, if present. It is clear that many of the crystals will not be transected exactly through the middle by the plane of the section, and therefore will probably not show the maximum  $A_n$  value of crystal they represent. This does not, however, prevent a true average composition from being estimated, nor does it affect the validity of the figure obtained for the minimum  $A_n$  content, estimated from the extinction angle of the outermost zone.

For orthopyroxene,  $2V$  ( $\pm 1^\circ$ ) was measured by direct rotation between optic axes, and  $N_z$  was determined on mineral concentrates by the immersion method. The curves used were those of Kuno (1954, p.40).

The composition of clinopyroxenes was estimated from measurement of  $N_y$  and  $2V$  ( $\pm 1^\circ$ ) using the method and curves of Hess (1949).

Olivine phenocrysts were relatively so rare that it was not practicable to measure  $2V$  in thin sections.  $N_z$  was therefore determined on mineral concentrates or hand-picked phenocrysts, and compositions were estimated by reference to the refractive index curves of Bowen and Schairer (1935, p.197), quoted by Deer, Howie and Zussman (1963, vol.1, p.22).

### 7. 3. BASALT FLOWS

Two principal varieties of basalt have been identified in the Soufrière region: aphyric, and porphyritic. The aphyric rocks appear to form a fairly homogeneous and distinct group. The porphyritic rocks, on the other hand, have either a microcrystalline or glassy groundmass, and show a wide variation in their content of phenocryst minerals. On the basis of this latter feature, they have been divided into two subgroups: plagioclase-phyric basalts, containing almost exclusively feldspar as phenocrysts, and plagioclase-pyroxene(-olivine)-phyric basalts, in which plagioclase is accompanied by clinopyroxene, with or without orthopyroxene and olivine phenocrysts.

#### 1. Aphyric basalts

The aphyric basalts are so extremely fine-grained that in hand specimen they could be mistaken for hard, dark, siltstone. They do however contain extremely rare phenocrysts, up to 2 mm. across, of plagioclase and ferromagnesian minerals. The rock is hard and splintery. It frequently shows flow-banding in the form of alternating sub-parallel layers or lenticles up to 5 mm. thick, of slightly darker and slightly paler colour. Veinlets of calcite, usually less than  $\frac{1}{2}$  mm. wide, cut irregularly across the rock, and enclose occasional crystals of pyrite.

In thin section (Plate 18a, 18b), the essential constituents are seen to be plagioclase and clinopyroxene. Extremely rare phenocrysts, of which not more than one occurs per sq. cm.,

consist of one or both of these minerals or olivine. Plagioclase consists of fresh looking, euhedral prisms up to 1 mm. long, the estimated composition of one unzoned phenocryst in L.153 (Plate 18a) being  $An_{34}$ . Olivine and clinopyroxene phenocrysts are of similar size to, although even rarer than, the feldspar. The groundmass, in one of the more coarsely crystalline samples (L.34, Plate 18b), contains an estimated 66% of lath-shaped plagioclases of average length 0.2 mm., 25% of clinopyroxene as 0.05 mm. prisms, and 7% of magnetite as evenly distributed, small grains. The plagioclase composition varies between  $An_{62}$  and  $An_{43}$ , though zoning, of a normal continuous kind, is detectable only in a few crystals. The aphyric basalts of finer grain size (L.153, L.424), characteristic of shoreline localities to the north and south of the Petit Piton, contain a similar mineral assemblage, with flow structure composed of alternating slightly glassy (darker) and paler, holocrystalline layers. This structure is emphasized by the preferred orientation parallel to the flow planes of lath-shaped feldspars up to 0.2 mm. long, in a matrix of 0.01 to 0.02 mm. grains of plagioclase, clinopyroxene and ore.

## 2. Plagioclase-phyric basalt

Porphyritic basalt from the south side of Soufrière Bay (L.251, Plate 19b) contains 30% of cumulophyric plagioclase and 2% of ophitic clinopyroxene in an intergranular groundmass consisting of the same minerals and ore.

### Plagioclase

Plagioclase phenocrysts are subhedral, often elongate, and of average size 1 mm. They frequently occur in glomeroporphyritic patches. Almost all crystals are normal-continuously zoned: in the microphenocrysts (up to 0.5 mm. long) zoning always begins at the core, the composition of which shows fairly constant values of between  $An_{56}$  -  $An_{61}$ . The larger phenocrysts have core compositions of up to  $An_{82}$ , and unzoned cores usually occupy at least half of these crystals by area. The outer parts of these crystals show zones which are usually of normal-discontinuous type. A few possess slight oscillatory zoning. Groundmass plagioclase consists of prisms down to 0.02 mm. in length. There is no clear distinction between the size of larger groundmass crystals and microphenocrysts, and their composition is closely similar.

### Clinopyroxene

Clinopyroxene is the most abundant ferromagnesian mineral. It occurs as relatively small, subhedral phenocrysts of up to 0.5 mm. which, like plagioclase, are often cumulophyric. Like plagioclase, also, pyroxene crystals grade downward in size from phenocrysts to groundmass of 0.02 mm. Larger pyroxenes are sub-ophitic, and completely enclose occasional small crystals of feldspar and ore. Variation in the extinction angle  $2\lambda c$  of up to  $5^\circ$  indicates slight zoning at the margins of larger crystals, and  $2V$  measurements range from a maximum of  $52^\circ$  at the core to  $44^\circ$  at the rim. Values of 1.700 ( $\pm 0.002$ ) were recorded for the

refractive index  $N_y$ , indicating a composition of approximately  $\text{Ca}_{42}\text{Mg}_{34}\text{Fe}_{24}$  (Hess, 1949, p.634).

### Accessories

Minor accessory minerals include magnetite as sub-hedral, 0.02 mm. crystals in the groundmass, and patches of interstitial calcite. Green, fibrous antigorite, associated with calcite, also occurs as rare, rectangular pseudomorphs up to 0.5 mm. across: this may be after orthopyroxene.

### 3. Plagioclase-pyroxene(-olivine)-phyric basalt, (Plate 19a)

Vitrophyric plagioclase-two-pyroxene(-olivine) basalt occurs in the southeastern part of the area mapped in detail, as the Mt. Gomier flow (L.570) and is also the characteristic lava type found in tuffs and bedded scoria in the northern part of St. Lucia (e.g. L.83). In hand specimen it appears dark and glassy, with abundant phenocrysts of translucent plagioclase, large, black pyroxenes and, in some rocks (e.g. L.83), occasional green olivines. Vesicles 2 mm. in diameter are common near the original surfaces. The basalts of Vieux Fort (L.565) and Réduit (L.189) contain similar phenocrysts in a microcrystalline groundmass.

In thin section, L.83 contains phenocrysts of plagioclase (25% of the rock), clinopyroxene (11%), olivine (3%) and rare crystals of orthopyroxene in a dark glassy matrix in which finely granular ore and crystallites of felspar are the only recognizable minerals. In the Mt. Gomier flow (L.570) olivine

is extremely rare, and orthopyroxene is more abundant than in L.83.

### Plagioclase

Plagioclase phenocrysts are subhedral to euhedral, rectangular prisms, varying in length from 1.5 - 0.1 mm. Core compositions show a maximum of An<sub>77</sub>, and about half of the total number of crystals are unzoned. Others possess normal-continuous zoning which, in the less calcic crystals, begins at the core and extends over the approximate range An<sub>70</sub> (innermost zone) to An<sub>40</sub> (rim). Oscillatory zoning is rare and of narrow compositional range.

### Clinopyroxene

Clinopyroxene occurs as subhedral 1 mm. crystals, often in cumulophyric clusters. Many crystals are twinned on the (100) plane. Optical measurements and the inferred composition are given in Table 7.

### Olivine

Rare, large phenocrysts of olivine are up to 2 mm. across, with broad serpentized cracks and margins. Refractive index measurements, made on separated crystals, are shown in Table 7.

### Orthopyroxene

Orthopyroxene occurs rarely, as subhedral, elongate prisms up to 1 mm. across, often rimmed by clinopyroxene. It is most abundant in L.570, which contains about 2% of fresh,

Table 6

MODAL COMPOSITION OF BASALTS

Specimen L	153 <sup>*</sup>	34 <sup>*</sup>	251	83
Quartz	-	0.2	-	-
Plagioclase	47.9	62.0	30.3	25.5
Olivine	0.4	tr.	-	3.5
Clinopyroxene	35.7	24.8	2.1	10.9
Orthopyroxene	-	-	-	0.2
Magnetite	9.2	7.2	n.d.	n.d.
Calcite	5.8	-	-	-
Alteration minerals	1.0	5.8	-	-
TOTAL PHENOCRYSTS	‡	-	32.4	40.1

\* Aphyric

For rock names and localities, see Table 13.

Table 7 MINERALOGICAL DATA FOR BASALTS

Specimen L	153	34	251	83
<u>Plagioclase An%</u>				
max. core composition	84*	61**	82	77
estimated average composition	53	50	55	65
<u>Clinopyroxene</u>				
2V (degrees)	n.d.	n.d.	52(core) -44(margin)	57-53
Ny	n.d.	1.703	1.700	1.704
Approximate composition			Ca <sub>42</sub> Mg <sub>34</sub> Fe <sub>24</sub> (core)	Ca <sub>44</sub> Mg <sub>30</sub> Fe <sub>26</sub> *
<u>Olivine</u>				
Nz	1.708	-	-	1.708
Fe%	82	-	-	82

\* lone phenocryst

\*\* microphenocryst

independent crystals, of which the refractive index ( $N_z = 1.713 \pm .002$ ) indicates a composition of  $En_{61}$ .

#### 7. 4. DARK ANDESITE FLOWS

This category includes non-vesicular, dark, greenish-grey lavas from Mt. Gimie and surrounding hills. They contain abundant, pale feldspar phenocrysts of 1 - 2 mm. in size, and well-shaped, elongate, black prisms of pyroxene. Similar rocks from Mt. Tabac and Coubaril (e.g. L.710) contain, in addition, occasional 1 mm. crystals of quartz.

Essential constituents in a typical specimen (L.38, Plate 20a) are given in Table 8. Minor accessory quartz and green hornblende are present in some samples. The groundmass is composed of cryptocrystalline, equigranular (felsitic) material which appears to be chiefly of light minerals less than 0.01 mm. across.

#### Plagioclase

Stout, euhedral phenocrysts of plagioclase vary in size from 2 mm. to 0.5 mm. Unlike those in the basalts, they show marked oscillatory zoning which sometimes extends from core to margin, and zones containing abundant pale brown glassy inclusions are common. The maximum recorded core composition is  $An_{79}$ , and rim compositions fall between  $An_{50-40}$ .

Zoning of plagioclase is much more conspicuous in andesites and dacites than in basalts from St. Lucia. This

feature is common to other islands of the Lesser Antilles, including Martinique and Dominica (Lacroix, 1904, p.591) and St. Kitts (Baker, 1963, p.116). The overall change is always from a more calcic core to a more sodic rim, though many minor reversals are superimposed on this general trend. Unzoned cores are often present in the larger crystals, and some of these cores are filled in their outer part by inclusions. In other phenocrysts, zoning begins at the centre. Vance (1962, pp.747-8) describes oscillatory zoning as a widespread feature in the plagioclases of plutonic rocks with a similar chemical composition, including quartz diorites and granodiorites, and summarizes the various possible explanations (Vance, 1962, pp.750-1). The more widely accepted of these include:

- 1) Repeated differential movement between plagioclase and a thermally or compositionally heterogeneous melt (Bowen, 1928, p.275).
- 2) The effect of pressure changes, which alter the water content of the magma (Tuttle and Bowen, 1958).
- 3) The product of alternating local supersaturation and diffusion of An molecules in the melt (Harloff, 1927; Hills, 1936, p.52), involving:
  - i) crystallization of a thin normal zone of calcic plagioclase in equilibrium with the closely adjacent liquid, becoming less calcic with falling temperature,
  - ii) resultant supersaturation in An molecules of the liquid more distant from growing crystals, i.e. inhomogeneity in the anorthite content of the liquid phase.

iii) Gradual diffusion of An molecules away from these supersaturated parts, i.e. return to homogeneity in the liquid phase.

Bowen's hypothesis of repeated differential movement is not readily applicable to magma of andesitic composition, whose high viscosity must limit the freedom of movement of plagioclase crystals within the liquid. It is noteworthy in this connexion that zoning is less conspicuous in basalts, which were undoubtedly less viscous when magma, whilst there is no evidence to suggest that they were thermally or compositionally more homogeneous than the andesites.

The second explanation is rejected with reference to plutonic igneous rocks by Vance (1962, p.750), who states that "repeated loss of volatiles is likely to be significant only in a near-surface, subvolcanic environment". The implication is that this process could well have operated in St. Lucia, particularly in view of the recurrent violent eruptions which are known to have taken place.

Ewart (1963, pp.419-20), in a discussion of oscillatory zoning in plagioclases from Quaternary pumice ash in the Taupo area, New Zealand, suggests that occasional, large compositional breaks in the rhythmic pattern may be caused by sudden decreases of pressure due to loss of volatiles at the time of an eruption, causing resorption of previously deposited zones, and subsequent deposition of a considerably more calcic zone. Ewart tentatively

attributes these major discontinuities to specific eruptions in his detailed sequence. The minor oscillations of zones, in his opinion, "still seem to be explained best as the result of movement of crystals in the magma chamber" (op. cit. p.420). The present author finds it difficult to accept the reality of a process of repeated rising and sinking of plagioclase in an acid, presumably viscous, magma, as outlined by Ewart. Moreover, if solely responsible, this process should have produced a uniform pattern of major zonal oscillations in neighbouring crystals, which manifestly does not exist in the St. Lucian plagioclases (e.g. Plate 20b). To satisfy this last condition, the supersaturation-diffusion mechanism seems most adequate: diffusion may be locally less or more effective, according, for example, to the number of centres towards which it is taking place in a given volume of magma. Contemporaneously grown zones may thus vary in width or composition from crystal to crystal, in the manner observed.

Plagioclase crystals frequently contain crowds of minute inclusions in one or more zones. A broad, inclusion-rich zone often occupies either the whole or the outer part of an unzoned core, and narrower zones containing inclusions may lie outside this, within the oscillatory-zoned portion of a phenocryst (Plate 21a). Some of the inclusions are so small that their composition is not distinguishable. Among those large enough to be identified, particles of glass are most common (e.g. Plate 29a, 29b) and are usually pale brown or colourless,

often being similar in appearance to the groundmass of the rock. Glass may also fill irregular cracks in plagioclase crystals, or form a complete or nearly complete zone (Plate 21b). Some phenocrysts contain trains of minute crystals of higher refractive index, showing first order polarization colours and straight extinction, which are almost certainly orthopyroxene (Plate 29b). Opaque oxide also occurs as finely crystalline inclusions.

MacGregor (1938, p.50) refers to spongy zones containing small glassy inclusions in plagioclase phenocrysts from Montserrat lavas, which he explains as the result of magmatic corrosion at a certain stage in the cooling history of the felspar. Following this, liquid was trapped and solidified as glass in the cavities left by corrosion. MacGregor also describes larger, isolated patches of brown or colourless glass, elongated parallel to crystallographic directions.

In phenocrysts from St. Lucia, the crystalline inclusions have obviously been poikilitically enclosed during growth of the phenocryst. The continuous glass zones represent liquid which was probably chilled onto the periphery of the growing phenocryst. For the broader zones containing minute glassy patches, MacGregor's explanation, involving magmatic corrosion, seems appropriate.

### Orthopyroxene

Orthopyroxene is the predominant ferromagnesian mineral. It occurs as subhedral 2 mm. phenocrysts which grade down in

seriate manner to microphenocrysts of 0.03 mm. The optical properties and inferred composition are given in Table 9 (specimen L.38). No zoning is perceptible.

### Clinopyroxene

Clinopyroxene occurs as sparse, independent crystals up to 2 mm. across, and also as cumulophyric clusters of 0.3 mm. subhedral prisms. For one crystal in L.38, a  $2V_z$  measurement of  $53^\circ$  was obtained. Due to the very small proportion of clinopyroxene in the rock (Table 8), this mineral could not readily be separated for refractive index measurement.

### Minor accessory phenocrysts

Quartz occurs as occasional, rounded and embayed, 0.5 mm. crystals. Green hornblende is present as rare phenocrysts up to 3 mm. across (L.11), showing marginal resorption to either pyroxene and ore, or to biotite.

## 7. 5. ANDESITE AGGLOMERATES

Lava blocks in both the older, Caldera-wall and younger, Vulcanian andesite agglomerates form a group which is heterogeneous in hand specimen and texture but relatively constant in mineralogy: they will therefore be described under the same heading.

Lavas vary greatly in colour, from almost white to red and dark grey. Pale to medium grey types are most common, and a large proportion have a mildly vesicular texture. Some blocks are banded, especially in the younger Vulcanian agglom-

erate. Phenocrysts are up to 2 mm. across: those recognisable in hand specimen include translucent or cloudy plagioclase, elongate black prisms of pyroxene, and occasional quartz crystals.

Many lavas of this group are characterized by a protoclastic texture, involving phenocrysts which are anhedral yet angular in shape, (see Plate 22b). In particular, the pattern of oscillatory zoning in the plagioclases indicates that they are broken fragments of formerly larger crystals. Phenocrysts are rarely larger than 1 mm. across, and consist principally of plagioclase (about 35%) with subordinate quartz, orthopyroxene and hornblende in varying proportions (together about 10%) and minor opaque oxide. The groundmass is either glassy or cryptocrystalline.

In the Caldera-wall agglomerate, lavas containing unbroken phenocrysts are more common (e.g. L.190), and many closely resemble the pale andesite dome lavas (e.g. L.290). Others are darker, with a glassy matrix, (e.g. L.203). The consolidated tuff matrix of this agglomerate (L.193, Plate 22a), however, contains highly angular, disrupted crystals of felspar, quartz and orthopyroxene, together with cryptocrystalline and glassy debris.

### Plagioclase

Plagioclase in most rocks occurs as anhedral, or occasionally subhedral crystal fragments, of all sizes up to 1 mm. In rocks which do not display a strongly protoclastic

texture, subhedral phenocrysts reach the size of 2 mm. Oscillatory zoning is common, and some crystals contain zones up to 0.3 mm. broad, full of minute glassy and crystalline inclusions. Cores are commonly of sodic bytownite, with a maximum recorded calcium content of  $An_{75}$  (L.203) decreasing to andesine with a minimum of about  $An_{40}$  at the rims. In the Caldera-wall agglomerate, crystals are often cloudy, with alteration concentrated along irregular cracks.

### Quartz

Quartz crystals, like the other phenocrysts, are often broken and angular, though many of the larger ones show evidence of having been globular before they were mechanically disrupted (Plate 22b). In some rocks, however, (e.g. L.235) numerous relatively small crystals of up to 0.2 mm. in diameter have a bipyramidal shape, with only slightly rounded corners, suggesting that they have not been strongly resorbed. In many cases the margins of quartz phenocrysts are minutely embayed, indicating that resorption has definitely taken place.

### Hornblende

Hornblende in the glassy rocks is most commonly fresh and is pleochroic according to the scheme: X = very pale yellow; Y = yellow-brown; Z = greenish brown. In occasional crystals, hornblende of this colour encloses ovate cores which are pleochroic from straw yellow (X), to deep walnut brown (Z). Deep chestnut brown crystals of oxyhornblende occur in a few rocks (L.48), and these contain abundant small plagioclase and magne-

tite inclusions, suggesting that they crystallized at a later stage than the greenish-brown hornblendes. One large crystal in L.48 encloses a core of clinopyroxene. Reddish-brown oxyhornblende in L.95 is almost completely resorbed to a black, nearly opaque substance, containing small grains of iron ore. Samples L.48, L.95, and L.235, which contain oxyhornblende, all have a cryptocrystalline groundmass. The association of green hornblende with glassy rocks in Montserrat was noted by MacGregor, (1938, p.53), who "therefore inferred that the much more abundant brown hornblende, which often occurs in holocrystalline or slightly glassy rocks, has been produced by partial auto-oxidation of green hornblende."

#### Orthopyroxene

Orthopyroxene occurs as subhedral, elongate prisms, which are poikilitic to small grains of ore and occasional small plagioclases. Narrow rims of finely granular, opaque oxide are common in lavas from the Caldera-wall agglomerate.

#### Minor accessories

Minor accessory minerals include opaque oxide, which appears to be magnetite, in grains of up to 0.2 mm.

#### Groundmass

The groundmass is glassy or cryptocrystalline, composed mainly of light minerals. In some rocks (e.g. L.239) it shows a flow structure consisting of paler (less glassy) and darker (more glassy) bands and lenticles between 0.1 and 0.5 mm. thick.

## 7. 6. ANDESITE PUMICE

Andesite pumice described in this section outcrops at two horizons: the older occurs below and the younger above the Vulcanian andesite agglomerate. The deposits consist of blocks of white andesite pumice in a fine matrix composed of dust and small crystals: only the pumice blocks are described here. These contain phenocrysts up to 1.5 mm. across of plagioclase, pyroxene and quartz in a white vesicular matrix, in which the larger vesicles often contain small strands of Pele's hair. The pumice has a specific gravity of slightly less than one.

In thin section, a representative rock (L.476, Plate 23a) contains 16% plagioclase, 2% quartz and 2% orthopyroxene, in a vesicular matrix of pale glass showing perlitic structure (Plate 23b).

### Plagioclase

Plagioclase commonly occurs as stout subhedral prisms 1 mm. across, which show oscillatory zoning over the relatively narrow compositional range  $An_{69-55}$ . Some crystals have abundant minute inclusions of pale brown glass, either in their cores or occupying a broad zone near the core. The outer parts of crystals invariably contain a large number of narrow oscillatory zones.

### Quartz

Quartz phenocrysts are up to 2 mm. across. Some of

the larger crystals show distinct crystal faces which appear not to have been significantly resorbed. Others represent angular, disrupted fragments. Some contain small ovate patches which are isotropic and may be either gas cavities or pale glass.

#### Orthopyroxene

Orthopyroxene forms elongate, subhedral prisms up to 2.5 mm. long, which contain abundant small inclusions of opaque ore and occasional small plagioclase crystals. Optical properties (Table 9, specimen L.476) correspond to a composition of approximately  $En_{45}$ . Some crystals have narrow coronas of opaque oxide.

#### Hornblende

Hornblende occurs in some specimens (e.g. L.680) as occasional, fresh, 0.5 mm. crystals which are subhedral and pleochroic from medium olive green (Z) to pale yellow (X). It is poikilitic to small crystals of plagioclase.

#### Minor accessories

Opaque oxide, which is probably magnetite, occurs as extremely fine particles scattered evenly throughout the ground-mass.

### 7. 7. PALE ANDESITE DOME LAVAS

Pale andesite lavas include material from the domes of Fond Doux (L.290) and Morne Bonin (L.5, Plate 20b). The appearance and texture of lavas from these two localities are

extremely similar. Specimens from both areas are very pale grey, compact rocks, with conspicuous elongate black prisms of pyroxene up to 5 mm. long, often showing preferred orientation. The only consistent difference is the higher percentage of small quartz phenocrysts in samples from Morne Bonin, a feature which is reflected in the silica content of the rock (Table 12).

In thin section, the pale andesites closely resemble the dark andesites, except that they tend to be notably fresher. Essential phenocrysts include plagioclase (40%), and orthopyroxene (8%), with subsidiary clinopyroxene (not more than 0.5%). The Morne Bonin material (L.5) contains 5% of modal quartz, whilst only about 1% is present in samples from Fond Doux. Total phenocrysts represent about 50 - 60% of the rock, which is slightly more than the proportion recorded in other andesites or dacites of the Soufrière region. The groundmass is microcrystalline to cryptocrystalline (felsitic), composed mainly of light minerals.

### Plagioclase

Plagioclase occurs as euhedral, rectangular prisms of average size 1 mm. Oscillatory zoning is common and often extends from centre to rim, including zones containing minute inclusions of pale brown glasses and small grains of hypersthene. As many as 40 oscillatory zones, including 4 zones crowded with inclusions, were recorded in one crystal in L.5 (Plate 21a). Core compositions show a maximum of An<sub>78</sub>, with rims ranging from An<sub>64-30</sub>. In general, crystals with more calcic cores also have

Table 8

## MODAL COMPOSITION OF ANDESITES

Specimen L	203	38	193	290	476	5	590
Plagioclase	36.5	36.7	25.0	40.0	16.3	43.7	58.7
Quartz	1.3	-	3.7	1.2	2.2	4.9	18.8
Orthopyroxene	4.2	2.5	4.3	8.1	1.6	8.7	8.3
Clinopyroxene	0.3	0.4	0.1	0.5	-	-	4.0
Amphibole	tr.	tr.	0.7	-	-	-	4.7
Biotite	-	-	-	-	-	-	4.0
Olivine	-	-	0.4	-	-	-	-
Opaque oxide	0.3	0.1	-	1.1	-	0.8	1.5
Calcite	-	0.3	0.7	-	-	-	-
TOTAL PHENOCRYSTS	42.6	40.0	34.9	50.9	16.1	58.1	holo-cry- stalline
GROUNDMASS	57.4	60.0	65.1	49.1	83.9	41.9	-

For rock names and localities, see Table 13.

Table 9 MINERALOGICAL DATA FOR ANDESITES

Specimen L	203	38	193	290	476	5	590
<u>Plagioclase An%</u>							
max. core composition	75	79	81	77	69	78	69
est. average composition	57	59	59	55	63	61	47
<u>Orthopyroxene</u>							
2Vx (degrees)	53	53	55-57	51-57	54-57	55	58
Nz max.	1.726	1.724	1.732	1.721	1.733	1.733	1.731
En%	49	52	46	54	45	45	47
<u>Clinopyroxene</u>							
2Vz (degrees)	n.d.	53	n.d.	n.d.	-	-	n.d.
Ny	n.d.	n.d.	n.d.	n.d.	-	-	n.d.
<u>Hornblende</u>							
Nz	1.686	1.686	-	-	-	-	1.687
Z <sub>Ac</sub> (degrees)	n.d.	12.5	-	-	-	-	8

more calcium-rich rims, so that cores of An<sub>75</sub> are commonly associated with rims of An<sub>55</sub>, though in one crystal in L.290 the range measured was from An<sub>76</sub> at the core to An<sub>30</sub> at the rim. The conspicuous variety in number and thickness of zones with glassy inclusions, and in the compositional range of the zoning, suggests a varied crystallization history for the individual plagioclase phenocrysts.

### Orthopyroxene

Orthopyroxene is by far the most abundant ferromagnesian mineral. Elongate, subhedral phenocrysts of average length 2 mm. are poikilitic to numerous, small (0.05 mm.) grains of ore and plagioclase. The estimated composition of the orthopyroxenes is given in Table 9.

### Quartz

Quartz occurs as euhedral to rounded phenocrysts of average size 1 mm. Some crystals show a bipyramidal outline with extremely little evidence of resorption. In the same slide, however, others are rounded, with corroded edges which have obviously been resorbed (c.f. Plate 24a).

### Accessory minerals

About 1% of opaque ore is present as 0.05 mm. anhedral grains in the groundmass and included in pyroxene phenocrysts.

7. 8. OLDER DACITES: ST. PHILLIP QUARTZ-POOR DACITE, AND  
PITON-TYPE DACITE DOME LAVAS AND AGGLOMERATES

This group incorporates all the older dacites of the Soufrière region, including those of the Gros Piton (L.329) and Petit Piton (L.13), together with the Plaisance (L.287) and Rabot (L.270) dome lavas which differ only slightly. With these are grouped the Piton-type agglomerates, and the quartz-poor dacites of St. Phillip. None of these rocks in thin section display features which differ sufficiently to justify a more detailed subdivision.

In hand specimen, the lavas are most commonly pale to medium grey, and occasionally slightly pinkish or, in the case of the St. Phillip quartz-poor dacite, darker grey in colour. The group is characterized especially by phenocrysts of globular quartz which are frequently 5 mm. across, and by dull charcoal-grey to brownish hornblende prisms with pseudo-hexagonal cross-sections, of similar size. Both quartz and hornblende occasionally reach 10 mm. in diameter. Quartz crystals are strongly cracked, and in weathered rock faces many have fallen out leaving small pits in the surface.

The phenocryst mineral assemblage in this group is notably varied: plagioclase is always present and consistently makes up 35 - 40 % of the rock, accompanied by quartz (usually

between 5 - 10%)\* and varying proportions of brownish-green hornblende, orthopyroxene and biotite. The last three minerals together seldom occupy more than 5% of the rock. Clinopyroxene and rare olivine crystals are also present in specimens from the Gros Piton (e.g. L.329). The groundmass is composed mainly of light minerals, and contains recognizable 0.3 mm. prisms of plagioclase, quartz and orthopyroxene, with 0.2 mm. grains of magnetite. The occurrence, in the dome lavas of this group (e.g. Plate 25), of a more coarsely crystalline groundmass than in other dacites of the Soufrière region, undoubtedly reflects the fact that rocks at present exposed are from deeper below the original surface of the domes, and therefore crystallized more slowly.

### Plagioclase

Plagioclase occurs as subhedral, 1 - 2 mm. phenocrysts which vary much in composition and structure. Core compositions in the Piton dacite are notably rich in calcium (see Table 11, specimens L.329 and L.13). Oscillatory zoning, though extending from core to rim in numerous crystals, is restricted to the approximate range  $An_{70} - 40$  and thus is not present in the bytownite cores. Many crystals are virtually devoid of inclusions, though some have rare, thin, inclusion-filled zones, and a few are crowded with extremely fine glass particles except in

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\* Estimation of the modal percentage of quartz phenocrysts in the dacites could not satisfactorily be made in thin section, because a large proportion of crystals had been torn out of the slide, even when impregnated with resin before grinding. The content was therefore estimated by using transparent graph paper and counting the quartz crystals at 0.1 x 0.1 in. intercepts in a large flat face of the hand specimen.

their outermost zones. The great variety of zonation and inclusions in plagioclase suggests that independent representatives of this mineral have had widely different crystallization histories.

A phenomenon seen in the cores of occasional large plagioclase crystals consists of a patchy inhomogeneity, due apparently to intergrowth of plagioclase of two compositions (Plate 24b). Skeletal patches in the core are distinctly more calcic in composition than the remainder of the crystal. This is shown by the extinction positions of albite twin lamellae, which continue through the patchy areas, though each lamella extinguishes in two different parts, corresponding to the two intergrowth compositions. The texture appears to be the result of corrosion of an originally calcic plagioclase crystal, which has been partially replaced by material whose composition is identical to that in the less calcic zones adjacent to the core.

Larsen and Irving (1938, pp.229-30) describe similarly resorbed plagioclase phenocrysts in Tertiary volcanic rocks from San Juan, Colorado, in which "only a skeleton of the original calcic core is left". They show (1938, Fig.15a) a crystal whose core is composed of a fine, irregular intergrowth of two feldspars of very different compositions, the more sodic ( $An_{43}$ ) occurring in patches and replacing the more calcic portion ( $An_{87}$ ). They note (1938, p.230) that "only a few of the plagioclase phenocrysts in this rock show calcic cores", and that "of the seventy rocks examined that contain plagioclase

phenocrysts, eight show conspicuously this type of zoning". This occurrence seems closely comparable to that of resorbed calcic cores in plagioclase phenocrysts from St. Lucia. Larsen and Irving suggest (1938, p.251) as the most likely explanation "that the calcic cores are due to contamination of a silicic magma by basaltic material". The present author explains these more specifically as incompletely fused material (probably basaltic or gabbroic) picked up by a magma formed in situ. This process is discussed in the section on the petrogenesis of the andesite-dacite series (section 9.3.)

#### Quartz

Quartz crystals are generally large, with a diameter of 2 - 5 mm. All are strongly fractured, and the majority are rounded and embayed (Plate 25a, 25b) indicating magmatic resorption: they should therefore be regarded as xenocrysts rather than phenocrysts, although occasional crystals have a modified yet still recognizable bipyramid form (Plate 24a).

It seems probable that quartz, like the other phenocrysts, once grew as euhedral crystals at depth in a magma whose composition was probably closely similar to the solidified matrix of the present dacite lava. This conclusion is based on the premise that it is unlikely that quartz would grow abundantly in a magma less siliceous, and equally unlikely that a more siliceous magma, if present at depth, would not be carried to the surface. It would therefore appear that the growth of the large quartz crystals resulted from a set of

physical conditions which could prevail at depth, though not at the surface. The most obvious of these is an increase of water vapour pressure, and reference to the experimental system  $Ab - Or - SiO_2 - H_2O$  (Tuttle and Bowen, 1958, pp.70-1, reproduced in Fig.35 of the present account) lends support to this hypothesis\*, since the field of quartz is significantly increased at higher pressures of water vapour. The extensive resorption which especially characterises the quartz in the Piton dacites probably results from the fact that they remained in a liquid at low  $P_{H_2O}$ , i.e. at or near the surface for a comparatively long period. The wider implications of this evidence are considered in the section (9.3.) devoted to the petrogenesis of the andesites and dacites.

### Hornblende

Hornblende occurs as stout, 0.5 - 1 mm. prisms, which commonly have broad coronas of finely granular ore plus minute laths of orthopyroxene. It is also present as larger crystals of 3 - 5 mm. which are always strongly resorbed. The smaller, less resorbed prisms are pleochroic according to the scheme: X = very pale yellow; Y = yellow-brown; Z = brownish green. Other optical properties are given in Table 11 (specimens L.329 and L.13).

Resorption of the formerly large hornblendes (e.g. in L.13) is of two types, involving:

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\* In the St. Lucian rocks, salic constituents minus An form only c. 60% of total normative minerals. Thus the  $Ab-Or-SiO_2-H_2O$  system must be regarded as only broadly applicable.

1) Alteration to a finely granular aggregate of orthopyroxene, plus clinopyroxene and subsidiary ore. The pyroxene consists of fine, parallel laths in optical continuity.

2) Alteration to a brownish-black substance which appears to consist largely of dusty iron oxide and contains discrete crystals of magnetite.

These two types of resorption were described by MacGregor (1938, p.54) as "pyroxenic" and "black" respectively. The "black" type of alteration was discussed by Washington (1896), who noted that these pseudomorphs were much more common in crystalline than in glassy rocks, and concluded that the alteration was due, not to reaction with the magma but to instability as the result of decreased pressure, occurring under conditions of slow cooling in a magma close to the surface. Lacroix (1904, p.507) and MacGregor (1938, p.54) came to similar conclusions with reference to West Indian lavas. The "pyroxenic" type of alteration, common in glassy rocks and in coarsely crystalline inclusions of Montserrat, and in the 1902 lavas of Mt. Pelée, was interpreted by these two authors as the result of resorption of hornblende at greater depths than that producing the "black" type.

### Biotite

Biotite is present as rectangular plates, 2 mm. long, which are pleochroic from deep walnut brown to very pale brown, and contain abundant small grains of ore. Like the green hornblende, they are often rimmed by finely divided black ore and orthopyroxene.

### Orthopyroxene

Prisms of fresh orthopyroxene, up to 2 mm. long and often euhedral, are most abundant in samples from the Petit Piton (L.13), where they form about 4% of the rock. The composition of these is  $En_{40}$ , which corresponds closely to that in other dacites of the Soufrière region (Table 11), yet is more iron-rich than the orthopyroxene of the Gros Piton (L.329) for which the value of  $En_{47}$  was obtained from refractive index measurements (see Table 11). In that the Petit Piton lava contains a higher proportion of orthopyroxene than other ferromagnesian phenocrysts (Table 10), it might be considered transitional in mineralogy from andesite to dacite. The Gros Piton specimens differ consistently in showing significant quantities of clinopyroxene.

### Clinopyroxene

This mineral is common only in the lavas from the Gros Piton (e.g. L.329), in which up to 2.1% was recorded. In all other dacites it is extremely rare or absent. It occurs in the Gros Piton rocks as occasional, cumulophyric clusters composed of crystals up to 1 mm. across, and as isolated, euhedral prisms up to about 0.3 mm. long, which frequently show zoned extinction.

### Olivine

Olivine, though extremely rare, was recorded in two thin sections of dacite from the Gros Piton (L.329a, L.225), where it forms anhedral, 1 mm. crystals rimmed by hornblende and orthopyroxene. Occasional larger phenocrysts are visible

in the hand specimen of these rocks, and the composition of one of these, determined by refractive index measurement (Table 11), was found to be  $Fe_{84}$ . This, in a silica-rich groundmass, must undoubtedly be a xenocryst. The occurrence of magnesian olivines in dacite from Clear Lake and Medicine Lake, California is mentioned by Williams, Turner and Gilbert (1958, p.125), who state that "they signify mingling of dacitic magma with more basic material."

### 7. 9. TERRE BLANCHE DACITE DOME LAVAS

Lavas in this category include material from Terre Blanche and four smaller domes to the south and south-east. The rocks in hand specimen are usually of pinkish-grey or dull brick-red colour, and contain conspicuously large, shattered phenocrysts of quartz, together with reddish-coated mafic minerals amongst which pseudo-hexagonal prisms of hornblende and small, tabular crystals of biotite are recognisable.

The Terre Blanche dacites in many features resemble the older dacites (section 7.8.). Plagioclase phenocrysts form 35 - 40% of the rock, and most of these exhibit extensive oscillatory zoning. Quartz phenocrysts occupy up to 10%, red-brown hornblende 4%, and orthopyroxene up to 2% of a typical rock (e.g. L.244, Plate 26a). Clinopyroxene is present in a few samples (e.g. L.6), and some contain occasional phenocrysts of olivine rimmed by pyroxene (L.169, L.214, L.215, L.217, L.220). Mafic phenocrysts are coated with finely divided haematite, which

also occurs as separate, elongate crystals which are only slightly larger than the groundmass. The groundmass is distinctly finer than that of the Piton dacites, being cryptocrystalline to glassy rather than microcrystalline. It is also darker in colour. In their finer groundmass, the occurrence of basaltic hornblende, and their commonly red colour in hand specimen (due to finely divided haematite), the Terre Blanche rocks differ from the older dacites.

### Plagioclase

Plagioclase phenocrysts are euhedral to subhedral, and grade in size from 0.2 to 2 mm. Some are crowded with small inclusions of orthopyroxene and glass, which are either concentrated in broad zones (Plate 26a) or fill the entire crystal. As in the Piton dacites, the composition of unzoned plagioclase cores is extremely calcium-rich: the highest An-content recorded was 88% (L.244). Oscillatory zoning was recorded only in the range  $An_{66-44}$ , and was present in more than half of the total plagioclase phenocrysts, often extending from core to rim (Plate 26a).

### Quartz

Quartz forms the largest phenocrysts in the rock, measuring up to 7 mm. across. The shape of the crystals varies greatly. They are frequently completely globular, (Plate 26a), as in the Piton dacite, though occasional almost euhedral bipyramids occur. All are severely fractured.

### Hornblende

Rare, large phenocrysts of hornblende are up to 3 mm. across, are strongly altered to an aggregate of pyroxene and ore (the "pyroxenic" type of alteration of MacGregor), and contain small plagioclase inclusions. A second generation consists of rectangular microphenocrysts of bright reddish-brown hornblende up to 0.3 mm. across with a narrow rim of opaque ore, which are more common (Plate 26a). In L.244,  $Nz = 1.747$ ,  $Z_{Ac} = 6^\circ$ , and  $2Vx = 74^\circ$ . Pleochroism corresponds to the scheme: X = straw-yellow; Y = yellow-brown; Z = rich chestnut-brown. These are the usual properties of basaltic hornblende (Deer, Howie and Zussman, 1963, Vol.2, p.315).

MacGregor (1938, p.52) noted that on Montserrat "the red-brown hornblende occurs only in rocks that are reddened and oxidised", and that "the analysis reflects the oxidation, in the excess of ferric over ferrous iron". These comments apply equally well to rocks from St. Lucia, and the analysis of L.244 (Table 12), compared with other dacites, shows the much higher proportion of ferric to ferrous iron.

Kuno (1950, p.981) recorded basaltic hornblende (oxyhornblende) at Hakone volcano only in two sub-aerial dacite flows, whilst green hornblende occurs in submarine flows or intrusive masses. He stated that: "The same relation seems to hold more generally in the Cenozoic volcanic rocks of Japan", and concluded that: "It may be suggested, though not conclusively in the absence of more extensive information, that the formation

of oxyhornblende is favoured by the subaerial condition."

Barnes (1930) showed that on heating to 800°C common hornblende is transformed into oxyhornblende, the oxygen necessary for this change being provided by the mineral itself, as a result of liberation of hydrogen from hydroxyl ions in the green hornblende. Kuno (1950, p.981) found no evidence for reheating of the Japanese lavas containing basaltic hornblende, and therefore concluded that "the oxidation may be brought about during the normal cooling of lavas, if the mineral is kept at an appropriate temperature for some time, under a condition which facilitates the escape of volatiles." In St. Lucia, the presence of green hornblende in the Piton dacite, and oxyhornblende in the Terre Blanche lava, may be accounted for by the fact that the Piton material now exposed represents lava which cooled in the core of the dome, from which volatiles could not easily escape. The Terre Blanche dacite, on the other hand, would appear to represent material from the original surface of the dome.

#### Orthopyroxene

Orthopyroxene is present as an alteration product after hornblende, forming aggregates of minute granules intergrown with ore. In some specimens (e.g. L.244) it also occurs as euhedral, 0.1 - 0.2 mm. microphenocrysts, rimmed by haematite. Optical data and the inferred composition of the orthopyroxene in L.244 are shown in Table 11.

Biotite

Biotite occurs as subhedral, 2 mm. plates, pleochroic from deep greenish-brown (Z) to pale brown (X), and often growing adjacent to large resorbed hornblendes. Rims are often irregular, and small inclusions of ore are common.

Clinopyroxene

Clinopyroxene is present as rare crystals in a few sections only (L.6, L.169, L.215), where it occurs as subhedral, lamellar-twinned crystals up to 2 mm. long.

Olivine

Olivine occurs (e.g. in L.169) as rare phenocrysts up to 2 mm. across, rimmed by small, elongate crystals of oxyhornblende, orthopyroxene and ore.

Olivine phenocrysts in metamorphosed picrite basalt lava from Hawaii, which show similar coronas of magnetite intergrown with hypersthene, have been described by Muir, Tilley and Scoon (1957, p.247 and Plate 1, Fig.4), who conclude (op. cit., p.251) that: "The strong development of magnetite associated with the olivine is a result of oxidation processes probably in the presence of water vapour." It is obvious that the Terre Blanche dacites have crystallized in an environment of this kind.

7. 10. BELFOND DACITE DOME LAVAS

Lavas included in this group (L.267, L.87) form the five small domes between Belfond and Étangs. The rocks are almost white, vesicular, and characterized by occasional large

crystals and innumerable small, black flecks of amphibole.

Under the microscope (L.267, Plate 27a), large phenocrysts are seen to consist of plagioclase (about 30% of the whole rock), quartz (15%), amphibole (6%) and biotite (1%), in a groundmass composed mainly of pale, vesicular glass showing a slightly perlitic texture.

### Plagioclase

Plagioclase phenocrysts are euhedral and up to 2 mm. across. Many are oscillatory-zoned, and some contain narrow zones rich in minute, glassy inclusions. The plagioclase of the Belfond dacites differs notably from that of the other dacite types in that many crystals are of almost unzoned labradorite, and oscillatory zoning, when present, seldom covers a compositional range of more than 5%. The cores of a few plagioclase phenocrysts, however, are in the bytownite range, with a maximum An% of 36, i.e. similar to those in the Piton and Terre Blanche dacites.

### Quartz

Quartz phenocrysts are up to 5 mm. across, i.e. of similar size to those in the earlier dacites. They differ, however, in that almost euhedral bipyramids are more common, and globular crystals relatively rare. Yet the margins are often minutely embayed, indicating mild resorption.

### Amphibole

Two generations of very pale green amphibole are

present: euhedral prisms of up to 10 mm. in length form the most conspicuous phenocrysts in the rock. They are poikilitic towards small plagioclase, magnetite and biotite crystals. Occasional phenocrysts are zoned, with inner deep green and outer very pale-coloured portions, e.g. L.267, Plate 27b. The second generation forms smaller, 0.2 - 1.0 mm. laths, which are rarely poikilitic. It was realised at an early stage that the pleochroic colours of the amphiboles were extremely pale, either for common hornblende or for oxyhornblende, and when the optical properties (Table 11, L.267 and L.87), failed to correspond to any member of the common hornblende group, a partial chemical analysis was made (Table 12, L.267 Hb) on carefully separated crystals. This revealed that the principal metallic cations were iron and magnesium alone, whose atomic ratio corresponded to that appropriate to the known optical properties of an iron-rich cummingtonite (Deer, Howie and Zussman, 1962, vol.II, p.242).

Cummingtonite has been reported as a rare constituent of intrusive dacites from Hakone volcano and other localities in Japan, where it was first recorded by Kuno (1938) who quoted optical properties of  $2V_x = 88-86^\circ$ ,  $2\Delta_c = 16^\circ$ ,  $N_y = 1.649$ , and an inferred atomic ratio of approximately  $Mg_{60}Fe_{40}$ . Kuno stated that the Japanese cummingtonite is often surrounded by common green hornblende, and concluded (1938, p.224) that: "the cummingtonitic hornblende is a product of primary crystallization from magma. The mineral, upon reaction with the magma, may have been successively made over to the common green hornblende".

This relationship is the converse of that seen in the St. Lucian dacite (Plate 27b), in which the calcium-poor amphibole surrounds and is therefore assumed to have crystallized after green hornblende. This suggests, in the Japanese example, an increase in the quantity of available calcium in the liquid fraction with progressive crystallization, whilst in St. Lucia the residual liquid appears to have become impoverished in calcium, probably due to growth of calcic plagioclase, at an early stage in the crystallization history of the amphibole. The latter hypothesis is supported by the fact that abundant prisms of plagioclase are poikilitically enclosed by the amphibole in the St. Lucian specimen. All evidence suggests that the cummingtonite in the Belford dacite, as in the Japanese rocks, is the product of magmatic crystallization.

#### Biotite

Biotite occurs as subhedral, 1 mm. plates, pleochroic from pale to deep walnut brown. It is poikilitic towards small plagioclase and opaque oxide crystals.

#### Orthopyroxene

Rare crystals of orthopyroxene, usually forming subhedral, rectangular prisms, are up to 1.5 mm. long and poikilitic towards small plagioclases.

#### Minor accessories

Opaque magnetic ore occurs as evenly dispersed, 0.03 mm. grains in the groundmass, and as inclusions in biotite.

## 7. 11. BELFOND DACITE PUMICE

Dacite pumice blocks from glowing avalanche deposits are of an almost white, vesicular rock containing large quartz phenocrysts, together with plagioclase which is more abundant, although smaller and less conspicuous. The ferromagnesian phenocrysts include biotite, and occasional pseudo-hexagonal prisms of amphibole which contain small white flecks of felsepar. Many of the dark minerals are conspicuously disrupted, the separated fragments often being streaked out into small schlieren.

In thin section, the phenocrysts are seen to possess a protoclastic texture, which is made especially evident by broken fragments of oscillatory-zoned plagioclase. The modal composition of specimen L.707 is given in Table 10. Phenocrysts form a notably lower proportion of this rock than of the related Belfond dome lavas.

### Plagioclase

The majority of plagioclase crystals are broken fragments, of less than 1 mm. in size. Some are "granulated", consisting of hundreds of minute, completely shattered yet adjacent, angular fragments which have slightly different extinction positions. Oscillatory zoning in the range  $An_{66-50}$  is common. In one crystal in L.707 an unzoned core composition of  $An_{34}$  was recorded, though no others in the slide were more calcic than  $An_{66}$ .

Quartz

Quartz phenocrysts are often euhedral and some, showing clear bipyramidal shape, are 2 - 3 mm. across. Others have been disrupted, like the plagioclase, into small, adjacent fragments.

Biotite

Biotite phenocrysts occur as subhedral plates up to 2 mm. across, and are pleochroic from pale to dark walnut brown. They are poikilitic to small plagioclases and to minute, hexagonal grains of magnetite. Some crystals are slightly contorted.

Orthopyroxene

Orthopyroxene forms 0.5 mm. crystals, which are poikilitic towards very small grains of opaque oxide. The optical measurements and inferred composition are given in Table 11.

Amphibole

The amphibole in the pumice blocks differs notably from that in the Belfond dome lavas. Crystals in the pumice are pleochroic according to the scheme: X = pale yellowish green; Y = yellowish brown; Z = deep brownish red. The extinction angle  $Z\wedge c$  is notably low (see Table 11). It seems likely that this amphibole, probably an oxyhornblende, was produced by oxidation of the cummingtonite present in the Belfond dome lavas. Kuno (1938, p.224) stated that "it is possible....that some of the oxyhornblende, so common in volcanic rocks, may have been derived from such (pyrogenetic cummingtonitic) hornblende through

oxidation." Kuno (loc. cit.) was able to produce oxyhornblende by heating the cummingtonite to 750°C for 10 hours, and it seems possible that this temperature would be attained, in an oxidising environment, in the pumice blocks caught up in a glowing avalanche.

#### 7. 12. TONALITE, GABBRO AND DOLERITE XENOLITHS

Coarse and medium-grained holocrystalline rocks, found in the Soufrière region, occur principally as inclusions in dacite and pale andesite lava. About 40 specimens of this type were collected. They have been divided into three categories, according to grain-size and mineralogy.

- 1) Coarse or medium - grained, quartz > 10% = TONALITES or MICROTONALITES.
- 2) Coarse-grained, equigranular, quartz absent or rare = GABBROS
- 3) Medium-grained, inequigranular, hornblende-rich = DOLERITES.

No very coarse-grained blocks containing anorthite, of the type present on St. Vincent (Flett, 1908, pp.317-20; Wager, 1962, pp.93-6) and on St. Kitts (Baker, 1963, pp.139-50), were found in the Soufrière region of St. Lucia.

#### Tonalites and microtonalites

Tonalite xenoliths occur as ovoid bodies, up to 1 ft. across, in Piton dacite lava. They are generally paler in colour than the enclosing lava, and equigranular plagioclase, quartz and ferromagnesian crystals, all approximately 2 mm. across, are recognisable in hand specimen. These crystals are not firmly cemented, and tend to crumble away from the surface when handled.

Table 10 MODAL COMPOSITION OF DACITES, TONALITE AND DOLERITE

Specimen L	244	329	13	267	67	707	313	717
Plagioclase	37.8	35.4	38.2	30.5	33.0	15.6	62.1	68.1
Quartz	9.0	7.8	9.6	13.0	16.5	5.5	19.5	2.1
Amphibole	4.1	0.6	0.1	5.9	5.6	0.2	-	21.3
Biotite	1.3	2.8	0.1	1.3	0.3	2.1	11.6	-
Orthopyroxene	1.6	1.2	4.3	0.3	0.2	1.1	3.8	6.9
Clinopyroxene	-	2.1	-	-	-	-	-	1.2
Olivine	tr.	0.2	-	-	-	-	-	0.1
Ore	0.7	-	0.5	0.5	0.2	-	3.0	0.3
TOTAL PHENOCRYSTS	54.5	50.1	52.8	51.5	55.8	24.5	holocrystalline	
GROUNDMASS	45.5	49.9	47.2	48.5	44.2	75.5	0	0

For rock names and localities, see Table 13.

Table 11 MINERALOGICAL DATA FOR DACITES, TONALITE AND DOLERITE

Specimen L	244	329	13	267	87	707	313	717	
<u>Plagioclase An%</u>									
maximum core composition	88	84	86	74	85	84	79	90	
est. average composition	70	66	61	57	63	57	57	68	
<u>Amphibole</u>									
	oxyhorn -blende	common hornblende		cummingtonite		oxyhorn -blende	-	common hornblende + cumming- tonite	
pleochroism: Z	red- brown	pale brownish -green		pale brownish -green		red- brown	-	pale brown -green	
Nz	1.747	1.675	n.d.	1.688	1.688	n.d.	-	1.686	
Z <sub>∞</sub> (degrees)	6	9½	n.d.	16½	15½	5	-	14 (core)	
2V <sub>x</sub> (degrees)	74	n.d.	n.d.	91-93	92	n.d.	-	84-72 (core)	
<u>Biotite pleochroism</u>									
X =	pale greenish -brown	(————— pale brown —————)							
Z =	deep greenish -brown	(————— deep walnut brown —————)					chest- nut brown	-	
<u>Orthopyroxene</u>									
2V <sub>x</sub> (degrees)	55	53	n.d.	62	n.d.	57-62	57	n.d.	
Nz	1.733	1.730	1.739	n.d.	1.741	1.739	1.739	1.706	
En%	45	47	40	n.d.	38	40	40	67	
<u>Clinopyroxene</u>									
2V <sub>z</sub> (degrees)	-	n.d.	-	-	-	-	-	57	
<u>Olivine</u>									
Nz	n.d.	1.704	-	-	-	-	-	n.d.	
For%	n.d.	84	-	-	-	-	-	n.d.	

The modal composition of a representative sample (L.313, Plate 28a) is given in Table 10. Plagioclase crystals are subhedral, and many have broad oscillatory zones ranging in composition from approximately An<sub>70-40</sub>. Larger crystals often have an unzoned core, usually occupying a third to a half of the area of the crystal, and showing blotchy extinction which appears to be the result of intergrowth of plagioclase of two compositions, e.g. An<sub>78</sub> and An<sub>47</sub> in one crystal in L.313. This texture is similar to that described in the Piton dacite (section 7.8.). Quartz occurs as anhedral, 2 mm. crystals which are interstitial and poikilitic towards plagioclase, and display shadowy extinction. Biotite is pleochroic from pale to chestnut brown, and forms anhedral, 2 mm. crystals which are poikilitic towards abundant, small plagioclases, and are crowded with small inclusions of opaque oxide, which commonly form narrow strands elongated parallel to the 001 cleavage plane. Orthopyroxene forms anhedral, 0.5 mm. crystals which in L.313 appear to have grown around the margins of biotite. In L.147, hornblende seems to have been completely replaced by cloudy aggregates of orthopyroxene and small, chestnut-brown biotites. The cores of some of these patches consist of fresh-looking 1.5 mm. crystals of orthopyroxene which are probably primary, and are poikilitic towards small plagioclases. Accessory minerals include apatite, and secondary haematite which occupies cracks in quartz crystals.

The crystallization sequence appears to have been (1) plagioclase, (2) orthopyroxene, (3) hornblende, altering to biotite and orthopyroxene, (4) quartz, (5) haematite + apatite.

These rocks are chemically identical to the enclosing dacite lava (c.f. Table 12, analyses 15 and 16): they are therefore regarded as plutonically crystallized equivalents of the Piton dacite, i.e. cognate xenoliths.

A number of similar rocks from Mt. Pelée in Martinique has been described by Lacroix (1904, p.544) in his category of "enclaves homologues allomorphes". The St. Lucian specimens correspond most closely to two rocks described by Lacroix as "norites quartzifères", characterized by a coarsely crystalline texture and the abundance of quartz and biotite. He describes a gradation from these rocks to cordierite-bearing micronorites, which he believes to have formed near the surface, being "probablement le résultat d'une cristallisation effectuée dans des parties très profondes du dôme".

A similar gradation to finer-grained, holocrystalline rocks is seen in specimens from St. Lucia, and blocks of this type are found in the Younger andesite pumice flows, especially at a horizon near the base of the thicker, upper unit, exposed to the east and north of Choiseul. These blocks contain abundant, equigranular quartz crystals (e.g. L.590, Plate 30a and Table 8), and for this reason the name microtonalite seems preferable to micronorite. Specimen L.590 has a seriate texture, with equidimensional, unorientated grains ranging in size from 2 to 0.1 mm. The equigranular, almost hornfelsic texture of some these rocks, appears to have developed as a result of mechanical deformation in a semi-solid state (i.e. protoclasia), and some

specimens, e.g. L.598, show a structure resembling strain-slip cleavage.

Plagioclase occurs as subhedral crystals up to 2 mm. across, and a large proportion show extensive oscillatory zoning and closely resemble phenocrysts in the andesites and dacites. Quartz forms anhedral grains which are rarely larger than 0.2 mm. in diameter and interstitial to the larger plagioclases. Brownish-green amphibole is the predominant ferromagnesian mineral and forms ragged, 2 mm. crystals which are strongly poikilitic towards oscillatory-zoned plagioclase and enclose or partly enclose dark, walnut-brown biotites, especially near their margins. Occasional, large aggregates consist of hornblende in small, sub-parallel prisms intergrown with skeletal, optically continuous shreds of orthopyroxene. In one aggregate, clinopyroxene in optical continuity was also identified. Clinopyroxene and orthopyroxene also occur as independent, anhedral grains of 0.1 mm. across, with which opaque oxide is sometimes associated.

The zoning and size of plagioclase crystals, which are similar to those in the normal andesites, suggests that the microtonalites are closely related to the more acid andesite lavas. The similarity in chemical composition between L.590 and, for example, the pale andesite dome lava L.5 (see Table 12), supports this hypothesis.

## Gabbros

The rocks included in this category are texturally similar to the tonalites, being hypidiomorphic-granular with an average grain size of 2 mm. They differ, however, in that quartz crystals are absent or rare. Although no chemical analysis was made, it is evident that the gabbros are less rich in silica than the tonalites and the enclosing dacite lava. In thin section, the rocks contain approximately 70% plagioclase, and varying proportions of hornblende, orthopyroxene, biotite and clinopyroxene.

Plagioclase occurs as subhedral crystals with an average size of 2 mm., and often shows irregularly extinguishing patches which extend across the entire crystal. These result from the intergrowth of material of two different compositions, e.g.  $An_{81}$  and  $An_{63}$  in L.430, and resemble textures described in the Piton dacite (section 7.8.). Oscillatory zoning is distinctly rare, although the outer parts of most crystals are normal-discontinuously zoned. Slightly elongate prisms show sub-parallel orientation in L.721 and L.427, emphasized by well-developed, polysynthetic albite twinning. In L.310, extensive pericline twinning on a fine scale is also common.

Biotite is less abundant than in the tonalites: the ferromagnesian mineral which originally predominated in the gabbros was undoubtedly green hornblende, which in some specimens (L.304) has altered only marginally to finely granular pyroxene and ore, and poikilitically encloses small flakes of chestnut-

brown biotite, whilst in other samples (L.310) it is almost entirely converted to fine-grained aggregates of these alteration minerals. The "black" type of alteration of hornblende (see section 7.8.) is common in L.721.

These rocks are coarse-grained and therefore crystallised slowly, yet contain little or no quartz. If co-magmatic with the Piton dacite, they must represent crystal accumulates.

Lacroix (1904, p.541) refers to moderately coarse-grained, quartz-free rocks containing essential plagioclase and hypersthene, with accessory hornblende and augite. The last two minerals are more important in one specimen, which he terms an amphibole-bearing gabbro. Lacroix states that the plagioclases are always basic (bytownite to labradorite) but, however, with little or no zoning.

#### Hornblende dolerites

These rocks are the most common type of inclusion in the dacite and pale andesite lavas, in which they occur as ovoid bodies up to 2 ft. in diameter. They are conspicuous on account of their colour, which is darker than that of the enclosing lava. In hand specimen they create the illusion of being finer-grained than the lava due to the greater rarity of crystals more than 2 mm. across. They consist principally of plagioclase and elongate, deep-green prisms of amphibole with occasional, spherical xenocrysts of quartz, which are up to 4 mm. across, and have coronas of dark minerals. The rock contains numerous, small, irregular cavities up to 5 mm. across.

into which acicular, deep-green amphibole crystals project.

The estimated modal composition of a typical specimen, L.717 (Plate 28b) is given in Table 10. The rocks are characterized by an inequigranular, mesh or pseudo-lamprophyric texture, in which the largest crystals are about 2 mm. across and grade downward in seriate fashion to a "groundmass" of 0.2 - 0.4 mm. crystals which make up about 50% of the rock.

Two generations of plagioclase appear to be present. The larger crystals of 1 - 2 mm. are equidimensional and often euhedral. They have cores, occupying approximately a half of the area of a crystal, composed of  $An_{90}$  max., containing abundant inclusions of glass and orthopyroxene, often as narrow patches elongated parallel to crystallographic directions (Plate 29). The outer parts of these crystals are strongly zoned, including slight oscillatory zoning, down to  $An_{23}$ . The second generation of plagioclase consists of smaller, lath-shaped crystals up to 0.5 mm. long, which rarely contain glass inclusions, and are normal-continuously zoned from  $An_{86}$  max. to  $An_{27}$  min.\*

Hornblende crystals are subhedral, elongate, and vary in length from 2 to 0.2 mm. They are pleochroic from X = pale yellow, Y = khaki, to Z = brownish-green. The larger crystals are zoned, with cores which show paler pleochroism and larger extinction angles (see Table 11) and may be cummingtonitic. Orthopyroxene occurs mainly as independent crystals similar in

size and shape to the hornblende. Specimen L.717 also contains numerous, interstitial patches of cristobalite.

Inclusions of a closely similar type seem to be common in andesite and dacite lavas throughout the world: examples from Martinique have been described by Lacroix (1904, pp.538-40), in whose classification they belong to the enclaves homoeogènes, groupe plésiomorphe, types antilogues. The rock is named a "diabase à facies lamprophyrique". Lacroix noted that the constituent minerals were identical to phenocrysts in the enclosing lava, and from this concluded that they had crystallized in the same magma at depth. He believed, on the other hand, that the entire rock had not consolidated at depth, since there was no evidence of thermal alteration: "elles n'ont pas constitué des masses consolidées en profondeur, car elles n'offrent aucune modification calorifique." In this connexion, the ovoid shape of the inclusions in St. Lucian dacite may be cited as additional evidence that the inclusions were probably plastic at the time of being carried to the surface.

Lamprophyric inclusions in the dacite of Lassen Peak, California, have been described by Williams, who points out (1932, p.312): "That the inclusions represent early crystallizations from the magma is suggested at once by the fact that they never contain biotite or acid plagioclase, being composed rather of the earlier members of the reaction series." In the absence of biotite, the St. Lucian inclusions resemble those from Lassen Peak. In the latter, however, the pyroxene is

commonly pale green augite and inclusions rich in hypersthene are absent, whereas in St. Lucia hypersthene is notably more abundant. Williams, Turner and Gilbert (1958, p.125) explain these rocks as "fragments torn from the walls of the feeding conduits and from the roofs of the underlying reservoirs." Similar inclusions have been described by Brouwer (1921, pp. 37-46) in the Galunggung and Kuang domes in the East Indies.

### 7. 13. PROBABLE METASEDIMENTS

A few rocks were found in the Soufrière region, as blocks in the Younger andesite pumice flows (e.g. L.572, L.700), and as xenoliths in the Piton dacite (L.724), which appear to be metamorphosed sediments. They are strikingly inhomogeneous in hand specimen, consisting of sharply defined, angular patches of very pale grey and almost black material, all of which is extremely fine-grained. In some specimens (e.g. L.700), the pale portion predominates, and encloses small fragments of dark material which appears to have been streaked out like schlieren. In other samples (e.g. L.572, Plate 11b) the dark material is more abundant, and occurs as angular, disrupted fragments, the whole rock being transected by a network of veins, up to 5 mm. wide, composed of coarsely granular quartz.

The light patches in these rocks (e.g. L.572, Plate 30b) are composed almost wholly of quartz, which is extremely fine-grained, with an average size of 0.05 mm. This material is crossed by occasional veinlets 0.5 mm. across of coarser quartz, of which single crystals often occupy the full width of

the veinlet. The patches rich in dark minerals are composed principally of greenish-brown biotite and plagioclase in approximately equal proportions, both of 0.05 mm. average grain size, i.e. similar to the quartzitic part of the rock. These are accompanied by large, shadowy crystals of cordierite up to 1 mm. across which poikilitically enclose large numbers of plagioclase and biotite grains. Characteristic interpenetration twine were observed in one cordierite crystal. Accessory minerals include subhedral grains of opaque ore, sometimes rimmed by haematite, and occasional clusters of apatite in hexagonal prisms.

The quartz-rich inclusion in Gros Piton dacite (L.724) is a homogeneous rock, similar in grain size and texture to the pale portion of L.700, and contains approximately 50% of quartz as 0.05 mm. grains, some of which are poikilitically enclosed by plagioclase and possibly some cordierite. The plagioclase is full of minute dust inclusions, and occupies 35 - 40% of the rock. About 10% of hypersthene is present, as fresh-looking, anhedral grains 0.5 mm. across, which poikilitically enclose grains of quartz and opaque oxide.

The origin of this group of rocks is uncertain.

Their fine grain size and high content of quartz suggest that they were probably once sedimentary material, and an origin of this kind could also account for their remarkable inhomogeneity in hand specimen. The presence of brecciation and veining indicates mechanical deformation, probably at depth, whilst the

occurrence of cordierite, and plagioclase which is poikilitic to quartz, indicate considerable reconstitution of the rock, probably by metamorphism of a relatively high grade. These rocks may therefore represent fragments of a silica-rich, meta-sedimentary formation which exists at depth beneath the Soufrière region.

PLATE 18.

a) Photomicrograph of aphyric basalt L.153. The rock has an intergranular texture, containing sub-parallel laths of plagioclase, with interstitial clinopyroxene and opaque magnetic oxide. In the lower part of the photograph, the groundmass is crossed by a veinlet of calcite, and contains a single phenocryst of plagioclase.

( x 25, crossed polarizers.)

b) Photomicrograph of aphyric basalt L.34. The specimen is slightly coarser-grained than L.153 (above), and without conspicuous orientation of the plagioclase. It contains notably larger crystals of opaque oxide, and anhedral quartz crystals in a discontinuous veinlet.

( x 25, crossed polarizers.)

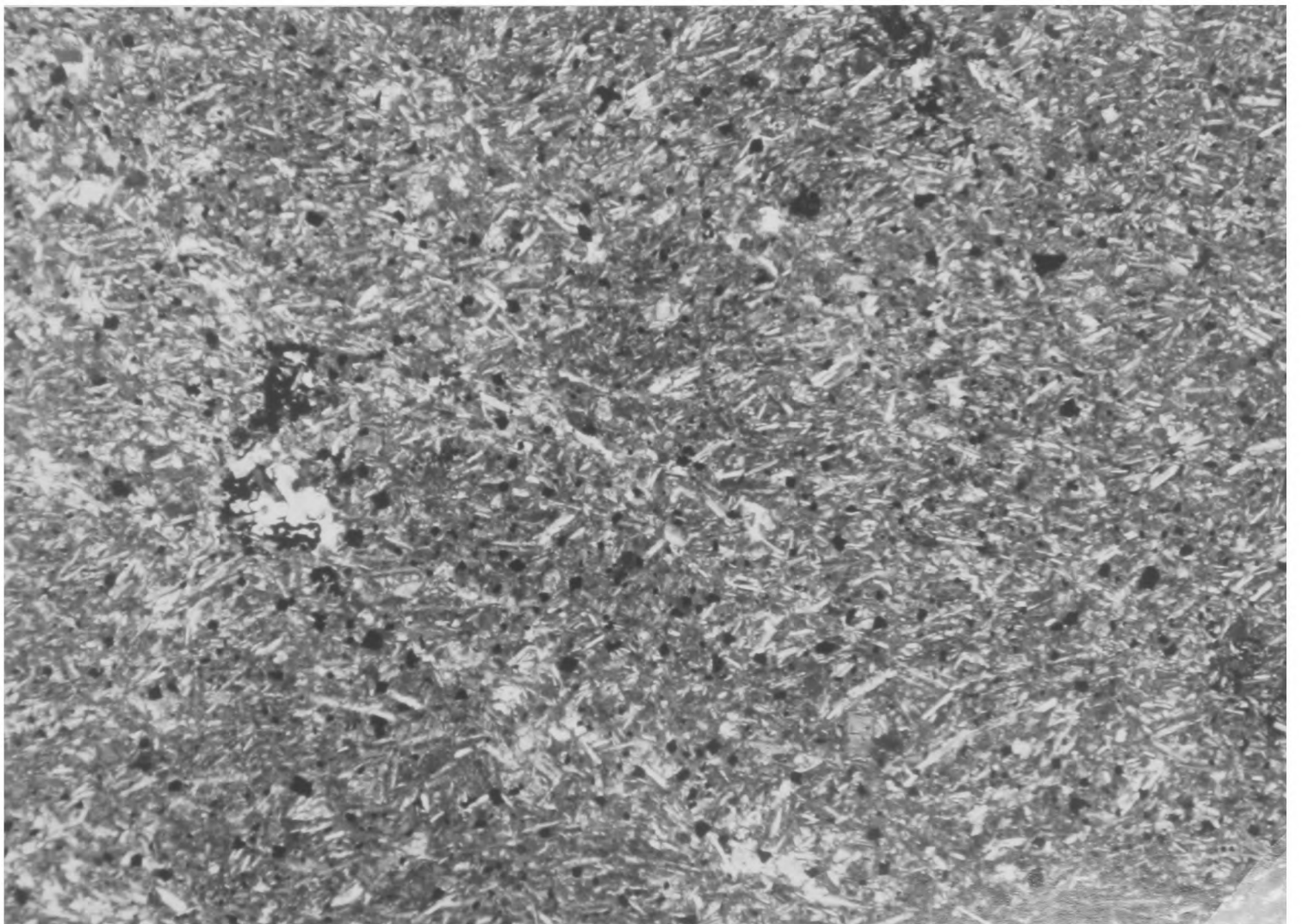
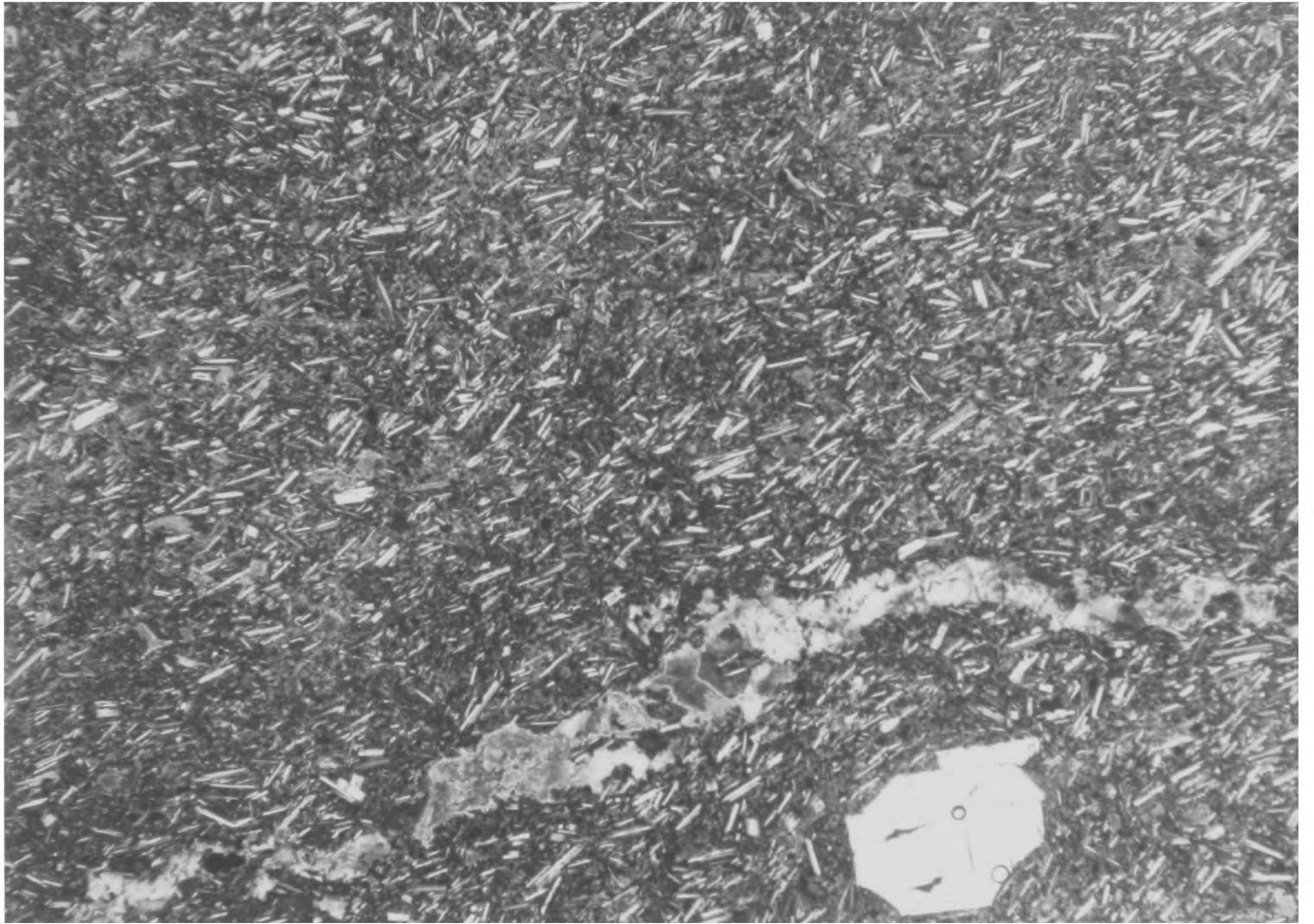


PLATE 19.

a) Photomicrograph of plagioclase-pyroxene-olivine-phyric basalt, L.83. The phenocrysts are set in a dark, glassy groundmass. The large olivine crystal is strongly serpentinized along cracks and margins. Clinopyroxene forms cusulophyric clusters towards the upper right.  
( x 25, crossed polarizers.)

b) Photomicrograph of plagioclase-phyric basalt, L.251. The largest phenocrysts are stout prisms, which grade into elongate microphenocrysts. As in L.83 (above), oscillatory zoning is virtually absent. In the intergranular groundmass, plagioclase is accompanied by clinopyroxene and opaque oxide.  
( x 25, crossed polarizers.)

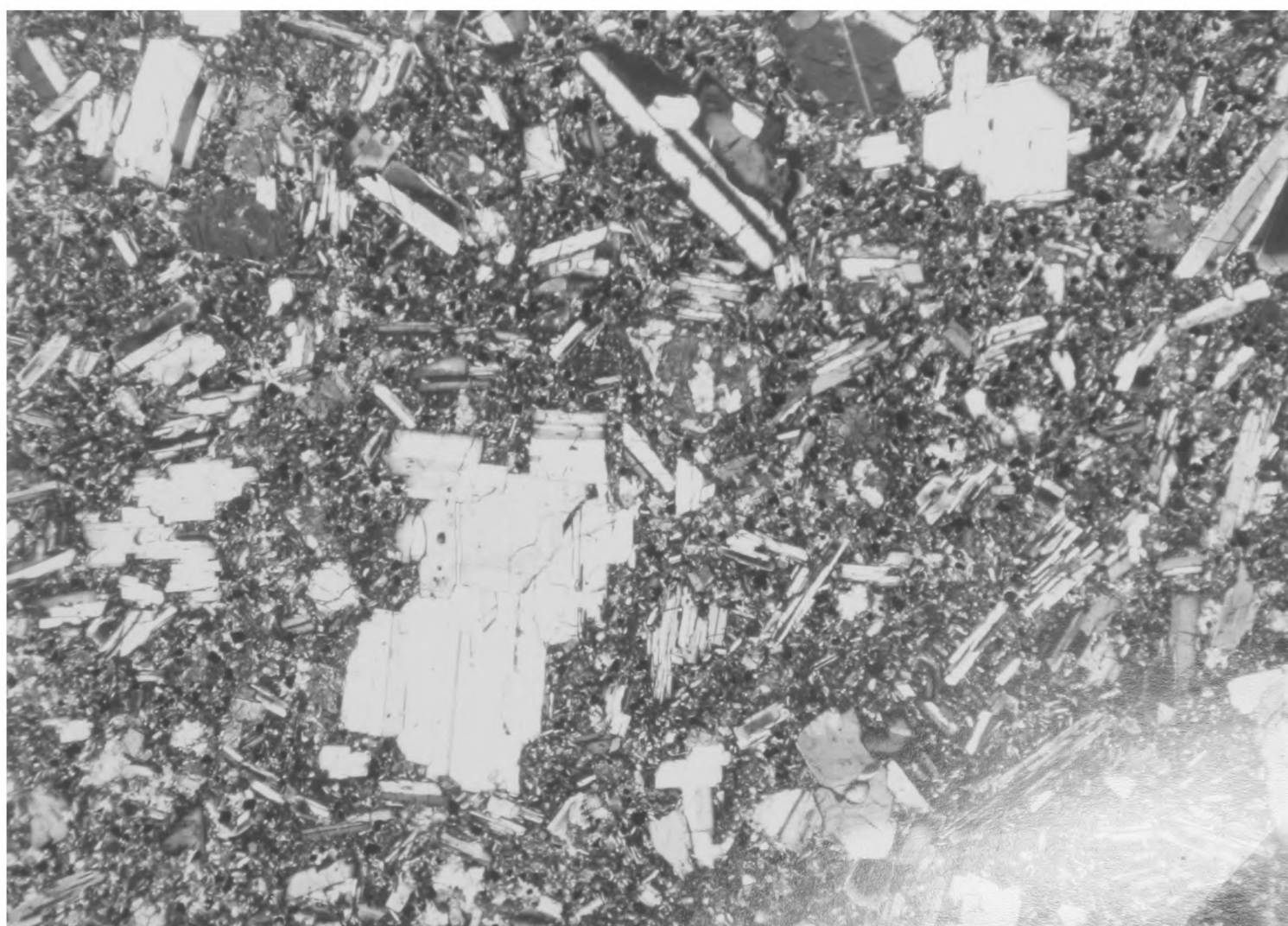
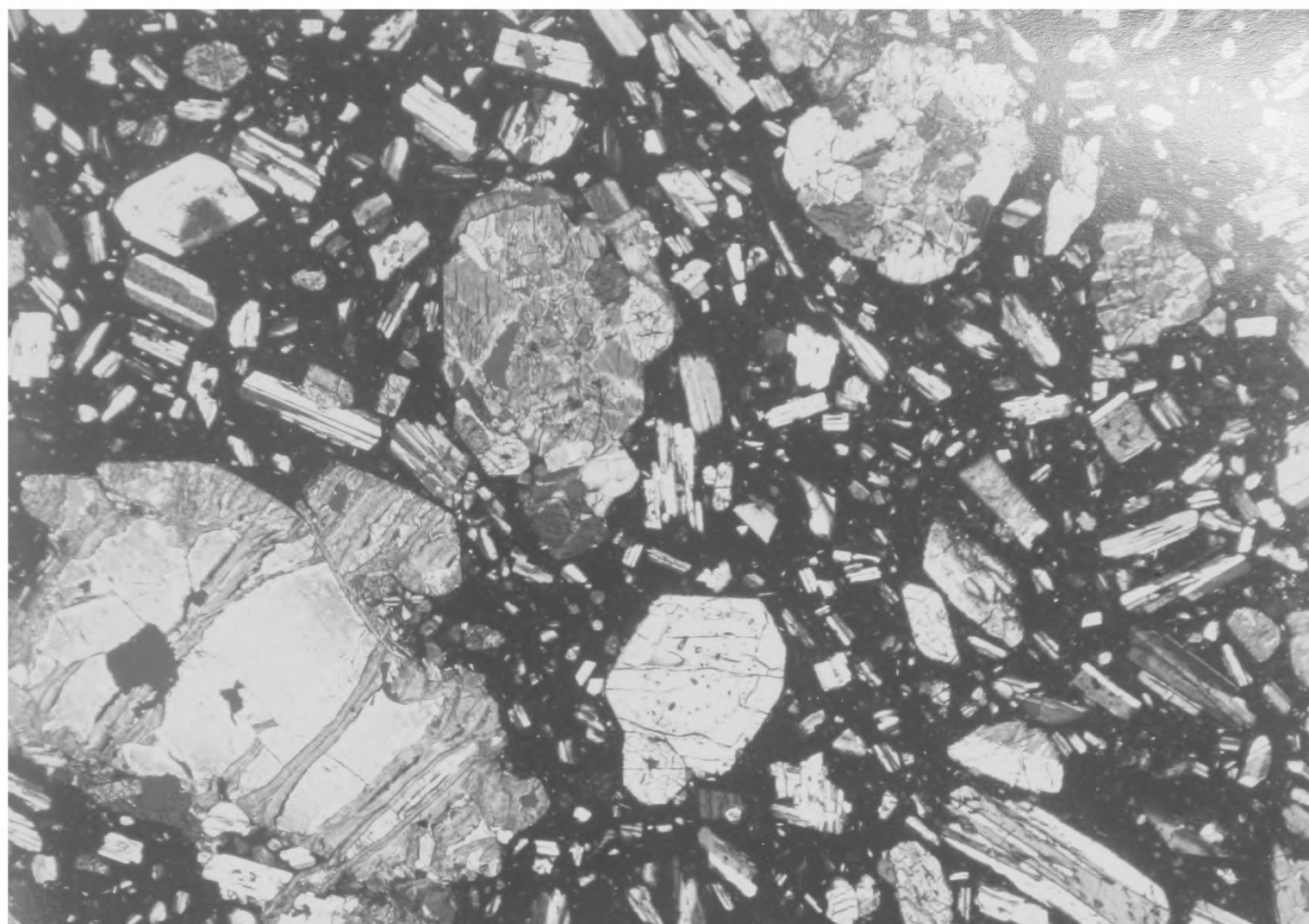


PLATE 20.

a) Photomicrograph of dark andesite, L.38. Phenocrysts of plagioclase are cloudy, with alteration concentrated along cracks. The larger inclusions in plagioclase are of pale brown glass, and marked oscillatory zoning extends from the core to the rim of several crystals. A phenocryst of orthopyroxene, in extinction, lies near the centre of the photograph. The groundmass is cryptofelsitic.

( x 25, crossed polarizers. )

b) Photomicrograph of pale andesite, L.5. Abundant phenocrysts, composed of oscillatory-zoned, fresh plagioclase, orthopyroxene with inclusions of black ore, and a single, shattered crystal of quartz in the top right, are set in a microfelsitic groundmass.

( x 25, crossed polarizers. )

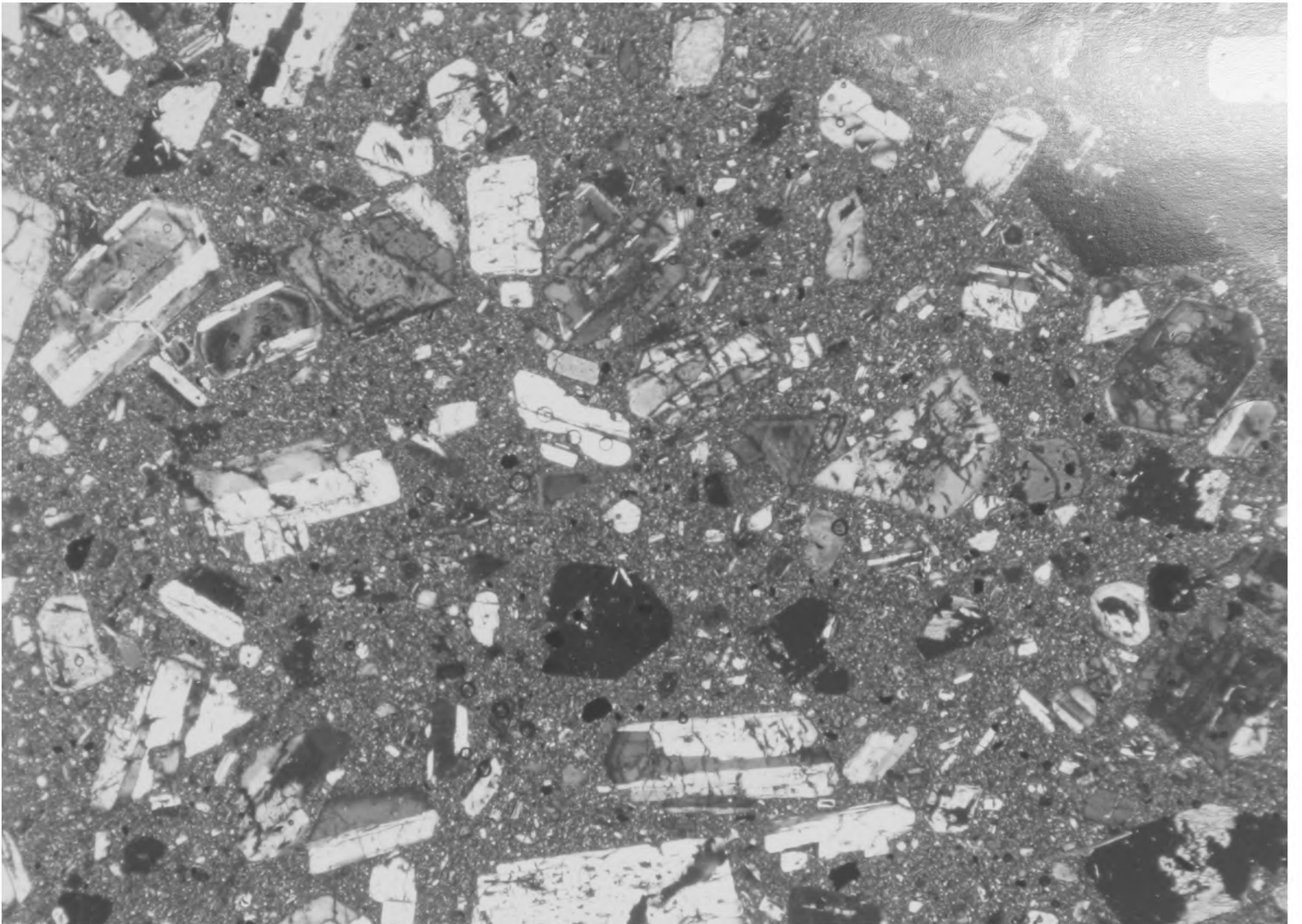


PLATE 21.

a) Photomicrograph of oscillatory-zoned plagioclase phenocryst in pale andesite dome-lava (L.5). The crystal has an unzoned core of  $An_{78}$ , containing abundant, small inclusions, surrounded by about 40 oscillatory zones ranging in composition from  $An_{65max}$ . adjacent to the core, to  $An_{55min}$ . at the rim. Three narrow, inclusion-rich zones are present within the oscillatory-zoned portion of the crystal.

( x 50, crossed polarizers. )

b) Photomicrograph of plagioclase phenocryst in dark andesite lava block, L.203, from the Caldera-wall agglomerate-tuff. The core of the phenocryst is on the left, and contains minute crystalline inclusions, probably of pyroxene. An incomplete, glassy zone (black in the photograph) surrounds the core, and has a sharp boundary with the outer part of the crystal. Abundant small, glassy and crystalline inclusions lie near the outer rim of the crystal (to the right of the photograph).

( x 500, crossed polarizers. )

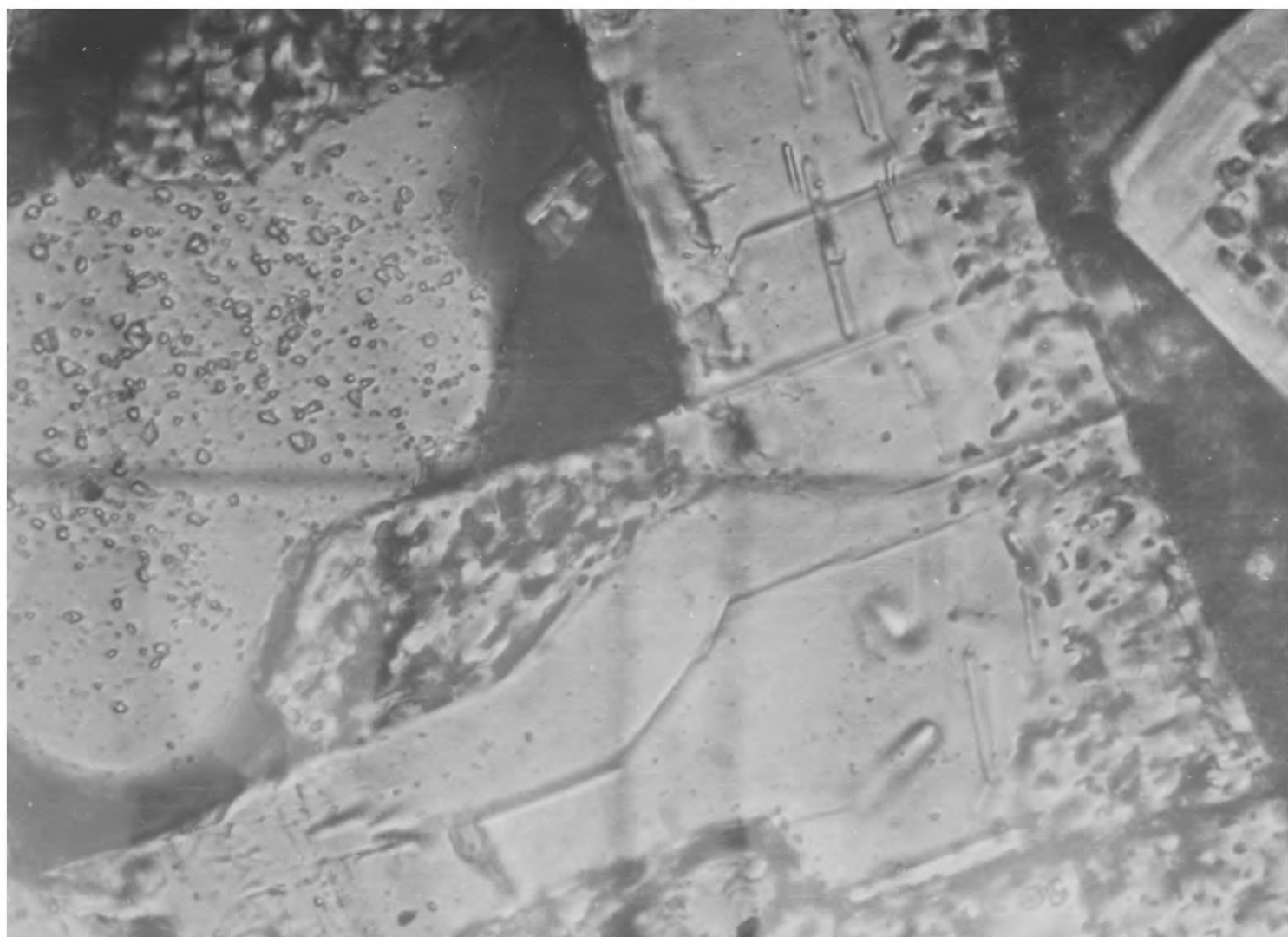


PLATE 22.

a) Photomicrograph of matrix of Caldera-wall andesite agglomerate-tuff, L.193. Conspicuous angular fragments of quartz, euhedral or broken crystals of oscillatory-zoned plagioclase, with subordinate orthopyroxene and green hornblende, are set in a matrix of finely comminuted glass and cryptocrystalline material.  
( x 25, crossed polarizers. )

b) Photomicrograph of andesite lava block L.258 from the Vulcanian agglomerate. Protoclastic phenocrysts of oscillatory-zoned plagioclase, rounded quartz crystals, orthopyroxene, and green hornblende (in the lower left corner), are set in a glassy groundmass.  
( x 25, crossed polarizers. )

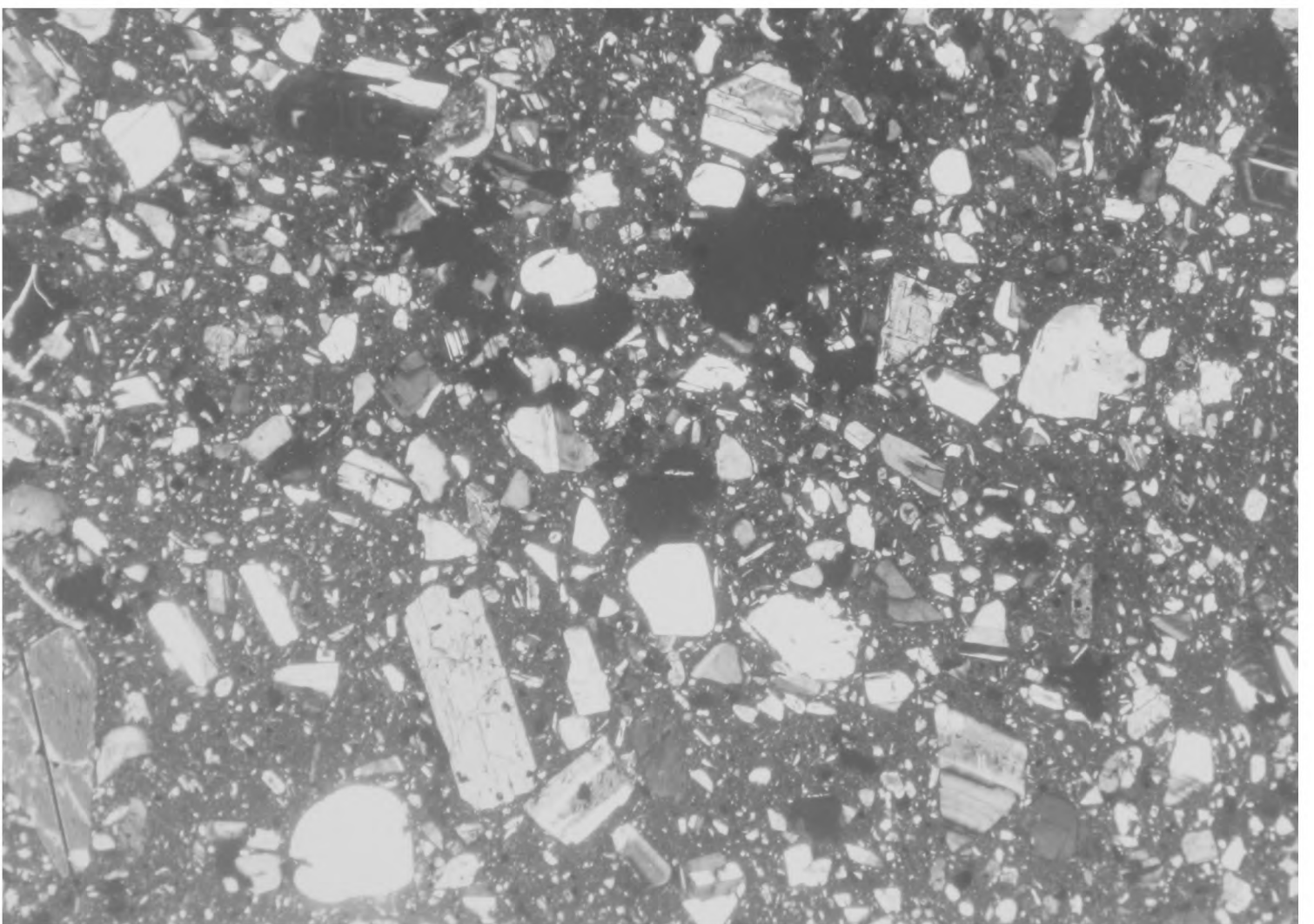
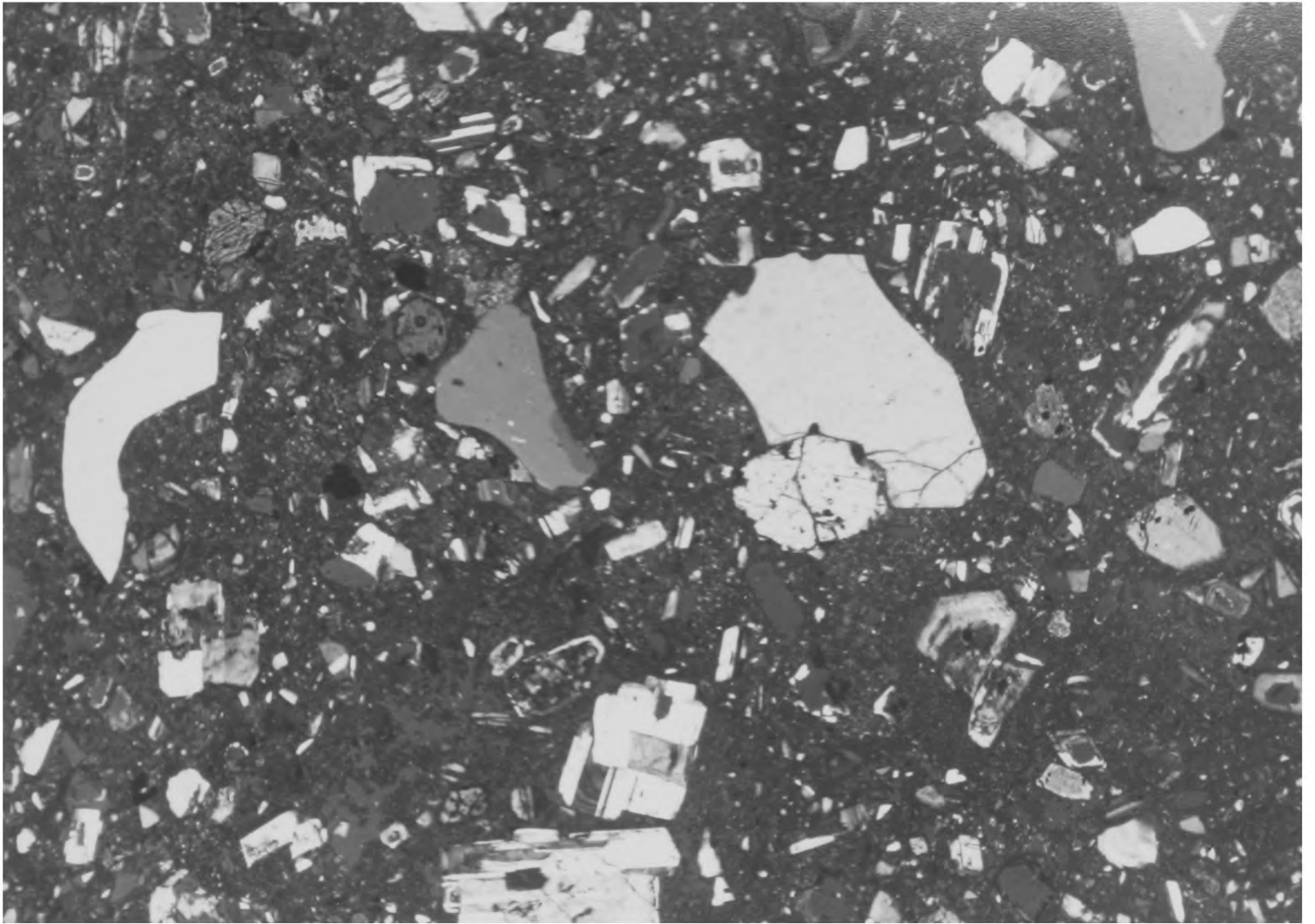


PLATE 23.

a) Photomicrograph of Younger andesite pumice block L.476. Phenocrysts of oscillatory-zoned plagioclase (centre), embayed quartz (upper left), and orthopyroxene with opaque oxide inclusions (lower right), lie in a glassy, vesicular groundmass.

( x 25, crossed polarizers. )

b) Photomicrograph of glassy groundmass of the Younger andesite pumice block L.476. The groundmass is of almost colourless, vesicular glass, which is slightly perlitic and contains finely-divided, opaque oxide.

( x 100, ordinary light. )

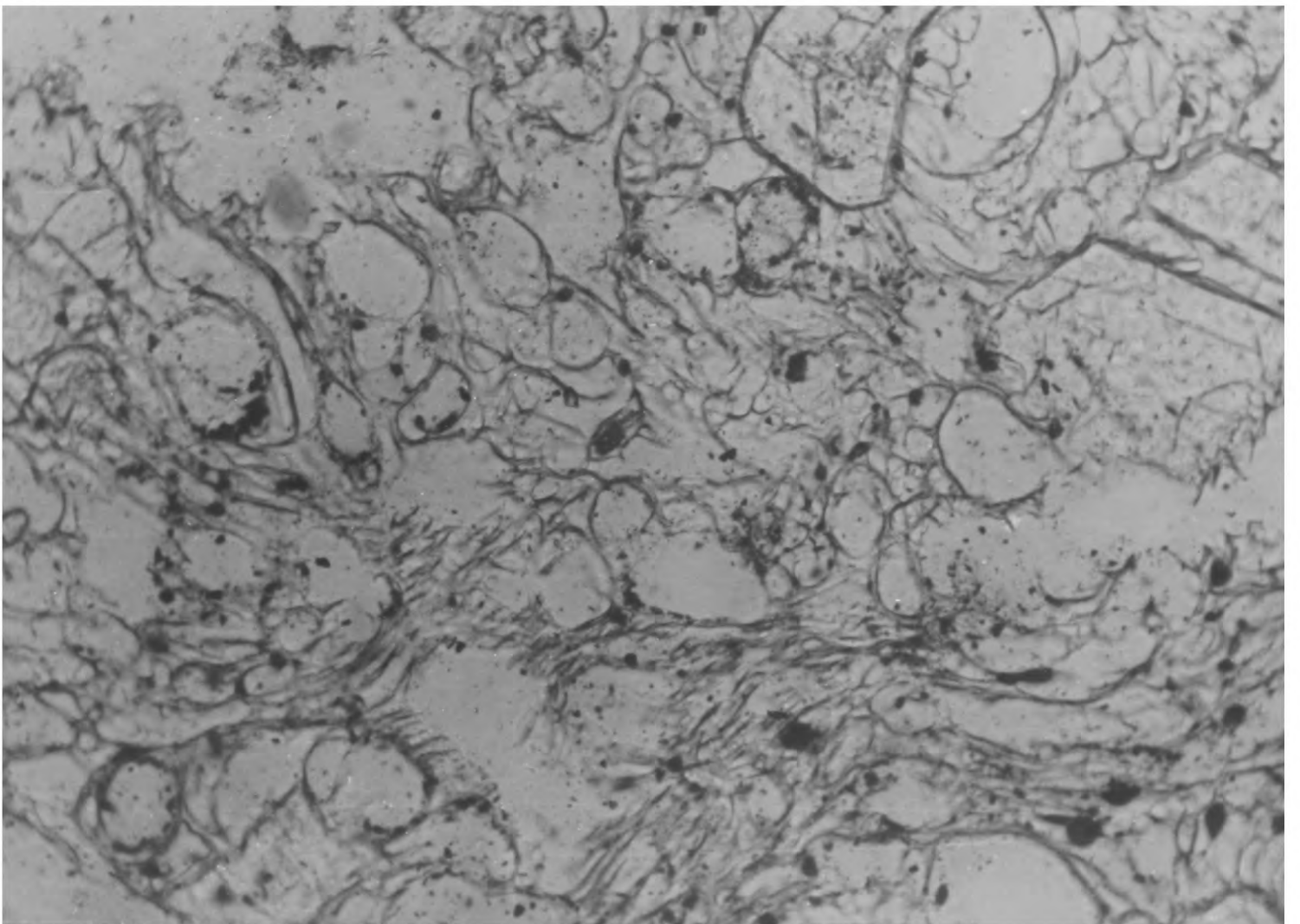
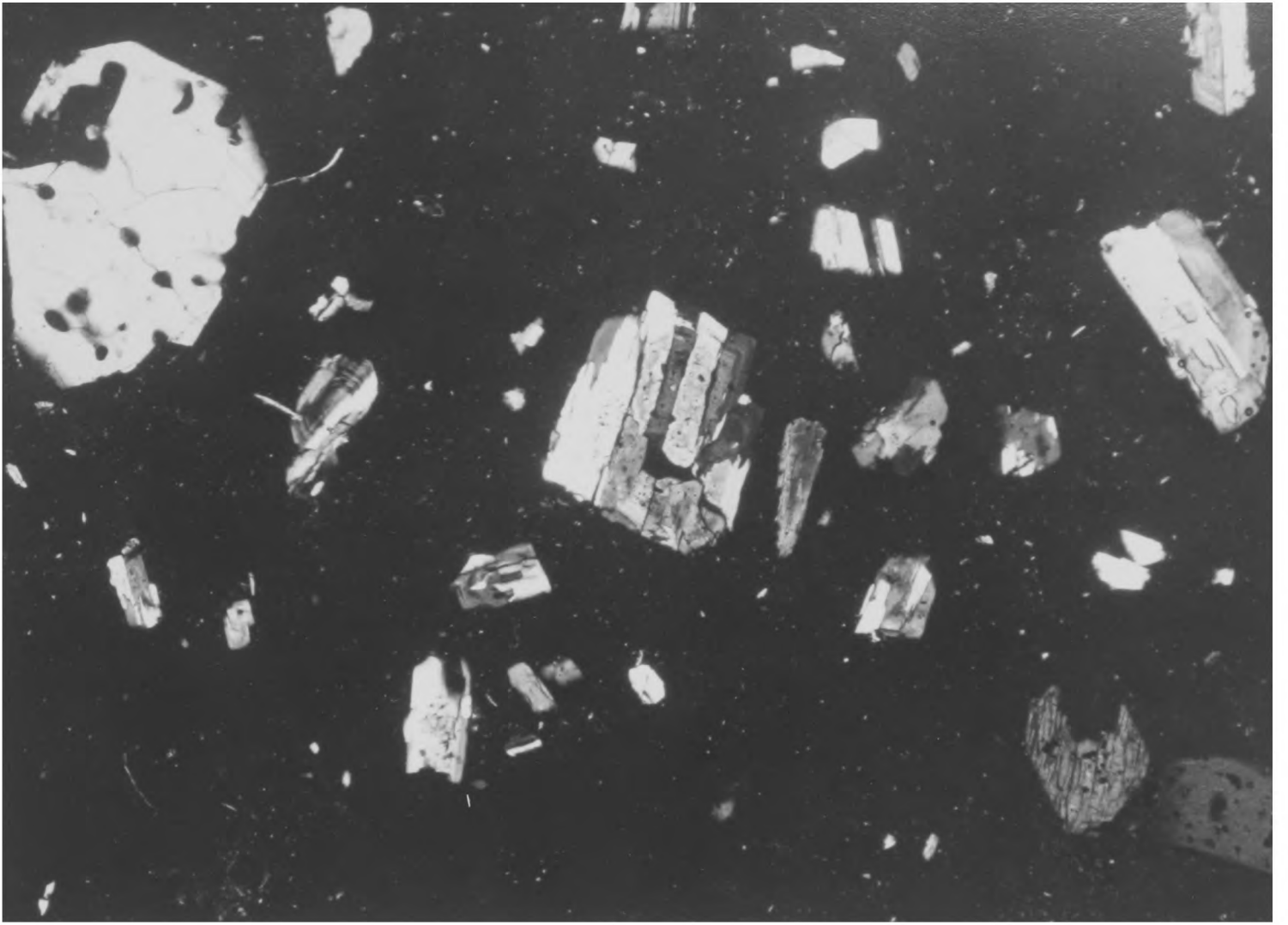


PLATE 24.

a) Photomicrograph of St. Phillip dacite L.91, showing the contrasting embayed and euhedral texture of adjacent quartz phenocrysts.

( x 15, crossed polarizers. )

b) Photomicrograph of plagioclase phenocryst in Petit Piton dacite L.13, showing a corroded, calcium-rich core, surrounded by an external portion composed of narrow, oscillatory zones. The crystal is twinned according to the Carlsbad (?) law, and the core in the lower twin is in partial extinction. The absence of albite twins made it impossible to estimate the core composition in this particular crystal. In other, similar plagioclase cores in L.13, compositions of up to  $An_{86}$  were recorded, with rims zoned down to a minimum of  $An_{30}$ .

( x 25, crossed polarizers. )

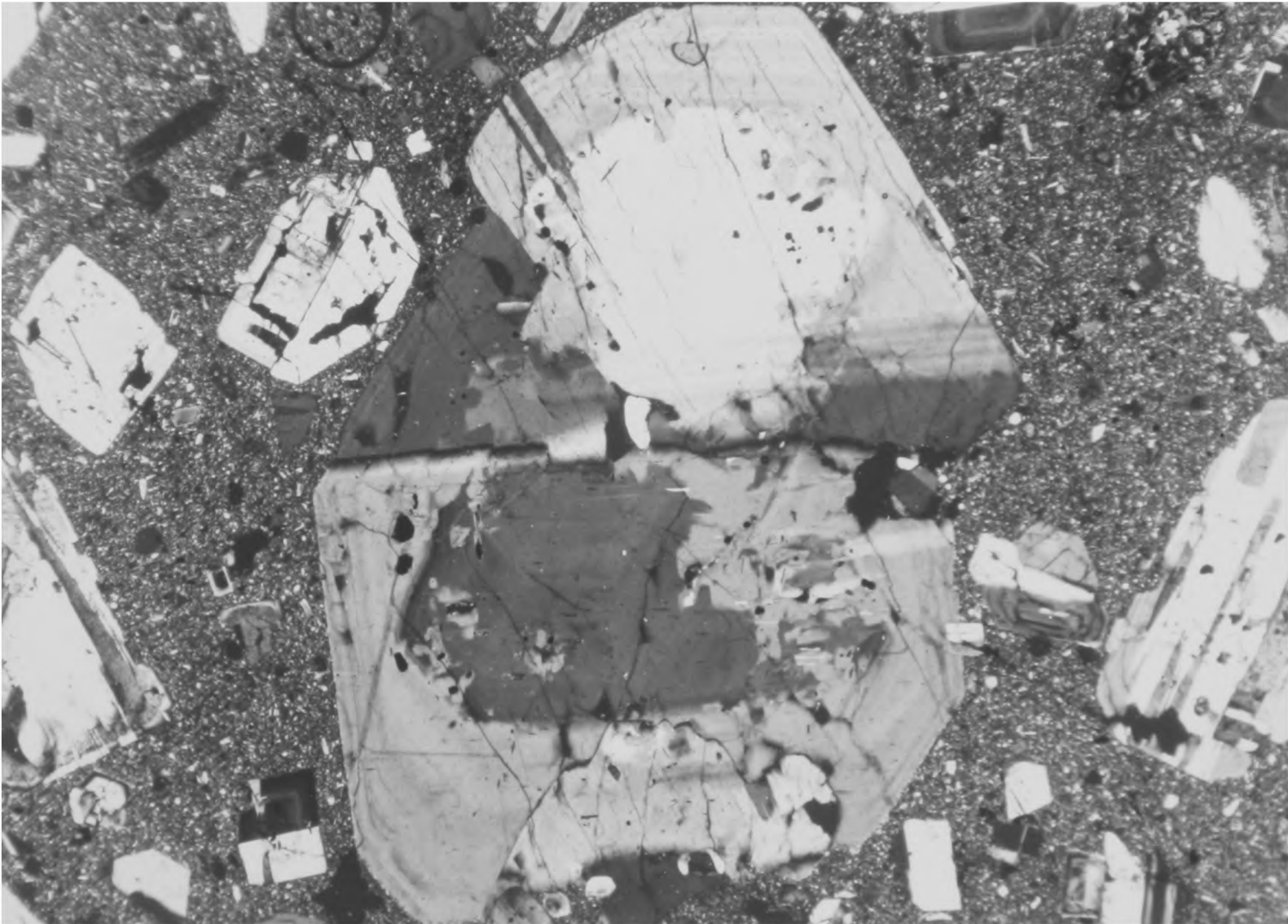
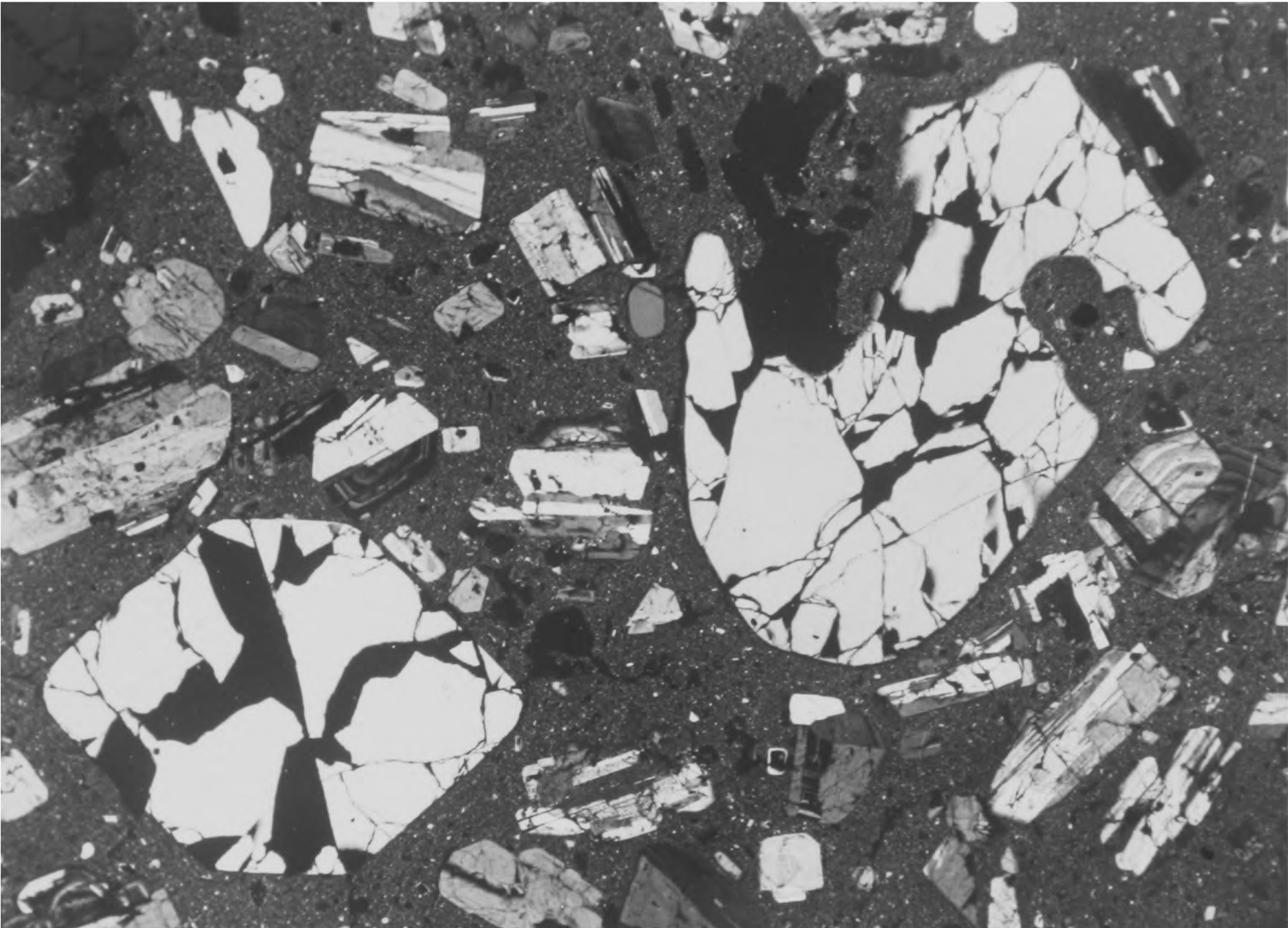


PLATE 25.

a) Photomicrograph of Petit Piton dacite, L.13. Plagioclase phenocrysts exhibit strong oscillatory zoning, and some have either cores or broad outer zones crowded with glass inclusions. A large, almost round "xenocryst" of quartz lies in the bottom left, and a small, anhedral orthopyroxene is visible towards the lower right. The groundmass is microfelsitic.

( x 25, crossed polarisers. )

b) Photomicrograph of Gros Piton dacite, L.329. Oscillatory-zoned plagioclase, partially resorbed quartz xenocrysts (lower left), pale green hornblende rimmed by opaque ore (bottom left), lie in a microfelsitic groundmass.

( x 25, crossed polarizers. )

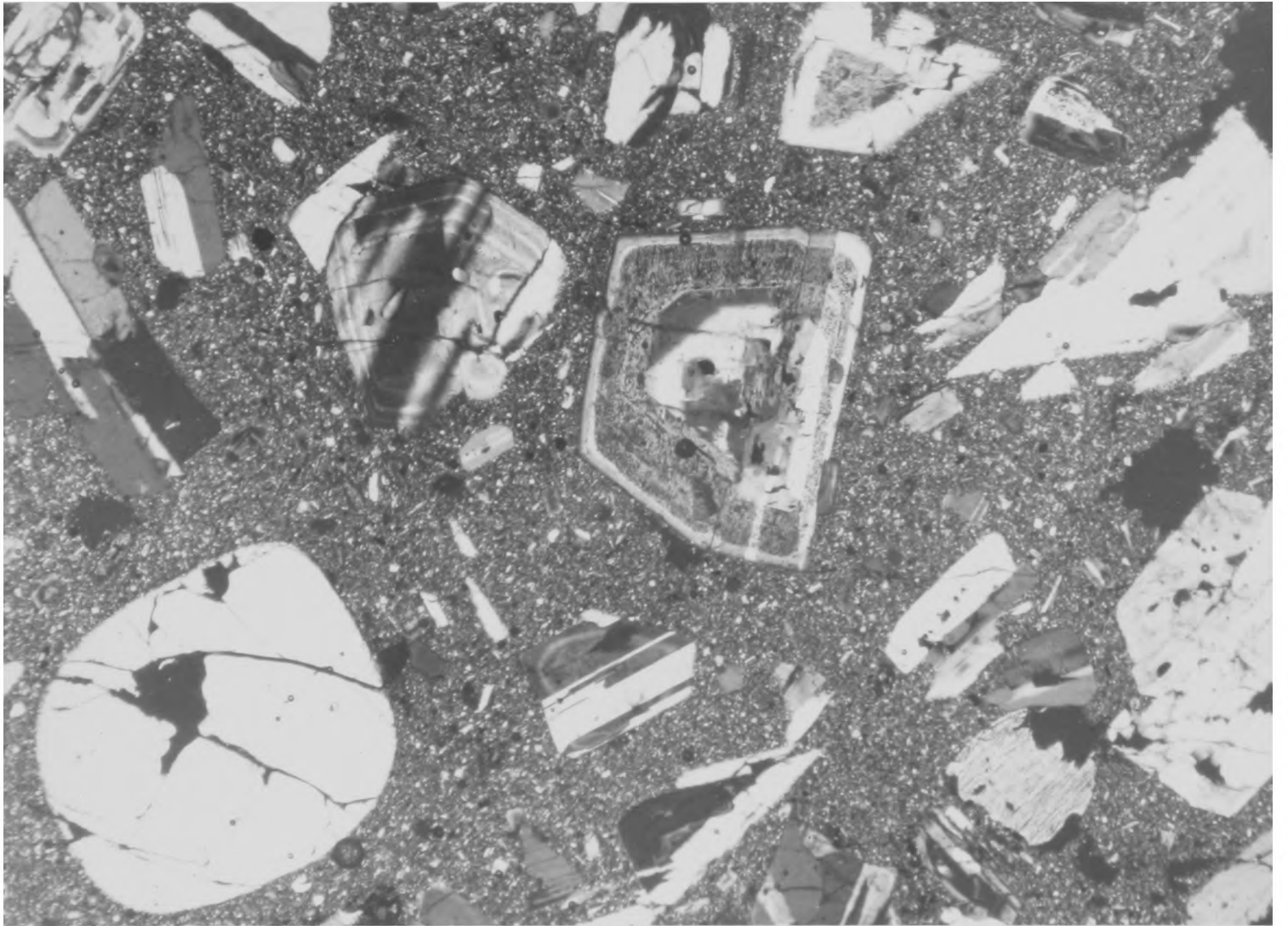


PLATE 26.

a) Photomicrograph of Terre Blanche dacite, L.244. The plagioclase phenocryst to the lower left exhibits fine-scale oscillatory zoning extending from core to rim, whilst a large, shattered quartz xenocryst occupies the top right of the picture. In the bottom centre, an elongate oxyhornblende is rimmed by opaque oxide. The groundmass is cryptofelsitic to glassy, with abundant haesatite.

( x 25, crossed polarizers. )

b) Photomicrograph of Terre Blanche dacite, L.245, showing extreme protoclastic texture. This sample was collected from a small exposure of flow-banded lava near the summit of the hill, which probably represents viscous material which was forced through the solid carapace of the growing dome. The mineralogy is as in L.244 (above), but almost all crystals are angular, comminuted fragments. The groundmass is cryptofelsitic to glassy.

( x 25, crossed polarizers. )

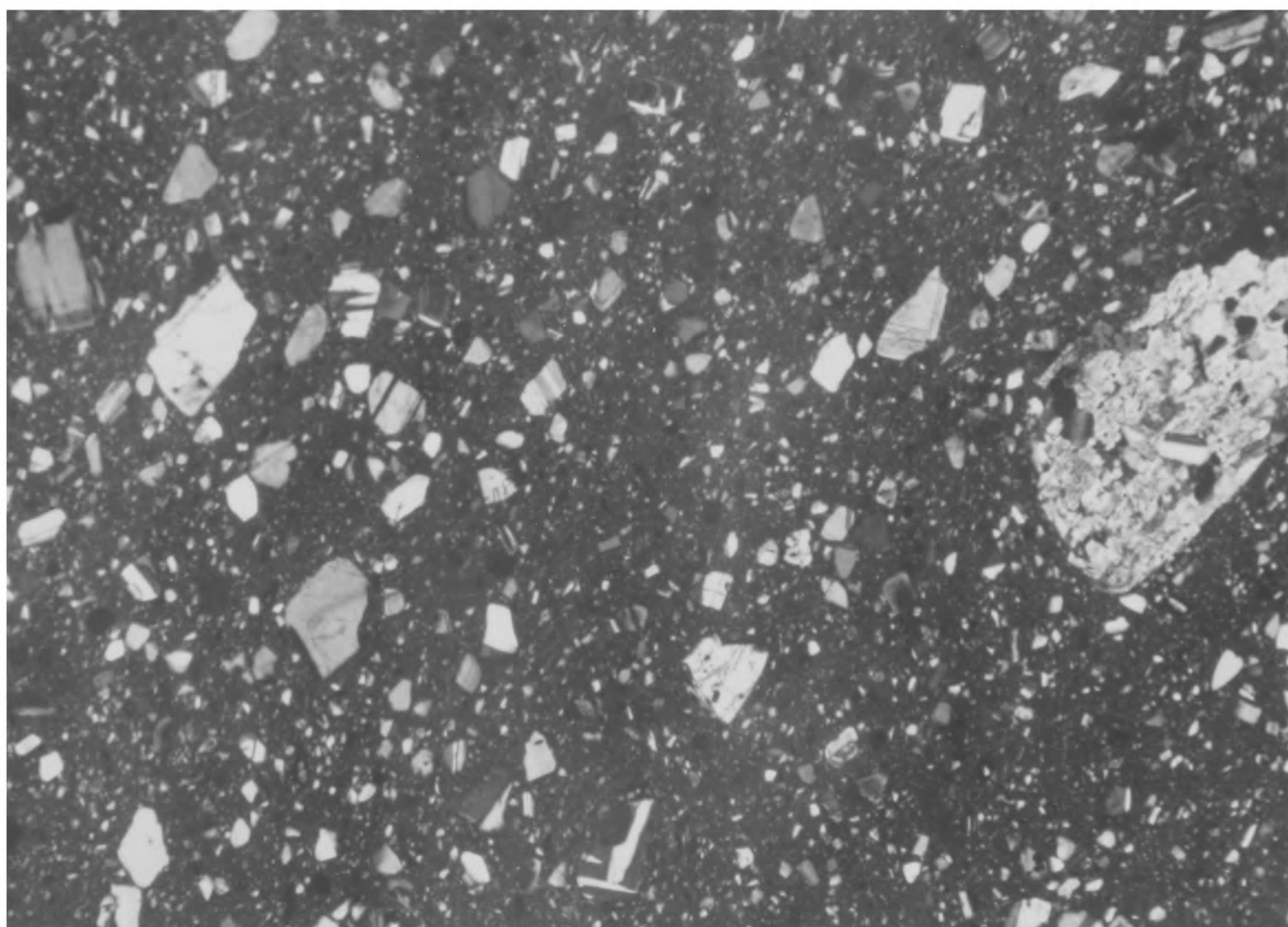
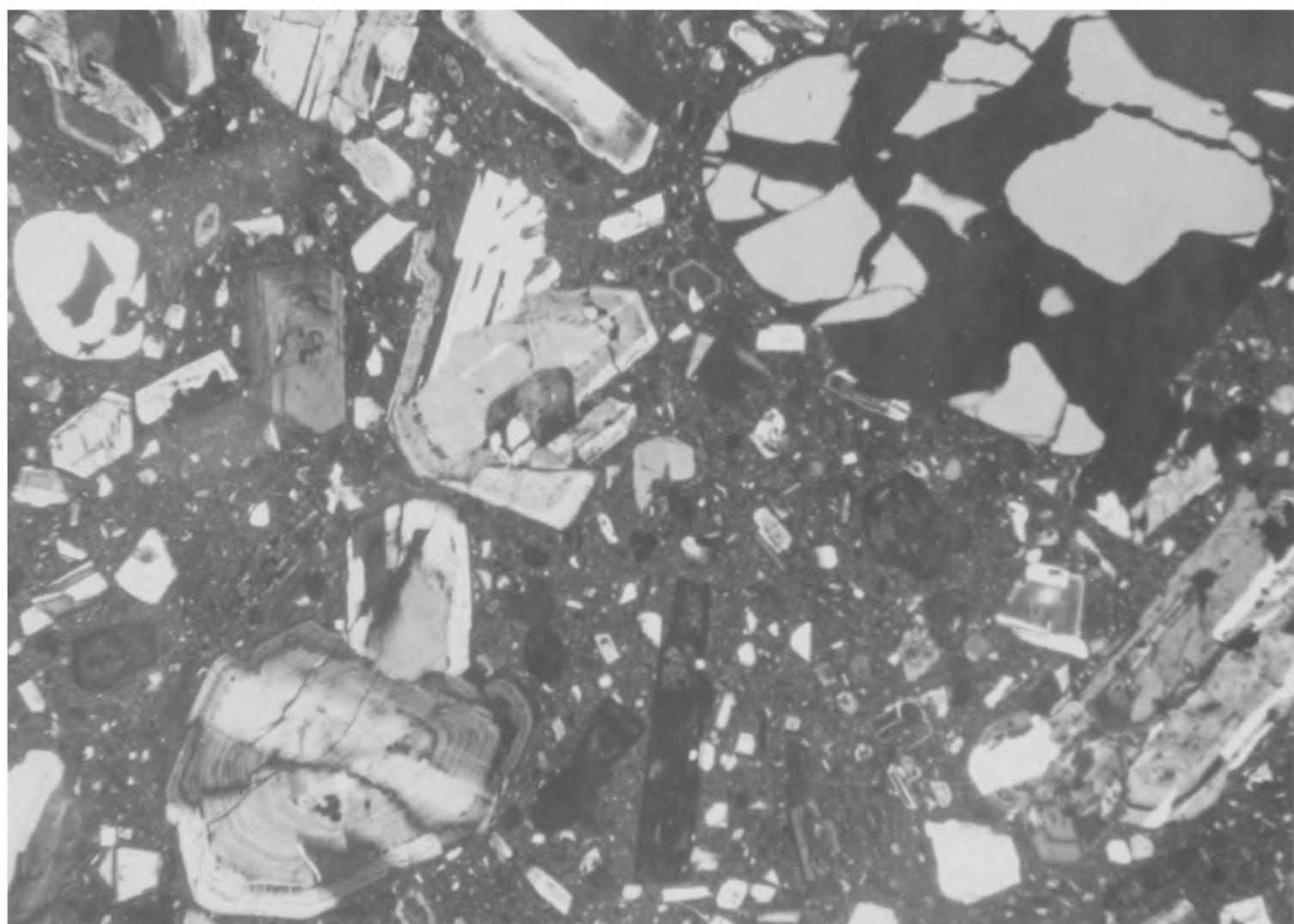


PLATE 27.

a) Photomicrograph of Belfond dacite, L.267. The slide contains plagioclase phenocrysts which show marked oscillatory zoning over a narrow compositional range, and are accompanied by subhedral quartz phenocrysts, in a glassy groundmass. A small crystal of cummingtonite lies near the upper right. The polarizers are not quite crossed, showing vesicles as evenly dark grey patches.

( x 25 )

b) Photomicrograph of zoned hornblende-cummingtonite phenocryst in Belfond dacite, L.267. The small core of the phenocryst, in partial extinction, is of dark green hornblende, which is surrounded by the almost colourless, twinned cummingtonite growing in optical continuity and poikilitically towards plagioclase crystals. A rectangular flake of biotite lies near the lower left corner.

( x 25, crossed polarizers. )

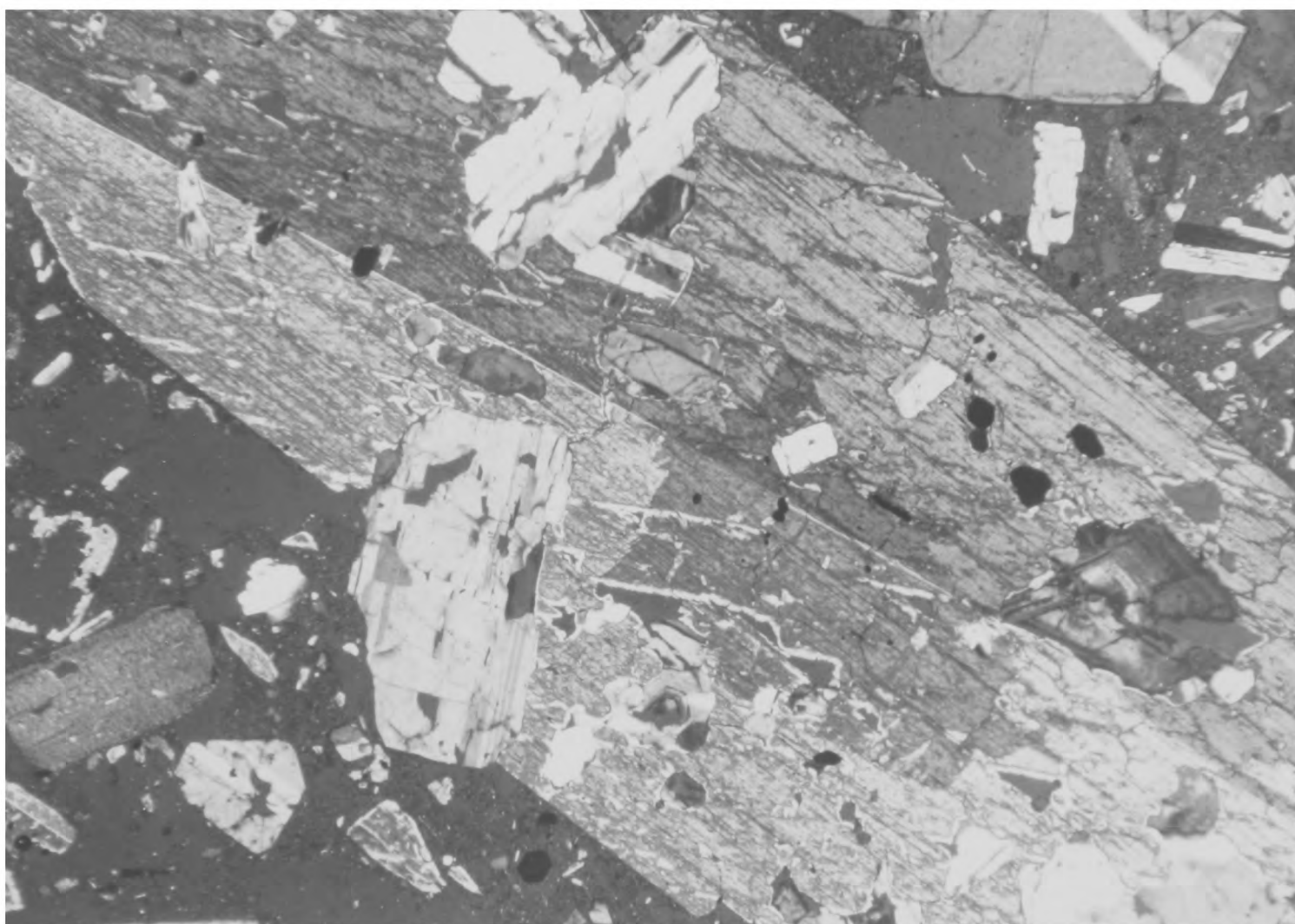
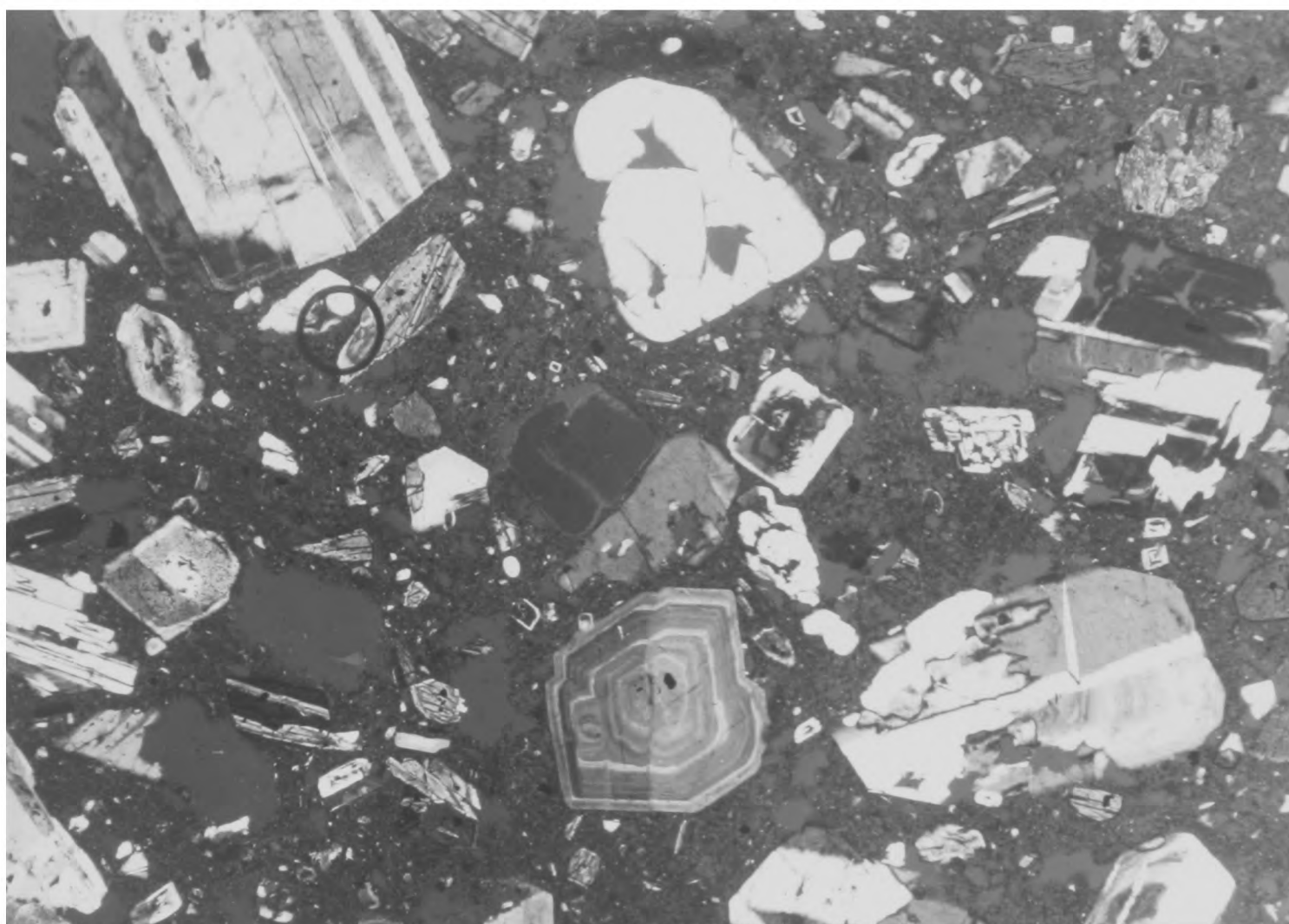


PLATE 28.

a) Photomicrograph of tonalite xenolith L.313, in Petit Piton dacite.

The outer halves of the plagioclase crystals contain broad, mildly oscillatory zones. The cores of the two crystals in the upper left, which are not in extinction, are of bytownite ( $An_{78}$ ) which has been corroded and partly replaced by small flecks of less calcic feldspar ( $An_{47}$ ), which extinguishes simultaneously with the outer zones. Abundant, granular quartz is interstitial between the plagioclases, and on the extreme left, part of a biotite crystal containing abundant inclusions of opaque oxide is visible.

( x 25, crossed polarizers. )

b) Photomicrograph of hornblende dolerite xenolith L.717, in Gros Piton

dacite. Large phenocrysts of plagioclase have cores containing abundant inclusions of glass, which are elongated parallel to consistent crystallographic planes. Green hornblende occurs as numerous elongate crystals, whilst orthopyroxene (right, centre) is less common. The "groundmass" consists of the same minerals, showing a pseudo-lamprophyric texture consisting of unorientated laths. The rock contains irregular-shaped vesicles.

( x 25, crossed polarizers. )

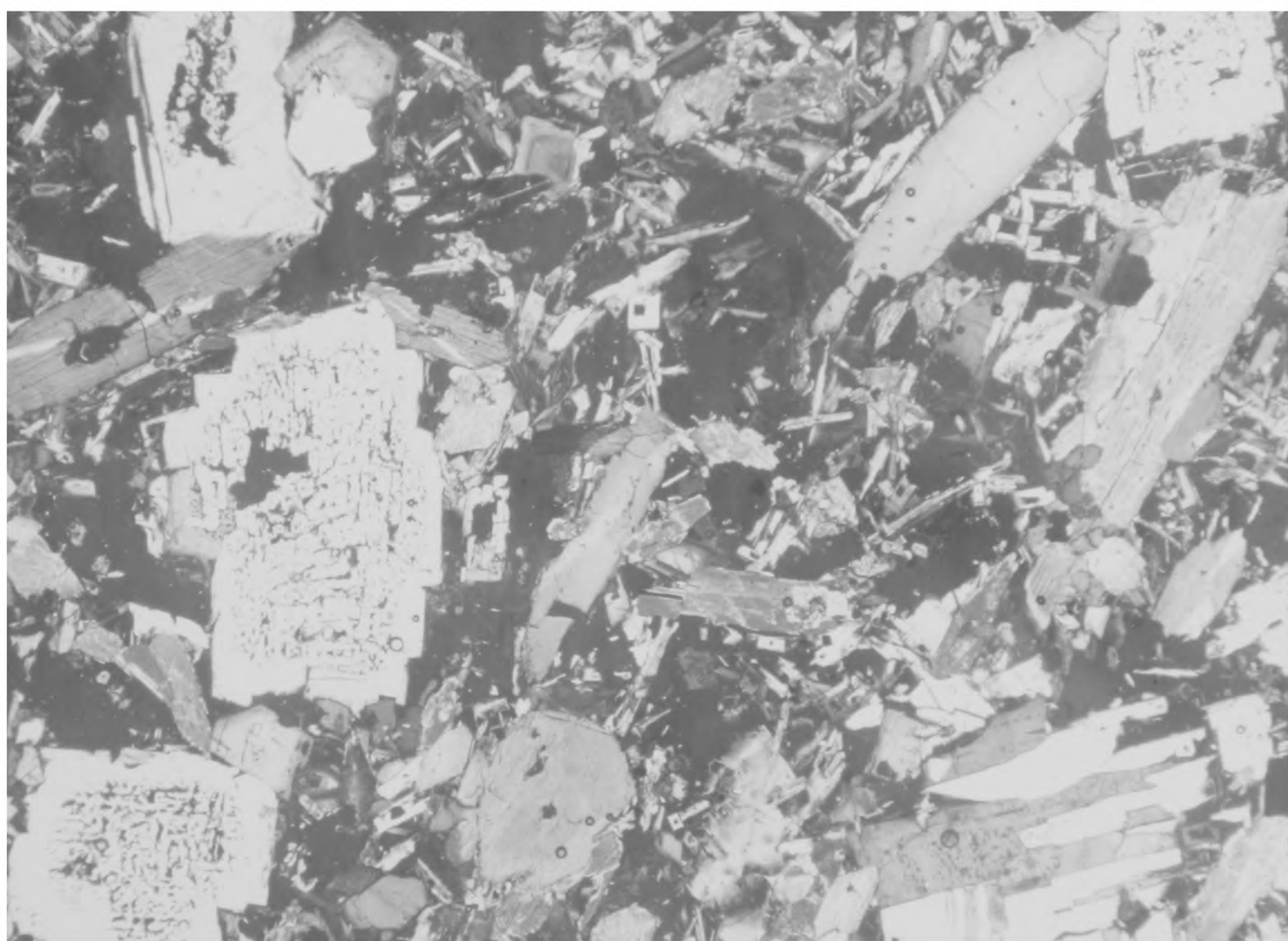


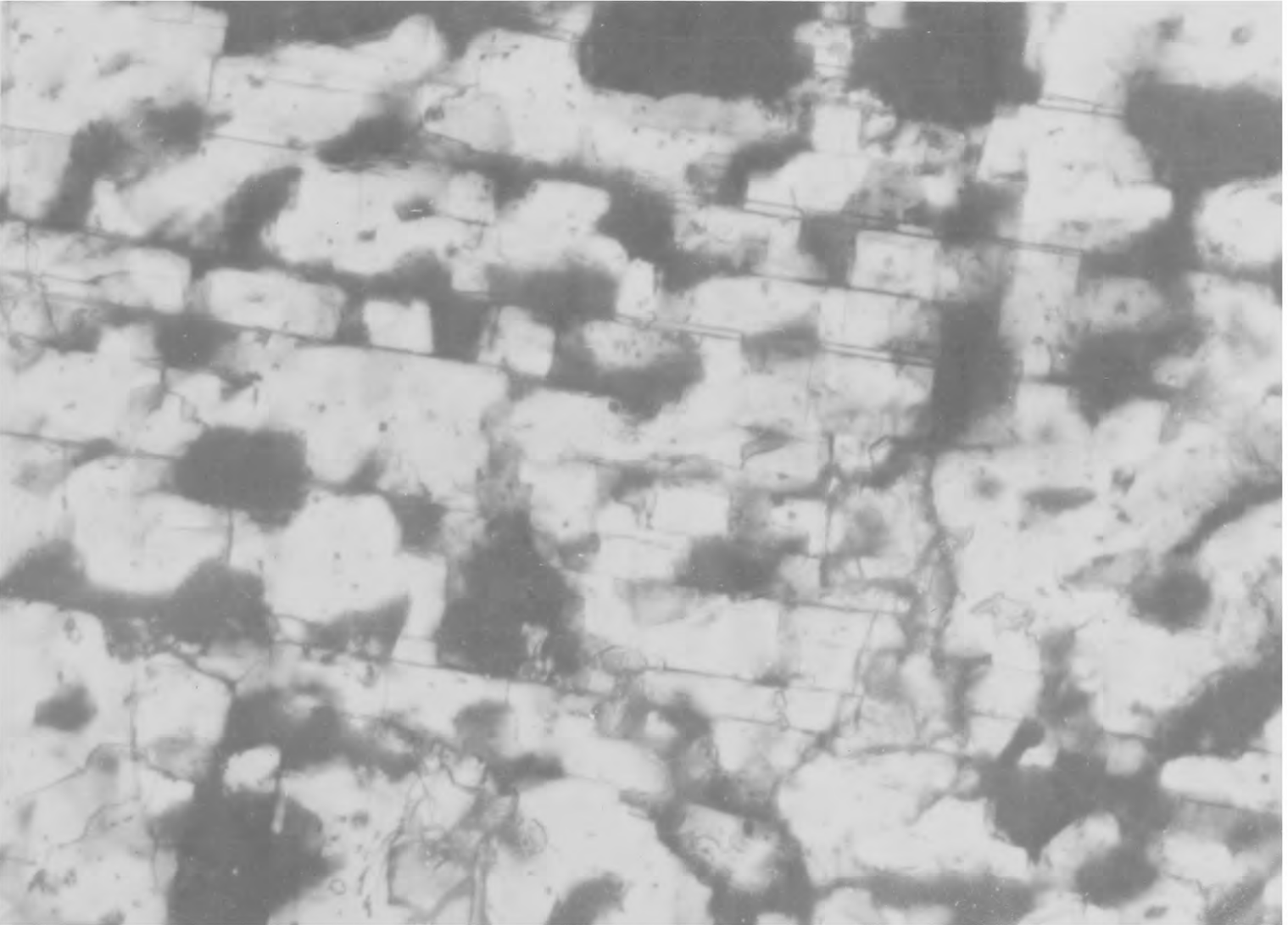
PLATE 29.

a) Photomicrograph of plagioclase phenocryst in hornblende dolerite xenolith L.717, showing inclusions of glass (opaque) and orthopyroxene, ( with higher relief).

( x 100, crossed polarizers. )

b) Photomicrograph of part of the same crystal as in Plate 29a, showing details of glass (opaque) and orthopyroxene (higher relief) inclusions, which are elongated parallel to crystallographic planes.

( x 500, crossed polarizers. )

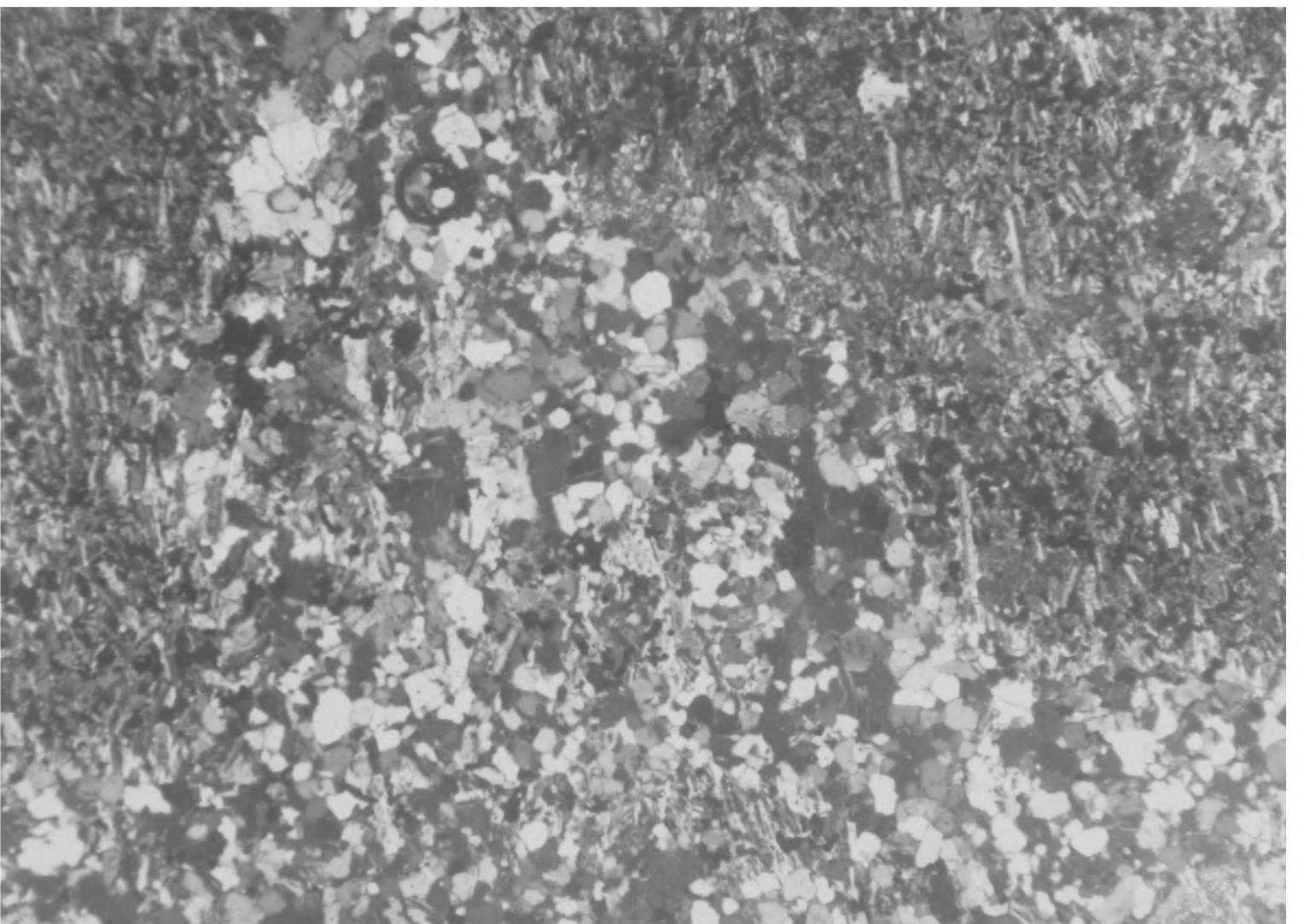
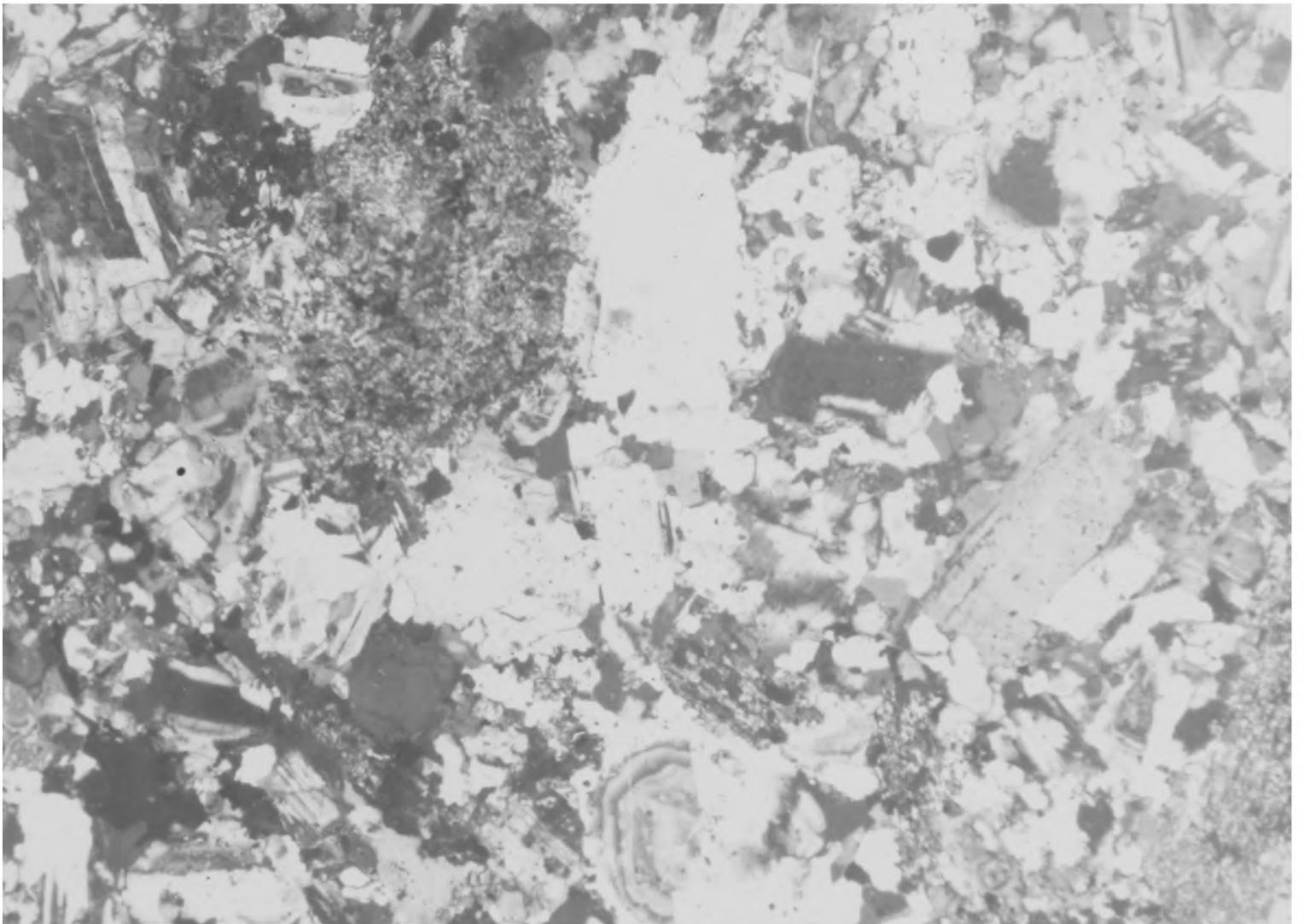


Photomicrograph of microtonalite, L.590. The rock has a seriate texture, being composed of equidimensional grains including oscillatory-zoned plagioclase and small, anhedral grains of quartz. Mafic minerals (including orthopyroxene, clinopyroxene, hornblende and biotite) occur in finely granular aggregates, e.g. towards the upper left of the photograph.

( x 25, crossed polarizers. )

b) Photomicrograph of hornfelsic breccia L.700. The rock is notably inhomogeneous, consisting of irregularly distributed patches of pale, quartzitic and darker, plagioclase-biotite-rich material. The plagioclase laths show preferred orientation.

( x 25, crossed polarizers. )



## 8. PETROCHEMISTRY

### 8. 1. MAJOR ELEMENTS

Twenty-four chemical analyses of rocks from St. Lucia are shown in Table 12. Details of the localities and rock types are given in Table 13. All but one of these (L.83), come from the Soufrière region. Twenty of these analyses were made by the present writer, and a further two incomplete analyses (Table 12, analyses 23 and 24) were made by Miss A. Herring, in the Department of Geology and Mineralogy at Oxford, using "rapid" methods based largely on those described by Riley (1958, pp.413-28), with the following exceptions: calcium was determined using the reagents of Weibel (1961, p.289), whilst for magnesium the method of Shapiro and Brannock (1962, p.435) was employed, although titrations for both elements were determined by comparison with standard solutions, after the manner of Riley. Details of this procedure are given in Appendix C. Alkalis were determined by the flame photometer method after the removal of interfering elements by precipitation with ammonium carbonate solution, as described by Vincent (in Smales and Wager, 1960, pp.53-5).

No. LA.40 is an analysis of the Petit Piton dacite made by Raoult, quoted by Lacroix (1926, p.403). No.26022 is an analysis of the Belfond dacite collected by Martin-Kaye and analysed by M. D. Hope at the Geological Survey Department, British Guiana. Discrepancies between Raoult's analysis and

Table 12. CHEMICAL ANALYSES OF ROCKS FROM ST. LUCIA

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Flows	L.83	L.153	L.251	L.34	.	.	L.38	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Domes	.	.	.	.	.	.	.	.	L.290	.	LA.40	L.244	L.5	L.329	.	L.13	.	26022	.	L.267	L.87	.	.	.
Pyroclastics	.	.	.	.	.	L.203	.	L.193	.	L.476	.	.	.	.	.	.	L.197	.	.	.	.	L.707	.	.
Other	.	.	.	.	L.717	.	.	.	.	.	.	.	.	.	L.313	.	.	.	L.590	.	.	.	L.267g	L.267hb.
SiO <sub>2</sub>	50.5	51.7	53.0	54.2	54.5	59.0	59.1	60.3	60.7	61.0	62.0	62.9	63.1	63.1	63.3	63.9	63.9	63.9	64.8	64.9	65.1	66.0	69.6	50.3
Al <sub>2</sub> O <sub>3</sub>	17.3	16.2	18.1	15.1	17.3	18.8	18.3	16.9	16.9	17.1	18.0	17.3	17.0	16.0	17.1	16.8	16.8	17.2	15.2	17.1	16.9	15.6	15.2	3.53
Fe <sub>2</sub> O <sub>3</sub>	2.54	3.68	1.98	3.82	1.80	0.77	0.85	1.41	0.68	0.04	3.31	2.65	0.44	1.01	2.37	0.97	1.57	1.80	1.33	0.43	0.36	0.00	0.30	4.60
FeO	5.78	7.52	6.74	7.76	4.45	4.18	3.62	3.43	4.09	4.60	2.08	1.42	3.71	3.21	1.89	2.97	2.85	2.25	3.74	3.13	3.36	3.56	1.13	21.1
MgO	5.37	3.28	3.73	3.49	6.12	2.88	2.86	0.88	2.80	1.74	2.95	1.92	1.80	2.48	1.66	1.48	1.64	1.60	1.96	1.46	1.56	1.80		
CaO	11.51	7.77	9.24	7.33	11.24	7.65	7.36	6.23	7.54	6.56	6.22	7.28	6.96	8.33	6.48	6.23	5.51	6.43	6.50	5.98	5.83	6.07	3.54	2.44
Na <sub>2</sub> O	2.47	3.59	3.26	3.23	2.49	2.61	2.34	2.25	2.77	2.87	2.24	2.84	2.81	3.01	3.32	3.38	2.95	3.20	3.00	3.04	3.24	3.13	2.77	0.49
K <sub>2</sub> O	0.56	0.47	0.76	0.72	0.74	1.44	1.45	1.28	1.55	1.32	1.57	1.28	1.31	1.02	1.43	1.57	1.31	1.80	1.43	1.55	1.70	1.70	3.70	0.27
H <sub>2</sub> O <sup>+</sup>	1.62	1.00	1.14	1.73	0.60	1.14	1.51	3.31	1.12	1.54	1.09	0.92	0.60	0.54	0.95	0.81	2.29	0.91	1.13	2.08	1.17	1.77	2.14	0.93
H <sub>2</sub> O <sup>-</sup>	0.64	1.25	0.64	0.43	0.14	0.84	2.04	2.37	0.48	0.22	0.28	0.66	0.21	0.34	0.89	0.35	0.36		0.23	0.30	0.29	0.28		
TiO <sub>2</sub>	0.69	1.03	1.14	1.05	0.63	0.53	0.50	0.60	0.55	0.46	0.59	0.46	0.55	0.45	0.56	0.42	0.40	0.63	0.38	0.42	0.47	0.35	0.12	0.94
P <sub>2</sub> O <sub>5</sub>	0.13	0.11	0.15	0.10	0.05	0.11	0.12	0.10	0.12	0.06	0.09	0.10	0.14	0.10	0.11	0.12	0.09	0.16	0.10	0.10	0.10	0.11	0.10	0.25
MnO	0.18	0.28	0.13	0.22	0.14	0.11	0.08	0.12	0.10	0.12	0.05	0.10	0.10	0.10	0.08	0.11	0.10	tr	0.08	0.09	0.09	0.09	0.05	0.68
CO <sub>2</sub>		2.54	0.91	0.30	0.03	0.16	0.48	1.06				0.06	0.07						0.08					
TOTAL	99.29	100.48	100.92	99.48	100.27	100.22	100.61	100.24	99.42	97.63	100.48	99.89	98.80	99.69	100.14	99.11	99.96	99.88	99.96	100.58	100.17	100.46	(98.30)	(85.61)
Norm																								
qu	2.87	10.40	5.96	10.35	6.15	15.67	19.18	28.85	17.40	19.64	25.44	24.46	22.79	21.30	22.97	21.99	26.18	22.73	24.73	24.49	23.21	24.45		
or	3.31	2.78	4.49	4.26	4.37	8.51	8.57	7.57	9.16	7.80	9.28	7.57	7.74	6.03	8.45	9.28	7.74	10.64	8.45	9.16	10.05	10.05		
ab	20.90	30.38	27.58	27.33	21.07	22.08	19.80	19.04	23.44	24.28	18.95	24.03	23.78	25.47	28.09	28.60	24.96	27.08	25.38	25.72	27.41	26.48		
an	34.48	21.80	32.44	24.67	33.86	35.23	32.71	23.56	29.22	29.81	30.28	30.61	29.90	27.15	27.41	25.93	26.76	27.26	23.66	28.48	26.53	23.40		
cor	-	1.84	-	-	-	-	0.88	3.17	-	-	1.49	-	-	-	-	-	0.72	-	-	-	-	-		
di	17.71	-	5.52	7.60	17.21	0.82	-	-	6.11	1.99	-	3.49	2.75	11.08	3.19	3.49	-	2.90	6.17	0.46	1.46	5.02		
hy	12.47	17.76	15.66	14.68	12.87	13.14	12.39	6.56	10.19	11.21	7.55	3.16	8.84	5.25	3.36	6.11	7.41	4.20	7.11	8.27	8.42	8.10		
mt	3.68	5.34	2.87	5.54	2.61	1.12	1.23	2.04	0.99	0.06	4.80	3.57	0.64	1.46	3.44	1.41	2.28	2.61	1.93	0.62	0.52	-		
hm	-	-	-	-	-	-	-	-	-	-	-	0.19	-	-	-	-	-	-	-	-	-	-		
ilm	1.31	1.96	2.17	1.99	1.20	1.01	0.95	1.14	1.04	0.87	1.12	0.87	1.04	0.86	1.06	0.80	0.91	1.20	0.72	0.80	0.89	0.67		
ap	0.31	0.26	0.35	0.24	0.12	0.26	0.28	0.24	0.28	0.14	0.21	0.24	0.33	0.24	0.26	0.28	0.21	0.38	0.24	0.24	0.24	0.24		

Table 13

DETAILS OF ANALYSED SPECIMENS

The rock name is given first, followed by its mode of occurrence, locality, and height above sea level. The principal mineral constituents are listed in order of decreasing abundance.

- 1) L.83 Vitrophyric clinopyroxene-olivine basalt. From bedded scoria, Dauphin Bay, 5 ft. a.s.l.  
Plagioclase, clinopyroxene, olivine, orthopyroxene, in a dark, glassy matrix.
- 2) L.153 Aphyric clinopyroxene basalt. Lava flow, forming coastal cliffs north of Malgrétoute. 10 ft. a.s.l.  
Plagioclase, clinopyroxene, magnetite, calcite, olivine, with intergranular texture.
- 3) L.251 Porphyritic clinopyroxene basalt. Lava flow. Northern end of coastal cliffs, south side of Soufrière Bay. 5 ft. a.s.l.  
Plagioclase, clinopyroxene, in an intergranular groundmass of the same minerals plus opaque oxide.
- 4) L.34 Aphyric clinopyroxene basalt. Lava flow, 1 mile E.N.E. of Migny, at 1,900 ft. a.s.l.  
Plagioclase, clinopyroxene, magnetite, quartz, with intergranular texture.
- 5) L.717 Hornblende dolerite. Xenolith in Gros Piton dacite lava, south of L'Ivrogne. 350 ft. a.s.l.  
Plagioclase, hornblende, orthopyroxene, quartz, cristobalite, clinopyroxene, olivine, with lamprophyric texture.
- 6) L.203 Orthopyroxene andesite. Dark-coloured lava block in caldera-wall agglomerate-tuff. L'Ivrogne river, S.E. of Gros Piton. 600 ft. a.s.l.  
Plagioclase, orthopyroxene, quartz, clinopyroxene, in a dark glassy to cryptocrystalline matrix.
- 7) L.38 Orthopyroxene andesite. Dark-coloured lava flow, N.E. of Migny. 1,350 ft. a.s.l.  
Plagioclase, orthopyroxene, clinopyroxene, calcite, in a microcrystalline (felsitic) groundmass.

Table 13 (continued)

- 8) L.193 Andesite agglomerate-tuff. From the lower part of the caldera wall, N. of Soufrière, 300 ft. a.s.l.  
Orthopyroxene-andesite lava fragments in crystal tuff matrix. Plagioclase, orthopyroxene, quartz, hornblende, calcite, olivine, opaque oxide, clinopyroxene.
- 9) L.290 Orthopyroxene andesite dome lava, pale coloured. Near the summit of Fond Doux, 1,550 ft. a.s.l.  
Plagioclase, orthopyroxene, quartz, opaque oxide, clinopyroxene, in a felsitic groundmass.
- 10) L.476 Andesite pumice. S.E. of Victoria Junction, beside the main road, at 780 ft. a.s.l.  
Plagioclase, quartz, orthopyroxene, opaque oxide, in a pale glassy groundmass.
- 11) LA.40 Dacite à hypersthène. Petit Piton (Lacroix, 1926, p.403)
- 12) L.244 Hornblende dacite. Terre Blanche summit, 1,900 ft. a.s.l.  
Plagioclase, quartz, oxy-hornblende, orthopyroxene, biotite, opaque oxide, haematite in a felsitic groundmass.
- 13) L.5 Orthopyroxene-quartz andesite, pale-coloured. Morne Bonin, northwest flank, 1,300 ft. a.s.l.  
Plagioclase, orthopyroxene, quartz, opaque oxide in a felsitic groundmass.
- 14) L.329 Clinopyroxene-biotite dacite. Gros Piton, east flank, 800 ft. a.s.l.  
Plagioclase, quartz, clinopyroxene, biotite, orthopyroxene, hornblende, olivine, opaque oxide, in a microcrystalline, equigranular groundmass.
- 15) L.313 Biotite tonalite. Inclusion in Petit Piton dacite lava. West flank of Petit Piton, 10 ft. a.s.l.  
Plagioclase, quartz, biotite, orthopyroxene, opaque oxide and haematite, with granitic texture.
- 16) L.13 Orthopyroxene dacite, dome lava. Petit Piton, north-northwest flank, 15 ft. a.s.l.  
Plagioclase, quartz, orthopyroxene, opaque oxide, hornblende, biotite, in a microcrystalline, equigranular groundmass.
- 17) L.197 Cummingtonite-biotite dacite pumice ash fall. St. Rémy River, 850 ft. a.s.l.  
Pumice fragments and crystals of plagioclase, quartz, hornblende, biotite, orthopyroxene, opaque oxide, in a matrix of glassy dust.
- 18) 26022 Hornblende-biotite dacite. Belfond. (Martin-Kaye, progress reports on the Geological Survey of the Windward Islands).

Table 13 (continued)

- 19) L.590 Two-pyroxene-biotite microtonalite. Block in andesite pumice flow. Beside the main road north of Choiseul, 350 ft. a.s.l.  
Plagioclase, quartz, orthopyroxene, clinopyroxene, biotite, opaque oxide, haematite, with microgranitic texture.
- 20) L.267 Cummingtonite-biotite dacite, dome lava. Belfond hill, south-east of the summit, 1,600 ft. a.s.l.  
Plagioclase, quartz, cummingtonite, biotite, opaque oxide, orthopyroxene, in a glassy groundmass.
- 21) L.87 Cummingtonite-biotite dacite, dome lava.  $\frac{1}{2}$  mile north of St. Rémy, beside the main road, 1,000 ft. a.s.l.  
Plagioclase, quartz, cummingtonite, biotite, orthopyroxene, opaque oxide, in a glassy groundmass.
- 22) L.707 Biotite-dacite pumice block, from pumice flow. The flow forms the highest layer in coastal cliffs  $\frac{2}{5}$  mile N.W. of Choiseul, 80 ft. a.s.l.  
Plagioclase, quartz, biotite, orthopyroxene, oxy-hornblende, in a glassy groundmass.

\* In a duplicate analysis of a basalt from St. Rémy, Rémy (1953, p.151) found 0.7% more water than in the original analysis by Macull.

that of the Petit Piton dacite made by the present writer involve  $\text{Fe}_2\text{O}_3$  (2.3% lower in L.13),  $\text{MgO}$  (1.5% lower in L.13), and  $\text{Na}_2\text{O}$  (1.1% higher in L.13). These are relatively large and should probably be attributed, at least in part, to analytical methods.\* Discrepancies between Hope's analysis of the Belfond dacite (26022) and the present analysis (L.267) are not large:  $\text{SiO}_2$  is 1% higher in L.267, and the ferrous:ferric iron ratio differs. These may well be discrepancies due to sampling.

### 8. 2. VARIATION OF OXIDES WITH SILICA

The silica, or Harker, variation diagram has recently been discussed in great detail by Chayes (1962; 1964, p.235), who has emphasised that it is "of little use in discriminating between the effects of nearly all the processes thought to be of major importance in the differentiation of volcanic rocks." It does, however, remain the most simple and convenient method of illustrating graphically the proportions of the major elements in a group of rocks. To this end, the 20 new analyses of whole rocks from St. Lucia, recalculated to 100% free of water and other volatiles, are plotted in Fig.24.

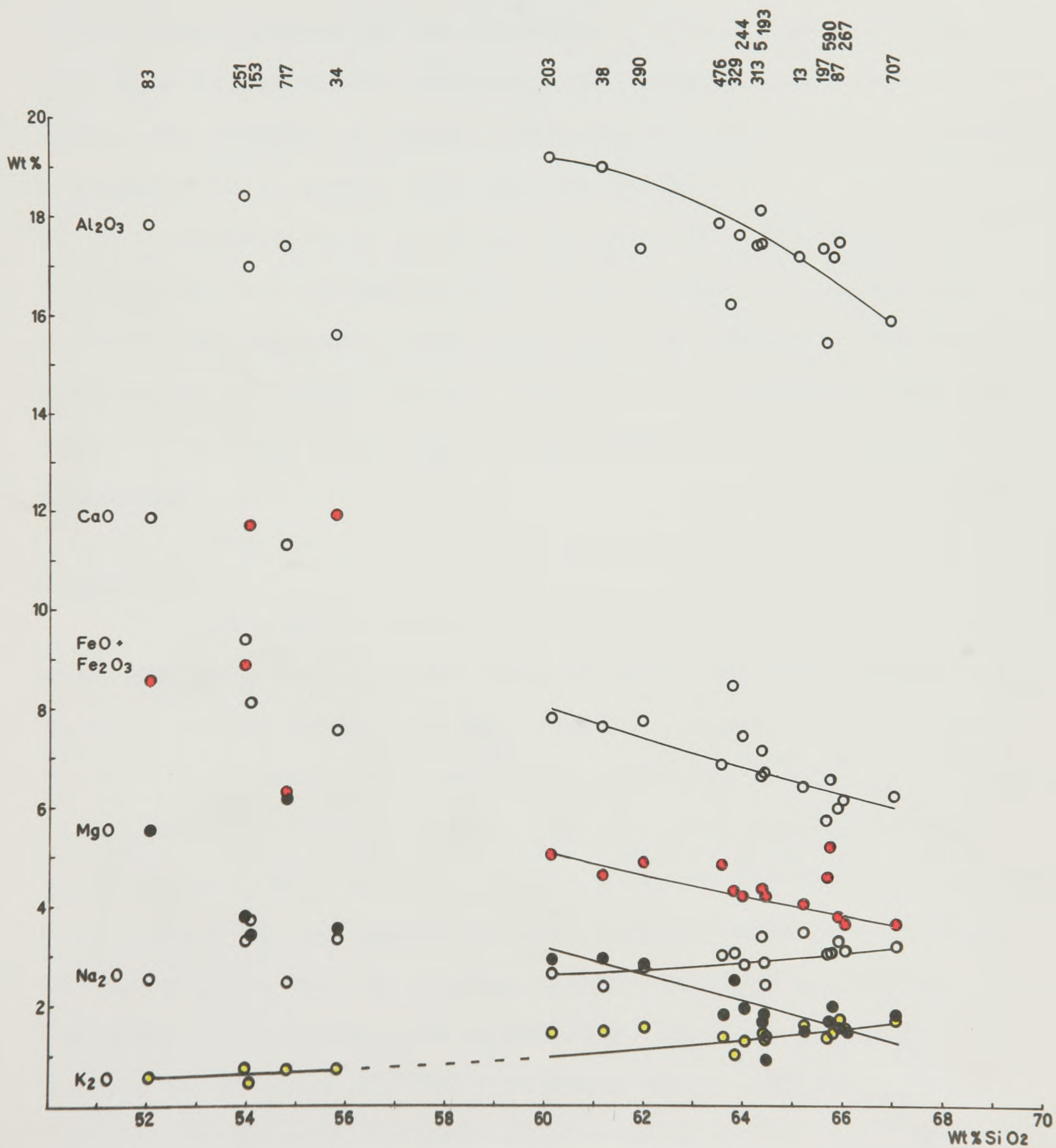
The principal features exhibited by this diagram are:

- 1) A scatter of compositions in the silica poor (basaltic) rocks. The aphyric and porphyritic basalts diverge widely.
- 2) Relatively smooth curves for the andesites and dacites.

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\* In a duplicate analysis of a basalt from St. Kitts, Baker (1963, p.151) found 0.7% more soda than in the earlier analysis by Raoult.

FIG. 24. VARIATION OF OXIDES WITH SILICA IN ROCKS OF ST LUCIA



3) A large gap in silica content, from 55.8 - 60.1%, between the basalts and andesites. This might have been filled by more comprehensive sampling over the island as a whole, or may represent a natural break. The gap corresponds to what was probably a long time interval in the Soufrière region. A gap of comparable size in the silica percentage of analysed rocks from Mt. Misery was recorded by Baker (1963, p.137), though this affected a slightly lower range, from 53.3 to 56.8%.

4) A concentration of rocks in the range 64 - 66%  $\text{SiO}_2$ . This is certainly not characteristic of the island as a whole, but reflects the relatively high proportion of dacites at the surface in the Soufrière region. Representative sampling from the island as a whole would undoubtedly increase the proportion of andesites.

#### $\text{Al}_2\text{O}_3$

The alumina content reaches a maximum of 19.1% at about 60%  $\text{SiO}_2$  (recalculated free of water and other volatiles) in rocks of St. Lucia. In this feature, they differ from the St. Kitts and Montserrat series, in which the basalts are richer in alumina, the average content for St. Kitts basalts being 19.6% (Baker, 1963, p.180). In the variance relations of alumina and silica, the St. Lucian analyses resemble more closely those of Crater Lake, with an alumina maximum of 18.8% at 56%  $\text{SiO}_2$  (Williams, 1942, p.154) and Lassen Peak, in which the  $\text{Al}_2\text{O}_3$  maximum is 18.4% at 58%  $\text{SiO}_2$  (Williams 1932, p.377).

The aphyric basalts from St. Lucia are notably lower in alumina than the porphyritic rocks with a similar silica content, and this may be related to the absence of plagioclase, which forms the predominant phenocryst mineral in the porphyritic basalts.

### CaO

The CaO content of the basaltic rocks shows a wide variation, and is relatively low in the aphyric basalts. The andesites and dacites, with the exception of L.329, lie on a straight line showing strong negative correlation with silica, and resembling the St. Kitts and other calcium-rich island arc and orogenic suites.

### $\text{Fe}_2\text{O}_3 + \text{FeO}$

Iron oxides are plotted together, since the ferric to ferrous ratio appears to vary arbitrarily, e.g. the pink dacite L.244 (Table 12) contains twice as much ferric iron as any of the analysed grey dacites, and correspondingly less ferrous iron. The curve for total iron in the andesites and dacites is similar to that for CaO, showing a steady decrease with increasing silica. In the basalts, there is a marked difference between porphyritic and aphyric specimens, the iron content in the latter being appreciably higher.

### MgO

MgO shows an almost linear descent with increasing silica. There is also a less pronounced scatter of points among the basic rocks, with the exception of the hornblende-rich

inclusion in dacite, L.717. Values, for a given silica percentage, are comparable to those of St. Kitts and many volcanic suites of the island arcs and orogenic regions, with the exception of Crater Lake and Lassen Peak, in which magnesia is more abundant. Specimen L.193 is unusually poor in MgO, but this may be due to mechanical separation of the ferromagnesian components in this pyroclastic deposit.

### Na<sub>2</sub>O

Soda shows little systematic variation. It ranges between 2.4 and 3.8%, being closer to the higher figure in the most acid dacites. The andesites have a slightly lower soda content than the average for basalts and dacites of St. Lucia.

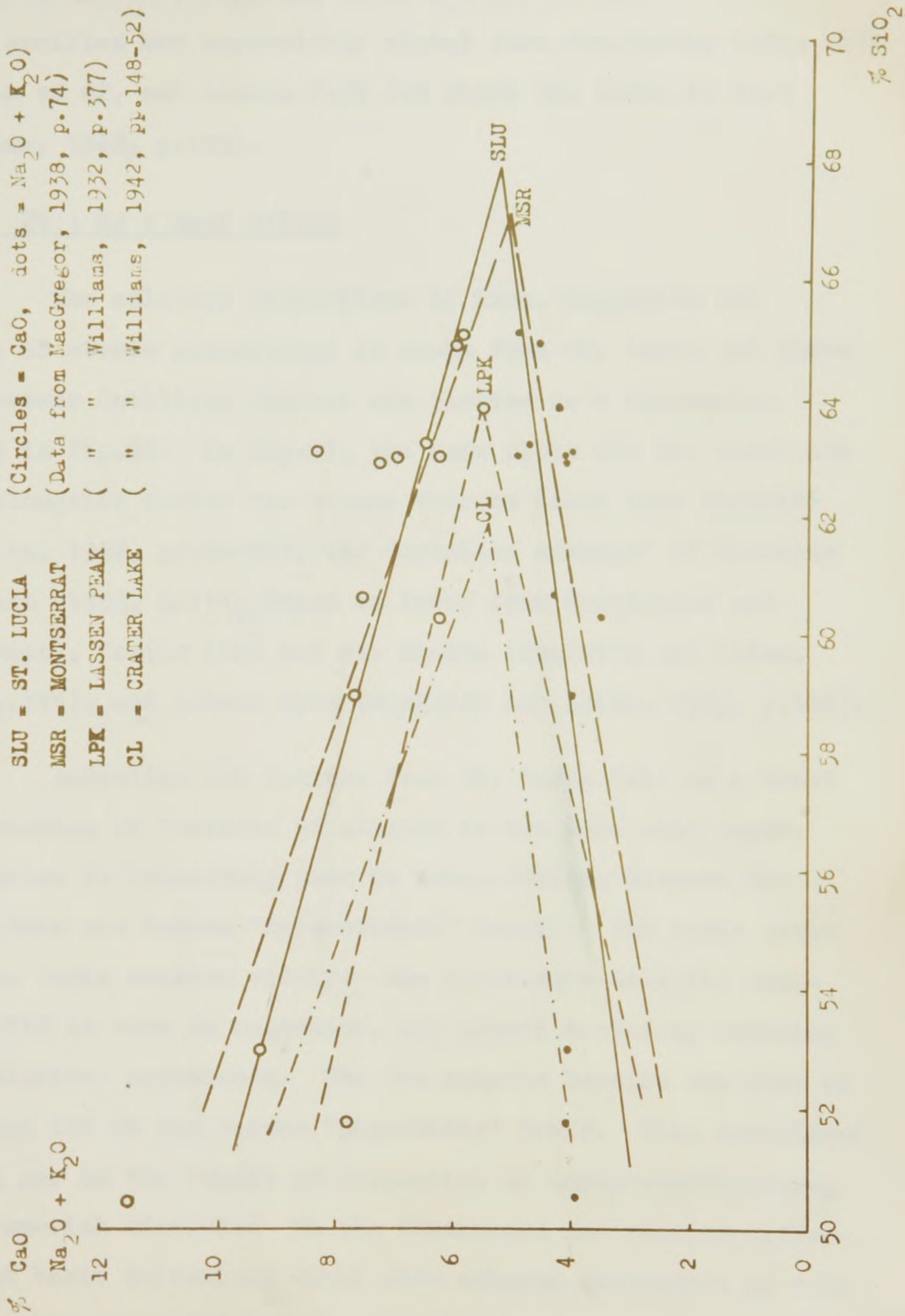
### K<sub>2</sub>O

Potash is less abundant in the basalts than in the andesite-dacite series, in which it rises steadily with increasing silica.

## 8. 3. ALKALI-LIME INDEX

The alkali-lime index (Fig.25) introduced by Peacock (1931), is the silica percentage at which alkalis (Na<sub>2</sub>O + K<sub>2</sub>O) are as abundant as lime. The value for the Soufrière region is 67.8, which is notably high, even among island arc volcanoes. In the Lesser Antilles, Montserrat (data from MacGregor, 1938, p.74) has an index of 67, whilst that of St. Kitts (Baker, 1963, p.160), is lower at 65. The Kamchatka average is 62.2, the Kuriles 64.8, and Japan 64.1 although individual volcanoes have

FIG. 25. ALKALI - LIME INDEX FOR ROCKS OF ST. LUCIA, MONTSERRAT, LASSEN PEAK AND CRATER LAKE.



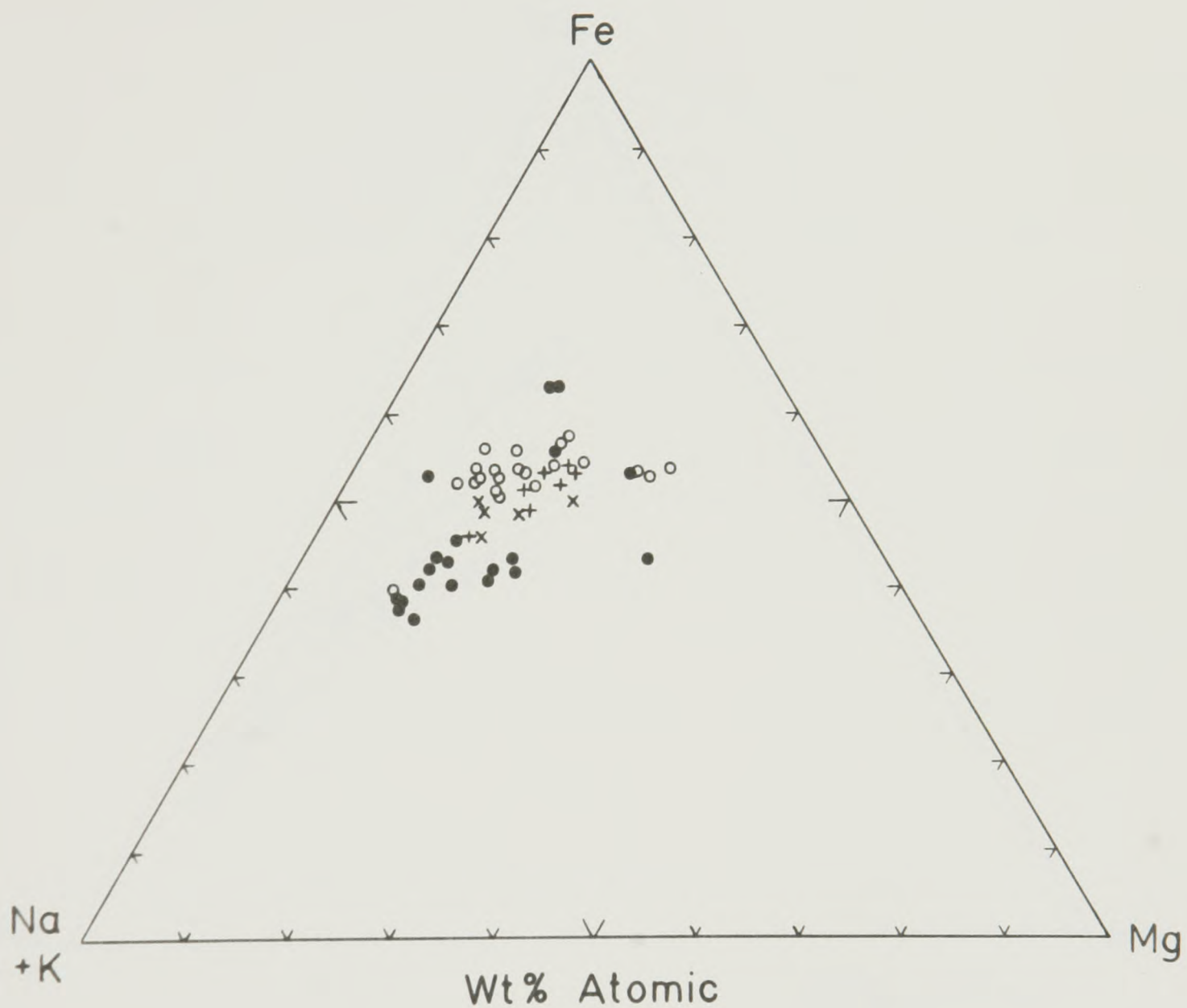
indices of up to 67 (Taneda, 1963, p.423). Values for the Lesser Antilles are appreciably higher than for Crater Lake, with an index of 62, and Lassen Peak for which the index is 63.9 (Williams, 1942, p.153).

#### 8. 4. Fe : Mg : Na+K RATIOS

The relative proportions of iron, magnesium and alkalis as atomic percentages in rocks from St. Lucia and three other Lesser Antillean islands are plotted on a triangular diagram in Fig.26. In Fig.27, the same plots for St. Lucia are shown alongside curves for Hakone volcano (data from Nockolds and Allen, 1956, pp.48-50), the "Antilles average" of Nockolds and Allen (1953, p.111, based on lavas from Martinique and Montserrat), Crater Lake and Mt. Shasta (Nockolds and Allen, 1953, p.111), and Lassen Peak (Nockolds and Allen, 1953, p.114).

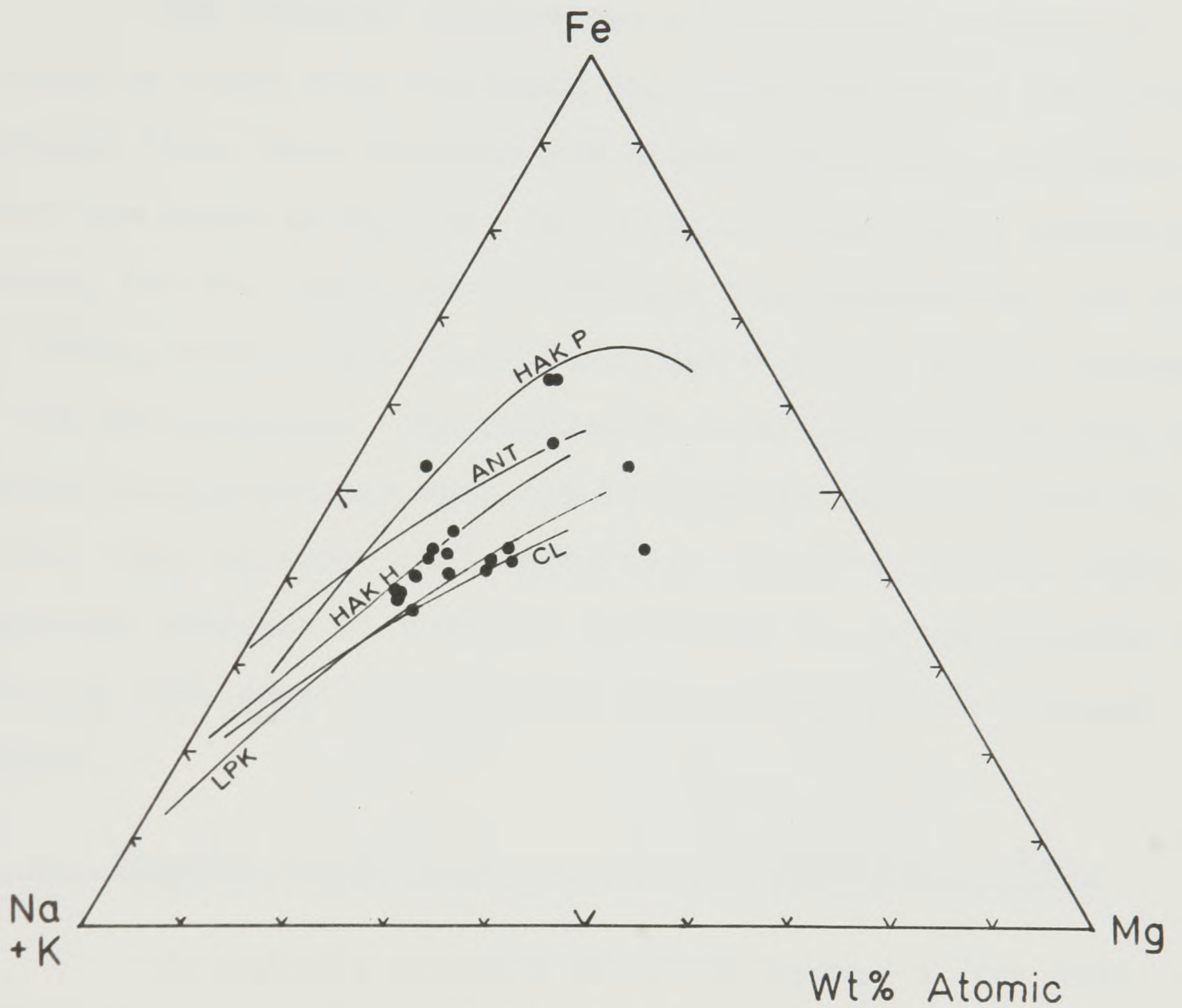
Andesites and dacites from St. Lucia fall on a short trend showing an increase of alkalis in the more acid rocks. This series is relatively poor in iron, falling between the Crater Lake and Hakone "hypersthenic" trends. The basic rocks from St. Lucia scatter widely: the hornblende dolerite xenolith L.717 is rich in magnesium, and almost certainly contains "accumulative" hornblende. The two aphyric basalts are rich in iron, and lie on the Hakone "pigeonitic" trend. This enrichment in iron may be the result of separation of early-crystallising magnesium-rich minerals: in the Skaergaard and similar differentiated basic intrusions which show extreme enrichment of iron in the later crystallizing liquids, it has been explained as

FIG. 26. PLOT OF Fe : Mg : Na+K RATIOS IN ROCKS OF THE LESSER ANTILLES



- St. Lucia
- x Martinique
- + Montserrat
- o St. Kitts

FIG. 27. VARIATION OF Fe : Mg : Na+K IN ROCKS OF THE LESSER ANTILLES AND SIMILAR PROVINCES



- ST LUCIA
- HAK P HAKONE PIGEONITIC SERIES
- ANT LESSER ANTILLES
- HAK H HAKONE HYPERSTHENIC SERIES
- CL CRATER LAKE
- LPK LASSEN PEAK

the result of fractional crystallization (Wager and Deer, 1939, p.313).

### 8. 5. K : Na : Ca RATIOS

The relative proportions of potassium, sodium and calcium in rocks from St. Lucia and other islands of the Lesser Antilles (data from Noekolds and Allen, 1953, and from Baker, 1963) are shown in Fig.28. This diagram shows three distinct trends, for St. Lucia, for Martinique plus Montserrat, and for St. Kitts, which result from differences in the potash content of the three series. The relatively abundant potash in the St. Lucian lavas contrasts with the low content in lavas from St. Kitts. Fig. 29 shows that lavas from these two islands also represent extremes of richness and poverty in potash relative to soda and lime compared with many other calcium-rich volcanic suites.

### 8. 6. BELFOND DACITE L.267 AND ITS GLASSY MATRIX L.267g

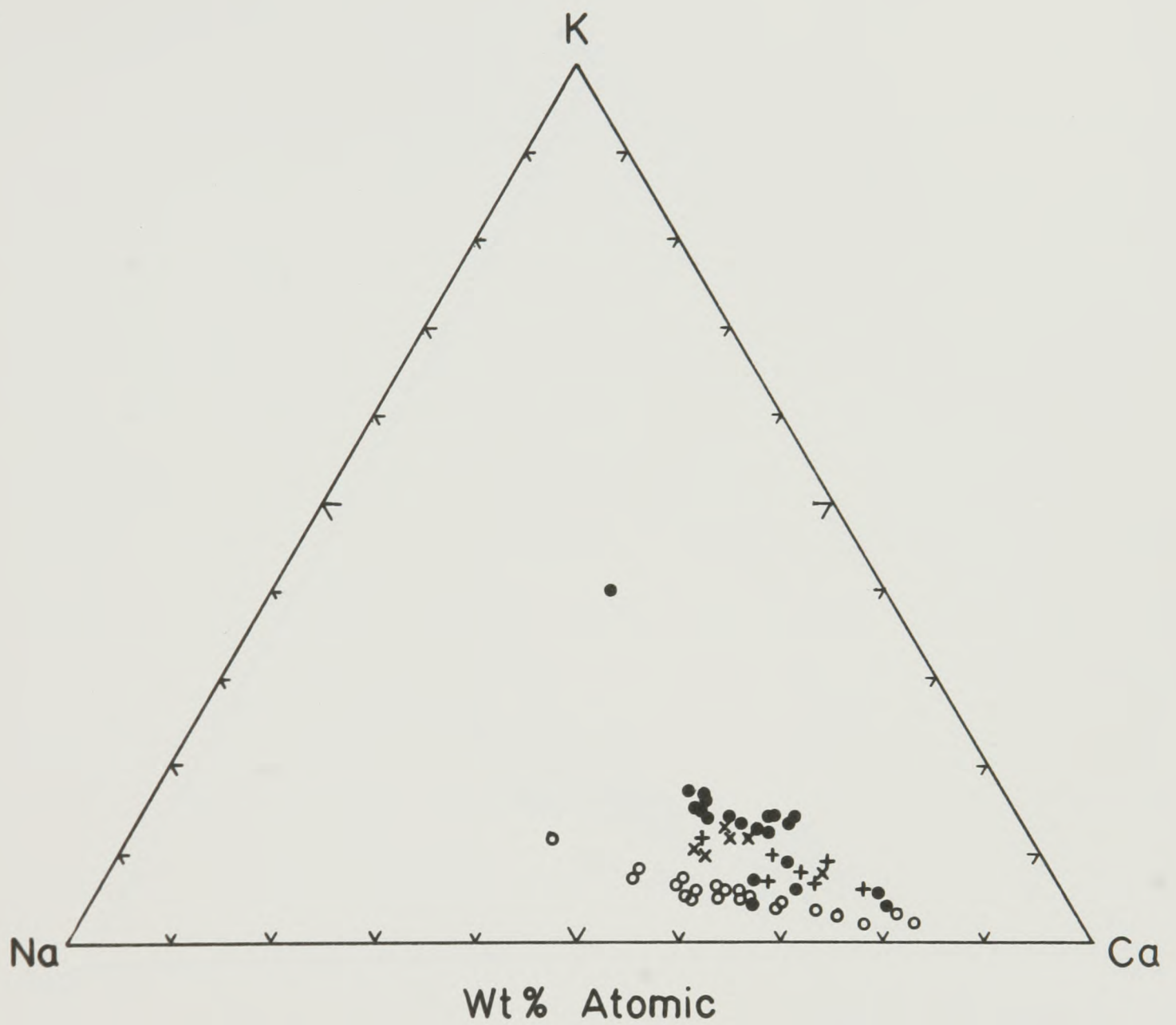
An analysis was made of glass separated from the Belfond dacite L.267. This differs from the whole rock in that it contains:

+ 4.7% $\text{SiO}_2$	- 1.9% $\text{Al}_2\text{O}_3$
+ 2.15% $\text{K}_2\text{O}$	- 2.0% $\text{FeO}$
	- 2.5% $\text{CaO}$

The decrease in alumina and lime reflects the subtraction of 33% of plagioclase phenocrysts, whilst the loss of  $\text{FeO}$  (and  $\text{MgO}$ \*) represent the cummingtonite, of which 5.6% is present in

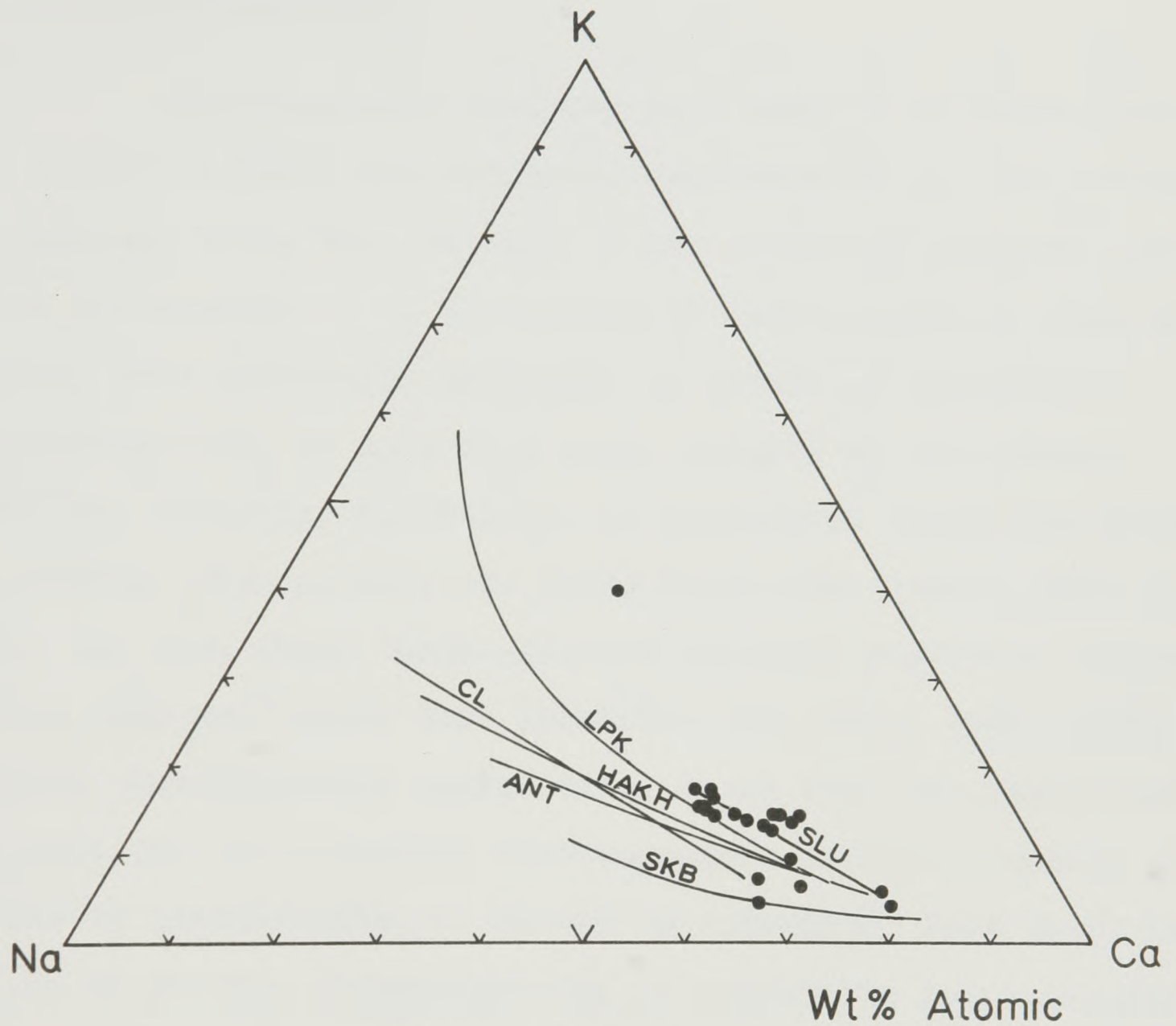
\* A satisfactory result for the  $\text{MgO}$  titration could not be obtained for L.267g, probably due to its very low abundance.

FIG. 28. PLOT OF K : Na : Ca RATIOS IN ROCKS OF THE LESSER ANTILLES



- St Lucia
- × Martinique
- + Montserrat
- St Kitts

FIG. 29. VARIATION OF K : Na : Ca IN ROCKS OF THE LESSER ANTILLES AND SIMILAR PROVINCES



- |       |                            |
|-------|----------------------------|
| SLU ● | ST LUCIA                   |
| LPK   | LASSEN PEAK                |
| CL    | CRATER LAKE                |
| HAK H | HAKONE HYPERSTHENIC SERIES |
| ANT   | LESSER ANTILLES            |
| SKB   | ST KITTS                   |

the whole rock. The glass fraction, on the other hand, is particularly rich in potash, and slightly richer in silica than the dacite lava.

#### 8. 7. MINOR ELEMENTS

Spectrographic analyses were made of 10 rocks from St. Lucia, in which the estimated abundance of 13 minor elements is shown in Table 14. Details of the method of analysis are given in Appendix D. A discussion of each element in turn will follow, with particular reference to trends of variation. Comparisons will be made with other islands of the Lesser Antilles, including Martinique and Montserrat (data from Hockolds and Allen, 1953, p.124), St. Kitts (data from Baker, 1963, p. 164), and with other "calc-alkaline" volcanic provinces, especially Lassen Peak and Crater Lake (Hockolds and Allen, 1953, p.114 and p.126). For numerical correlation, these data are summarized in Table 15. In comparing spectrographic results obtained at different laboratories, it should be remembered that there is likely to be some discrepancy due to systematic inter-laboratory errors. Neither this nor the magnitude of experimental error have been evaluated, though the close agreement between values for many of the minor elements determined by Hockolds and Allen for the Lesser Antillean islands and those made at Oxford suggests that inter-laboratory discrepancies in this case are not large.

The concentration of each minor element in parts per million has been plotted against the function  $\frac{1}{3}\text{Si} + \text{K} - \text{Ca} - \text{Mg}$

Table 14.                      MINOR ELEMENTS IN ROCKS OF ST. LUCIA.

Spec. L.	83	34	717	203	38	290	313	13	590	87
ppm. Ga	10	11	9	17	14	16	14	15	15	17
V	245	290	246	48	59	48	33	37	43	34
Cu	99	88	15	8	8	7	15	6	48	4
Ni	42	10	73	6	6	5	5	4	9	7
Zr	69	90	63	94	116	80	98	90	87	85
Co	18	17	19	11	10	7	5	5	7	4
Sc	58	47	42	17	15	14	11	8	9	6
Cr	176	10	191	28	42	25	17	18	41	36
La	-	-	-	44	-	59	72	53	44	61
Sr	310	273	305	278	295	239	235	268	234	286
Ba	169	190	190	296	378	341	343	237	343	249
Li	12	18	15	19	17	28	34	33	27	34
Rb	29	16	22	48	60	46	72	101	117	122
K/Rb	166	381	277	250	208	280	165	129	102	116

For rock names and localities, see Table 13 (pp. 149-51).

**Table 15.** AVERAGE ABUNDANCE OF MINOR ELEMENTS IN BASALTS, ANDESITES AND DACITES OF THE LESSER ANTILLES AND THE CASCADE PROVINCE, NORTHWESTERN UNITED STATES.

	ST. LUCIA		MPQ. and.	MONTSERRAT		ST. KITTS		LASSEN PEAK		CRATER LAKE			
	bas.	and. dac.		bas.	and. dac.	bas.	and.	bas.	and. dac.	bas.	and. dac.		
Ga	11	16	24	27	25	20	17	17	20	21	20	23	19
V	268	52	100	350	168	100	250	100	235	107	50	138	43
Cu	94	8	n.d.	n.d.	n.d.	n.d.	42	25	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	26	6	1	12	7	-	3	2	100	35	3	44	3
Zr	80	97	86	87	106	100	90	92	130	97	110	118	180
Co	18	9	13	32	20	10	23	16	45	17	5	18	1
Sc	52	15	5	35	25	-	29	15	50	19	-	110	2
Cr	93	32	3	20	8	-	20	7	210	82	8	62	3
La	-	34	-	-	-	-	-	-	-	-	-	-	-
Sr	290	270	325	625	312	250	261	287	825	1100	1250	840	670
Ba	180	383	233	88	162	300	130	263	260	780	750	480	930
Li	15	21	38	13	23	45	n.d.	n.d.	18	44	50	20	34
Rb	23	51	40	15	21	40	n.d.	n.d.	50	84	125	22	84
K/Rb	775	207	234	538	347	228	n.d.	n.d.	160	193	298	523	271

Note. MPQ = MARTINIQUE.

Data for Martinique, Montserrat, Lassen Peak, and Crater Lake from Nockolds & Allen (1953).  
Data for St. Kitts from Baker (1963, p.164).

FIG. 30

## VARIATION OF Ga, V, Co, Ni, Cu, IN ROCKS OF ST. LUCIA

(Figs. 30, 31, 32), allowing direct comparison to be made with similar diagrams presented by Baker for St. Kitts (1963, Figs. 31, 32) and by Nockolds and Allen for world-wide calc-alkaline and other igneous rock series (1953, 1956).

Seven minor constituents of rocks from St. Lucia have also been plotted on a covariance basis (Fig. 33) using a logarithmic scale for the concentration. It is noteworthy that the sequence obtained from this plot (along the abscissa) corresponds remarkably closely to the sequence according to silica content (see Fig. 24), and to the sequence of eruption in time.

### Gallium

Gallium shows little systematic variation. It is, however, invariably lower in the basalts and dolerite inclusion L.717 (9 - 11 p.p.m.) than in the andesite-dacite series (14 - 17 p.p.m.). It increases with Al-content from basalts to andesites, and reaches a maximum of 17 p.p.m. in the rock which is richest in aluminium (L.203). Gallium does not, however, decrease with decreasing aluminium in the dacites. Nockolds and Allen (1953, p.117) comment on this mild enrichment in Ga with respect to Al at the extreme acid end of some series (e.g. Lassen Peak, Scottish Caledonian). Table 15 shows that gallium tends to be slightly less abundant in St. Lucian rocks than in other similar series. This applies especially to the basalts, and may be explained at least in part by the fact that these rocks are distinctly poorer in alumina (average 16.2%) than, for example, their counterparts from St. Kitts, which contain

FIG. 30

VARIATION OF Ga, V, Cu, Ni, Co, IN ROCKS OF ST LUCIA

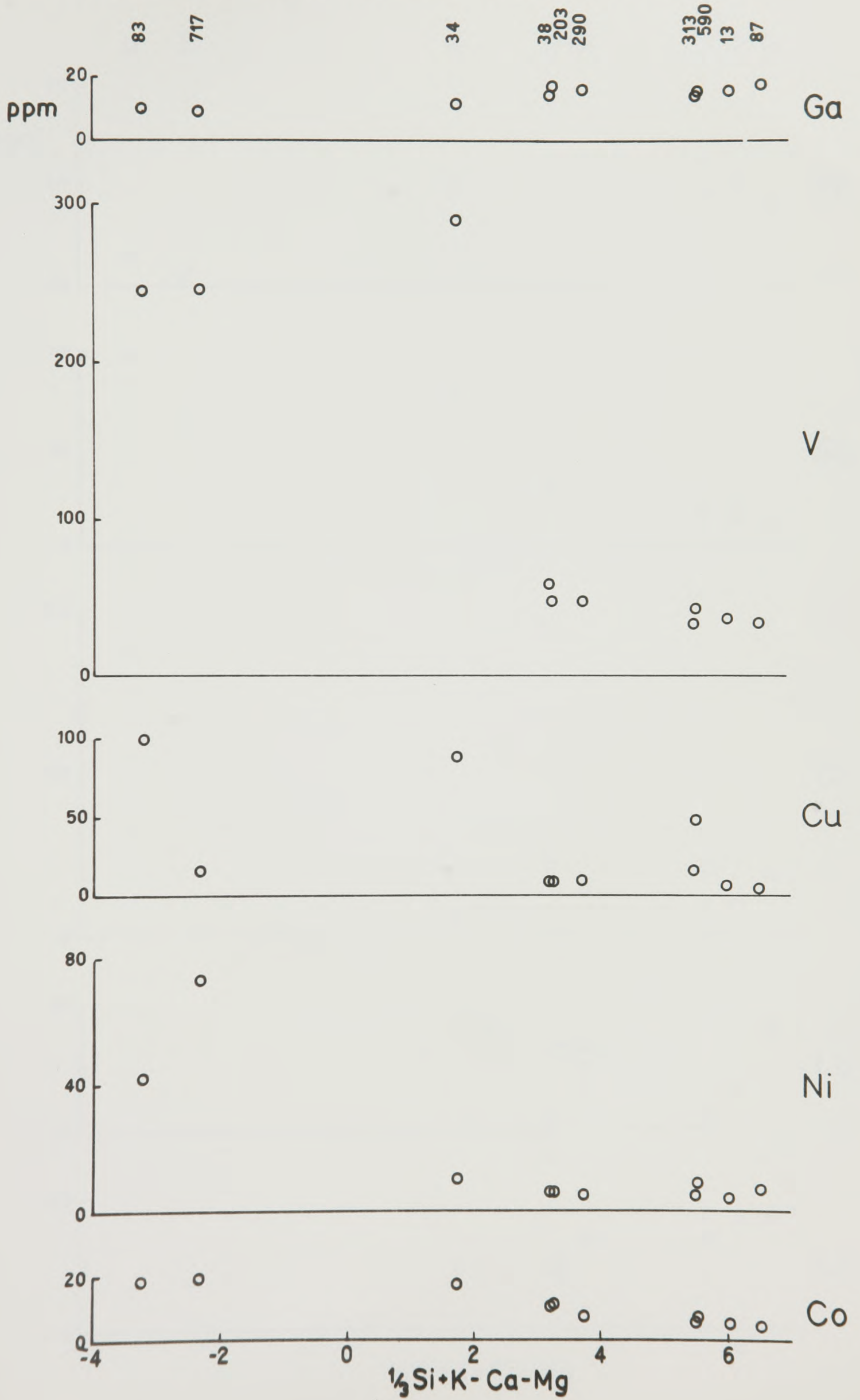


FIG. 31

VARIATION OF Zr, Sc, Cr, La, Li IN ROCKS OF ST LUCIA

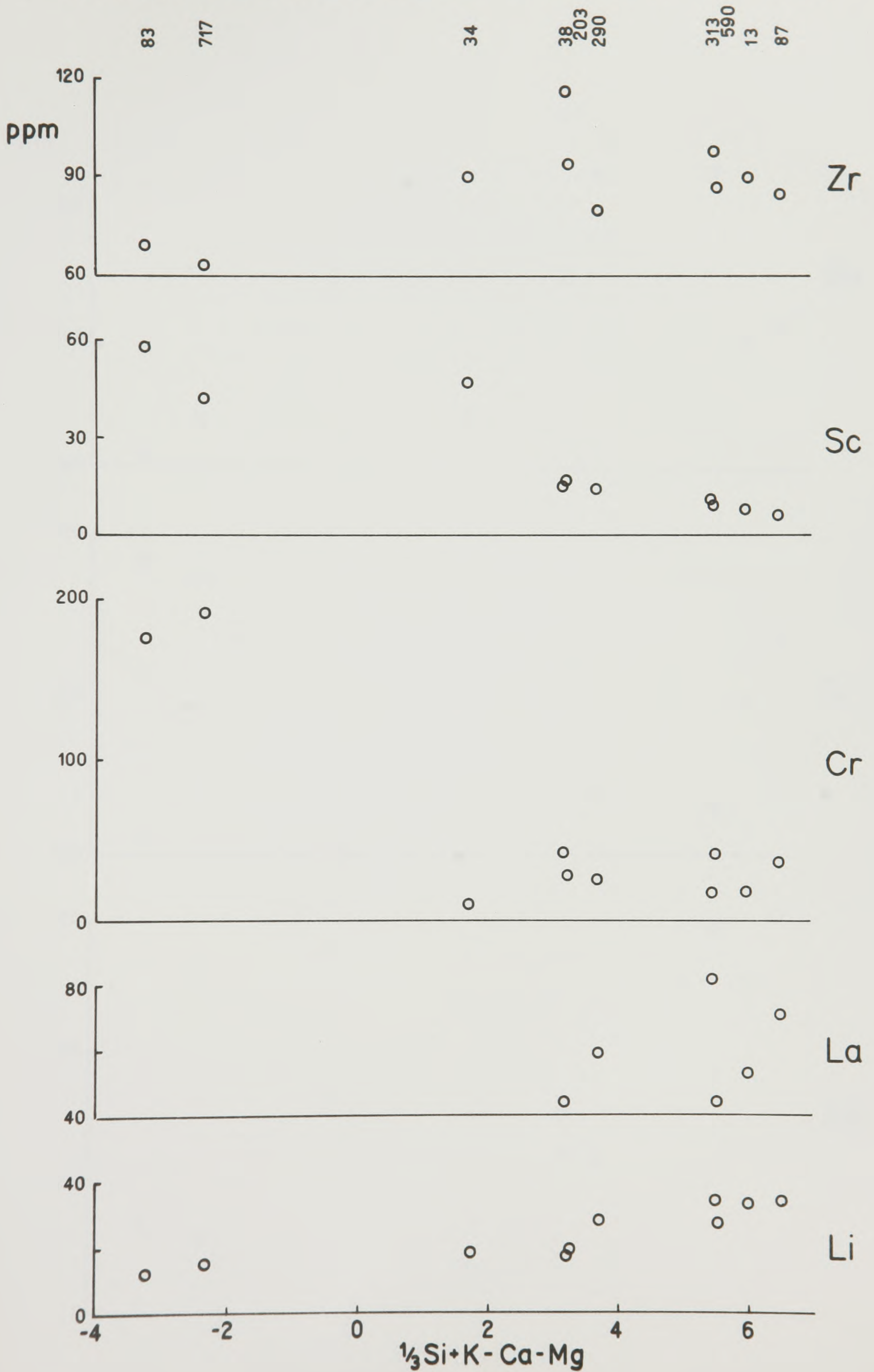


FIG. 32

VARIATION OF Ba, Sr, Rb IN ROCKS OF ST LUCIA

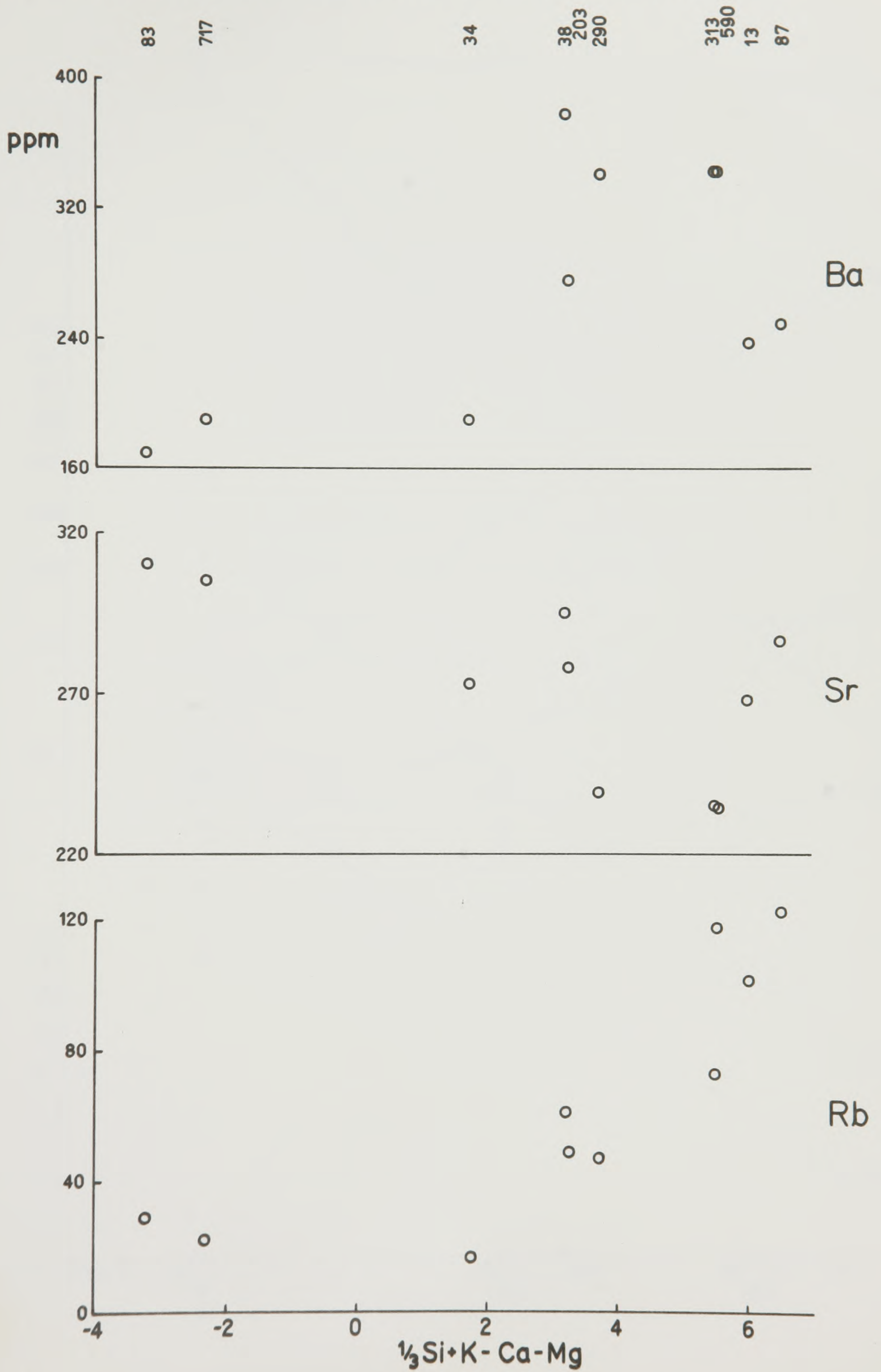
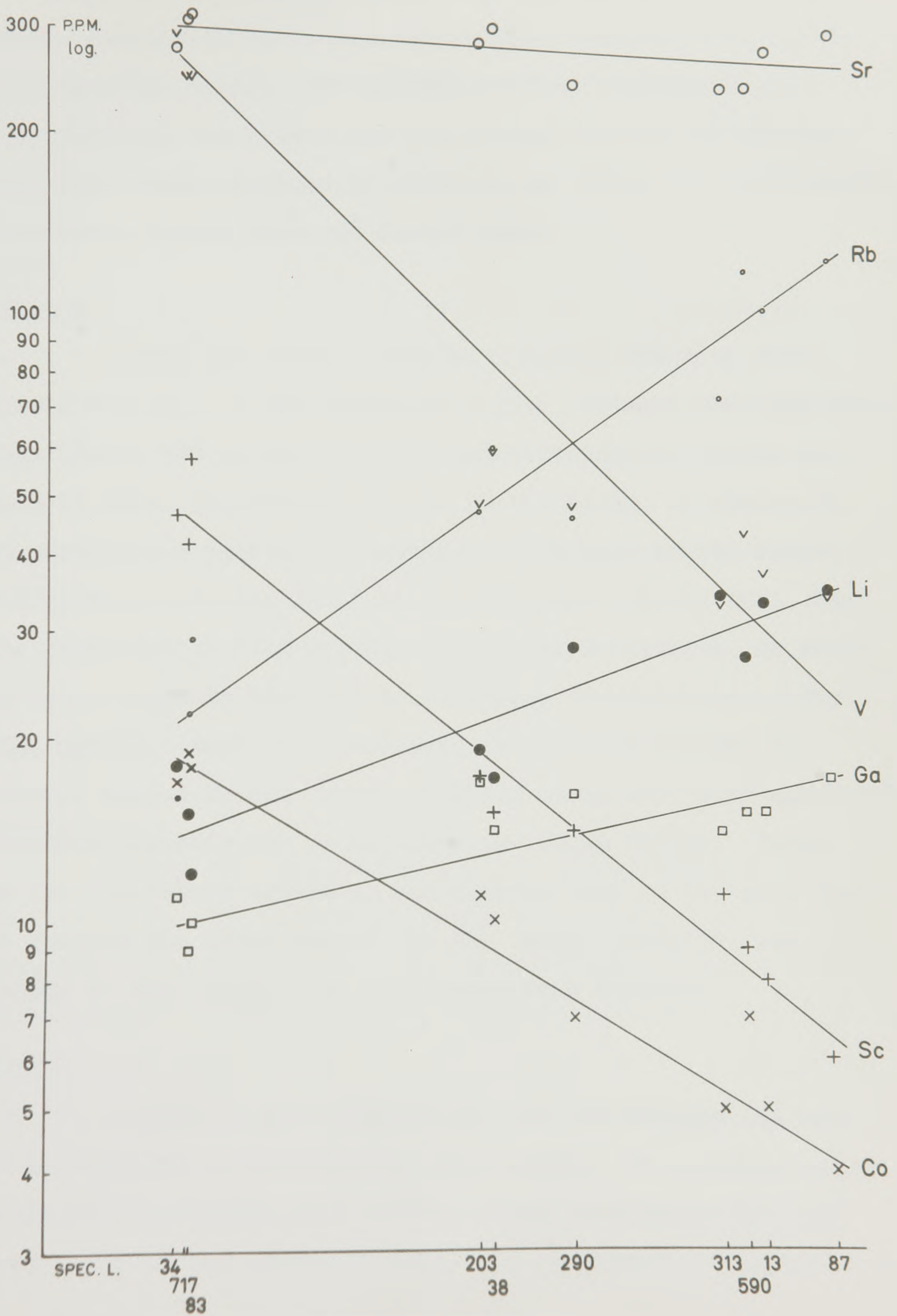


FIG. 33. CO-VARIATION OF TRACE ELEMENTS IN ROCKS OF ST LUCIA



an average of 19.6%  $Al_2O_3$ . The St. Kitts andesites are more closely similar in aluminium and gallium content to andesitic rocks from St. Lucia. The gallium values recorded by Baker (see Table 15, St. Kitts) and the present author are slightly lower than those obtained by Hockolds and Allen for Martinique, Montserrat, Lassen Peak and Crater Lake.

### Vanadium

Among the minor elements, vanadium shows up most clearly the gap, in the Soufrière region, between the basaltic rocks (245 - 290 p.p.m.) and the andesite-dacite series, in which it never exceeds 59 p.p.m. On St. Kitts, no comparable gap occurs, and points are evenly distributed on the curve which plunges steeply from 300 to 40 p.p.m. (Baker, 1963, Fig. 31). The same applies for Martinique and Montserrat, in which the total range is from 400 to 50 p.p.m. (Hockolds and Allen 1953, p.132). This rapid decrease in vanadium content is, however, unique to the Lesser Antilles among the "calc-alkaline" provinces investigated by Hockolds and Allen (1953). Values for the St. Lucian andesites and dacites tend to be lower than the average for other islands of the Lesser Antilles, but are similar to the Crater Lake and Lassen Peak dacites.

### Copper

Copper is most abundant in the two basalts (nearly 100 p.p.m.) and in the microtonalite L.590. It probably occurs mainly in association with pyrite, which is visible only in these three of the analysed rocks. It is slightly less abundant

in the dacites (5 p.p.m.) than in the andesites (8 p.p.m.), and least abundant in the most acid member of the series. The range of values resembles that recorded by Baker (1963, p.170) for St. Kitts, although the average abundance in the andesites is notably less in those from St. Lucia.

### Nickel

Nickel is relatively abundant in the porphyritic basalt L.83 (42 p.p.m.) and most abundant in the hornblende dolerite inclusion L.717 (73 p.p.m.). It is as low in the aphyric basalt L.34 as in the andesites and dacites, in which it ranges from 4 - 10 p.p.m. with no systematic variation. Hockolds and Allen (1953, p.122) comment on the relative paucity of nickel in rocks of the Lesser Antilles, compared with other series included in their "calc-alkali" group. Except for L.83 and L.717, the St. Lucian values closely resemble others from the Lesser Antilles.

### Zirconium

Zirconium fluctuates little: between 85 - 98 p.p.m. are present in all St. Lucian specimens except three: in the porphyritic basalt and the hornblende dolerite it is slightly less abundant (63 - 69 p.p.m.). The dark andesite L.38 contains 116 p.p.m. The zirconium range in basalts of St. Lucia is slightly lower, but in the andesites and dacites is similar to other islands of the Lesser Antilles, and to the Cascade province.

### Cobalt

Cobalt is twice as abundant in the basaltic rocks (17 - 19 p.p.m.) as in any of the andesite-dacite series, in which it falls from 10 to 4 p.p.m. with increasing acidity. Values for the andesite-dacite series are about half those recorded for other islands of the Lesser Antilles, whilst the cobalt content of the basaltic rocks of St. Lucia is slightly lower than average. The St. Lucian dacites, however, resemble those of Lassen Peak.

### Scandium

Scandium follows a similar pattern to cobalt: basaltic rocks, which contain 58 - 42 p.p.m., are clearly separated from andesites and dacites, in which scandium decreases with increasing acidity from 17 to 6 p.p.m. The scandium content of the basalts is slightly higher than that of other Lesser Antillean centres and of the Cascade province.

### Chromium

Chromium, like nickel, is most abundant (176 - 191 p.p.m.) in the porphyritic basalt (L.83) and in the dolerite inclusion (L.717), and relatively rare in all other rocks, which contain less than 50 p.p.m. It is least abundant in the aphyric basalt L.34, and relatively scarce in the Piton dacite (L.13) and tonalite xenolith (L.313). Wager and Mitchell (1951, p.183) have shown that chromium is especially concentrated in the early-formed pyroxenes, e.g. the porphyritic pyroxenes of basalts, and this explanation certainly seems appropriate for

the St. Lucian porphyritic basic rocks. The hypothesis is further supported by the fact that the aphyric lava L.34, which contains 25% groundmass clinopyroxene, of later crystallization, contains only 10 p.p.m. chromium. Chromium does not appear to be associated with the orthopyroxene phenocrysts of the andesites. It is worthy of note that St. Lucian lavas contain five times as much chromium as other islands of the Lesser Antilles. The St. Lucian values, on the other hand, are comparable with those for the Cascade and other provinces included by Nockolds and Allen (1953) in their "calc-alkali" group.

#### Lanthanum

Lanthanum, whose presence cannot be detected below about 40 p.p.m., was recorded only in 6 of the more acid rocks from St. Lucia. It was not recorded in rocks from St. Kitts, and was detected by Nockolds and Allen (1953) only in granites from the Southern California Batholith and the Scottish Caledonian Series, and in East Central Sierra Nevada rhyolites.

#### Strontium

The range of values for strontium is similar to that quoted by Baker (1963, p.164) for St. Kitts (250 - 350 p.p.m.), but low in comparison with the Montserrat basalt, and with Lassen Peak and Crater Lake rocks, all of which contain over 600 p.p.m. Strontium shows no systematic variation in the rocks of St. Lucia. Turekian and Kulp (1956, p.294) state that strontium is independent of calcium in basaltic rocks. This applies

in the basalts of St. Lucia, in which a higher content of calcium is not accompanied by increased strontium.

### Barium

Barium contents vary between 150 - 400 p.p.m. and are comparable with those of other islands of the Lesser Antilles and with the Crater Lake series. In St. Lucia, barium is more abundant in the andesites and dacites (237 - 343 p.p.m.) than in the basaltic rocks (160 - 190 p.p.m.). If the microtonalite (L.590) is ignored, there appears to be a slight decrease in the most acid rocks (L.13 and L.87), as observed in the Lassen Peak and Scottish Caledonian Series by Hockolds and Allen (1953).

### Lithium

Lithium shows a steady increase with the function  $Si + K - Ca - Mg$ , from 12 p.p.m. in the porphyritic basalt L.83, to 34 p.p.m. in the Belfond dacite L.87. A gap from 19 - 28 p.p.m. exists between the dark and pale andesites. The range of values is similar to those for Montserrat, Lassen Peak and Crater Lake.

### Rubidium

Rubidium in the St. Lucian rocks is of particular interest, because it shows a sharp increase in abundance towards the acid end of the andesite-dacite series. The basaltic rocks contain between 16 - 29 p.p.m., the andesites 46 - 60 p.p.m., and the dacites from 72 - 122 p.p.m. This last figure is larger than any recorded elsewhere in the Lesser Antilles, and

causes a remarkably low value for the  $K/Rb$  ratio, comparable only to the extreme acid end of the Scottish Caledonian series among the "calc-alkali" group investigated by Hockolds and Allen (1953). With reference to the Scottish Caledonian rocks, these authors state (1953, p.137) that in view of the ionic radii of the two elements, the  $K/Rb$  ratio might be expected to decrease in the later rocks, but that such a decrease is "very small and only becomes appreciable at the final residual stage". This ratio does, however, decrease steadily in the Montserrat and Crater Lake series, as well as in the St. Lucian rocks.

- 3) A gap in chemical composition (and time) between the basaltic and andesitic.
- 4) Chemical and mineralogical continuity between the andesites and basaltic.
- 5) A high proportion of andesites and basaltic, relative to basaltic, exposed at the surface.
- 6) The occurrence in almost all areas of crystalline-cored, calcite-rich plagioclase phenocrysts (including calcite crystalline cores).
- 7) The occurrence of large quartz crystals, often forming glaucophane phenocrysts, in the andesites and basaltic.

### 3.2.2.2.2.2

The principal types of basalt occur in the basaltic region: aphyric and porphyritic. The aphyric basalt is rich in iron and poor in alumina, and contains a high percentage of normative quartz and hypersthene (see table 12, analyses 2 and 4). In these features they compare closely to the andesites.

## 9. PETROGENESIS

### 9. 1. PRINCIPAL FEATURES OF THE SOUFRIÈRE REGION

The principal features which must be accounted for in a system of rock genesis applicable to the Soufrière region are:

- 1) An increase in silica content with time, from basalts with 50%, to dacites with 66%  $\text{SiO}_2$ . There appear to have been no reversions of this trend.
- 2) The presence of two distinct types of basalt.
- 3) A gap in chemical composition (and time) between the basalts and andesites.
- 4) Chemical and mineralogical continuity between the andesites and dacites.
- 5) A high proportion of andesite and dacite, relative to basalt, exposed at the surface.
- 6) The occurrence in almost all rocks of oscillatory-zoned, calcium-rich plagioclase phenocrysts (including calcic bytownite cores).
- 7) The occurrence of large quartz crystals, often forming globular xenocrysts, in the andesites and dacites.

### 9. 2. BASALT TYPES

Two principal types of basalt occur in the Soufrière region: aphyric and porphyritic. The aphyric lavas are rich in iron and poor in alumina, and contain a high percentage of normative quartz and hypersthene (see Table 12, analyses 2 and 4): in these features they correspond closely to tholeiitic

basalt (e.g. Turner and Verhoogen 1960, p.208-9). In the porphyritic basalts, on the other hand, normative quartz is present but less abundant (not >6%), and the rocks are relatively rich in alumina, being chemically very close to the average high-alumina basalt of Japan (Table 16, column 9). The presence or absence of phenocrysts in the basalts cannot be attributed simply to their crystallization history, since their bulk chemical compositions are different (Table 12).

Basalts have recently been discussed (Kuno, 1960; Yoder and Tilley, 1962) in terms of three principal types, namely alkali, tholeiitic, and high-alumina. Alkali basalts are not present in St. Lucia. Aphyric basalts of tholeiitic type are found in St. Lucia, together with porphyritic basalts with a high alumina content. The field and chemical relationships of these two types provide some evidence bearing on the validity of high-alumina basalt as a distinct type.

In his definition of high-alumina basalt, Kuno (1960, p.122) specified the following properties:

- 1) A higher content of  $Al_2O_3$  than tholeiite with corresponding  $SiO_2$  and alkalis,
- 2) Lower total alkalis than alkali-basalt,
- 3) Aphyric texture.

To illustrate the first two characteristics, he used a diagram in which  $Al_2O_3$  is plotted against  $Na_2O + K_2O$  for rocks within a given silica range (see Fig. 34), and stated (Kuno, 1960, p.131) that "the points for each type of basalt, including both

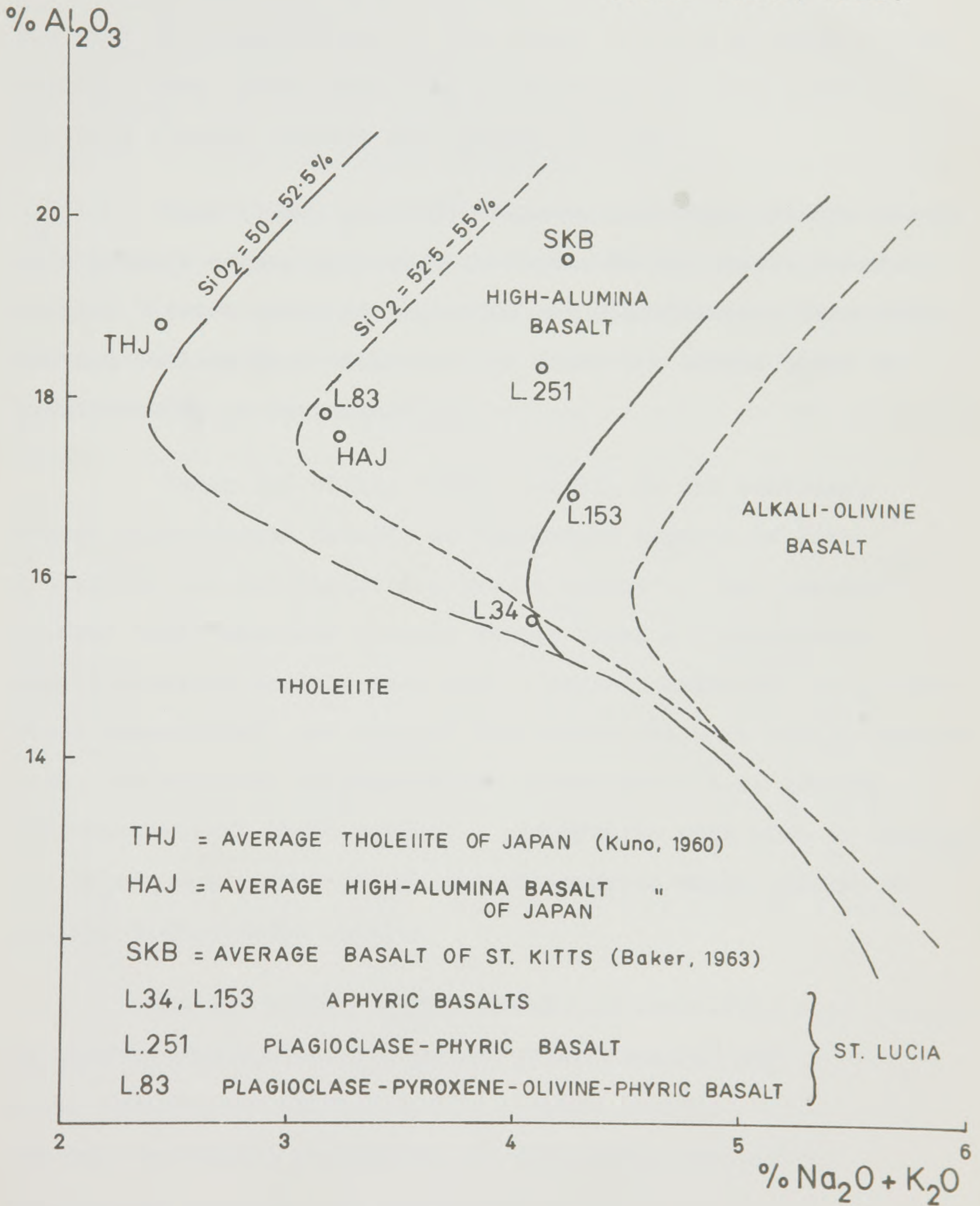
Table 16 COMPARISON OF CHEMICAL COMPOSITIONS OF BASALTIC ROCKS FROM ST. LUCIA AND OTHER AREAS. (all analyses recalculated to 100%, volatile-free).

	1	2	3	4	5	6	7	8	9
SiO <sub>2</sub>	52.0	54.3	54.0	52.0	54.9	51.8	51.2	51.0	50.2
Al <sub>2</sub> O <sub>3</sub>	17.8	16.2	18.4	15.1	16.3	19.6	15.3	15.6	17.6
Fe <sub>2</sub> O <sub>3</sub>	2.6	2.7	2.0	2.7	3.8	3.5	5.0	1.1	2.8
FeO	5.9	9.2	6.9	9.9	7.9	5.5	7.9	9.8	7.2
MgO	5.5	3.3	3.8	5.5	3.5	4.0	5.7	7.0	7.4
CaO	11.8	9.1	9.4	10.2	7.9	10.1	9.3	10.5	10.5
Na <sub>2</sub> O	2.5	2.6	3.3	1.7	3.5	3.6	3.1	2.2	2.8
K <sub>2</sub> O	0.6	0.8	0.8	0.8	0.6	0.5	0.7	1.0	0.4
TiO <sub>2</sub>	0.7	1.2	1.2	1.7	1.0	1.0	1.4	1.4	0.8
P <sub>2</sub> O <sub>5</sub>	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2
MnO	0.2	0.3	0.1	0.2	0.3	0.2	0.3	0.3	0.2

1. Plagioclase-clinopyroxene-olivine-phyric basalt, St. Lucia. L.83.
2. Analysis 1, minus phenocrysts\* (25.5% An<sub>64.6</sub>; 11.0% Wo<sub>46</sub>En<sub>39</sub>Fe<sub>15</sub>; 3.5% Fo<sub>82</sub>).
3. Plagioclase-phyric basalt, St. Lucia. L.251.
4. Analysis 3, minus phenocrysts\* (30% An<sub>55.2</sub>).
5. Average aphyric (tholeiitic) basalt from St. Lucia: average of analyses L.153, L.34.
6. Average basalt of Mt. Misery, St. Kitts (Baker, 1963, p.193).
7. Average basalt of Mt. Misery, minus phenocrysts (Baker, 1963, p.193).
8. Average tholeiite. (Green and Foldervaart, 1955, p.185).
9. Average high-alumina basalt of Japan (Kuno, 1960, p.141).

\* Representative chemical compositions of phenocryst minerals were taken from Deer, Howie and Zussman, 1963, Vols. 1, 2, 4.

FIG. 34.  $\text{Al}_2\text{O}_3 - \text{Na}_2\text{O} + \text{K}_2\text{O} - \text{SiO}_2$  DIAGRAM  
 (after Kuno, 1960)



the porphyritic and aphyric rocks, lie in a definite field".

Yoder and Tilley (1962, p.419), however, rejected the need for restrictions in the alkali content of high-alumina basalt. They stated that "the distinction of these rocks is the high alumina content and aphyric texture".

Kuno (1960, p.141-2) believes that high-alumina basalt is a primary magma, generated at depths in the mantle intermediate between those of tholeiite and alkali-basalt formation, and not derived from either of the other two basalt types by fractionation or contamination.

Yoder and Tilley (1962, p.419), on the contrary, regard high-alumina basalts as "important members of both tholeiitic and alkali-olivine basalt groups". They conclude (p.420) that "whatever process brings forth a high-alumina basalt involves for the most part a concentration of the plagioclase components", and suggest that among the more likely mechanisms, the settling of plagioclase phenocrysts (i.e. gravity differentiation) might produce a porphyritic rock rich in alumina, and subsequent re-melting of the phenocrysts might produce an aphyric high-alumina basalt.

In St. Lucia, aphyric basalt of tholeiitic type (L.153) is closely associated with basalt which contains 30% of plagioclase phenocrysts and is rich in alumina (L.251). This demonstrates the strong possibility of mechanical concentration of plagioclase crystals and consequent increase of  $Al_2O_3$  in the

porphyritic rock. In Table 16, the chemical compositions of both basalt types are shown alongside the calculated chemical composition of analysed porphyritic rocks minus phenocrysts, and these are compared with the compositions of average tholeiite and average high alumina basalt. In particular, attention is drawn to the similar content of alumina (15-16%) and total iron (11-13%) in the porphyritic basalts minus phenocrysts (Table 16, columns 2, 4, 7), and in the aphyric basalts (Table 16, columns 5, 8). It is noteworthy that truly aphyric basalts of the type found in St. Lucia seem to be rare in the Lesser Antilles in general, although apparently widespread at depth in the Soufrière region, since they occur as inclusions in several of the more recent dome lavas (e.g. Plate 7a). In the island as a whole, however, porphyritic basalts greatly predominate at the surface (see Fig. 8). No aphyric, alumina-rich basalts of the type recorded in Honshu and Izu, Japan (Kuno, 1960, p.124), and the Medicine Lake Highlands (Anderson, 1947, p.387), i.e. high-alumina basalt, *sensu stricto*, have been identified in St. Lucia. Two specimens, described as "almost aphyric" have been reported by Baker (1963, Plate 16, samples K.14 and K.244) from St. Kitts. It is clear that the critical factor, in a discussion of the validity of high-alumina basalt, is the origin of the plagioclase phenocrysts. If co-magmatic with the groundmass of the porphyritic basalt, i.e. originating from the same liquid, then this liquid was a potential high-alumina basalt, *sensu stricto*, in that it might have crystallized as an aphyric rock.

In addition to the evidence from St. Lucia, the occurrence on St. Vincent (Wager, 1962) and St. Kitts (Baker, 1963) of holocrystalline ejected blocks which are almost certainly accumulative, and of similar plutonic blocks together with highly porphyritic and almost aphyric lavas in the South Sandwich Island arc (collected by Baker and Tomblin in 1964, and currently being studied at Oxford), provide additional evidence that crystal differentiation is a process which may operate in basaltic magmas beneath island arcs. It seems doubtful, however, that in St. Lucia this process has contributed significantly to the production of the andesites (see section 9. 3.).

Hence, if a single, homogeneous parent of the St. Lucian basalts ever existed, it seems likely that this had a composition lying between that of the aphyric (tholeiitic) and porphyritic (alumina-rich) rocks, and that the accumulation of early-crystallizing, plagioclase feldspar produced the alumina-rich, plagioclase-phyric rocks. As an equally possible alternative, however, it is suggested that there may have been two different, primary basalt magmas in the Soufrière region, and this is supported by the fact that no types gradational between the porphyritic and aphyric lavas have been found.

### 9. 3. ORIGIN OF THE ANDESITE - DACITE SERIES

The andesites and dacites of the Soufrière region form a series of chemically and mineralogically gradational

types, showing progressive enrichment in silica corresponding to the chronological sequence of emission. They occupy approximately 90% of the Soufrière region, and an estimated 75% of the island as a whole: thus they predominate greatly over the basaltic rocks.

Most theories to explain the origin of the intermediate and acid rocks of orogenic regions invoke one or more of three principal processes, involving:

- 1) Fractionation of a basic "parental" magma formed at depth, i.e. derived from the mantle by crystal fractionation.
- 2) Contamination of a mantle differentiate by "granitic" crustal material.
- 3) Melting, in part or whole, of crustal material, i.e. a magma formed solely within the crust.

The first process, involving simple fractionation of a basaltic parent, has been rejected by many authors (e.g. Turner and Verhoogen, 1960, p.286) as incapable, alone, of accounting for the production of andesites and dacites to form island arc volcanoes, principally on account of the frequent, large predominance of andesitic over basaltic material exposed at the surface.

The second process, involving the mixing of basic and acid material (c.f. Wager and Deer, 1939, p.335), or a combination of this process and the first, e.g. sialic contamination of a basaltic parent, followed by fractional crystallization

(c.f. Tilley, 1950, p.59), have enjoyed a much wider popularity as a means of explaining the origin of many andesites and dacites. In this case, however, doubt may again be cast on the ability of a basaltic magma to assimilate, in the course of its passage upward through the crust, a sufficiently large amount of granitic material to produce the high proportion of acid rocks often observed. Moreover, acid xenoliths which might represent partially assimilated material are extremely rare in the lavas of St. Lucia, and although Kuno (1950, p.999) has described examples from Japan of granitic and sandstone xenoliths in basalts of the hypersthenic series, Schmidt (1957, p.172) with reference to the Mariana Islands, Japan, concluded that fractional crystallization and assimilation were probably accompanied by the third process, namely differential fusion. It seems unlikely that a combination of the first two processes (i.e. assimilation and fractional crystallization), even if it were to occur extensively, would follow such a pattern that each successive pulse of magma would be progressively more silica-rich, as is the observed sequence in St. Lucia.

The third process, which invokes the concept that magmas may be derived by downbending of the normally horizontally layered crust and consequent fusion of those layers with lower melting-temperatures, was proposed by Kennedy and Anderson (1938). This hypothesis was elaborated by Buddington (1943), who emphasised that partial rather than complete fusion was likely to occur in any given layer. Hess (1950b, p.182) pointed

out that "In orogenic belts the chronological sequence of intrusion of calc-alkaline magmas is commonly from mafic to felsic", a fact which he related to the partial fusing of successively higher, more acid crustal layers. Hess also pointed out the relatively restricted range of solid-solution mineral compositions theoretically obtainable by partial melting. As a hypothetical example, he described the material obtained by partial fusion at depth of a dolerite with an MgO:FeO ratio of 60:40. He stated (1960b, p.183) that "The first pyroxene crystals to melt (referring to the data by Bowen and Schairer for synthetic pyroxenes) would have an MgO:FeO ratio of 35:65, but this would increase to 45:55 by the time enough liquid was formed to be removable from the crystal mush. The final ratio for complete fusion might well be expected to be stopped by the refractory brake when a ratio of 55:45 was reached. Thus the total range of liquids which might be intruded into higher horizons would lie between MgO:FeO ratios 45:55 to 55:45 or a total variation of about 10 per cent."

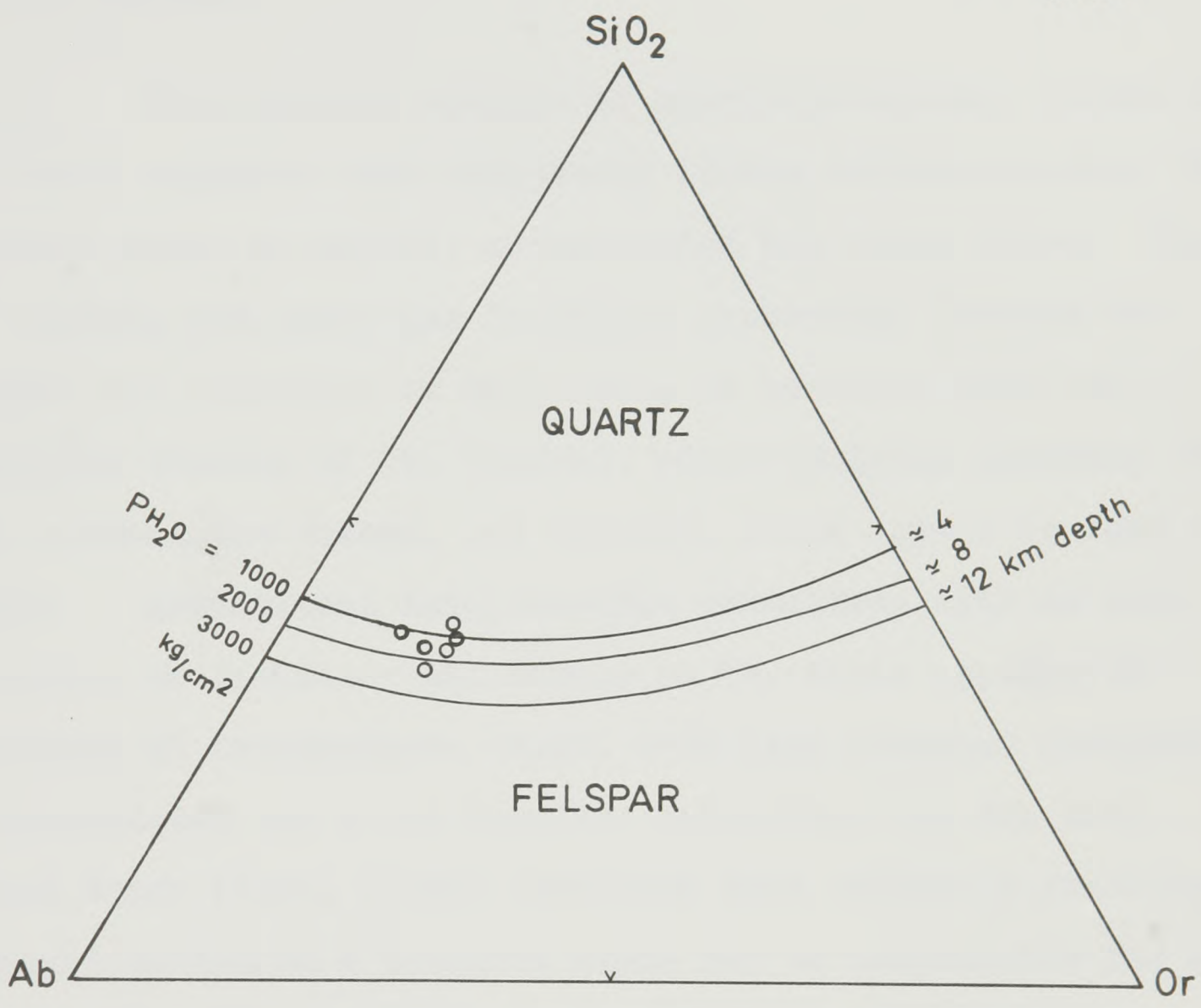
It is noteworthy that in the andesite-dacite series of St. Lucia, the pyroxenes fall in the relatively narrow range  $En_{54-38}$  with the higher values ( $En_{45-54}$ ) in the andesites, which according to the system of Hess would represent lower, earlier and more fully melted crust. Hess also stated (1960b, p.184) that "an entirely analogous situation exists as regards the An:Ab ratio with partial fusion as compared to fractional crystallization." In the andesites and dacites of St. Lucia,

the estimated average composition of plagioclase phenocrysts lies between An<sub>70-57</sub>\*. A process of partial fusion, moreover, could account for the existence of corroded cores of bytownite, including those showing replacement structure (see section 7.8) which are believed by the present author to represent incompletely fused, pre-existing material carried to the surface. The "xenocrysts" of globular quartz on the other hand, which are common in the andesites and dacites of St. Lucia, are believed to represent not relict crystals carried away by the fused portion of the crust, but rather genuine phenocrysts which grew in the new acid magma whilst still at depth, i.e. under a water vapour pressure at which they were in equilibrium with the melt (see Fig. 35). Subsequent lowering of the water vapour pressure, during a prolonged period in which the quartz crystals remained in a liquid near the surface (e.g. in the Piton dacites, see section 7.8.), allowed resorption to take place. If, as several authors (e.g. Larsen and Irving, 1938, p.253) have suggested, the rounded quartz crystals are regarded as xenocrysts entrained in the ascending magma in the same manner as the calcic plagioclase cores, an explanation remains to be given of the co-existence of coarsely crystalline quartz and bytownite at depth. This does not, of course, imply that all quartz xenocrysts (e.g. those in the basalt lavas of San Juan, Colorado, described by Larsen and Irving in 1938) are the result of physical changes operating in a single, relatively homogeneous magma.

As final evidence in favour of a process of crustal fusion. Hess cites the position of a partially melted grano-

FIG. 35. NORMATIVE % Qz, Or, Ab IN DACITES OF ST. LUCIA

Isobars after Tuttle & Bowen  
1958



diorite xenolith (Larsen and Switzer, 1939) and its glass fraction on the MgO:FeO:total alkalis diagram as an example of differentiation along the calc-alkaline trend, resulting from partial fusion.

NO. OF ANALYSES

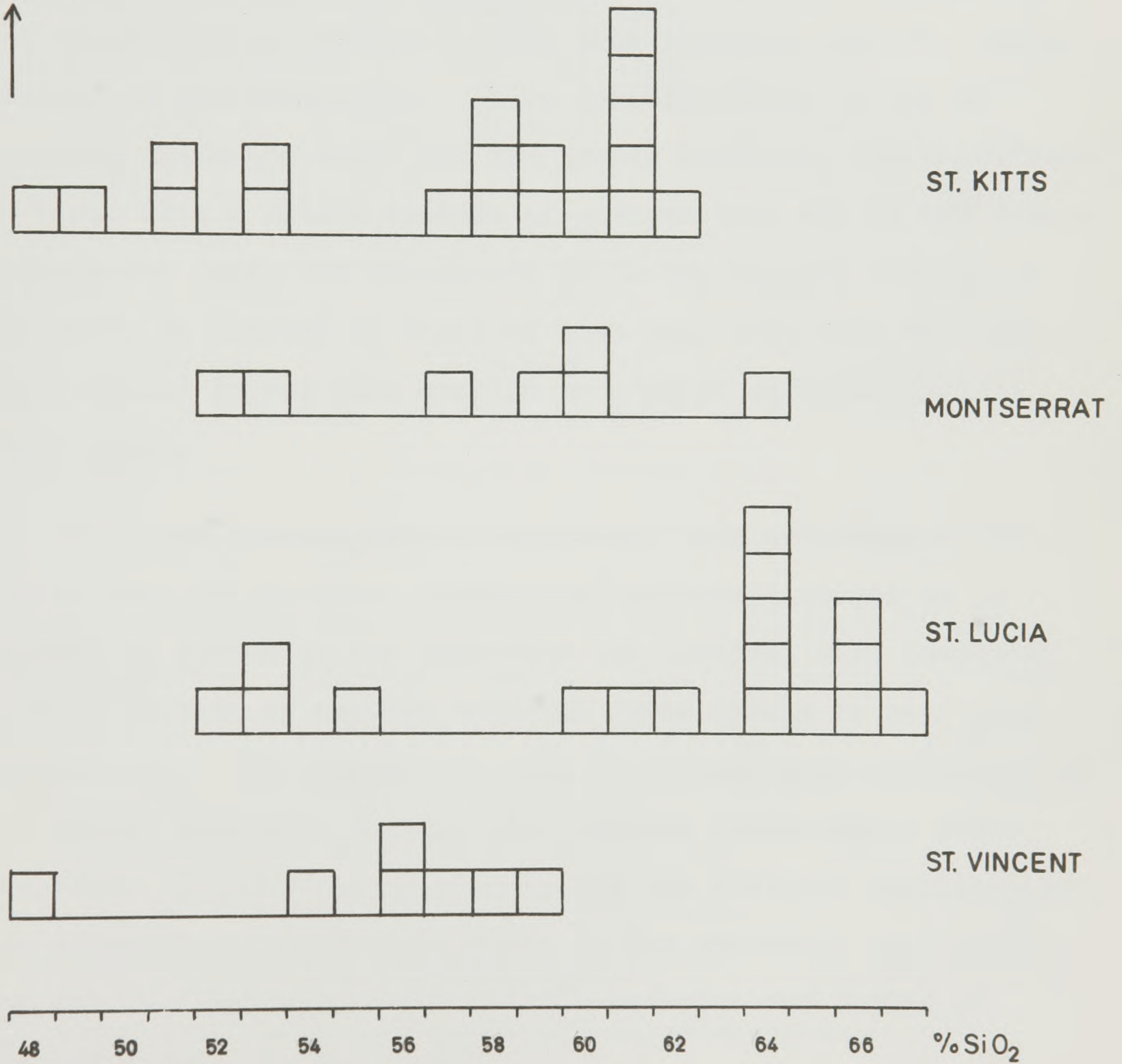
The apparent absence of anorthite-bearing blocks in St. Lucia suggests that relatively little differentiation of basaltic magma by crystal accumulation has taken place. This may explain the large gap in silica percentage between the basalts and andesites of St. Lucia, in contrast with the Soufrière volcano of St. Vincent, where abundant plutonic "crystal accumulates" occur, and basaltic rocks appear to form a series gradational into basaltic andesites, with no acid andesites or dacites. Mt. Misery on St. Kitts appears to represent an intermediate stage, with less abundant plutonic differentiates and a few basaltic andesites, and for this island Baker (1963, p.188) concluded that "although fractional crystallization of a basaltic magma may be responsible for a few of the Misery andesites, it is likely that additional processes, such as the partial fusion of crustal material, have contributed to the formation of the majority of the andesites". Histograms showing the frequency distribution by silica percentage of analysed lavas from St. Kitts, St. Lucia and St. Vincent are shown in Fig. 36.

From the geophysical evidence, it is concluded that the thick and gradational lower velocity layers below the volcanic island arc represent thickened crust, "kneaded together

FIG. 36.

LESSER ANTILLES: FREQUENCY DISTRIBUTION OF ANALYSES  
BY  $\text{SiO}_2\%$

NO. OF  
ANALYSES



as a heterogeneous mixture"....which has "gradually become adjusted to the normal thermal gradient in the crust" (Hess, 1960b, p.184), by fusion and upward migration of lower-melting constituents. Hess emphasizes the possibilities for variation in the magmas formed by fusion, depending on the depth, composition and proportions of crust melted. This could account for the occurrence of dacites on only some islands, e.g. St. Lucia, Martinique and Montserrat. It is possible that, of the 90 analyses which now exist for the Lesser Antilles, the restriction of lavas with a silica content of greater than 62% to the islands between St. Lucia and Montserrat (i.e. the central section of the arc), is related to the fact that only here have the more acid crustal layers been carried to a depth at which fusion could begin.

The present writer concludes, with reference to St. Lucia, that of the three fundamental processes stated to be capable of producing the andesites and dacites, that involving partial melting of crustal material seems likely to have been predominant. This process is able to explain most satisfactorily the steady evolution through time towards increasingly acid material. It accounts adequately for the textural relationships and composition of the phenocrysts in the andesites and dacites, and for the high proportion of acid andesite and dacite at present exposed in the island.

## 10. COMPARISONS WITH OTHER VOLCANOES OF THE OROGENIC REGIONS

### 10. 1. MORPHOLOGY AND STRUCTURE

The Soufrière region of St. Lucia is unusual in the Lesser Antilles in that it represents an old caldera. The only other island in the West Indies, on which it is believed that comparable structures may exist, is Dominica. Calderas, however, are common in the Japanese island arcs, where, according to Kuno, (1953, p.267), as many as 16 have been definitely identified. Calderas also occur in the Cycladean (Aegean) island arc, in the island of Santorini (Reck et al., 1936; Williams 1941, pp.265-9); in the Indonesian arc, e.g. Krakatau in the Sunda Strait (Williams 1941, pp.253-65); in the Scotia Arc or Southern Antilles, e.g. Deception Island (Hawkes, 1961); and in the Aleutians, e.g. Okmok caldera, Umnak Island (Byers, 1961).

Calderas typify a mature stage in the volcanic cycle, e.g. Reck (1936, quoted in Williams, 1941, p.241) in his discussion of Santorini, states that "the caldera is a mark of decadence and age, even though its formation may be followed by a renewal of activity on the floor". Thus the Soufrière region of St. Lucia appears to have reached a more advanced stage of evolution than most of the other volcanic centres of the Lesser Antilles. The last large eruptions, according to radiocarbon measurement, took place 39,050 years ago, i.e. considerably later than caldera collapse, so that the age of formation of the caldera must be appreciably older than this (see section 5.6). The

presence of numerous, younger domes and craters within the caldera indicates that post-caldera activity has also reached a more advanced stage than in many of the world's calderas, e.g. Crater Lake, Oregon (Williams 1942), formed about 7,500 years ago, has only one post-caldera conelet within it. Several of the Japanese calderas, however, are more closely comparable in their morphology to the Soufrière region of St. Lucia: e. g. Hakone volcano, Japan (Kuno 1953, pp.270-2), which comprises six lava domes and one steep-sided stratovolcano within a double (concentric) collapse-structure. The dimensions and ages of some of the world's better-known calderas are given in Table 17. The large proportion of calderas for which ages of less than 50,000 years have been obtained, and the relative rarity throughout the world of pre-Quaternary calderas, indicates that in most regions the "life" of a caldera, from initial collapse to the time of morphological decay beyond the point of recognition, is probably less than a million years. The existence of at least five calderas with measured ages of less than 8,000 years indicates the relative frequency of caldera formation as a geological phenomenon, at least in recent geological time. The caldera of St. Lucia, with an age of considerably more than 50,000 years (see section 5.6.), appears therefore to be relatively old compared with many of the world's calderas. It is, indeed, already approaching the limits of recognition.

The domes which lie within the caldera on St. Lucia, of which Terre Blanche (Frontispiece, Plate 2b and Fig.12) is

Table 17. MORPHOLOGY AND AGE OF CALDERAS OF KRAKATAU TYPE

CALDERA	AGE (years)	AREA (km.)	DEPTH (m.)	ESTIMATED VOLUME OF MATERIAL REMOVED (km <sup>3</sup> )	POST-CALDERA STRUCTURES
KRAKATAU, Indonesia. (Padang, 1951, p.51)	80	7 x 5.5	730	?	one cone
OSIMA-Ō-SIE, Japan. (Kuno, 1962, p.279)	1,500	4 x 3	7200	3.7	one central cone + flows
SANTORINI, Greece. (Georgalas, 1962, p.14)	3,500-3,800	11 x 7.5	390	?	12 domes (forming 2 islands)
MASNU, Japan. (Katsui, 1963, p.637)	6,490-7,190	7.5 x 5.5	?	?	one dome one cone
CRATER LAKE, U.S.A. (Williams, 1942)	7,500	8 x 9.6	1200	70	one cone
AYARZA, Guatemala. (Williams, 1960, p.54)	5,000-10,000 (no radio-carbon age)	7 x 5	930	8.2	none above lake level
SHIKOTSU, Japan. (Katsui, 1963, p.632)	20,000	13 x 15	500	80	3 vents (7 craters)
HAKONE, Japan. (Kuno, 1962, p.70)	?	11 x 7	1000	?	6 domes 1 cone
DECEPTION, S. Shetland Is. (Hawkes, 1961, pp.39-41)	?	11.2 x 9.6	730	?	12 small marginal cones + lava flows from mounds and fissures
BATUR, Bali, Indonesia. (Padang, 1951, pp.159-62)	?	13.8 x 10	1120	?	one central cone formed within a younger, concentric caldera (7 km. diam.)
OKMOK, Aleutians.	?	9.6 x 9.6	300	?	15 cinder cones, mainly marginal
SOUPRIÈRE, St. Lucia.	substantially > 50,000	6.4 x 6.4	240	?	15 domes 7 craters

morphologically the most perfect example, are similar in shape and composition to numerous other domes in the Lesser Antilles, e.g. Brimstone Hill, St. Kitts (Baker 1963, p.35 and Plate 8); The summit dome of La Soufrière de la Guadeloupe (Barrabé and Jolivet, 1958, Plate 1); and the historic domes of Mt. Pelée (Lacroix 1904, p.145; Ferret 1937, p.163). A comparison of the sizes and compositions of West Indian domes is given by Westermann and Kiel (1961, pp.90-1). Similar structures characterize virtually all calc-alkaline volcanic provinces where the effusion of acid andesite and dacite lavas has taken place. Better-known examples include the domes of Lassen Volcanic National Park, in western U.S.A. (Williams, 1932, p.358); the historic dome of Santa Maria, Guatemala (Sapper, 1926); the dome of Novarupta in Alaska, formed in 1912 (Fenner, 1920); the 1909 dome of Tarumai, in Japan (Tanakadate, 1917); the domes of Galunggung and Ruang in the East Indies (Brouwer, 1921), of Mt. Lamington in Papua (Taylor, 1958), and Santorini in the Aegean (Georgalas, 1962, p.14).

## 10. 2. PYROCLASTICS

Among the pyroclastic deposits on St. Lucia, flows predominate over fall, and this appears to be the case in most other Lesser Antillean islands. The pumice flows of Crater Lake type, which are present in the Soufrière region of St. Lucia are, however, not common in the Lesser Antilles, and Dominica is the only other island in the arc on which the present author has observed comparable deposits. Thus there appears, in the

West Indies as elsewhere in the world, to be a characteristic association of thick pumice flows, acid calc-alkaline lavas, and calderas of Krakatau type. Examples of this association include Hakone (Kuno, 1953, p.267), Crater Lake (Williams, 1942), Krakatau and Santorini (Williams, 1941, pp.235-69). In his discussion of the relative sizes of pyroclastic flow deposits, Aramaki (1957, pp.24-6) points out the fact that pumice flows connected with caldera formation usually have a very large volume, of greater than  $15 \text{ km}^3$ , whilst block-plus-ash flow deposits (= nuée ardente in the strict sense) are very much smaller.

### 10. 3. LAVA TYPES AND SEQUENCE

The Soufrière region of St. Lucia exposes a sequence of lavas derived from one centre (which shifted slightly) during a relatively long period of time. The absence of very recent eruptions has meant that erosion has cut deeply into the landscape, revealing a fuller record of the earlier history than is visible in many of the youngest West Indian volcanic centres, e.g. the Soufrière of St. Vincent, and Mt. Pelée on Martinique, where much of the landscape has been mantled by thick ash deposits from historic activity. At the same time, the Soufrière region of St. Lucia provides an example of a particularly full and varied sequence of volcanic events subsequent to caldera-collapse.

In common with many other volcanoes of island arcs

and of orogenic regions, including all the more fully investigated islands of the Lesser Antilles, andesitic and dacitic rocks predominate over basalt on St. Lucia. The Soufrière centre is, however, unusual in demonstrating a regular evolution with time towards more acid volcanic products. This feature contrasts with the alternation of basalt and andesite eruptions from Mt. Misery on St. Kitts (Baker, 1963), and with the sequence at Crater Lake (Williams, 1942, pp.155-6) and Lassen Peak (Williams, 1932, p.376) in the Cascade province, U.S.A., where the eruption of basaltic magmas has followed, and in the Lassen region alternated with, dacites and andesites.

#### 10. 4. MINERALOGY

The characteristic phenocryst minerals of St. Lucian lavas are summarised in Table 4, and are closely parallel to those of most rocks from the Lesser Antilles, although aphyric basalts, which outcrop in the Soufrière region of St. Lucia, seem to be rare in the West Indies as a whole. Basalts under-saturated in silica, of the type described in Grenada by Harrison (1896), have not been found in St. Lucia, or in other islands of the Lesser Antilles except Grenada.

In the andesites and dacites, the predominance of hypersthene or ferrohypersthene as the pyroxene, oscillatory zoned plagioclase, and the absence of orthoclase and feldspaths, are characteristic of all the Lesser Antilles (e.g. Lacroix 1904, p.601), as of many other calc-alkaline provinces. Quartz,

occurring as large, euhedral bipyramids as well as rounded xenocrysts, is more common in the acid lavas of the Soufrière region than in most other centres of the Lesser Antilles, with the sole exception of dacites from the Pitons du Carbet on Martinique. Quartz phenocrysts and xenocrysts, though virtually absent from the dacites of Crater Lake (Williams, 1942), are present in dacites and andesites from Saipan, Japan (Schmidt, 1957, p.134).

The compositional range of the plagioclase phenocrysts from St. Lucia is from  $An_{38}$  (maximum, core) to about  $An_{30}$  (minimum, rim), and there is no association of the most calcium-rich feldspars with the most basic lavas, as found in differentiated plutonic igneous rocks, exemplified by the Skaergaard intrusion (Wager and Deer, 1939). No anorthite-rich, coarse-grained blocks were found on St. Lucia, although these are relatively common in several islands of the Lesser Antilles (Wager, 1962; Baker, 1963, pp.139-50).

The range of orthopyroxene compositions in lavas of the Soufrière region, from  $En_{52-38}$ , is slightly more iron rich than other recorded values from the Lesser Antilles. In St. Kitts, for example, Baker (1963) quotes compositions which range mainly from  $En_{65-60}$ , although in one andesite lava a zoned orthopyroxene of  $En_{67-50}$  is reported (Baker 1963, p.120). In the lavas of Hakone volcano, Japan, Kuno (1950, p.978) reports "a continuous reaction series at least from about  $En_{70}$  to about  $En_{40}$ , the later-formed members being more ferriferous."

The presence of iron-rich cummingtonite in dacite from St. Lucia provides the first known occurrence of this mineral in the Lesser Antilles, though its presence in unmetamorphosed dacite lava from a few localities in Japan has been described previously by Kuno (1938).

Biotite, which is relatively common as phenocrysts in the dacites of St. Lucia, is not found in many other localities in the Lesser Antilles. It is not recorded by Williams (1942) in dacites from Crater Lake, nor by Kuno (1950) as phenocrysts in dacites of Hakone volcano, Japan, although in the latter locality it forms the only mafic silicate mineral in the groundmass of the most acid dacites. In this context, Kuno (1950, p.982) comments upon the association of biotite with mineral assemblages which "appear to have been formed from lower-temperature, residual magmas enriched in volatiles."

#### 10. 5. PETROCHEMISTRY

The most noteworthy petrochemical features of the Soufrière region, St. Lucia, are the richness of  $\text{SiO}_2$  relative to the other Lesser Antillean volcanic centres (Fig. 36), and the high content of  $\text{K}_2\text{O}$  relative to world-wide calc-alkaline volcanic suites (see Fig. 29). The rocks of St. Lucia are relatively rich in alumina by world-wide standards, although they contain less than most other islands of the Lesser Antilles (see section 8.2). Thus St. Lucia contains rocks which show closer affinities to the tholeiitic magma type than most other

Lesser Antillean islands, and the aphyric basalts of the Soufrière region (see Table 16) are truly tholeiitic. Similar, aphyric lavas occur in the island arcs of Japan (Kuno 1950, p.1004-5) and the South Sandwich Islands (Tyrrell 1945, p.95, and Table 8, column 3; and current investigations by P. B. Baker and the present author).

All lavas from St. Lucia, except the aphyric basalts, are closely related in both chemical and mineralogical composition to the hypersthenic series of Japan (Kuno 1950, p.994). The aphyric basalts of St. Lucia, by contrast, show close affinities to the pigeonitic series of Kuno (see Fig. 27), who believes that this series represents primary, tholeiitic magma and its differentiation products, uncontaminated by sialic material (Kuno 1950, p.994). Thus, according to Kuno's beliefs, there is no evidence in St. Lucia for pure differentiation of a primary basaltic magma. Kuno (1950, p.996) also comments on the field distribution of the two rock series, and observes that: "The hypersthenic rock series tends to associate with the thick deposits of geosyncline . . . , whereas the pigeonitic rock series predominates over the hypersthenic in the volcanic suites developed in the area which has not undergone geosynclinal subsidence." In St. Lucia, the tholeiitic lavas are among the oldest exposed rocks.

In addition to the comparisons which have already been made with the Japanese and Cascade petrographic provinces (see section 8), the lavas of St. Lucia are chemically similar



**Table 18.** AVERAGE CHEMICAL COMPOSITIONS OF ANDESITES FROM ST. LUCIA AND OTHER AREAS. (All analyses recalculated to 100%, volatile-free).

	1	2	3	4	5	6	7
$\text{SiO}_2$	62.6	61.0	59.8	59.7	61.1	59.6	60.6
$\text{Al}_2\text{O}_3$	18.1	16.8	18.4	17.8	18.0	18.0	16.4
$\text{Fe}_2\text{O}_3$	0.7	2.9	2.3	3.4	2.4	2.3	4.5
$\text{FeO}$	4.0	3.2	4.3	4.0	3.0	4.1	3.4
$\text{MgO}$	2.3	3.0	3.1	2.6	3.1	3.1	2.7
$\text{CaO}$	7.3	8.0	7.7	7.0	6.1	8.6	6.2
$\text{Na}_2\text{O}$	2.7	3.1	2.8	3.9	4.1	2.9	3.8
$\text{K}_2\text{O}$	1.4	1.0	0.8	0.6	1.4	0.6	1.2
$\text{TiO}_2$	0.5	0.7	0.5	0.6	0.6	0.5	0.8
$\text{P}_2\text{O}_5$	0.1	0.2	0.1	0.1	0.2	0.1	—
$\text{H}_2\text{O}$	0.1	0.1	0.2	0.2	tr.	0.1	0.2

1. Average andesite, St. Lucia. Includes Table 12, analyses 6-10, 13.
2. " " , Martinique. Lacroix, 1926, p.395, analyses 2-10.
3. " " , Montserrat. MacGregor, 1938, p.74, analyses II, III, IV.
4. " " , St. Kitts. Baker, 1963, p.194.
5. " " , Crater Lake. Williams, 1942, pp.149-50, analyses 13-18.
6. " " , Saipan, Mariana Islands, Japan. Schmidt, 1957, p.164.
7. " " , Kamchatka & Kuriles. Markhinin and Sapozhnikova, 1962, p.429.

Table 19. AVERAGE CHEMICAL COMPOSITIONS OF DACITES FROM ST. LUCIA AND OTHER AREAS. (All analyses recalculated to 100%, volatile-free).

	1	2	3	4	5	6	7
$\text{SiO}_2$	65.4	64.4	70.2	66.4	80.3	65.4	70.1
$\text{Al}_2\text{O}_3$	16.9	16.8	15.3	16.5	10.9	15.6	14.3
$\text{Fe}_2\text{O}_3$	0.91	3.75	1.32	2.13	0.48	4.20	2.86
FeO	2.99	1.77	1.66	1.67	0.95	2.54	3.27
MgO	1.81	2.22	0.87	2.21	0.23	1.94	0.25
CaO	6.73	6.04	2.57	4.29	1.32	5.26	3.08
$\text{Na}_2\text{O}$	3.16	3.40	4.93	3.87	3.64	3.14	4.19
$\text{K}_2\text{O}$	1.49	1.09	2.49	2.27	1.74	1.00	1.52
$\text{TiO}_2$	0.44	0.34	0.49	0.46	0.17	0.72	0.15
$\text{P}_2\text{O}_5$	0.11	0.09	0.13	0.11	0.12	n.d.	0.14
MnO	0.10	0.11	0.01	0.05	0.04	0.11	0.07

1. Average dacite, St. Lucia. Includes Table 12, analyses 12, 14, 16, 20-22.
2. Dacite, Montserrat. MacGregor, 1938, p.74, analysis 1.
3. Average dacite, Crater Lake. Williams, 1942, p.151, analyses 19-23; and p.152, analyses 29, 31, 32.
4. Average dacite, Lassen Peak. Williams, 1932, p.335, analyses 17-19, 21-25.
5. Average dacite, Saipan, Mariana Islands, Japan. Schmidt, 1957, p.164.
6. Average of 10 dacites, Kamchatka and the Kuriles. Markhinin & Sapozhnikova, 1962, p.429.
7. Dacite, Thule Island, South Sandwich Islands. Tyrrell, 1945, p.101.

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DETAILS OF CHEMICAL TREATMENT:

Boiled in 1% HCl for 15 minutes  
boiled in 5% NaOH for 15 minutes

$$R_p^{14} = \frac{\text{Activity of Sample} - 0.75 \text{ Activity of Standard}}{0.75 \text{ Activity of Standard}}$$

STANDARD USED AS REFERENCE FOR C<sup>14</sup>:

National Bureau of Standards, Oxalic Acid C<sup>14</sup> Standard

$$R_p^{13} = \frac{C^{13}/C^{12} \text{ of Sample} - C^{13}/C^{12} \text{ of Standard}}{C^{13}/C^{12} \text{ of Standard}}$$

STANDARD USED AS ULTIMATE REFERENCE FOR C<sup>13</sup>:

University of Chicago 100 C<sup>13</sup> Standard

/ s.

DATE 22nd July, 1964

REFERENCE C.S.

*[Handwritten signature]*



## NATIONAL PHYSICAL LABORATORY

Teddington, Middlesex, England

## REPORT

ON  
RADIOCARBON MEASUREMENT

FOR: DEPARTMENT OF GEOLOGY AND MINERALOGY,  
UNIVERSITY MUSEUM,  
OXFORD.

1. LABORATORY REFERENCE: NPL-79
2. DESCRIPTION OF SAMPLE AND  
SITE REFERENCE: Charcoal St. Lucia Sample L708
3. SUBMITTED BY: J.F. Tomblin, Esq.
4. DETAILS OF CHEMICAL PRETREATMENT:  
Boiled in 1% HCl for 15 minutes  
Boiled in 1/2% NaOH for 15 minutes
5.  $\delta C^{14} = \frac{\text{Activity of Sample} - 0.95 \text{ Activity of Standard}}{0.95 \text{ Activity of Standard}} \times 1000 = -992 \pm 1.2$
6. STANDARD USED AS REFERENCE FOR  $C^{14}$ :  
National Bureau of Standards, Oxalic Acid  $C^{14}$  Standard
7.  $\delta C^{13} = \frac{\frac{C^{13}}{C^{12}} \text{ of Sample} - \frac{C^{13}}{C^{12}} \text{ of Standard}}{\frac{C^{13}}{C^{12}} \text{ of Standard}} \times 1000 = -26.5 \pm 1$
8. STANDARD USED AS ULTIMATE REFERENCE FOR  $C^{13}$ :  
University of Chicago PDB  $C^{13}$  Standard

/ 9.

DATE 22nd July, 1964

G. B. B. M. SUTHERLAND

REFERENCE C.64

Director

*G. B. B. M. Sutherland*  
for Superintendent, Applied Physics Division

## NATIONAL PHYSICAL LABORATORY

-2-

CONTINUATION  
of Report on  
Radiocarbon Measurement  
-----9. NORMALIZED  $C^{14}$  ABUNDANCE ( $\Delta$ ):

$$= \delta C^{14} - (2 \delta C^{13} + 50) \left(1 + \frac{\delta C^{14}}{1000}\right) = -992 \pm 1.3$$

10. AGE IN YEARS BEFORE PRESENT (BP) A.D. 1950: 39050  $\begin{matrix} +1,450 \\ -1,230 \end{matrix}$ 

11. NOTE:

The precision quoted in 5. and 9. is that of the physical measurement only and is one standard deviation.

The half life of  $C^{14}$  used in the calculation of the age is 5,568 years: see Nature, 1962, 195 (4845), 984.

DATE 22nd July, 1964

G. B. B. M. SUTHERLAND

REFERENCE C.64

Director


  
for Superintendent, Applied Physics Division

C.S. 2

## APPENDIX B.

Method of granulometric analysis

The pyroclastic sample, of which about 1,000 g. was normally collected, was quartered to provide a test sample of approximately 500 g. The latter was weighed to the nearest gram, and poured into the uppermost of a nest of 10 sieves, stacked with the mesh size decreasing downward. The sieves are 10 in. in diameter, constructed of double-crimped brass wire mesh, with square apertures (to B.S. 410/43). Gaps between the mesh range from  $32 - 1/16$  mm., conforming to the Wentworth scale.

Each sample was shaken for 15 minutes in an electrically powered shaking machine, in which the sieves, covered by a lid and clamped together, are suspended on springs and shaken by a flywheel which is eccentrically balanced and rotates about a vertical axis. Material passing through the finest sieve falls down an enclosed chute and is collected in a polythene bag.

The optimum shaking time is one which is long enough to separate efficiently each size fraction (the finer fractions were found to separate more slowly), but not so long as to cause excessive abrasion of larger, single lumps of soft pumice. To determine this, experiments were conducted on two typical samples, of which the fractions retained by the different sieves were inspected at intervals of 5 minutes, i.e. after 5, 10, 15, 20 minutes. The finer fractions were examined microscopically for efficiency of sorting, and the coarser fractions were examined by eye for extent of abrasion. The optimum shaking time was found to be 15 minutes.

After shaking, the fractions retained by each sieve were weighed to the nearest gram, and recalculated as weight percentages. The total weight of the separate fractions normally fell within 2 g. ( $\pm 0.4\%$ ) of the original sample weight.

## APPENDIX C.

Method for the determination of CaO

Rock solutions are titrated using the reagents described by Weibel (1961, p.289, 292), but employing the principle of comparison with a standard solution after the method of Riley (1958). Weibel's paper is in German, and his description of the method is highly abbreviated. For this reason, and because it was necessary to adjust the strengths of the standard solution used by Riley, a full description of this "hybrid" method is given here.

## PROCEDURE:

N.B. De-ionized water is used throughout.

10 ml. of solution B (unknown rock solution, prepared as by Riley, 1958) are pipetted into the titration beaker.

5 ml. Triethanolamine 7.5% are added from a tilt measure. This reagent masks the Fe and Ti.

50 ml. de-ionized water are added from a tilt measure.

10 ml. 10% NaOH are added from a tilt measure.

The solution should now have a pH = 13. It is normally sufficient to check only one or two samples in a batch, if identically prepared. If the pH falls below 13, Al interferes in the titration. At pH 13, a flocculent precipitate of  $Mg(OH)_2$  forms, which absorbs a small amount of the indicator, but otherwise does not interfere.

e. 10 drops are added of the indicator HHSNH (Patton and Reeder's reagent), prepared as a 2% aqueous solution, to which 1%  $Na_2CO_3$  or NaCl have been added.

Titrate with EDTA (disodium salt) 0.00335M (prepared as by Riley, 1958), using the Metrohm-Herissau mechanical burette, and "EEL" Quantitrator with blue-green filter no. 603.

The end-point is reached when the solution becomes a pure blue-green, and is determined graphically by plotting the galvanometer readings against the volume of EDTA titrated.

#### STANDARD SOLUTION:

The standard solution is prepared by dissolving exactly 0.3570 g. of A.R. calcium carbonate (dried at 110°C) in dilute HCl, and diluting to 2 litres in a volumetric flask. This solution is equivalent to 100  $\mu$ g. CaO/ml. 10 ml. of the standard solution are titrated identically to the Solution B aliquots.

#### CALCULATION OF CaO%:

10 ml. Ca standard contain 0.001 g. CaO.

Let C be the quantity of CaO in the solution B aliquot.

$$\text{Then } \frac{\text{solution B titre}^*}{\text{standard Ca titre}} = \frac{C}{0.001} \text{ g. CaO.}$$

$$\text{And 10 ml. solution B contain } \frac{0.5 \times 10}{500} = 0.01 \text{ g. rock.}$$

$$\text{Hence } \% \text{ CaO} = \frac{C}{0.01} \times 100$$

$$\begin{aligned} &= \frac{0.001 \times \text{Soln. B titre}^* \times 100}{\text{standard Ca titre} \quad 0.01} \\ &= \frac{10 \times \text{Soln. B titre}^*}{\text{standard Ca titre}} \end{aligned}$$

\* corrected for reagent blank (= solution C of Riley, 1958).

Method for the determination of MgO

The sum of CaO + MgO (+ MnO) is determined by the method described by Shapiro and Brammick (1962, p.A35-36), which has been modified to employ the principle of comparison with a standard solution after the manner of Riley (1958). The Quantitrator (with filter 603) and EDTA solution are used as for the Ca titration. The indicator is Eriochrome black (c. 2% solution in alcohol), which should be prepared freshly every 3 days.

## PROCEDURE:

10 ml. of solution B (unknown rock solution, prepared as by Riley, 1958) are pipetted into the titration beaker.

5 ml. of 10% hydroxylamine hydrochloride solution are added.

This is allowed to stand for 5 mins.

50 ml. of de-ionized water are added from a tilt measure.

5 ml. of complexing solution are added from a tilt measure. This is prepared by dissolving 16 g. KCN in 150 ml. water, and adding 100 ml. of triethanolamine.

20 ml. of buffer solution (66 g.  $\text{NH}_4\text{Cl}/500 \text{ ml. H}_2\text{O} + 500 \text{ ml. concentrated NH}_4\text{OH}$ ) are added from a tilt measure.

c. 10 drops Eriochrome black (solution in alcohol) are added.

Titrate with EDTA 0.00335M to pure blue-green.

## STANDARD SOLUTION:

The standard solution is prepared by dissolving exactly 0.1206 g. of "Specpure" magnesium in a few ml. of dilute hydrochloric acid, and diluting to volume in a 2 litre volumetric flask. This solution is equivalent to 100  $\mu\text{g. MgO/ml.}$

10 ml. of the standard solution are titrated identically to solution B samples.

## CALCULATION OF MgO %:

10 ml. Mg standard contain 0.001 g. MgO.

Let M be the quantity of MgO in the solution B aliquot.

$$\text{Hence } \frac{\text{solution B titre} - \text{Ca titre}^*}{\text{standard Mg titre}} = \frac{M}{0.001} \text{ g. MgO}$$

And 10 ml. solution B contain  $0.5 \times \frac{10}{500} = 0.01 \text{ g. rock.}$

$$\begin{aligned} \text{Hence } \% \text{ MgO (+MnO}^{**}) &= \frac{M}{0.01} \times 100 \\ &= \frac{0.001 \times (\text{soln. B titre}^* - \text{Ca titre}^*)}{\text{standard}} \times \frac{100}{0.01} \\ &= \frac{10 \times (\text{soln. B titre}^* - \text{Ca titre}^*)}{\text{standard Mg titre}} \end{aligned}$$

\* corrected for reagent blank (= solution C of Riley, 1958)

\*\* Riley (1958) states that according to his method, 1% of MnO in a rock requires 0.38 ml. of EDTA solution for its titration in the magnesium titration. In the method described by the present writer, the weight of the rock (0.01 g.) in an aliquot for titration, and the strength of the EDTA solution are identical to those used by Riley. Thus a similar correction, of  $\text{MnO} \% \times 0.38$ , should be subtracted from the MgO total.

Advantages of the methods described in Appendix C.

The main advantages of the methods here described over those recommended by Riley (1958) are that:

- 1) They are twice as rapid, since they avoid the time-consuming extraction of interfering elements with chloroform, and
- 2) Both titrations can be made using the Quantitrator, thus avoiding, in the calcium titration, the visual determination of the end-point under ultra-violet light, which was found by the present author to give less satisfactory



## APPENDIX D.

Method of Spectrographic Analysis

## Instrumental details:

- SPECTROGRAPH:** Hilger large, automatic, quartz and glass. Littrow type.
- CONDENSING OPTICS:** Arc 52 cm. from slit.  
6.5 cm. focal length spherical lens 41 cm. from slit.  
6 mm. aperture diaphragm 27 cm. from slit.  
30 cm. focal length spherical lens 12 cm. from slit.  
30 cm. focal length spherical lens at the slit.
- INTENSITY CONTROL:** Seven step rotating sector at the slit, 2:1 ratio.
- SLIT HEIGHT:** 11 mm.
- ARC GAP:** 8 mm. Central 5 mm. of arc focussed onto the diaphragm.
- DISPERSION:** Quartz optics:  $5.2 \text{ \AA}/\text{mm.}$  at 3000  $\text{ \AA}$  and  $13 \text{ \AA}/\text{mm.}$  at 4000  $\text{ \AA}$ .  
Glass optics:  $4.5 \text{ \AA}/\text{mm.}$  at 4000  $\text{ \AA}$  and  $35 \text{ \AA}/\text{mm.}$  at 8000  $\text{ \AA}$ .
- ELECTRODES:** Anodes (sample cup) from Johnson-Matthey graphite rods, 6.5 mm. in diameter. Electrode cavity either  $2\frac{1}{2} \times 2\frac{1}{2}$  mm. (B.2) or  $5 \times 2\frac{1}{2}$  mm. (B.1) for depth  $\times$  diameter. Tapered cathodes from 5 mm. diameter Morganite carbon rod.
- PLATE PROCESSING:**  $3\frac{1}{2}$  minutes tank development with Ilford I.D. 2 developer at 20 C. 15 seconds stop bath of distilled water. 10 minutes in HyPam Fixer. 30 minutes wash in sink.
- VOLTAGE:** 240 volts D.C. on clear circuit.
- PHOTOMETRY:** Hilger non-recording microphotometer; galvanometer readings 0 to 50 (clear plate). Background readings taken adjacent to analysis line on unfiltered step.
- INTENSITY EVALUATION:** Self calibration method. Transmission readings converted to arbitrary intensity units graphically using a Seidel function plot.
- WORKING CURVES:** Log. concentration in p.p.m. plotted vs.  $\log \frac{\text{intensity unknown}}{\text{intensity internal std.}}$
- For volatile runs using Na as variable internal standards:  
 $\log \frac{\text{concentration p.p.m.}}{\text{Na}_2\text{O } \%}$  vs.  $\log \frac{\text{intensity unknown}}{\text{intensity Na line}}$
- REPLICATE ANALYSIS:** Always in triplicate.

## INSTRUMENT SETTINGS FOR DIFFERENT RUNS:

RUN:	<u>Ultraviolet</u>	<u>Blue</u>	<u>Alkali</u>
Wavelength	2470 - 3550 Å	3850 - 5480 Å	4600 - 9600 Å
Prism	quartz	glass	glass
Slit width	0.01 mm.	0.01 mm.	0.02 mm.
Current	6.8 amps.	6.8 amps.	4.4 amps.
Anode	B-2	B-1	B-1
Arc time	to completion	to completion	to end of alkali phase
Plates	Ilford Ordinary N.30	Ilford Ordinary N.30	Kodak I.R.E.R.
Lines read	Ga 2944 V 3185 Cu 3274 Ni 3414.76 Zr 3438 Co 3453 Pd 3258.8	Pd 3958.64 Se 4246 Cr 4254 La 4333 Sr 4607 Ba 4934	Li 6707 Rb 7800 Na 5688

## SAMPLE MIX FOR ULTRA-VIOLET AND BLUE RUNS:

Speopure tetramminepalladous nitrate } 2 parts to 1 part rock  
 " graphite powder } powder (per 120 mesh)

Palladium acts as internal standard

FOR ALKALI RUN: rock powder is arced neat.  
 Na (determined independently by flame photometer) is  
 used as variable internal standard.

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