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III. PETROLOGY OF THE VOLCANIC ROCKS

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P. E. BAKER, B.Sc., D.Phil.

Department of Earth Sciences,
University of Leeds

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ABSTRACT

THE Pliocene–Recent arc of the South Sandwich Islands is built of volcanic rocks belonging to both the island-arc tholeiite and calc-alkali series. The tholeiitic rocks, which are most abundant, range from porphyritic and aphyric varieties of basalt through iron-rich andesitic types to dark aphyric dacites. The only known rhyolite is a pumice from the 1962 submarine eruption of Protector Shoal. Calc-alkaline rocks are most clearly represented by the two-pyroxene andesites of Leskov Island.

Unlike calc-alkaline arcs, where andesite is the principal eruptive rock, basalt is dominant in the South Sandwich Islands. Freezland Rock, previously thought to comprise part of a metamorphic and sedimentary basement, is now known to be composed of pyroclastic rocks cut by andesitic dykes (ca. 4 m. yr. old).

Calcic plagioclase, sometimes extending into the anorthite compositional range, is the most abundant phenocryst mineral. Other common phenocrysts are olivine, clinopyroxene (usually diopsidic augite), orthopyroxene (usually hypersthene) and magnetite. Groundmass clinopyroxenes reach a subcalcic augite composition. Quartz and amphibole are known only from the two-pyroxene andesites of Leskov Island, but cristobalite occurs in many of the basaltic andesites.

In the tholeiitic series there is moderate enrichment of Fe relative to Mg and alkalis; this suite is also distinguished by low concentrations of K, Rb, Ba and Sr when compared with most other volcanic rocks except ocean-floor basalts.

The tholeiitic series of the South Sandwich Islands probably represents an early stage in island-arc evolution. Dehydration of subducted oceanic crust is thought to be responsible for partial melting in the overlying mantle. Subsequent calc-alkaline volcanism may be connected with continued dehydration at greater depths. Such a relationship is consistent with the more westerly situation of Leskov Island, with its calc-alkaline andesites, over the deeper part of the Benioff Zone. In both cases, more differentiated lavas are probably evolved by fractionation at shallow levels.

* Formerly at Department of Geology and Mineralogy, University of Oxford.

CONTENTS

	PAGE
I. Introduction	3
II. Summary of the geology of the South Sandwich Islands	4
1. Zavodovski Island	6
2. Leskov Island	6
3. Visokoi Island	6
4. Candlemas Island	6
5. Vindication Island	7
6. Saunders Island	7
7. Montagu Island	7
8. Bristol Island	7
9. Bellingshausen Island	8
10. Cook Island	8
11. Thule Island	8
III. Petrography	8
1. Zavodovski Island	9
2. Leskov Island	9
3. Visokoi Island	9
4. Candlemas Island	11
5. Vindication Island	11
6. Saunders Island	12
7. Montagu Island	12
8. Bristol Island	12
9. Freezland Rock	12
10. Bellingshausen Island	12
11. Cook Island	13
12. Thule Island	13
IV. Mineralogy	13
1. Plagioclase feldspar	13
2. Olivine	14
3. Clinopyroxene	14
4. Orthopyroxene	16
5. Amphibole	16
6. Silica minerals	16
7. Refractive indices of whole-rock glasses	16
V. Geochemistry	16
1. Major elements	17
2. Minor elements	18
VI. Petrogenesis	21
1. Tholeiitic series	22
2. Calc-alkaline andesites	23
3. Discussion	23
VII. Acknowledgements	24
VIII. References	24
Appendix. Sketch maps of the South Sandwich Islands showing the locations of geological stations	26

I. INTRODUCTION

THE South Sandwich Islands form an active volcanic island arc along the eastern margin of the Scotia Sea. There are 11 main islands, together with a number of islets and rocks which are spaced over a distance of about 300 km. between lat. 56°18′ and 59°28′S., and long. 26°14′ and 28°11′W. (Fig. 1).

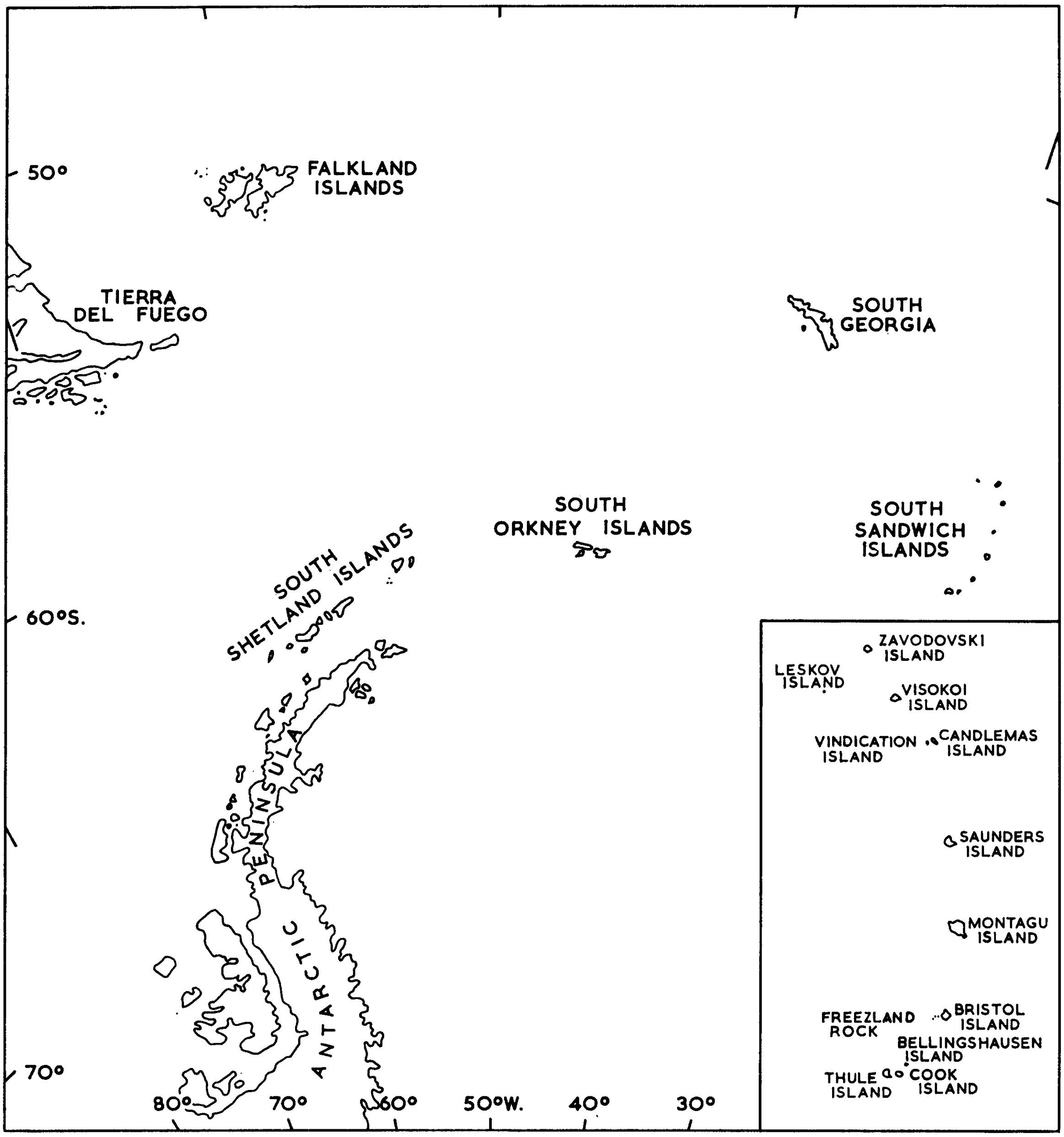

FIGURE 1
Location map of the South Sandwich Islands.

Although the group was discovered by Captain James Cook in 1775 and was visited intermittently by navigators, sealers and whalers in the nineteenth century, it was not until the R.R.S. *Discovery II* expedition of 1930 (Kemp and Nelson, 1931) that any systematic scientific investigation was attempted. Weather conditions, however, imposed severe restrictions upon the *Discovery II* expedition and a landing was effected only on Thule Island. Although knowledge of these islands remains very inadequate, considerable advances have been made in recent years during visits by R.R.S. *Shackleton*, R.R.S. *John Biscoe* and H.M.S. *Protector* (Holdgate, 1963). This report on the petrology of the islands is based largely on specimens collected and observations made during a 3 week survey of the islands from H.M.S. *Protector* in March 1964. The effectiveness of this investigation was due in no small way to the use of H.M.S. *Protector*'s helicopters in landing on the islands under conditions where boat landings would have been impossible. An outline of this survey has already been published (Baker and others, 1964), and a full account of the itinerary, landing sites, topography, climatology, general biology and geology appears in the first part of this series of scientific reports on the South Sandwich Islands (Holdgate and Baker, 1978).

The geological work during the 1964 survey was divided into two parts, the first of which involved a detailed investigation of the geology of Candlemas Island by J. F. Tomblin; the results of this work form the subject of a separate scientific report (Tomblin, 1978). The second part of the work was a general reconnaissance survey of the geology of the remaining islands; although this was largely the responsibility of the writer, the collaboration of Dr. Tomblin in the field studies on Leskov, Visokoi and Vindication Islands is gratefully acknowledged.

Previous contributions to the petrology of the South Sandwich Islands include:

- i. Baeckström (1915) described specimens collected by Captain C. A. Larsen in 1908 from Zavodovski, Candlemas, Saunders, Montagu and Bristol Islands. He included a chemical analysis of an "olivine-free basalt" from Saunders Island.
- ii. Douglas and Campbell Smith (1930) described basaltic scoria and lava fragments dredged from a depth of about 38 m. whilst aboard *Quest*.
- iii. Tyrrell (1931) described samples collected from Beach Point, Thule Island, by members of the 1930 R.R.S. *Discovery II* expedition and included chemical analyses by F. Herdsman of a hypersthene-andesite and a dacite.
- iv. Tyrrell (1945) summarized existing petrographic data and incorporated descriptions of samples from Nattriss Point, Saunders Island, collected by G. W. Rayner off *William Scoresby* in 1937.
- v. Holdgate (1963) reviewed existing geological and biological data on the South Sandwich Islands and collated information on volcanic and fumarolic activity.
- vi. Gass and others (1963) described the petrography and chemistry of pumice emitted in a submarine eruption 56 km. north-west of Zavodovski Island in March 1962.

The following account of the petrology is based mainly on material collected from all islands except Zavodovski Island during the 1964 survey by H.M.S. *Protector*. This collection has been supplemented, however, by specimens obtained by P. H. H. Nelson and P. Kennett (from R.R.S. *Shackleton* during the 1960–61 season) and by M. W. Holdgate (from H.M.S. *Protector* in 1962). All of these specimens were previously undescribed and were generously made available to the writer. The total number and distribution of samples from the South Sandwich Islands used in this study are shown in Table I, together with an indication of which islands had been sampled on previous occasions. The meaning of sample prefixes used throughout the text is also indicated in Table I.

II. SUMMARY OF THE GEOLOGY OF THE SOUTH SANDWICH ISLANDS

A GENERAL account of the geology of the islands is available in *British Antarctic Survey Scientific Report* No. 91, so that only a summary of the more important features of each island will be given below. Maps showing specimen localities are, for convenience of reference, reproduced in the Appendix to this report. All of the islands are exclusively of volcanic origin, and volcanic or fumarolic activity has been witnessed on eight of the 11 islands; no evidence of historic activity exists for Vindication, Montagu or Cook Islands, but only the first of these has been reasonably well explored.

The South Sandwich Islands do not appear to have evolved in any strict chronological sequence and activity has doubtless fluctuated from one island to another with a great deal of overlap. It is possible, however, to distinguish groups of older and younger islands; in doing so, it is necessary to consider the oldest material exposed on a certain island which may, of course, bear no relationship to the time at

TABLE I

ROCK COLLECTIONS FROM THE SOUTH SANDWICH ISLANDS AND GUIDE TO SAMPLE PREFIXES USED IN THIS REPORT

Island	*Prefix used for 1964 samples (Baker and Tomblin)*	*Number of specimens collected in 1964*	*Number of specimens collected in 1962 by M. W. Holdgate (sample prefix MWH)*	*Number of specimens collected in 1961 by P. Kennett (sample prefix SHA)*	*Number of specimens collected in 1961 by P. H. H. Nelson (sample prefixes D.3783 and D.3784)*	*Rock collection made by G. W. Rayner; William Scoresby, 1937*	*Discovery II expedition, 1930*	*C. A. Larsen; Undine, 1908*
Zavodovski				19	11			*
Leskov	SSL	23		3				
Visokoi	SSW	32		15				
Candlemas	SSC	125	20	8	6			*
Vindication	SSV	24	7	7				
Saunders	SSS	41	22	9		*		*
Montagu	SSM	28						*
Bristol	SSR	4						*
Freezland Rock	SSF	8						
Bellingshausen	SSB	37	16					
Cook	SSK	4						
Thule	SST	16	10				*	
TOTAL		342	75	61	17			

* Indicates landing and collection of unknown number of samples.

which volcanic activity ceased. For instance, Bristol Island is a large, complex and obviously relatively old island but this has erupted several times this century, the last occasion being 1956 (Secretaria de Marina, Republica Argentina, 1958). The northern and southern parts of Candlemas Island are treated separately in view of the obvious difference in age.

Recognizing these limitations, the following categories may be distinguished:

i. Small youthful volcanic islands which have probably developed entirely in very recent times:
   Candlemas Island (north),
   Bellingshausen Island,
   Zavodovski Island.

ii. Larger but probably relatively young strato-volcanoes with recent lava fields and/or recent parasitic cones:
   Saunders Island,
   Visokoi Island,
   Thule Island.

iii. Small islands probably of intermediate age:
   Leskov Island (K-Ar age determination 700,000 yr.),
   Vindication Island.

iv. Larger complex islands, which are probably the oldest in the South Sandwich Islands group:
   Candlemas Island (south),
   Cook Island,
   Bristol Island (K-Ar age determination, Freezland Rock 4 m. yr.),
   Montagu Island.

1. *Zavodovski Island*

The island consists of a strato-volcano, Mount Asphyxia, which rises to 551 m. a.s.l. and is flanked by low-lying lava flows on all but its western side. Intense fumarolic activity has evidently persisted on Zavodovski Island at least from the time of its discovery until the present day, and there is a report of a lava flow having been observed in 1830 (Fanning, 1834). It is likely that eruptions of basaltic cinders have occurred since that date.

2. *Leskov Island*

Leskov Island is the smallest of the South Sandwich Islands and is situated about 56 km. west of the arcuate axis upon which the remaining islands lie. It is built almost entirely of two-pyroxene andesite lava, which does not occur commonly elsewhere in the South Sandwich Islands group; there is also a small pyroclastic sequence. The large embayment of the east coast probably coincides with an old crater wall. Although Leskov Island has the appearance of a relatively old and considerably eroded volcano, active fumaroles were discovered along the summit ridge in 1964. A K-Ar determination on a specimen of the pyroxene-andesite lava indicated an age of ca. 0·7 m. yr. (determination by courtesy of J. G. Simons, Department of Geology and Mineralogy, University of Oxford). In spite of its anomalous situation, there is nothing remarkable about the age of Leskov Island. The date obtained implies that Leskov Island has been active more or less contemporaneously with some of the islands on the main arcuate axis.

3. *Visokoi Island*

The island is a single strato-volcano constructed chiefly of basaltic lava flows and pyroclastic rocks cut by dykes; it is completely bounded by high sea cliffs. Several of the basaltic scoria cones on the lower flanks of the main volcano, Mount Hodson, have probably formed in very recent times. Vapour has been observed issuing from the summit on various occasions and in 1930 Kemp and Nelson (1931) recorded a fumarole on the north coast; a patch of warm ground found in a scoria mound behind Finger Point in 1964 probably corresponds to the site of the fumarole.

4. *Candlemas Island*

The northern and southern parts of this island are quite distinct and have clearly developed at very different times. Southern Candlemas Island is very much older than the adjacent low-lying northern area; it has been considerably reduced by marine erosion, and Tomblin (1978) believed that the lavas and pyroclastic rocks of which it is composed were emitted from a source which lay off the present east coast of the island. However, the more recent lava flows of the south may have issued from vents at the foot of the main volcanic pile. There have been no reports of either volcanic or fumarolic activity on the southern part of Candlemas Island. The lavas range from strongly porphyritic basalts to dacitic obsidian which is known only as blocks in a talus slope facing northern Candlemas Island.

The northern part of Candlemas Island almost certainly emerged as a separate island in very recent times and subsequently became attached by bars of detrital material to southern Candlemas Island. It consists of a small scoria cone 231 m. a.s.l., surrounded by lava flows which have issued from its flanks. The lavas are for the most part aphyric and are of andesitic to dacitic composition. In 1964 there was intense fumarolic activity on the western slopes of the cone and below this, at sea-level, a small steaming lake. A glowing lava field is said to have been observed in 1953–54 during the visit of *John Biscoe*. Tomblin (1978) reported that in 1964 steam was issuing from the youngest lava flow, suggesting that it was not more than a decade or two old.

5. *Vindication Island*

This small island is bounded by high sea cliffs and has been greatly reduced by marine erosion so that only a segment of the original volcano now remains. The attitude of the lavas and pyroclastic rocks suggests in fact that the island was built about at least three volcanic centres, the principal one of which seems to have been Quadrant Peak in the south-west. No volcanic or fumarolic activity has ever been reported. The lavas of Vindication Island are almost entirely porphyritic basalts and basaltic andesites, many of them very similar to those of the southern part of Candlemas Island.

6. *Saunders Island*

Saunders Island is dominated by the 991 m. high strato-volcano of Mount Michael, whose cone is flanked by low-lying terrain built mostly of basaltic lava flows overlain by a sprinkling of ash. In the north-east, two old sea stacks, Yellowstone Crags, composed of yellowish tuff and agglomerate protrude through the recent lava field of Blackstone Plain. In the south-east, in the vicinity of Nattriss Point, is a group of recent pyroclast cones, Ashen Hills, built mainly of vitric ash. Fumarolic activity has been repeatedly reported and vapour was still issuing from the summit of Mount Michael in March 1964. The lavas collected from Saunders Island are entirely basaltic in composition.

7. *Montagu Island*

This, the largest of the South Sandwich Islands, is almost entirely ice-covered. It is not known whether one or more major volcanic centres are situated within the high interior dominated by Mount Belinda. The conspicuous feature of Mount Oceanite in the south-east is probably a large secondary cone or dome and at least three smaller parasitic cones, probably of fairly recent origin, occur on the edge of the high plateau. No volcanic or fumarolic activity has been observed at this island. Only basaltic lavas are known from Montagu Island.

8. *Bristol Island*

The island appears to have been built around several eruptive centres which form a group of peaks in the interior (Mount Darnley, Mount Sourabaya and Havfonen Peak). The great bluff at Turmoil Point on the west coast is probably the relic of another centre to which the offlying rocks may also belong. An eruption occurred on Bristol Island in January 1956 (Secretaria de Marina, Republica Argentina, 1958) and the site of this may have been a small crater 2 km. east of Turmoil Point (Holdgate, 1963, p. 400).

As suggested above, the three large rocky islets, Freezland Rock, Wilson Rock and Grindle Rock, may formerly have been part of a volcano which included Turmoil Point bluff. There is a possibility, however, that they may represent traces of an even older centre which was independent of the subsequent Bristol Island. A lower limit to the age of Freezland Rock was obtained by a K-Ar determination on one of the andesite dykes forming the massive spine of the islet—it indicated an age of ca. 4 m. yr. (personal communication from J. G. Simons).

9. *Bellingshausen Island*

This small island is composed of a relatively simple volcanic cone built of lava flows and pyroclastic rocks, and containing a large summit crater. Lava flows of fairly uniform basaltic andesite composition form much of the lower ground around the cone. Active fumaroles occur along the southern rim of the crater.

10. *Cook Island*

Evidence from oblique air photographs suggests that Cook Island has been built about several closely associated volcanic centres which are possibly represented by the high peaks such as Mount Harmer. Intense marine erosion has greatly reduced the extent of these volcanoes and the island is now bounded by precipitous sea cliffs. There is no record of volcanic or fumarolic activity nor do there appear to be any parasitic cones or lava flows of obviously recent origin. The lavas apparently range in composition from porphyritic basalts to aphyric dacites.

11. *Thule Island*

The island apparently consists of a single strato-volcano with a broad summit plateau and a small crater near its centre. The island has been considerably eroded, especially along the east coast facing Douglas Strait; there is a suggestion (Kemp and Nelson, 1931, p. 179) that Thule Island may at least in part have developed as a result of eruptions from a crater situated in Douglas Strait. It seems more probable, however, that Douglas Strait may be the site of a caldera. The lava flow which forms the low ground at Hewison Point appears to have been emitted from a parasitic centre in the south-east. Fumarolic activity was first reported on Thule Island in March 1962 (Holdgate, 1963), when steam was observed coming from the water-filled summit crater. Holdgate also observed ash lying on the surface of the ice in the south-west, suggesting that there has been recent volcanic activity.

III. PETROGRAPHY

THE volcanic rocks of the South Sandwich Islands have been classified as basalts, basaltic andesites, andesites, dacites and rhyolites, although in fact both tholeiitic and calc-alkaline affinities are evident. In spite of the range of variation, it seemed desirable to adopt broad and flexible divisions which could be readily applied to the majority of the rocks, conveying a reasonably accurate impression of the mineralogy and chemistry. In many instances, however, the lavas are aphyric or glassy, so that a strictly mineralogical scheme of classification is unworkable. The basis of the classification used in this report is outlined in Table II; as far as possible, it takes into account both mineralogical and chemical features and also the general usage of the terms.

The approximate proportions of different rock types which have been collected from the South Sandwich Islands since 1960 are illustrated by the histograms of Fig. 2. It should be emphasized that these relative proportions apply to specimens in the collections and they do not therefore necessarily reflect the actual areal or volumetric abundances on the islands. The numbers of samples available are also no real guide to the reliability of the histograms as indicators of actual proportions. For example, Saunders Island, with 72 specimens, is very inadequately known and sampled but the much smaller Leskov Island, with only 26 specimens, is almost certainly entirely andesite.

In most cases it is impossible, on the basis of existing data, to provide any meaningful estimate of real abundances. In several instances (e.g. Montagu, Bristol and Saunders Islands), collecting was limited to reasonably accessible ice-free areas. In some cases, however, notably on the smaller relatively ice-free islands (e.g. Leskov, Bellingshausen and Vindication Islands), the figures probably provide a fairly good indication of at least the near-surface abundances. The general prevalence of basaltic rocks on most of the islands is apparent from Fig. 2. Conspicuous and also quite reliable is the complete dominance of andesite on Leskov Island and basaltic andesite on Bellingshausen Island. Although the histograms suggest greater compositional diversity on the southern Cook and Thule Islands, the limited sampling makes this of dubious significance.

A rough estimate of the overall volumetric proportions of rock types occurring in the South Sandwich

TABLE II
CLASSIFICATION OF LAVAS FROM THE SOUTH SANDWICH ISLANDS

Rock type	*Characteristic phenocrysts in order of abundance*	*Comments*	*Approximate SiO_2 per cent*
Oceanite and related cumulophyric types	Plagioclase Olivine Augite	Total of olivine and pyroxene phenocrysts exceeds plagioclase	49–50
Basalt	Plagioclase Augite Olivine	Some almost aphyric. Groundmass clinopyroxene is augite or subcalcic augite. Cristobalite also occurs	50–54
Basaltic andesite	Plagioclase Augite Hypersthene	Some aphyric types. Groundmass pyroxenes—augite, subcalcic augite or hypersthene. Cristobalite occurs	54–57
Andesite	Plagioclase Hypersthene Augite	Some aphyric. Hypersthene and augite in groundmass	57–63
Dacite	Aphyric	No porphyritic types known	63–70
Rhyolite	Plagioclase Hypersthene	Only specimen is pumice from Protector Shoal	70

Islands arc as a whole is shown in Fig. 3. The figures are based partly on the relative abundance in the collections but pertinent field data have also been taken into account.

A list of analysed rocks and other important or representative rock types from the South Sandwich Islands, indicating localities, textures and mineral assemblages, is given in Table III. The list is not comprehensive and is given partly to provide some information on the range of rock types occurring and partly for the guidance of future investigations in these islands. General comments on the petrography of the lavas of each island are made below and any particular points of interest are noted.

1. *Zavodovski Island*

Samples from this island were collected by P. H. H. Nelson and P. Kennett in 1961 from the sea cliffs on the eastern side of Zavodovski Island or from the slopes above these cliffs. All of the samples, whether lava flows or scoria, are porphyritic or vitrophyric basalts with phenocrysts of plagioclase, olivine and augite (Plate Ia). Where the groundmass is crystalline, the texture is intergranular and the constituents are plagioclase, clinopyroxene (possibly subcalcic augite or pigeonite in some cases) and magnetite.

2. *Leskov Island*

Petrographically, Leskov Island is quite distinct from the remainder of the South Sandwich Islands. Apart from a small sequence of pyroclast-fall deposits exposed on a platform high on the east coast, the island is built up entirely of two-pyroxene andesite with abundant plagioclase phenocrysts (Plate Ib).

The samples collected during the 1964 survey all came from the upper part of the island but those collected by P. Kennett in 1961 from near sea-level are very similar. In general, the main variation between one sample and another is in the degree of crystallinity of the groundmass. One sample (SSL.10.1) from the edge of the cliffs at the southern end of Leskov Island is somewhat different as it contains occasional large olivines, basaltic hornblendes and small clusters of quartz. Loose blocks of norite or gabbro also occur on this island.

3. *Visokoi Island*

Specimens were collected from Irving Point (Plate Ic and d), Shamrock Hill, Finger Point and Sulphur Point. The great majority are basalts but there are gradations to basaltic andesite and possibly andesite in the case of one flow at Irving Point.

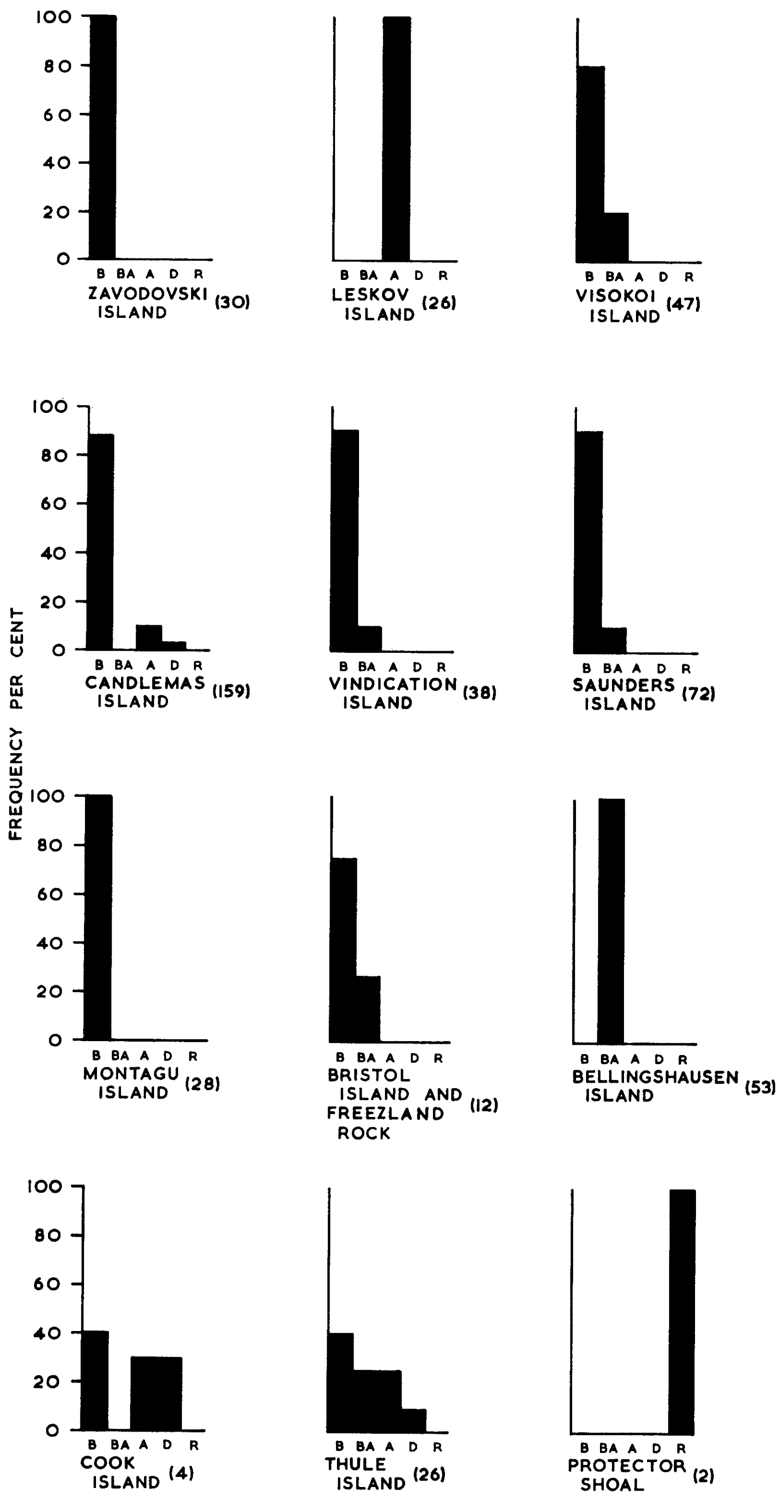

FIGURE 2

Histograms showing relative abundance of different rock types in the existing collections from the South Sandwich Islands. The number of samples on which each diagram is based is given in parentheses. Localities of the 1964 collection are given in the Appendix.

TABLE III

REPRESENTATIVE ROCK TYPES FROM THE SOUTH SANDWICH ISLANDS

Rock type	Specimen number	Occurrences	Texture	Mineralogy
Zavodovski Island				
Olivine-basalt	SHA.4.2*	Cliffs on east coast (collected by P. Kennett, 1961)	Porphyritic Intergranular groundmass	*Phenocrysts:* plag, aug, ol *Matrix:* plag, cpx, mt
Basalt	D.3783.4*	East coast (collected by P. H. H. Nelson, 1960)	Vitrophyric	*Phenocrysts:* occasional phenocrysts of plag, ol, aug *Matrix:* glassy with plag microlites
Basalt e.g.	SHA.5.1	Loose on slopes (collected by P. Kennett, 1961)	Porphyritic Intergranular groundmass	*Phenocrysts:* plag, ol and occasional aug *Matrix:* plag, subcalcic aug, mt
Basaltic scoria e.g.	D.3783.7	General	Vitrophyric	*Phenocrysts:* plag, ol and occasional aug *Matrix:* dark, glassy with few plag microlites
Leskov Island				
Two-pyroxene andesite	SSL.4.1*	North-east ash platform	Porphyritic	*Phenocrysts:* plag, hyp, aug, mt *Matrix:* plag, opx and cpx, mt, glass
Two-pyroxene andesite	SSL.4.2*	North-east ash platform	Porphyritic Groundmass—part crystallized part glassy	*Phenocrysts:* plag, hyp, aug, mt *Matrix:* plag, opx, cpx, brown glass
Two-pyroxene andesite	SSL.10.1	Cliff top south side of island	Vitrophyric	*Phenocrysts:* plag, hyp, aug, mt and occasional ol Occasional microphenocrysts of basaltic hb and qtz *Matrix:* turbid, glassy
Norite block	SSL.16.1	Loose high on west slopes	Coarse-grained; inequigranular partly recrystallized	Plag, hyp, aug, mt, ol, qtz
Visokoi Island				
Basalt	SSW.1.1*	Irving Point, base of 70 m. flow	Porphyritic to seriate	*Phenocrysts:* plag, mt, aug, ol and occasional microphenocrysts of ol *Groundmass:* abundant px (subcalcic aug) plag and occasional mt grains
Basalt	SSW.9.3*	Low bluff to west side Finger Point	Fine-grained sparsely porphyritic	*Phenocrysts:* occasional microphenocrysts of plag and aug *Matrix:* plag laths (An_{50}), cpx, mt
Basalt	SSW.6.3*	Shamrock Hill	Aphyric	Apart from very occasional microphenocrysts of plag, the rock consists entirely of extremely fine-grained plag laths, cpx and mt
Basalt	SSW.8.1	Finger Point	Sparsely porphyritic, remainder seriate	*Phenocrysts:* occasional plag microphenocrysts *Matrix:* plag, cpx, ol and mt
Basalt	SSW.13.1	Sulphur Point	Sparsely porphyritic —matrix intergranular	*Phenocrysts:* plag, ol, aug *Matrix:* plag, cpx, mt, cristobalite
Basalt	SSW.10.1	Loose in scree above Finger Point	Porphyritic (to vitrophyric)	*Phenocrysts:* abundant large plag and cpx, with microphenocrysts of ol *Matrix:* dark, partly glassy but with plag laths, cpx, ol and mt
Andesite	SSW.2.1	7 m. flow at Irving Point	Porphyritic	*Phenocrysts:* plag, hyp, aug *Groundmass:* very fine-grained, turbid but with plag, px, mt and cristobalite
Basaltic scoria	SSW.11.1	Finger Point	Vitrophyric	*Phenocrysts:* plag *Matrix:* plag microlites and mt grains in dark glassy base
Vindication Island				
Basalt	SSV.9.1*	Flow on upper west slope of island (the majority of the flows on the island are of this type)	Porphyritic	*Phenocrysts:* plag, aug, ol, hyp *Matrix:* plag, cpx, mt
Andesite	SSV.7.1	Cliff top 300 m. west of Braces Point	Porphyritic	*Phenocrysts:* plag, aug, hyp, mt *Matrix:* fluidal texture—plag, px, mt, cristobalite
Gabbroic block	SSV.8.1	Loose north-central part of island	Coarse-grained, seriate	Plag (zoned An_{65}–An_{35}) aug, hyp, qtz
Palagonite-tuff	SSV.6.2	North coast between Crosscut Point and Braces Point	Fragmental—partly welded	Crystalline constituents—plag, aug, ol, calcite. Assorted dark lithic fragments, yellow glass and pale brown glass, both partly devitrified
Saunders Island				
Olivine-basalt	SSS.10.1*	Blackstone Plain	Porphyritic Matrix intergranular	*Phenocrysts:* plag, ol, aug *Matrix:* plag, cpx and mt
Basalt	SSS.15.1	North side of Nattriss Point	Almost aphyric intergranular	Very rare microphenocrysts of plag and aug in matrix of plag, cpx, opx and mt
Basalt	SSS.11.1	North side of eastern Yellowstone Crag	Microporphyritic	*Phenocrysts:* plag, and aug *Matrix:* plag, cpx, mt and cristobalite
Basalt	SSS.5.4	Loose block from Yellowstone Crag tuff	Vitrophyric	*Phenocrysts:* plag, ol and aug *Matrix:* partially devitrified dark glass
Basalt	SSS.5.2	Block from Yellowstone Crag tuff	Aphyric intergranular	Plag, cpx, mt
Basaltic andesite	MWH.33.b	Block from Yellowstone Crag tuff	Porphyritic	*Phenocrysts:* plag, aug, hyp *Matrix:* very fine-grained, plag, cpx, mt, cristobalite
Dolerite	MWH.40	Block from Yellowstone Crag tuff	Porphyritic	*Phenocrysts:* plag *Matrix:* cpx and mt with interstitial scoria material
Gabbro	MWH.46	Block from Yellowstone Crag tuff	Coarse, seriate	Plag, cpx (mostly altered), mt, chlorite, calcite, serpentine minerals
Palagonite-tuff	SSS.3.1	Lower part of pinnacle east of Yellowstone Crag	Vitrophyric	*Phenocrysts:* plag, aug, ol, mt *Matrix:* pale brown glass, partly devitrified, with some zeolites
Palagonite-tuff	SSS.14.1	Nattriss Point—slope down to Cordelia Bay	Vitric	Almost entirely welded pale brown glassy fragments of varying vesicularity and structure. Occasional crystalline fragments—plag, cpx, ol, mt
Montagu Island				
Oceanite	SSM.5.2*	Mathias Point (typical of lavas of Allen Point promontory)	Strongly porphyritic	*Phenocrysts:* ol, aug, plag *Matrix:* plag, cpx, mt
Basalt	SSM.4.1*	Horsburgh Point	Porphyritic	*Phenocrysts:* plag, and occasional aug and ol *Matrix:* plag, cpx, mt, cristobalite
Palagonite-tuff	SSM.4.4	Cliffs behind Horsburgh Beach	Vitric, clastic	Almost entirely fragmentary pale brown glass with plag and px microlites. Occasional larger crystals of ol, plag and hyp. Zeolite in vesicles
Bristol Island and Freezland Rock				
Basalt	SSR.1.3*	Headland 5 km. north-west of Harker Point, Bristol Island	Porphyritic	*Phenocrysts:* plag, ol *Matrix:* plag, cpx, mt
Andesite	SSF.2.1*	Dyke, west end of southern beach of Freezland Rock	Porphyritic	*Phenocrysts:* plag, hyp, aug *Matrix:* plag, cpx, mt
Palagonite-tuff	SSF.3.1	South side, lower part of Freezland Rock	Clastic Vitrophyric	*Phenocrysts:* plag, aug, mt *Matrix:* pale brown glass, partially devitrified
Bellingshausen Island				
Basaltic andesite	SSB.5.1*	Loose block of common type north slopes of cone	Porphyritic	*Phenocrysts:* plag, hyp, aug *Matrix:* plag, cpx, mt
Basaltic andesite	SSB.11.1*	South of Hardy Point	Porphyritic	*Phenocrysts:* plag, aug, hyp *Matrix:* plag, cpx, hyp, mt
Basaltic andesite	SSB.12.1*	Hardy Point	Porphyritic	*Phenocrysts:* plag, hyp, aug *Matrix:* plag, cpx, hyp, mt, cristobalite
Basaltic andesite	SSB.17.2*	Lowest flow—north foot of crater wall	Porphyritic	*Phenocrysts:* plag and very occasional aug *Matrix:* plag, subcalcic aug, mt, cristobalite
Scoria	SSB.3.2	From red agglomerate south side of crater rim	Vitrophyric	*Phenocrysts:* plag, aug, hyp *Matrix:* dark red-black glass
Palagonite-tuff	MWH.19	North wall of crater	Vitrophyric clastic, partially welded	*Phenocrysts:* plag, ol, aug, hyp, mt *Matrix:* pale brown glass, interstitial patches and blobs of bright yellow glass, partly devitrified. Some calcite
Cook Island				
Andesite	SSK.1.1*	Dyke at Reef Point	Aphyric	Banded dark brown to black glass with microlites, very occasional larger plag crystals
Dacite	SSK.1.3*	Flow at Reef Point	Nearly aphyric (mottled due to devitrification)	Very sparse microphenocrysts of plag in glassy banded matrix. Pale brown glass encloses grey blocks of devitrified material
Olivine-basalt	SSK.1.2	Loose at Reef Point	Porphyritic	*Phenocrysts:* plag, ol, aug *Matrix:* plag, aug, cpx, mt
Thule Island				
Andesite	SST.5.1*	Hewison Point	Almost aphyric	Sparse microphenocrysts of plag, hyp, ol, aug, sometimes in clusters *Matrix:* plag, cpx, mt, cristobalite
Andesite	SST.1.2	Beach Point	Porphyritic	*Phenocrysts:* plag, hyp, aug, ol *Matrix:* plag, cpx, hyp, mt, cristobalite
Olivine-basalt	SST.6.3	Loose on platform at Hewison Point	Porphyritic, groundmass intergranular	*Phenocrysts:* plag, ol, aug *Matrix:* plag, cpx, mt
Palagonite-tuff	MWH.11	Parasitic centre, west end of platform at Hewison Point	Vitrophyric	*Phenocrysts:* plag, occasional hyp *Matrix:* dark scoriaceous glass enclosing some yellowish glass

* Denotes analysed rock; see Table VII.

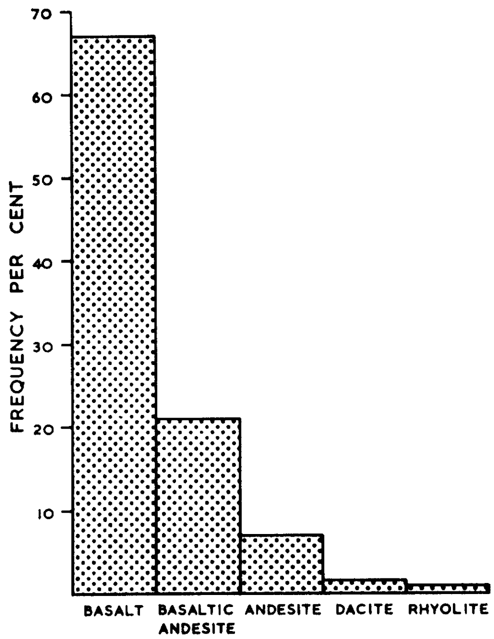

FIGURE 3

Histogram showing estimated relative abundances of rock types in the South Sandwich Islands.

Samples from the parasitic centre at Shamrock Hill on the lower eastern slope of Mount Hodson are all virtually aphyric basalts or basaltic andesites similar to the analysed specimen SSW.6.3 (Table VII, No. 17; Plate Ie). A fine-grained olivine-basalt forms the low promontory at Finger Point in the north (Plate If) but the low cliff on the western side of the point is composed of a flow-banded basalt of a different type. Extremely porphyritic basalts with large plagioclase, clinopyroxene and olivine phenocrysts feature prominently amongst the older rocks collected from the cliffs behind Finger Point. Specimens from Sulphur Point are all microporphyritic basalts commonly containing cristobalite in the groundmass.

4. *Candlemas Island*

The lavas of Candlemas Island have been described by Tomblin (1978). The southern part of the island is composed largely of porphyritic basalts, although dacitic obsidian fragments occur in the scree slopes descending from the northern cliffs. The recently formed northern part of Candlemas Island is, however, built entirely of aphyric andesites and dacites.

5. *Vindication Island*

This small island has been fairly widely sampled. Much of the upper part was traversed during the 1964 survey and also by M. W. Holdgate in 1962. Other specimens from lower levels around the coast were collected by P. Kennett in 1961. The great majority of the lavas are porphyritic basalts of rather uniform type, all containing abundant plagioclase phenocrysts together with varying proportions of olivine, augite and hypersthene (Plate IIa).

Olivine-phyric types, with small amounts of augite, are common in the south-east near Chinstrap Point. Olivine-augite-hypersthene-phyric types occur in the eastern central part, and in the west and north-west hypersthene becomes a more abundant constituent of the lavas (Plate IIb). Flows which crop out in the south-east are generally darker in colour than those of the north-west as they tend to have a fine-grained to glassy matrix. Some paler lavas occurring at the edge of the cliffs in the north-west may be of andesitic composition.

A coarse-grained block found loose about 250 m. inland from the north coast is a gabbro with plagioclase, augite, hypersthene, magnetite and interstitial quartz.

6. *Saunders Island*

The northern part of Saunders Island consists of a relatively low-lying and probably fairly recent basalt platform referred to as Blackstone Plain. Here the lava is a fresh porphyritic olivine-basalt with phenocrysts of plagioclase, olivine and augite in an intergranular matrix of plagioclase, augite and magnetite (Plate IIc). Yellowstone Crags, which project through this platform and are believed to be old sea stacks, consist of vitric tuffs and agglomerates. Small outcrops of basaltic andesite in the vicinity of these hills may represent an older lava possibly *in situ*. Assorted blocks of porphyritic basalt, aphyric basalt, dolerite and quartz-gabbro have been collected from the agglomerate.

The lava forming Nattriss Point, described by Baeckström (1915) as an "olivine-free basalt" is a pale rock with well-developed flow structure. The vitric tuffs and ashes which occur on and around the cones above Nattriss Point headland are partly palagonitized.

7. *Montagu Island*

Sampling from this island was restricted to the Allen Point promontory in the south-east and the cliffs north of Horsburgh Point on the west coast. The conspicuous conical hill behind Allen Point is apparently composed of pyroclastic rocks and lava flows cut by dykes. Lava specimens collected from the surface and edge of the sea cliffs at Allen Point are without exception extremely porphyritic basalts which, in view of the abundance of large olivine and augite phenocrysts in addition to plagioclase, might be termed oceanites (Plate IId).

Behind the beach north-west of Horsburgh Point a pyroclastic succession, in part re-distributed and including palagonite-tuffs, agglomerates and scoria, is overlain by a pale plagioclase-phyric basalt.

8. *Bristol Island*

Baeckström (1915, p. 175–76) described samples collected by Larsen from the north-eastern side of the island as microporphyritic basalts with sparse olivine. The only samples collected from this island in 1964 came from a small headland in the south-west approximately 2·5 km. north-west of Harker Point; they are specimens of pale grey, sometimes reddish, porphyritic olivine-basalt.

9. *Freezland Rock*

Kemp and Nelson (1931, p. 177) considered the three large islets off Bristol Island, Freezland Rock, Wilson Rock and Grindle Rock, to be of greater interest than any other place in the entire South Sandwich Islands. They thought that Freezland Rock was composed partly of sedimentary and partly of metamorphic rocks, that Wilson Rock was composed of basalt and Grindle Rock of tuffs similar to those exposed in the nearby western bluff of Bristol Island. They concluded that, "if our conjectures are correct, the whole succession of rock formation in the Sandwich Group is to be found in these three islets. Freezland Rock shows the only likely exposure of the underlying sedimentary series that we know to exist, Wilson is of the overlying basalt, here seen in far greater thickness than elsewhere, while Grindle is formed of the superposed tuffs which are characteristic of all the islands of the group". However, observations in 1964 revealed that Freezland Rock is composed of yellow, red and greenish tuffs and agglomerates ((?) the sediments of Kemp and Nelson) cut by well-jointed dykes ((?) their metamorphic rocks). Wilson Rock may well be composed of basalt and Grindle Rock of tuffs as Kemp and Nelson supposed but this has still to be confirmed.

In March 1964 a landing was made on Freezland Rock and samples of the dykes and pyroclastic rocks were collected. The tuff from the lower part of Freezland Rock is pale greenish in colour and contains crystals of plagioclase, clinopyroxene and magnetite together with scoria fragments in a pale brownish glass. It is probably the product of a submarine eruption. The dykes which cut the pyroclastic rocks and form the backbone of the island are composed of two-pyroxene andesite.

10. *Bellingshausen Island*

The remarkable uniformity in the lavas of Bellingshausen Island is apparent from both their mineralogical and chemical compositions. With the possible exception of the palagonite-tuff, which crops out in the northern half of the crater wall, all of the rocks appear to be basaltic andesites. Typically, the basaltic

TABLE IV

MODAL ANALYSES OF LAVAS FROM THE SOUTH SANDWICH ISLANDS

Number in Table VII	*Basalts* 4	5	6	8	10	11	12	13	15	16	*Basaltic andesites* 17	19	20	21	22	23	*Andesites* 24	26	27	28	*Dacite* 32
Sample number	SSM.5.2	SSS.10.1	SSR.1.3	SSW.1.1	SSV.9.1	SHA.4.2	SSW.9.3	SSM.4.1	D.3783.4	SHA.15.6	SSW.6.3	SSB.12.1	SSB.5.1	SSF.2.1	SSB.11.1	SSB.17.2	SST.5.1	SSL.4.2	SSL.4.1	SSK.1.1	SSK.1.3
Phenocrysts				(total as seriate texture)																	
Plagioclase	24·3	26·4	39·7	39·1	34·0	6·4	<1	18·1	1·2	1·5	<1	14·1	15·1	23·0	7·3	14·6	<1	29·5	25·8	<1	<1
Olivine	16·5	5·1	2·1	0·8	2·2	0·7	—	0·1	0·7	—	—	—	0·2	—	—	—	—	—	—	—	—
Clinopyroxene	11·7	2·3	0·8	54·1	4·4	0·4	<1	0·2	—	0·4	—	1·1	2·1	1·0	0·4	0·5	<1	1·1	1·2	—	—
Orthopyroxene	—	—	—	—	1·7	—	—	—	—	0·4	—	1·0	0·1	0·6	0·3	—	<1	1·7	4·7	—	—
Magnetite	1·4	2·1	0·5	6·0	—	—	—	—	—	—	—	—	—	—	—	—	—	1·0	1·2	—	—
Groundmass	46·1	64·1	56·9	—	57·7	92·5	99	81·6	98·1	97·7	99	83·8	82·5	75·4	92·0	84·9	99	66·7	67·1	99	99

TABLE V

MINERALOGICAL DATA FOR LAVAS FROM THE SOUTH SANDWICH ISLANDS

	Basalts															Basaltic andesites					Andesites				Dacite	Rhyolite†
	1	2	3*	4	5*	6	7*	8	9	10*	11*	12	13	14*	15	16*	17*	18*	19*	20*	21*	22*	23	24*	25*	26*
Plagioclase composition (An)	75–64	77–71	89–65	82–66	77–65	76–66	81–62	87–68	66–52	77–40	83–66	88–75	85–76	79–66	87–68	65	80–73	68–55	81–64	68–42	77–66	76–55	58–44	50‡	50‡	55–46
Olivine composition (Fo) from X-ray methods d_{062}	83		82		77		76								84											
Olivine composition (Fo) from X-ray methods d_{130}	85	80	84	80	80	83		75	81		80	75	74													
Olivine R.I. $\beta \pm 0{\cdot}002$	1·679				1·691						1·691															
Clinopyroxene R.I. $\beta \pm 0{\cdot}002$	1·681	1·685	1·697	1·698	1·694	1·697		1·697		1·708‡	1·688	1·686	1·694							1·707‡			1·700			
Clinopyroxene 2V +ve	51°	51–44°	57–47°	56–51°	51–48°	51–41°		52–45°		40°‡	48–46°	51–44°	53–46°							36°‡			47°			
Orthopyroxene R.I. $\gamma \pm 0{\cdot}002$											1·698												1·712			1·722
Orthopyroxene 2Vα −ve											74°												59°			50°
Orthopyroxene composition from optics											En_{75}												En_{65}			En_{68}

* Analysed rock. † Data from Gass and others (1963). ‡ Groundmass constituent.

1. SSW.10.1 Porphyritic basalt; behind Finger Point, Visokoi Island.
2. SSW.4.2 Porphyritic basalt; Irving Point, Visokoi Island.
3. SSM.5.2 Oceanite; Allen Point, Montagu Island.
4. SSM.5.5 Oceanite dyke; Mathias Point, Montagu Island.
5. SSS.10.1 Olivine-basalt; Blackstone Plain, Saunders Island.
6. SHA.4.1 Olivine-basalt; east coast, Zavodovski Island.
7. SSR.1.3 Olivine-basalt; south coast, Bristol Island.
8. SSK.1.4 Olivine-basalt; loose block, Reef Point, Cook Island.
9. SHA.9.9 Olivine-basalt; behind Finger Point, Visokoi Island.
10. SSW.1.1 Basalt; Irving Point, Visokoi Island.
11. SSV.9.1 Porphyritic basalt; west side, Vindication Island.
12. SSV.13.1 Porphyritic basalt; north-east side, Vindication Island.
13. SSV.4.1 Porphyritic basalt; south-east side, Vindication Island.
14. SSW.9.3 Fine-grained basalt; north-west side Finger Point, Visokoi Island.
15. D.3783.7 Olivine-basalt; east coast, Zavodovski Island.
16. SSW.6.3 Aphyric basaltic andesite; Shamrock Hill, Visokoi Island.
17. SSB.5.1 Basaltic andesite; loose on northern slopes of cone, Bellingshausen Island.
18. SSF.2.1 Porphyritic andesite; dyke, Freezland Rock.
19. SSB.11.1 Basaltic andesite; south-west coast, Bellingshausen Island.
20. SSB.17.2 Basaltic andesite; north side of crater wall, Bellingshausen Island.
21. SSL.4.2 Two-pyroxene andesite; Leskov Island.
22. SSL.4.1 Two-pyroxene andesite; Leskov Island.
23. SSL.10.1 Two-pyroxene andesite; Leskov Island.
24. SSK.1.1 Andesite dyke; Reef Point, Cook Island.
25. SSK.1.3 Aphyric dacite; Reef Point, Cook Island.
26. SSE.MWH Rhyolite-pumice; Protector Shoal (1962 submarine eruption).

[face page 13

andesites of this island contain very common plagioclase phenocrysts (<1 mm.) and microphenocrysts with rather sparse augite and hypersthene phenocrysts (usually <1 mm. but occasionally up to 2 mm. long). The groundmass is usually very fine-grained and sometimes intergranular, consisting of plagioclase laths, pyroxene granules and magnetite (Plate IIe). The groundmass pyroxene separated and analysed from specimen SSB.17.2 is a calcium-poor augite (Table VI), and it is likely in view of the general similarity of the rocks that this is the composition of the other groundmass pyroxenes. Cristobalite also occurs in the groundmass of several of the lavas.

The palagonitic pyroclastic rocks forming much of the northern half of the crater wall are well stratified but in general unconsolidated, although some bands within the sequence show more cohesion than the remainder. Most of the material is ash size and has a generally greyish colour in contrast to most of the other palagonitic rocks of the South Sandwich Islands which are yellowish or greenish. In addition to the glass which is in part palagonitized, there are dark scoriaceous fragments, probably subaerial cinders, lithic fragments of basaltic andesite, like the lava flows, and various separate crystalline fragments.

11. *Cook Island*

The only specimens available from Cook Island were collected in 1964 from Reef Point which projects from the western side of the island into Douglas Strait. The promontory itself is built of a dark, very vesicular, aphyric dacite (Plate IIf) and on the northern side this is cut by a thin glassy andesite dyke. Blocks of highly porphyritic olivine-basalt, presumably carried to their present position by glaciers, lie on the surface of the dacite promontory.

12. *Thule Island*

Members of the *Discovery II* expedition landed at Beach Point, and Tyrrell (1945, p. 100) described the specimens collected from here as hypersthene-andesite, olivine-andesite, dacite and also andesitic pyroclastic rocks. Tyrrell (1945, p. 101) also presented chemical analyses of the dacite and hypersthene-andesite. Similar samples, apart from the dacite, which was not found, were collected in 1964 from Beach Point. The Hewison Point promontory is formed by what is probably a relatively recent flow of aphyric andesite. A palagonite-tuff was found at the small parasitic centre where the promontory joins the main part of the island.

IV. MINERALOGY

1. *Plagioclase feldspar*

Plagioclase feldspar is invariably the most abundant phenocryst mineral in the volcanic rocks of the South Sandwich Islands (Table IV) and it is generally also the commonest of the groundmass minerals, exceeded only occasionally by clinopyroxene. In most cases the plagioclase phenocrysts are strongly zoned with cores of bytownite and rims of labradorite. The mean composition of all the plagioclase phenocrysts measured is An_{72} and the most common compositional range is from around An_{80} to about An_{65}. Anorthite, as large unzoned crystals, probably occurs in many of the lavas and has been definitely identified in specimen D.3783.10 from Zavodovski Island by a refractive-index determination on the glass prepared by fusing the feldspar. The refractive index of 1·571 indicates a composition of An_{95} using the curve of Schairer and others (1956). Tomblin (1978) has also identified anorthite in the lavas of Candlemas Island.

The plagioclase phenocrysts commonly show albite and Carlsbad twinning; although normal zoning is more usual, oscillatory zoning also occurs. Inclusions are common and are often distributed in zones near the margin of a crystal; in some instances, these inclusions are minute opaque specks though sometimes pyroxenes are recognizable, and in other cases the inclusions consist of blebs of pale brown glass.

There appears to be no systematic variation of the anorthite content of the plagioclase phenocrysts with the chemical composition of the rocks in which they occur. The plagioclase phenocrysts in many of the basaltic andesites and andesites have cores of bytownite composition but the smaller crystals, which appear occasionally in the almost aphyric andesites and dacites, have a composition of about An_{50}.

2. *Olivine*

Olivine is almost entirely confined to the basalts, although occasional crystals, probably xenocrysts, occur in some of the andesites (e.g. SSL.10.1 from Leskov Island). Olivine phenocrysts are most abundant in the oceanites of Allen Point, Montagu Island, where they form more than 16 per cent of the rock. The compositional range is relatively small, from Fo_{84} to Fo_{74}. The mean olivine composition is Fo_{79} and the mean core composition of the co-existing plagioclase phenocrysts is An_{81}. The association of olivine of this compositional range with plagioclase of anorthite or bytownite composition is commonly found in rocks of the calc-alkali suite, as for example in Hakone and the Izu Islands (Kuno, 1950, p. 964). In both tholeiitic and alkali-basalts, olivine of comparable composition usually occurs with a more sodic plagioclase, generally of labradorite composition, as for example in the lavas of Gough Island (Le Maitre, 1962, p. 1311–13) or Hawaii (Richter and Murata, 1966, p. D11). Olivine compositions were determined by X-ray diffraction methods using CuKα radiation. The compositions obtained, using both d_{130} and d_{062} spacings, are shown in Table V.

3. *Clinopyroxene*

Clinopyroxene occurs abundantly both as phenocrysts and as a groundmass constituent of the lavas of the South Sandwich Islands. It reaches its maximum dimension of about 7 mm. in the oceanites of Allen Point, Montagu Island, and is also very large in some of the basalts of Visokoi and Cook Islands.

Some optical properties of clinopyroxenes from the South Sandwich Islands are given in Table V and four chemical analyses, two of phenocrysts and two of groundmass pyroxenes, are shown in Table VI.

The bulk composition of the analysed clinopyroxene phenocrysts is that of diopsidic augite though both these and other pyroxene phenocrysts are zoned. Optical properties of the remaining specimens are close to those of the analysed ones, suggesting a similar composition. The two analysed groundmass pyroxenes are relatively depleted in Ca^{2+} and enriched in Fe^{2+}. Analysis No. 3 in Table VI plots just within the augite field (Fig. 4), almost on the boundary with subcalcic augite and No. 4 is a subcalcic augite.

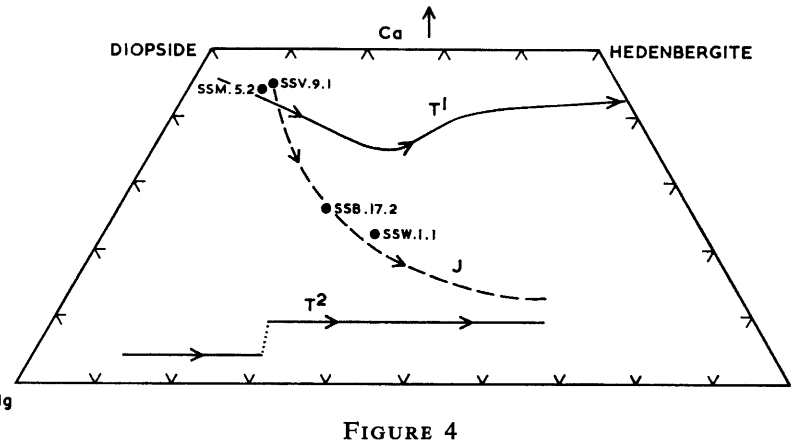

FIGURE 4

Plot of the analysed clinopyroxenes from the South Sandwich Islands (see Table VI). Shown for comparison are trend lines for pyroxenes of the pigeonitic rock series of Japan (Kuno and others, 1957, p. 197) (J), and Ca-rich (T^1) and Ca-poor (T^2) pyroxenes from tholeiitic type basic rocks and their likely differentiates (Brown and Vincent, 1963, p. 193).

The crystallization trend of clinopyroxenes in the lavas of the South Sandwich Islands, from diopsidic augite to subcalcic augite, is therefore similar to that reported by Kuno (1955, p. 70–93) in the lavas of the Izu–Hakone province of Japan. Kuno considered that subcalcic augite forms during rapid cooling from relatively high temperatures, relating its stability to the occupation of tetrahedral sites by Fe^{3+}.

Chemically, the diopsidic augites are similar to the early formed pyroxenes from many other suites. Like the salites of Tago Volcano (Kuno, 1955, p. 73, table 2, Nos. 1 and 2), they have a relatively high content of Al_2O_3. In this respect, they are also similar to a diopsidic augite from Gough Island (Le Maitre, 1962, p. 1318, table 4, No. 1) but the latter has higher contents of TiO_2 and alkalis.

The subcalcic augites of the South Sandwich Islands have a higher Al_2O_3 content and in the case of No. 4 (Table VI) a higher TiO_2 content than those from the Japanese lavas described by Kuno (1955, p. 75, table

TABLE VI

CHEMICAL ANALYSES AND OPTICAL PROPERTIES OF CLINOPYROXENES

		1		2		3		4	
SiO_2		50·23		51·05		51·02		49·38	
Al_2O_3		5·10		4·35		4·72		4·33	
Fe_2O_3		2·34		1·70		1·88		5·62	
FeO		3·88		4·79		13·65		14·73	
MgO		16·41		15·87		15·32		13·86	
CaO		21·61		21·96		11·80		9·94	
Na_2O		0·27		0·29		0·42		0·46	
K_2O		0·03		0·05		0·10		0·06	
TiO_2		0·29		0·31		0·42		1·40	
MnO		0·13		0·26		0·36		0·41	
TOTAL		100·29		100·63		99·69		100·19	
Atomic	Ca	43·9		44·6		26·0		22·1	
per	Mg	46·4		44·9		47·0		42·9	
cent	Fe	9·7		10·5		27·0		35·0	
$\beta \pm 0{\cdot}002$		1·697		1·688		1·707		1·708	
2V +ve		52°		47°		36°		40°	
		CATIONS ON BASIS OF 6 OXYGENS							
Si		1·841	2·00	1·869	2·00	1·905	2·00	1·860	2·00
Al		0·159		0·131		0·095		0·140	
Al		0·061	2·02	0·055	2·02	0·114	1·98	0·148	2·04
Fe^{+3}		0·064		0·046		0·054		0·158	
Fe^{+2}		0·119		0·147		0·426		0·464	
Mg		0·896		0·866		0·833		0·778	
Ca		0·848		0·862		0·471		0·400	
Na		0·020		0·020		0·031		0·034	
K		0·002		0·002		0·004		0·002	
Ti		0·009		0·009		0·011		0·041	
Mn		0·004		0·009		0·011		0·014	

1. Diopsidic augite, phenocrysts; oceanite, Allen Point, Montagu Island. (SSM.5.2)
2. Diopsidic augite, phenocrysts; basalt, west side, Vindication Island. (SSV.9.1)
3. Augite, groundmass; basaltic andesite, north side of crater wall, Bellingshausen Island. (SSB.17.2)
4. Subcalcic augite, groundmass; basaltic andesite, Irving Point, Visokoi Island. (SSW.1.1)

3). The crystallization trend of clinopyroxenes in tholeiitic volcanic rock suites may be distinguished both from the trend in alkaline volcanic rock series and from that in more slowly cooled tholeiitic magmas (Fig. 4).

4. *Orthopyroxene*

Although orthopyroxene phenocrysts are not usually abundant in the South Sandwich Islands lavas, they do feature prominently in certain groups of lavas, such as the andesites of Leskov Island and the porphyritic basalts of Vindication Island. Hypersthene occurs as sporadic phenocrysts and sometimes as a groundmass constituent in some of the basaltic andesites, e.g. of Bellingshausen Island, and also appears as small phenocrysts in the rhyolitic pumice emitted during the submarine eruption of March 1962 (Gass and others, 1963). Optical properties of three orthopyroxenes are given in Table V, from which it appears that the composition ranges from that of bronzite (En_{75}) to hypersthene (En_{55}).

5. *Amphibole*

Apart from the isolated occurrence of small basaltic hornblendes in one of the andesite specimens from Leskov Island (SSL.10.1), amphiboles have not been recorded in the lavas or pyroclastic deposits of the South Sandwich Islands. Their absence is particularly notable in contrast with the common occurrence of amphiboles in the more siliceous lavas of other island-arc volcanoes, such as those of the Lesser Antilles (e.g. Robson and Tomblin, 1966, p. 2, 16 and 42).

6. *Silica minerals*

Quartz appears only rarely in rocks from the South Sandwich Islands, for example, as occasional fragments in one of the Leskov Island andesites (SSL.10.1) and also in a gabbroic xenolith from Vindication Island (SSV.8.1). Cristobalite is much more abundant, especially in the groundmass of basaltic andesites (e.g. from Bellingshausen Island) and basalts (e.g. from Visokoi, Saunders and Montagu Islands). Tridymite has not been identified in any of the rocks of the South Sandwich Islands.

7. *Refractive indices of whole-rock glasses*

Small samples of analysed whole rocks were fused in a graphite crucible by means of a Radyne heater and induction coil. The quenched samples were crushed and the refractive indices of the glasses determined by the immersion method. The results are shown in Fig. 5 where refractive indices are plotted against percentage SiO_2. Plots of refractive index against CaO, MgO and total iron were also made but the correlation is less marked. George (1924, p. 365) plotted refractive indices of assorted natural glasses against percentage SiO_2 but the correlation was considerably less than in the case of the glasses prepared from South Sandwich Islands lavas. In this closely related group of rocks, in which there is a compositional gradation, there is evidently a close relationship between SiO_2 content and the refractive indices of artificially prepared glasses.

V. GEOCHEMISTRY

CHEMICAL analyses of rocks from the South Sandwich Islands, together with their C.I.P.W. norms, are shown in Table VII. The rocks are quartz-normative except for some basic specimens whose origin has clearly been in part accumulative. The analyses quoted are from the following sources:

i. Older analyses taken from Tyrrell (1945, p. 101).
ii. Analyses of the pumice from the 1962 submarine eruption and also of its gabbroic inclusion are taken from Gass and others (1963, p. 327).
iii. Analyses by J. F. Tomblin were made in 1964 by colorimetric methods.
iv. Analyses by J. R. Bowden-Dan, N. Walsh, A. Hering and P. E. Baker were made in 1964–65; SiO_2, R_2O_3, CaO and MgO were determined by gravimetric methods; Fe_2O_3, MnO, TiO_2, P_2O_5 and Al_2O_3 were determined on a UNICAM spectrophotometer; Na_2O and K_2O on an EEL flame photometer; and FeO by the "vanadate method" (Wilson, 1955, p. 56–58).

TABLE VII

CHEMICAL ANALYSES OF VOLCANIC ROCKS FROM THE SOUTH SANDWICH ISLANDS

	1 SSC.24.3	2	3 SSC.41.1	4 SSM.5.2	5 SSS.10.1	6 SSR.1.3	7 SSC.43.1	8 SSW.1.1	9 SSS.1.2	10 SSV.9.1	11 SHA.4.2	12 SSW.9.3	13 SSM.4.1	14	15 D.3783.4	16 SHA.15.6	17 SSW.6.3
SiO_2	42·8	48·34	48·5	49·71	49·94	50·22	50·60	51·04	51·11	51·38	51·91	52·32	52·53	52·68	53·05	53·80	54·00
Al_2O_3	21·9	13·45	23·1	19·28	17·53	19·59	18·60	17·12	17·95	18·25	15·58	16·70	19·29	16·38	14·98	14·25	14·84
Fe_2O_3	1·12	1·12	1·56	2·84	2·28	3·82	2·26	3·90	1·84	2·23	2·77	2·48	1·88	3·11	4·41	4·62	2·93
FeO	6·48	11·34	5·00	7·07	7·43	6·16	6·46	6·97	8·49	7·11	9·15	9·03	7·31	7·98	9·67	9·30	10·18
MgO	11·19	6·62	4·24	8·91	6·93	5·60	6·40	5·91	5·48	6·13	5·00	5·14	3·88	7·47	4·71	3·90	4·17
CaO	13·02	11·43	13·54	10·17	11·52	12·53	11·56	11·76	11·42	11·81	11·36	10·38	10·88	8·08	9·19	8·43	8·86
Na_2O	1·09	2·22	1·80	1·28	2·12	1·76	1·92	1·96	1·91	1·81	3·05	2·40	2·02	2·75	2·62	3·04	2·82
K_2O	0·03	0·19	0·13	0·20	0·41	0·15	0·13	0·37	0·19	0·26	0·20	0·52	0·24	0·44	0·27	0·82	0·60
H_2O+	1·35	2·94	1·18	0·13	0·28	0·10	1·44	0·31	0·27	0·24	0·16	0·20	0·12	0·20	0·13	0·20	0·14
H_2O-	0·31	0·30	0·27	0·00	0·04	0·03	0·32	0·03	0·06	0·05	0·20	0·00	0·05		0·01	0·24	0·06
TiO_2	0·22	1·47	0·55	0·50	0·80	0·56	0·70	0·87	0·98	0·57	0·79	1·16	0·70	0·77	1·10	1·78	1·31
P_2O_5	0·01	—	0·03	0·04	0·07	0·05	0·04	0·07	0·11	0·02	0·07	0·12	0·00	0·02	0·07	0·15	0·14
MnO	0·09	0·32	0·09	0·09	0·17	0·17	0·14	0·19	0·17	0·18	0·19	0·19	0·18	0·16	0·22	0·24	0·22
TOTAL	99·61	99·70	99·99	100·23	99·52	100·74	100·57	100·50	99·98	100·04	100·43	100·64	99·08	100·04	100·43	100·77	100·27
																C.I.P.W. NORMS	
Qz	—	—	1·70	2·79	0·55	4·52	3·90	5·09	4·60	4·43	1·60	4·66	8·13	3·47	8·10	8·51	7·55
C	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Or	0·18	1·12	0·77	1·18	2·42	0·89	0·77	2·19	1·12	1·54	1·18	3·07	1·42	2·60	1·60	4·85	3·55
Ab	6·45	18·78	15·23	10·91	17·94	14·89	16·24	16·58	16·16	15·31	25·81	20·31	17·09	23·27	22·17	25·72	23·86
An	54·78	26·18	54·57	46·23	37·11	45·12	41·75	36·83	39·85	40·91	28·24	33·26	42·86	31·06	28·32	22·82	26·07
Ne	1·50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Di	7·84	25·34	10·14	3·20	15·96	13·57	12·46	17·12	13·28	14·35	22·96	14·44	9·24	7·24	13·95	14·96	14·21
Hy	—	17·01	12·76	30·62	20·23	14·90	18·98	14·88	19·85	18·85	14·61	18·61	16·11	26·19	17·51	13·04	17·79
Ol	25·13	3·66	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Mt	1·62	1·62	2·26	4·12	3·31	5·54	3·28	5·65	2·67	3·23	4·02	3·60	2·73	4·51	6·39	6·70	4·25
Il	0·42	2·79	1·04	0·95	1·52	1·06	1·33	1·65	1·86	1·08	1·50	2·20	1·33	1·46	2·09	3·38	2·49
Ap	0·02	—	0·07	0·09	0·17	0·12	0·09	0·17	0·26	0·05	0·17	0·28	—	0·05	0·17	0·35	0·33
H_2O	1·66	3·24	1·45	0·13	0·32	0·13	1·76	0·34	0·33	0·29	0·36	0·19	0·17	0·20	0·14	0·43	0·19
Differentiation index	8·1	19·9	17·7	14·9	20·9	20·3	20·9	23·9	21·9	21·3	28·6	28·0	26·6	29·3	31·9	31·9	34·9
100 Fe/(Fe+Mg)	23	45	34	25	32	29	30	31	42	35	45	44	47	31	45	46	52

	18	19 SSB.12.1	20 SSB.5.1	21 SSF.2.1	22 SSB.11.1	23 SSB.17.2	24 SST.5.1	25	26 SSL.4.2	27 SSL.4.1	28 SSK.1.1	29 SSC.20.2	30 SSC.54.2	31 SSC.29.2	32 SSK.1.3	33	34
SiO_2	54·90	55·17	56·22	56·43	56·98	57·10	57·82	58·14	58·33	58·62	60·01	60·9	62·7	64·4	66·26	69·45	73·04
Al_2O_3	17·62	17·29	16·79	20·17	16·14	16·06	15·44	15·19	18·65	18·29	14·87	14·8	14·5	14·4	13·23	14·20	13·61
Fe_2O_3	2·70	1·96	3·64	2·97	2·50	4·24	3·43	2·95	2·04	1·92	1·95	1·44	3·16	1·38	1·09	2·83	0·69
FeO	6·80	8·59	6·99	4·20	8·34	6·95	7·96	5·99	5·05	4·72	9·01	7·04	5·57	6·45	7·67	3·24	2·13
MgO	3·93	3·33	3·18	1·82	2·80	2·58	2·67	3·77	2·89	3·04	2·47	2·35	2·40	1·84	0·85	0·25	0·50
CaO	9·05	9·59	8·36	8·39	8·32	8·21	7·23	8·05	7·96	7·94	6·03	6·09	5·96	5·28	4·06	3·05	3·25
Na_2O	2·90	2·89	3·19	3·47	3·44	3·23	3·41	3·48	2·94	3·05	3·39	3·67	3·52	3·79	4·16	4·15	4·66
K_2O	0·54	0·48	0·45	0·85	0·60	0·62	0·93	0·33	0·76	0·94	1·18	0·39	0·33	0·45	1·57	1·51	0·67
H_2O+	0·30	0·02	0·07	0·40	0·15	0·14	0·20	} 1·31	0·02	0·30	0·01	0·84	0·88	0·11	0·13	0·40	1·04
H_2O-	0·20	0·05	0·06	0·26	0·01	0·11	0·02		0·01	0·03	0·02	0·19	0·14	0·30	0·03	0·60	0·04
TiO_2	0·70	0·79	0·88	0·67	0·91	0·88	1·04	0·81	0·76	0·72	1·13	0·95	0·93	0·85	0·69	0·15	0·30
P_2O_5	0·09	0·12	0·17	0·12	0·12	0·14	0·18	—	0·48	0·12	0·21	0·12	0·11	0·13	0·20	0·14	0·12
MnO	0·23	0·19	0·17	0·14	0·18	0·19	0·21	0·10	0·16	0·14	0·20	0·11	0·15	0·15	0·17	0·07	0·08
TOTAL	99·96	100·47	100·17	99·89	100·49	100·45	100·54	100·12	100·05	99·83	100·48	98·89	100·35	99·53	100·11	100·04	100·13
Qz	8·97	8·36	12·01	11·47	10·46	13·84	12·99	13·65	15·48	14·39	15·08	18·56	23·33	23·53	22·33	31·43	34·87
C	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0·53	—
Or	3·19	2·84	2·66	5·02	3·55	3·66	5·50	1·95	4·49	5·56	6·97	2·31	1·95	2·66	9·28	8·92	3·96
Ab	24·54	24·45	26·99	29·36	29·11	27·33	28·85	29·44	24·87	25·81	28·68	31·05	29·78	32·07	35·20	35·11	39·43
An	33·47	32·79	30·17	36·96	26·83	27·50	24·08	24·86	35·45	33·44	21·88	22·76	22·80	20·96	12·79	14·22	14·25
Ne	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Di	8·96	11·77	8·46	3·21	11·52	10·28	8·92	12·38	0·75	4·24	5·66	5·62	5·02	3·72	5·26	—	—
Hy	14·88	15·57	12·41	7·36	13·24	9·45	12·62	10·72	13·46	11·64	16·71	13·39	9·84	12·27	11·74	—	0·93
Ol	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4·12	3·76
Mt	3·91	2·84	5·28	4·31	3·62	6·15	4·97	4·28	2·96	2·78	2·83	2·09	4·58	2·00	1·58	4·10	1·00
Il	1·33	1·50	1·67	1·27	1·73	1·67	1·97	1·54	1·44	1·37	2·15	1·80	1·77	1·61	1·31	0·28	0·57
Ap	0·21	0·28	0·40	0·28	0·28	0·33	0·42	—	1·13	0·28	0·50	0·28	0·26	0·31	0·47	0·33	0·28
H_2O	0·50	0·06	0·12	0·65	0·15	0·24	0·21	1·31	0·01	0·32	0·02	1·02	1·02	0·40	0·15	0·99	1·07
Differentiation index	36·7	35·6	41·7	45·8	43·1	44·8	47·3	45·0	44·8	45·7	50·7	51·9	55·1	58·2	66·8	75·5	78·3
100 Fe/(Fe+Mg)	43	55	46	43	57	49	54	38	41	38	62	57	45	61	82	81	65

1. SSC.24.3 Anorthite-olivine block from flow 500 m. east of summit of scoria cone; northern part of Candlemas Island. (Anal. J. F. Tomblin.)
2. Olivine-basalt; dredged from near Cook Island. (Tyrrell, 1945, p. 100–01; Anal. F. Herdsman.)
3. SSC.41.1 Porphyritic basalt; southern part of Candlemas Island. (Anal. J. F. Tomblin.)
4. SSM.5.2 "Oceanite", dyke; Mathias Point, Montagu Island. (Anal. J. R. Bowden-Dan.)
5. SSS.10.1 Porphyritic basalt; sea cliffs at edge of Blackstone Plain 450 m. north of Yellowstone Crags, Saunders Island. (Anal. P. E. Baker.)
6. SSR.1.3 Porphyritic basalt; unnamed promontory on south-west coast of Bristol Island. (Anal. P. E. Baker.)
7. SSC.43.1 Porphyritic basalt; southern part of Candlemas Island. (Anal. J. F. Tomblin.)
8. SSW.1.1 Fine-grained basalt; near foot of 70 m. flow, Irving Point, Visokoi Island. (Anal. P. E. Baker.)
9. SSS.1.2 Basaltic cinders; probably recently erupted from Mount Michael; northern part of Blackstone Plain, Saunders Island. (Anal. N. Walsh.)
10. SSV.9.1 Porphyritic basalt; west side of Vindication Island; 300 m. south-south-east of Splinter Crag. (Anal. P. E. Baker.)
11. SHA.4.2 Porphyritic basalt (collected by P. Kennett, 1961); cliffs, east coast of Zavodovski Island. (Anal. A. Hering and P. E. Baker.)
12. SSW.9.3 Almost aphyric basalt; 20 m. cliff on north-west side of Finger Point promontory, Visokoi Island. (Anal. P. E. Baker.)
13. SSM.4.1 Microporphyritic basalt; 200 m. north-west of Horsburgh Point, Montagu Island. (Anal. J. R. Bowden-Dan.)
14. "Olivine-free basalt"; Nattriss Point, Saunders Island. (Quoted from O. Baeckström (1915, p. 173).)
15. D.3783.4 Glassy matrix from sparsely porphyritic basalt (collected by P. H. H. Nelson, 1961); eastern slopes of Zavodovski Island. (Anal. J. Goodenough.)
16. SHA.15.6 Glassy vein in fine-grained basalt; from Nattriss Point, Saunders Island (collected by P. Kennett, 1961 and probably equivalent to No. 14). (Anal. A. Hering and P. E. Baker.)
17. SSW.6.3 Aphyric basaltic andesite; Shamrock Hill, eastern slopes of Visokoi Island. (Anal. P. E. Baker.)
18. Hypersthene-andesite; Beach Point, Thule Island (Tyrrell, 1945, p. 101; Anal. F. Herdsman).
19. SSB.12.1 Aphyric basaltic andesite; Hardy Point, Bellingshausen Island. (Anal. P. E. Baker.)
20. SSB.5.1 Microporphyritic basaltic andesite; loose block of common type; 3 m. below Basilisk Peak, Bellingshausen Island. (Anal. P. E. Baker.)
21. SSF.2.1 Porphyritic andesite, dyke; south-east side Freezland Rock. (Anal. P. E. Baker.)
22. SSB.11.1 Sparsely porphyritic basaltic andesite; south-west coast of Bellingshausen Island, 200 m. east of Hardy Point. (Anal. P. E. Baker.)
23. SSB.17.2 Microporphyritic basaltic andesite; lowest lava flow, northern wall of crater, Bellingshausen Island. (Anal. P. E. Baker.)
24. SST.5.1 Aphyric basaltic andesite; south-western side of Hewison Point promontory, Thule Island. (Anal. P. E. Baker.)
25. Xenolith in pumice from 1962 submarine eruption 56 km. north-west of Zavodovski Island. (Gass and others, 1963, p. 327; Anal. M. Kerr.)
26. SSL.4.2 Porphyritic two-pyroxene andesite; from large block on high platform on eastern side of Leskov Island. (Anal. J. R. Bowden-Dan.)
27. SSL.4.1 Porphyritic two-pyroxene andesite; from large block on high platform on eastern side of Leskov Island. (Anal. P. E. Baker.)
28. SSK.1.1 Andesite glass, dyke; Reef Point, Cook Island. (Anal. P. E. Baker.)
29. SSC.20.2 Aphyric andesite; northern part of Candlemas Island. (Anal. J. F. Tomblin.)
30. SSC.54.2 Aphyric andesite; northern part of Candlemas Island. (Anal. J. F. Tomblin.)
31. SSC.29.2 Aphyric dacite; northern part of Candlemas Island. (Anal. J. F. Tomblin.)
32. SSK.1.3 Aphyric dacite; lava flow forming Reef Point, Cook Island. (Anal. N. Walsh.)
33. Aphyric dacite; Beach Point, Thule Island. (Tyrrell, 1945, p. 101; Anal. F. Herdsman.)
34. Rhyolitic pumice from 1962 submarine eruption 56 km. north-west of Zavodovski Island (Gass and others, 1963, p. 327; Anal. P. G. Harris and M. Kerr).

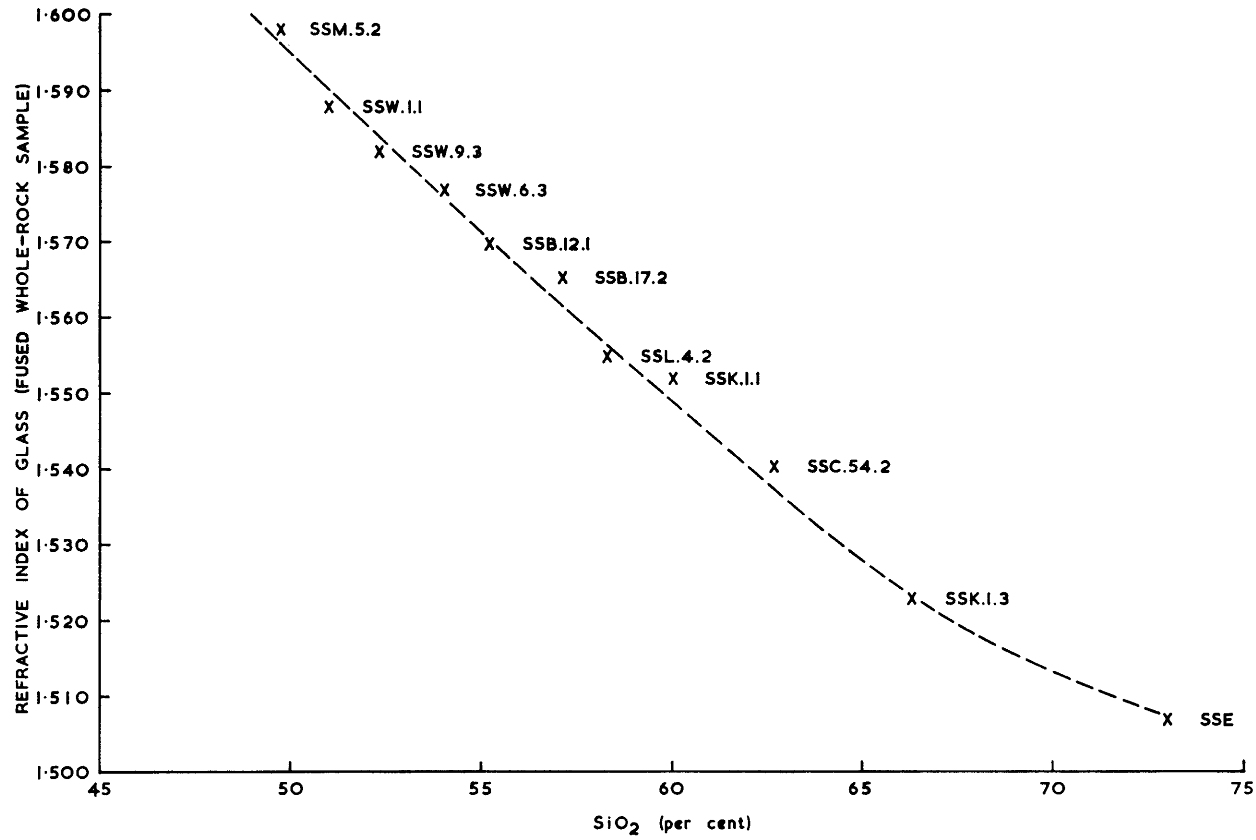

FIGURE 5

Plot of refractive index of whole-rock glass against silica content. The glass was obtained by fusing the rock powder in a graphite crucible using Radyne heater and induction coil. Sample numbers are indicated and their analyses are given in Table VII.

1. *Major elements*

The variation of the major oxides with differentiation index is shown on a variation diagram in Fig. 6. Al_2O_3 shows a considerable spread of values amongst the more basic rocks but there is an overall decrease with increasing D.I. The basalt dredged from near Cook Island (Table VII, No. 2) has a particularly low alumina content, whereas alumina is notably high both in the andesite from Freezland Rock (No. 21) and in the two-pyroxene andesites from Leskov Island (Nos. 26 and 27).

The content of total iron oxides increases with increasing D.I. through the basic rocks to a maximum of about 14 per cent and then decreases through the remainder of the series to a value of less than 3 per cent in the rhyolitic pumice (No. 34). The ratio of Fe_2O_3/FeO is persistently low throughout the lavas of the South Sandwich Islands in comparison with series from other island-arc environments, e.g. the Lesser Antilles (Robson and Tomblin, 1966). Both MgO and CaO diminish fairly steadily in concentration from the basic to the more acid end of the series. There are exceptions to this general trend; for instance, MgO is enriched in the oceanite from Montagu Island (Table VII, No. 4) and also in the basalt from Nattriss Point, Saunders Island (No. 14).

Na_2O rises through the series from a little over 1 per cent in the most basic rocks to more than 4 per cent in the most differentiated specimens. K_2O increases somewhat erratically from very low concentrations ($<0 \cdot 2$ per cent) in the most basic rocks to a maximum of only about 1·5 per cent in some of the dacites. Some of the andesites and dacites from Candlemas Island, which are remarkably impoverished in K_2O, provide the most striking exceptions to this general trend. The behaviour of TiO_2 resembles that of iron, tending to increase through the basalts and then to decline towards the more siliceous members of the series. TiO_2 is, however, anomalously high in the sample dredged from near Cook Island (Table VII, No. 2).

MnO, like TiO_2 and iron oxides, reaches a maximum in the more siliceous basalts. The content of P_2O_5 is generally lower in the more basic rocks.

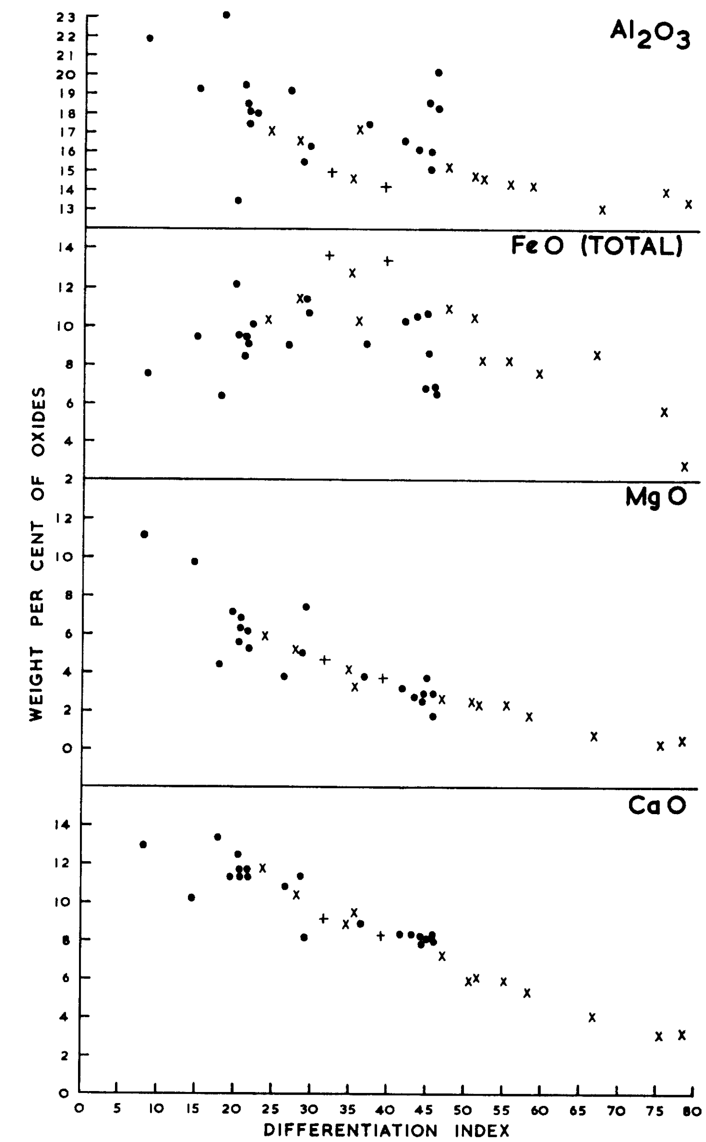

FIGURE 6

Variation of Al_2O_3, FeO, MgO and CaO with differentiation index (normative Qz+Or+Ab) in the South Sandwich Islands suite. FeO = total iron calculated as FeO. × aphyric rock; + glassy matrix or vein; ● porphyritic and accumulative types.

The tendency towards iron enrichment in the intermediate members of the series is illustrated on a FMA diagram (Fig. 7). Such enrichment is most noticeable in the case of basaltic andesites and andesites from Visokoi, Bellingshausen and Cook Islands.

2. *Minor elements*

Minor elements were determined spectrographically; the results are shown in Table VIII and the variation of some elements with differentiation index is illustrated in Fig. 8. Both *chromium* and *nickel* are concentrated in the most basic rocks and fall rapidly to very low concentrations throughout the remainder of the series. *Vanadium* diminishes fairly steadily from around 300 p.p.m. in the basalts to less than 30 p.p.m. in the rhyolitic pumice (Table VIII, No. 34), a range which is similar to that for vanadium in other island-arc suites (e.g. Nockolds and Allen, 1953, p. 132). Vanadium, however, shows a distinctly high concentration (615 p.p.m.) in the segregation vein from the Nattriss Point basalt, Saunders Island (Table VIII, No. 16).

Table VIII

MINOR ELEMENTS (p.p.m.) IN VOLCANIC ROCKS FROM THE SOUTH SANDWICH ISLANDS

Number in Table VII	1	4	5	6	8	9	10	12	13	16	17	19	20	21	22	23	24	26	27	28	29	32	34
Sample number	SSC.24.3	SSM.5.2	SSS.10.1	SSR.1.3	SSW.1.1	SSS.1.2	SSV.9.1	SSW.9.3	SSM.4.1	SHA.15.6	SSW.6.3	SSB.12.1	SSB.5.1	SSF.2.1	SSB.11.1	SSB.17.2	SST.5.1	SSL.4.2	SSL.4.1	SSK.1.1	SSC.20.2	SSK.1.3	SSE
Ba	44	28	59	46	75	80	28	95	44	105	85	90	105	150	110	120	185	205	195	225	105	355	125
Co	26	60	45	40	47	36	39	41	25	39	44	36	32	18	34	28	34	12	16	24	20	10	4
Cr	25	340	185	29	65	115	43	30	21	10	20	24	15	19	14	15	17	37	40	24	9	21	6
Cu	70	55	140	75	175	175	80	165	210	375	125	85	35	130	65	80	180	30	34	125	18	65	5
Ga	11	10	12	13	18	15	18	20	13	20	21	13	12	14	14	13	22	11	15	12	12	16	13
Li		3	7	4	5	6	5	10	5	11	9	7	3	14	9	7	9	9	11	13		20	14
Ni	3	80	80	11	27	46	24	14	5	3	3	8	3	2	4	9	2	7	15	1	1	1	1
Rb		10	15	5	12	12	5	18	8	23	19	16	11	28	16	16	25	29	27	30		42	21
Sc	33	65	39	50	50	46	50	44	49	44	46	35	38	24	36	35	34	30	27	33	39	20	14
Sr	130	105	140	155	135	150	105	145	140	125	130	145	150	180	160	150	155	205	210	150	135	150	160
U					0·13												0·26	0·38		0·30	0·53		0·68
V	195	300	350	295	290	395	270	325	315	615	415	285	205	165	240	210	245	155	205	100	130	31	24
Zr	27	31	65	41	100	65	55	120	34	155	130	70	80	85	95	75	170	80	105	140	85	205	80

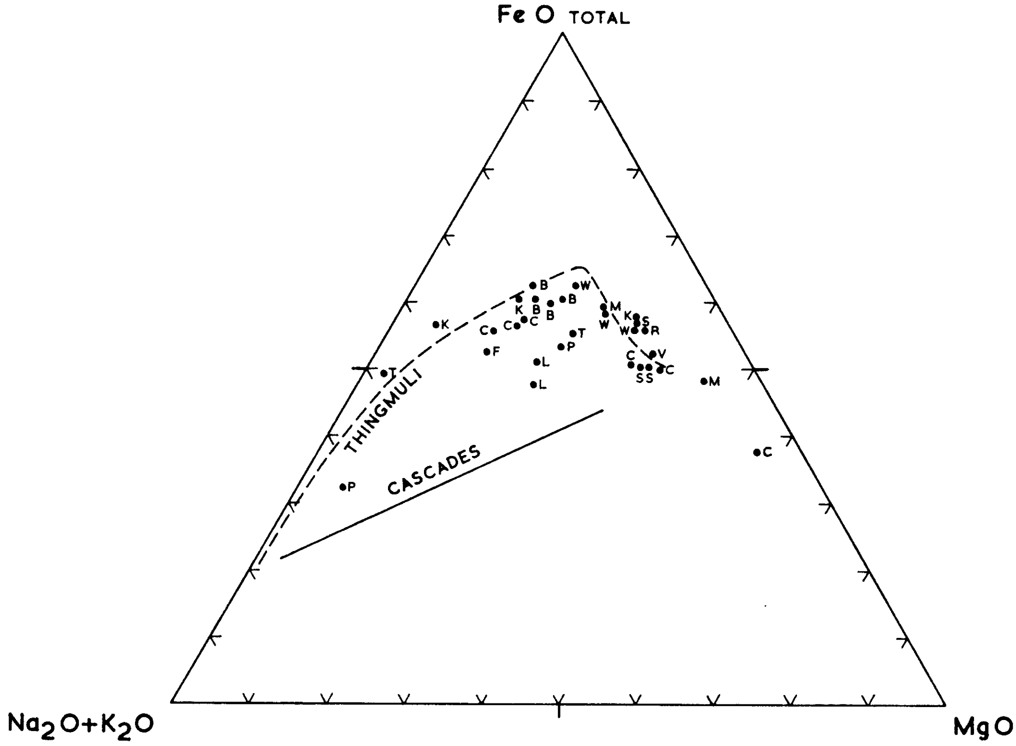

FIGURE 7

FMA (total iron as FeO : MgO : Na_2O+K_2O) diagram for the South Sandwich Islands suite. The letters represent the islands as indicated in Table I. Generalized trends for the tholeiitic series of Thingmuli (Carmichael, 1964) and the calc-alkaline series of the Cascades (Williams, 1942) are shown for comparison.

Cobalt diminishes fairly regularly from a maximum of 60 p.p.m. in the basalts to less than 5 p.p.m. in the rhyolitic pumice, and the range and behaviour of *scandium* is very similar. The *copper* content of the South Sandwich Islands lavas does not vary systematically with D.I. or silica content, although it does tend to be slightly more concentrated in the basic rocks. Like vanadium, copper is particularly enriched in the segregation vein from Saunders Island.

Gallium, the concentration of which is almost entirely within the range 10 to 20 p.p.m., shows no evidence of systematic variation with D.I.

The behaviour of *lithium*, *rubidium*, *zirconium* and *barium* is almost identical in the rocks from the South Sandwich Islands and is similar to the variation of potassium. Although there is some spread of values, the overall tendency is for an increase in the concentration of each of these constituents, reaching a maximum in the dacite from Cook Island (Table VIII, No. 32) and then falling to a lower value in the most siliceous member of the series (No. 34). There is a remarkably close co-variation of these particular minor elements in the analysed rocks; for example, a specimen such as the aphyric basalt from Finger Point (Tables VII and VIII, No. 12), which shows a higher K_2O content than the other basalts, also shows higher concentrations of Li, Rb, Zr and Ba. The segregation vein from Saunders Island (Table VIII, No. 16) is similarly enriched in these elements.

Strontium behaves in a different manner; its range is almost entirely between 100 and 200 p.p.m., and it appears to be slightly enriched in the intermediate members of the series, particularly in the two andesites from Leskov Island (Nos. 26 and 27).

Dr. E. I. Hamilton kindly determined the uranium content of six samples from the South Sandwich Islands; it ranges from 0·13 p.p.m. in a basalt from Visokoi Island (No. 8) to 0·68 p.p.m. in the rhyolitic pumice (No. 34) from the 1962 submarine eruption at Protector Shoal.

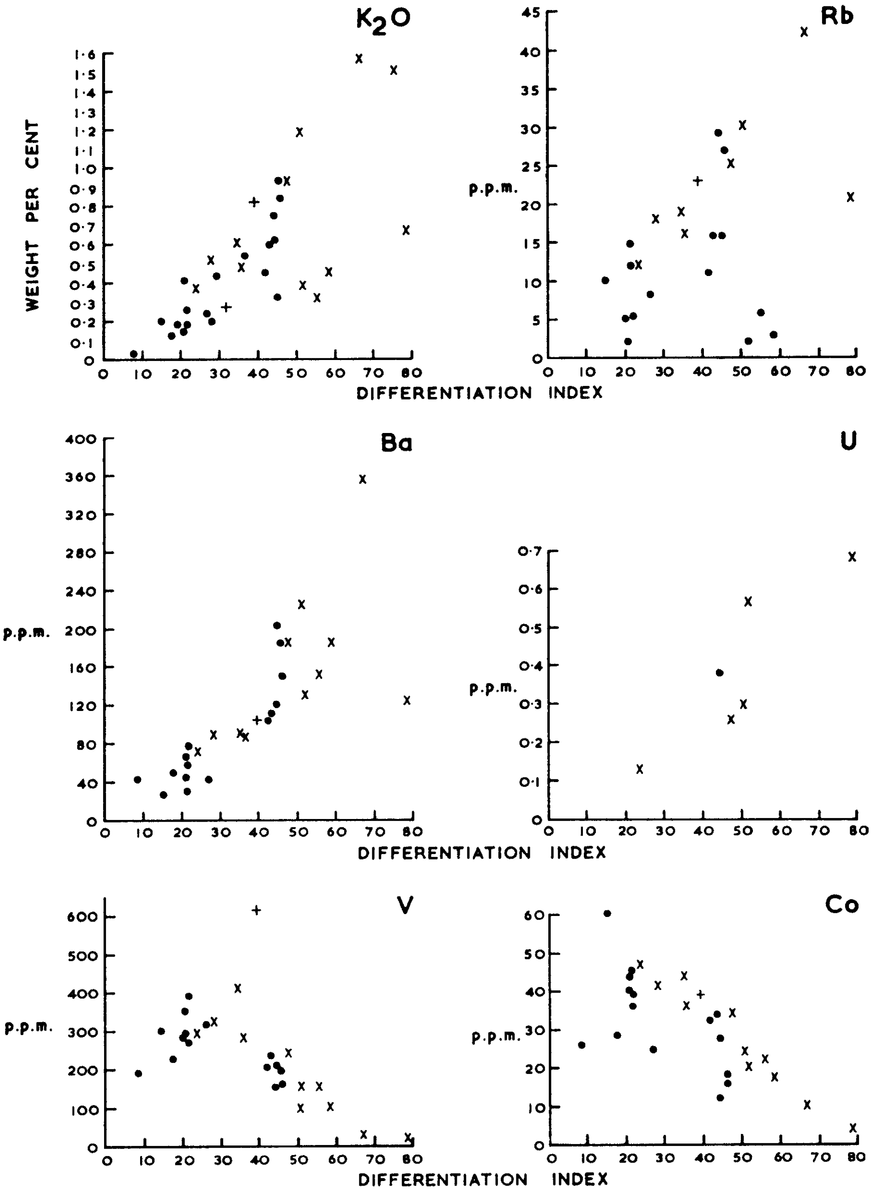

FIGURE 8

Variation of K_2O and a selection of trace elements with differentiation index in the South Sandwich Islands suite. The symbols are as in Fig. 6. Includes data for three Candlemas Island rocks from Tomblin (1978). Uranium values by courtesy of E. I. Hamilton.

VI. PETROGENESIS

DESPITE their association with an island arc and the many obvious analogies of that arc with the Caribbean and various Pacific arcs, the lavas of the South Sandwich Islands do not on the whole conform to the basalt–andesite–dacite–rhyolite series which usually prevails in the orogenic environment. Although calc-alkaline lavas occur, they are considerably less abundant than those of tholeiitic affinity. The two series which appear in the South Sandwich Islands are broadly equivalent to the "hypersthenic" and "pigeonitic" series formerly recognized by Kuno (1959) in the Japanese islands. Although the two suites are quite distinct in the intermediate and more siliceous rocks, differences are less obvious in the basaltic rocks.

1. *Tholeiitic series*

The majority of the South Sandwich Islands lavas belong to this suite which has the following features:

i. The dominant rock type is basalt which is usually porphyritic, although aphyric types occur especially on Visokoi Island.
ii. The basaltic "andesites" and "dacites", on the other hand, are almost exclusively aphyric.
iii. The suite shows quite marked iron enrichment in intermediate members (Table VII and Fig. 7). The andesites, e.g. from Candlemas Island (Table VII, Nos. 29 and 30) and Cook Island (Table VII, No. 28), resemble in texture and chemistry the iron-rich intermediate rocks from Thingmuli Volcano which Carmichael (1964, p. 441–42) referred to as "icelandites."
iv. The groundmass pyroxene in some of the basaltic andesites is an iron-rich subcalcic augite (Table V, No. 4).
v. Compared with calc-alkaline rocks from the South Sandwich Islands and elsewhere, this suite has distinctly low concentrations of K, Rb, Ba and Sr.

Further evidence of the tholeiitic nature of the rocks comes from a comparison of the chemical composition of the basalt at Nattriss Point, Saunders Island, with a segregation vein from within it. In 1961, P. Kennett collected a series of samples from the south coast of Saunders Island (SHA.15.1–9). He reported that they came from between 20 and 40 ft. a.s.l. and were almost vertically one above the other. From their situation and petrography, it would seem that these samples are from the Nattriss Point basalt, which was analysed by Baeckström (1915, p. 173) and is reproduced in Table VII (No. 14); the flow was subsequently re-collected by the writer in 1964 (SSS.15.1).

One of the Nattriss Point samples collected by Kennett (SHA.15.6) contains black glassy veins, an analysis of which is given in Table VII (No. 16) with minor elements in Table VIII. Compared with the whole-rock lava, the vein is enriched in TiO_2, K_2O, total iron and SiO_2, and is depleted in MgO and Al_2O_3. It is precisely in these respects that the tholeiitic basalts and their segregation veins described by Kuno (1965, p. 304) differ from each other. Comparing the Saunders Island example with the analyses quoted by Kuno (1965, p. 304, table 1) and with the information on his total iron–silica and total alkalis–silica plots (Kuno, 1965, p. 312 and 313, figs. 3 and 4), it is apparent that the Saunders Island basalt and segregation vein compositions lie close to those of Kuno's samples from Kilauea caldera and Vizzini.

Carmichael (1964, p. 446–55) emphasized the significance of the mode of occurrence of iron-titanium oxides in the lavas of Thingmuli, and it is interesting to note that magnetite occurs in a very similar way in the lavas of the South Sandwich Islands. In the most basic rocks, as well as in the more siliceous andesites and dacites, magnetite has an irregular interstitial form and is evidently late-stage. In contrast, in some of the basalts and basaltic andesites, magnetite appears as discrete euhedral to subhedral microphenocrysts and was clearly precipitated at an early stage. The best examples of such an occurrence are the basalts (SSW.1.1 and 4.2 from Irving Point, Visokoi Island (Plate Ic and d).

In the case of the Thingmuli series an early tendency towards increasing Fe/Mg ratio was suppressed as iron-titanium oxide began to precipitate as an early formed phenocryst phase. As the oxide subsequently reverted to a later crystallizing mineral, the Fe/Mg ratio again increased more sharply in the residual liquid. However, such stages are not recognizable in the South Sandwich Islands suite which shows a more continuous and progressive increase in Fe/Mg ratio (Fig. 9).

The following lines of evidence suggest that fractional crystallization is likely to have been the mechanism linking the differentiated rocks of the tholeiitic series with the associated basalts:

i. The volume of differentiated rocks is very small in comparison with that of the basalts. The relative volumes of each rock type do not preclude a connection through fractional crystallization.
ii. There is a continuum of chemical properties consistent with a fractionation link.
iii. The occurrence of some highly porphyritic lavas (e.g. SSM.5.2 and SSW.10.1) and occasional cumulate blocks (e.g. SSC.24.3) provides tangible evidence of the products of fractionation. The trend of Fe enrichment relative to Mg and alkalis (Fig. 7) is observed elsewhere as the consequence of fractional crystallization in tholeiitic magmas (e.g. Wager and Deer, 1939; Kuno and others, 1957).

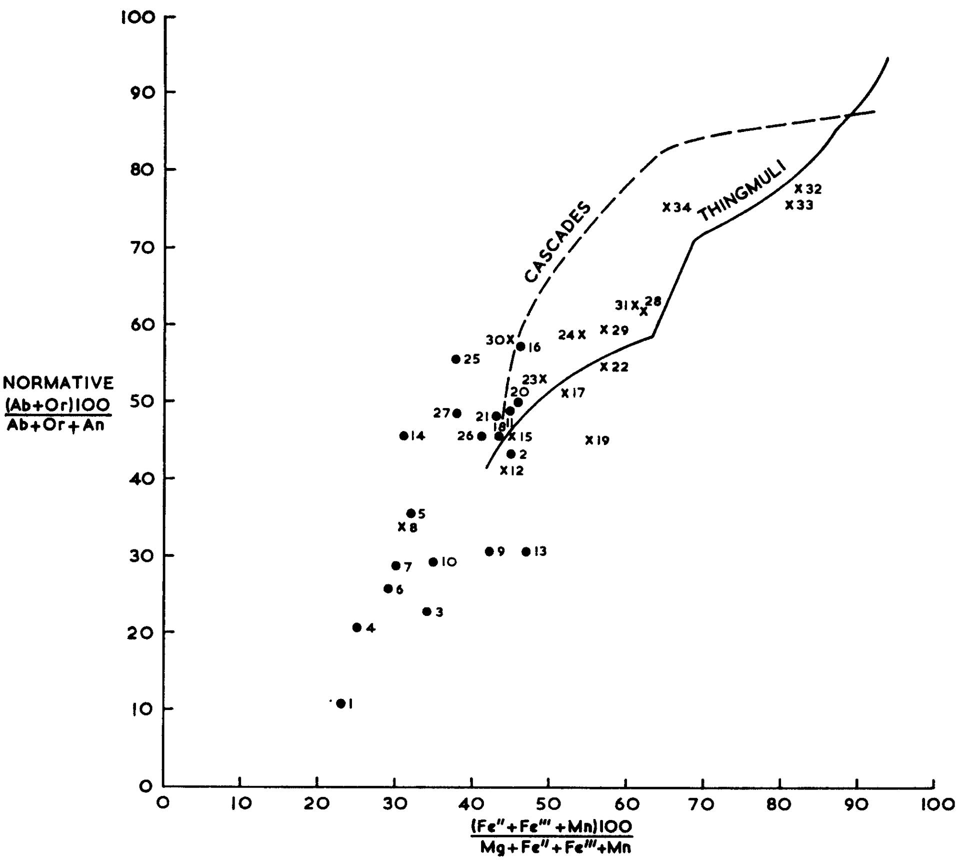

FIGURE 9

Normative feldspar ratio (Ab+Or)100/Ab+Or+An plotted against the atomic ratio (Fe''+Fe'''+Mn)100/Mg+Fe''+Fe'''+Mn. Numbers refer to analysis numbers in Table VII. × aphyric lavas; ● porphyritic and coarser-grained rocks, etc. as in Table VII. Generalized trends for Cascades and Thingmuli lavas from Carmichael (1964, p. 452).

2. *Calc-alkaline andesites*

Some of the andesites of the South Sandwich Islands are petrographically and chemically dissimilar from those of the tholeiitic series and instead resemble the typical andesites which are widely distributed throughout the orogenic environment. The most conspicuous examples of this category are the two-pyroxene andesites of Leskov Island (e.g. SSL.4.1 and 4.2) which perhaps significantly is situated in an anomalous position 50 km. west of the arcuate axis along which the other islands of the group are distributed. The andesite of Freezland Rock (SSF.2.1) and the hypersthene-andesite recorded by Tyrrell (1945, p. 101) from Beach Point, Thule Island, also appear to be of a similar type. Unlike the tholeiitic andesites, these rocks are strongly porphyritic and are distinguished chemically by lower iron and titanium contents and higher aluminium and strontium.

On variation diagrams for the South Sandwich Islands lavas, these rocks fall upon a different trend from those of the tholeiitic series (e.g. Figs. 7 and 9).

3. *Discussion*

The South Sandwich Islands constitute one of the few island arcs, where rocks of both tholeiitic and calc-alkaline affinity occur in close juxtaposition. Basalts are the dominant rock type and most rocks belong to the tholeiitic series. The tholeiitic basalts show certain resemblances to ocean-floor basalts (Baker, 1968) and are quite distinct from calc-alkaline lavas such as those of the Lesser Antilles. The tholeiitic lavas of the South Sandwich Islands are clearly equivalent to that designated as the island-arc tholeiitic series (Jakeš and Gill, 1970) with representatives in Izu, Mariana and Tonga. The series is characterized by a tholeiitic trend on the FMA diagram, an unfractionated rare-earth element pattern and low concentrations of incompatible elements such as K, Ba, U and Zr (Jakeš and Gill, 1970; Ringwood, 1974).

Two stages of development were thought to be represented in the South Sandwich Islands (Baker, 1968), the earlier characterized by the dominant tholeiitic lavas and the later by the somewhat sparse calc-alkaline andesite. Evidence for petrological/compositional evolution in island arcs is also to be found in Fiji (Gill, 1970) and has been discussed more recently by Ringwood (1974). K-Ar dating, which indicates an age of 0·7 m. yr. for a Leskov Island andesite (Baker, 1968, p. 192), does not suggest that this, the only exclusively calc-alkaline island, is significantly younger than the islands of the main tholeiitic arc. However, the off-axis westerly situation of Leskov Island and the higher potash content of its lavas are consistent with the K_2O *versus* depth to Benioff Zone relationship recognized by Dickinson (1968).

The oceanic situation of the South Sandwich Islands arc would seem to preclude involvement of sialic crust in the generation of either of the volcanic suites. There can be little doubt that they originated from the interplay of processes within and above a subducted lithospheric plate that bears only oceanic crust. From the work of Nicholls and Ringwood (1973) and Ringwood (1974), it seems probable that the initial stimulus for generation of the island-arc tholeiite series comes from dehydration of amphibolite forming the subducted oceanic crust, at depths of 80–100 km. The rising water induces partial melting of the overlying mantle pyrolite to form a tholeiitic magma. Subsequent crystallization of olivine, followed by amphibole and/or pyroxene and plagioclase, is then capable of yielding the entire range of compositions encountered in the island-arc tholeiite series.

In the South Sandwich Islands we are probably seeing the beginning of the second stage in island-arc volcanism, where tholeiitic products are giving way to calc-alkaline types. According to Ringwood (1974), with continued subduction to depths of 100–300 km., the oceanic crust is converted to quartz-eclogite, which partially melts forming rhyodacite–rhyolite magmas. The process is aided by water from dehydration of serpentinite bodies and the hydrous acid magma subsequently reacts with mantle pyrolite to form pyroxenite. Wet pyroxenite diapirs ascend from the Benioff Zone and undergo partial melting. The magma that segregates is relatively enriched in incompatible elements, has a high K/Na ratio and a fractionated rare-earth element pattern—it is of calc-alkaline type. Fractionation of this magma, involving, for example, separation of silica-poor amphibole at depths of less than 100 km., would lead to the generation of increasing siliceous residual liquids and hence the differentiated rocks of the calc-alkali suite. On the basis of this model, the maximum development of calc-alkaline andesites on Leskov Island is in accord with its westerly situation over the deeper part of the Benioff Zone.

VII. ACKNOWLEDGEMENTS

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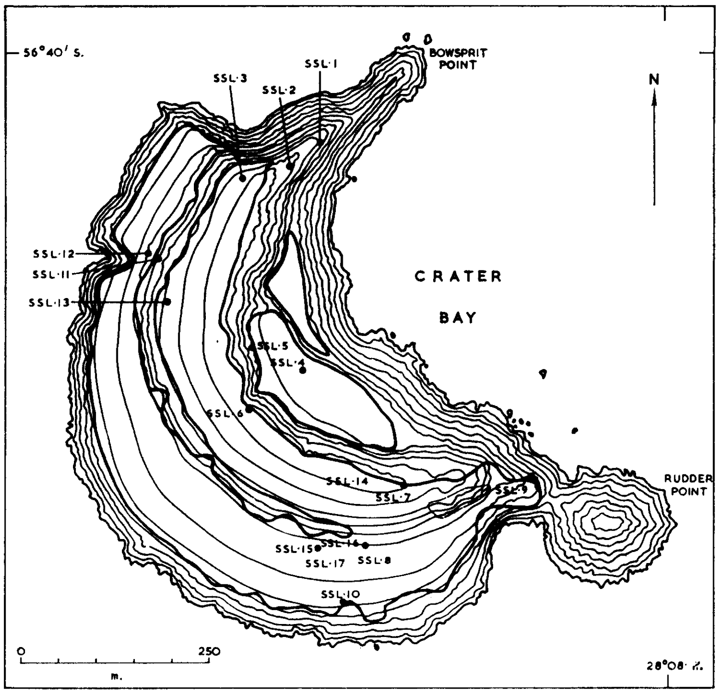
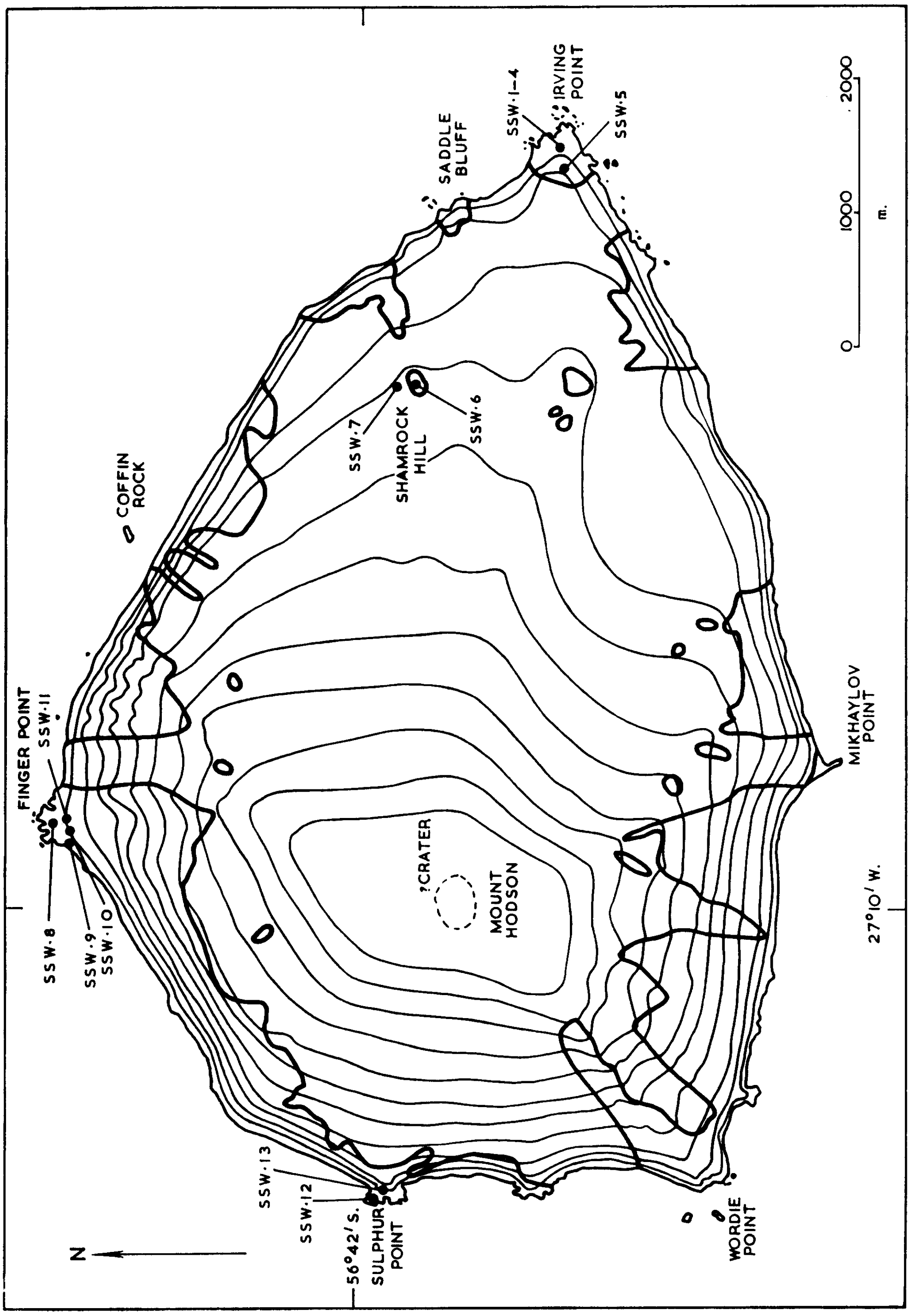
APPENDIX

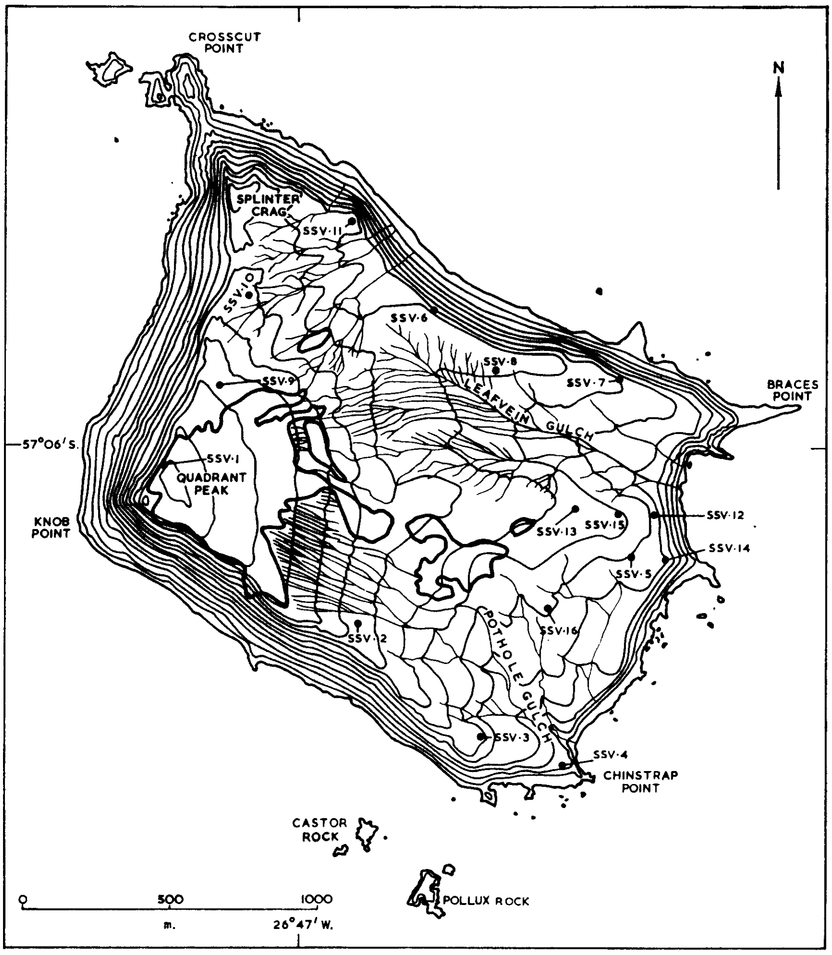
SKETCH MAPS OF THE SOUTH SANDWICH ISLANDS SHOWING THE LOCATIONS OF GEOLOGICAL STATIONS



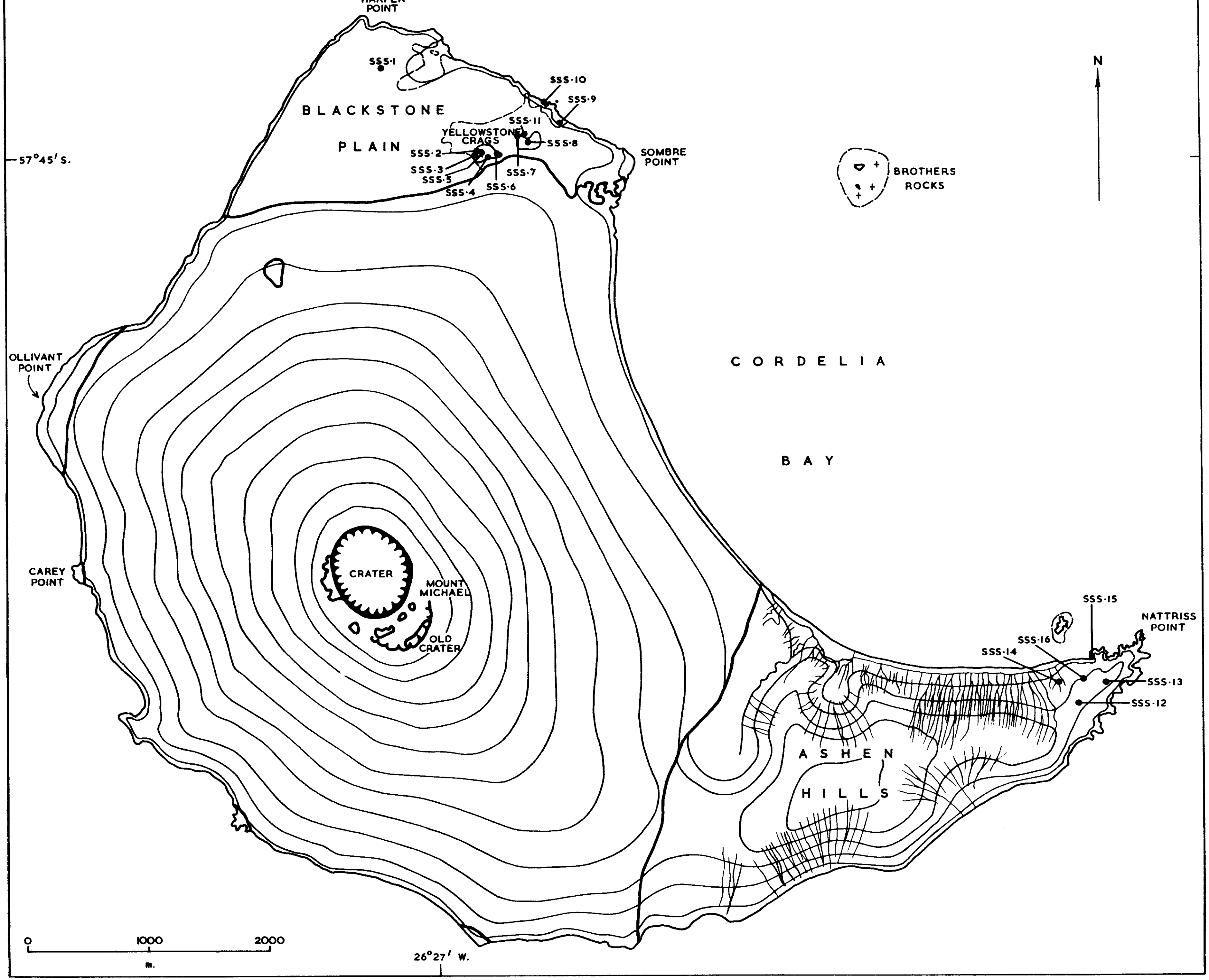
1. Leskov Island (stations SSL.1–17).



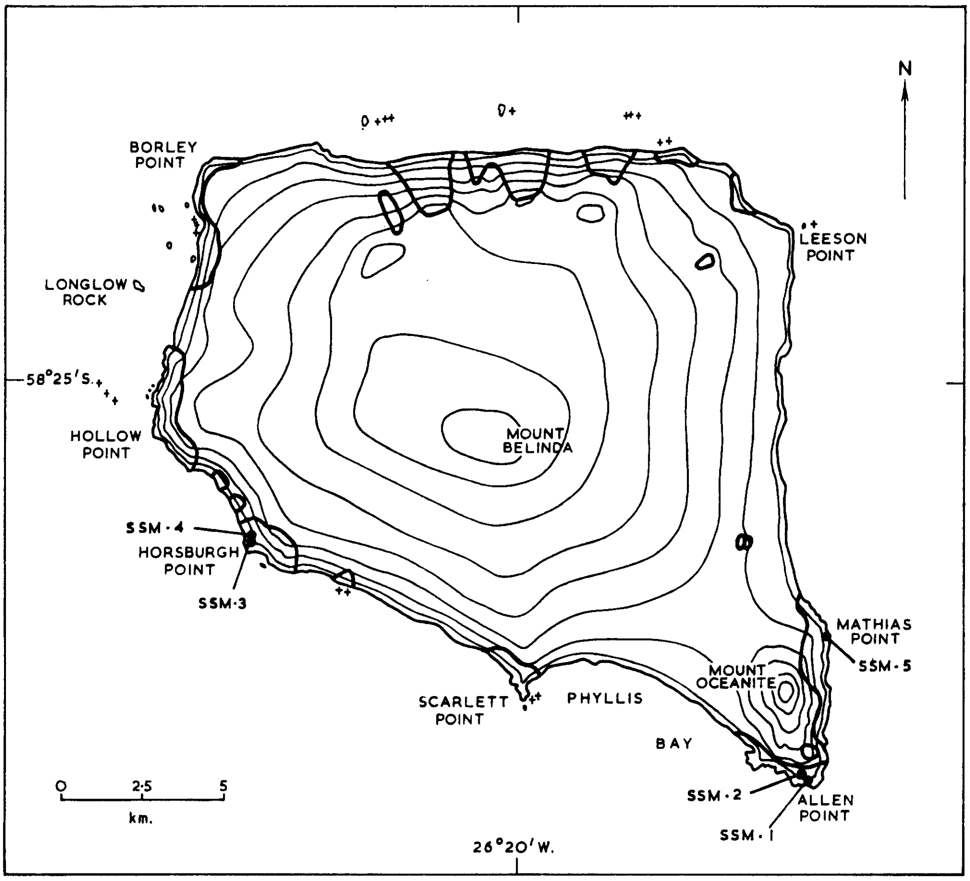
2. Visokoi Island (stations SSW.1–13).



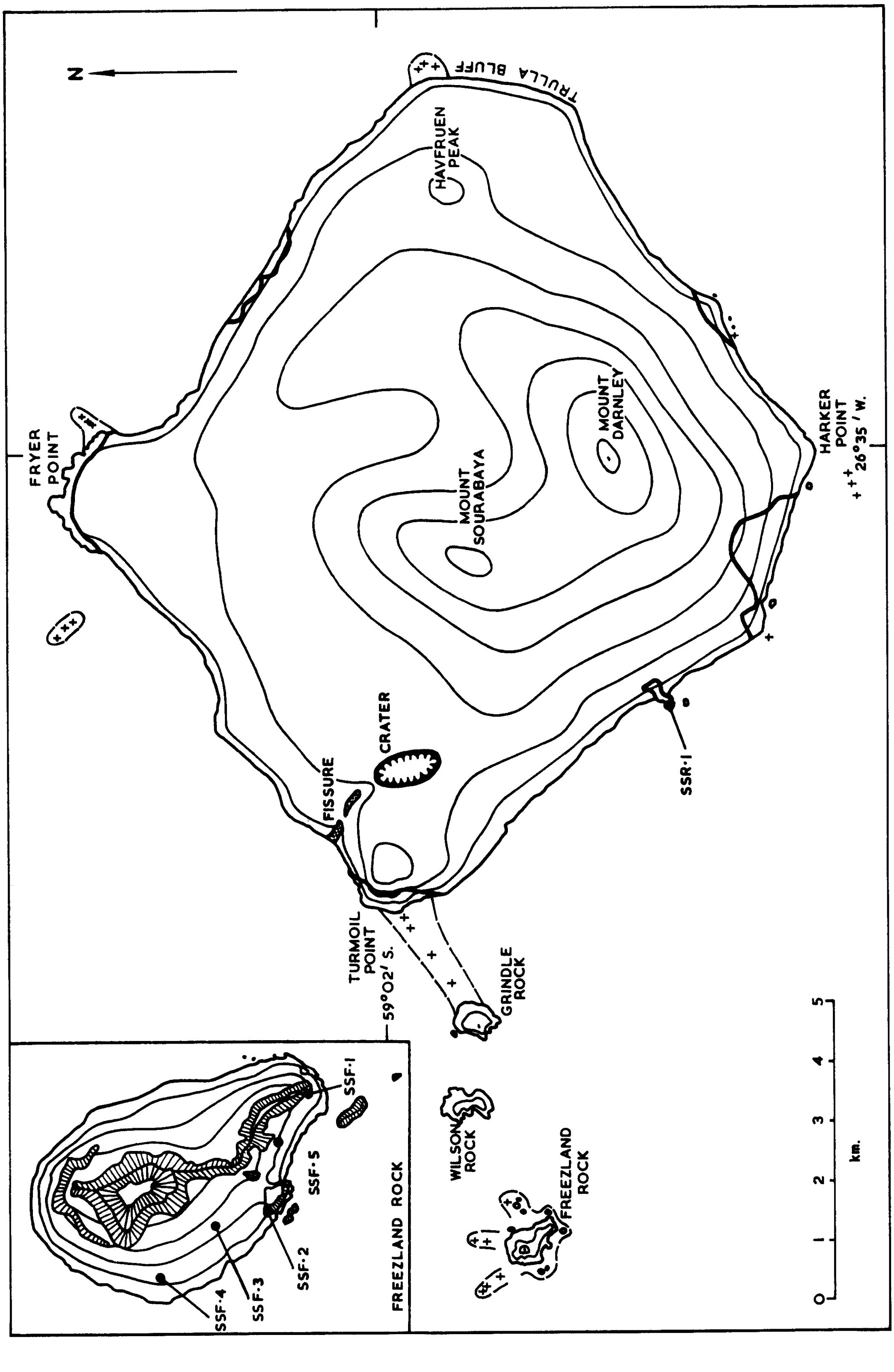
3. Vindication Island (stations SSV.1–16).



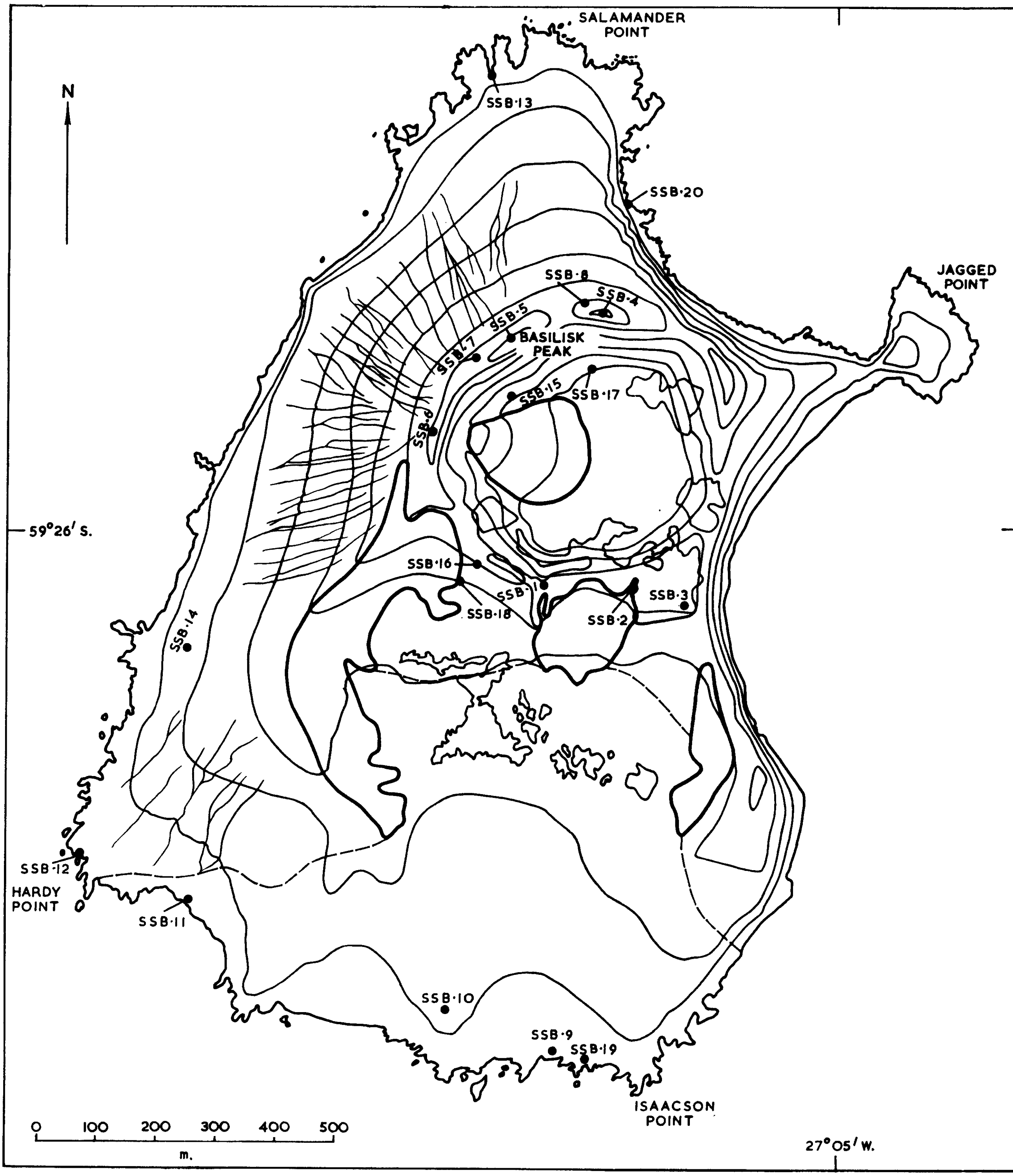
4. Saunders Island (stations SSS.1–16).



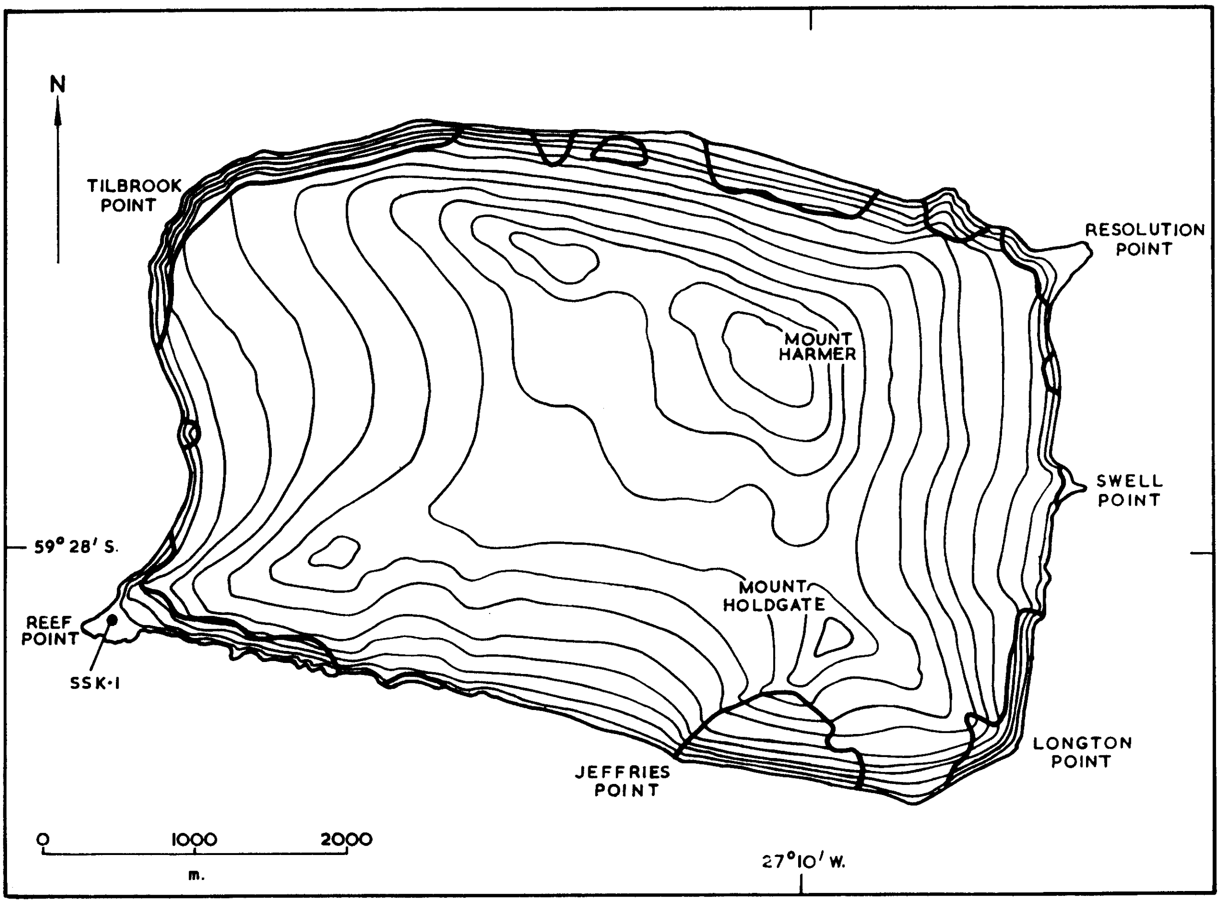
5. Montagu Island (stations SSM.1–5).



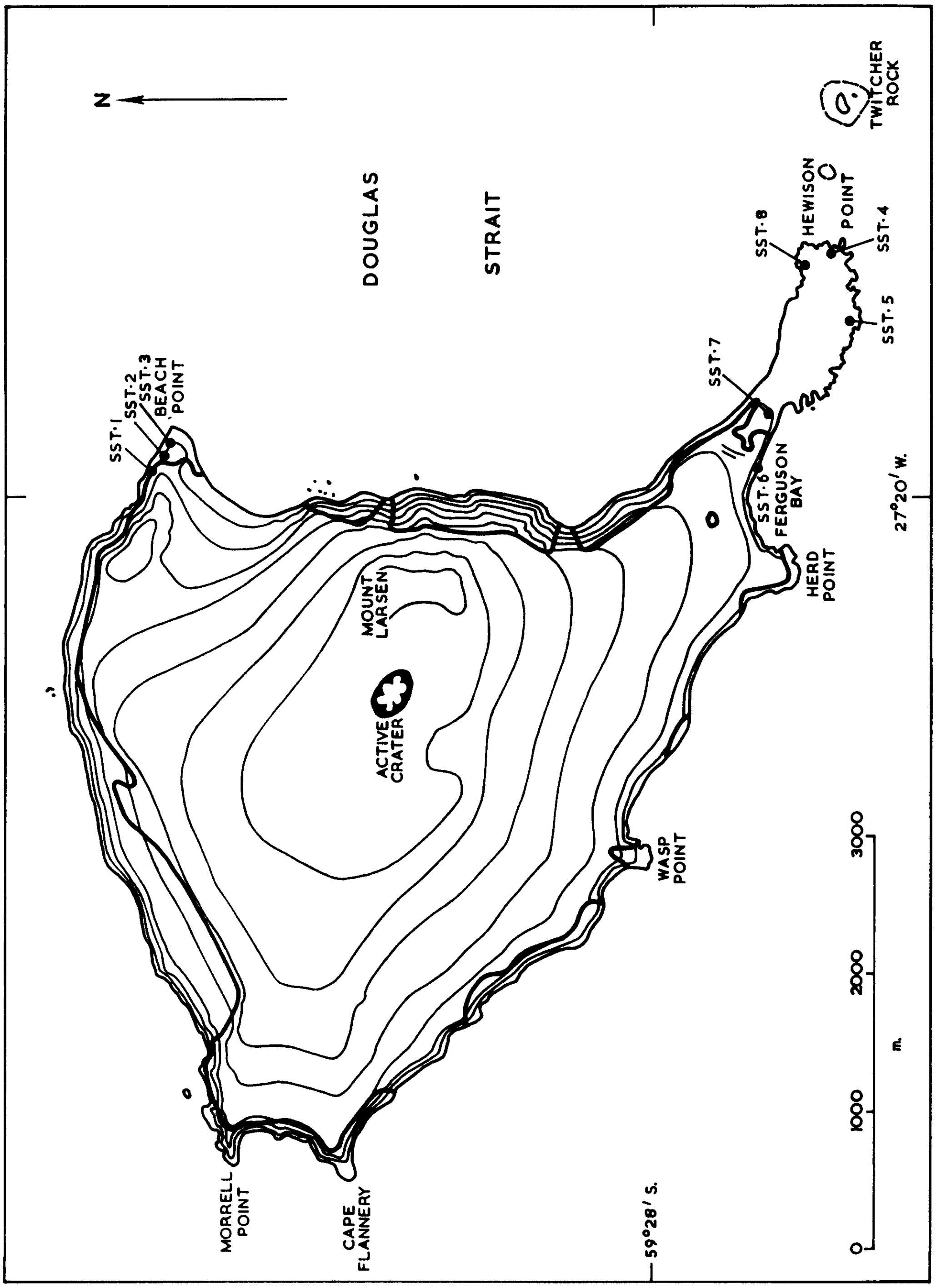
6. Bristol Island (station SSR.1) and Freezland Rock (stations SSF.1–5).



7. Bellingshausen Island (stations SSB.1–20).



8. Cook Island (station SSK.1).



9. Thule Island (stations SST.1–8).

PLATE I

a. Porphyritic basalt, east coast of Zavodovski Island. Microphenocryst of olivine with a reaction rim in the matrix of plagioclase laths, clinopyroxene and opaque oxides (SHA.4.1; ordinary light; ×85).

b. Porphyritic to vitrophyric two-pyroxene andesite, east side of Leskov Island. Phenocrysts of plagioclase, hypersthene and augite in a fine-grained partly glassy matrix. The largest phenocryst shows contiguous sub-parallel growth of ortho- and clinopyroxene (SSL.4.2; X-nicols; ×35).

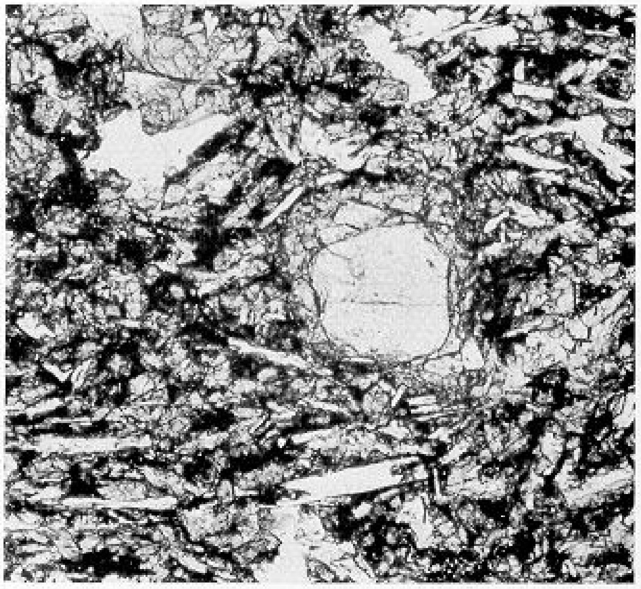
c. Tholeiitic basalt from Irving Point, Visokoi Island. Poikilitic magnetites and olivine microphenocrysts in a matrix of plagioclase and clinopyroxene, with some orthopyroxene (SSW.1.1; ordinary light; ×35).

d. Basalt from Irving Point, Visokoi Island. Plagioclase phenocrysts and conspicuous small opaque oxides in a very fine-grained matrix of plagioclase and pyroxene (SSW.4.2; ordinary light; ×85).

e. Aphyric, iron-enriched basaltic andesite from Shamrock Hill, Visokoi Island. Uniformly microcrystalline. Plagioclase microlites with intergranular pyroxene and opaque oxides (SSW.6.3; ordinary light; ×85).

f. Fine-grained basalt, north-west side of Finger Point promontory, Visokoi Island. Plagioclase microphenocryst in a matrix of plagioclase laths, clinopyroxene granules, small olivines and opaque oxides (SSW.9.3; ordinary light; ×85).

PLATE I



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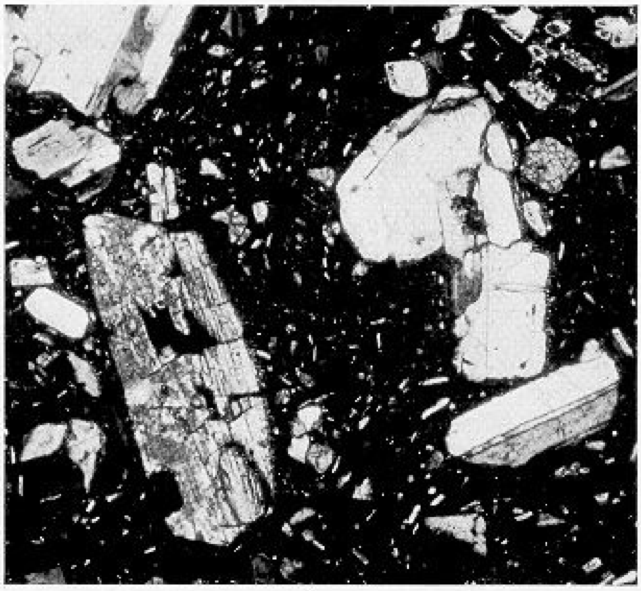

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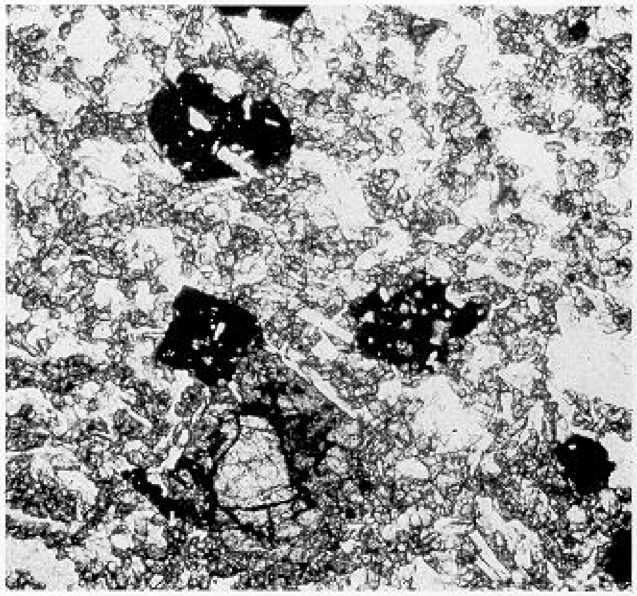

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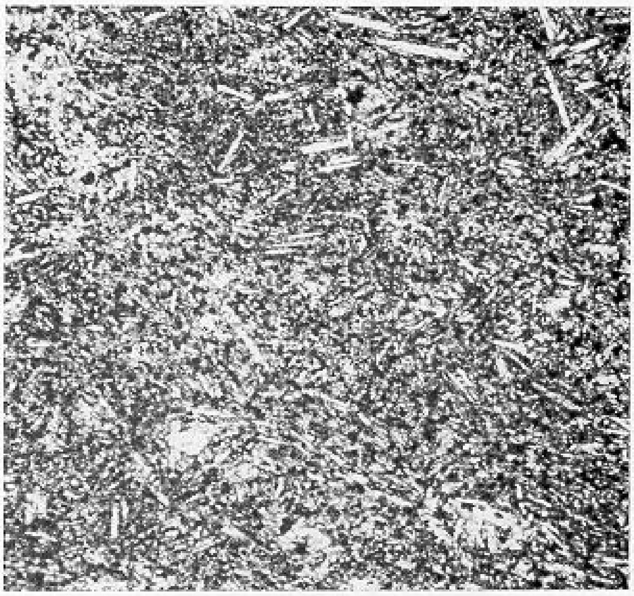

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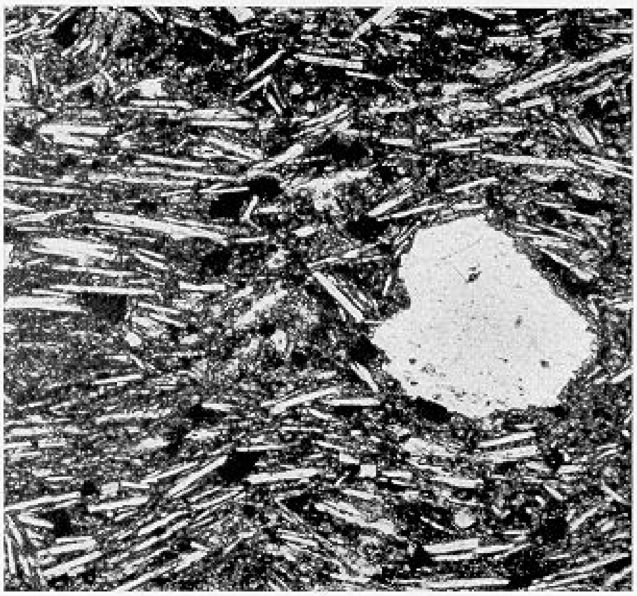

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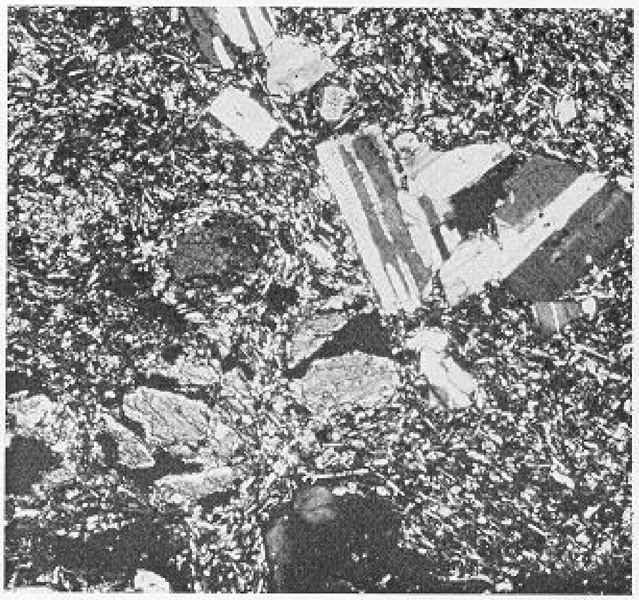

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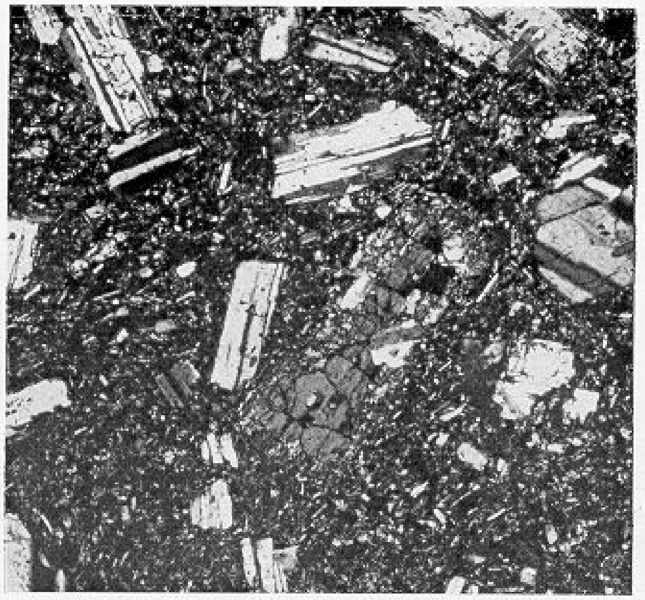

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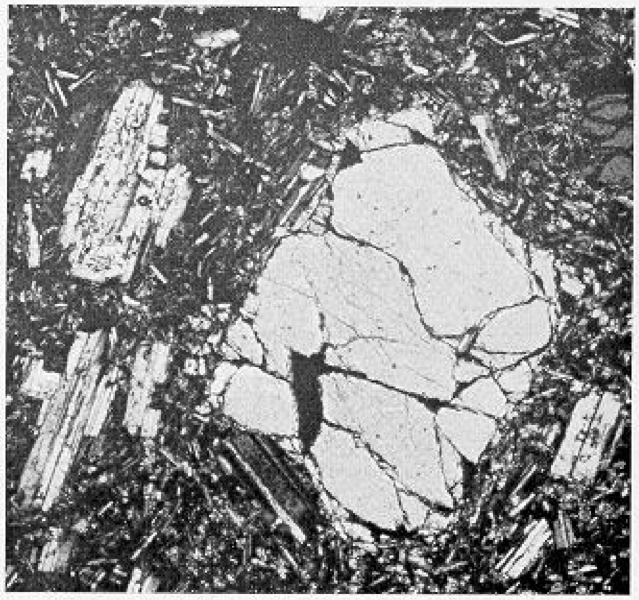

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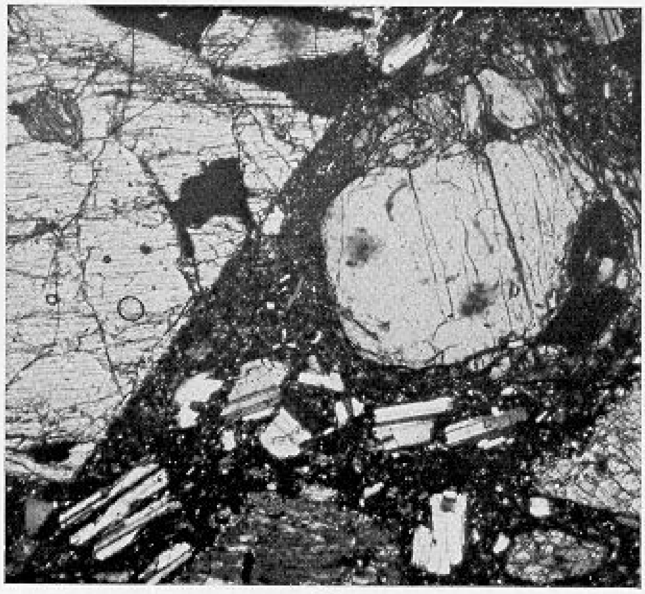

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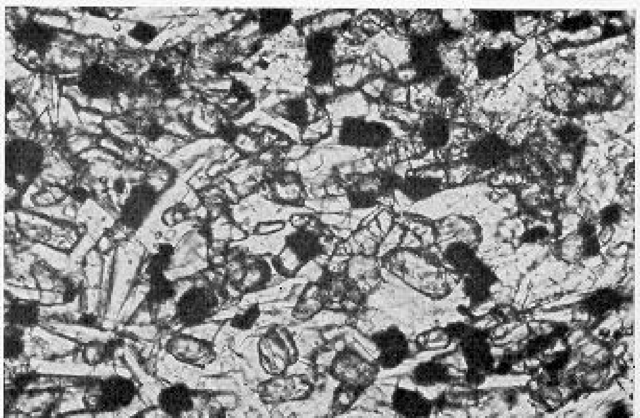

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PLATE II

a. Porphyritic basalt, south-central Vindication Island, east of Pothole Gulch. Plagioclase and olivine phenocrysts (some with a reaction corona) in a matrix of plagioclase, ortho- and clinopyroxene, and opaque oxides (SSV.16.2; X-nicols; ×35).

b. Porphyritic basalt, west side of Vindication Island, south-south-east of Splinter Crag. Phenocryst of orthopyroxene enclosed by clinopyroxene. Also shown are plagioclase microphenocrysts. The matrix is plagioclase, ortho- and clinopyroxene, and opaque oxides (SSV.9.1; X-nicols; ×35).

c. Porphyritic basalt from Blackstone Plain, Saunders Island. Olivine phenocrysts and plagioclase microphenocrysts in a matrix of clinopyroxene, plagioclase and opaque oxides (SSS.10.1; X-nicols; ×35).

d. Oceanite from Mathias Point, Montagu Island. Large diopsidic augite phenocrysts together with olivine phenocrysts and smaller plagioclases in a matrix which is dominantly plagioclase and clinopyroxene (SSM.5.2; X-nicols; ×35).

e. Matrix of a plagioclase-phyric basaltic andesite, north wall of crater, Bellingshausen Island. Composed of plagioclase, granular Ca-poor augite and opaque oxides. An analysis of the pyroxene is given in Table VI (SSB.17.2; ordinary light; ×250).

f. Aphyric dacite from the lava flow forming Reef Point, Cook Island. Plagioclase microlites and opaque oxide grains, with occasional pyroxenes, in a pale brown glassy base. The patchiness is due to partial devitrification (SSK.1.3; ordinary light; ×250).