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II. THE GEOLOGY OF CANDLEMAS ISLAND

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ABSTRACT

CANDLEMAS ISLAND is a recently active volcanic island in the South Sandwich Islands group. The southern part of the island, composed of anorthite-olivine-phyric basalt lava flows alternating with scoria layers, is extinct and ice-capped. The northern part of Candlemas Island is a young volcanic centre, consisting of a scoria cone rising to 229 m. above sea-level, surrounded by lava flows which radiate up to 0·8 km. from the foot of the cone. The lavas of northern Candlemas Island are called andesites; they are almost aphyric, contain up to 64 per cent of SiO_2, and are unusually rich in iron and poor in potash. Xenoliths of strongly porphyritic lava and gabbroic material, which are probably crystal accumulates, are present in the andesites. The andesites and xenoliths are believed to have originated by a process of rock genesis involving simple fractional crystallization of basaltic parent magma.

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CONTENTS

INTRODUCTION

THIS report is based on field work which formed part of the British Antarctic Survey expedition to the South Sandwich Islands in March 1964 aboard the Royal Navy's ice patrol ship H.M.S. *Protector*. 13 days were spent ashore on Candlemas Island, during which a geological map (Fig. 6) was produced of the northern part of the island,* and sketch maps were made of all accessible rock exposures in southern Candlemas Island. 124 lava and ash specimens were collected. From these, material was selected for petrographic and chemical studies, which were carried out between August and November 1964 at the Department of Geology and Mineralogy, University of Oxford. 40 specimens were examined in thin section and six rocks were analysed chemically for major elements and spectrographically for trace constituents.

1. *Physical geography*

The South Sandwich Islands lie on an arc extending approximately north–south for almost 320 km., between lat. 56° 15′ and 59° 30′ S., and long. 26° 15′ and 28° 15′ W. All of the islands are young and volcanic, and many contain centres where activity is either known or believed to have occurred within the last 200 years.

The islands lie on the easternmost salient of the Scotia arc, a crustal upwarp extending from South Georgia through the South Sandwich Islands to the South Shetland Islands, connecting the Andean chain of South America with the Antarctic Peninsula (Fig. 1). In keeping with the typical structure of

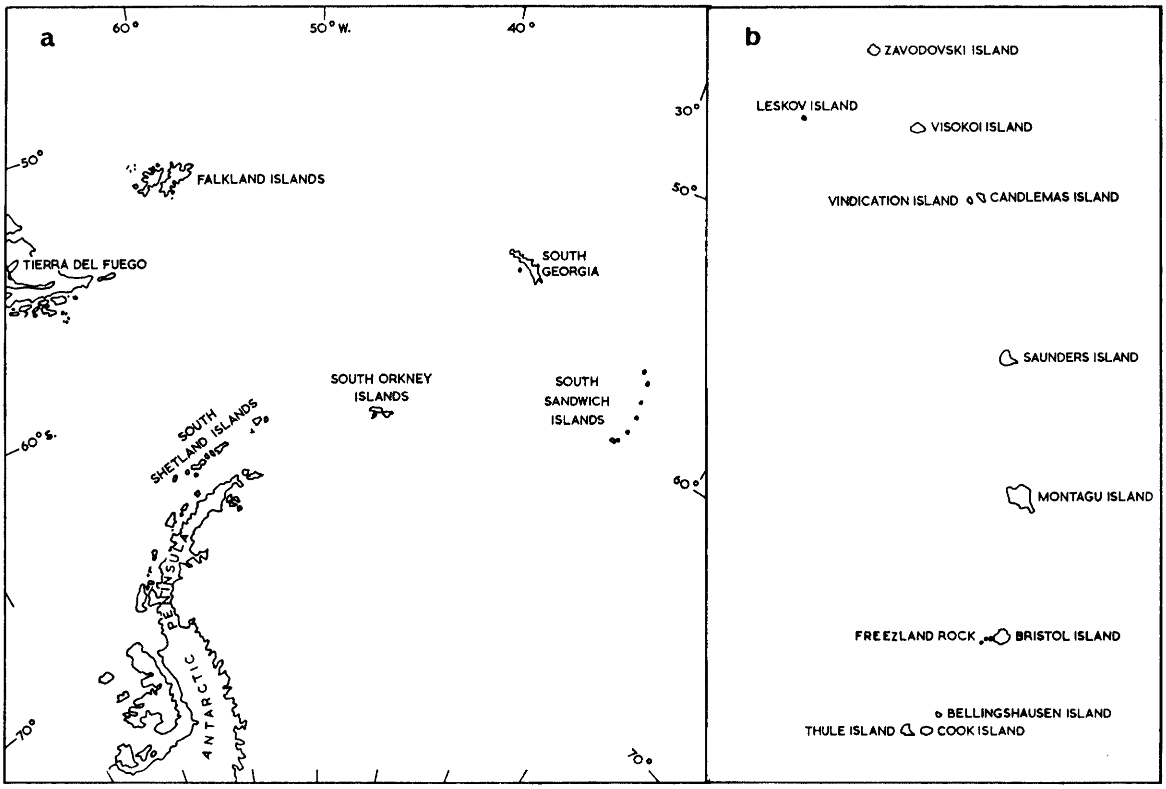

FIGURE 1

a. Sketch map showing the location of the South Sandwich Islands on the Scotia Ridge.
b. Sketch map of the South Sandwich Islands showing the position of Candlemas Island in relation to other islands in the group.

* Using a topographic map of approximate scale 1 : 4,800, constructed from air photographs taken by *Protector*'s helicopters during a visit in March 1962.

island arcs, to the east of the South Sandwich Islands there is an external deep-sea trench (Griffiths and others, 1964, fig. 40). In addition to the geophysical investigations reported by Griffiths and others (1964), some aspects of the structure of the Scotia arc have been discussed by Matthews (1959) and Hawkes (1962).

Candlemas Island lies in lat. 57° 02′ S., long. 26° 40′ W. It is the third large island southward in the South Sandwich Islands group, being 42 km. distant from Visokoi Island to the north, and 76 km. from Saunders Island to the south. Candlemas Island is separated from Vindication Island to the west by 3·7 km. of water with an average depth of only 15 fathoms [27 m.], known as Nelson Channel. The 100 fathom [183 m.] submarine contour which circumscribes Candlemas and Vindication islands (Fig. 2)

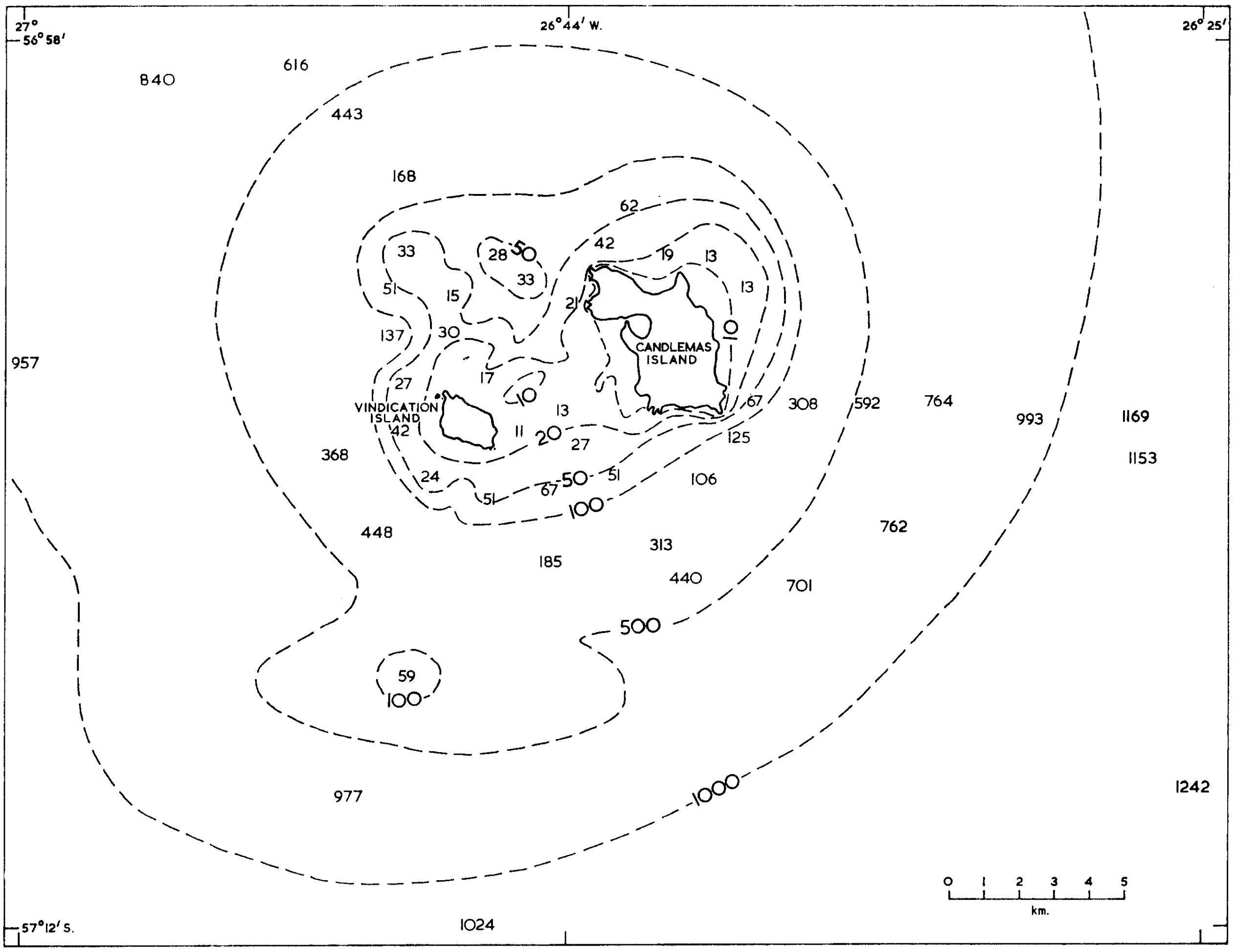

FIGURE 2

Bathymetric map of the Candlemas Islands group showing the position of the 100 fathom [183 m.] isobath.

has a diameter of approximately 8·8 km., whilst water about 1,000 fathoms [1,830 m.] deep separates these two islands from the adjacent major islands of the group. Vindication and Candlemas Islands therefore form part of a single volcanic pile, which has been named the Candlemas Islands group (Kemp and Nelson, 1931, p. 165).

Except for the vertical cliffs which surround much of the coast, the whole of the northern part of Candlemas Island is accessible on foot. Rock exposure in northern Candlemas Island is good, since only 2 per cent of this area is covered by snow and ice, and no soil is present. Southern Candlemas Island, in contrast, is largely capped by ice, so that rock exposures occur only around the margins. Along the eastern and southern coasts, rock cliffs rise to between 30 and 300 m. These are not easily approached and were not sampled during the present investigation.

Much of the northern cone is kept warm by volcanic heat and this accounted for the rapid disappearance of several light falls of snow (maximum 5 cm.) which occurred during the visit. Skies were almost permanently overcast; during 13 days ashore the sun was seen for a total of about 30 min. On only 3 days, however, was field work hampered by cloud below 150 m. Westerly winds predominated and were frequently strong; for one 48 hr. period a speed of about 35 kt. [17·8 m./sec.] was maintained. Mid-day temperatures rose above freezing on about one day in two, the maximum recorded being 3·5° C.

Vegetation is sparse, consisting only of small patches of lichen and moss which grow around mildly active fumaroles. In penguin rookeries the rock exposures are less fresh.

2. *Previous visits to Candlemas Island*

The Candlemas Islands group was discovered by Captain James Cook in H.M.S. *Resolution* on 2 February (Candlemas Day) 1775, during his second voyage round the world. No scientific visits were made until the present century and all previous visits were much briefer than the present one. The first collection of rocks was made by the Norwegian, Captain C. A. Larsen, who landed at the south-eastern end of the island (Shrove Point) in 1908 (Kemp and Nelson, 1931, p. 170). These specimens were later described petrographically by Baeckström (1915, p. 169–70). The only other visits to Candlemas Island by scientists have been made in the last few years, by R.R.S. *Shackleton* in January 1961, when a number of rocks were collected, and by *Protector* in March 1962, when in the course of a 3 hr. visit 20 rock specimens were collected by Sub-Lt J. A. M. Preus. No geological mapping of the island had been carried out before the present visit.

A summary of visits to the South Sandwich Islands up to 1930 has been given by Adie (1957). A list of known visits to the South Sandwich Islands up to 1962, and of geological and botanical collections from them has been given by Holdgate (1963, p. 395–97).

3. *Recorded volcanic activity*

Fumarolic activity in the northern part of Candlemas Island has been reported by passing ships since 1927. There is, however, only one record of magmatic activity on the island; this is a report from R.R.S. *John Biscoe* in 1953–54 (Holdgate, 1963, p. 401) that a glowing lava field was observed in northern Candlemas Island. At the time of *Protector*'s visit in March 1962, a geyser not far north of Cauldron Pool (Fig. 6) was reported to be jetting to a height of 4·6 m. at 5–10 sec. intervals (Holdgate, 1963, p. 401). There was no sign of this in March 1964, although a temperature of 53° C was recorded at the northern edge of Cauldron Pool. At several points along the western side of the lake, a temperature of 31° C was recorded in the uppermost layer of water to a depth of about 30 cm. The water below this layer had a temperature of about 20° C.

Visits to Candlemas Island, as to all the South Sandwich Islands, have been rare and poorly documented. Thus the record of volcanic activity over the 190 years since the discovery of the islands is not wholly reliable and almost certainly incomplete.

II. GEOMORPHOLOGY OF CANDLEMAS ISLAND

1. *Factors controlling morphogenesis*

The morphology of Candlemas Island is the result of two opposing forces: the constructive process of active volcanism and the destructive force of mechanical erosion. The effusion of lava and eruption of scoria have built up the volcanic pile, which is now being demolished by the action of water, frost and wind. Of these destructive agents, marine erosion is probably the most effective, since the coastline is heavily battered by the stormy seas of the Southern Ocean. Frost shattering also plays an important part, causing the disintegration of large boulders and steep rock faces. In the southern part of the island, the products of glacial erosion are heaped around the fringe of the ice cap in terminal moraines, which in turn are re-distributed during warm weather by localized fluviatile action. Fine morainic dust and volcanic ash are re-worked or removed by the frequent strong winds. It is noteworthy that all erosion is effected by mechanical processes and that the influence of organic or chemical weathering is insignificant.

2. *Geomorphological units*

Five morphologically distinct areas (Fig. 3) can be recognized on Candlemas Island.

a. *The southern massif* (Plate IIa) forms the bulk of southern Candlemas Island and it is the remnant of a volcanic structure which has been long extinct. The geology of this structure is largely concealed beneath the ice cap which in coastal cliffs has a thickness of up to 23 m. There are two peaks, of which

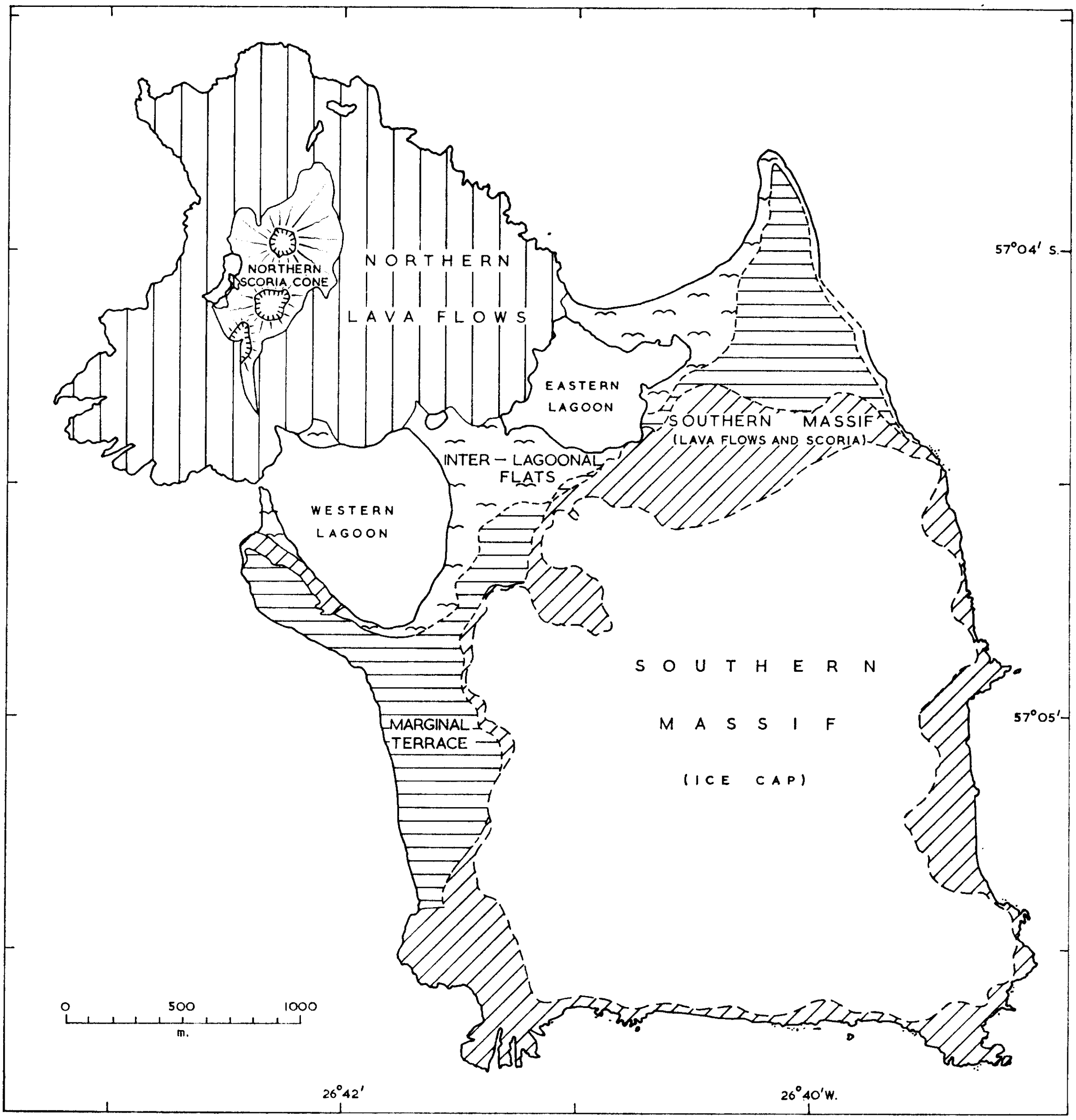

FIGURE 3

Sketch map of Candlemas Island showing the distribution of the five morphological units comprising the island.

the southern (Mount Andromeda) is slightly the higher and rises to about 600 m. a.s.l.* These peaks are connected by a ridge and the whole structure may represent the western rim of a former larger crater whose centre lay beneath the sea to the east of the present coastline. The topographic elevation of southern Candlemas Island increases from west to east, and terminates abruptly in cliffs up to 300 m. a.s.l. along

* The maximum elevation of Candlemas Island, given in Admiralty Chart 3593 (1960) is 2,580 ft. [787 m.] and this has been used in the form lines shown on the geological map (Fig. 6). A more recent measurement, made by helicopter altimeter (Holdgate, 1963, p. 401), indicates that southern Candlemas Island rises to a maximum of only 550 m. a.s.l.

the central part of the eastern coast (Fig. 6). Vindication Island is morphologically similar to southern Candlemas Island in that it is surrounded for the most part by high cliffs and exhibits no youthful volcanic landforms.

b. *The 18 m. terrace* (Plate I) borders the western and northern sides of southern Candlemas Island. This is a level platform, 18 m. above sea-level and up to 600 m. wide, which has been only superficially dissected by small rivulets. Deposits forming this feature closely resemble those at present being laid down on Chimaera Flats and thus probably originated in a sheltered environment of lagoonal type. The 18 m. terrace may have continued farther westward and northward before the growth of the northern centre, since the semi-consolidated material of which it is composed is subject to rapid marine erosion.

c. *Chimaera Flats* (Plate IIc) occupy the area between the 18 m. terrace and the lava flows of northern Candlemas Island. They are formed of material from two sources:

i. Fluviatile outwash from the moraines of southern Candlemas Island.
ii. Water and wind-borne volcanic ash from northern Candlemas Island.

The distribution of land and water in the lagoon area seems to be a transient one; it is possible that significant changes have occurred during historical time, since it was reported by several visitors between 1830 and 1927 (Kemp and Nelson, 1931, p. 165) that the Candlemas Islands group consisted of three separate islands. At present Gorgon Pool is enclosed completely by a shingle bar about 3 m. a.s.l. whilst Medusa Pool is connected with the sea by a narrow channel about 9 m. wide.

d. *Lucifer Hill* (Plate IIIa) forms the central and most prominent feature in the northern part of Candlemas Island. The whole structure is conical sided, flat-topped and rises to 230 m. a.s.l. A shallow saucer-shaped crater 137 m. in diameter and 15 m. deep lies at the northern end, and a second crater of similar size has been excavated in the upper part of the southern flank (Plate IIIc). Between these two craters, the top of the central cone is almost flat, although crossed by three low north–south ridges. The diameter of the top of the central cone, including the northern crater, is about 274 m.

A subsidiary scoria conelet lies to the south-west, independently of the central structure, to which it is connected by a low saddle formed by the coalescing outer slopes. This conelet is breached on its south-west side and has been the source of a large lava field (Plate IIIb).

Two adventive bocas, situated about half-way up the flank of the central cone, on opposite (northern and southern) sides, are the sources of the north and south lava flows, respectively. The southern boca and lava flow are shown in Plate IIIc.

e. *The northern lava field* (Plate I) is composed of five major flows which almost encircle Lucifer Hill, forming a series of overlapping plateaux at between 30 and 90 m. a.s.l. The older of these broad flows is mantled by ash and lapilli deposits, which leave the surface relatively smooth and flat (Plate IIIa). The younger lavas have surfaces which, whilst in general flat, are in detail extremely irregular, with adjacent gullies and ridges up to 4·6 m., often arranged concentrically about the source of the flow (Plate IIIb). The size of individual blocks of lava varies from 0·2 to 4·6 m. Larger blocks are often more numerous at the margin of a flow, where they appear to have been heaped into lava levées.

III. GEOLOGY OF THE SOUTHERN PART OF CANDLEMAS ISLAND

1. *Cliffs south of the lagoon area*

Rock exposures occur at the northern end of southern Candlemas Island in two high cliffs to the south of the lagoon area (Fig. 4). The western cliff (Fig. 4), which overlooks Chimaera Flats is about 244 m. high and exposes lavas up to 21 m. thick, separated by scoria beds up to 30 m. in thickness. The cliff is cut by several dykes, one of which forms the face of the lower western part and dips northward at 68°. Only the foot of this cliff was accessible. Lava collected *in situ* from the lowest flow (SSC.32.1)

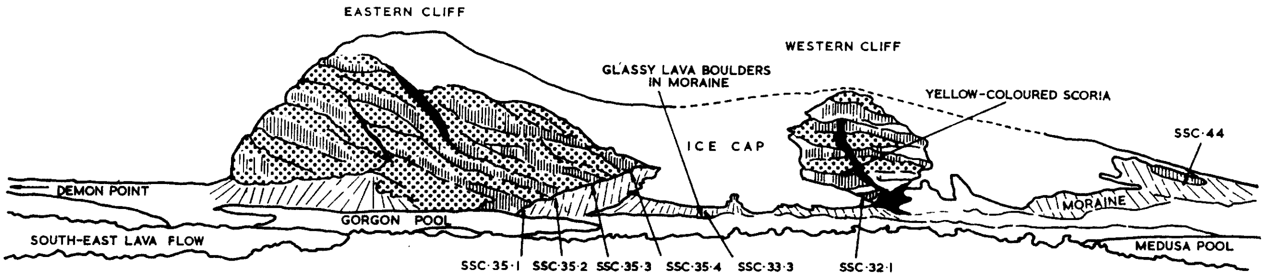

FIGURE 4

Sketch of cliffs at the northern end of southern Candlemas Island. Vertical shading indicates lava flows, heavy stipple represents scoria, and solid black areas are dykes.

is markedly porphyritic and appreciably weathered, as are all loose boulders from the base of the cliffs and from the adjacent moraines. The scoria are mostly vermillion coloured, except at one horizon half-way up the cliffs where they are distinctly yellow, probably due to sulphur deposits around the site of an ancient solfatara.

The eastern cliff is over 300 m. high and extends from the south-eastern corner of Gorgon Pool to the eastern coast of the island, south of Demon Point. Like the western cliff, it exposes a sequence of alternating lava flows and scoria layers. It was possible to climb as far as the fourth lava flow upward in the succession at the western end of the cliff. These four flows (SSC.35.1–4) are porphyritic and resemble the lavas at the foot of the western cliff. At the eastern end of the eastern cliff, the strata dip westward at 30° and are intruded by a network of dykes and sills. The dykes have been offset in numerous places, indicating post-intrusive earth movements. It is possible that tilting of the eastern margin of southern Candlemas Island has occurred, although it seems more likely that the present dips of the lava flows and scoria horizons are original, and that the material was derived from a large crater which formerly lay to the east of the present coastline, of which more than half has been removed by subsequent marine erosion.

2. *The west peninsula*

The west peninsula is a narrow arm of land which projects from the north-western corner of southern Candlemas Island, terminating in Sarcophagus Point. It is composed mainly of stratified deposits of silt- to pebble-sized material similar to those forming the 18 m. terrace. Like the main part of this terrace, the west peninsula has a strikingly flat surface. It differs, however, in that the land surface and the stratification of the beds in the west peninsula are not horizontal, but dip south-westward at about 5°. The fact that the 18 m. terrace deposits in all other parts of southern Candlemas Island are perfectly horizontal suggests that those of the west peninsula have been tilted subsequently to deposition. The tilting of this peninsula may have been caused by a local uplift accompanying the growth of northern Candlemas Island.

In addition to the bedded clastic material, two lava flows are exposed in cliffs around the margins of the west peninsula. The lower flow is porphyritic and resembles the lavas of southern Candlemas Island, whilst the upper flow is vitrophyric, finely vesicular and contains angular xenoliths of lava and tuff. Both lavas differ appreciably from those exposed in northern Candlemas Island, and this supports the morphological evidence that the flows of the west peninsula issued from southern Candlemas Island. The present shape of the west peninsula may mark approximately the original extent of these lava tongues, whose greater resistance to marine erosion would account for the preservation of the overlying, bedded clastic deposits.

A sketch showing the sequence visible on the western side of the west peninsula is given in Fig. 5. The lower lava is exposed only at the northern end of the peninsula. It is capped by scoria and overlain by a stratified sequence 6 m. thick consisting of sub-angular or rounded pebbles of tuff and porphyritic lava in a matrix of unconsolidated greyish brown or black silt- to sand-grade material. This material appears mainly to be re-worked, although occasional layers consist of homogeneous finer ash which may represent primary fall deposits. The sequence is separated by a sharp upper boundary from a 1·8 m. layer of dark pumiceous scoria which is entirely homogeneous, and for this reason it is believed to

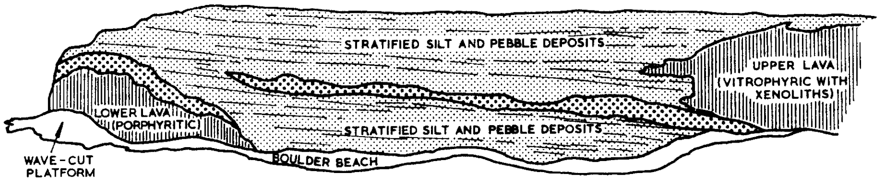

FIGURE 5

Sketch of sea cliffs on the western side of the west peninsula of Candlemas Island. Vertical shading indicates lava flows and heavy stipple represents dark scoria.

represent a primary scoria-fall deposit. It is exposed continuously in the coastal cliffs from this locality round to the north-east side of the peninsula, forming a conspicuous horizon which dips gently to the south-west, i.e. concordantly with the tilted top of the peninsula. Similar dark scoria are seen 1·07 km. farther south along the west coast, where the thickness is 4·6 m. On the assumption that the deposit thickens towards its source, it is concluded that these scoria were erupted from southern Candlemas Island.

Except at the southern end of the west peninsula, the scoria horizon grades upward into stratified silt- to pebble-sized material similar to the stratified deposits below the scoria. To the south, the scoria horizon is overlain by a vesicular glassy lava enclosing a great variety of small angular inclusions, including pumice and other rock fragments, of which the largest are up to 30 cm. across. This lava wedges out rapidly northward but it is seen again at the top of cliffs on the east side of the west peninsula overlooking Medusa Pool.

3. *Exposures along the western margin of southern Candlemas Island*

The coastal cliffs from the west peninsula southward, along the edge of the 18 m. terrace, consist of stratified material similar to that in the west peninsula. The even well-sorted strata (cf. Plate IVa) suggest deposition in a quiet aqueous environment, probably a lagoon, into which primary deposits of freshly erupted ash fell at intervals. The broad flat strip of land between the coast and the present-day moraine is thus believed to represent the floor of a former shallow lagoon now elevated to 18 m. a.s.l.

Immediately below the ice cap along the western side of southern Candlemas Island, exposures at two separate localities reveal a sequence of three lava flows, each of which is capped by a thin scoria layer. In the more southerly, topographically lower outcrop, the lava flows are up to 4 m. thick, whilst in the northern outcrop the thickness of each flow does not exceed 1·5 m. It is likely that the two exposures are of the same three lava flows and that these flowed south-westward, thickening down-hill.

The two headlands at the south-western corner of the island (Plate IIa) are formed by flows which appear to have been emitted near sea-level from points at the foot of the main cliffs.

IV. GEOLOGY OF THE NORTHERN PART OF CANDLEMAS ISLAND

THE geological observations on the northern part of Candlemas Island, including the volcanic evolution of that part of the island, are recorded on the geological map (Fig. 6).

1. *Lucifer Hill*

Lucifer Hill (Plate IIIc) rises to 229 m. a.s.l. and forms the central and highest feature in northern Candlemas Island. It consists mainly of unconsolidated dark grey scoria and ash in which the largest blocks measure up to 60 cm. across, whilst the majority of the material falls in the size range 5–15 cm. A thin flow of lava is exposed on the upper south-eastern flank of the cone (Plate IIIc) and is underlain by 11 m. of scoria interstratified with finer tuffaceous layers. The northern and the southern craters both contain similar scoria and ash which are superficially reddened. On the north-western flank of the cone, fumarolic activity is strong, and the dark scoria have been altered and buried by deposits of loose crystalline sulphur up to 23 cm. thick. Ground temperatures in this area are over 50° C at 45 cm. depth

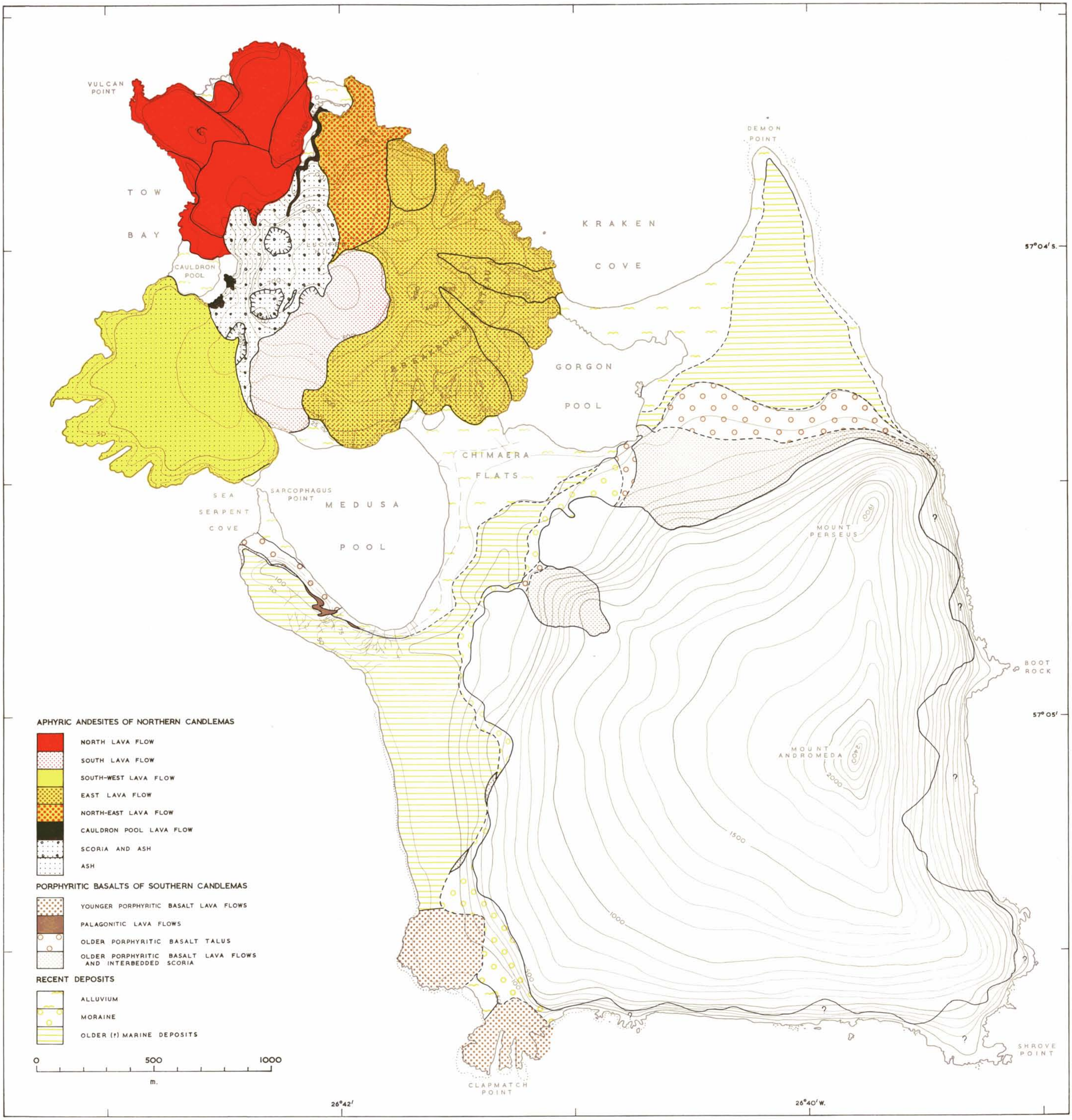

FIGURE 6

Geological sketch map of Candlemas Island.

[face page 9

below the surface. The northern cone is the oldest structure in the northern part of the island, since one of the earliest lava flows is exposed at the head of Clinker Gulch, high on the north-east flank of the cone at 183 m. a.s.l.

2. *The south-west scoria conelet*

The south-west scoria conelet (Plate IIIa) is 46 m. high and 122 m. in diameter at the base. It adjoins the south-western flank of Lucifer Hill. There is a wide breach on the south-west side, through which a large lava flow has emerged. The north-eastern rim of the conelet is low at the point where it abuts upon Lucifer Hill. The highest parts of the present rim therefore form two crescentic mounds (Plate IIIc) on the north-west and south-east sides.

The inner and outer flanks of the conelet are covered by irregularly shaped lumps of dark scoria, of which the majority are between 5 and 30 cm. across and closely resemble specimens from the flanks of the central cone. An exposure of dark scoria 6 m. thick is visible on the north-west flank of the conelet, at the top of lava cliffs overlooking Cauldron Pool (Plate IIb). No lava flow is visible in the flanks of the conelet and the whole structure appears to consist of scoria which below the rim is probably over 30 m. thick. This conelet has grown by the accumulation of products of mild scoria eruptions from the vent, which was also the source of a much greater volume of fluid lava.

3. *Lava flows*

Almost the whole of northern Candlemas Island beyond the central cone of Lucifer Hill and the south-west conelet is composed of lava flows which have been emitted successively to add broad tongues of new land to the island. These flows have a thickness of between 15 and 46 m., and rose through vents on the flank of the central cone to spread out into shallow sea-water. In the older of the lava flows, it is not possible to distinguish the separate lava tongues. The boundaries of younger flows, however, are clearly defined; from their field relationships, and by taking into account the amount of frost shattering and lichen or moss growth, it has been possible to establish with reasonable certainty the chronological sequence of the five principal lava flows. In addition to the lava flows, there were two periods of ash and scoria eruption, deposits from which mantled the pre-existing flows and thus divide the effusive sequence into three distinct phases.

a. *Pale flow-banded lavas in Clinker Gulch and above Cauldron Pool.* Pale grey, flow-banded lavas are seen in a low ridge on the eastern side of Clinker Gulch (Plate IVb) and in cliffs which overlook Cauldron Pool. The outcrops in these two localities appear to mark the site of a former shoreline, which has been preserved in Clinker Gulch. Similar massive lava is exposed to the east of Cauldron Pool in two cliffs 24 m. high (Plate IIb) which appear to mark the position of the coastline prior to the effusion of the north lava flow. It is possible that the Cauldron Pool and Clinker Gulch outcrops are part of two more or less contemporaneous flows. The upper flow exposed in Clinker Gulch crops out as high as 183 m. a.s.l. on the flank of the cone (Fig. 6), thereby demonstrating that the cone must already have been a large structure when this flow was emitted. Both flows thicken down-hill and the underlying unit reaches a maximum of 21 m. at the lower end, including a mantle of 6 m. of consolidated scoria which has been eroded into sharp pinnacles at the northern end of Clinker Gulch (Plate IVb).

b. *North-east lava flow.* The north-east flow (Plate IId) is composed of lava containing sparse cumulophyric clusters of plagioclase and olivine up to 2 cm. across. These tend to be more abundant towards the margins than in the central part of the flow. The flow extends westward as far as the eastern side of Clinker Gulch, where it overlies the earlier, pale flow-banded lava. The eastern margin of the flow is marked by a small east–west gully separating it from the east lava flow. The north-east flow is mantled by ash-fall deposits which overlie a large part of the original surface. Only the taller blocks project through this ash cover, which appears to have been concentrated, due to local re-distribution, into former hollows in the surface of the flow (Plate IVc).

c. *East lava flow.* The east lava flow (Plate IId) is one of the largest in northern Candlemas Island, occupying the sector from south to east of Lucifer Hill, and with an estimated volume of 0·35 km.^{3}.

Along the eastern coast, cliffs of massive lava rise to an average height of 30 m., of which the top 3 to 6 m. are composed of loose scoriaceous blocks. Along the southern fringe, which adjoins Medusa and Gorgon Pools and Chimaera Flats (Plate IIIa), almost no massive lava is exposed and the loose scoriaceous blocks probably represent the original front of the flow, which appears never to have been exposed to marine erosion.

Three lower-lying areas of larger blocks are present near the margin of the east lava flow: two of these are V-shaped, widening towards the coast (Plate IId). The third is U-shaped and also opens seaward. These more coarsely blocky areas may represent the margins of adjacent lava tongues, although no systematic variation was detected in hand specimens from different parts of the flow. Disintegration, erosion and the mantle of overlying ash have together concealed any flow lines and topographic features which might once have existed.

The whole of the flow is covered by stratified ash and therefore preceded the lowest of the stratified ash deposits. The flow appears to overlap the southern margins of the north-east flow, although the relationship of these two lava flows was not established with certainty.

Samples from the lower parts of the east lava flow are of non-vesicular, greenish grey lava, whilst rocks from near the surface often contain relatively few, large contorted vesicles up to 2 cm. long (e.g. SSC.54.1).

d. *South-west lava flow.* The south-west flow (Plate IIIb) is a single unit with an estimated volume of $0 \cdot 184$ km.^{3}. The surface of the flow lies at an average of about 36 m. a.s.l., being in general flat, although in detail it is crossed by furrows up to $4 \cdot 6$ m. deep, many of which are concentric about the south-western conelet (Plate IIIb), showing clearly that this was the source. A vertical section across the flow is exposed in cliffs to the south-west of Cauldron Pool, where the lower 15 m. of the flow are massive and medium grey in colour. This massive part is overlain by a 6 m. layer of scoria, of which all but the topmost metre or so is deep red. The broad flat surface of the flow as a whole, and the concentric ridges, indicate that the magma was not viscous and was supplied during a single effusive episode.

The flow has a superficial cover of fine ash with an average thickness of $7 \cdot 5$ cm. near the south-western extremity, and of 15 cm. near the south-eastern margin adjacent to the south lava flow. The ash cover does not increase in thickness from the latter locality towards the south-western conelet and may not have originated from this vent.

e. *South lava flow.* The south lava flow issued from a vent on the southern side of Lucifer Hill (Plate IIIc). It varies in thickness from 12 m. at the south-eastern end to 46 m. at the south-western extremity, where it spills into Medusa Pool. It has an estimated volume of $0 \cdot 052$ km.^{3}. There appear to have been two main flow axes, to the east and to the south-west (Plate IIIb), although there is no morphological evidence that either of these two lobes preceded the other. The longer south-western tongue has flowed down a 10° slope into the northern end of Medusa Pool and the movement of the magma down this slope has left larger blocks stranded at the margins of the flow to form levées, whilst the central part appears to have subsided due to the continued flow of magma along the axial area. Ridges up to $4 \cdot 6$ m. high and concentric about the source are poorly developed, and are transected by gullies of similar size running parallel to the axis of the flow. The latter are lava channels and appear to have formed due to local differential rates of flow on a smaller scale than that responsible for the levées. The south lava flow is not covered by ash deposits and shows only mild signs of disintegration by frost action, although growths of crustose lichen are relatively common, and rare small patches of moss (*Bryum* sp.) were observed.

f. *North lava field.* The north lava field (Plate I) is composed of at least four very recent tongues, all of which have issued from a boca half-way up the northern flank of the central cone. The entire lava field has an estimated volume of $0 \cdot 117$ km.^{3}, and an average elevation above sea-level of 37 m. The average thickness of each flow is about 21 m. The oldest lava is exposed in four small areas near the coast and their relative ages cannot be established. These have been overlapped by three successive flows with distinct boundaries. The surfaces of the flows are composed of large dark grey blocks up to $4 \cdot 6$ m. across, in which concentric ridges up to 6 m. high are poorly developed.

Small wisps of steam, rising from many points at the surface of the latest flow of the north lava field, indicate that this lava has not yet completely cooled and must therefore be very young. It is probably the flow which was reported to be glowing by *John Biscoe* in 1953–54 (Holdgate, 1963, p. 401).

4. *Ash and scoria deposits on the lava flows*

In addition to being almost the only visible components of the northern cone of Lucifer Hill and the south-west conelet, ash and scoria form a thin mantle on the oldest lava flows. Deposits on the east lava flow are composed of up to five distinct layers, which could be recognized in pits dug at 122 m. intervals along a traverse from the south-eastern foot of Lucifer Hill to the south-eastern extremity of the east lava flow. The vertical sections exposed in the pits are drawn to scale in Fig. 7. The recorded decrease

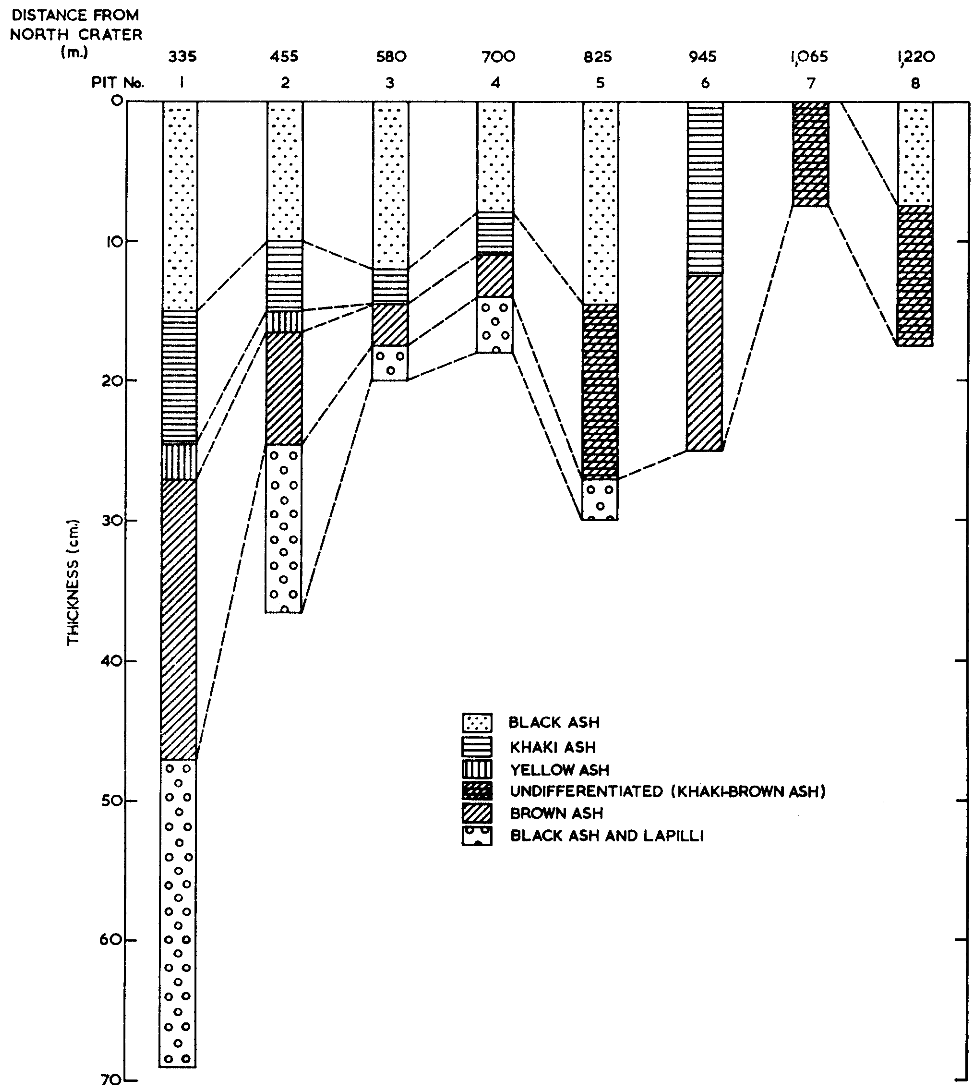

FIGURE 7

Vertical sections through ash and scoria deposits exposed in pits dug along a traverse from the south-eastern foot of Lucifer Hill to the south-eastern extremity of the east lava flow.

in thickness away from the active centre is characteristic of pyroclastic fall deposits (cf. Kuno, 1941, p. 146). A similar thickness of ash and scoria mantles the north-east flow, although the more irregular surface of this flow appears to have led to greater local re-distribution of the ash (Plate IVd). On the west lava flow, a single black ash layer was identified, and this appears to be the equivalent of the highest layer on the east lava flow. It is therefore believed that the south-west flow was emitted between the periods of explosive activity represented by the khaki and the upper black ash.

The upper black ash on the east lava plateau is itself sprinkled with large bombs of vesicular or compact, glassy, mildly cumulophyric lava, which are especially concentrated in an arc around the southern boca. The bombs appear to have been ejected by explosions from this boca during the effusion of the south lava flow. In addition to the glassy and scoriaceous bombs, there are numerous blocks of other types, including pebbly tuff (SSC.10.2) and lumps of pale grey flow-banded lava (SSC.10.1) similar to that found *in situ* beside Cauldron Pool. Both types of ejected block have been greatly affected by frost action; the tuff has disintegrated into heaps of small fragments, whilst the banded lava has split along the flow planes into flat slate-like slabs (Plate IVc). The blocks of tuff may represent fragments of a formation which underlies the lava flows and pyroclastics now exposed in northern Candlemas Island.

V. VOLCANIC HISTORY OF CANDLEMAS ISLAND

THE volcanic history of Candlemas Island can be divided into two principal periods: the first is that of the formation of the older southern part of the island which is now extinct; the second is that of the growth of the recent eruptive centre of northern Candlemas Island.

1. *First period: the growth of southern Candlemas Island*

During the first period, lavas consisting mainly of porphyritic basalt were emitted and formed a large pile of flows with interbedded scoria. The precise location of the eruptive vent is uncertain but it presumably lay near the eastern higher side of the present land, probably beyond the present eastern coastline.

After the growth of the main volcanic pile, activity took place around the flanks of southern Candlemas Island, where younger porphyritic basalts were emitted as flows from isolated points near sea-level at the south-western and south-eastern corners of the island. These relatively small, marginal effusions reflect the waning eruptive powers of the southern centre, and they may be compared with the recent flank eruptions involving small quantities of new lava on Bouvetøya (Baker and Tomblin, 1964) and on Tristan da Cunha (Baker and others, 1964).

It should be noted that the first period represents the major part of the volcanic history of Candlemas Island, during which 90 per cent of the total present volume of lava above sea-level was erupted.

2. *Second period: the growth of northern Candlemas Island*

The second period of activity on Candlemas Island opened with the formation, to the north of the old volcanic centre, of a new eruptive vent which emitted lavas of a character substantially different from those of southern Candlemas Island. The younger lavas are almost aphyric and relatively rich in silica (see Fig. 9 and Table II). This suggests that a period of dormancy intervened between the first and second periods of activity, during which the nature of the Candlemas Island magma changed.

The development of the northern centre can be traced in detail, due both to the excellent exposure of the lava flows and to the occurrence, at two periods in the succession, of widespread pyroclastic deposits. A diagrammatic reconstruction of the growth of northern Candlemas Island is presented in Fig. 8.

The first eruptions from the northern centre took place probably beneath shallow sea-water and led to the emergence of a small scoria cone. The early growth stages are likely to have been comparable with the development of the new volcano of Capelhinos in the Azores (Zbyszewski, 1960), or to Surtsey, the new island off Iceland (Thorarinsson, 1967). Lava flows were then emitted and the earliest, in the sequence now visible, crops out to the north and to the south-west of the central cone (Fig. 8a).

The next important event involved the effusion of a large volume of lava from the eastern side of the scoria cone to form the north-east and east lava flows (Fig. 8b). The east lava flow is probably composite, consisting of a number of adjacent tongues, and it appears to be younger than the north-east flow. There followed a renewal of pyroclastic activity involving the vertical eruption of ash and scoria to form four recognizable layers which mantled the pre-existing lava flows (Figs. 5 and 6). This activity must have enlarged the central scoria cone from which the pyroclastics were erupted.

A new vent then opened at the south-western foot of the northern scoria cone of Lucifer Hill, around which dark-coloured scoria were piled to form a small conelet and from which a single, large lava flow

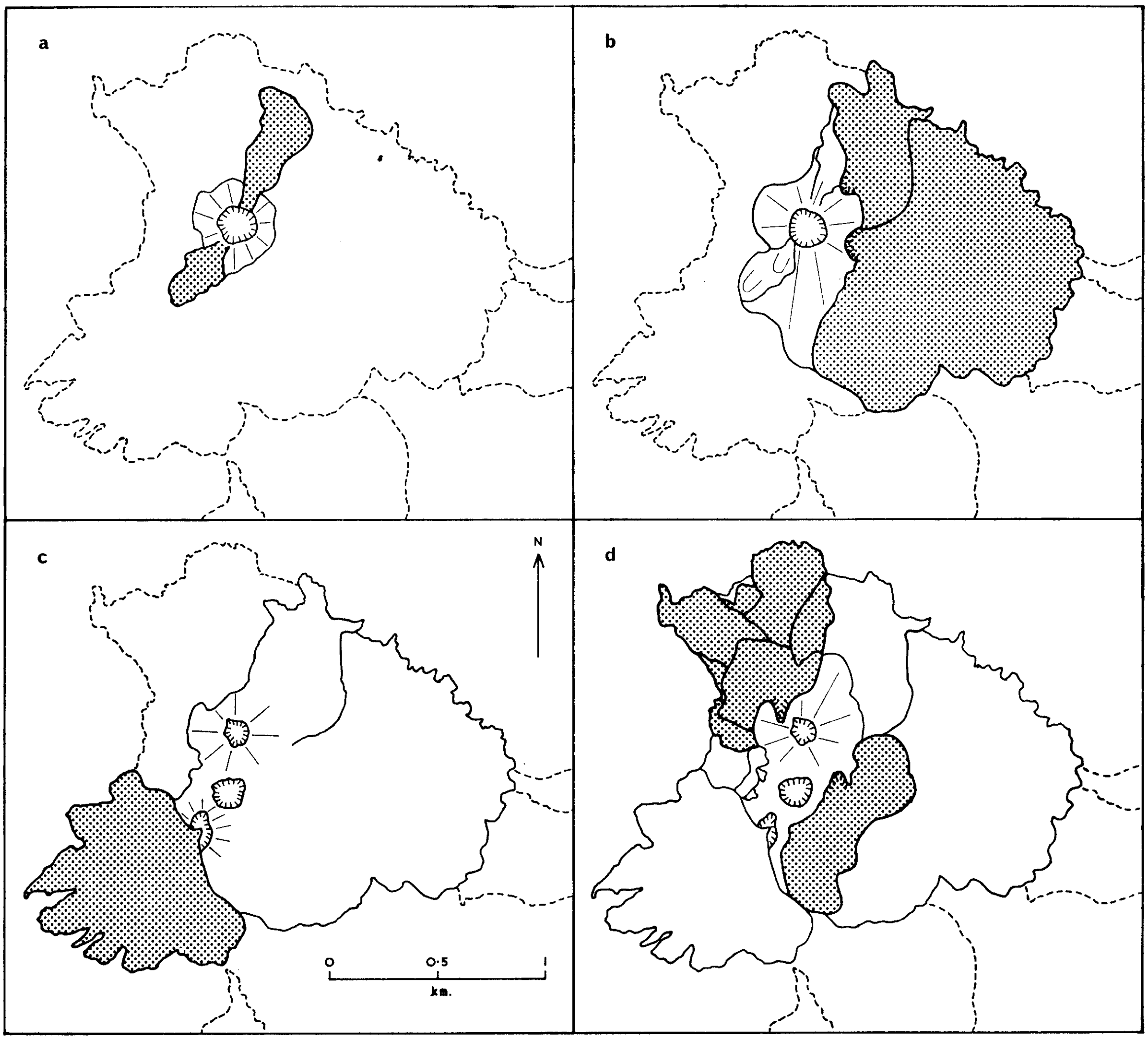

FIGURE 8

Four sketch maps illustrating the probable sequence of growth of northern Candlemas Island. The pecked lines indicate the present coastline.

(the south-west lava flow) was emitted (Fig. 8c). The south-west lava flow is overlain by the highest pyroclastic layer which mantles the east and north-east lava flows. The opening of the southern crater, high on the southern flank of Lucifer Hill may have taken place at this period.

Since the most recent pyroclastic eruptions, two bocas half-way up the flanks of Lucifer Hill have emitted lava flows (Fig. 8d). The earlier of these was the southern boca, from which the south lava flow issued. This flow has two lobes, directed to the east and to the south-west, which appear to have grown during a single effusive phase. The youngest lava field on Candlemas Island lies to the north-west; it is composed of at least four lava tongues, all of which issued from the northern boca. The most recent lava tongue is still emitting steam from many points on its surface and it is probably the flow which was reported by *John Biscoe* to be glowing in 1953–54 (Holdgate, 1963, p. 401). Like the south lava flow, the north lava flow is not overlain by any pyroclastic deposits.

The entire sequence of events in northern Candlemas Island, i.e. the second period as a whole, has been brief by geological standards, having probably occupied not many thousands of years. This is also likely to have been brief in comparison with the period of growth of southern Candlemas Island, which is possibly to be reckoned in millions of years. Northern Candlemas Island is probably the youngest island volcano in the South Sandwich Islands group, although it may not be so young as the submarine volcano to the north of Zavodovski Island (Gass and others, 1963).

VI. PETROGRAPHY

1. *Classification and nomenclature*

The rocks of Candlemas Island are members of an assemblage which has been variously called the basalt–andesite–rhyolite association (Turner and Verhoogen, 1960, p. 272), the calc-alkali series (Nockolds and Allen, 1953) and the calcic series (Peacock, 1931). This assemblage especially characterizes volcanoes of island arcs and orogenic regions.

The Candlemas Island lavas fall into two principal types which differ both mineralogically and chemically. These are called basalt and andesite. The andesites, which are almost aphyric, are named on the basis of their chemical composition (Table II). A third rock type, which is very subordinate in volume, occurs as xenoliths in the andesites. These xenoliths are extremely rich in phenocrysts, which are believed to be accumulative, and the rocks are therefore called accumulative xenoliths.

2. *Optical methods*

Modal analyses were made by automatic point counter at $\frac{1}{3}$ by $\frac{1}{3}$ mm. intervals. About 2,000 points were counted on each slide.

The core composition of large plagioclase phenocrysts was determined by refractive index measurements on hand-picked crystal fragments, using the curves of Chayes (1952, p. 85). The range of the zoning was determined by measuring the extinction angles of albite twin lamellae in sections perpendicular to (010), using the curve of Winchell and Winchell (1951, p. 262). Olivine compositions were determined by measurement of the refractive indices of hand-picked or magnetically separated crystals, using the curves quoted by Deer and others (1963, p. 22). Optic axial angles of the olivines were also measured on the universal stage where possible and, using the values of Tomkeieff (1939, p. 235), these gave compositions agreeing closely with those determined from refractive index measurements. For the clinopyroxenes, the refractive index β and 2V were measured after the method of Hess (1949, p. 627), and the composition was estimated using the curves of Hess by measurement of the refractive index and $2V\alpha$ with reference to the curves of Deer and others (1963, p. 28).

3. *Porphyritic basalts of southern Candlemas Island*

Porphyritic basalts are exposed around the margins of southern Candlemas Island, forming a series of alternating flows and scoria layers (p. 7–9). Samples were collected only from the northern and western sides of southern Candlemas Island, although similar exposures were observed from the air in high cliffs along the eastern coast. A collection of rocks from the south-eastern extremity of the island, Shrove Point, made by Capt. C. A. Larsen in 1908, has been described petrographically by Baeckström (1915, p. 169–70).

The porphyritic basalts are dark or pinkish grey in colour, and either non-vesicular or with few irregular vesicles up to 5 mm. across. Phenocrysts visible in the hand specimen include plagioclase, greenish black pyroxene and yellowish green olivine. The modal compositions of two specimens (SSC.43.1, Plate Va; SSC.41.1, Plate Ve) are given in Table I. In most of the porphyritic basalts, olivine and clinopyroxene are the predominant mafic minerals. Orthopyroxene is subordinate except in a few specimens which contain less olivine (e.g. SSC.44.1–3 and 48.1). The groundmass is intergranular, being composed of plagioclase, clinopyroxene and opaque oxide which is often rimmed by haematite. In one rock (SSC.32.1, Plate Vd), cristobalite is abundant in the groundmass.

a. *Plagioclase*. Phenocrysts of plagioclase are subhedral to euhedral, and range from 0·5 to 5 mm. in size. They show albite, pericline and Carlsbad twinning. Most crystals have cores of bytownite or anorthite (max. An_{91}) and an outer rim which often shows oscillatory zoning over a range ending with andesite at the periphery. In a few crystals, oscillatory zones occupy as much as the outer half by area, including narrow zones crowded with dust and minute clinopyroxene inclusions. In some rocks (e.g. SSC.43.1), the zoning is mainly of the normal-continuous type and it affects approximately the outer half by area of the larger phenocrysts. There is a wide variation in the number and type of zones in different plagioclase phenocrysts in a single thin section, and this suggests a variety in the crystallization

TABLE I

MODAL ANALYSES OF ROCKS FROM CANDLEMAS ISLAND

Specimen number	SSC.43.1	SSC.41.1	SSC.20.2	SSC.54.2	SSC.29.2	SSC.10.4	SSC.24.3
Plagioclase	28·5	45·4	4·4	4·4	6·4	35·9	71·4
Olivine	2·1	0·5	–	tr	–	4·8	12·8
Clinopyroxene	1·4	0·5	0·4	0·6	0·3	2·7	11·9
Orthopyroxene	0·6	0·2	0·5	0·5	0·6	6·2	3·9
Ore	–	–	0·1	–	0·2	–	–
Groundmass	67·4	53·4	94·6	94·5	92·5	31·0	–
Vesicles (percentage of slide)	1·5	12·1	–	0·4	0·9	19·4	26·0

Figures quoted for minerals and groundmass are percentages of the total solid material (excluding vesicles).

SSC.43.1 Porphyritic basalt, older lava flow, southern Candlemas Island.
SSC.41.1 Porphyritic basalt, younger lava flow, southern Candlemas Island.
SSC.20.2 Aphyric andesite, Cauldron Lake lava flow, northern Candlemas Island.
SSC.54.2 Aphyric andesite, east lava flow, northern Candlemas Island.
SSC.29.2 Aphyric andesite, north lava flow, northern Candlemas Island.
SSC.10.4 Accumulative lava, bomb lying on the surface of the east lava flow.
SSC.24.3 Gabbroic inclusion, south lava flow, northern Candlemas Island.

history of independent crystals. The groundmass plagioclase consists of elongate prisms up to 0·3 mm. in maximum size, often forming a seriate texture, gradational into microphenocrysts.

The more northerly of the two flows extending into the sea at the south-western corner of the island (Carbon Point; SSC.41.1) contains 45 per cent of 2–5 mm. plagioclase phenocrysts with only a few crystals intermediate in size between these and the groundmass. One large phenocryst in specimen SSC.41.1 (Plate Ve) contains a string of small olivine inclusions near its rim, showing that in this rock calcic plagioclase probably began to crystallize earlier than olivine.

Plagioclase phenocrysts of unusually large size are present in boulders from the moraine south of Gorgon Pool (SSC.34.1–6). These crystals measure up to 15 mm. across and contain polysynthetic twin lamellae up to 1 mm. wide which are visible in the hand specimen. One crystal in specimen SSC.34.6 (Plate Vb) is totally enveloped by a corona 6–10 mm. wide of granular olivine poikilitically enclosed by large skeletal clinopyroxenes. Other large (5–10 mm.) plagioclase phenocrysts are without the corona and some enclose small (1 mm. or less) crystals of olivine and pyroxene near their cores. Refractive index measurements made on hand-picked fragments from the cores of these crystals correspond to a maximum composition of An_{92}. The olivine crystals mantling the plagioclase in specimen SSC.34.6 have a composition, estimated from refractive index measurements, of Fo_{84}.

Similar large anorthite crystals have been reported from several other calc-alkaline island-arc volcanoes. They are relatively common as phenocrysts, especially in andesite and less commonly in basalt lavas from Honshu and the Izu Islands, Japan, and have also been reported from the islands of Ketoi and Shinshiru in the Kurile Islands. Details of these occurrences have been given by Ishikawa (1951, p. 340–42), who commented on the fact that they are restricted mainly to the Quaternary volcanic zones of north-east Japan, where the rocks are poorest in alkalis. In the Japanese rocks, as in the Candlemas Island specimens, the large anorthites are commonly surrounded by a narrow margin of more sodic composition and accompanied by smaller phenocrysts of a more sodic plagioclase. In the island arc of the Lesser Antilles, large crystals of anorthite in lava have been reported from St. Vincent (Lewis, 1964, p. 41), whilst Byers (1961, p. 99) recorded anorthite phenocrysts in the lavas of the Okmok volcano, north-eastern Umnak, Aleutian Islands.

b. *Clinopyroxene.* Phenocrysts of clinopyroxene are subhedral to anhedral, equidimensional and up to 1·5 mm. in maximum size. Some occur as cumulophyric clusters up to 2 mm. across, composed of as many as ten adjacent or interpenetrating crystals. Several of the larger crystals show strong zoning. Rims not more than 0·02 mm. wide, of finely granular pyroxene, often surround phenocrysts of olivine (e.g. in specimen SSC.43.1).

Like the plagioclase, clinopyroxene grades in size from phenocrysts to groundmass grains of about 0·05 mm. Clinopyroxene inclusions are present in some of the larger plagioclase phenocrysts, as anhedral crystals which are often elongated parallel to the *c*-axis of the plagioclase host. Occasional microphenocrysts are ophitic to groundmass-sized prisms of plagioclase (SSC.43.1). In specimen SSC.35.3, microphenocrysts of clinopyroxene are poikilitically enclosed within some of the plagioclase phenocrysts.

c. *Olivine.* Olivine phenocrysts are present in most of the lavas from southern Candlemas Island. The phenocrysts are usually subhedral, seldom larger than 0·5 mm., strongly cracked and in most cases completely fresh. In specimen SSC.43.1, some of the cracks are filled by narrow strands of bright orange iddingsite, and the crystals are rimmed by finely granular pyroxene. In specimen SSC.32.1 (Plate Vc) all of the olivines have a conspicuous corona of iron ore, and cracks are filled by this mineral and iddingsite, whilst some of the smaller olivines are almost or completely pseudomorphed by the ore. In specimen SSC.47.1, serpentinization has predominated, and most crystals are half replaced by a greenish brown alteration product which is probably antigorite, rimmed by a narrow corona of chrysotile and dendritic opaque oxide.

d. *Cristobalite.* Angular patches of cristobalite are particularly abundant in the groundmass of one specimen (SSC.32.1, Plate Vd), in which it appears as faintly pinkish, finely granular aggregates showing low refractive index and "tile" structure.

4. *Vitrophyric lava flow of the west peninsula*

A vitrophyric lava flow crops out near the top of the succession in the west peninsula (Fig. 4a). This is a dark grey mildly vesicular flow-banded rock, which contains abundant angular inclusions up to 10 cm. across of paler grey tuff or weathered lava, together with sparse 1 mm. feldspar phenocrysts and occasional ferromagnesian crystals of similar size.

In thin section (SSC.38.1, Plate Vf), the groundmass is seen to consist of dark, nearly opaque glass with a few granules of clinopyroxene and opaque oxide. Plagioclase phenocrysts are less abundant than, although similar to, those in the older porphyritic lavas. They are subhedral, equidimensional, up to 2 mm. in diameter and display albite, Carlsbad and pericline twinning. Most crystals show fine-scale oscillatory zoning which commonly affects only the outer half by area and surrounds an unzoned core, whilst small elongate patches of brown glass occur along cracks or parallel to crystallographic directions. Clinopyroxene forms subhedral, often elongate crystals, up to 1·5 mm. in length, some of which enclose small plagioclase prisms near their margins. Occasional pyroxenes are poikilitic to small olivines. Larger olivines are subhedral to euhedral, fresh and up to 2 mm. across. Inclusions in the lava consist mainly of small angular fragments of porphyritic lava with an intergranular groundmass, which is similar to that of the older porphyritic basalts.

5. *Glassy lava boulders in moraine from southern Candlemas Island*

Blocks of black glassy lava are common at one locality in southern Candlemas Island. These are compact and without phenocrysts or flow structure. They form about 5 per cent of the boulders in the moraine to the south of Gorgon Pool and their restriction to this area suggests that they were derived from a nearby source, which may now be concealed beneath the ice cap.

The refractive index of specimen SSC.33.3 is $1\cdot532\pm0\cdot002$, suggesting that the glass, if not hydrated, probably contains more than 60 per cent of SiO_2 (cf. the curves given by Williams and others, 1954, p. 28).

6. *Almost aphyric andesites of northern Candlemas Island*

The lava flows and scoria of northern Candlemas Island are readily distinguishable from those of southern Candlemas Island on account of their almost aphyric texture and fresh appearance. They contain not more than 6 per cent of phenocrysts, mainly of feldspar (Table I). In the hand specimen they can be divided into three categories:

i. Medium to dark grey lavas with a few microphenocrysts (east, south-west and north flows).
ii. Medium to dark grey lavas with a few microphenocrysts plus occasional glomerophyric clusters of large crystals (north-east and south flows).
iii. Medium to pale grey flow-banded lavas with a few microphenocrysts (Clinker Gulch and Cauldron Pool flows).

Within the uppermost quarter of each flow, a gradation is seen from non-vesicular to progressively more vesicular material as the surface is approached. The specimens selected for detailed petrographic description come mainly from the lower parts of the flows and are therefore without or almost without vesicles. No change in the mineralogy of the lava was discernible in specimens from the upper and lower parts of the same flow.

In thin section (Plate VIa–d), the lavas contain phenocrysts of plagioclase, accompanied by occasional orthopyroxene and clinopyroxene with extremely rare olivine. The groundmass of almost all rocks has a pilotaxitic fabric, composed essentially of lath-shaped feldspar microlites which often show sub-parallel flow orientation, accompanied by clinopyroxene and opaque oxide.

a. *Plagioclase*. Phenocrysts of plagioclase are subhedral, up to 2 mm. across and often form small cumulophyric clusters. They are twinned especially according to the Carlsbad, and less commonly according to the albite and pericline laws. The most calcic cores are of An_{75} and zoning affects the outer one-sixth to one-half of the area of the phenocrysts, and usually consisting of a large number of very fine oscillations with a narrow compositional range. The cores of a few of the largest crystals contain evenly dispersed dust inclusions. The groundmass plagioclase consists of narrow laths with a maximum length of 0·2 mm., grading downward in size to cryptocrystalline material. Albite twinning is discernible in the larger laths, which in many specimens lie sub-parallel to one another, indicating flow orientation.

b. *Clinopyroxene*. Clinopyroxene occurs as microphenocrysts, which are subhedral to anhedral and rarely larger than 0·4 mm. in diameter. These often accompany plagioclase in cumulophyric clusters and are poikilitic to small crystals of plagioclase and opaque oxide. Twinning on the (100) plane is present in occasional crystals. Clinopyroxene also occurs as narrow, finely granular mantles to orthopyroxene phenocrysts, and in the groundmass, intergranular prisms which are rarely larger than 0·02 mm. in diameter.

c. *Orthopyroxene*. Microphenocrysts of orthopyroxene are subhedral or anhedral and similar in size to the clinopyroxenes. Many have narrow rims of clinopyroxene and plagioclase. Inclusions of small plagioclase prisms and opaque oxide are commonly present. Occasional pyroxenes, however, are partially enclosed in the outer parts of large plagioclase crystals, indicating that orthopyroxene began to crystallize during the later stages of plagioclase phenocryst growth. In most rocks, microphenocrysts of orthopyroxene are fewer than clinopyroxene.

d. *Olivine*. Olivine is rare, being present in only two of the 20 thin sections of the andesites examined. In specimen SSC.56.1, a single, anhedral 1 mm. prism is poikilitically enclosed by a large (4 mm.) plagioclase phenocryst. In specimen SSC.24.5 (Plate VId), a 2 mm. olivine phenocryst is partially enclosed by cumulophyric plagioclase and isolated from the adjacent groundmass by a narrow rim of clinopyroxene. Olivine is also visible as pale yellowish green 1 mm. crystals which are present only in the central part of cumulophyric clusters in several hand specimens of rocks from the north-east and south lava flows (SSC.18.1, 56.1, 24.5, 14.1, and 5.2). Olivine therefore appears not to have been in equilibrium with the liquid at the time of its extrusion.

e. *Accessory minerals.* Opaque oxide is present both as subhedral grains up to 0·3 mm. across, which are often associated with cumulophyric pyroxenes, and also as fine granules dispersed evenly through the groundmass.

7. *Accumulative xenoliths in the lavas of northern Candlemas Island*

Four specimens of rocks, which appear to be accumulative, were found in northern Candlemas Island. Three of these occurred as inclusions in lava (SSC.56.2, 24.2 and 3) and one as a lava-coated bomb (SSC.10.4).

In the hand specimen, the rocks are rich in crystals of plagioclase (<5 mm.), accompanied by yellowish green olivine (except in specimen SSC.56.1) and dark green pyroxene, both up to 2 mm. across. These are set in an interstitial, dark-coloured, finely vesicular groundmass, containing cavities of 0·5 mm. average and 4 mm. maximum diameter. Large crystals of plagioclase with subordinate olivine, clinopyroxene and orthopyroxene occupy at least 50 per cent of the rock and lie in a vesicular matrix of finely crystalline or glassy material. The modal compositions of two specimens (SSC.10.4, Plate VIe; SSC.24.3, Plate VIf) are given in Table I. The vesicular groundmass is either hyalo-ophitic with abundant pale or dark brown glass within an open network of plagioclase and clinopyroxene laths, and equigranular opaque ore (SSC.10.4 and 56.1); or felty with radiating clusters of lath-shaped plagioglase and clinopyroxene microlites accompanied by equigranular opaque oxide without glass (SSC.24.2 and 3).

a. *Plagioclase.* Plagioclase occurs as subhedral to anhedral, equidimensional crystals which commonly reach 3 mm. in diameter, and in specimen SSC.24.3 especially (Plate VIf) are poikilitic to small olivines. Small plagioclase prisms are poikilitically enclosed by clinopyroxenes. Twinning is well developed according to the albite and Carlsbad laws, whilst pericline twins are less common. Extremely fine-scale oscillatory zoning, mainly in the labradorite range, is common in specimens SSC.24.2, 54.2 and 10.4, and up to 100 oscillations are seen between the core and rim of several large phenocrysts in specimen SSC.10.4. However, in specimen SSC.24.3 oscillatory zoning is much less conspicuous and broader normal–discontinuous zoning of restricted compositional range affects the outer halves by area of most phenocrysts. In the groundmass, the larger laths of plagioclase show albite twinning and normal–continuous zoning in the range An_{60-40}.

b. *Olivine.* Olivine is most abundant in specimen SSC.24.3 (Table I), where it occurs as anhedral rounded crystals ranging in size from 0·1 to 2 mm. (Plate VIf), in which slight alteration of the margins and along cracks has produced pale brown serpentinous material. Many of the smaller crystals are poikilitically enclosed by plagioclase and clinopyroxene. In specimens SSC.24.2 and 10.4, anhedral 1–2 mm. olivines are mantled by orthopyroxene growing in optical continuity. Crystals are only rarely enclosed by plagioclase and small olivines of the type common in specimen SSC.24.3 are not abundant.

c. *Orthopyroxene.* Crystals of orthopyroxene are numerous in all of the xenoliths (Table I), occurring as independent subhedral to anhedral prisms up to 2 mm. across or as mantles to olivines. The larger crystals often enclose groundmass-sized plagioclase laths, accompanied in specimen SSC.24.3 by small olivines.

d. *Clinopyroxene.* Clinopyroxene occurs as anhedral crystals up to 2 mm. across, which are poikilitic to olivine and plagioclase (Plate VIf). Crystals are zoned, including both normal and slight oscillatory zones. Extinction angles, $\gamma \wedge c$, increase slightly towards the cores. Clinopyroxene is less abundant than orthopyroxene in all specimens and rare in specimen SSC.24.2, in which it occurs only in the groundmass as lath-shaped prisms.

VII. GEOCHEMISTRY

1. *Methods of analysis*

Six chemical analyses of rocks from Candlemas Island are given in Table II. These were made by the author in the Department of Geology and Mineralogy at Oxford, using "rapid" methods based on those of Riley (1958, p. 413–28) with the following exceptions: calcium was determined using the same

TABLE II

CHEMICAL ANALYSES OF ROCKS FROM CANDLEMAS ISLAND

Specimen number	SSC.24.3	SSC.41.1	SSC.43.1	SSC.20.2	SSC.54.2	SSC.29.2
SiO_2	42·8	48·5	50·6	60·9	62·7	64·4
TiO_2	0·22	0·55	0·70	0·95	0·93	0·85
Al_2O_3	21·9	23·1	18·6	14·8	14·5	14·4
Fe_2O_3	1·12	1·56	2·26	1·44	3·16	1·38
FeO	6·48	5·00	6·46	7·04	5·57	6·45
MnO	0·09	0·09	0·14	0·11	0·15	0·15
MgO	11·19	4·24	6·40	2·35	2·40	1·84
CaO	13·02	13·54	11·56	6·09	5·96	5·28
Na_2O	1·09	1·80	1·92	3·67	3·52	3·79
K_2O	0·03	0·13	0·13	0·39	0·33	0·45
H_2O+	1·35	1·18	1·44	0·84	0·88	0·11
H_2O-	0·31	0·27	0·32	0·19	0·14	0·30
P_2O_5	0·01	0·03	0·04	0·12	0·11	0·13
TOTAL	99·61	99·99	100·57	98·89	100·35	99·43
			C.I.P.W. NORM			
Q	0·00	1·70	3·90	18·56	23·33	23·53
or	0·18	0·77	0·77	2·31	1·95	2·66
ab	6·45	15·23	16·25	31·05	29·78	32·07
an	54·78	54·57	41·76	22·76	22·80	20·96
ne	1·50	0·00	0·00	0·00	0·00	0·00
di	7·84	10·14	12·47	5·62	5·02	3·72
hy	0·00	12·76	18·98	13·39	9·85	12·27
ol	25·14	0·00	0·00	0·00	0·00	0·00
mt	1·62	2·26	3·28	2·09	4·58	2·00
il	0·42	1·04	1·33	1·80	1·77	1·61
ap	0·02	0·07	0·09	0·28	0·26	0·31

For the explanation of the specimen numbers, see the legend to Table I.

reagents as Weibel (1961, p. 289), and magnesium was measured by the method of Shapiro and Brannock (1962, p. A35), although titrations for both of these elements were calibrated by comparison with standard solutions, after the principle employed for numerous elements by Riley (1958). Alkalis were determined by flame photometer using the method described by Vincent (*in* Smales and Wager, 1960, p. 53–55).

2. *Variation of oxides with silica*

The silica variation diagram for the rocks of Candlemas Island is shown in Fig. 9. Although six analyses provide barely sufficient data to justify the drawing of curves, it is believed, on the basis of the more comprehensive petrographic studies which have been made, that the specimens selected for analysis represent the principal rock types exposed on the island.

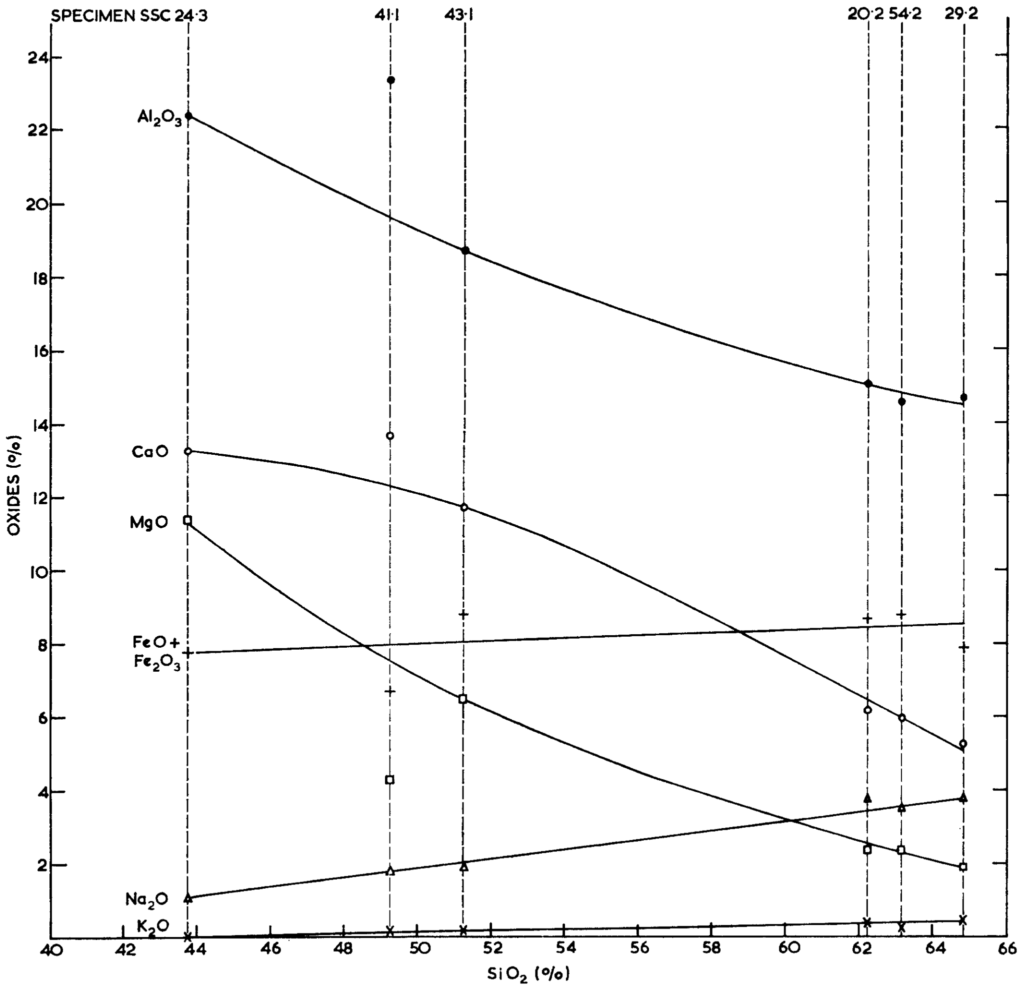

FIGURE 9

Silica variation diagram for the analysed rocks of Candlemas Island. For the chemical analyses see Table II; the explanation of the specimen numbers is given in the legend to Table I.

a. SiO_2. The analysed specimens cover a wide range in silica content. The recent, almost aphyric andesites of northern Candlemas Island (SSC.20.2, 54.2 and 29.2) contain between 61 and 65 per cent and they are separated by a large compositional gap from the porphyritic basalts of southern Candlemas Island (SSC.41.1 and 43.1). The latter with 48–51 per cent of SiO_2 are separated by a smaller gap from the gabbroic inclusion from northern Candlemas Island (SSC.24.3), in which 43 per cent of silica was recorded.

b. Al_2O_3. The alumina content of the andesites of northern Candlemas Island (14·4–14·8 per cent) is close to the average for acid members of the basalt–andesite–rhyolite association of Turner and

Verhoogen (1960, p. 272), and the porphyritic basalt specimen SSC.43.1 corresponds closely in alumina content to the basic members of this association. The alumina content of specimen SSC.41.1, by contrast, is unusually high and reflects the large proportion of plagioclase phenocrysts in this rock (Table I). From the position of this specimen with respect to the trend lines on the silica variation diagram, and especially the line for alumina, it is believed that the lava contains "accumulative" plagioclase which is rich in calcium (Table III). This preponderance of calcic feldspar is also reflected in the analysis by the high content of lime and by the low iron and magnesium relative to the other basic rocks.

c. $FeO+Fe_2O_3$. One of the most unusual features of the Candlemas Island suite, compared with most other volcanic suites from island-arc regions, is the behaviour of the iron oxides. Whereas in most island-arc and orogenic volcanic suites (e.g. Turner and Verhoogen, 1960, p. 275, 283; Baker, 1963, fig. 27; Tomblin, 1964, fig. 24) the iron curve shows a strong negative correlation with silica and is generally

TABLE III

MINERALOGICAL DATA FOR ROCKS FROM CANDLEMAS ISLAND

Specimen number	SSC.43.1	SSC.41.1	SSC.20.2	SSC.54.2	SSC.29.2	SSC.10.4	SSC.24.3
Plagioclase An (per cent)							
(± 5 per cent)							
Phenocryst core (max.)	91	91	59	75	75	89	87
Phenocryst rim (min.)	32	51	43	56	45	47	43
Groundmass core (max.)	59	64	n.d.	n.d.	60	62	–
Olivine							
2Vα (± 1°)	89°	n.d.	–	n.d.	–	90°	88–90°
γ (± 0·002)	1·703	1·703	–	1·730	–	1·700	1·704
Fo (per cent)	85	85	–	72	–	86	84
Clinopyroxene							
γ (± 0·002)	1·705	1·708	n.d.	n.d.	n.d.	n.d.	n.d.
β (± 0·002)	1·695	n.d.	n.d.	n.d.	1·697	1·698	1·698
γ∧c	n.d.	41°	n.d.	n.d.	n.d.	n.d.	n.d.
2Vγ (± 1°)	n.d.	n.d.	n.d.	n.d.	n.d.	55°	55°
Ca : Mg : Fe						45 : 34 : 21	
Orthopyroxene							
2Vα (± 1°)	n.d.	n.d.	58°	59°	58°	72°	n.d.
γ (± 0·002)	1·706	1·711	n.d.	n.d.	n.d.	1·700	1·700
En (per cent)	66	63	$64_{(34)}$	$65_{(33)}$	64	72	72

n.d. Not determined.

For the explanation of the specimen numbers, see the legend to Table I.

more or less parallel to that of CaO, in the Candlemas Island suite it shows a slight increase with increasing silica. An increase of iron in the more acid members of a series, although unusual in island-arc volcanoes, is well known in differentiated plutonic intrusions of Skaergaard type (e.g. Wager and Deer, 1939, p. 313), where it is the result of fractional crystallization.

d. *CaO*. The lime curve, which falls from between 11 and 14 per cent in the basic rocks to about 6 per cent in the andesites, is normal for calcium-rich rock suites from island arcs. The relative abundance of lime, as calcium-rich feldspar, in specimen SSC.41.1 corresponds with the high percentage of calcic plagioclase phenocrysts.

e. *MgO*. The curve for magnesia, similarly to calcium, exhibits a strong negative correlation with silica. It falls from over 11 per cent in the gabbroic inclusion to between 6·5 and 4·3 per cent in the basalts, and finally to less than 2·5 per cent in the andesites. Specimen SSC.41.1, which is rich in plagioclase, is correspondingly poor in magnesium-bearing minerals.

f. Na_2O. Soda displays a steady increase with increasing silica, from 1 per cent in the gabbroic inclusion to nearly 4 per cent in the andesites. It compares closely in abundance with other island-arc and orogenic suites.

g. K_2O. A feature which particularly characterizes the lavas of the South Sandwich Islands is their low content of potash. This was first pointed out by Tyrrell (1931, p. 196) and is fully confirmed by the present set of analyses. The K_2O percentage rises from 0·03 per cent in the gabbroic inclusion to a maximum of 0·45 per cent in the most acid andesite. The latter figure is, for example, less than half of that found in West Indian lavas with a similar silica content (MacGregor, 1938, p. 74; Tomblin, 1964, p. 148), whilst it is approximately one-fifteenth of the value obtained for the trachyte lavas of Tristan da Cunha on the Mid-Atlantic Ridge (Baker and others, 1964, p. 531), where rocks with an average of 60 per cent of SiO_2 contain 6·1 per cent of K_2O.

3. *Alkali-lime index*

The alkali-lime index, introduced by Peacock (1931), is the silica percentage at which the alkali oxides (Na_2O+K_2O) are as abundant as lime. The index of the Candlemas Island suite is 66·2 (Fig. 10). This figure is high, although comparable to those for several other island-arc volcanic suites, for which the index is also shown in Fig. 10. Although potash is exceptionally low in the rocks of Candlemas Island, this does not lead to an abnormal ratio of alkali oxides to lime. This feature can at least partly be explained by the relative rarity and by the less calcic composition of the plagioclase phenocrysts in the andesites.

4. *Fe : Mg : Na + K ratios*

The relative proportions of iron, magnesium and alkalis as atomic percentages are plotted in Fig. 11. All the points for the analysed rocks of Candlemas Island lie close to a curve which follows a most unusual direction. This is dominated by the magnesium content, which decreases sharply with increasing acidity, whilst iron shows almost no variation and alkalis increase only slightly in the more acid rocks. For comparison, the curves for a selection of volcanic suites from island arcs and orogenic regions are also plotted in Fig. 11. These curves without exception are dominated by an increase of alkalis and a corresponding marked decrease in iron in the more acid rocks. The position of the Candlemas Island curve suggests a process of rock genesis involving the accumulation of the high-temperature magnesium-rich minerals.

5. *K : Na : Ca ratios*

The relative proportions of potassium, sodium and calcium in the rocks from Candlemas Island and other island-arc suites are shown on the triangular diagram (Fig. 12). This serves to emphasize the paucity of potassium in the Candlemas Island rocks, a feature which is characteristic of all rock analyses from the South Sandwich Islands (cf. Tyrrell, 1945, p. 101). For comparison, the curves are also shown for

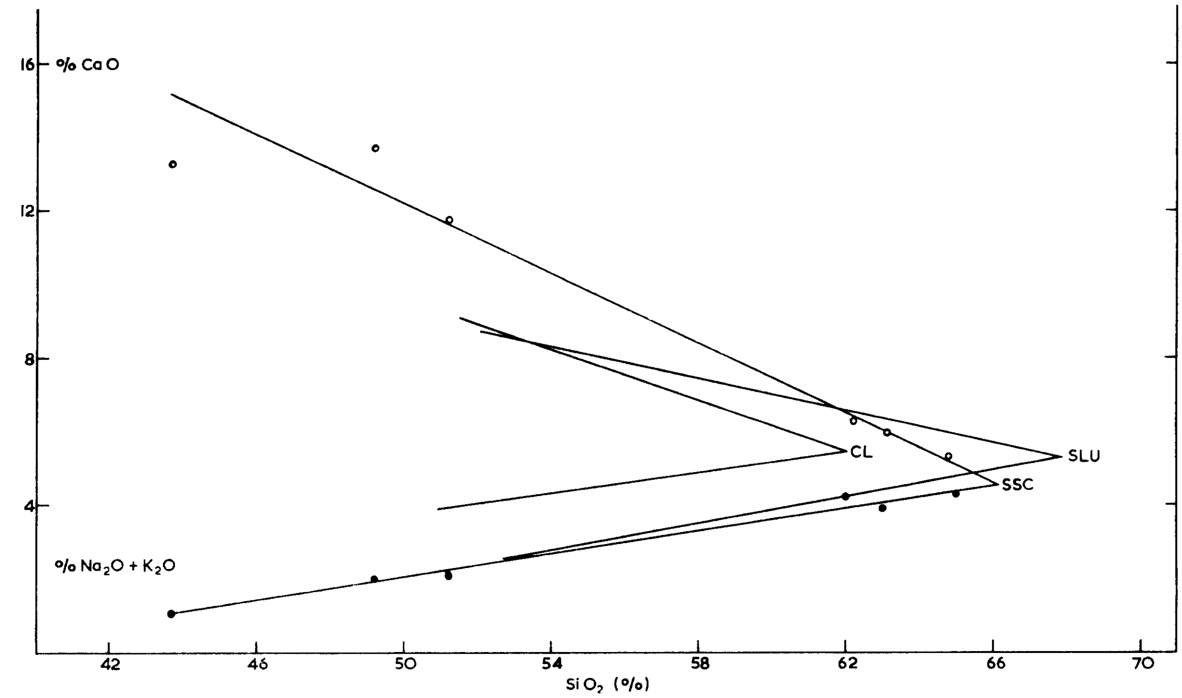

FIGURE 10

The alkali-lime index (Peacock, 1931) for analysed rocks from Candlemas Island (SSC). The alkali-lime indices for rock suites from Crater Lake (CL) and St. Lucia (SLU) are given for comparison. For the chemical analyses see Table II.

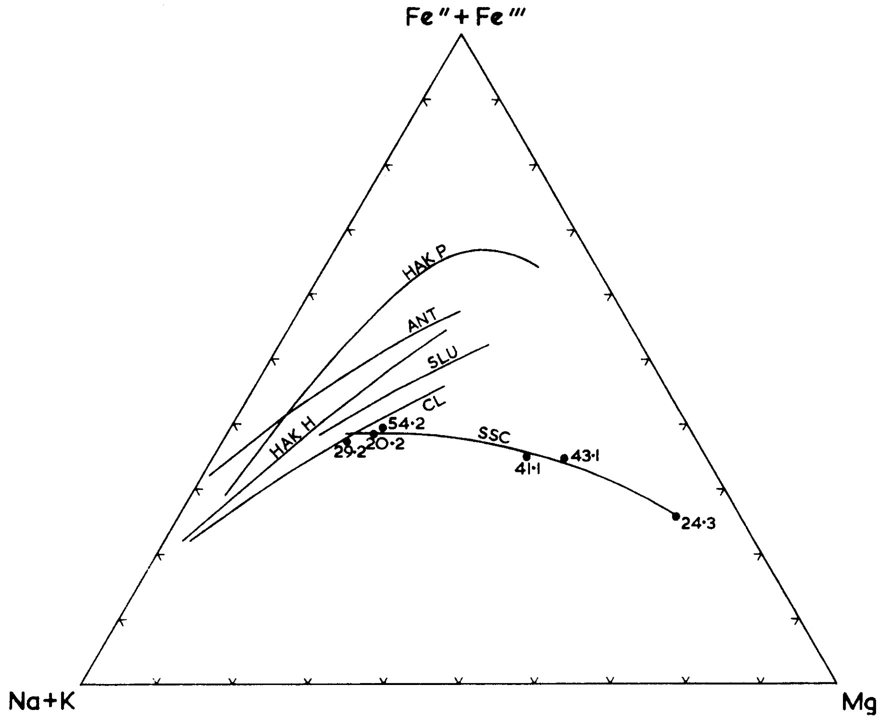

FIGURE 11

Triangular variation diagram for the atomic percentages of elements in analysed rocks from Candlemas Island (SSC) plotted on the coordinates (Fe″+Fe‴)–Mg–(Na+K). Plots for rock suites from Crater Lake (CL), St. Lucia (SLU), the Lesser Antilles (ANT) and the two series of lavas from Hakone volcano, Japan (HAK H and HAK P), are given for comparison. For the chemical analyses see Table II.

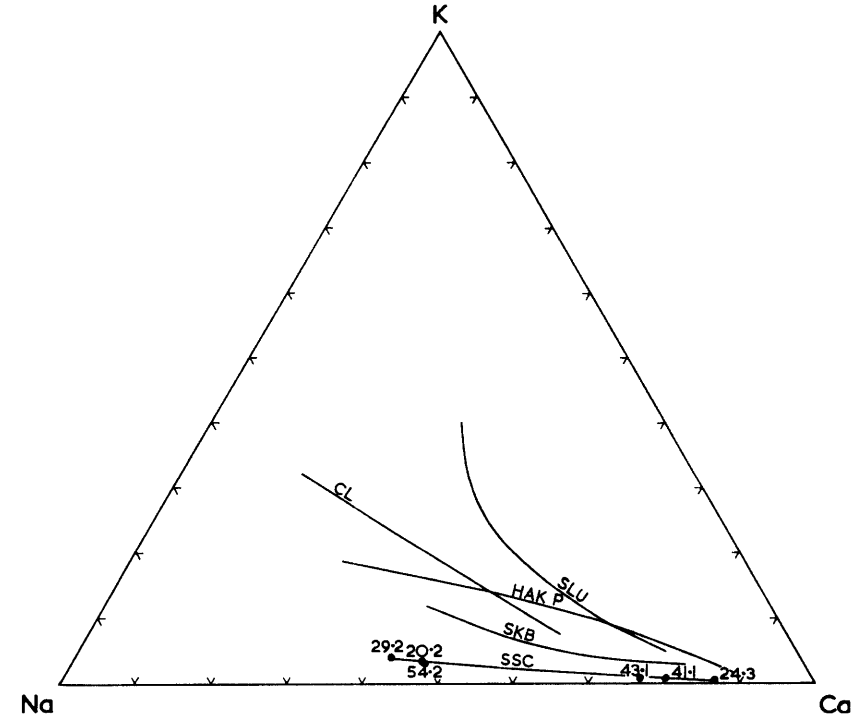

FIGURE 12

Triangular variation diagram for the atomic percentages of elements in analysed rocks from Candlemas Island (SSC) plotted on the coordinates K–Ca–Na. Plots for rock suites from Crater Lake (CL), St. Lucia (SLU), St. Kitts (SKB) and one of the series of lavas from Hakone volcano, Japan (HAK P), are given for comparison. For the chemical analyses see Table II.

rocks of St. Lucia and St. Kitts, in the Lesser Antillean arc, and for the two series of lavas from Hakone volcano, Japan. The curves for all except the Candlemas Island suite are roughly parallel to each other.

6. *Trace elements*

Table IV shows the abundance of 11 trace elements in the six rocks from Candlemas Island whose major oxides are given in Table II. Analyses for strontium and rubidium were made by the author in the Department of Geology and Mineralogy at Oxford, using a Philips X-ray fluorescence spectrometer, whilst other trace constituents were determined at Oxford by Mrs. N. Garton, using a Hilger large quartz and glass prism spectrograph.

In Fig. 13, the trace elements have been plotted against the differentiation index of Thornton and Tuttle (1960), using a logarithmic scale for the concentration. It is noteworthy that the sequence obtained from this plot, along the abscissa, corresponds closely to the sequence according to silica content (Fig. 9).

a. *Gallium*. The gallium content of the analysed rocks from Candlemas Island varies between 12 and 20 p.p.m. This range is comparable with those of other island-arc and orogenic volcanic suites (Table V), although it is noteworthy that among the lavas from Candlemas Island the ratio of gallium to aluminium is appreciably higher in the andesites than in the basalts. Nockolds and Allen (1953, p. 117) have commented on the mild enrichment of Ga with respect to Al among the most acid rocks in some of the calc-alkaline volcanic series which they investigated (e.g. Lassen Peak), and a similar relationship exists in the rocks of St. Lucia (Tomblin, 1964, p. 161). In neither the Lassen Peak nor the St. Lucia suites, however, is the increase in the Ga/Al ratio so marked as in the Candlemas Island lavas.

b. *Vanadium*. Vanadium is most abundant in the basalts of Candlemas Island, which contain 222–280 p.p.m. It is approximately one-half as abundant in the andesites and in the gabbro xenolith specimen SSC.24.3. With the exception of the latter specimen, the analysed rocks from Candlemas Island exhibit

TABLE IV

TRACE ELEMENTS IN ROCKS FROM CANDLEMAS ISLAND (p.p.m.)

Specimen number	SSC.24.3	SSC.43.1	SSC.41.1	SSC.20.2	SSC.54.2	SSC.29.2
Ga	12	15	17	19	16	20
V	131	284	227	167	156	105
Cu	24	105	73	21	81	24
Ni	37	17	9	<1	<1	<1
Zr	42	64	54	89	100	98
Co	56	44	31	22	22	17
Sc	37	53	39	42	42	37
Cr	172	44	32	9	9	9
Sr	88	101	104	89	98	87
Ba	52	65	56	156	152	185
Rb	<1	2	0	2	6	3

For the explanation of the specimen numbers, see the legend to Table I.

the usual decrease of vanadium with increasing acidity. The overall range in the vanadium content of the Candlemas Island rocks is comparable to that for other island-arc and orogenic volcanic suites.

c. *Copper*. There is a wide range, between 21 and 105 p.p.m., but no systematic variation in the copper content of the Candlemas Island rocks. Both of the analysed basalts and one andesite (SSC.54.2) are richer in this element.

d. *Nickel*. Nickel shows a systematic decrease in abundance from the most basic rock (37 p.p.m.) to the most acid (<1 p.p.m.). This trend and range are similar to those recorded in the basalts and andesites of other island-arc and orogenic volcanic suites.

e. *Zirconium*. The abundance of zirconium in the Candlemas Island rocks increases steadily with increasing acidity from 42 p.p.m. in the accumulative gabbro specimen SSC.24.3 to a maximum of 100 p.p.m. in the aphyric andesite specimen SSC.54.2. Values recorded for the gabbro xenolith and basalt lavas from Candlemas Island are low by comparison with those for basic rocks from the Lesser Antilles and from the Cascade Province, where all rock types contain about 100 p.p.m. of zirconium, and none has an average of less than 80 p.p.m.

f. *Cobalt*. Cobalt in the Candlemas Island suite decreases in abundance as the rocks become more acid, from 56 p.p.m. in the gabbroic inclusion to 17 p.p.m. in the andesite specimen SSC.29.2. This element is slightly more abundant in the Candlemas Island rocks than the average for rock suites of island-arc and orogenic regions, although the distribution trend relative to silica is similar.

g. *Scandium*. The scandium content of the Candlemas Island suite lies in the range 37–53 p.p.m., within which no systematic variation can be detected. This feature is noteworthy, however, since similar rock suites from the Lesser Antilles and the Cascade Province (Table V) are characterized by a trend involving the decrease of scandium with increasing acidity.

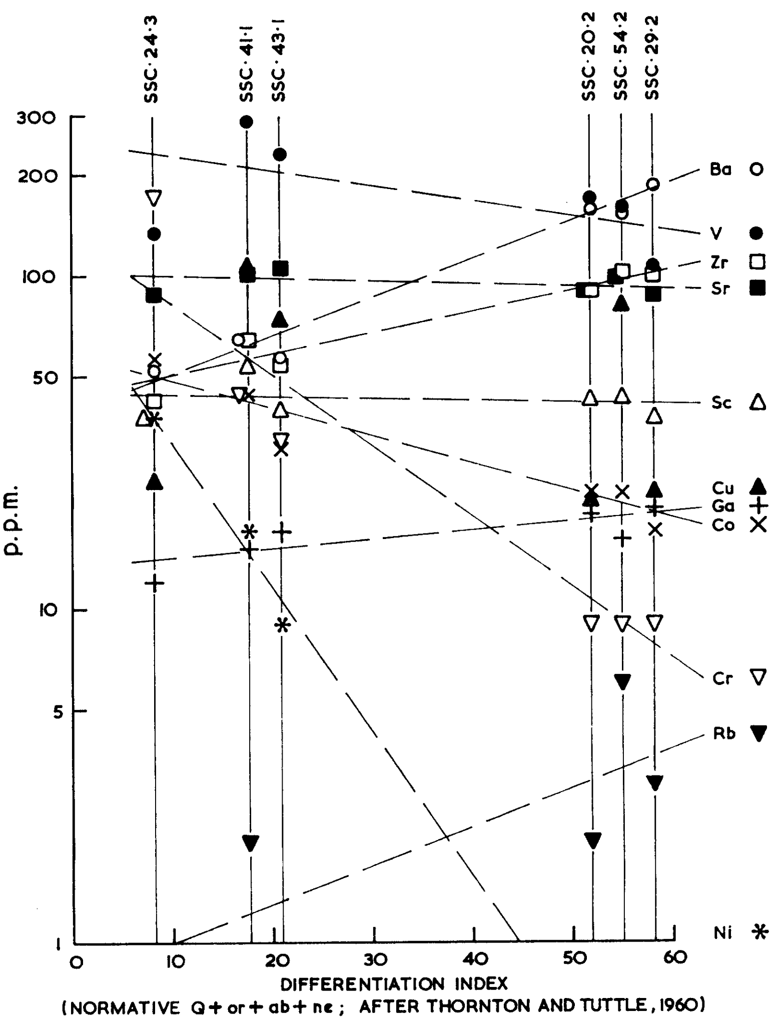

FIGURE 13

Variation of the trace elements in rocks from Candlemas Island plotted against the differentiation index (Thornton and Tuttle, 1960), using a logarithmic scale for the concentration of the trace elements (as p.p.m.). For the chemical analyses see Table IV.

h. *Chromium.* This element is strongly concentrated in the more basic rocks of Candlemas Island, especially in the gabbroic xenolith specimen SSC.24.3, which contains 172 p.p.m. The range in the Candlemas Island basalts (44–32 p.p.m.) and andesites (9 p.p.m.) is close to the average for lavas of island arcs and orogenic regions (Table V). In their discussion of trace-element distribution in the Skaergaard intrusion, Wager and Mitchell (1951, p. 183) observed that chromium enters abundantly into the early formed pyroxenes. In view of the abundance of large pyroxene crystals in the accumulative gabbro specimen SSC.24.3 (Table I), it is concluded that chromium has probably been concentrated in the early pyroxenes in the Candlemas Island magma.

i. *Strontium.* The variation shown by strontium in the Candlemas Island suite is slight and not systematic, although the abundance of this element (87–104 p.p.m.) is notably lower than in other island-arc suites (Table V). Approximately three times more strontium, for example, is present in the Lesser Antillean volcanic suites, whilst that of Lassen Peak contains ten times more strontium. Wager and Mitchell (1951, p. 194) found that widely different quantities of strontium may replace calcium in plagioclase feldspar. It appears that the amount of ionic substitution of Ca by Sr in the Candlemas Island plagioclase remains low and constant.

TABLE V

AVERAGE ABUNDANCE (p.p.m.) OF MINOR ELEMENTS IN BASALTS, ANDESITES AND DACITES OF ISLAND ARCS AND OROGENIC REGIONS

	St. Lucia			*Martinique*		*Montserrat*		*St. Kitts*		*Lassen Peak*			*Crater Lake*		*Umnak and Bogoslof (Aleutian Islands)*		*Kamchatka and Kuriles*			*Candlemas Island (South Sandwich Islands)*	
Reference	(Tomblin, 1964)			(Nockolds and Allen, 1953)				(Baker, 1963)		(Nockolds and Allen, 1953)					(Byers, 1961)		(Markhinin and Sapozhnikova, 1962)			(This paper)	
Rock type	bas.	and.	dac.	and.	bas.	and.	dac.	bas.	and.	bas.	and.	dac.	and.	dac.	bas.	and.	bas.	and.	dac.	bas.	and.
Number of analyses	2	3	2	6	2	4	1	5	15	2	6	2	7	5	9	4	14	21	10	2	3
Ba	180	383	243	233	88	162	300	130	263	260	780	750	480	930	311	550	–	–	–	61	164
Co	18	9	5	13	32	20	10	23	16	45	17	5	18	1	29	20	56	29	17	38	20
Cr	93	32	27	3	20	8	*	20	7	210	82	8	62	3	149	51	89	26	12	38	9
Cu	94	8	5	1	12	7	*	42	25	*	*	*	*	*	159	49	63	34	25	89	42
Ga	11	16	16	24	27	25	20	17	17	20	21	20	23	19	10	14	–	–	–	16	18
La	*	34	57	*	*	*	*	*	*	*	*	*	*	*	*	*	–	–	–	*	*
Li	15	21	34	38	13	23	45	–	–	18	44	50	20	34	–	–	–	–	–	–	–
Ni	26	6	5	1	12	7	*	3	2	100	35	3	44	3	61	20	61	33	12	13	<1
Rb	23	51	112	40	15	21	40	–	–	50	84	125	22	84	–	–	–	–	–	1	4
Sc	52	15	7	5	35	25	*	29	15	30	19	*	?10	2	40	6	–	–	–	46	40
Sr	290	270	277	325	625	312	250	261	287	825	1,100	1,250	840	670	756	650	–	–	–	103	91
V	268	52	35	100	350	168	100	250	100	235	107	50	138	43	267	145	520	280	176	256	143
Zr	80	97	88	86	87	106	100	90	92	130	97	110	118	100	57	78	–	–	–	59	96

* Not detected.
bas. Basalt; and. Andesite; dac. Dacite.

j. *Barium.* The analysed rocks of Candlemas Island fall into two distinct groups according to barium content; the basic rocks contain 52–65 p.p.m., whilst the andesites contain 152–185 p.p.m. These respective abundances are approximately one-half of those found in Lesser Antillean basalts and acid andesites.

k. *Rubidium.* Rubidium in the Candlemas Island rocks does not exceed 6 p.p.m., being approximately one-tenth as abundant as in the basalts and andesites of the Lesser Antilles. Due to the low concentration, the measurements of rubidium may be in error by a relatively large factor.*

VIII. PETROGENESIS

1. *Principal features of the Candlemas Island suite*

The following features must be accounted for by any system of rock genesis which attempts to explain the Candlemas Island suite:

i. The existence of two main lava types: older porphyritic basalts and younger aphyric andesites, separated by a gap in chemical composition and also, apparently, in time.
ii. The occurrence of calcium-rich plagioclase phenocrysts with cores of anorthite in the basalts and of bytownite in the andesites, and with rims formed of fine-scale oscillatory zones.
iii. The relatively low ratio of andesite to basalt exposed in Candlemas Island.
iv. The presence in the aphyric andesites of accumulative lava and gabbroic xenoliths.

2. *Possible genetic relationships of the Candlemas Island suite*

The basaltic rocks occupy an estimated 90 per cent of the total volume of Candlemas Island. For this reason, and in view of the abundance of basalt in many other parts of the world, they are assumed to represent primary magma derived from the mantle. Whilst a discussion of the generation of basaltic magma of the appropriate composition is beyond the scope of this report, it is however of interest to compare the particular characteristics of the Candlemas Island basalts with those of basalt types from other parts of the world.

The basalts of Candlemas Island are rich in alumina and it can be shown (Table VI, columns 1–4) that this feature is closely related to their content of plagioclase phenocrysts. The category of high-alumina basalts in the strict sense (Kuno, 1960, p. 122; Yoder and Tilley, 1962, p. 419) includes aphyric rocks only, and the basalts of Candlemas Island therefore do not belong to this group. Table VI shows that, when the plagioclase phenocrysts are subtracted from a Candlemas Island basalt, the chemical composition of the remainder, recalculated to 100 per cent (Table VI, columns 2 and 4), shows close affinities to that of a typical tholeiitic basalt (Table VI, column 5). An understanding of the origin of the plagioclase phenocrysts is therefore of primary importance in establishing the nature of the magma which was parental to the Candlemas Island suite. If the phenocrysts represent accumulative crystals, the parental magma may have been tholeiitic with a chemical composition close to that given in Table VI, columns 2 and 4. If, on the other hand, the large plagioclases are assumed to be simply early crystal phases in a primary magma which has not undergone significant crystal fractionation, this primary magma must have been rich in alumina before the first minerals crystallized, i.e. potentially an aphyric high-alumina basalt.

A variety of hypotheses has been proposed to explain the origin of highly calcic plagioclase phenocrysts in volcanic rocks, of which numerous occurrences have been reported from Japan (p. 16). Tsuboi (1920, p. 108–12) suggested that anorthites in lavas were formed by slow cooling under perfect equilibrium with the surrounding magma, i.e. as in plutonic intrusions, and therefore, in the case of a lava, before effusion and rapid cooling at the surface. Kozu (1927, p. 440–48) considered that calcium-rich plagioclase could form due to rapid growth in a low-viscosity melt rich in volatiles. Harada (1936, p. 330–49), on the other hand, preferred to regard the anorthites as xenocrysts, or as the product of

* In their analyses of rubidium in Hawaiian lavas using X-ray fluorescence, Lessing and others (1963, p. 5851) quoted a detection limit of 5 p.p.m. Rb, because the standard deviation at this level is ± 50 per cent.

TABLE VI

CALCULATED COMPOSITIONS OF BASALTS FROM CANDLEMAS ISLAND MINUS PLAGIOCLASE PHENOCRYSTS, AND COMPARISONS WITH AVERAGE THOLEIITIC AND HIGH-ALUMINA BASALTS

(All analyses recalculated to 100 per cent, volatile-free.)

	1	2	3	4	5	6	7	8
SiO_2	51·2	50·1	49·2	48·9	51·0	50·2	51·8	52·0
TiO_2	0·71	0·94	0·56	1·03	1·4	0·8	1·0	0·51
Al_2O_3	18·8	13·6	23·4	15·9	15·6	17·6	19·6	19·5
Fe_2O_3	2·29	3·00	1·58	2·73	1·1	2·8	3·5	1·97
FeO	6·54	8·96	5·07	9·37	9·8	7·2	5·5	6·27
MnO	0·14	0·19	0·09	0·17	0·3	0·2	0·2	0·11
MgO	6·48	8·74	4·30	7·95	7·0	7·4	4·0	6·83
CaO	11·70	10·48	13·74	12·44	10·5	10·5	10·1	10·47
Na_2O	1·94	1·36	1·83	1·13	2·2	2·8	3·6	2·11
K_2O	0·13	0·18	0·13	0·25	1·0	0·4	0·5	0·15
P_2O_5	0·04	0·05	0·03	0·06	0·1	0·2	0·1	0·05

1. Porphyritic basalt lava flow, Candlemas Island (SSC.43.1).
2. Porphyritic basalt lava flow, Candlemas Island (SSC.43.1), minus plagioclase phenocrysts.*
3. Porphyritic basalt lava flow, Candlemas Island (SSC.41.1).
4. Porphyritic basalt lava flow, Candlemas Island (SSC.41.1), minus plagioclase phenocrysts.†
5. Average tholeiite (Green and Poldervaart, 1955, p. 185).
6. Average high-alumina basalt of Japan (Kuno, 1960, p. 141).
7. Average (porphyritic) basalt of Mount Misery, St. Kitts (Baker, 1963, p. 193).
8. Chemical composition of a mixture of gabbroic xenolith specimen SSC.24.3 and aphyric andesite specimen SSC.54.2 (Table II) in the ratio of 3 : 2.

* Estimated average composition An_{75}.

† Estimated average composition $An_{76\cdot3}$.

mixing of two different magmas just before effusion. Harada's hypothesis was supported by Ishikawa (1951, p. 349).

In Candlemas Island, there is evidence to support the hypothesis that crystal fractionation of basaltic magma has probably taken place; the occurrence of xenoliths of accumulative lava and of gabbroic material (p. 19) in northern Candlemas Island is particularly significant in this respect, and it can be shown by calculation that the mixing of 60 per cent of gabbroic material with 40 per cent of aphyric andesite produces a rock whose chemical composition closely resembles that of the porphyritic basalt specimen SSC.43.1 (cf. Table VI, columns 1 and 8). This process of crystal fractionation, which requires that magma should be retained at depth for a prolonged period, would also provide conditions which permitted the slow growth of large, calcium-rich plagioclase crystals in the manner proposed by Tsuboi. If the Candlemas Island plagioclase phenocryst cores grew under conditions of equilibrium and were not subsequently separated from the parent liquid by crystal fractionation, their relationship to the normative plagioclase in the whole rock should correspond to the solidus and liquidus, respectively, in the experimental system albite–anorthite (Bowen, 1913). The two basalts from Candlemas Island and two of the three andesites correspond closely with the experimental system at atmospheric pressure. The Candlemas Island basalts differ from anorthite-phyric basalts from St. Vincent and Japan, in which the composition of the plagioclase cores lies to the calcium-rich side of the solidus. The latter can be explained by the hypothesis that crystallization occurred at a high water-vapour pressure, since the normative and phenocryst plagioclase pairs for the St. Vincent and Japanese samples correspond more closely to the liquidus and solidus in the experimental system at 5,000 bar (Yoder and others, 1957) than at atmospheric pressure. This suggests that the St. Vincent and Japanese magmas began to crystallize at a water-vapour pressure in excess of 5,000 bar and a correspondingly low temperature, whilst the Candlemas Island magma was poor in volatiles and therefore began to crystallize at a higher temperature. It appears unnecessary to postulate the existence of special magmas or contamination to explain the anorthite phenocrysts in the Candlemas Island rocks. No evidence was found in the Candlemas Island rocks to support the hypothesis that the plagioclases were xenocrystic or that mixing of magmas had occurred, as proposed by Harada for the Japanese anorthites.

It is concluded that the porphyritic basalts of southern Candlemas Island represent a primary magma which has not undergone crystal fractionation, whilst the aphyric andesites and ultrabasic xenoliths of northern Candlemas Island may be satisfactorily explained by a process of rock genesis involving simple fractional crystallization of a similar primary magma. There is no evidence in the Candlemas Island suite for assimilation or re-melting of crustal material as a significant process in the production of the andesites.

IX. COMPARISONS WITH OTHER VOLCANOES OF ISLAND ARCS AND OROGENIC REGIONS

1. *Morphology and structure*

Whilst the southern part of Candlemas Island is a relatively old volcanic structure, which has undergone extensive marine and glacial erosion, northern Candlemas Island by contrast is an example of a youthful volcanic centre which is excellently exposed and has remained little modified by weathering or erosion. Candlemas Island is notable among the island-arc volcanoes for the relative abundance of lava flows and the subordinate volume of pyroclastics. In this feature, it differs from most of the volcanic centres of the Lesser Antillean, Japanese and Indonesian island arcs, where pyroclastic deposits predominate greatly in volume over massive lavas. In keeping with their small volume, the pyroclastics present in Candlemas Island appear to have been the products of only mildly explosive Strombolian eruptions, forming scoria cones and thin layers of tephra fall. No thick Vulcanian or glowing avalanche agglomerates of the type emitted in great quantity by the Lesser Antillean and other island-arc volcanoes are present in Candlemas Island. It is unusual that eruptions involving andesite lava in northern Candlemas Island have been no more violent than those accompanying the effusion or ejection of basalt in southern Candlemas Island and in other parts of the world. The broad lateral extent of the andesite flows of northern Candlemas Island, indicating the low viscosity of the magma at the time of effusion, contrasts with the dome-like structures which are commonly formed in other parts of the world by lavas of this composition.

2. *Petrography*

The basalts of Candlemas Island, like the majority of their chemical analogues from other island-arc volcanoes, are porphyritic and contain phenocrysts of calcium-rich plagioclase with oscillatory zoned rims, clinopyroxene, orthopyroxene and olivine in a matrix composed mainly of plagioclase and clinopyroxene. The andesites of northern Candlemas Island, on the other hand, differ from the majority of island-arc andesites; whilst the latter commonly contain between 20 and 50 per cent of large phenocrysts, those from Candlemas Island are almost aphyric and completely lack the hydrous minerals (amphibole and biotite) which characterize lavas from the West Indies with a similar silica content.

3. *Geochemistry and petrogenesis*

The chemical differences between the Candlemas Island rocks and the lavas of other island arcs have already been outlined on p. 23–25. The most striking difference is the relatively high percentage of iron in the andesites of Candlemas Island, which in this respect differ from almost all other known island-arc suites, whilst they follow a trend which broadly resembles that of some differentiated plutonic intrusions (cf. Hess, 1960, pl. 11). This evidence, supported by the fact that the Candlemas Island suite, thus far investigated, plots on smooth curves on the triangular diagrams (Figs. 11 and 12), suggests that the andesitic magma of northern Candlemas Island, unlike many island-arc andesites, may represent the late-stage differentiate of a basaltic parent.

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XI. REFERENCES

ADIE, R. J. 1957. Geological investigations in the Falkland Islands Dependencies before 1940. *Polar Rec.*, **8,** No. 57, 502–13.

BAECKSTRÖM, O. 1915. Petrographische Beschreibung einiger Basalte von Patagonien, Westantarktika und den Süd-Sandwich-Inseln. *Bull. geol. Instn Univ. Upsala*, **13,** Pt. 1, 115–82.

BAKER, P. E. 1963. *The geology of Mt. Misery volcano, St. Kitts.* D.Phil. thesis, University of Oxford, 225 pp. [Unpublished.]

————. *and* J. F. TOMBLIN. 1964. A recent volcanic eruption on Bouvetøya, South Atlantic Ocean. *Nature, Lond.*, **203,** No. 4949, 1055–56.

————., GASS, I. G., HARRIS, P. G. *and* R. W. LE MAITRE. 1964. The volcanological report of the Royal Society Expedition to Tristan da Cunha, 1962. *Phil. Trans. R. Soc.*, Ser. A, **256,** No. 1075, 439–578.

BOWEN, N. L. 1913. The melting phenomena of the plagioclase feldspars. *Am. J. Sci.*, Ser. 4, **35,** 577–99.

BYERS, F. M. 1961. Petrology of three volcanic suites, Unmak and Bogoslof Islands, Aleutian Islands, Alaska. *Geol. Soc. Am. Bull.*, **72,** No. 1, 93–128.

CHAYES, F. 1952. Relations between composition and indices of refraction in natural plagioclase. *Am. J. Sci.*, Bowen Volume, Pt. 1, 85–105.

DEER, W. A., HOWIE, R. A. *and* J. ZUSSMAN. 1963. *Rock-forming minerals. Vol. 2. Chain silicates.* London, Longmans, Green and Co. Ltd.

GASS, I. G., HARRIS, P. G. *and* M. W. HOLDGATE. 1963. Pumice eruption in the area of the South Sandwich Islands. *Geol. Mag.*, **100,** No. 4, 321–30.

GREEN, J. *and* A. POLDERVAART. 1955. Some basaltic provinces. *Geochim. cosmochim. Acta*, **7,** Nos. 3/4, 177–88.

GRIFFITHS, D. H., RIDDIHOUGH, R. P., CAMERON, H. A. D. *and* P. KENNETT. 1964. Geophysical investigation of the Scotia arc. *British Antarctic Survey Scientific Reports*, No. 46, 43 pp.

HARADA, Z. 1936. *Bull. volcan. Soc. Japan*, **2,** 330–49. (In Japanese.)

HAWKES, D. D. 1962. The structure of the Scotia arc. *Geol. Mag.*, **99,** No. 1, 85–91.

HESS, H. H. 1949. Chemical composition and optical properties of common clinopyroxenes. Part I. *Am. Miner.*, **34,** Nos. 9–10, 621–66.

————. 1960. Stillwater igneous complex, Montana. A quantitative mineralogical study. *Mem. geol. Soc. Am.*, No. 80, 230 pp.

HOLDGATE, M. W. 1963. Observations in the South Sandwich Islands, 1962. *Polar Rec.*, **11,** No. 73, 394–405.

ISHIKAWA, T. 1951. Petrological significance of large anorthite crystals included in some pyroxene andesites and basalts in Japan. *J. Fac. Sci. Hokkaido Univ.*, Ser. 4, **7,** No. 4, 339–54.

KEMP, S. W. *and* A. L. NELSON. 1931. The South Sandwich Islands. *'Discovery' Rep.*, **3,** 133–98.

KOZU, S. 1927. *The Globe* (*Chikyu*), **7,** 440–48. (In Japanese.)

KUNO, H. 1941. Characteristics of deposits formed by pumice flows and those by ejected pumice. *Bull. Earthq. Res. Inst. Tokyo Univ.*, Ser. B, **19,** Pt. 1, 144–49.

————. 1960. High alumina basalt. *J. Petrology*, **1,** Pt. 2, 121–45.

LESSING, P., DECKER, R. W. *and* R. C. REYNOLDS. 1963. Potassium and rubidium distribution in Hawaiian lavas. *J. geophys. Res.*, **68**, No. 20, 5851–6065.

LEWIS, J. F. 1964. *Mineralogical and petrological studies of the ejected blocks of the Soufrière volcano, St. Vincent.* D.Phil. thesis, University of Oxford, 270 pp. [Unpublished.]

MACGREGOR, A. G. 1938. The Royal Society Expedition to Montserrat, B.W.I. The volcanic history and petrology of Montserrat, with observations on Mt. Pelé, in Martinique. *Phil. Trans. R. Soc.*, Ser. B, **229**, No. 557, 1–90.

MARKHININ, E. K. *and* A. M. SAPOZHNIKOVA. 1962. O soderzhanii Zr v vulkanicheskikh porodakh Kamchatki i Kurilskikh ostrovov [Zr content in volcanic rocks of Kamchatka and the Kurile Islands]. *Geokhimiya*, No. 9, 838–39. [English translation: *Geochemistry, Ann Arbor*, No. 9, 965–66.]

MATTHEWS, D. H. 1959. Aspects of the geology of the Scotia arc. *Geol. Mag.*, **96**, No. 6, 425–41.

NOCKOLDS, S. R. *and* R. ALLEN. 1953. The geochemistry of some igneous rock series. *Geochim. cosmochim. Acta*, **4**, No. 3, 105–42.

PEACOCK, M. A. 1931. Classification of igneous rock series. *J. Geol.*, **39**, No. 1, 54–67.

RILEY, J. P. 1958. The rapid analysis of silicate rocks and minerals. *Analytica chim. Acta*, **19**, No. 5, 413–28.

SHAPIRO, L. *and* W. W. BRANNOCK. 1962. Rapid analysis of silicate, carbonate, and phosphate rocks. *Bull. U.S. geol. Surv.*, No. 1144–A, 56 pp.

SMALES, A. A. *and* L. R. WAGER, *ed.* 1960. *Methods in geochemistry.* New York and London, Interscience Publishers Ltd.

THORARINSSON, S. 1967. Review of geological and geophysical research connected with the Surtsey eruption. (*In Proceedings of the Surtsey Research Conference, Reykjavík, 1967*, 20–29.)

THORNTON, C. P. *and* O. F. TUTTLE. 1960. Chemistry of igneous rocks: I. Differentiation index. *Am. J. Sci.*, **258**, No. 9, 664–84.

TOMBLIN, J. F. 1964. *The volcanic history and petrology of the Soufrière region, St. Lucia.* D.Phil. thesis, University of Oxford, 213 pp. [Unpublished.]

TOMKEIEFF, S. I. 1939. Zoned olivines and their petrogenetic significance. *Mineralog. Mag.*, **25**, No. 164, 229–51.

TSUBOI, S. 1920. Volcano Ôshima, Idzu. *J. Coll. Sci. imp. Univ. Tokyo*, **43**, Art. 6, 146 pp.

TURNER, F. J. *and* J. VERHOOGEN. 1960. *Igneous and metamorphic petrology.* 2nd edition. New York, Toronto and London, McGraw-Hill Book Company, Inc.

TYRRELL, G. W. 1931. Report on rock specimens from Thule Island, South Sandwich Islands. '*Discovery*' *Rep.*, **3**, 191–97.

————. 1945. Report on rocks from west Antarctica and the Scotia arc. '*Discovery*' *Rep.*, **23**, 37–102.

WAGER, L. R. *and* W. A. DEER. 1939. Geological investigations in East Greenland. Pt. III. The petrology of the Skaergaard intrusion, Kangerdlugssuak, East Greenland. *Meddr Grønland*, **105**, No. 4, 1–352.

————. *and* R. L. MITCHELL. 1951. The distribution of trace elements during strong fractionation of basic magma—a further study of the Skaergaard intrusion, East Greenland. *Geochim. cosmochim. Acta*, **1**, No. 3, 129–208.

WEIBEL, M. 1961. Die Schnellmethoden der Gesteinsanalyse. *Schweiz. miner. petrogr. Mitt.*, **41**, No. 2, 285–94.

WILLIAMS, H., TURNER, F. J. *and* C. M. GILBERT. 1954. *Petrography: an introduction to the study of rocks in thin sections.* San Francisco, W. H. Freeman and Co.

WINCHELL, A. N. *and* H. WINCHELL. 1951. *Elements of optical mineralogy. An introduction to microscopic petrography. Pt. 2. Description of minerals.* 4th edition. New York, John Wiley and Sons, Inc.; London, Chapman and Hall, Limited.

YODER, H. S. *and* C. E. TILLEY. 1962. Origin of basalt magmas: an experimental study of natural and synthetic rock systems. *J. Petrology*, **3**, Pt. 3, 342–532.

————., STEWART, D. B. *and* J. R. SMITH. 1957. Ternary feldspars. *Yb. Carnegie Instn Wash., No.* 56, 206–14.

ZBYSZEWSKI, G. 1960. L'éruption du volcan de Capelinhos (Ile de Faial, Açores). *Bull. volcan.*, Sér. 2, **23**, 77–100.

PLATE I

Oblique air photograph of northern Candlemas Island, from the north. The northern scoria cone (Lucifer Hill), in the centre, rises to 229 m. a.s.l. This is surrounded by lava flows which have issued from the flanks of the cone to form a series of overlapping plateaux 30–90 m. a.s.l., extending up to 800 m. into the sea. The most recent of these lava flows occupies the lower right of the photograph and is composed of at least four separate lava tongues. Beyond Lucifer Hill lies Medusa Pool. Behind this is the western peninsula, forming a north-westward extension of the older lavas and scoria of southern Candelmas Island. The top left of the picture shows the western margin of the ice cap which covers the greater part of southern Candlemas Island. Between the ice cap and the coast lies the 18 m. terrace. (Photograph reproduced by courtesy of the Admiralty.)

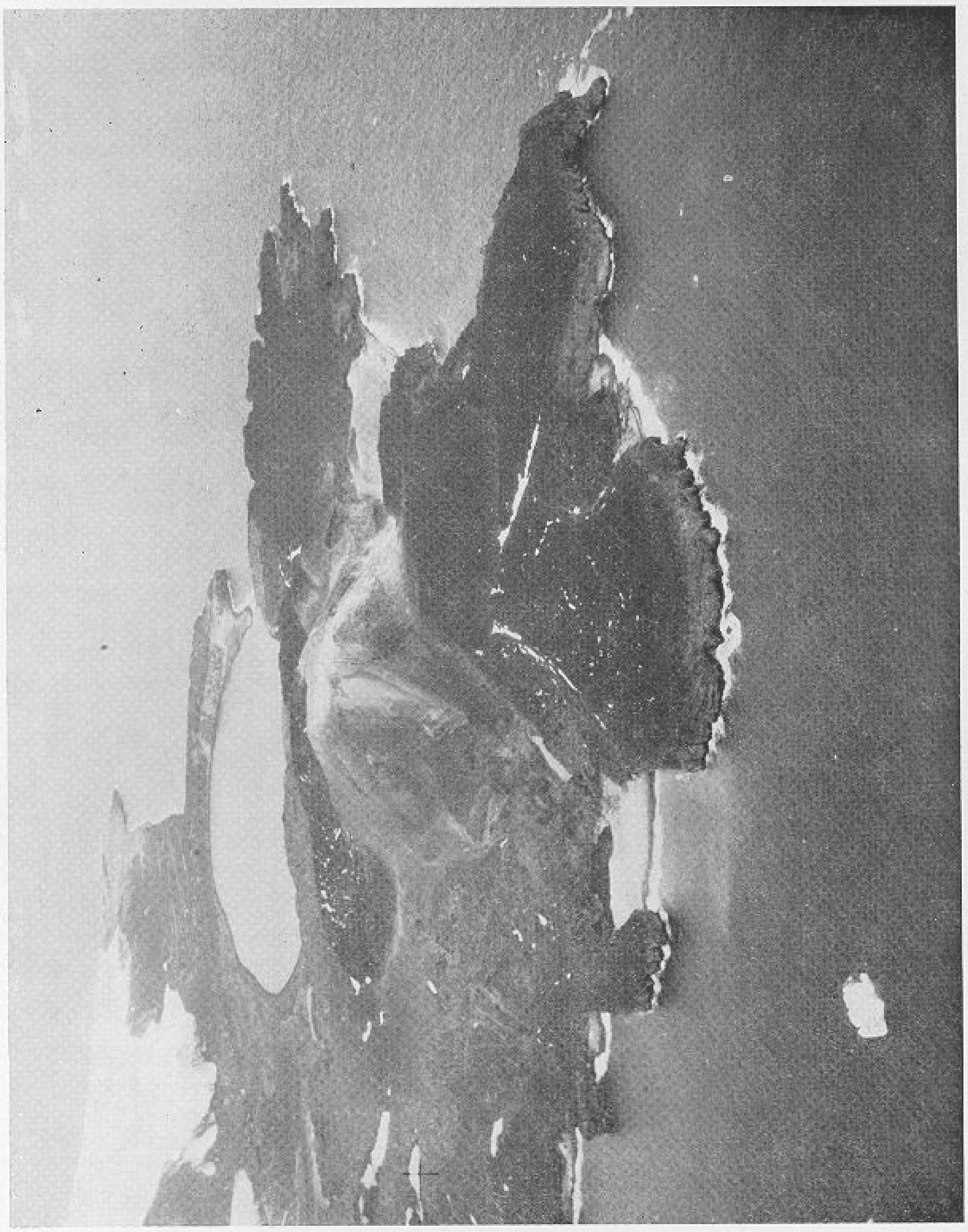

PLATE II

a. Panorama of Candlemas Island from the summit of Vindication Island, looking east-north-east. Candlemas Island is separated from Vindication Island (in the foreground) by Nelson Channel, which is 3·7 km. across. The southern part of Candlemas Island, rising to about 600 m. a.s.l., is volcanically extinct and is covered except along its margins by an ice cap. The active volcanic centre of northern Candlemas Island, by contrast, is completely free of ice. The northern scoria cone (Lucifer Hill) rises to 229 m. a.s.l. and is surrounded by recent lava flows forming overlapping plateaux. The two halves of the island are joined by low-lying inter-lagoonal flats (Chimaera Flats) (see Plate IIc).

b. Cauldron Pool; oblique air photograph from the south-west showing in the centre Cauldron Pool, which is 290 m. long. This lake is isolated from the sea (bottom left) by a broad shingle bar which rises to 6 m. a.s.l. The two prominent lava cliffs behind the lake are former sea cliffs, which mark the coastline of northern Candlemas Island, before the effusion of the west lava flow (right foreground) and of the north lava flow (left middle ground). Steam is rising from around the northern boca and from many small fumaroles on the north-western flank of Lucifer Hill. (Photograph reproduced by courtesy of the Admiralty.)

c. Chimaera Flats; oblique air photograph looking north-east. To the lower left is part of the western peninsula, composed largely of stratified water-laid deposits forming an extension of the 18 m. terrace (lower right). Medusa Pool occupies the left middle ground, and it is separated from Gorgon Pool (beyond, right) by an area of stratified ash and lapilli deposits not more than 6 m. a.s.l. Gorgon Pool is separated from the sea to the east by a narrow shingle bar, which curves eastward to join Demon Point. Beyond Medusa Pool lies the south-east lava flow which is part of the young volcanic centre of northern Candlemas Island. The ice-capped cliffs on the extreme right belong to southern Candlemas Island. (Photograph reproduced by courtesy of the Admiralty.)

d. Northern Candlemas Island; oblique air photograph from the north-east, showing the ash-covered east and north-east lava flows (left foreground) with two elongate V-shaped gullies containing coarsely blocky lava on which there is no ash cover. In the background, to the right, lies Vindication Island. (Photograph reproduced by courtesy of the Admiralty.)

a

b

c

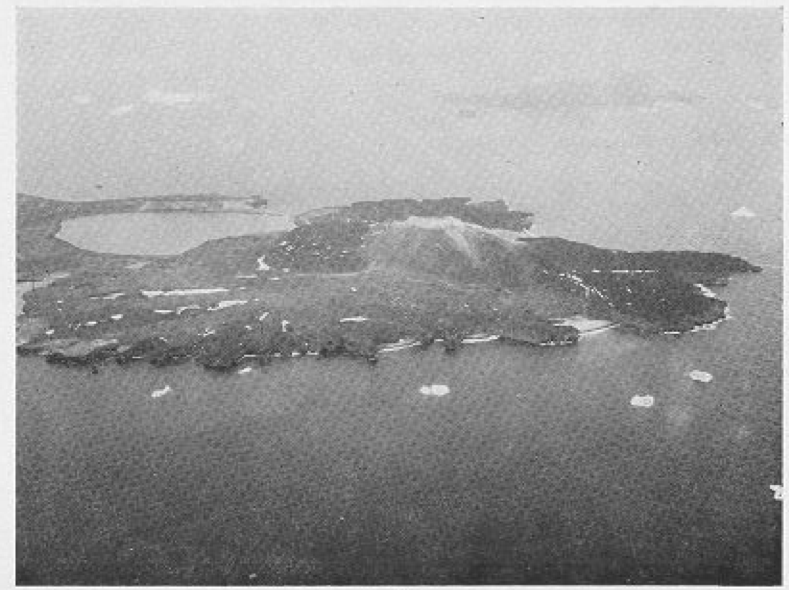

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PLATE II

PLATE III

a. Panorama of northern Candlemas Island from Sarcophagus Point looking north. The photograph shows Lucifer Hill (centre background) with the southern crater just below the skyline. Below and slightly to the left of the northern cone is the south-west scoria conelet. The latter is the source of the west lava flow which occupies the left-hand half of the photograph, The rugged skyline to the east (right) of the northern scoria cone is formed by the south lava flow. To the right of this is the smooth, gently shelving surface of the south-east lava flow, which is covered by ash.

b. Northern Candlemas Island; oblique air photograph from the south, showing the west lava flow (middle left) with ridges concentrically about its source, the south-west scoria conelet. Beyond and to the right of the latter lies Lucifer Hill. The west peninsula, enclosing Medusa Pool, occupies the lower right of the picture. (Photograph reproduced by courtesy of the Admiralty.)

c. Lucifer Hill; oblique air photograph from the east showing, in the centre foreground, the south lava flow of which the source, the southern boca, lies on the flank of Lucifer Hill. The photograph shows the complex structure of the summit of Lucifer Hill, which includes two distinct craters and several shallow depressions. Steam rises from the north crater (to the right) which is 140 m. in diameter and 16 m. deep. The south crater (to the left) is inactive. Between the two craters, three slight depressions indicate the probable site of earlier vents. The dark mass in the right background is the north lava flow, lying beyond and below Lucifer Hill. To the left of the south crater, the south-western scoria conelet is visible. (Photograph reproduced by courtesy of the Admiralty.)

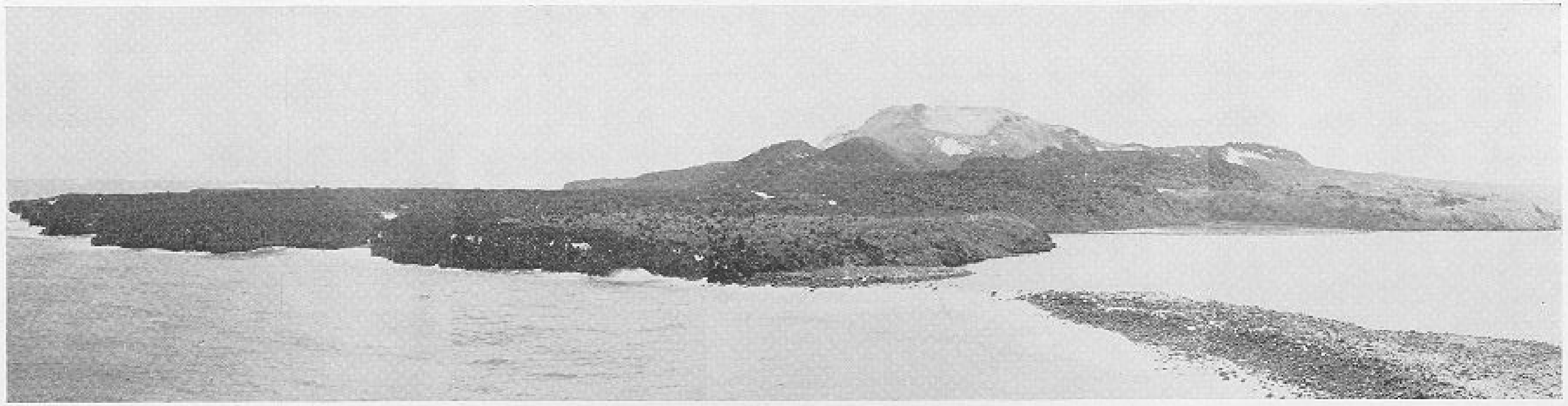

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PLATE III

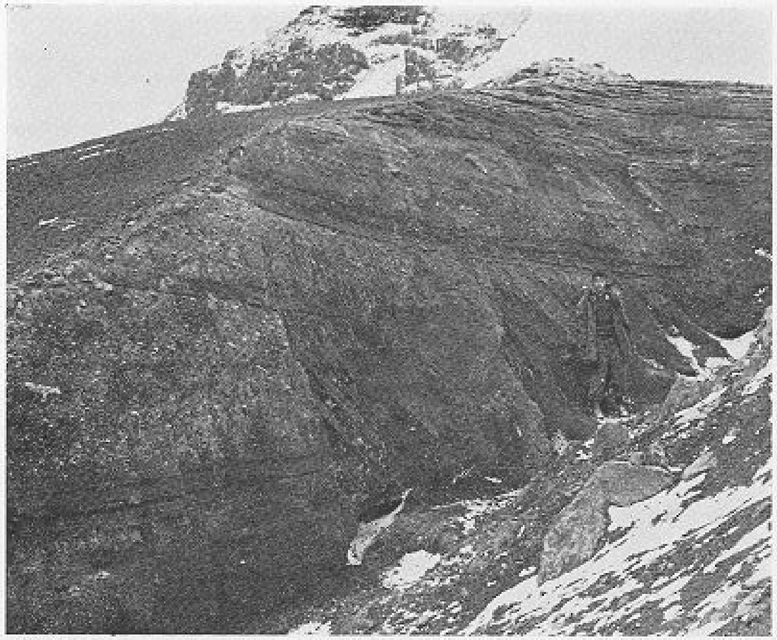
PLATE IV

a. Vertical section showing stratified water-laid deposits of the 18 m. terrace, south of Chimaera Flats. The material includes sub-angular to rounded pebbles which in some of the thicker layers are mixed with fine silt, whilst at other horizons the finer grades are virtually absent. The good sorting of numerous of these layers, together with their perfectly horizontal attitude and even thickness, suggests that the material was laid down in a quiet aqueous environment, probably comparable to that on the floor of the present lagoons.

b. Clinker Gulch seen from high on the north flank of Lucifer Hill. The lake in the centre of the photograph is 150 m. long with its water at sea-level. It represents an area which was formerly open sea but which has been isolated by a tongue of the recent north lava flow, occupying the western (left-hand) side of the picture. To the right of the lake, at the foot of the former sea cliffs, is black beach sand.

c. Block of pale grey flow-banded lava lying on the ash-covered surface of the east lava flow. This lava (SSC.10.1) is similar to that found *in situ* beside Cauldron Pool (SSC.20.2). Frost shattering has cleaved the lava along the flow planes.

d. Ash-mantled surface of the north-east lava flow. In this area, lying near the foot of Lucifer Hill, the blocky surface of the flow is mantled by about 70 cm. of more recent ash and scoria, through which protrude only the largest blocks at the surface of the flow.



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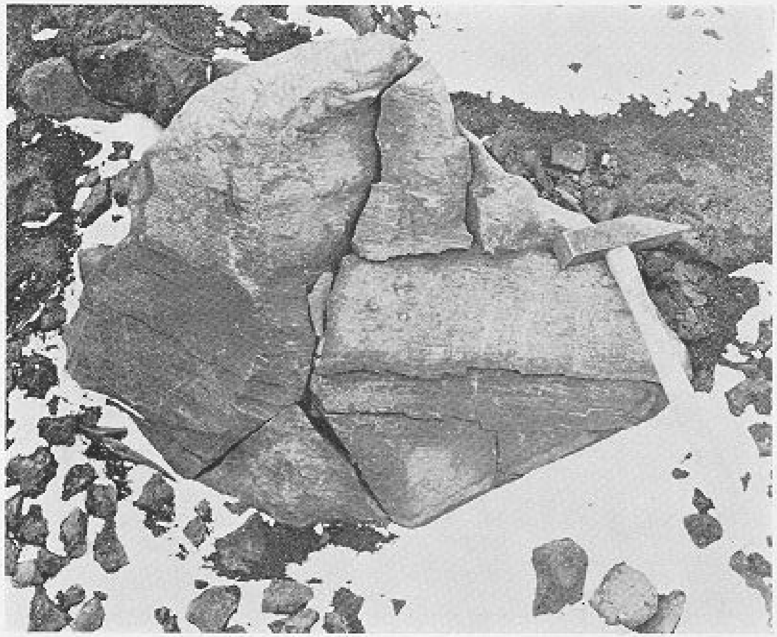

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PLATE IV

PLATE V

Photomicrographs of rocks from southern Candlemas Island.

a. Older porphyritic basalt from a lava flow on the western side of southern Candlemas Island. This lava is the commonest type in southern Candlemas Island. Plagioclase phenocrysts show albite and pericline twinning and one crystal towards the upper right contains small inclusions orientated parallel to the principal crystallographic directions. At the bottom centre is a cumulophyric cluster of clinopyroxene and olivine. The texture of the rock is seriate with a gradation in crystal size from the intergranular groundmass to the phenocrysts. (SSC.43.1; X-nicols; ×17)

b. Large anorthite phenocryst in porphyritic basalt from moraine to the south of Gorgon Pool. The anorthite crystal is 15 mm. across and contains polysynthetic twin lamellae up to 1 mm. wide. It is surrounded by a corona 6–10 mm. wide of granular olivines with interstitial clinopyroxene and plagioclase. (SSC.34.6; ordinary light; ×1·6)

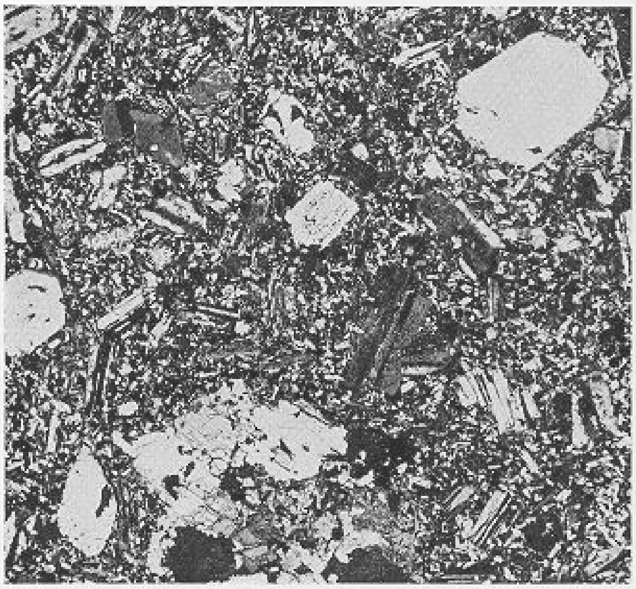
c. Older porphyritic basalt from a lava flow at the base of the western cliff, showing large plagioclase phenocrysts with inclusions and olivine microphenocrysts with broad rims of opaque oxide. The groundmass is intergranular, composed of plagioclase, clinopyroxene, opaque oxides and tridymite. (SSC.32.1; ordinary light; ×17)

d. Groundmass of older porphyritic basalt. The material in the centre with moderately high relief is cristobalite, distinguished by its low refractive index and "tile" structure. The discrete grains with high relief are clinopyroxene, whilst plagioclase and glassy material both have low relief, and the opaque mineral is iron ore. (SSC.32.1; ordinary light; ×150)

e. Younger porphyritic basalt from the south-western corner of the island. The large phenocryst is of calcic plagioclase with a core of An_{91}. A zone near the rim of this phenocryst contains olivine and glass inclusions. The groundmass of the rock is fine and intergranular. (SSC.41.1; X-nicols; ×17)

f. Vitrophyric lava from the west peninsula. The rock is composed of flow-banded, dark brown glass containing trains of small vesicles with phenocrysts of plagioclase and occasional mafic crystals. (SSC.38.1; ordinary light; ×17)

PLATE V



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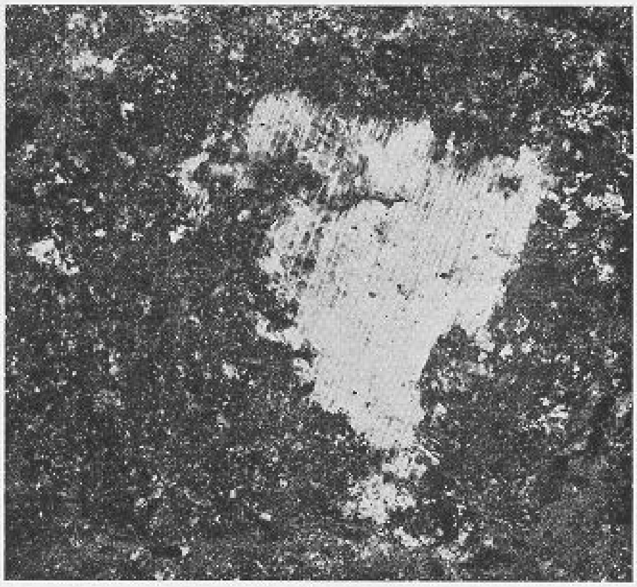

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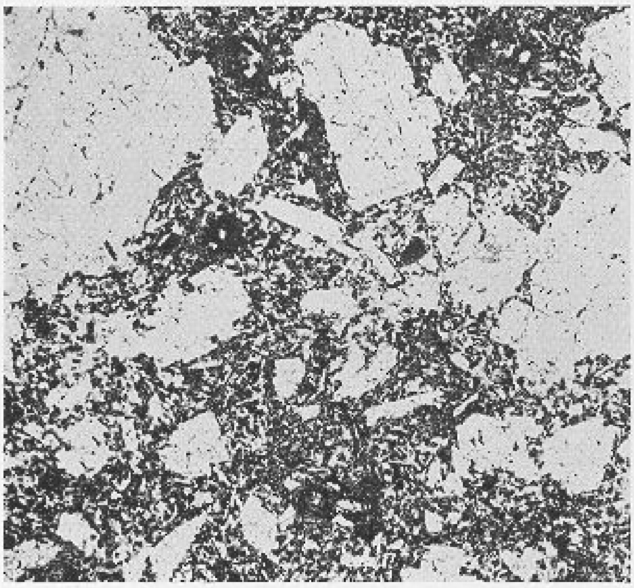

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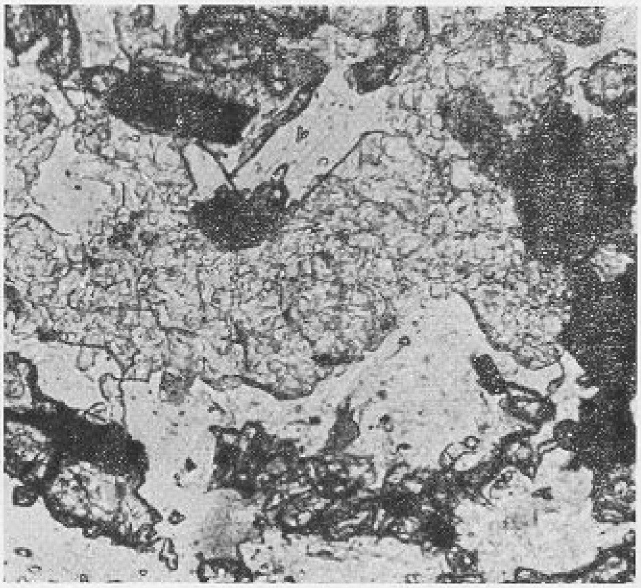

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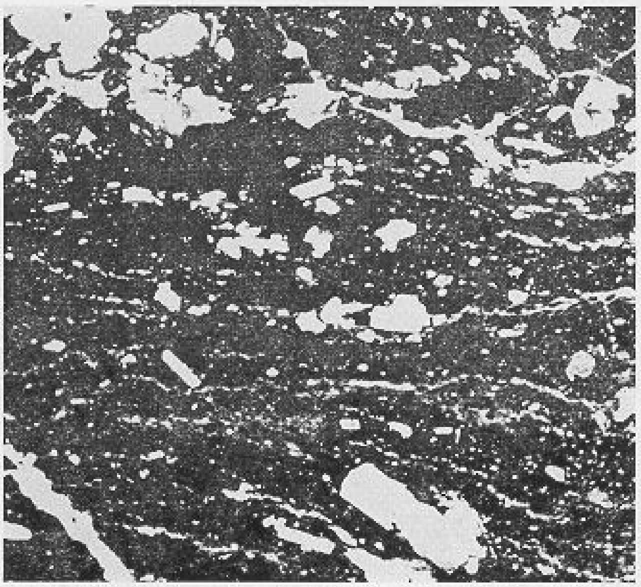

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PLATE VI

Photomicrographs of rocks from northern Candlemas Island.

a. Nearly aphyric andesite from the cliffs behind Cauldron Pool. This lava contains about 5 per cent of microphenocrysts, including plagioclase and subordinate pyroxenes, which often occur in cumulophyric clusters. The groundmass is pilotaxitic, being composed of lath-shaped feldspar microlites accompanied by clinopyroxene and opaque oxide. (SSC.20.2; X-nicols; ×17)

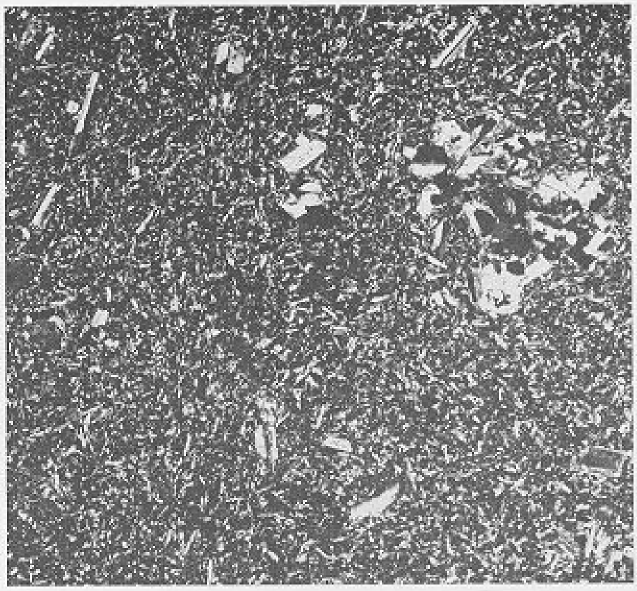
b. Nearly aphyric andesite from the east lava flow. This is similar to specimen SSC.20.2 except that it contains a few irregular vesicles. (SSC.54.2; X-nicols; ×17)

c. Nearly aphyric andesite from the north lava flow. The small cluster contains clinopyroxene, plagioclase and ore. Plagioclase laths in the groundmass show sub-parallel flow orientation. (SSC.29.2; X-nicols; ×17)

d. Cumulophyric cluster in an almost aphyric andesite from the south lava flow. A large anhedral olivine is enclosed by a single crystal of plagioclase showing albite and pericline twinning. The groundmass of this rock is glassy and partly devitrified. (SSC.24.5; partly X-nicols; ×17)

e. Accumulative xenolith forming a lava-coated bomb in tephra overlying the east lava flow. The colourless mineral with low relief is bytownite, whilst a large crystal of olivine lies towards the upper left, and small anhedral pyroxenes show high relief and good cleavage. Interstitial patches of pale brown glass contain laths of plagioclase and clinopyroxene. (SSC.10.4; ordinary light; ×17)

f. Gabbroic xenolith from the south lava flow. Small rounded olivines are poikilically enclosed by plagioclase and clinopyroxene. The rock contains irregularly shaped vesicles and a small area of interstitial lava with a felty texture is visible in the lower left. (SSC.24.3; X-nicols; ×17)



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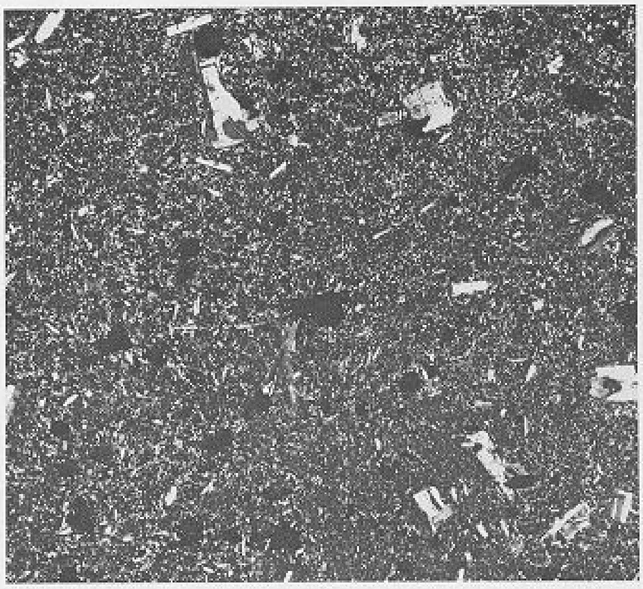

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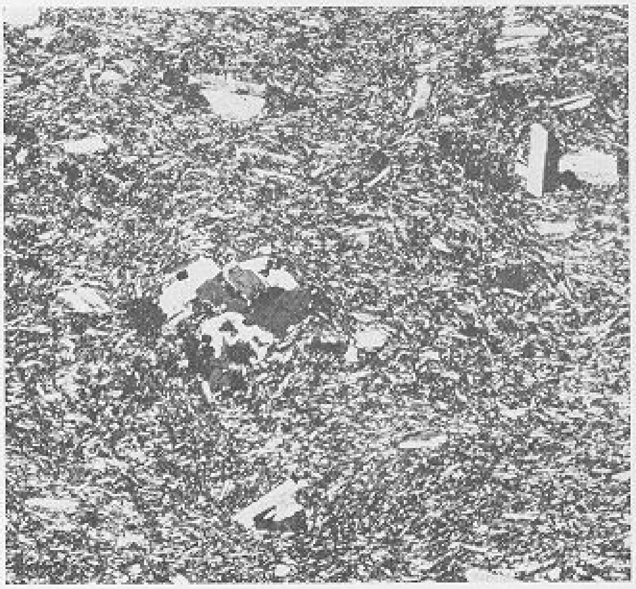

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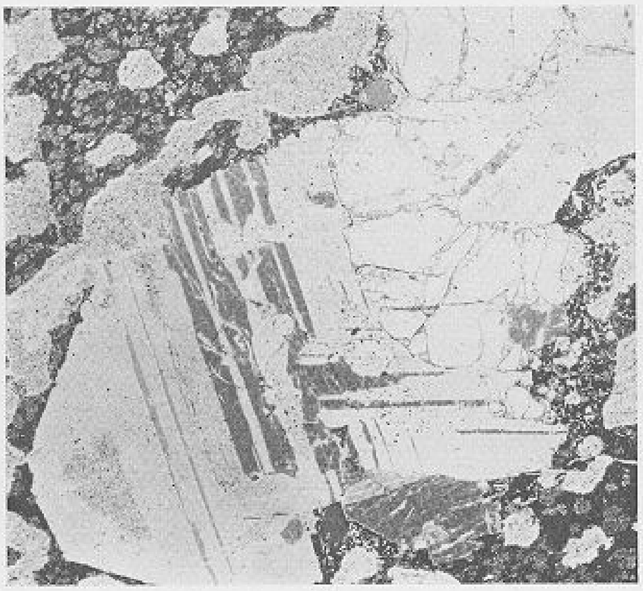

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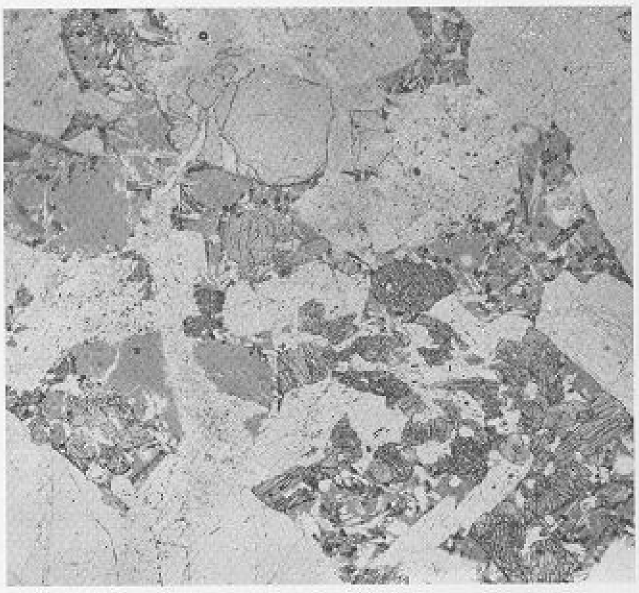

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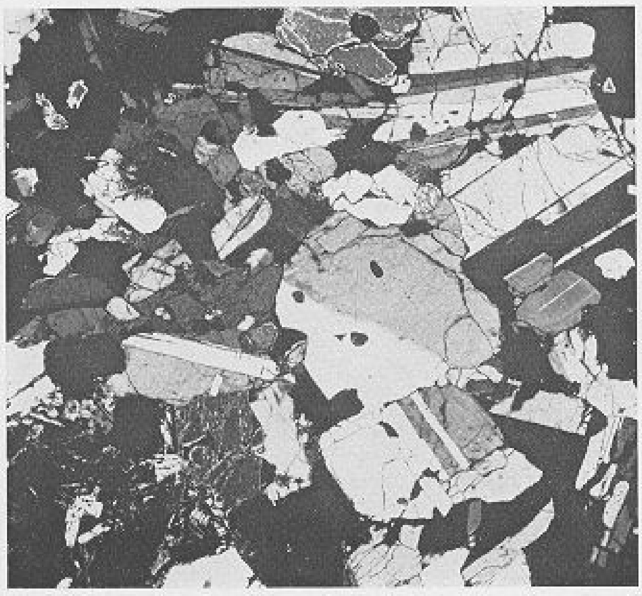

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