FALKLAND ISLANDS DEPENDENCIES SURVEY

SCIENTIFIC REPORTS

No. 34

THE PETROLOGY OF ANVERS ISLAND AND ADJACENT ISLANDS

By

P. R. HOOPER, B.Sc., Ph.D.

Falkland Islands Dependencies Survey
and
Department of Geology, University of Birmingham

LONDON: PUBLISHED FOR THE COLONIAL OFFICE
BY HER MAJESTY'S STATIONERY OFFICE: 1962

THE PETROLOGY OF ANVERS ISLAND AND ADJACENT ISLANDS

By

PETER R. HOOPER, B.Sc., Ph.D.

Falkland Islands Dependencies Survey
and
*Department of Geology, University of Birmingham**

(Manuscript received 22nd July, 1960)

ABSTRACT

THE petrology of Anvers, Wiencke and Doumer Islands and the Wauwermans, Outcast and Joubin Islands is described.

Upper Jurassic volcanics of andesitic composition crop out on Wiencke Island, the Outcast and Joubin Islands and on islands off the north-west coast of Anvers Island. On Wiencke Island the succession is nearly horizontal, over 4,000 ft. thick and intruded by coarse Andean rocks along faulted contacts. The faults form a block system of deep channels parallel to and perpendicular to the Graham Land axis. They are probably responsible for the present elevation of Graham Land and may have been initiated during the final stages of the intrusion.

On the Outcast Islands the succession is compressed at right angles to the vertical contact with Andean tonalite. The metamorphic aureole is divided into structural/petrological zones in which most of the rocks are altered to the amphibolite facies. A pyroxene-hornfels occurs close to the contact but further examples of this facies are obscured by retrograde metamorphism associated with contact faulting.

On the Joubin Islands the Upper Jurassic Volcanics are not only contact metamorphosed adjacent to Andean tonalite, but also metasomatized in areas adjacent to the Cape Monaco Granite. The metasomatized rocks have a rhyolitic composition and a low temperature mineral assemblage (quartz, albite, epidote, chlorite). Analyses for alkalis on four specimens indicate an irregular distribution of Na_2O and K_2O and one complete analysis shows nearly 80 per cent of silica in a rock still carrying andesine phenocrysts. Associated with the metasomatized volcanics is at least one band of cordierite/andalusite-bearing rock presumably of sedimentary origin.

Rocks which acquired their most obvious features during Andean (late Cretaceous to early Tertiary) times include the Andean Intrusive Suite and associated hybrid rocks, the Cape Monaco Granite and the Altered Assemblage.

The Andean Intrusive Suite and associated hybrid rocks, ranging from anorthite-gabbro to granodiorite, form the greater part of the Anvers Island area. The only primary rocks recognized are gabbros and tonalites which are comparable to the Andean Intrusive Suite of Graham Land. For the remainder a hybrid origin is deduced from their lack of primary structures, their marked and irregular variations in texture and composition, their association with large quantities of hybrid aplitic material and their apparent replacement textures. Evidence for considering the granodiorite as representative of a further stage in the hybridization process, involving some remobilization, is discussed.

The Cape Monaco Granite forms an elongate structureless mass of variable granite with indistinct contacts along the north-west coast of Anvers Island, parallel to the Graham Land axis. Variation in the type area is from "porphyritic" granodiorite to an equigranular alkali-granite, and textural evidence suggests, first, that the alkali-granite developed from the granodiorite by the growth of quartz and alkali-feldspars to the detriment of earlier andesine and, secondly, that the earlier quartz and andesine "phenocrysts", identical to porphyroblasts developed in inclusions, are also of metasomatic origin.

The principal rock types of the Altered Assemblage, which crops out between Cape Monaco and Arthur Harbour, are the dioritic rock, the trondhjemitic rock, the feldspar rock and the trondhjemitic porphyry. The first two form the greater part of the assemblage and the field and microscope evidence

* Now at Department of Geology, University College of Swansea, Swansea.

suggest they are the metasomatized equivalents of Upper Jurassic Volcanics and Andean tonalites respectively. The remaining two rock types occur in smaller areas of more intense metasomatism. The gradual transition from dioritic rock to trondhjemitic porphyry is described. Transitional types indicate plastic flow and the final porphyry forms a sharp-sided vein.

Eight new chemical analyses of the Andean rocks are presented. Plotted on triangular diagrams these show significantly higher Na_2O/K_2O ratios than the Andean Intrusive Suite of Graham Land, particularly among the acid members. It is argued that this evidence supports the theory developed from the field and microscope work, that much of the area suffered silica/alkali metasomatism in late Andean times, that many of the intermediate rocks were hybridized in this way and that the Altered Assemblage represents an early stage in the process which culminated in the formation of the Cape Monaco Granite.

Post-Andean basaltic volcanics, which form a 4,000 ft. succession in the north-eastern corner of Anvers Island, are briefly described and tentatively correlated with the Miocene-Recent volcanics of the South Shetland Islands.

CONTENTS

		PAGE
I.	Introduction	3
	A. Physiography	3
	B. Stratigraphy	5
II.	The Upper Jurassic Volcanics	6
	A. Wiencke Island	6
	1. North Wiencke Island	6
	2. South Wiencke Island	8
	3. Summary	9
	B. The Outcast Islands	10
	Tonalite Veins	15
	Summary	15
	C. The Joubin Islands	16
	1. Thermally Metamorphosed Volcanics	16
	2. Metasomatized Volcanics	20
	3. Thermally Metamorphosed and Metasomatized Volcanics	23
	4. Summary	26
III.	The Andean Intrusive Suite and Associated Hybrid Rocks	27
	A. Primary Gabbros	27
	B. Primary Tonalites	30
	C. The Hybrid Rocks	31
	1. Doumer Island	31
	2. Fang Buttress	31
	3. Ridge below Green Spur	32
	4. The Wauwermans Islands	34
	D. Granodiorites	34
	E. Inclusions	35
	F. Discussion	37
IV.	Metasomatized Mylonites	39
V.	Metasomatized Tonalites	41
VI.	The Cape Monaco Granite	42
	A. Cape Monaco and the Gossler Islands	42
	B. South of Cape Monaco	45
	1. The Joubin Islands	45
	2. Wylie Bay	46
	3. Summary	47
	C. North of Cape Monaco	47
	1. Contact Phenomena between Cape Monaco and Gerlache Island	47
	2. Peninsula opposite Gerlache Island	48
	3. Between Hamburg and Perrier Bays	49
	4. Cape Bayle	49
	D. Discussion	49
VII.	The Altered Assemblage	50
	A. The Principal Rock Types	50
	1. The Dioritic Rock	50
	2. The Trondhjemitic Rock	52
	3. The Trondhjemitic Porphyry	52
	4. The Feldspar Rock	52
	5. The Volcanic Rocks	54
	B. Field Relations	54
	1. Janus Island	54
	2. Norsel Point	55
	3. Wylie Bay	56
	C. Discussion	57
VIII.	The Geochemistry of the Andean Rocks	58
	The Metasomatic Process	62
IX.	The Post-Andean Volcanics	63
	A. Petrology	64
	B. Discussion	65
X.	The Geological History of Anvers Island and its Relation to Graham Land	66
XI.	Acknowledgements	68
XII.	References	68

I. INTRODUCTION

ANVERS ISLAND lies off the north-west coast of Graham Land between latitudes 64° and 65°S. and longitudes 62° 30′ and 64° 30′W. The largest and most southerly member of the Palmer Archipelago, it is rectangular in shape, approximately forty miles long in a north-east/south-west direction and thirty miles wide, covering an area of nearly 1,000 square miles.

With the discovery of Graham Land in 1820 the broken north-west coastline became familiar to sealers in the following decades but it was not until 1897 that scientific exploration began (Adie, 1957*a*). In that year de Gerlache explored the area in his ship *Belgica* and the expedition's geologist, Arçtowski, made valuable glaciological observations and the first systematic rock collection (Arçtowski, 1900*a*, *b*, 1901). His specimens were later described, with chemical analyses, by Pelikan (1909) and Sistek (1912), the former giving the first geological map of the area.

Two expeditions led by Charcot (1903–05 and 1908–10) explored a large part of the west coast of Graham Land. They made landings on Wiencke and Anvers Islands and wintered on Booth Island a few miles to the south. Gourdon (1905, 1906, 1907, 1908, 1917) divided the rocks into two groups: coarse-grained and fine-grained. The former included amphibole-granites, quartz-diorites and uralitized gabbros which he considered a continuous series. He remarked on the mottled appearance of the quartz-diorites and the large number of basic inclusions.

Much of this work was confirmed by Ferguson (1921) in a prospecting expedition which took him to the Danco Coast during 1913 and 1914. Ferguson considered the fine-grained stratified rocks to be of Jurassic age and largely sedimentary but Tyrrell (1921), describing the petrology of Ferguson's specimens, emphasized the great preponderance of volcanic rocks. He did, however, describe a mudstone from the northern end of Wiencke Island.

In 1927 Holtedahl visited the area with the Norwegian Antarctic Expedition. From Port Lockroy he made excursions to Flandres Bay, Victor Hugo Island and the Joubin Islands. In his well-illustrated paper (Holtedahl, 1929), he gives a detailed account of the physiography and geomorphology of the Palmer Archipelago and the Danco Coast.

Specimens collected by Holtedahl were studied by Barth and Holmsen (1939). These included interleaved eucrites and anorthosites from a small islet off Victor Hugo Island, igneous breccias from the Joubin Islands and the Peltier Channel (Fig. 1), and many specimens of quartz-diorite and adamellite. The authors drew attention to the sub-alkalic nature of the quartz-diorite/adamellite suite, to the metasomatism and prehnitization of the breccias and to the large number of basic dykes in the area. They suggested that the rock collection represented a basement area brecciated by downwarping of the crust in orogenesis, followed by partial melting to form a palingenetic magma of quartz-diorite composition which then differentiated by fractional crystallization to adamellite.

Rocks collected from the Melchior Islands (Fig. 1) by the United States Antarctic Service Expedition, 1939–41 have been briefly described by Stewart (1945, 1947) with a number of modal analyses. Others collected from Wiencke Island by Mackintosh during the voyages of R.R.S. *Discovery II* have been described by Tyrrell (1945).

The most recent work on the geology of Graham Land has been presented by Adie (1953, 1954, 1955, 1957*b*). This includes twelve new chemical analyses of the major and trace elements of the Andean Intrusive Suite of Graham Land, which are used to demonstrate a close similarity between these rocks and the calc-alkali volcanic and plutonic suites of North America and Scotland (Nockolds and Allen, 1953). Adie concludes that the Andean rocks of Graham Land represent the differentiated products of one basic magma for which he gives the interpolated composition.

A. PHYSIOGRAPHY

Anvers Island is dominated by the Mount Français massif (9,060 ft.). From this focus the Achæan, Trojan and Osterrieth Ranges trend northwards and eastwards to form a discordant north-east coastline. A fourth range trends south-west from Mount Français to Mount Moberly. Between Mounts Moberly (5,030 ft.) and William (5,250 ft.) a low pass gives access to Hooper Glacier flowing east and William Glacier flowing south into Börgen Bay. The long Iliad Glacier flows north from Mount Français to Lapeyrère Bay between the Achæan and Trojan Ranges.

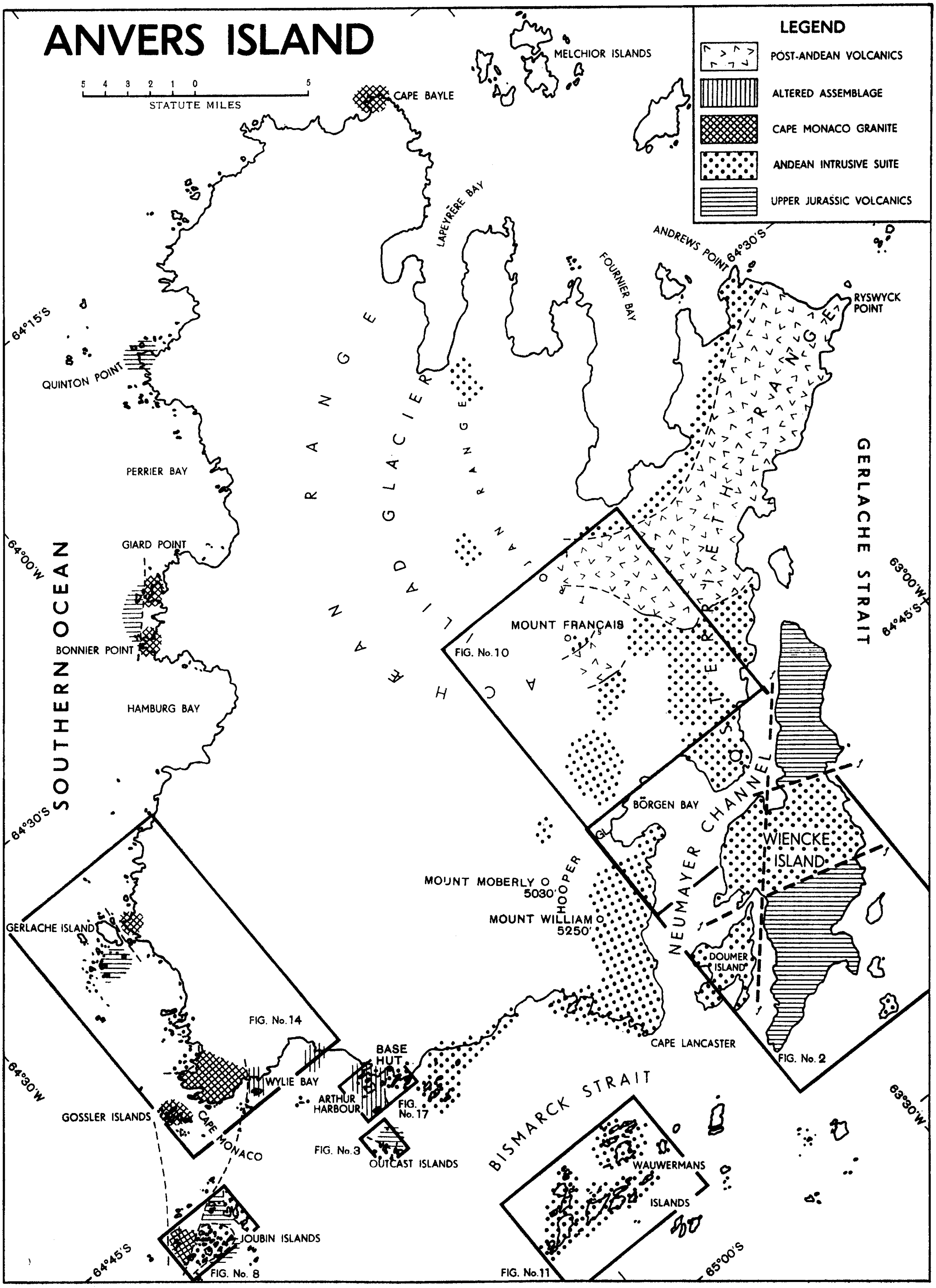


FIGURE 1

Geological map of Anvers Island and adjacent islands. The respective positions and figure numbers of the larger scale geological maps are indicated.

Wiencke Island is separated from the south-east coast of Anvers Island by the narrow Neumayer Channel. A chain of mountains running the length of the island is broken only by the transverse Channel and Thunder Glaciers, which thus divide the island into northern, central and southern parts.

The north-western half of Anvers Island is covered by a comparatively low ice sheet, which slopes gently from 3,000 ft. below Mount Français to the cliffs of the western coasts. Except at the heads of the larger bays, rock is exposed below the ice cliffs all around the island, while some of the larger headlands on the western coasts are ice-free. Innumerable small islands and rocks fringe these outer coasts from Cape Bayle to Cape Lancaster.

In a detailed discussion of the physiography of the Palmer Archipelago and the Danco Coast, Holtedahl (1929, pp. 9–28, 118–22) suggested that the present topography was formed by uplift and denudation of a post-Andean peneplain. The denudation was primarily the work of "strandflat glaciers" and Holtedahl pointed to the broad ice sheets on the western sides of Anvers and Adelaide Islands as mature examples. To explain the more juvenile topography along the straits separating the islands from Graham Land he suggested that until recently the straits had been filled with permanent ice, thus reducing the erosive powers of the glaciers.

Holtedahl compared the many low islands and skerries off the south-west and north-west coasts of Anvers Island to the Norwegian strandflats. He argued that their formation was due primarily to the greater extension of the "strandflat glaciers" in the recent past and that marine erosion was of little significance.

More detailed observations have revealed a platform of hard rock standing approximately 12 ft. above the present mean sea-level. Rock towers standing above this platform are covered with lichens and are well weathered above the 25 ft. mark. Below this they are clean and fresh. On Dream Island, near Cape Monaco, sea-caves have been cut into one such tower and areas of the platform are covered by large rounded boulders (Plate Ib). The platform is wave-cut and a drop in sea-level of approximately 20 ft. is apparent.

Small moraines are a constant feature where the Anvers Island ice sheet terminates on the western peninsulas but they are seldom found more than a hundred yards beyond the present ice front. Similarly, glacial striations occur up to three hundred yards from the ice front but no farther, and they have never been recorded on the offshore islands. It is concluded that the submergence of this area is more recent than the time when, as Holtedahl supposed, it was covered by an enlarged "strandflat glacier". Moreover, marine erosion has had a considerable influence on the present form.

B. Stratigraphy

The general stratigraphy of Anvers Island is summarized in Table I.

Table I

THE STRATIGRAPHY OF ANVERS ISLAND

Miocene to Recent	Volcanics Dykes
Late Cretaceous to Early Tertiary (Andean)	Altered Assemblage Cape Monaco Granite Andean Intrusive Suite and associated hybrids
Upper Jurassic	Dykes Volcanics

II. THE UPPER JURASSIC VOLCANICS

VOLCANIC rocks, intruded and altered by the Andean Intrusive Suite, crop out at three localities in the Anvers Island area: on Wiencke Island, on the Outcast Islands and on the Joubin Islands. They have also been identified at two localities to the west of the Cape Monaco Granite on the north-west coast (Fig. 1).

There is no further direct evidence for the age of the succession but pre-Andean volcanic rocks have been traced down both sides of the Graham Land peninsula. At Hope Bay in the north-east they are known to be of Upper Jurassic age (Andersson, 1906) and in Marguerite Bay in the south-west they are known to be pre-Aptian and post-Middle Jurassic.*

A. WIENCKE ISLAND

Of the exposures in the Anvers Island area, the succession on Wiencke Island is the least disturbed. The volcanic beds dip gently (0–10°) to the south-east but faulting and erosion have reduced the succession to ranges of ragged unscaleable peaks along the northern and southern parts of the island. Large faults separate the Andean intrusions of the central part from the volcanics (Fig. 2).

The succession has a minimum thickness of over 4,000 ft., rising unbroken from the Peltier Channel to the top of Luigi di Savoia Peak (4,640 ft.). No systematic study of the succession has been made. The author paid brief visits to the lower areas along the Peltier Channel and to the north-west ridges of Luigi di Savoia Peak, but for the northern parts he has had to rely on a well-controlled collection made by personnel from Port Lockroy in 1948.

1. *North Wiencke Island*

Six specimens collected to the east and north-east of Nipple and Nemo Peaks (Fig. 2), at altitudes ranging from 500 to 1,200 ft., have been examined microscopically. Three are recognized as highly altered andesites and one is probably an andesitic tuff. The two remaining specimens have been crushed prior to a chemical alteration, but where primary relics can be distinguished they are of volcanic origin.

In all three andesites (A.2.1, A.4.1, A.4A.2†) the only primary mineral remaining is plagioclase. With a composition between acid andesine and oligoclase it shows considerable alteration to epidote and sericite, and may occur either as phenocrysts (1.0 to 4.0 mm.) or as small laths in the groundmass. Occasional patches of calcite and iron ore can be recognized as pseudomorphs after small pyroxene phenocrysts.

The groundmass is largely cryptocrystalline and only secondary minerals can be discerned beyond the considerable quantities of iron ore. These form well over 50 per cent of most specimens. Most abundant is calcite, forming crystals of all sizes. Epidote, often subhedral, is equally abundant in some rocks but totally absent in others. Chlorite (nearly isotropic, with deep purple-brown interference colours) is also plentiful and in some cases appears to form most of the fine groundmass. Small but abundant ragged areas of a brown material with very high relief are probably aggregates of sphene. Vesicles are common, containing calcite, euhedral crystals of epidote, quartz and at least two varieties of zeolite, one length fast with a small extinction angle (? stilbite) and the other thomsonite.

The matrix of the altered tuff (A.3.3) is now represented by a brown-grey featureless material rich in epidote. Embedded in this are less altered fragments of andesite and andesine-oligoclase crystals, while plagioclase laths are occasionally visible. Large elongated patches, carrying both epidote and chlorite, are composed mainly of semi-radiating fibres of stilbite.

Crushed or sheared rocks are abundant in the specimens collected from the northern part of Wiencke Island.

A.4A.1 is an epidote-quartz rock with very little iron ore and calcite. Approximately 70 per cent of the rock is epidote. Secondary alteration is so extreme that no relics of the original rock remain and there are few signs of the subsequent crushing.

In the hand specimen A.4A.4 is a patchy red-purple rock which has been severely sheared. The red patches are jasper and grade into the purple substance. Under the microscope the latter is almost opaque,

* Personal communication from Dr. R. J. Adie.

† Numbers in brackets refer to the Falkland Islands Dependencies Survey geological collection which is housed in the Department of Geology, University of Birmingham.

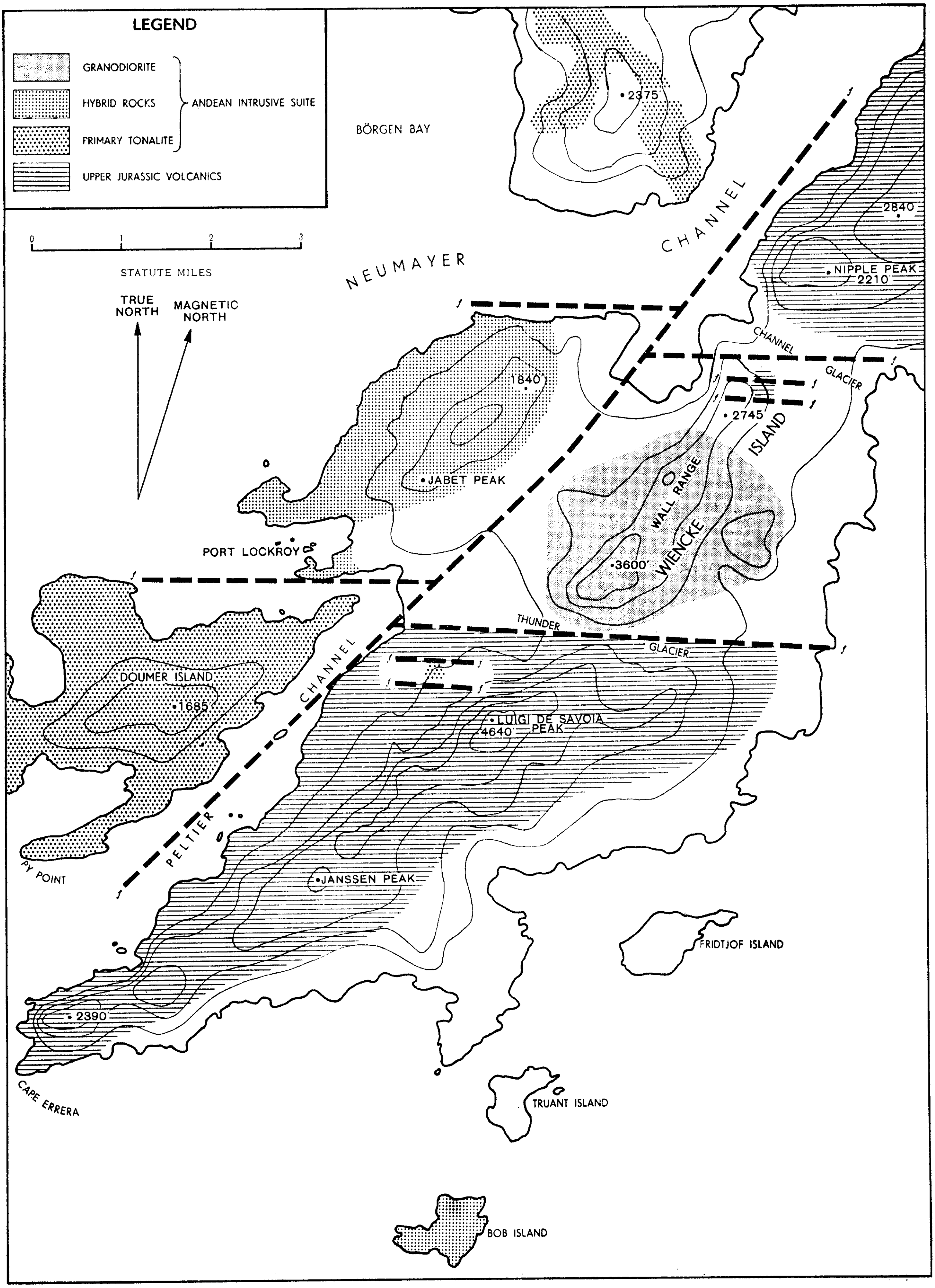


FIGURE 2
Geological map of Wiencke and Doumer Islands.

transmitting red light only along its margins. It forms the greater part of the rock, streaked around variable patches of anisotropic material, in some of which plagioclase laths can be recognized. The purple substance is probably a chalcedony-ore mixture, richer in iron ore than the normal jasper, formed by the introduction of iron and silica to the mylonitized rock.

Station A.5 is situated on the southern side of Channel Glacier. In the four sectioned specimens from this station the progressive effects of shearing, mylonitization and subsequent chemical alteration can be followed.

The physical forces have created fault breccias in which the less altered fragments are surrounded by zones and "veins" of highly mylonitized material. The fragments show a partial recrystallization of the quartzo-feldspathic groundmass into very small irregular crystals and a considerable increase in iron ore as small grains. These effects tend to obscure the primary laths of plagioclase. Andesine phenocrysts are severely cracked and pyroxene phenocrysts, when present, have been replaced by epidote and iron ore with a margin of chalcedony-ore. Large crystals of epidote may form in the matrix and narrow quartz veins, again rimmed by the semi-opaque chalcedony-ore material, penetrate the fragments and are displaced by narrow "veins" of mylonite.

The highly mylonitized zones are very similar to the sheared rock A.4A.4 (p. 6). Almost opaque chalcedony-ore material forms most of the rock, streaming around elongated patches of both the volcanic material and patches of quartz mosaic associated with sericite and grains of epidote.

In specimen A.5.7 a quartz-porphyry has entered between the angular volcanic fragments. The large quartz crystals are occasionally subhedral and enclose patches of the groundmass. Areas of sericite represent crystals of plagioclase. The matrix is very fine-grained and similar to that of the altered volcanics. This rock shows similarities to the metasomatic veins of the Altered Assemblage which are discussed further on p. 52.

2. *South Wiencke Island*

Two specimens from the Sierra du Fief have been examined microscopically. One (A.17.1) is an even-textured andesite, and the other (A.17.4) is a highly altered tuff. Both have suffered hydrothermal alteration with the formation of calcite, sericite and secondary iron ore.

Along the north-east side of the Sierra du Fief and the shores of the Peltier Channel the andesites and andesitic tuffs are contact metamorphosed, being hard, compact rocks unaffected by hydrothermal alteration.

A specimen from Priest Island (A.16.1) in the Peltier Channel is a coarse hornblende-andesine-hornfels. A recrystallized lithic tuff from the north-west spur of Luigi di Savoia Peak is cut by a coarse tonalitic vein composed of andesine, quartz and biotite (N.211.1). The quartz and biotite have formed along the margins of the vein. Patches of similar material associated with flakes of muscovite in the neighbouring rock indicate a considerable introduction from the vein.

On a small exposure on the Wiencke Island shore opposite Py Point hard recrystallized volcanics are cut by numerous dykes of almost identical appearance and composition, and by coarser angular veins of tonalite (N.208.1–4). The volcanics and associated dykes are recrystallized hornblende-andesites. The hornblende (α' = pale yellow, γ' = pale blue-green) occurs as ragged to acicular crystals which penetrate both the labradorite-andesine phenocrysts and the andesine laths of the groundmass. Also, they appear to have replaced an earlier ferromagnesian mineral with the liberation of iron ore. Veins composed almost entirely of this mineral cross specimen N.208.1. Concentrations of tiny ore grains have formed in the phenocrysts. One of the dykes (N.208.4) is slightly more acid than the rest. It contains a few quartz phenocrysts in addition to those of andesine, while in the groundmass biotite is prominent together with more quartz.

The tonalite veins consist of rather large tabular to equant crystals of medium andesine with slightly more sodic rims and interstitial groups of smaller plagioclase, quartz, hornblende, biotite and iron ore crystals. The hornblende has similar properties to that in the andesite.

A group of skerries in the Peltier Channel, south of Priest Island and close to the Wiencke Island shore, are brecciated with a considerable development of sericite. The specimen sectioned (N.100.3) is a coarsely porphyritic basic andesite or basalt. The matrix is of chlorite in one part of the slide and of chalcedony-ore material in the other. The plagioclase phenocrysts show some shattering and a coarse alteration to chlorite and iron ore. These rocks may be compared with the shattered rocks formed by faulting in Channel Glacier.

3. *Summary*

The great majority of rocks examined from the northern and southern parts of Wiencke Island are andesitic. Porphyritic and non-porphyritic types are approximately equal in quantity, and there is a marked predominance of andesine phenocrysts over those of pyroxene when these can be identified from their pseudomorphs.

A basic porphyritic andesite with acid labradorite phenocrysts occurs in the Peltier Channel, probably the lowest exposure in the volcanic succession. The only other variant is a dacitic dyke cutting andesites

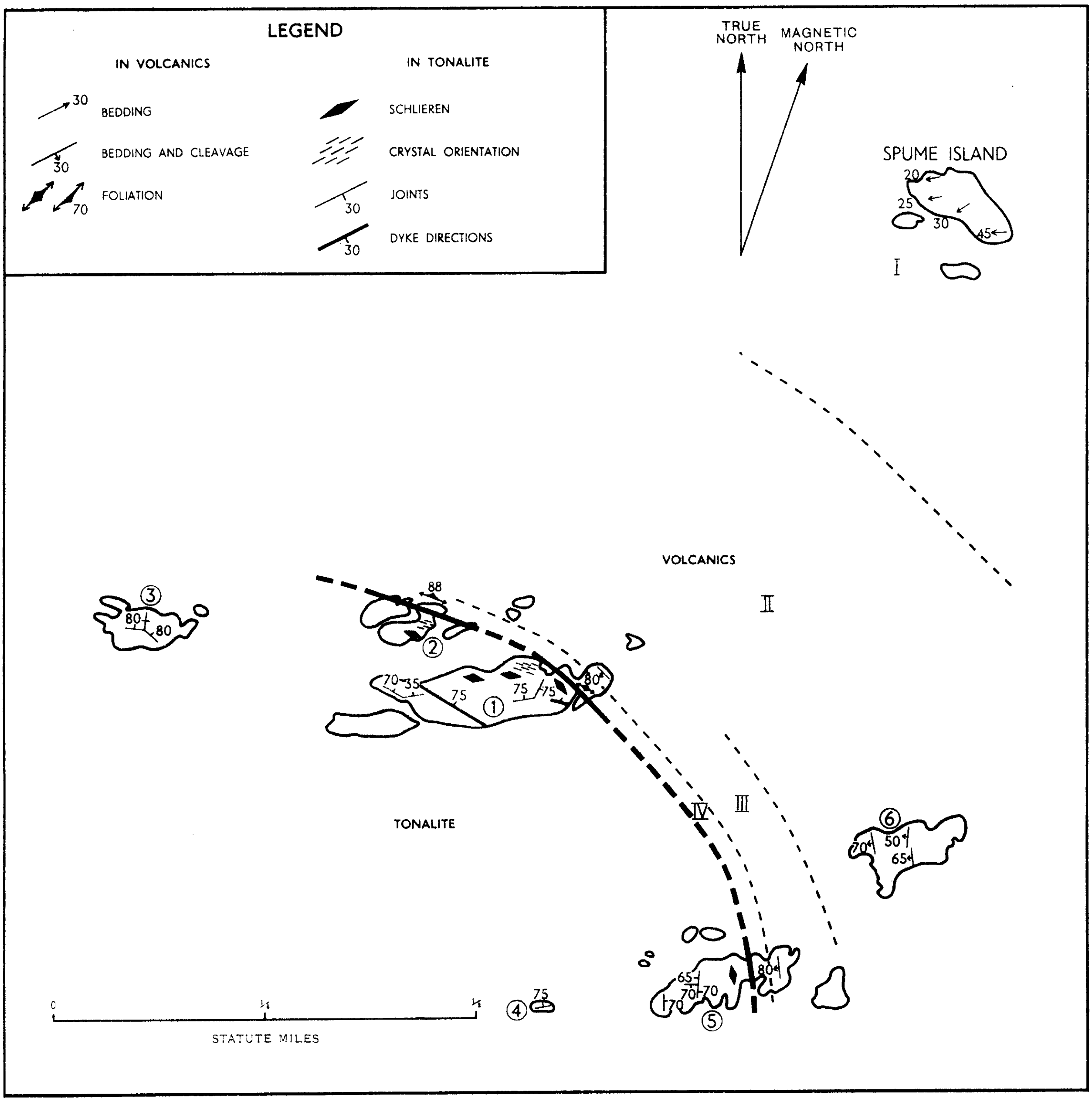


FIGURE 3
Geological map of the Outcast Islands.

low in the series. This dyke may well be associated with extrusion higher in the succession. What little evidence is available is thus in accord with the normal basic to acid order of extrusion.

The andesites have undergone three types of alteration, all associated with the Andean intrusions:

i. Contact metamorphism, which may be compared with the more complete study of this effect made on the Outcast Islands (see below).

ii. Brecciation and mylonitization caused by severe faulting along the intrusive contacts. This probably lowered the volcanics in relation to the intrusions.

iii. Hydrothermal alteration, associated with the final phases of the intrusions, has been concentrated in the crushed rocks of the faulted contacts.

It follows that the faults, which are later than the main phase of the intrusion, are earlier than the hydrothermal activity which must be associated with the final phases of the intrusion.

B. The Outcast Islands

The Outcast Islands form a small group of seven members and their satellites 3¼ miles off the south coast of Anvers Island, south-west from Arthur Harbour (Fig. 1). The islands are well scattered but almost free of permanent ice.

Bedded volcanic tuffs form those islands to the north-east and tonalite those to the south-west. The vertical contact cuts across the north-eastern tips of island (*2*), island (*1*) and island (*5*) (Fig. 3). All the volcanics exposed have suffered some degree of metamorphism. The structural pattern of the alteration and the general increase in its intensity towards the contact indicate that the intrusion of the tonalite was responsible for all these effects.

Structural and petrological changes involved in the progressive increase in metamorphism towards the contact are correlated in Fig. 4 and Table II. The section (Fig. 4) has been composed by piecing together the evidence from the individual islands. For descriptive purposes six structural-petrological zones are recognized from the least altered rocks on Spume Island (Zone I) to the rocks forming schlieren within the granite along the contact (Zone VI).

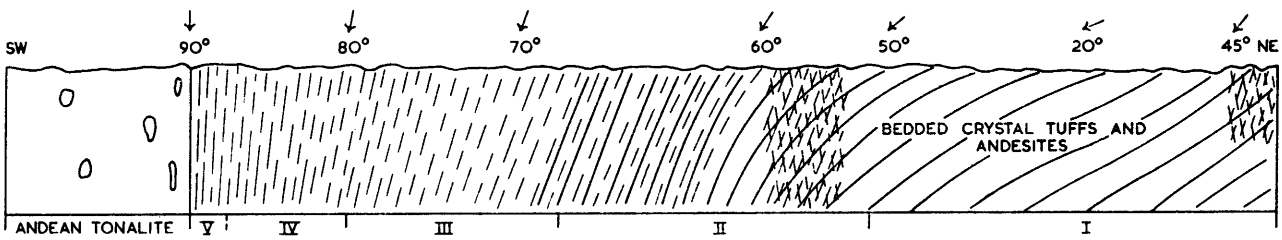


FIGURE 4

Diagrammatic section through the Outcast Islands perpendicular to the tonalite/volcanics contact. The length of the section is ¾ mile; close to the contact the scale is exaggerated and away from it correspondingly reduces (see Table II).

Zone I. Rocks of this zone show the lowest grades of metamorphism in the group. Those from the central and eastern parts of Spume Island are considered typical.

Beds of volcanic tuffs and breccias with occasional andesites have a gentle undulating dip of between 20° and 45° to the west (Fig. 3). Despite considerable recrystallization of the rocks many primary depositional structures are still visible. The variable size and angularity of the fragments is apparent and larger blocks can be seen to have penetrated into the finer tuffs below (Fig. 5). Where the dip of the bed approaches 45°, as on the most easterly tip of the island, intricate shattering occurs along two or three planes striking approximately 20° on either side of the bedding strike and are either vertical or dip steeply to the west. This structure is better illustrated in Zone II (Fig. 6), where it can be shown that fractional movement along each shatter plane has the cumulative effect of increasing the dip of the beds.

TABLE II

STRUCTURAL-PETROLOGICAL ZONES IN THE CONTACT METAMORPHOSED VOLCANICS OF THE OUTCAST ISLANDS

(SEE FIG. 4)

ZONES			V	IV	III	II	I
Induced structures			Strong foliation Granitic veining		Strong cleavage with faint lineation	Cleavage parallel to bedding (*No fracture cleavage*) ⋮ Fracture cleavage	Gently folded succession, dipping towards contact, and occasional fracture cleavage when dip reaches 45°
PETROLOGY	Crystal Tuffs	*Relict structures*	None		Relict crystal fragments from original tuffs (andesine)		Relict crystal fragments (andesine) from original tuffs and also relict laths of plagioclase in matrix
PETROLOGY	Crystal Tuffs	*General petrology and veins*	Quartz-plagioclase-hedenbergite-hornfels	Coarse quartz-andesine-hornblende-hornfels	Schistose quartz-andesine-hornblende-biotite-hornfels. Medium to coarse (i) vague quartz veins (ii) later plagioclase-ilmenite-hornblende-epidote veins	Quartz-plagioclase-biotite-anthophyllite (cummingtonite) rock	Hardened crystal tuffs with variable, fine matrix, through which has developed acicular hornblende. Quartz veins associated with pyrite and biotite
PETROLOGY	Crystal Tuffs	*Amphiboles*	Quartz-plagioclase-hedenbergite-hornfels	Equant crystals α' = yellow γ' = olive-green	Ragged crystals α' = yellow γ' = bluish green, going to pale blue in veins	Colourless needles of Ca-free amphibole	Acicular pale green hornblende
PETROLOGY	Andesites		Quartz-plagioclase-hedenbergite-hornfels	Coarse andesine-hornblende-hornfels	?	?	Sericitization of plagioclase. Primary green hornblende ragged crystals of blue-green variety. Epidote veinlets and pyrite
Sections used			N.253.5	N.242.1, 2	N.245.1, N.247.1	N.256.1, N.257.1	N.248.2, N.251.1, N.252.1

Three specimens from this zone have been sectioned. Two are altered andesitic tuffs and the third is an altered andesite. In the tuffs (N.251.1, N.252.1) both the large crystal fragments of basic andesine and the plagioclase laths of the groundmass remain as relics, although showing marginal resorption by the fine recrystallized matrix. The matrix is of plagioclase or plagioclase and quartz, penetrated by a felted mass of acicular hornblende crystals of random orientation (pale green colour, $\gamma{:}c = 18°$) (Plate IVa).

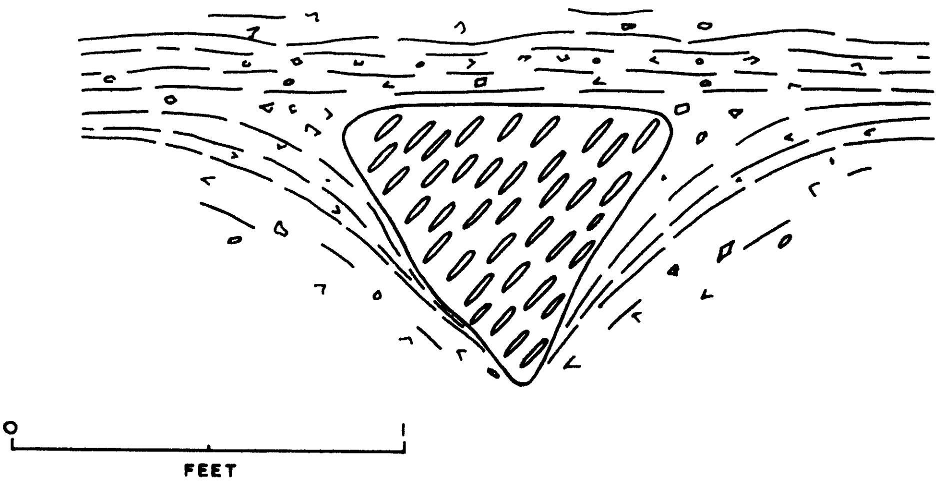


FIGURE 5

Field sketch of a large volcanic fragment which has fallen into and penetrated beds of finer tuff, Zone I, Spume Island, Outcast Islands.

The altered andesite (N.248.2) is comparatively coarse with anhedral laths of plagioclase (medium andesine with slight normal zoning) between 0.5 and 0.7 mm. long, which are surrounded and crudely penetrated by ragged crystals of an actinolitic hornblende (α' = pale straw, γ' = blue-green) and a few small grains of iron ore. The plagioclase is partially altered to sericite. The ragged outline of the hornblende suggests that it has replaced an earlier ferromagnesian mineral. That the change was from a primary to a secondary hornblende is indicated where subhedral hornblende crystals of slightly different pleochroism (α' = pale yellow, γ' = green) can be recognized inside the larger irregular crystals of blue-green material. A large crystal of pyrite, surrounded by a concentration of the actinolitic hornblende, and an epidote vein emphasize the presence of a mobile phase during the alteration.

A wide zone on the western end of the island has a deep iron stain and, although bedding can still be discerned here and there, large lenses of secondary quartzite occur and mica is developed extensively along joint planes. In general the rocks are more altered than elsewhere on the island.

Apart from rare crystals of interstitial chlorite the quartzite is almost pure (N.249.1). The tuffaceous material is completely recrystallized into a very fine hornfels in which much larger crystals of biotite have developed (N.249.1, N.249.3). Muscovite, probably replacing plagioclase, is common in patches and specimen N.249.3 is crossed by veins of quartz, biotite and plagioclase.

These rocks possibly represent a fault zone formed during the initial intrusion and along which the hydrothermal solutions had easier access during the final stages.

Zone II. Rocks belonging to Zone II occur on island (*6*). The volcanic beds dip west towards the contact at angles between 50° and 70°. Where the dip is nearer 50°, as in the central and eastern parts, a system of nearly vertical shatter planes is developed (Fig. 6), but on the south-west of the island, where the dip is 60–65°, the shatter planes are absent and their place is taken by a strong cleavage developed in the bedding plane. On the extreme west tip bedding cannot be recognized and the cleavage dips at 70° towards the contact. Here the rocks are approaching Zone III.

The main shatter planes on both Spume Island and island (*6*) lie at an angle of 40° to each other. These are believed to be fracture cleavages formed by compression at right angles to the tonalite contact.

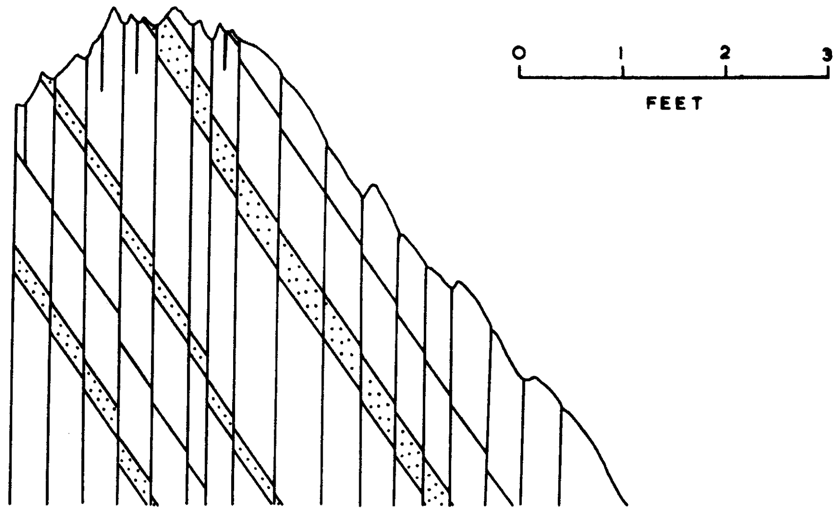


FIGURE 6

Field sketch of shatter cleavage cutting bedding planes, Zone II, island (*6*), Outcast Islands. Movement along the cleavage planes has increased the dip of the beds.

The three axes of stress can be plotted stereographically (Fig. 7). It will be noticed that the plane bisecting each cleavage pair is common to both islands and that this plane is approximately parallel to the plane of the tonalite/volcanics contact. Its strike is within a few degrees of the average strike of the bedding

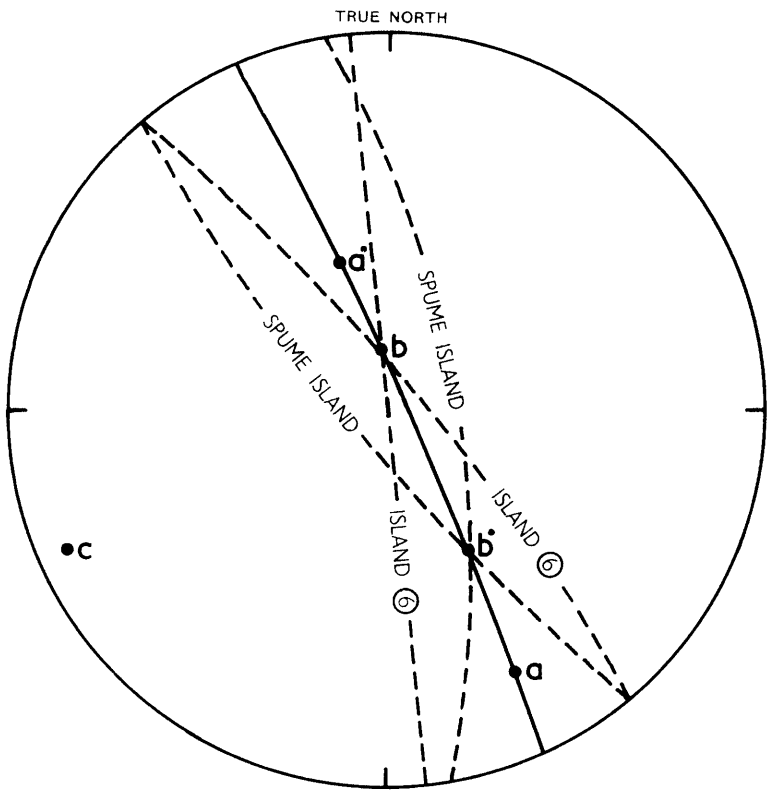


FIGURE 7

Stereographic representation of shatter cleavage on island (*6*) and Spume Island, Outcast Islands. The plane a• bb• a bisects the cleavage pairs from both islands. It is also parallel to the volcanics/tonalite contact and to the strike of the folds on the two islands. c is the pole of this plane and represents the axis of maximum stress. a and a• represent the axes of minimum stress, while b and b• represent the axes of intermediate stress on the respective islands.

(identical for both islands, i.e. 160° mag.). The pole of this plane (c) represents the axis of maximum stress which must have been constant over the whole area, causing not only the fracture cleavage but also the folds, the strong cleavage and the foliation which occur closer to the contact.

The axis of minimum stress (a) along which relief was achieved varies from one locality to another. On Spume Island it plunges 45° south, while on island *(6)* it plunges 15° north. Yet on island *(6)* the vertical component of this essentially horizontal relief was quite considerable. This is illustrated in Fig. 6 where slight movement on every plane has had the cumulative effect of increasing the dip. Unfortunately the horizontal component was never observed. Nearer the contact in Zone III a faint nearly vertical lineation is present within the cleavage plane, indicating that here the maximum relief was achieved upwards.

Where the dip of the beds has increased to 60–65° fracture cleavage is absent but a strong cleavage is developed parallel to the bedding. It is evident that at this critical angle (60°) relief was met more easily along this single plane of weakness.

Two specimens from this zone have been examined under the microscope. They are recrystallized tuffs with large relic crystal fragments of andesine in a recrystallized groundmass of quartz and plagioclase with biotite and cummingtonite (colourless; $2V\gamma$ medium to large; $\gamma{:}c = 20°$) in one section (N.256.1), and anthophyllite ($2V\gamma = 84° \pm 3°$; $\alpha = 1.653 \pm 0.004$, $\gamma = 1.676 \pm 0.002$) in the other (N.257.1). The andesine relics (0.5 to 2.0 mm.) contain blebs of quartz, specks of biotite and grains of iron ore, and only rarely show albite twinning. The calcium-free amphiboles occur as short needles without orientation and the cummingtonite appears to be concentrated in vague veins across the thin section. The anthophyllite rock is somewhat richer in quartz than the other, being cut by irregular quartz veins and containing lenses of fairly coarse quartzite (Plate IVb).

Zone III. This zone is exposed on the extreme north-east tips of islands *(1)* and *(5)*. It is distinguished from Zone II by its stronger cleavage with a steeper dip (70–80°), the lack of obvious bedding planes and an indistinct, nearly vertical, lineation. From Zone IV it is distinguished by its lack of granite veins which impart to that zone a coarse foliation.

Both sectioned specimens (N.245.1, N.247.1) are quartz-andesine-hornblende-biotite-hornfelses, the biotite forming a strong schistosity parallel to the cleavage plane. The hornblende is pleochroic (α' = pale yellow, γ' = blue-green), forming ragged crystals similar in size to the rest of the hornfels (approx. 0.1 mm.) but lacking sharp outlines.

N.245.1 is from a distinct band of coarse material lying in the plane of cleavage. Large andesine crystals, relics from the original tuff, are partially replaced by small crystals of hornblende, plagioclase and quartz, and the schistosity of the groundmass swings around their margins.

N.247.1 shows considerable segregation into bands which may be due to original bedding or to metamorphic differentiation. Narrow veins of quartz lie parallel to the bands and are associated with a concentration of iron ore in minute grains. These veins may represent the early stages of the foliation which is so conspicuous nearer the contact. They suggest an introduction of silica and iron. Later composite veins of plagioclase, ilmenite, hornblende (α' = yellow, γ' = pale blue) and epidote run both parallel to the cleavage and at 45° to it, again illustrating the extensive movement of material that accompanied the alteration.

Zone IV. This zone is exposed most typically on the north-eastern end of island *(1)* where it lies between Zone III and the contact. In most of this area it represents the highest grade of metamorphism reached. Structurally, it is characterized by a coarse foliation dipping towards the contact at between 80° and 90°. Granite dykes and veins are abundant, some cutting across the foliation irregularly at approximately 90°, the majority running parallel to and intensifying the foliation.

Away from the most obvious influence of granite veins the rocks are true quartz-andesine-hornblende-hornfelses, differing from those of Zone III in the absence of biotite, the coarse texture and the tendency for the hornblende (α' = yellow, γ' = olive-green) to form equant crystals with sharp outlines (N.242.1) or to participate in the schistosity by developing elongated crystals (α' = yellow, γ' = blue-green) (N.242.2).

N.242.1 has no schistose structure and the foliation, caused by lens-shaped areas of different mineral composition, is more obvious in the hand specimen than in the thin section. Occasional relics of larger plagioclase crystals can be discerned but they are almost completely resorbed.

N.242.2 is dense and unfoliated in the hand specimen and probably represents a metamorphosed andesite. In thin section a faint schistosity can be seen, owing to the elongation of the hornblende crystals. The feldspar is medium andesine and occasional biotite flakes are present. Approximately 5 per cent of iron ore is present in both specimens.

As granite veins are approached a number of changes occur within the hornfels. The grain-size increases, the hornblende is replaced by brown biotite (the stable ferromagnesian mineral of the veins), and the quartz/plagioclase and the plagioclase/biotite ratios increase.

Zone V. One dark inclusion of quartz-plagioclase-hedenbergite-hornfels, collected from the drawn-out contact rocks on island (*2*), is the sole representative of this zone (N.253.5). It, alone, has reached a higher grade of metamorphism than the amphibolite facies. It is a fine-grained hornfels (grain-size 0.05 mm.) and the hedenbergite (ferrosalite; Hess, 1941, p. 516) ($2V\gamma = 65° \pm 3°$; $\gamma{:}c = 48° \pm 3°$; $\alpha = \beta$ = pale green, γ = pale yellow-green; $\alpha = 1.710 \pm 0.002$, $\gamma = 1.736 \pm 0.002$) forms approximately 30 per cent of the rock. The plagioclase, with a refractive index higher than quartz, forms small porphyroblasts (0.4 mm.). Quartz lenses include tiny specks of high birefringence. A few cracks crossing the slide have epidotized margins. The fresh state of the specimen is in marked contrast to the epidote-actinolite rocks of Zone VI which are typically developed in this area.

Zone VI. Rocks referred to this zone occur along the contact where volcanic schlieren and granitic material are intimately mixed and drawn out in a plane parallel to the contact. Epidote and blue-green actinolitic hornblende are the characteristic minerals.

N.253.6, from island (*2*), is an example. Originally a fine-grained hornfels of quartz and andesine with lenses rich in ferromagnesian minerals, the latter have been altered to ragged epidote crystals with occasional tight sheaves of blue-green actinolitic hornblende. Chlorite and secondary sphene are both present but neither albite nor sericite have been identified.

Such rocks must have been formed by retrograde metamorphism towards the end of the intrusive process, when only the final low temperature fluids were active. They were possibly associated with local movement along the contact zone.

The schlieren from within the tonalite close to the contact are much coarser (N.259.2) with highly altered crystals of medium andesine up to 2.0 mm. long. Secondary actinolitic hornblende (α' = pale yellow, γ' = green-blue) and quartz form the greater part of the rock, the latter enclosing areas of andesine, sericite, biotite and chlorite with sphene.

Tonalite veins

The veins close to the contact are similar to the tonalite (N.254.1, Table VII). Within 5 ft. of the contact (N.241.1) they are composed of approximately 70 per cent andesine with 15 per cent each of quartz and ferromagnesian minerals. The andesine shows discontinuous zoning with occasional reversals (e.g. core An_{42} — An_{50} — An_{32} margin) and slight alteration to sericite. The quartz extinguishes unevenly. Subhedral grains of hornblende (α' = pale yellow, γ' = bright green) are more abundant than the ragged crystals of brown biotite. The iron ore is a titanium-bearing variety associated with sphene. A little secondary epidote is present.

In veins farther from the contact (N.253.1, 3) the quartz increases to approximately 30 per cent, the plagioclase has a margin of oligoclase and the smaller proportion of ferromagnesian minerals consists mainly of biotite altering to chlorite and granular sphene along the cleavage planes. Accessory apatite is present.

Summary

While all the volcanic rocks exposed on the Outcast Islands have suffered some degree of alteration, it is clear that in this area the succession was composed essentially of andesitic crystal tuffs with occasional bands of andesite.

The alteration is due to the intrusion of a large body of tonalite which has compressed the volcanics in a horizontal direction at right angles to the contact, thus inducing a structural pattern on the succession increasing in intensity towards the contact. Petrological changes, caused by an increase of temperature in the presence of emanations from the magma, can be correlated with the structural pattern (Fig. 4; Table II).

From the simple relation of all the structural features of the altered volcanics (folding, cleavage and foliation) to the plane of contact it is concluded that all these features are the result of the tonalite intrusion alone and that prior to that event they were unfolded with little or no dip. This is compatible with the very gently inclined andesites on Wiencke Island (p. 6).

The dip of the bedding and foliation planes into the contact is slightly unusual but it may be explained by assuming a magmatic mass, fed from below, starting as a small lens within a horizontal or gently inclined succession and expanding in three dimensions. Thus the upper beds would sweep up over the mass and the lower beds sweep below. Those on a level with the centre of the intrusion would be turned through 90° parallel to the margins of the expanding body and suffer considerable compression.

For the most part the rocks have been metamorphosed to the amphibolite facies (Zones II, III and IV) (Turner and Verhoogen, 1951). Zone I may be referred to a very low position in the amphibolite facies or, more likely, to the actinolite-epidote-hornfels facies. Only one example of the pyroxene-hornfels facies has been found. Retrograde metamorphism along the contact may have obliterated further examples.

To what extent metasomatism has been responsible for these changes is not clear, but a number of points may be listed which indicate the presence of a mobile phase during the reactions:

i. Pyrite, while seldom abundant, may be found anywhere in these rocks.
ii. Nearly every specimen examined under the microscope is crossed by quartz veins.
iii. One specimen (N.247.1) from Zone III is crossed by veins containing plagioclase, ilmenite, pale blue amphibole and epidote, suggesting that the components of all these minerals were mobile at one stage.
iv. The granitic veins extending in from the contact become very rich in quartz and sometimes in iron ore (e.g. N.253.2).

C. The Joubin Islands

The Joubin Islands are a large group of small, closely packed islands lying approximately five miles south-west of Cape Monaco (Fig. 1). The centre of the group is well sheltered and the quantity of permanent ice is small. Holtedahl visited them in 1928 and collected specimens of "volcanic breccia" described later by Barth and Holmsen (1939, p. 28). The map accompanying Holtedahl's paper is misleading in that two groups of islands are shown lying south of Cape Monaco. In fact there is but one group and Holtedahl's photograph (1929, p. 23) makes it clear that these are the islands referred to in his paper.

Fig. 8 is a geological map embracing the central islands of the group. The Upper Jurassic Volcanics were first disrupted by two tonalite masses of Andean age which pushed the adjacent volcanic beds into a vertical position, altering the contact rocks and marginal screens into compact hornfelses by a combination of thermal metamorphism and local metasomatism.

During the formation of the later Cape Monaco Granite widespread metasomatism was suffered by both the volcanics and the tonalites. Basic dykes both older and younger than the tonalite have been recognized.

In the following description the volcanics have been subdivided into three groups:

1. Those thermally metamorphosed by the primary tonalite.
2. Those metasomatized by the Cape Monaco Granite.
3. Those which have suffered both these alterations in turn.

No volcanic rocks in the area remain unaltered.

1. *Thermally metamorphosed volcanics*

The main tonalite mass forming the central and southern part of the Joubin Islands is discussed later (p. 31). It is a primary tonalite of uniform composition carrying numerous, small, rounded inclusions and cut by both microgranite veins and later basic dykes.

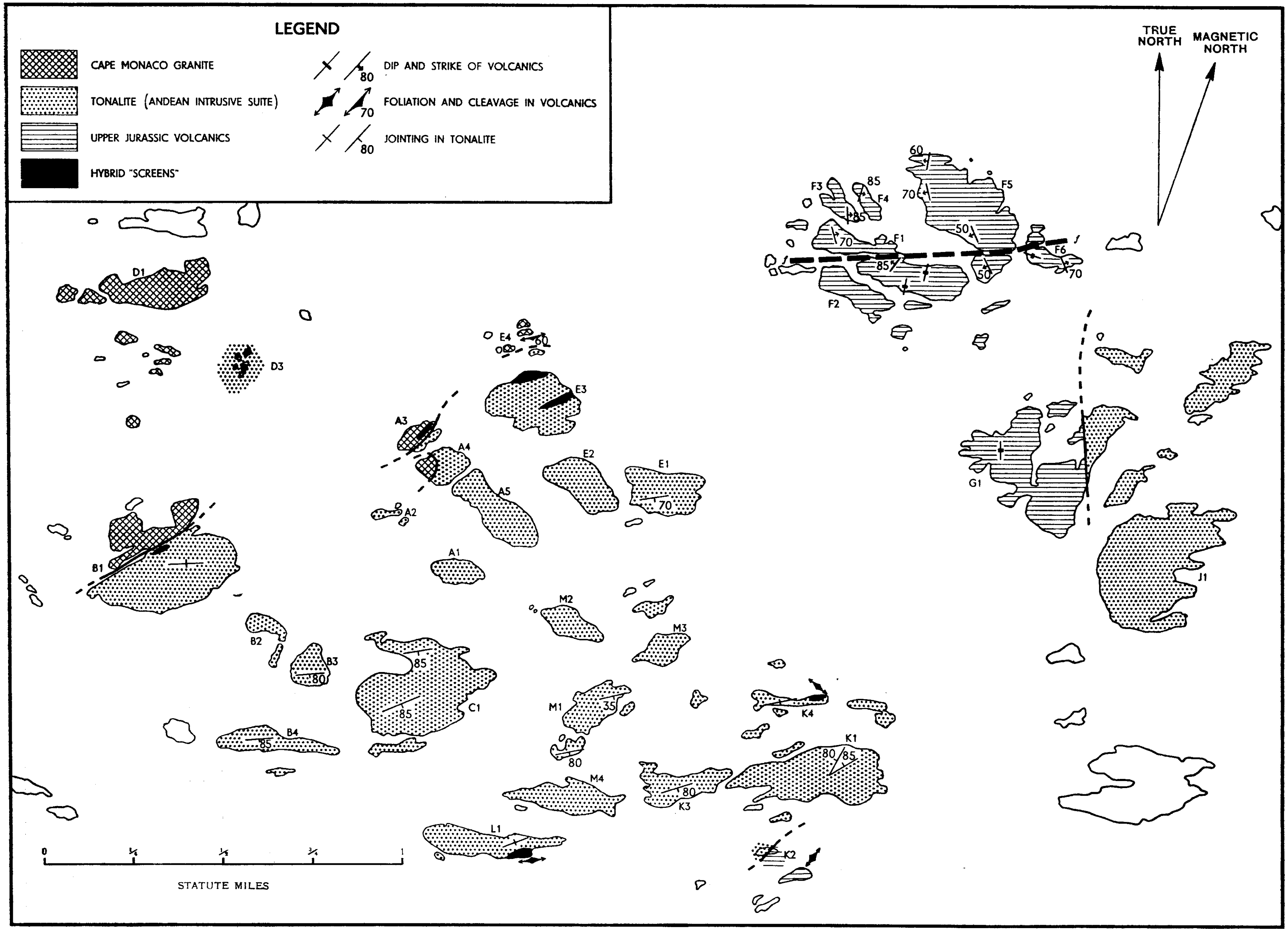


FIGURE 8
Geological map of the Joubin Islands.

To the south-east, on islands *K2*, the vertical contact of the tonalite against the volcanics is exposed. On islands *L1*, *K4*, *E4*, *E3*, *A3* and *B1* (Fig. 8) large screens of volcanic origin are included in the mass. These lie parallel to the tonalite contact and it is probable that a line drawn just outside the screens is a close approximation to the position of the contact. Islands *E4*, *E3*, *A3*, and *B1* also lie along the tonalite/Cape Monaco Granite contact. This coincidence is discussed further on p. 46.

On islands *K2* the contact is well exposed. It is sharp, locally irregular, with a few tonalite apophyses entering along the foliation planes. The tonalite shows no peculiarities other than a slight concentration of its dark rounded inclusions. The volcanics close to the contact are strongly foliated in a vertical plane and 200 yd. away they possess a strong cleavage in the vertical bedding plane which strikes parallel to the contact. No lineation was recorded.

Although they are entirely recrystallized, the coarser structures of tuff and breccia may be recognized in many of the beds. Pre-Andean dykes are pinched out by the foliated volcanics, illustrating the plastic flow suffered by the volcanics and the more resistant nature of the dykes. Numerous granite veins pierce these dykes, originating at the dyke/volcanics margins but failing to penetrate the volcanics.

The hornfelsed volcanics are granoblastic (N.299.1, N.415.1, 3, 4). Bands of different composition and grain-size reproduce the original bedding and the shape of the breccia fragments may be similarly preserved. The average grain-size is approximately 0.1 mm.

Most typical is a quartz-orthoclase-andesine-biotite-hornfels. Quartz is always predominant and the orthoclase, absent in only one specimen (N.415.3), frequently shows a slight porphyroblastic tendency. The latter has $2V\alpha = 66° \pm 3°$. The andesine is rarely twinned and then usually according to the Carlsbad law. Biotite, pleochroic in straw to deep brown, occurs as small flakes with sharp outlines. Poikilitic hornblende which is present in some specimens (N.299.1, N.415.4) encloses blebs of quartz and plagioclase, has sharp outlines and a pleochroic scheme α = pale straw, β = olive-green, γ = blue-green. Iron ore is present in small quantities and frequently associated with leucoxene or sphene. Isolated crystals of sphene have also been recorded (N.415.1).

An irregular veinlet of quartz and orthoclase in one rock (N.299.1) and the apparent replacement of the plagioclase by orthoclase in others suggest that local metasomatism has played some part in the recrystallization of the rocks.

Close to the tonalite contact the rock is a quartz-andesine-biotite-hornfels (N.415.3) without orthoclase. Biotite is partially altered to chlorite and the plagioclase to sericite. Iron ore is more abundant than normal and the rock is cut by a quartz-epidote veinlet.

In the pre-Andean dykes (N.415.2, N.299.2) the ferromagnesian minerals total approximately 40 per cent of the rock. Coarse laths of medium andesine are eaten into by poikiloblastic crystals of hornblende (α' = pale yellow, γ' = blue-green) which have sharp boundaries. A smaller quantity of brown biotite is present with an iron ore frequently rimmed by sphene.

Near the granite veins this basic hornfels is modified both by the development of biotite to the virtual exclusion of hornblende and by an increase in the grain-size of the biotite from 0.1 mm. to poikilitic flakes over 0.5 mm. across.

The veins themselves vary greatly in coarseness but they normally average between 1.0 and 2.0 mm. They are of quartz, andesine and biotite (N.299.2). The andesine is zoned from a medium to an acid variety and, like the quartz, forms equant grains. The biotite forms brown non-poikilitic flakes. Veins in a dyke adjacent to the tonalite contact have a similar mineral assemblage in rather smaller grains which are isolated in huge poikilitic plates of orthoclase (N.415.2).

The two large volcanic screens on island *L1* to the south-east of the tonalite mass and on island *K4* to the north-east present features similar to the contact volcanics. In the screens, however, no comprehensive area of cleaved volcanics is present, such rocks being limited to large inclusions set in the fine-grained rock of the screen. Masses of the hornfelsed pre-Andean dykes occur within the screen rock together with their granitic or pegmatitic veins. Outside the screen the normal tonalite again shows a concentration of dark inclusions.

A typical volcanic inclusion from within the screen rock is a quartz-oligoclase-orthoclase-biotite-hornfels with a grain-size of approximately 0.1 mm. (N.414.1). In it occur occasional patches of slightly finer-grained quartz-orthoclase-hornfels. The biotite flakes give the rock a crude schistosity and that this runs parallel to the original bedding is demonstrated by a series of groups of garnet-muscovite-cordierite-hornfels lying in a similar plane, each of which is separated from the next by the more normal hornfels in which a chlorite takes the place of the biotite. The garnet is very slightly pink with $n = 1.808 \pm 0.003$. The cordierite is altered to pinite and the orthoclase has $\alpha = 1.518 \pm 0.001$, $\gamma = 1.524 \pm 0.001$.

The screen rock forms sharp contacts with both the surrounding tonalite and its cleaved inclusions. With the composition of an acid tonalite it has the granoblastic texture of the hornfelsed volcanics (grain-size 0.1 to 0.2 mm.) (N.413.1). The orientation of the non-poikilitic flakes of biotite give the whole rock a distinct schistosity. Small interstitial areas of orthoclase are occasionally recognized and the plagioclase is twinned on both the albite and the Carlsbad Laws. Apparently it is a volcanics/tonalite hybrid formed by the introduction of tonalite material into a volcanic inclusion by local metasomatism. The shape of the screens and their lack of the crude cleavage typical of the contact hornfels indicate their greater mobility.

The acid veins which cut the pre-Andean dykes within the screens probably provide a close approximation to the metasomatic material introduced to the screens from the tonalite. The dyke material was both more brittle and more resistant to the metasomatism than the surrounding volcanics. Cracks, formed during the movements of the surrounding volcanics, were filled by the more fluid solutions bearing the metasomatic material.

A coarse example of one such vein (N.413.2) has a centre of large intergrown crystals of blue quartz and pink orthoclase up to 2.0 cm. across. Outside is a zone of quartz-albite rock, the separate crystals being about 2.0 mm. in size, and associated with chlorite pseudomorphs after biotite which contain sphene, epidote and iron ore. The albite carries numerous flecks of sericite and grains of epidote while prehnite occurs as interstitial flakes or veinlets. Between this and the plagioclase-hornblende-hornfels of the dyke there is an area of fresh andesine crystals (0.4 mm.) zoned normally from An_{38} to An_{30} and surrounded by large quartz crystals (2.0 to 3.0 mm.) with poikilitic crystals of hornblende partially altered to chlorite.

Along the north-west margin of the tonalite mass, volcanic screens occur on islands *E4*, *E3*, *A4* and *B1* (Fig. 8). On all but the first two, Cape Monaco Granite occurs in addition to the tonalite and volcanics, and on island *A3* the granite is the country rock, including blocks of tonalite, blocks of hornfelsed volcanics and blocks of tonalite which themselves include blocks of volcanics.

The Cape Monaco Granite is described on p. 42–50, where it is argued that it is of metasomatic origin. Along its margin the tonalite and volcanic screens have been metasomatized by the granite and in the case of the volcanics it is frequently difficult to differentiate the effects of the granite from those of the tonalite.

Cleaved inclusions within the screen rock have been least affected by the Cape Monaco Granite. A typical example (N.418.4) is a fine-grained quartz-plagioclase-hedenbergite-garnet-hornfels. Coarser bands with hedenbergite crystals (0.4 mm.) set in smaller bytownite grains alternate with finer bands rich in garnet but lacking hedenbergite. The hedenbergite (ferrosalite; Hess, 1941) has a pleochroism α = pale green, γ = yellow-green, $\gamma : c = 50°$, medium to large $2V\gamma$ and $\alpha = 1.714 \pm 0.002$, $\gamma = 1.736 \pm 0.002$. The garnet is yellow with a refractive index just above 1.810. A similar rock (N.423.2) lacking quartz and containing patches of granular sphene surrounding iron ore forms abundant pink lenticles within the granite.

A large pale inclusion within the tonalite on island *A4* (N.425.2) is 150 ft. long and is rich in iron ore. The latter is mainly pyrrhotite with some pyrite and a very little chalcopyrite. The ore is surrounded by small flakes of muscovite and set in interlocking grains of oligoclase and cordierite, the latter altering to pinite. The rock is pierced by fibres of colourless sillimanite (Plate IVc). The assemblage suggests a sedimentary origin and may be compared with the cordierite-andalusite band described on p. 21.

Beyond the development of ragged margins to the hornblende crystals, the inclusions of pre-Andean dykes are little affected by the proximity of the Cape Monaco Granite (N.423.3). But the more acid volcanic inclusions and the previously metasomatized screen rocks have been more readily affected. Because the marked development of quartz as large crystals is confined to those inclusions close to the Cape Monaco Granite, and because this development is typical of the alteration of tonalite to the granite, it has been used as an indication of metasomatism by the granite. The growth of quartz is frequently accompanied or preceded by the formation of plagioclase porphyroblasts.

This alteration may be followed in a series of thin sections. In the first instance the quartz-plagioclase-biotite-hornfels develops larger plagioclase crystals (N.418.3), which are then surrounded, cracked and partially replaced by swollen grains of quartz. At this stage biotite flakes still impart a faint schistosity (N.418.1, 5) to the rock. Such rocks grade into a coarser non-foliated quartz-andesine rock (N.418.2) with large poikiloblastic crystals of biotite. Iron ore is relatively abundant as large grains and poikiloblastic flakes of tremolite are developed in one case (N.418.2). This rock includes ill-defined areas of coarse tonalite with zoned plagioclase crystals up to 2.0 mm. surrounded by yet larger shapeless masses of quartz.

2. *Metasomatized volcanics*

Volcanic rocks with original porphyritic textures and flow banding, but which are exceptionally rich in quartz and either albite or orthoclase characterize the "*F*" group of islands (Fig. 8). The group is low-lying and its members are separated by shallow water.

The original volcanic nature of the majority of these rocks is never in doubt. Fine and coarse pyroclastics predominate and are separated by strongly banded lava flows. Exceptional beds, rich in andalusite and cordierite are probably of sedimentary origin.

Since its formation the succession has been tilted into a vertical position, intruded by dykes, metasomatized and faulted. In Table III these events are listed in stratigraphical order. With this history it is possible to associate both the intrusions of tonalite and the formation of the Cape Monaco Granite. Some difficulty is encountered, however, in determining how much is due to the one and how much is due to the other.

TABLE III

SEQUENCE OF EVENTS ON THE "*F*" GROUP OF ISLANDS

Event		Age	
		↑ Younger	
Dykes			
Faulting in a vertical plane striking 070° mag.	Metasomatism		*Formation of the Cape Monaco Granite*
(Possible dyke formation)	Metasomatism		*Formation of the Cape Monaco Granite*
Porphyritic intrusion and breccia dykes.	Metasomatism		*Formation of the Cape Monaco Granite*
Basic dykes			
Folding into vertical position			*Intrusion of tonalite*
(Possible dyke formation)			
Volcanic succession			
		Older ↓	

That the tilting of the beds is due to the intrusion of the tonalite may be inferred from the strike of the vertical beds which is parallel to the tonalite/volcanics contact exposed on island *G1*. This is in accordance with the tonalite/volcanics contacts studied on the Outcast Islands and on islands *K2* of the Joubin Islands.

Coincident with the folding there must have been considerable recrystallization but, in contrast to island *G1*, this was not intense enough within the "*F*" group to obscure porphyritic textures or flow banding. What recrystallization there was is now totally obscured by later metasomatism.

The coarse porphyritic intrusions and the faulting may be related to the formation of the Cape Monaco Granite. A major fault bisects the group and smaller faults in the same plane are not uncommon. The main horizontal movement along these faults was dextral.

Alteration of the volcanics differs from one specimen to another, a difference due apparently to original composition rather than geographical position within the group. Thus a particularly dense flow (N.288.2) from the eastern half of island *F1* has an indistinct groundmass of untwinned plagioclase largely obliterated by the formation of green-brown biotite as tiny flakes and iron ore as euhedral grains, which together form the greater part of the rock. Different concentrations of biotite accentuate the flow banding.

Another flow (N.410.1), from the west end of island *F5*, contains small phenocrysts of acid andesine with slight normal zoning to basic oligoclase and considerable alteration to fine-grained material which is epidote in part and may contain areas of quartz. No formation of albite is apparent. The matrix is of small irregular crystals of a colourless mineral of low birefringence, probably plagioclase, speckled with biotite. A narrow vein of muscovite with occasional quartz crystals is present.

In contrast, a specimen of the junction between two flows (N.288.1), collected within a few feet of N.288.2, contains well-developed albite (An_5) and quartz porphyroblasts in a granoblastic matrix of quartz, albite and orthoclase with minor quantities of chlorite, epidote, granular iron ore and specks of biotite. The albite porphyroblasts are subhedral to euhedral, comparatively fresh with only a faint dusty pink alteration and carrying a few grains of epidote. Many are surrounded by a narrow rim of orthoclase which appears to have replaced the albite to form a fine marginal intergrowth. Of the large quartz crystals some show a distinct tendency towards idiomorphism while the largest possess embayments of the groundmass. All show undulose extinction. Occasional clusters of biotite flakes may be pseudomorphing original microphenocrysts of a ferromagnesian mineral. The chilled margin of the later lava proved more resistant to metasomatism, so that the original flow banding of the plagioclase laths is still apparent.

A striking spherulitic rock (N.410.2) was collected from the west tip of island *F5*, but its relation to the other volcanics was hidden by ice. Black, almost perfect spherulites, 2.0–4.0 mm. in diameter, are set in a pale matrix. The spherulites are composed of radiating ellipsoidal forms which are frequently centred on euhedral crystals of albite (Plate IVd). Each ellipsoid extinguishes as a unit, if somewhat vaguely. They are of low birefringence and a uniaxial positive figure has been obtained in a few cases. Apparently these are of quartz with included specks of alkali-feldspar. Between the spherulites large crystals of albite and quartz are developed in a matrix of the same minerals, probably accompanied by some potash feldspar. Patches of quartz mosaic associated with sericitic mica also occur. Flakes of biotite and grains of iron ore tend to form around the spherulites while radial veinlets of groundmass material penetrate to their centres.

The albite contains less than 4 per cent of the anorthite molecule and carries quite substantial patches of orthoclase. The ore includes both ilmenite and pyrite, the latter replacing the former and occurring more frequently in the centres of the spherulites. Collected in the field as a spherulitic lava, the microscopic study suggests the spherulites are entirely secondary in origin and due to metasomatism of a crystal tuff.

Two potash-rich specimens collected from island *F2* contain recognizable rock fragments. In the one from the south-west shore of the island (N.291.2) the fragments tend to be richer in biotite than the interfragmental material and they often possess relict laths of plagioclase now converted to albite. Interlocking grains of quartz and orthoclase with sericitic mica and a small quantity of brown biotite comprise most of the interfragmental material. Large crystals of quartz and albite are sparsely distributed through both the fragments and the intervening material. Iron ore is rimmed by brown biotite throughout.

The second specimen (N.291.1) is mottled purple and green with an abundance of pyrite. Under the microscope the fragments are angular, often rimmed by flecks of deep brown biotite, and composed mainly of orthoclase and mica. Colour in the mica varies from deep brown to colourless, but in all cases it has a small 2V. The interfragmental material is finer-grained and richer in quartz with mica and orthoclase present in small amount, the latter forming occasional large crystals ($\alpha : (001) \simeq 12°$; $2V\alpha = 77° \pm 3°$; $\alpha = 1.517 \pm 0.001$, $\gamma = 1.522 \pm 0.001$). Coarse quartz lenses and veins traverse the interfragmental material.

The cordierite-andalusite rocks form a narrow band between thick flows in the succession immediately north of the major fault on island *F1*. A felted mass of black euhedral andalusite prisms forms the weathered surfaces along joint planes (N.290.1). Under the microscope both the andalusite and the cordierite include as many quartz and iron ore granules as occur in the groundmass, but they are free of sericite which is the most abundant mineral of the groundmass (Plate IVe). The cordierite shows typical interpenetrating twins. Crystals of both minerals average approximately 1.0 mm. in size. The sericite imparts a fine schistosity to the groundmass while many of the quartz grains, both within and outside the poikiloblasts, are distinctly angular.

A second specimen (N.290.2) is sheared. The ragged crystals of cordierite and andalusite, together with patches of fine quartz mosaic, are drawn out parallel to the shear planes. Little prisms of green mica and chlorite are associated with the quartz patches while the groundmass is again of sericitic mica with (?) plagioclase and quartz. Within the drawn-out crystals of incipient andalusite smaller crystals of clear andalusite, with pleochroism in colourless to pink and with well-developed prismatic cleavage, have developed, pushing aside the streams of inclusions to form an eye structure. In another case a well-formed andalusite crystal lies between a pair of the incipient variety against which it has sharp boundaries. Thus there are two distinct generations of andalusite, one prior to and the other later than the shearing.

Such rocks must be interpreted as thermally metamorphosed sediments. Together with the cordierite-sillimanite screen rocks on island *A4* they appear to represent one or more narrow sedimentary bands within the volcanic succession. The angular quartz fragments indicate a pyroclastic origin for some of the material.

Towards the western end of island *F1* two broad vertical intrusions, 12–15 ft. wide, of pale porphyritic material strike approximately parallel to the bedding but occasionally transgress. They also cut across a basic dyke. It can be assumed that the basic dyke was intruded vertically, that is, after the succession was tilted through 90°. Thus it can be deduced that the pale intrusions entered after the beds were tilted.

Petrographically the pale dykes consist of groups of albite porphyroblasts and occasional quartz porphyroblasts set in a recrystallized matrix of quartz and albite (N.289.2).

The larger albite porphyroblasts (up to 4.0 mm.) carry considerable quantities of epidote with some quartz, calcite and chlorite; smaller examples contain little or no epidote. The quartz porphyroblasts show embayments of the groundmass within the crystals, while isolated blebs around their margins have the same or closely similar optical orientations. In the groundmass a general tendency for the small crystals of albite to have a lath form is still recognizable despite the general recrystallization. Other minerals are present only in small quantities. They include calcite, chlorite (green with anomalous deep blue interference colours), epidote, sphene and ilmenite. An elongated pseudomorph of epidote is probably after an earlier ferromagnesian phenocryst.

These intrusions are petrographically similar to the surrounding volcanics despite their later formation. This may be due to the unifying nature of the metasomatism or possibly to a remobilization of volcanic material during the metasomatism. If the former is the case, then lack of drastic alteration to the dyke which is intermediate in age between the volcanics and the intrusions indicates that the materials of the second two possessed similar original compositions. This in turn makes it necessary to postulate the presence of closely similar magmas during both Jurassic and Andean times. The remobilization of solid rock by the addition of silica and potash, however, seems hardly more likely. This point is discussed again later in connection with similar intrusions within the Altered Assemblage (p. 52).

The character of the rocks of the "*F*" group of islands may be summarized as follows:

i. The vast majority represent an upturned volcanic succession of lava flows and pyroclastic rocks.
ii. These possess a low temperature mineral assemblage.
iii. While rich in quartz, albite and orthoclase, they are very poor in the ferromagnesian minerals.
iv. Some examples (probably originating as pyroclasts) possess spherulitic structures (N.410.2).
v. Relict plagioclase laths in the denser chilled margins (N.288.1) and andesine phenocrysts in the denser flows (N.410.1) indicate that the low temperature assemblage is secondary.
vi. A thin band of sediment within the succession shows low grade metamorphism (cordierite, andalusite).

It is apparent that the original succession has been recrystallized under low temperature conditions, while the abundance of quartz, albite and orthoclase suggests some degree of metasomatism. To test this, the alkalis of four typical members of the succession have been determined (Table IV). When plotted on a Na_2O/K_2O diagram (Fig. 9), they show considerable scatter compared with a suite of recent rhyolitic rocks and they fail to follow a general linear zone across the diagram, as might be expected had the scatter been the result of autometasomatism (Battey, 1955). A full analysis has been carried out on N.410.1. In the field this rock shows well-developed flow banding and still carries phenocrysts of andesine. It may thus be considered less affected by any possible metasomatism than the majority, yet its remarkably high silica content virtually excludes it from the field of normal rhyolites.

TABLE IV

CHEMICAL ANALYSES OF METASOMATIZED VOLCANIC ROCKS, JOUBIN ISLANDS

	N.288.1	N.289.2	N.291.1	N.410.1		
SiO_2	—	—	—	79.95		
TiO_2	—	—	—	0.16		
Al_2O_3	—	—	—	12.34	*Norm*	
Fe_2O_3	—	—	—	0.66	Q	53.28
FeO	—	—	—	0.71	or	15.57
MnO	0.09	0.10	0.06	0.05	ab	19.91
MgO	—	—	—	0.26	an	5.00
CaO	—	—	—	1.17	C	3.67
Na_2O	3.86	4.04	0.84	2.34	hy	1.36
K_2O	3.86	2.54	6.52	2.65	mt	0.93
H_2O+	—	—	—	0.33	il	0.30
H_2O-	—	—	—	0.03	ap	0.34
P_2O_5	0.04	0.08	0.16	0.10		
TOTAL				100.75		

N.288.1 Junction between two lava flows, eastern half of island *F1*, Joubin Islands.

N.289.2 Pale porphyritic dyke rock, western end of island *F1*, Joubin Islands.

N.291.1 Brecciated volcanic rock, eastern tip of island *F2*, Joubin Islands.

N.410.1 Lava flow, west end of island *F5*, Joubin Islands.

Two further points are relevant. Outside this group all the volcanic rocks found so far within the Anvers Island area are andesitic. This, together with the andesine phenocrysts in specimen N.410.1, suggests that the volcanics of the "*F*" group of islands were originally andesitic. This would imply a considerable addition of material, mainly silica and potash, by metasomatism. Secondly, the "metasomatized volcanics" crop out close to and probably overlie the Cape Monaco Granite. It seems not unreasonable to conclude that the introduction of silica and potash into the volcanics was associated with the development of this large granite mass.

3. *Thermally metamorphosed and metasomatized volcanics*

Island *G1* lies to the south of the "*F*" group (Fig. 8). Its north-eastern end is composed of a coarse intrusive alkali-granite, believed to have been intruded as a primary tonalite (p. 41). West of this is a series of steeply dipping and highly altered rocks in which the alteration becomes less extreme towards the western end. Here, dark and pale bands may be recognized as lava flows and pyroclastics respectively and, while complicated minor folding is present, the succession as a whole has a near vertical dip striking north-south. Close to the contact the banding is so contorted that no pattern could be obtained (Plate IIa). As in the previous examples it is assumed that the tilting and contortion of the beds is due to the tonalite intrusion.

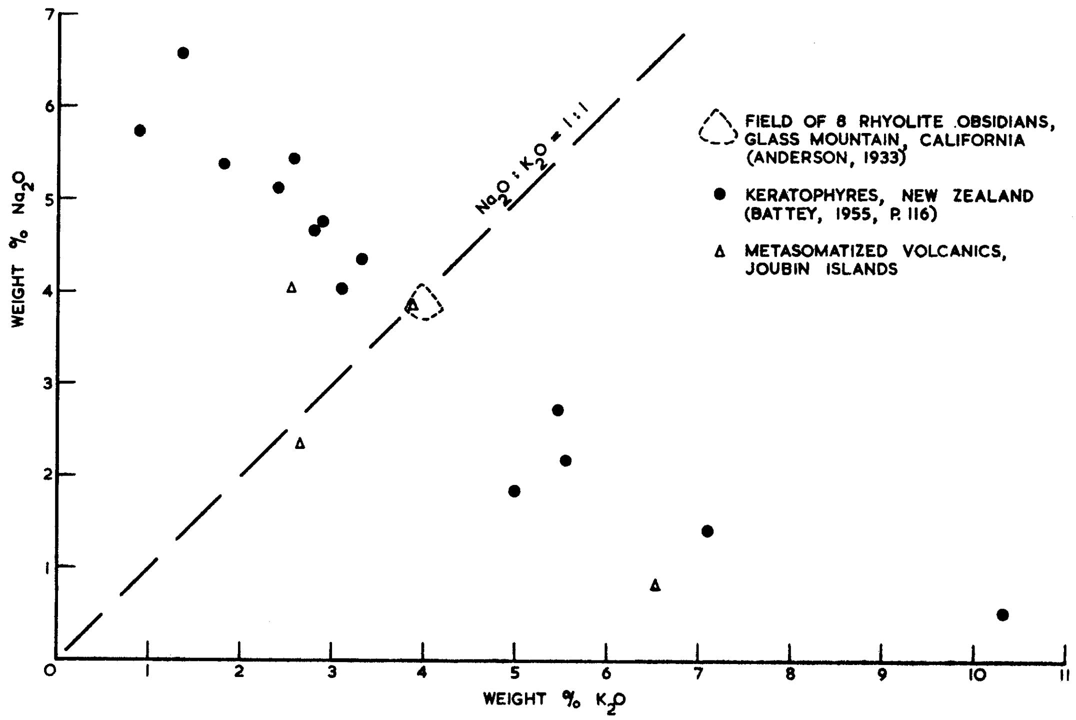


FIGURE 9

Diagram of alkali ratios of metasomatized volcanics from the Joubin Islands compared with New Zealand keratophyres and unaltered obsidians from Glass Mountain, California.

Table V sets out the geological history of the rocks. Basic pre-Andean dykes are present close to the contact. Breccia dykes may either cut or be cut by doleritic dykes, of which the earlier may represent less altered pre-Andean members. Small planes of movement are later than both the doleritic dykes and the breccia dykes but they are earlier than porphyritic dykes. Metasomatism has affected both the altered volcanics and the primary tonalite and with this process the breccia dykes are thought to be associated.

The volcanics/tonalite contact crosses the island in an approximately vertical plane (Fig. 8). On the east it is sharp and welded, but on the west there is a more gradual transition from one type to another.

Dense, basic dyke material cut by a host of granitic veins crops out close to the contact in two places. They are similar to the pre-Andean dykes described from island *K2* (p. 18), but for the margins of the hornblende crystals which are ragged to the extent of forming needles which penetrate the surrounding feldspar. In this they resemble the pre-Andean dykes close to the Cape Monaco Granite. The examples from island *G1* are also rich in iron ore which forms both large independent crystals and small grains packing the andesine and hornblende.

The volcanic rocks are extremely fine-grained (0.01 mm. or less). One specimen collected 2 ft. from the tonalite contact (N.273.3) differs from the majority in its fine but clearly granoblastic texture. Quartz and slightly altered albite are the chief constituents with small grains of olive-green biotite and patches of tiny sericite flakes within the quartz. Iron ore is also present.

Others within 300 yd. of the contact are almost cryptocrystalline and consist of two essential minerals, quartz and potash feldspar. These form monomineralic patches with a wide area of intergrowth where they are in contact (N.275.1). The intergrowth consists of a large number of small irregular quartz crystals enclosing numerous specks and patches of the feldspar, suggesting replacement of feldspar by quartz. The later formation of the quartz is confirmed by quartz veins linking one quartz patch with another.

In two other specimens (N.276.1, N.280.1), farther west from the contact, feldspar is less abundant than quartz, hence patches of quartz and intergrowth occur but there are few patches of pure feldspar. As the quartz increases it forms coarser lenses and in the more westerly example (N.280.1) the development of these lenses along the banding was noted in the field. In the same specimen patches of sericite occur with the quartz, and ilmenite forms large grains surrounded by epidote. A sericite-chlorite clot was also noted.

TABLE V

SEQUENCE OF EVENTS ON ISLAND *G1*

Younger ↑

Event			
Porphyritic dykes			
Faulting	Metasomatism		*Formation of Cape Monaco Granite*
Basic (dolerite) dykes	Metasomatism		
Breccia dykes	Metasomatism		
Basic (dolerite) dykes	Metasomatism		
Folding			*Intrusion of tonalite*
Basic dykes			
Volcanics			

Older ↓

Late-stage veins, carrying epidote with quartz and muscovite, occur in the more quartz-rich examples and they may link the coarse quartz patches.

The pale recrystallized breccias on the west coast contain pink, greenish grey and white fragments. Under the microscope, however, these (N.282.1) closely resemble the various types described above. Quartz predominates in some, while others contain an equal amount of feldspar and they possess the same extremely fine-grain and intergrowth structures. Peculiar to this rock, however, is the development of the feldspar as porphyroblasts, usually associated with coarse quartz lenses. Its optical properties resemble those of the orthoclase on island *F2* (p. 21).

The darker lavas (N.281.1) are largely cryptocrystalline with vague quartz crystals developing out of an essentially sericitic groundmass which includes epidote. Biotite occurs sparsely as nodules of tiny interlocking plates. Distinct banding results from the different proportions of sericite and quartz in adjacent layers and the rock is crossed by a narrow vein of acid oligoclase with some quartz. The oligoclase is altered to sericite and a clay mineral.

Another lava flow from the south-west shore (N.283.1) has small laths of acid oligoclase set in a quartz/potash feldspar groundmass similar to that of the rocks nearer the contact. Tiny crystals of greenish biotite, specks of iron ore and small granular aggregates of sphene are also present.

Viewing the volcanic rocks of island *G1* as a whole, the specimen from the contact, with its granular texture and essential quartz-albite composition, stands apart from the rest. In texture and composition it is comparable with the volcanic screens within the southern mass of tonalite (p. 19). In composition it is also comparable to the nearby tonalite in which the basic plagioclase has been altered to albite (p. 41). It is concluded that this rock has first suffered local metasomatism from the intruding tonalite, taking on a similar composition to that rock (as did the screens), and has reacted to the later granite metasomatism in the same way as the tonalite.

The contorted ultra-fine-grained rocks from the centre of the island are all quartz-orthoclase rocks without substantial quantities of sericite and biotite. Their present composition can only be due to metasomatism. Whether they are all of a similar, presumably pyroclastic, origin or whether original lava flows and pyroclastic rocks have been metasomatized to a common quartz-orthoclase end product is uncertain.

The less contorted rocks on the west shore may be separated into lava flows and pyroclastic rocks with a general vertical trend parallel to that of the contact. The breccias still retain the vague outlines of the original fragments but have the mineralogy of the contorted rocks nearer the contact. They bridge the gap between the metasomatized volcanics on the "*F*" island group and the metasomatized and contorted quartz-orthoclase rocks nearer the contact. The increased contortions and the apparent mineralogical convergence towards the contact was probably controlled by the degree of contact alteration and possible crushing inflicted by the earlier tonalite intrusion.

Curious breccia dykes cut the highly contorted beds within 300 yd. of the intrusive contact. Of dyke form, variable in width from 2 in. to 12 ft., they have a coarse central part with large angular fragments and a much finer margin of strong purple tint.

The coarse rock (N.279.1) contains angular volcanic rock fragments up to 4 mm. long and angular crystal fragment of quartz and sodic plagioclase. These are set in a matrix of olive-green biotite and quartzo-feldspathic material with euhedral grains of magnetite. The biotite forms at least 50 per cent of the matrix and penetrates the rock fragments (Plate IVf).

The rock fragments vary considerably in size, texture and composition. All are recrystallized to some extent but many show relics of primary feldspar laths. Others are cryptocrystalline quartz-feldspar aggregates similar to the surrounding country rock, although normally with a more granular texture. The crystal fragments of both minerals are cracked and show undulatory extinction. Quartz-biotite veins have penetrated the cleavage planes of the plagioclase and this mineral may have narrow margins of potash feldspar. In some of the dykes the plagioclase carries occasional sericite flakes, but more normally they show only the pink dusty alteration typical of alkali-feldspars. Twinning, simple and multiple, is often present but always vague.

The fine-grained marginal rock still contains clear but much smaller, angular fragments of quartz and sodic plagioclase. However, the rock fragments are hardly recognizable as such, merging with the groundmass and drawn out parallel to the contact to form a crude schistosity, a texture emphasized by orientation of the green-brown biotite crystals. The groundmass forms a higher proportion of this rock than of the coarser centre. The junction between central and marginal facies is sharp and paralle to the outer margins. It is a shear plane. Other subsidiary shear planes parallel to the first traverse the marginal type (Plate IVf). The contact of the finer margins with the country rock is also sharp but welded, parts of the country rock being included within the dyke material.

With the present evidence no satisfactory conclusion can be reached concerning the origin of the breccia dykes. They were intruded after the folding (caused by the tonalite) and probably after the bulk of the metasomatism, yet their distribution is limited to those volcanic rocks fairly close to the tonalite contact. The mode of their intrusion appears to have involved a partially solid volcanic rock so that the margins were mylonitized. It is possible only to postulate a volcanic rock brecciated and then partially mobilized by an uprush of volatile material, rich in silicon and potassium, squeezed into the overlying rocks with the pressure and movement continuing after the rock had lost most of its mobility.

4. *Summary*

The Upper Jurassic Volcanics on the Joubin Islands have been altered twice, first by the forceful intrusion of a pair of primary tonalite bosses and secondly by the metasomatism associated with the Cape Monaco Granite. The first may be compared with the contact metamorphism on the Outcast Islands. On the Joubin Islands, however, the effect of strictly local metasomatism by the tonalite is better illustrated and volcanic inclusions within the tonalite reveal higher grades of thermal metamorphism.

Those volcanics metasomatized during the formation of the Cape Monaco Granite are represented by a low temperature assemblage. Their mineralogy and chemistry indicate the introduction of silica and potash. Where these rocks had previously been thermally metamorphosed an extremely fine-grained quartz-orthoclase rock with contorted banding was formed. This is penetrated by curious breccia dykes which appear to have formed by the brecciation and partial mobilization of volcanic material during an uprush of volatiles rich in silicon and potassium.

The intensity of the metasomatism found on both the "*F*" group of islands and on island *G1* implies the presence of the Cape Monaco Granite immediately below these areas. If this is so, there is a marked contrast between the comparatively limited metasomatism associated with the granite across its vertical contacts

(as on island *B1*) and that found above the granite. This contrast is to be expected if the metasomatism is due to volatile material escaping upwards along zones of weakness.

Finally, one or more narrow bands of sedimentary origin occur within the volcanic succession. These are now represented by cordierite-sillimanite and cordierite-andalusite rocks.

III. THE ANDEAN INTRUSIVE SUITE AND ASSOCIATED HYBRID ROCKS

ROCKS which acquired their most obvious characteristics during the Andean period include:

i. The Andean Intrusive Suite and associated hybrid rocks.
ii. The Cape Monaco Granite.
iii. The Altered Assemblage.

Metasomatism associated with the Cape Monaco Granite has transformed Upper Jurassic Volcanics and primary members of the Andean Intrusive Suite. Similarly, the Altered Assemblage has been derived by regional metasomatism from Upper Jurassic Volcanics and Andean intrusions. Both forms of metasomatism appear to be part of the same process of late Andean age, the Altered Assemblage representing an early stage, the Cape Monaco Granite the final product.

Of the Andean Intrusive Suite the only rocks showing primary features are gabbros and tonalites.* The remainder, by far the largest proportion of the suite, are thought to have been altered *in situ* so that their primary features have been lost. They are regarded as hybrids, formed by the addition of more aplitic material to the primary intrusions. The added material may be associated with the late Andean metasomatism.

A. PRIMARY GABBROS

Banded gabbros occur on Gateway Ridge (Fig. 10), on the northern and western members of the Wauwermans Islands (Fig. 11) and on a group of islands two miles south-east of Arthur Harbour. They are coarse-grained dark rocks and the banding is always vertical or nearly so. Variation in both composition and texture from one band to another is considerable. Various types of banding are illustrated in Plates IIb and c.

On Gateway Ridge the darker bands are coarse ophitic anorthite-gabbros (N.11.1, N.58.2). The anorthite (An_{90}) is tabular, 3.0 mm. long and has negligible zoning. Clinopyroxene crystals (4.0 mm.) enclose both the anorthite and pyroxene-magnetite pseudomorphs after olivine. Schiller structure may be present (N.58.2). Hornblende (α' = pale fawn, γ' = yellow-brown) forms a narrow margin around the pyroxene and many small optically continuous blebs within the pyroxene. Iron ore, as small grains, is associated with these blebs and also forms larger masses around the pyroxene margins. Interstitial sheaves of a paler acicular amphibole (α' = colourless, γ' = pale green) appear to have caused the only alteration to the anorthite.

A typical pale band from Gateway Ridge (N.11.1) is equigranular with equidimensional crystals (average diameter 0.3 mm.). Bytownite (An_{80}), clinopyroxene and iron ore are the chief minerals. The pyroxene is altered marginally to a blue-green hornblende.

On the Wauwermans Islands, a dark band (N.133.4) from a small island east of Miller Island is an anorthite (An_{90})—amphibole rock with accessory iron ore, epidote and calcite. The amphibole is almost colourless with faint pleochroism from α' = pale yellow to γ' = pale green. The birefringence is low and the large ragged plates (7.0 mm.) show repeated twinning ($2V\alpha$ = 86–92°). This mineral has attacked the anorthite and an abundance of anorthite fragments within its crystals indicates that the reaction was extensive.

Orthopyroxene and fresh olivine occur in a granular gabbro from the north of Pardoner Island (N.137.1). More often the olivine is largely replaced by pink hypersthene, iron ore and talc (N.134.1).

* The mineralogical classification of igneous rocks suggested by Nockolds (1954) has been strictly adhered to throughout this report.

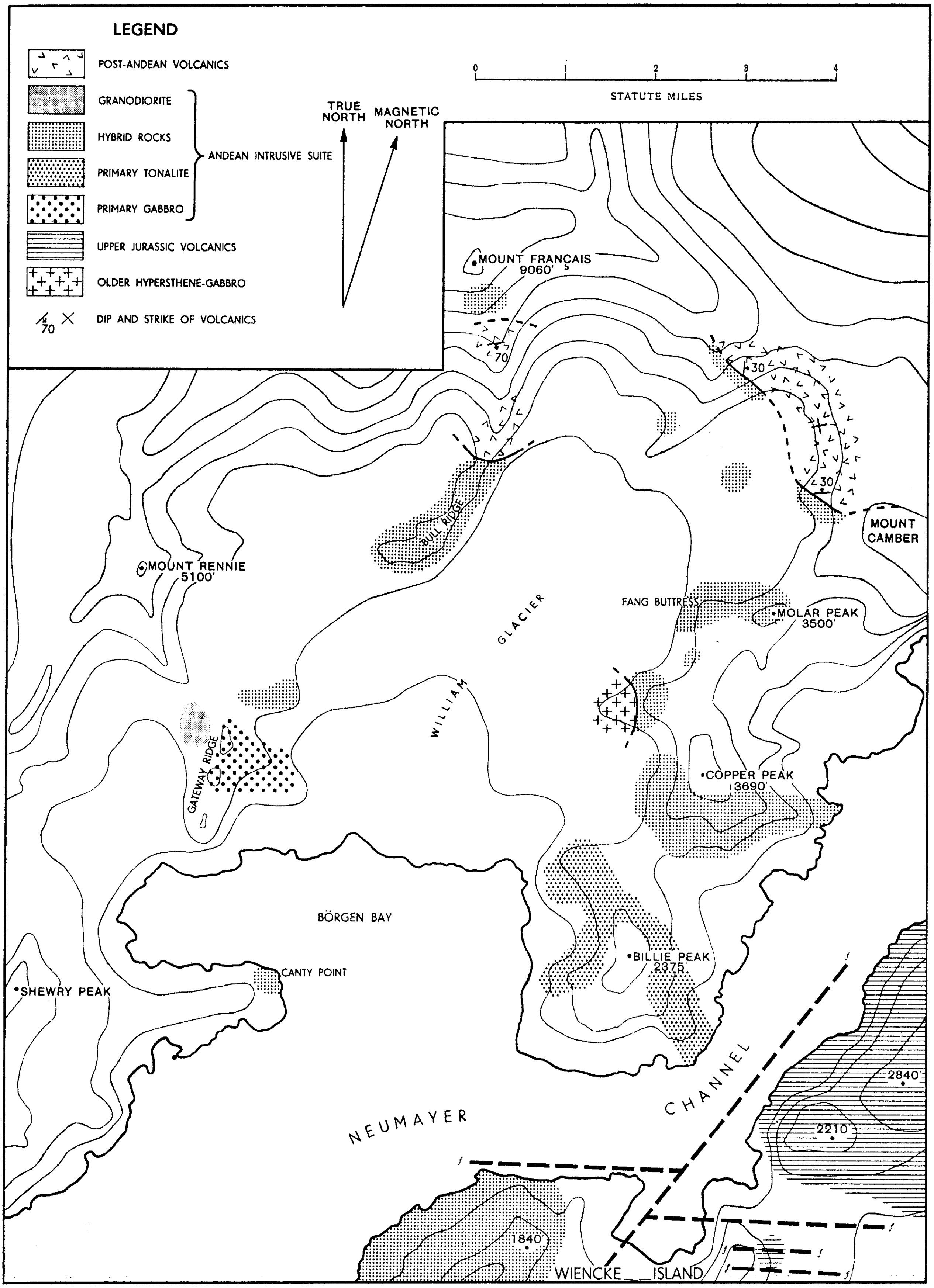


FIGURE 10
Geological map of the Börgen Bay area, Anvers Island.

Gabbros from the islands two miles south-east of Arthur Harbour contain a more acid plagioclase (An_{66-55}), and more hornblende than pyroxene. One (N.204.1) carries approximately 40 per cent of hornblende (α' = pale yellow, γ' = dull blue-green), while another (N.205.1) with approximately 25 per cent of hornblende (α' = pale yellow, γ' = pale blue-green) has approximately 15 per cent hypersthene and only 5 per cent augite. The associated pale bands are anorthosite, which is almost entirely composed of slightly zoned labradorite (approx. An_{60}) with 5–10 per cent of hornblende (α' = pale yellow, γ' = blue-green) forming optically continuous interstitial stringers. Broad bands of hornblende-pegmatite are another feature of these islands.

Occasional patches and veins of acid material occur in most gabbro outcrops. An example from Gateway Ridge (N.11.3) is an ill-defined patch showing a gradation from the anorthite-gabbros to a small central area of alkali-feldspar/quartz intergrowth. Another, from near Miller Island (N.135.1), is a coarse-grained quartz-oligoclase rock with biotite largely altered to an isotropic chlorite and epidote. Between this and the gabbro is a much coarser zone (N.135.2) composed largely of magnetite bordered by a broad rim of almost isotropic chlorite in well-developed plates and associated with a pale brown mica, a pale brown amphibole with blue-green margins and a considerable quantity of calcite. An intricate iron ore/mica intergrowth has developed.

The modal analyses of four primary gabbros are given in Table VI.

TABLE VI

MODAL ANALYSES OF PRIMARY GABBROS

	N.137.1	N.58.1	N.133.4	N.134.1
Plagioclase	71.4	73.1	60.9	53.5
Biotite	—	—	—	5.9
Clinopyroxene/hornblende	17.2	26.1*	36.9*	} 37.9
Hypersthene	1.0	—	—	
Olivine	3.9	+	—	+
Iron ore	6.5	0.8	0.4	1.9
Apatite	+	—	—	0.8
Epidote	+	+	1.8	—
Chlorite	+	+	+	—
Calcite	+	—	+	+
Plagioclase composition	An_{90}	An_{90}	An_{90}	An_{90-63}

* mainly amphibole
\+ present in small quantity

N.137.1 Olivine-gabbro, Pardoner Island, Wauwermans Islands.
N.58.1 Gabbro, Gateway Ridge, Anvers Island.
N.133.4 Amphibole-gabbro, near Miller Island, Wauwermans Islands.
N.134.1 Hypersthene-gabbro, near Miller Island, Wauwermans Islands.

B. Primary Tonalites

Primary tonalites with well-developed igneous lamination occur on Billie Peak (Fig. 10) and on Tangent and Knight Islands (Fig. 11). In both cases they are closely associated with primary gabbros and the hybrid rocks. On the Outcast and Joubin Islands isolated bosses of tonalite intrude the Upper Jurassic Volcanics. In all cases they are characterized by a constant texture and composition over a wide area, being coarse basic tonalites with 8–14 per cent modal quartz (Table VII).

Table VII

MODAL ANALYSES OF PRIMARY TONALITES AND ASSOCIATED APLITE

	N.133.2	N.136.1	N.75.1	N.74.1	N.254.1	N.239.1
Quartz	8.5	12.8	11.7	11.8	13.7	34.4
Alkali-feldspar	—	—	—	—	—	24.7
Plagioclase	68.1	55.7	61.9	58.4	62.6	37.5
Biotite/chlorite	9.9	11.2	5.3	6.0	9.0	2.9
Hornblende	11.8*	18.8	19.9*	20.0	13.1	—
Pyroxene					—	—
Iron ore	1.7	1.0	1.2	1.7	1.6	0.3
Apatite	+	0.5	—	0.1	+	—
Sphene	—	—	+	+	+	0.2
Epidote	—	+	—	—	—	+
Haematite	—	—	—	+	—	—
Plagioclase composition	An_{66-36}	An_{55-38}	An_{55-33}	An_{70-37}	An_{40-16}	An_{43-18}

* includes orthopyroxene
\+ present in small quantity

N.133.2 Quartz-diorite, Knight Island, Wauwermans Islands.
N.136.1 Tonalite, Tangent Island, Wauwermans Islands.
N.75.1 Tonalite, Billie Peak, Anvers Island.
N.74.1 Tonalite, Copper Peak, Anvers Island.
N.254.1 Tonalite, Outcast Islands.
N.239.1 Aplite vein in tonalite, Outcast Islands.

The rock from Billie Peak (N.75.1) has tabular crystals of plagioclase (up to 5.0 mm. long) which are zoned normally from An_{55} to An_{33}. Small elongated crystals of hypersthene ($2V\alpha = 48° \pm 3°$), with lamellae parallel to their length, are enclosed by large crystals of augite ($2V\gamma = 53° \pm 3°$; $\gamma : c = 40° \pm 3°$) which have lamellae parallel to the twin plane. The augite is altered marginally to hornblende ($2V\alpha \simeq 75°$; $\gamma : c \simeq 19°$; α = yellow-green, γ = fresh green). The large crystals of augite form clusters, while biotite and iron ore tend to be associated with interstitial quartz away from the clusters.

On Tangent Island the tonalite (N.136.1) shows a greater alteration of the pyroxene to hornblende, forming a sieve structure packed with small grains of iron ore. The interstitial quartz has an undulose extinction.

Of the isolated tonalite bosses, that of the Outcast Islands (N.254.1) may be considered typical. Rather more acid than the previous examples, the plagioclase is zoned from a core of An_{40} to a margin of An_{16}, and the core is usually slightly sericitized. Pyroxenes are absent. The large subhedral hornblende crystals have a pleochroism α = pale yellow, β = brown-green, γ = pale green, are frequently twinned and include many small tabular plagioclase crystals.

The southern tonalite boss on the Joubin Islands and rocks on islands midway between Arthur Harbour and Cape Monaco are similar to the tonalite of the Outcast Islands but increased sericitization of the feldspar, and a greater quantity of chlorite and epidote reflect the proximity of the Cape Monaco Granite.

Veins of aplitic material are associated with the primary tonalites. One such vein (N.239.1), from the Outcast Islands, consists of coarse crystals of plagioclase (2.0 mm., zoned An_{43-18}) and quartz surrounded by a much finer quartz-orthoclase material (Table VII). More common are narrow fine-grained (0.1–0.2 mm.) veins involving two rock types, one of plagioclase and quartz, the other of orthoclase and quartz (N.255.3). In an example from Billie Peak (N.78.1) the quartz-plagioclase type appears to be the earlier.

C. The Hybrid Rocks

The majority of rocks in the Börgen Bay area, in the central part of Wiencke Island, on Doumer Island (Fig. 2) and on the Wauwermans Islands are interpreted as hybrid rocks. Variable and patchy in the field, they range from gabbros to acid tonalites and are cut by irregular patches and veins of more acid material. Gradation from one type to another is typical while contacts and igneous laminations are absent. A number of outcrops are described in detail to illustrate these points.

1. *Doumer Island*

The primary tonalite on Doumer Island (Fig. 2) may be briefly mentioned here as an example of an early stage in the hybridization of the primary intrusions. This tonalite is more variable in texture and composition than that on Billie Peak. Its much weaker igneous lamination is a direct reflection of the greater alteration of pyroxene to hornblende and iron ore. Large tabular crystals of plagioclase (N.95.1) are zoned normally from An_{65} to An_{28}. Relics of both ortho- and clinopyroxene remain within the hornblende crystals (α' = yellow-green, γ' = rich green with paler blue-green borders), and large plates of biotite surround groups of the pyroxene-hornblende crystals and the associated iron ore.

These ferromagnesian clots are typical of the hybrid rocks. Barth and Holmsen (1939, p. 20) suggest they are the remnants of inclusions but their derivation from the large ophitic clinopyroxene crystals of the primary tonalite is indisputable. Moreover, their great number, small size and even distribution is evidence against that mode of origin.

2. *Fang Buttress*

Fang Buttress protrudes into the eastern side of William Glacier (Fig. 10) where it terminates in a large cliff face. From north to south a bytownite-gabbro changes gradually to a basic diorite. In the gabbro (N.64.2) the large tabular crystals of bytownite (3.0 mm.) are zoned normally from An_{85} to An_{68}. Both the bytownite and pyroxene ($2V\gamma = 56° \pm 3°$; $\gamma : c = 37° \pm 3°$) appear to have crystallized simultaneously, but the pyroxene has been extensively altered to hornblende ($2V\alpha = 78° \pm 2°$; $\gamma : c \simeq 17°$; α' = colourless, β' = pale yellow-green), which has developed as small optically continuous blebs within the pyroxene to form a sieve structure. Anhedral masses of iron ore are concentrated around the pyroxene-hornblende crystals. Biotite and chlorite are also present, and the thin section is cut by a narrow vein of quartz, chlorite, hornblende and epidote.

Aplites and pegmatites cut the gabbro. The pegmatite shows obvious contamination. Adjacent to the country rock it is composed of andesine, epidote and chlorite, and the larger crystals of andesine (2.0 mm.) are partially altered to sericite and epidote. A few ragged relics of pale green hornblende are altered to chlorite and in some instances to calcite. Nearer the centre of the vein the plagioclase has broken down to small crystals of a more sodic type, surrounded and largely replaced by orthoclase, the remnants still crowded with sericite-epidote material. Chlorite flakes are abundant but the rock is essentially one of quartz and orthoclase, and the average grain-size is approximately 0.5 mm. In the centre of the vein only quartz and orthoclase occur as large interlocking grains up to 3.0 mm. across.

The variable composition of the basic diorite at the southern end of the cliff face (N.62.1) is reflected in the plagioclase (3.0 mm.). In these the zoning is normal and continuous. While some crystals have a core to margin variation from An_{55} to An_{44}, others vary from An_{43} to An_{35}. Occasional examples have cores as basic as An_{62}. These compositions were measured accurately on the Universal Stage at right angles to the (001) and (010) cleavage traces. The variation in the crystal margins is most significant, indicating a considerable lack of equilibrium.

Large augite crystals, as much as 4.0 mm. square, are ophitic towards the plagioclase and enclose smaller orthopyroxenes. They show considerable alteration to hornblende (α' = pale yellow, γ' = olive-green), which also forms separate poikilitic crystals, often as isolated but optically continuous interstitial areas including grains of iron ore. More iron ore occurs around their margins and separate groups have formed in association with biotite. The biotite forms late-stage veinlets. A small quantity of interstitial quartz is present.

High in the centre of the cliff face is a large unorientated mass of acid material which sends out veins and stringers into the surrounding rock. Specimen N.63.1 was collected from one such vein 12 in. wide. Long plagioclase crystals (1.0 mm.), zoned sharply from An_{47} to An_{20}, are set in a fine groundmass of quartz, orthoclase, biotite, hornblende and iron ore. Quartz and orthoclase are approximately equal in quantity and together equal the amount of ferromagnesian minerals, of which biotite is the most abundant. The groundmass has attacked the margins of the plagioclases and veins them. Apatite needles are numerous.

3. *Ridge below Green Spur*

Green Spur, on the east side of Copper Peak (Fig. 10), presents a dramatic cliff face to the Neumayer Channel. A rock ridge leads up from the shore towards this face, in the centre of which there is a large malachite stain.

On the shore the rock is a diorite (N.91.1), in which large tabular crystals of plagioclase (2.0 mm.) have a discontinuous zoning from bytownite to oligoclase, thus:

core An_{86} An_{64}–An_{40} An_{24} *margin*

One or more of the most basic patches occur towards the centre of the crystals with compositions varying from An_{86} to An_{74}. In a number of cases the intermediate zone is missing and the composition changes abruptly from bytownite to oligoclase. The hornblende ($2V\alpha = 65° \pm 4°$; $\gamma : c \simeq 15°$; α' = pale yellow, γ' = brown-green) includes relics of an earlier pyroxene. The outer margins of the hornblende are blue-green, and this late variety occurs with sericite as an alteration product of the plagioclase.

Higher on the ridge the rock becomes paler and is brecciated by large quantities of aplite material. Towards the top the country rock (N.92.2) is again variable with the overall composition of a tonalite. Most plagioclase crystals (0.5–1.0 mm.) are zoned normally from An_{65} to An_{20} but occasional larger crystals have highly altered cores representing still more basic relics. Subhedral hornblende crystals (α' = pale yellow, γ' = olive-green) have margins of a blue-green variety. Interstitial quartz forms over 10 per cent of the rock and orthoclase forms small interstitial patches and veins. Sphene is rather abundant and is associated with iron ore and occasionally chlorite.

In the aplite (N.92.1) plagioclase crystals (0.5 mm.), zoned normally from An_{67} to An_{16} with some sericitization, form approximately 15 per cent of the rock. They are set in a finer (0.3 mm.) matrix of quartz and orthoclase which forms a web-like texture. Small biotite flakes with some hornblende (α' = colourless, γ' = blue-green) and iron ore form approximately 5 per cent. Replacement of the plagioclase by quartz and orthoclase is very obvious, the former proving the more active marginally, while the latter tends to form patches and stringers through the plagioclase centres.

A pale grey dyke, 60 ft. wide, which cuts across the primary tonalite of Billie Peak, is similar to the hybrid diorites already described. 65 per cent of the rock (N.79.1) is composed of small plagioclase crystals (0.5–1.0 mm.), zoned from a fairly extensive core of An_{90} to margins of An_{16}. The central parts are severely cracked and partially altered to epidote which is associated with some hornblende blebs and iron ore. Many of the basic cores are welded together by the marginal oligoclase. No quartz or potash feldspar was identified. Severely cracked crystals of clinopyroxene are surrounded by a broad rim of hornblende (α' = pale yellow, γ' = pale yellow-green). A second amphibole, which forms either sheaves of elongated crystals or ragged crystals of low birefringence, comprises approximately 10 per cent of the rock. Interstitial patches of bright green chlorite with deep blue interference colours are common.

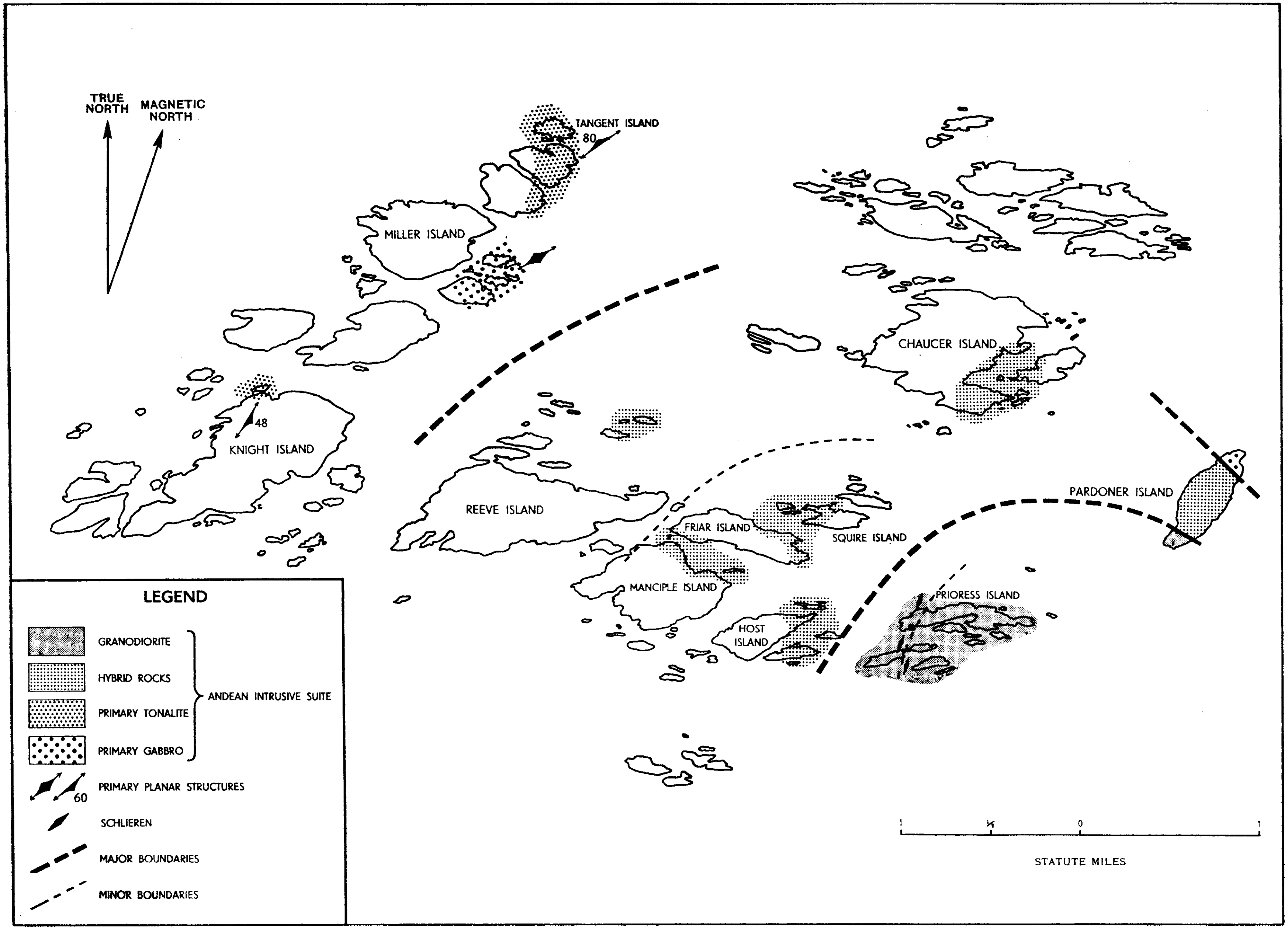


FIGURE 11
Geological map of the Wauwermans Islands

4. *The Wauwermans Islands*

The central group of the Wauwermans Islands (including Reeve, Chaucer, Manciple, Friar, Squire and Host Islands; Fig. 11) is composed of variable and patchy hybrid rocks which lack primary structures. To the west and north the intrusive structures of the primary tonalite and gabbro strike parallel to the approximate boundary between these rocks and the hybrids. As indicated in Fig. 11 all these structures conform to a concentric pattern.

On the south-east corner of Chaucer Island the country rock (N.124.1) is very dark in the hand specimen but has the composition of a quartz-diorite. The plagioclase, zoned normally from An_{56} to An_{40}, has suffered some alteration to sericite and epidote in the crystal cores and is cut by stringers of hornblende. The crystals are tabular and up to 5.0 mm. long. The quartz forms interstitial patches apparently replacing the plagioclase. Stout prisms of hypersthene are surrounded by clinopyroxene, and both are surrounded and replaced by hornblende (α' = pale yellow, γ' = blue-green). Both pyroxenes possess a Schiller structure. Biotite, chlorite and iron ore are also present in fair quantity.

On small islands north-east of Reeve Island the country rock (N.130.2) is rather paler. The plagioclase is zoned normally from An_{44} to An_{33} and is replaced around its margins by quartz, which occurs in patches and has shadowy extinction. Both ortho- and clinopyroxene are present but they are extensively replaced by hornblende, biotite and iron ore. Biotite and iron ore also form separate groups. Most of the hornblende is in ragged crystals (α' = pale yellow, γ' = blue-green) but some pyroxenes have been altered to an almost colourless, fibrous mineral with a small extinction angle. Occasional large apatite crystals are present.

To the south-west, on Manciple, Friar, Squire and Host Islands, the hybrid rocks are particularly variable and patchy. The physical mixing of a basic and acid type is obvious in the field. On the north-east tip of Host Island and the adjoining smaller islands the two types are most distinct. The basic rock (N.122.1) is a coarse-grained gabbro in which the plagioclase crystals (An_{70-64}) are cracked and bent. Large crystals of clinopyroxene, orthopyroxene, hornblende and iron ore form large clots. The pyroxene crystals are altered to hornblende with a typical sieve structure and are separated by large masses of iron ore (Plate Va). The hornblende has a pleochroism α' = pale yellow, γ' = pale brown at the crystal centres but blue-green at their margins. The plagioclase crystals reach a length of 6.0 mm. and the clinopyroxenes 4.0 mm. Leucoxene and apatite are present as accessories.

The acid rock (N.121.2) is pale grey and medium-grained. Large ragged crystals of plagioclase (2.0–4.0 mm.), zoned normally from An_{37} to An_{24}, are surrounded and often crossed by a slightly finer-grained material composed of equant grains of quartz and plagioclase with clinopyroxene, biotite and iron ore. The pyroxene is partially altered to hornblende. Apatite is abundant. This rock is an augite-tonalite in which both the mineralogical composition and the texture indicate a hybrid origin.

The modal analyses of four hybrid rocks are given in Table VIII.

D. Granodiorites

Unlike the hybrid rocks just described the granodiorites have a uniform appearance. Pale grey and medium-grained in the field, they have a distinctive texture under the microscope. They crop out on the west side of Gateway Ridge (Fig. 10), on Wall Range, Wiencke Island (Fig. 2) and on Prioress Island in the Wauwermans Islands (Fig. 11).

A modal analysis is given in Table VIII. The plagioclase zoning, while complicated and often oscillatory, changes overall from a core of An_{50} to a margin of medium oligoclase. The orthoclase has $2V\alpha = 51–60°$, and the hornblende has $2V\alpha = 72° \pm 4°$; $\gamma : c \simeq 16°$; α = colourless, $\beta = \gamma$ = pale green. In one case (N.47.2) interstitial calcite has replaced hornblende.

The plagioclase occurs in all shapes and sizes with marked zoning and exceptionally complex twinning. It is the unusual structure in this mineral which gives the granodiorite its characteristic texture. Zoned crystals have been split apart and injected by the marginal oligoclase, and large groups of crystals with separate orientations show the same zonal pattern (Plate Vb). Resorption of the plagioclase is indicated by the presence of small crystals surrounded by large irregular masses of quartz and alkali-feldspar. The hornblende, still ragged but showing an obvious tendency in places to develop a prismatic form, is closely

TABLE VIII

MODAL ANALYSES OF HYBRID ROCKS AND GRANODIORITE

	N.91.1	N.124.1	N.49.1	N.132.1	N.126.1
Quartz	7.5	6.5	20.4	22.0	24.2
Alkali-feldspar	—	—	—	0.9	10.1
Plagioclase	59.2	63.4	55.5	59.3	58.2
Biotite/chlorite	4.1	5.6	6.0	11.3	5.3
Hornblende	27.0*	23.9*	16.3	5.1	1.4
Iron ore	2.2	0.6	1.8	1.1	0.6
Apatite	+	—	+	+	0.1
Sphene	+	—	+	0.3	0.1
Epidote	—	—	—	+	—
Zircon	—	—	—	—	+
Plagioclase composition	An_{86-24}	An_{56-38}	An_{63-26}	An_{50-30}	An_{50-22}

* includes pyroxene
\+ present in small quantity

N.91.1 Gabbro-diorite, below Green Spur, Anvers Island.
N.124.1 Gabbro-diorite, Chaucer Island, Wauwermans Islands.
N.49.1 Tonalite, north of Gateway Ridge, Anvers Island.
N.132.1 Tonalite, small island south-west of Prioress Island, Wauwermans Islands.
N.126.1 Granodiorite, Prioress Island, Wauwermans Islands.

associated with iron ore, sphene and apatite. Such groups may be seen huddled together in the centre of a quartz mass.

The field relations between the granodiorite and other members of the Andean Intrusive Suite are only exposed on the Wauwermans Islands. On Prioress Island the number of inclusions in the granodiorite increases rapidly towards the west, where a zone of orientated inclusions runs across the island (Fig. 11). With their increase the country rock becomes darker in colour (N.132.1; Table VIII). The plagioclase is fresher and the hornblende/biotite ratio is higher. Quartz has replaced plagioclase, some crystals of which show the truncated oscillatory zoning characteristic of the normal granodiorite. The occurrence of orthoclase is sporadic and it forms large interstitial masses where it does occur. This rock is hybrid and grades into the acid types of Host Island.

On Pardoner Island simple physical mixing between the granodiorite of the southern tip and the primary gabbro of the northern tip can be demonstrated, since many sheets and veins of granodiorite penetrate the earlier gabbro. One such vein collected from the northern end of the island (N.137.3) contains interlocking crystals of plagioclase (An_{46-18}) and quartz (1.0 mm.) with interstitial orthoclase. The small quantity of ferromagnesian material is mainly biotite altering to chlorite and iron ore. Occasional larger crystals of plagioclase are present.

E. INCLUSIONS

Inclusions have not been recorded in the primary gabbros but are usually present in the primary tonalite and are abundant in both the hybrid rocks and the granodiorites. With one exception, they are finer-grained and darker than the country rock.

South of Fang Buttress, on the east side of William Glacier (Fig. 10), a fine dark rock is exposed on the lower parts of a rock ridge. Veins of hybrid tonalite, from a mass exposed higher on the ridge, penetrate the dark rock.

The latter is a hornfelsed hypersthene-gabbro (N.73.1). Unzoned plagioclase (An_{59}), with simple Carlsbad twinning, and hypersthene ($2V\alpha = 56° \pm 2°$) are the essential minerals. A narrow reaction rim of clinopyroxene surrounds the orthopyroxene and iron ore is present. Grains are interlocking and equidimensional, the feldspars being slightly larger (0.8 mm.) than the hypersthene (0.3 mm.) and the iron ore (0.1 mm.).

Smaller inclusions in the hybrid rocks around William Glacier are elongated bodies with parallel sides, and easily mistaken for dykes from a distance (Fig. 12). They terminate abruptly, however, and are crossed by veins from the country rock. Petrologically they are similar to the hornfelsed hypersthene-gabbro mass. Plagioclase crystals vary in size from 0.80 to 0.25 mm. and the ferromagnesian minerals are always slightly smaller. The plagioclase composition is usually similar to that of the country rock. Hypersthene, clinopyroxene, hornblende or any combination of these may comprise the ferromagnesian minerals. Hornblende invariably encloses pyroxene relics, usually clinopyroxene. Both augite and hypersthene occur in N.77.1. The augite ($2V\gamma \simeq 45$–$55°$) is rather patchy and encloses ill-defined orthopyroxene relics ($2V\alpha \simeq 52°$), while independent crystals of fresh hypersthene ($2V\alpha = 45° \pm 2°$) are also present.

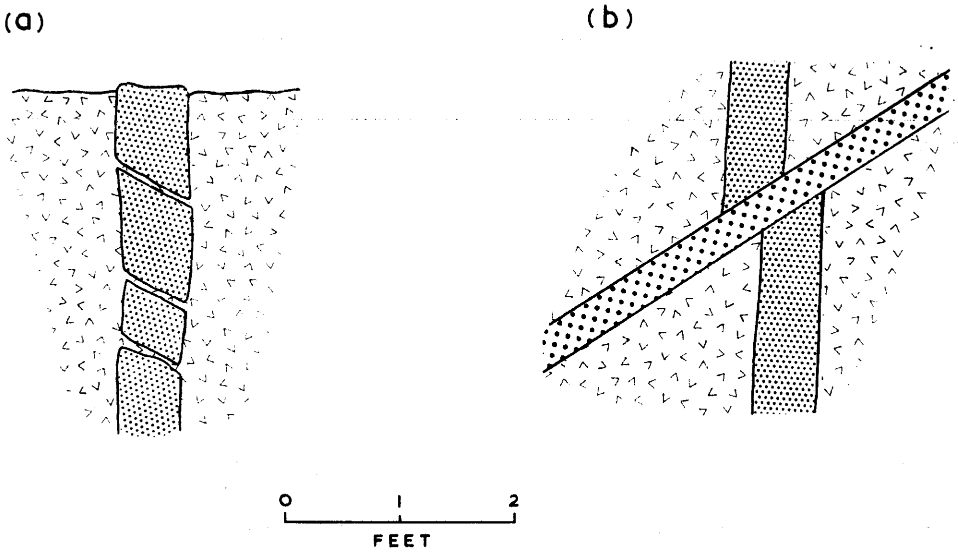


FIGURE 12

Field sketch of dyke-like inclusions in the hybrid rocks of the Börgen Bay area. In (a) the inclusion is crossed by narrow veins of the country rock, and in (b) both country rock and inclusion are cut by a feldspathic vein.

Occasional smaller inclusions are rounded with graded contacts (N.74.1). Towards the inclusion the large poikilitic hornblende crystals (4.0 mm.; $\alpha' =$ yellow, $\gamma' =$ olive-green) of the tonalite become smaller, paler and more poikilitic ($\alpha' =$ pale yellow, $\gamma' =$ green). Quartz is absent near the centre of the inclusion and the hornblende gives way to small colourless crystals of clinopyroxene.

Frequently inclusions become so numerous in the hybrid tonalites that the country rock is reduced to an interfragmental veining. Such veins are paler than the normal country rock. Examples may be cited from the spotted nunatak on the east side of William Glacier, from Port Lockroy and from the Wauwermans Islands (Plate IId).

On the Wauwermans Islands inclusions are particularly abundant in the variable hybrid rocks of Host, Friar and Squire Islands. The larger (very approx. from 6 in. to 6 ft.), more clearly defined examples (N.127.3) have two generations of plagioclase. Larger crystals (1.0 mm.), zoned normally from An_{40} to An_{20}, include small crystals of hornblende and biotite similar to those in the groundmass. The groundmass is composed of the smaller generation of plagioclase crystals which are zoned normally from An_{52} to An_{34} with hornblende ($\alpha' =$ pale yellow, $\gamma' =$ pale green). Quartz is usually absent. The hornblende crystals include small grains of iron ore and carry relics of either clinopyroxene or orthopyroxene. Narrow veinlets, some of hornblende and others of hornblende and biotite, cross the rock. The hornblende in these veins is a deeper green than that of the country rock.

Smaller (usually < 6 in.), ill-defined inclusions differ from the country rock in their finer grain-size (0.3 mm.) and higher proportion of ferromagnesian minerals. Quartz is usually absent but potash feldspar may occur with the two generations of plagioclase (N.127.1).

The pale rock in and around the larger groups of inclusions has a granodiorite composition (Plate IId; N.128.1B). The majority of plagioclase crystals are approximately 1.0 mm. long with vaguely-defined twin planes and uneven zoning. A few have fairly clear twinning but severely sericitized cores, and there is one fresh crystal, 4.0 mm. long, zoned from An_{42} to An_{24}, which includes a few grains of hornblende and biotite at its centre. Reaction between the margins of these crystals and the interstitial quartz and feldspar is particularly obvious.

The quartz has an undulose extinction and has replaced both plagioclase and hornblende. The potash feldspar is interstitial towards the quartz, often separating that mineral from the plagioclase. Hornblende (α' = pale yellow, γ' = green) is the predominant ferromagnesian mineral; it has been attacked by both quartz and biotite. One case of a pyroxene relic within hornblende was noted. The iron ore is ilmenite and is almost invariably surrounded by sphene. Accessory apatite is present. All stages in the formation of this rock by the introduction of aplitic material into the included rock may be followed in the hand specimen (Plate IId) and under the microscope. Crystals of zoned plagioclase and hornblende appear to have formed first, only to be attacked at a later stage by quartz and potash feldspar.

Small, rounded grey inclusions with ill-defined borders are typical of the granodiorite. The smallest of these form microscopic patches in which the plagioclase is smaller and more highly altered than in the surrounding rock. Quartz is absent and the predominant ferromagnesian mineral is hornblende (α' = pale yellow, γ' = pale blue-green) partially altered to chlorite, iron ore and sphene.

Larger inclusions (6 in. diameter) in the granodiorite have a hornfelsic texture with small subhedral grains of hornblende (α' = pale yellow, γ' = blue-green) embedded in a mosaic of equidimensional plagioclase and quartz crystals, of which the former are predominant. The grain-size averages 0.5 mm. The plagioclase crystals are oligoclase (An_{20}) but a few larger crystals have an altered, more basic, core. Comparatively large poikilitic flakes of biotite are scattered through the rock with occasional small grains of interstitial potash feldspar.

One inclusion, paler than the country rock, was found in the hybrid tonalite on Wiencke Island, near Port Lockroy (N.311.2). Large crystals of albite (3.0 mm.) show well-developed twinning and carry considerable quantities of epidote, chlorite and calcite. Hornblende (α' = pale yellow, γ' = olive-green), now largely replaced by chlorite, is associated in clots with iron ore and sphene. The interstitial quartz is remarkable for not possessing undulose extinction.

F. Discussion

From their banding and igneous lamination it is concluded that the primary gabbro and primary tonalite were intruded into their present position. They may be compared with the Andean Intrusive Suite (Adie, 1955). It is possible that magmas of other compositions were intruded at the same time but these have not been recorded from the Anvers Island area. There is, however, some variation in the compositions of the various primary gabbros and tonalites which may reflect normal magmatic differentiation.

The persistently high dip of the banding in the gabbro is in contrast to the typical layering (horizontal) of larger gabbro masses (e.g. the Bushveld Complex and the Skaergaard Intrusion). There is no evidence for subsequent tilting of the Andean rocks of Anvers Island so it can be concluded that the banding is due to injection of a heterogeneous gabbro magma rather than to convection currents and gravity settling *in situ*. Thus the first episode in the formation of the coarse Andean rocks within the Anvers Island area was the rising of two distinct magmas, a heterogeneous gabbro magma and a homogeneous basic tonalite magma.

The contacts of the intrusions are frequently faulted. This is particularly obvious on Wiencke Island and is reflected in the retrograde metamorphism on the Outcast Islands (p. 15). On Wiencke Island (Fig. 2) the faults control the positions of the deep channels, trending either north-east/south-west parallel to the axis of Graham Land or east/west across this axis. All are approximately vertical. Similar faulting is a feature of the Graham Coast south of Anvers Island.* It is suggested that a system of regional block faulting occurred during the intrusion of the Andean Intrusive Suite and that this played an important part in the elevation of Graham Land during Andean times. In this respect the structure of Graham Land can be compared to that of the western zone of the Andes (Oppenheim, 1947).

Evidence for the hypothesis that the vast majority of intermediate rocks of the area do not represent original magmas but were formed by the later addition of aplitic material to the two intrusive rocks may be summarized as follows:

i. Lack of primary structures.
ii. The patchy composition of the rocks, in particular the variable composition of the plagioclase, which is often associated with extreme zoning, two generations of plagioclase and the very patchy distribution of the quartz.
iii. Complete gradation between the various types.
iv. The presence of large quantities of more acid hybrid material in veins and patches.
v. The textures.
vi. The physical mixing and concentric pattern on the Wauwermans Islands.

Points i–iv have been discussed in the previous sections. Because textures are frequently ambiguous, a brief review of the more important types is given below together with the writer's interpretations of their origin and significance.

Most important are the large ferromagnesian clots which are typical of all the hybrid rocks. Normally they consist of pyroxenes, hornblendes and iron ore. Olivine pseudomorphs may be present in the centre while biotite and chlorite may be marginal associates. Every gradation is present from large ophitic pyroxene crystals with slight marginal alteration to hornblende, through masses in which pyroxene crystals are surrounded and riddled by small hornblende blebs in optically continuous groups and peppered with iron ore, to poikilitic hornblende crystals with ragged margins and surrounded by large anhedral crystals of iron ore. It is at this later stage that biotite and chlorite become more abundant and the marginal hornblende develops a blue-green colour when light is transmitted parallel to the slower ray. In the more acid tonalites the hornblendes are rather smaller and may begin to develop their crystal boundaries although they remain ragged. In the granodiorite biotite is more abundant than these subhedral grains of hornblende.

Progressive replacement of pyroxene by hornblende and iron ore might be expected in a normal magmatic sequence. It is the failure of the replacement products to disperse that gives to the hybrid rocks their peculiar clotted texture and indicates that the replacement took place in an essentially solid medium.

The replacement of plagioclase by quartz is frequently mentioned in the preceding pages. It is characteristic of the more acid hybrid rocks and of the granodiorite. Plagioclase crystals with well-developed faces, when in contact with other plagioclase crystals, frequently surround patches of granular quartz, against which their boundaries are undulating with a lobate form. Little grains of plagioclase are frequently isolated from the main crystal to lie just inside the quartz. In addition, twin planes become blurred and finally disappear as the boundary with quartz is approached. Their zoning may also become uneven and patchy. That quartz has replaced plagioclase seems beyond doubt and such replacement indicates the addition of silica-rich material.

In the granodiorite the chief textural characteristics are the apparent splitting and rewelding of the plagioclase crystals, their subhedral form, their oscillatory zoning, the grouping of larger plagioclase crystals and the presence of an apparently later oligoclase-quartz-orthoclase matrix which has replaced the earlier plagioclase and hornblende. The plagioclase crystals are identical to plagioclase porphyroblasts formed metasomatically in the Altered Assemblage (p. 52), and similar features have been described by Misch (1949) and Goodspeed (1959) in rocks which they interpret as hybrid or metasomatic in origin.

It is suggested that the granodiorite represents a further stage in the hybridization process, that stage at which the addition of aplitic and volatile material was great enough to produce slight mobilization. Early plagioclase crystals appear to have been cracked during the movement and subsequently recemented and enlarged to produce their peculiar zonal pattern. The band of drawn-out schlieren may be interpreted as the margin of mobilization.

* Personal communication from Dr. R. Curtis.

This hypothesis may also be used to explain the concentric pattern of rock types and structures on the Wauwermans Islands. From the primary rocks of the north and west margins the addition of aplitic and volatile material increases towards the granodiorite. Here it was enough to remobilize the hybrid rocks.

Alternatively, the pattern could be explained by the rise of a normal granodiorite magma. Against this, however, is:

i. The peculiar texture of the rock.
ii. The large area of hybrid rocks between the granodiorite and the primary intrusions.
iii. The great volume of similar hybrid rock not directly associated with granodiorite intrusions in the Börgen Bay/Wiencke Island area.

If the added material needed to form this volume of hybrid rock entered as a magma, then that magma must have been alpitic, fluid and abundant.

IV. METASOMATIZED MYLONITES

On a pair of minor ridges trending east–west at the north end of Gateway Ridge a hybrid tonalite, more altered than normal, is cut by wide dyke-like bodies of recrystallized mylonite. On the more easterly ridge most of the rock appears to have been affected by the crushing and recrystallization but broad zones of more highly altered rock stand out like large pale dykes (Fig. 13). Similar rock is exposed on Bull Ridge to the north-west (Fig. 10).

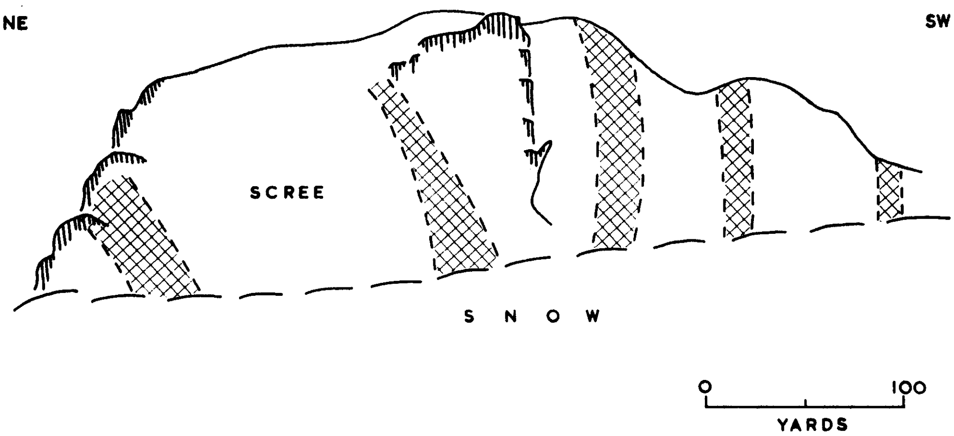


FIGURE 13

Field sketch of minor ridge at the north end of Gateway Ridge showing the wide zones of recrystallized mylonite (cross-hatched).

The country rock at the west end of the more westerly ridge (N.48.8) still shows faint igneous lamination but the original plagioclase crystals (An_{32}) have been extensively replaced by potash feldspar and quartz. They are now mere ghosts surrounded and crossed by stringers of quartz blebs which are optically continuous over areas the size of the original plagioclase crystals (3.0 mm.). Interstitial areas are filled with poikilitic hornblende (α' = pale yellow, γ' = blue-green) now largely replaced by biotite and iron ore. Apatite and leucoxene are present.

A sharply defined mylonite zone, 6 ft. wide, crosses the country rock and its associated aplites. The margins of the zone (N.48.6) possess a contorted banding and they are cut by chilled basic dykes. Under the microscope small angular fragments of quartz and plagioclase lie in a finer matrix of the same minerals, together with chlorite, epidote and iron ore. The banding is the result of the streaking out of even finer bands or veins. This rock is a mylonite which has suffered little recrystallization.

In the centre of the zone the rock (N.48.5) has a vague groundmass of quartz and plagioclase in very small irregular crystals, in which have grown porphyroblasts (1.0–4.0 mm.) and glomeroporphyroblastic groups of plagioclase (Plate Vc). All stages in the development of the porphyroblasts are present from vague areas, distinguished only by a common extinction, to crystals with euhedral faces and sharp complicated twinning. A faint normal zoning can occasionally be discerned. In all cases the porphyroblasts are packed with inclusions and cannot be distinguished under ordinary light. Chlorite, epidote and iron ore occur throughout the groundmass.

The rocks of the more easterly ridge show similar features. Some have a uniform fine grain-size without porphyroblasts, while others carry large well-developed porphyroblasts and glomeroporphyroblastic groups. In addition to their complicated twinning and crystal faces the better developed porphyroblasts possess an oscillatory zoning (N.51.1; Plate Vd). The composition of the plagioclase is within the oligoclase range.

On Bull Ridge the rocks are both more acid and more completely recrystallized than the rocks described above. The majority of porphyroblasts are of quartz with a few of sodic plagioclase, probably albite. Development of the quartz porphyroblasts can be traced from small groups of differently orientated crystals, through groups of larger crystals separated by stringers and interstitial areas of the groundmass and with orientations, which are similar but not the same (Plate Ve), to large crystals with undulose extinction (Plate Vf). Thus the larger crystals appear to have the power to re-orientate their smaller neighbours until their optical directions coincide (N.212.1).

As the porphyroblasts increase in size and number, the groundmass is reduced to interstitial patches and a general debris through the now well-developed crystals of albite (N.219.1). The final stage is a coarse microcline-granite (N.216.1) in which the only signs of a mylonitic origin are occasional groups of small rounded inclusions within the plagioclase and microcline, and the marked undulose extinction of the quartz grains. Hornblende, biotite and iron ore fill areas interstitial to the major constituents (Table IX).

TABLE IX

MODAL ANALYSES OF GRANITES

	N.216.1	N.145.1	N.140.2	N.140.3
Quartz	31.0	27.5	} 61.4	} 40.5
Alkali-feldspar	17.5	20.4		
Plagioclase	38.8	43.9	26.1	42.7
Chlorite	11.2*	6.7*	2.9	3.7
Iron ore	1.5	1.5	1.7	1.6
Apatite	+	+	+	+
Sphene	+	—	+	+
Epidote	+	+	7.9	11.5
Prehnite	—	—	+	—
Zircon	—	—	—	—
Plagioclase composition	An_{37-27}	An_{23-10}	An_{10}	An_{0-3}

* includes relics of hornblende and biotite
\+ present in small quantity

N.216.1 Microcline-granite, Bull Ridge, Anvers Island.
N.145.1 Cape Monaco Granite, Cape Monaco, Anvers Island.
N.140.2 Cape Monaco Granite, Gossler Islands.
N.140.3 Inclusion in Cape Monaco Granite, Gossler Islands.

Thus the growth of plagioclase porphyroblasts with oscillatory zoning and of quartz porphyroblasts with irregular extinction can be followed step by step from mylonite to a microcline-granite. The apparent relation between the degree of recrystallization (measured by the ratio of porphyroblasts to matrix) and composition could be due to coincidence or to the greater ability of the more acid mylonite to recrystallize. Yet the most obvious explanation is that the degree of recrystallization was controlled by the introduction of silica and potash. This is enhanced by the lack of any known granite of the Andean Intrusive Suite in the area. If such material was present at depth in a volatile state it would find in such major crush zones a natural route towards the surface. Evidence from the hybrid rocks associated with the Andean Intrusive Suite, from the Altered Assemblage and from the Cape Monaco Granite indicates that such material was indeed available.

V. METASOMATIZED TONALITES

ON a small group of islands immediately west of Dream Island (Fig. 14) small patches of Cape Monaco Granite have developed within an altered country rock. The alteration of the country rock is due to the metasomatic introduction of silica and alkalis from the granite, and the wide extent of the alteration indicates the presence of the granite just below most of the rocks exposed.

In the typical metasomatized rock (N.268.1, N.272.1) anhedral to euhedral crystals of plagioclase (0.5–1.0 mm.) are surrounded by a finer quartz/alkali-feldspar material. The crystals of plagioclase are zoned normally in most cases from medium andesine to albite. Some have cores packed with epidote and flakes of brown biotite while the larger examples, which in general have oscillatory zoning and better developed crystal faces, are oligoclase with wide albite margins. Instances of single plagioclase crystals or groups apparently split and recemented by the marginal albite have been recorded.

The feldspar of the finer interstitial material is in part albite and in part a potash variety. The irregular grains of quartz have an undulose extinction and have replaced much of the plagioclase, penetrating the crystals and frequently enclosing relics. A narrow reaction zone of albite always separates the more basic plagioclase from the quartz. Clusters of small brown biotite flakes are scattered through the rock, and are associated with epidote, iron ore and chlorite. Apatite is also present.

It is concluded that the original rock had a dioritic or tonalitic composition and that it has been soaked in material rich in silica and alkalis. Primary andesine has been largely replaced by quartz and albite, the oscillatory zoning being a result of diffusion of more sodic material towards the andesine cores. The albite has a tendency to develop crystal faces. Original ferromagnesian minerals have been altered to biotite with epidote and iron ore.

The patches of Cape Monaco Granite are circular, about 12 ft. in diameter, with their contacts graded over approximately one inch. Close to these patches the country rock (N.271.1) is darker than usual, being much richer in biotite and with occasional crystals of plagioclase with cores as basic as An_{60}. The general features of the rock, however, are similar to those of the typical example described. The biotite appears in two generations, an earlier brown variety and a later deep green variety. Both form clusters and stringers of small flakes. Iron ore, epidote and sphene are associated with biotite.

The granite itself is composed of large crystals of albite and quartz in a finer matrix of quartz and perthite with smaller clusters of brown and green biotite. It differs from the country rock in its smaller quantity of dark minerals, the larger proportion, smaller grain-size and more potash-rich nature of the matrix, and the larger and better developed porphyroblasts of quartz and albite.

Coarse-grained rocks on islands *J1* and *G1* of the Joubin Islands have the same rather blotchy appearance in the field as the metasomatized rocks described above but they are coarser and slightly paler (N.286.1, N.421.1, 3). Large subhedral crystals of albite (An_9) include considerable quantities of chlorite and epidote. Between these are rather smaller quartz crystals which enclose relics of albite and develop intergrowth structures with a potash feldspar. The most important dark mineral is epidote which occurs with chlorite, biotite and iron ore. Allanite is associated with the epidote.

The texture is very variable. In some patches large albite crystals are absent and their place is taken by smaller, zoned plagioclase crystals similar to those in the metasomatized rock just described. In others, long thin albite crystals form a vague radiating pattern surrounded by a quartz/potash feldspar intergrowth (N.421.3). This rock is now an alkali-granite. Close to the contact against volcanics on island *G1* (N.273.1) the larger plagioclase crystals are zoned with cores as basic as An_{26} and in many the zoning is oscillatory.

It is concluded that these rocks originated as a more basic intrusion, probably a primary tonalite and that they have been metasomatized to an alkali-granite by an underlying mass of the Cape Monaco Granite.

VI. THE CAPE MONACO GRANITE

THE Cape Monaco Granite occupies a narrow belt at least forty miles long and five miles wide along the north-west coast of Anvers Island. In the field the rock has a distinctive appearance with large crystals of quartz and white feldspar in a finer matrix. The texture varies from one in which the large crystals are sparsely scattered through an aplitic matrix to one in which a coarser matrix is confined to small areas interstitial to the large crystals.

The type locality includes the peninsula immediately north of the main cliffs of Cape Monaco and the neighbouring Gossler Islands (Fig. 14). The granite crops out on the north-west members of the Joubin Islands to the south and on most of the isolated headlands as far north as Cape Bayle. The approximate north-west and south-east boundaries are shown in Fig. 1. Dark rocks form the islands north-west of island *D1* in the Joubin Islands, the Rosenthal Islands and the offshore islands opposite Bonnier and Giard Points. North-west of Perrier Bay the rock of the offshore islands is dark compared with the granitic material exposed below the ice cliff of the main island. The rock at Quinton Point has an intermediate colour.

A gradual change from Cape Monaco Granite to dark rock can be observed between Bonnier and Giard Points. The granite country rock of the two points contains dark inclusions which become increasingly abundant towards the north-west until, on those islands farthest from the shore, the rock is wholly dark. On the Rosenthal Islands the dark rocks are altered volcanics. At Quinton Point the rocks of intermediate colour are brecciated and recrystallized volcanics, similar in many respects to the metasomatized volcanics on the Joubin Islands (p. 20).

The south-east boundary of the granite is exposed on the Joubin Islands where it follows an earlier tonalite/volcanics contact. It occurs again on the small islands immediately west of Dream Island and can be located within half a mile on the south-west coast of Anvers Island. In detail it is much more irregular than indicated and the granite probably underlies much of the area eastwards to Arthur Harbour (Fig. 1; p. 58).

A. CAPE MONACO AND THE GOSSLER ISLANDS

At the type locality the Cape Monaco Granite is massive without any structural features beyond a jointing which may be well-developed locally, but which possesses no comprehensible pattern over a wider area. It is crossed by various types of fine-grained acid veins and sparsely distributed basic dykes. Only one small inclusion was recorded. Two modal analyses are given in Table IX.

Microscopic examination reveals large rounded crystals of quartz and plagioclase (2.0–5.0 mm.) separated by smaller crystals of quartz and potash feldspar. Ferromagnesian minerals form 5–10 per cent of the rock.

The larger plagioclase crystals either possess, or by a concentration of epidote grains show signs of once having possessed, cores of andesine or basic oligoclase surrounded by albite. With the more basic cores is associated a faint but intricate oscillatory zoning superimposed on normal zoning from acid andesine to albite-oligoclase (An_{10}) (N.141.4, N.145.1; Plate VIa). The zoning becomes progressively fainter as albite replaces the more calcic material. In the final stage of the replacement the crystals have a uniform composition of almost pure albite (α': (010) = —18°) speckled with sericite (N.148.3). The cores may still include small grains of epidote and chlorite.

Normally the potash feldspar is associated with quartz in comparatively small grains to form the matrix, but in those rocks in which the matrix is reduced to a minimum and the plagioclase is a uniform albite,

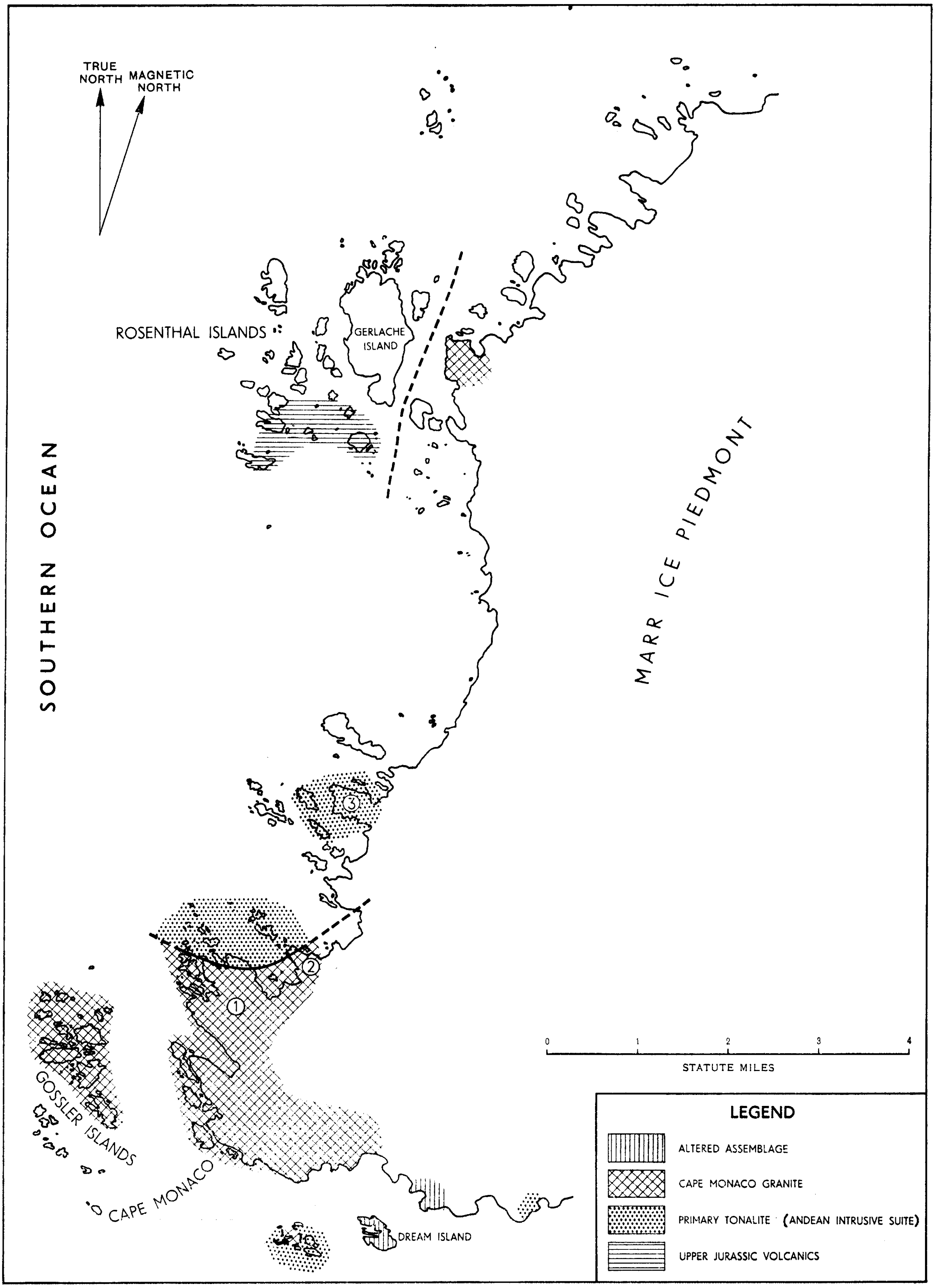


FIGURE 14
Geological map of the south-west coast of Anvers Island.

well-formed crystals of potash feldspar almost as large as those of quartz and albite, are typical (N.147.2, N.148.3, N.149.1; Plate VIb).

Potash feldspar has replaced plagioclase, forming ill-defined areas throughout the earlier crystals but concentrated towards the margins. Separate crystals of potash feldspar frequently contain ghost albite twinning. In those rocks where the potash feldspar is better developed a vague perthitic structure is present and in a few cases apparent microcline twinning has been noted ($2V\alpha = 84° \pm 4°$; N. 148.3).

The size of the quartz crystals varies from that of the potash feldspars (usually < 1.0 mm.) to that of the larger plagioclases (approx. 5.0 mm.). The smaller crystals form optically continuous groups and the extinction of the larger ones is irregular. In addition, the larger ones are speckled with foreign material and towards their margins they enclose cresent-shaped relics of plagioclase and potash feldspar. Two or more large adjacent crystals frequently show almost identical orientations. The crystal margins are extremely irregular, penetrating between and enclosing feldspar crystals and ferromagnesian material, so that crude intergrowths are formed with isolated blebs of quartz optically continuous with the main crystal (Fig. 15). It appears that the large quartz crystals have formed in the solid rock by the growth and coalescence of many smaller crystals, and that the patches of extinction in the large crystals represent former individuals.

FIGURE 15

Irregular quartz crystals in the Cape Monaco Granite. The single crystal (Q_2) is full of inclusions and appears to have replaced the feldspar. Other minerals present include potash feldspar (stippled), albite (lined) and epidote (N.149.1; × 17).

The small quantity of dark minerals is mainly in the form of small green chlorite flakes. These are virtually isotropic and enclose stringers of leucoxene or sphene or both along their cleavages, indicating their formation from biotite. In some rocks this chlorite is rimmed by another with deep blue interference colours. Iron ores include magnetite and ilmenite. The former is rare, remaining unaltered and enclosing needles of apatite, whereas the latter, in small grains scattered through the rock, is almost entirely altered to leucoxene. Occasionally the ferromagnesian minerals are grouped into small clots in which occur crystals of pale green hornblende. Allanite and tourmaline are rare accessories.

There are many varieties of the finer-grained acid veins. In common they lack ferromagnesian material and have a strong tendency to form quartz/orthoclase intergrowths.

Thin pink veins (N.141.2) on one of the Gossler Islands are of quartz and potash feldspar, the two minerals forming either small crude intergrowth structures or separate grains. Small ragged groups of magnetite occur with interstitial epidote. Another narrow vein (N.146.2) high on the Cape Monaco cliffs is formed of intricate intergrowths of the same two minerals often in a radial pattern. Other parts of the vein have a more aplitic appearance with the feldspar predominating. A third (N.149.2), from a nunatak about a mile east of Cape Monaco, is an ill-defined vein 1 in. wide. Its margins grade into the country rock and its intergrowth structures are large and simple. Epidote is abundant with occasional specks of ilmenite altered to leucoxene.

On the east side of the Gossler Islands a wave-washed rock, 30 ft. across, has a gently inclined joint system which is regular. As in the normal granite the quartz grades from small optically continuous grains to large irregular crystals with patchy extinction. Spherical intergrowth structures are centred on one or more of the large quartz grains. Minor quantities of epidote, chlorite (bright green with deep blue interference colours) and magnetite are also present.

The only inclusion (N.140.3) recorded from the type locality is finer-grained and darker than the country rock (Table IX). Albite laths (α' : (010) $= -17°$) with inclusions of epidote, chlorite and a dusty alteration product are surrounded and penetrated by interstitial masses of quartz optically continuous over some distance. Smaller patches of feldspar associated with the quartz are of a potash variety. The quartz has the same patchy extinction as in the country rock. Other minerals include granular iron ore and long groups of chlorite flakes, probably pseudomorphs after hornblende.

Adhering strictly to Nockolds's (1954) classification, the type Cape Monaco Granite varies from granodiorite to alkali-granite. This is due to an admittedly slight variation in the plagioclase composition but is accompanied by a real change in the overall composition and texture of the rock. In the granodiorite large crystals of andesine and quartz are surrounded by a fine quartz/potash feldspar matrix but the alkali-granite is almost equigranular. Textural evidence suggests that the alkali-granite was formed from the granodiorite *in situ* by an increase in the quantity and size of the quartz and potash feldspar constituents, both of which have replaced the plagioclase. The alteration would involve the introduction of silica and potash. Sometime during this process earlier ferromagnesian minerals, either biotite or hornblende, were altered to chlorite while ilmenite altered to leucoxene. The narrow acid veins represent a further stage in the enrichment in silica and potash.

There is an interesting difference in the mode of replacement of plagioclase by quartz and by potash feldspar: the quartz attacks from the outside, breaking off portions and digesting them, whereas the potash feldspar appears to soak through the plagioclase altering large areas simultaneously, and frequently leaving ghost structures.

B. South of Cape Monaco

1. *The Joubin Islands*

Of the Joubin Islands, island *D1* is composed entirely of Cape Monaco Granite, island *B1* is bisected by a granite/tonalite contact and contact types occur on islands *A3* and *A4*. Metasomatism associated with the granite has been recorded from islands *E3* and *E4*, the whole "*F*" group and islands *G1* and *J1* (Fig. 8).

On island *D1* the granite is massive and when jointing is present it is irregular. The numerous dark inclusions frequently form clusters of broad bands and the granite is cut by narrow veins of aplite and basic dykes. Under the microscope the country rock (N.295.1) is similar to that of the type locality. Large crystals of quartz and unzoned albite are separated by slightly smaller grains of quartz and potash feldspar.

One unusual aplitic vein (N.295.2) has fine-grained margins against the granite. Interlocking grains of quartz and alkali-feldspar (0.3 mm.) are in equal proportions. The feldspar has an indistinct perthitic structure and is encircled and penetrated by quartz. The accessories include iron ore, biotite, chlorite and an epidote mineral of low birefringence. Occasional large crystals of quartz and highly sericitized feldspar occur. The fine-grained marginal phase penetrates the country rock and for some distance from the vein it fills angular interstitial areas where it is unusually rich in iron ore. Near the vein the potash feldspar of the granite forms larger, better developed crystals than normal.

The inclusions (N.295.3, 4) have indistinct margins. Large crystals of quartz and plagioclase have developed within them, becoming progressively rarer away from the granite (Plate IIIa). They are composed of medium-sized albite-oligoclase laths with interstitial areas of quartz which are optically continuous over distances up to 3.0 mm. The laths show considerable alteration to sericite and epidote, and often contain patches of potash feldspar around their margins.

The plagioclase porphyroblasts are mainly of albite, well-speckled with sericite, but some have an unaltered core of andesine (An_{32}) with oscillatory zoning. They form isolated crystals and groups from 1.0 to 3.0 mm. across. Once again the quartz crystals form a continuous series from small optically continuous groups, through crude intergrowths, to large crystals with solid centres but abundant relic feldspar towards their margins. The extinction is patchy and the margins are irregular. The ferromagnesian material is more abundant in the inclusions than in the granite. It consists of groups of green biotite flakes associated with iron ore and epidote.

On island *B1* the Cape Monaco Granite is in contact with an earlier boss of primary tonalite belonging to the Andean Intrusive Suite. Here it is exceptional in being straight and vertical (Fig. 8). On a smaller scale, however, it is less regular (Plate IIIb) and to the north it becomes extremely irregular.

The tonalite adjacent to the Cape Monaco Granite contains a concentration of dark inclusions and a number of volcanic lenses trending parallel to the contact. Both are characteristic of its marginal facies against the volcanics. In addition, large plagioclase porphyroblasts are developed within 20 ft. of the contact, increasing in number towards the granite. Two or three feet from the contact they are joined by similar crystals of quartz. These porphyroblasts are similar to those developed in the inclusions on island *D1*. The granite is younger but the present granite/tonalite contact has followed an earlier tonalite/volcanics contact.

A specimen (N.296.1) collected across a comparatively sharp part of the contact has, on the granite side, large rounded crystals of quartz and plagioclase (An_{35}) 2.0–4.0 mm. across. The plagioclase has normal-oscillatory zoning with little difference in composition between alternate zones and includes rounded blebs of biotite and quartz, the latter in optically continuous groups. An interlocking aggregate of smaller crystals (approx. 1.0 mm.) of quartz and plagioclase, accompanied by a fair proportion of biotite, separates the large crystals. Associated with the biotite is a little chlorite, ilmenite and apatite. In composition the rock is a tonalite but it has the texture of the Cape Monaco Granite.

The change across the contact takes place over a few centimetres. On the tonalite side the grain-size is smaller and more even (approx. 1.0 mm.). The plagioclase is more abundant and more basic ($An_{54\text{-}36}$) with normal or normal-oscillatory zoning, the largest crystals having the most distinct oscillatory zoning and including small blebs of hornblende, biotite and iron ore. The quantity of ferromagnesian minerals is greater than in the rock on the granite side and they include as much hornblende (α' = pale yellow, γ' = blue-green) as brown biotite. Ilmenite and apatite are also present. The large porphyroblasts noted in the field do not appear in the thin section.

Two feet from the contact the tonalite (N.296.2) contains plagioclase with cores of An_{68} but still zoned to margins of An_{36} with faint oscillatory zoning. The hornblende crystals are larger and are now well in excess of the biotite which forms large ragged crystals and small veins between the plagioclase and quartz.

A broad aplitic vein crossing the contact (N.296.5) consists largely of quartz and potash feldspar with a few plagioclase crystals zoned from basic andesine to acid oligoclase. Flakes of biotite and chlorite are also present. The grain-size is very irregular (0.1–1.0 mm.), the larger crystals being mainly of quartz and plagioclase and the smaller of quartz and potash feldspar. Most of the latter have an irregular perthitic structure. Some plagioclase crystals are bent and show signs of marginal replacement by quartz.

To the north-east of island *B1* the Cape Monaco Granite is again in contact with the marginal facies of the primary tonalite on islands *A3* and *A4*. Thus for some distance the margin of the granite follows the older tonalite/volcanics contact. The main features of island *B1* are repeated here, although the contact is much less regular, the granite developing in patches within the tonalite. An even greater irregularity is apparent from the presence of a coarse breccia of volcanic and tonalitic blocks on the islands *D3* immediately south-east of island *D1* (Fig. 8).

On islands *A3* and *A4* the inclusions in the granite are of a great variety: various types of hornfelsed volcanics, partially metasomatized volcanics, hornfelsed pre-tonalite dykes and blocks of tonalite. The effect of the granite on these various inclusions has been described on p. 19 – 20, and it need only be repeated here that in many of the inclusions plagioclase and quartz porphyroblasts are developed.

2. *Wylie Bay*

On a small group of islands lying immediately to the west of Dream Island, in Wylie Bay (Fig. 14), three patches of Cape Monaco Granite, each approximately 10 ft. in diameter, have formed within an earlier dioritic rock. The margins of the patches are vague and they contain equally vague aplitic bands which do not penetrate the country rock.

The aplitic material (N.271.3) consists of small interlocking grains (0.2 mm.) of quartz and potash feldspar with groups of epidote crystals associated with bright green biotite and iron ore. The granite consists of large crystals of quartz and albite surrounded by aplitic material. The albite is speckled with sericite and some epidote. Ferromagnesian material forms little clusters of green-brown biotite with iron ore, a little chlorite and a few comparatively large crystals of epidote. The country rock of these islands and its relation to the granite has been described on p. 41.

3. *Summary*

Dark inclusions within the Cape Monaco Granite on island *D1* appear to have originated as basic dykes or volcanics which have been metasomatized. Towards their margins there have developed large porphyroblasts of plagioclase with normal-oscillatory zoning from acid andesine to albite and equally large porphyroblasts of quartz which include numerous crescent-shaped patches of feldspar. These crystals may occur separately or in groups, the latter forming a pseudo-glomeroporphyritic texture. Similar phenomena are present along the granite/tonalite contact on island *B1*, where it appears that the plagioclase porphyroblasts formed slightly in advance of the quartz.

These crystals are identical to the coarser phase of the Cape Monaco Granite itself. It has already been suggested (p. 45) from textural evidence in the type locality that the oscillatory-zoned plagioclase formed first with quartz, followed by quartz and potash feldspar and that quartz crystals grew in the solid rock. Detailed similarity to known porphyroblasts in the Joubin Island inclusions suggests that the plagioclase also developed in a solid medium. Thus, original more basic plagioclase crystals may simultaneously have grown larger and have been altered towards albite with oscillatory zoning developing as a result of the diffusion of more sodic material from the outside of the crystal or group towards the centre. The Cape Monaco Granite close to the contact on island *B1* certainly formed in this manner. That the whole granite mass is a result of a similar process is an obvious possibility.

C. North of Cape Monaco

1. *Contact phenomena between Cape Monaco and Gerlache Island*

On the two peninsulas ((1) and (2); Fig. 14) immediately north of Cape Monaco the granite includes large masses of dark medium-grained rock. At the base of the peninsulas the granite is slightly finer-grained than the type granite and contains a higher proportion of ferromagnesian minerals. Towards the included masses at the tip these differences are more pronounced and patches and veins of quartz-rich material occur within the granite adjacent to the inclusions. The smaller inclusions are medium-grained with characteristic long prisms of hornblende. To the north these become larger and more numerous, and are probably still in place. The offshore islands appear to be composed entirely of the dark rock. The margins of the large inclusions are indistinct, grading into the country rock over distances up to 12 ft.

Granite from the base of the peninsulas (N.150.1, N.156.1) consists of large crystals (1.0–3.0 mm.) of quartz and plagioclase (An_{28} with normal-oscillatory zoning to acid oligoclase) separated by smaller crystals of quartz and potash feldspar (0.5–1.0 mm.). The potash feldspar has an irregular perthitic structure and the quartz is similar to that of the type locality. Ferromagnesian material forms approximately 10 per cent of the rock. Most of it is brown biotite with slight alteration to chlorite. Ilmenite is rimmed by leucoxene.

Quartz-rich patches and veins found in the granite near the inclusions (N.150.3) are distinct from the majority of aplitic veins in the type locality. They have a very fine-grained matrix consisting mainly of quartz and a feldspar, probably albite, speckled with tiny flakes of green ferromagnesian minerals most of which are biotite, although both chlorite and hornblende are represented. Small radiating aggregates of quartz and albite occur and ragged areas of iron ore are altered marginally to brown biotite. Stringers of epidote cross the section.

Large euhedral crystals of fresh albite and quartz (0.5–1.0 mm.) which occur separately or in groups, have developed within this matrix. The albite seldom encloses foreign material but the quartz typically encloses or almost encloses areas of the matrix in a manner normally explained by resorption. These features are illustrated in Fig. 16a. That the crystal illustrated has grown around the groundmass and has not been resorbed is demonstrated by the development of a crystal face against the included material. A more striking example is given in Fig. 16b, in which many subhedral crystals are in optical continuity. Theoretically such skeletal crystals could develop either by the rapid and preferential growth of a few

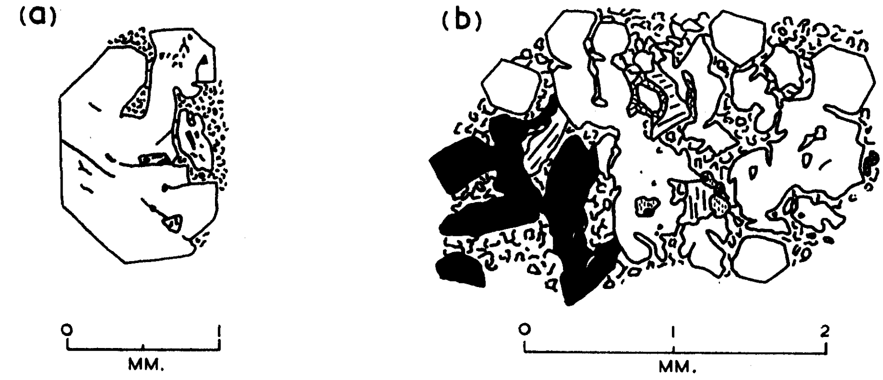


FIGURE 16
Development of euhedral quartz porphyroblasts in the quartz-rich veins associated with the marginal facies of the Cape Monaco Granite on the peninsulas north of Cape Monaco. In both (a) and (b) crystal faces are developed against included patches of groundmass (N.150.3).

crystals in a liquid of low viscosity or as porphyroblasts in an already solid medium. It is thought unlikely that such a delicate structure as that in Fig. 16b would survive in an injected liquid of low viscosity so the second alternative is preferred.

The presence of euhedral and apparently porphyroblastic crystals of quartz and albite in a very fine matrix is characteristic not only of veins associated with the mixed contact rocks in this area but also of the metasomatized tonalite on Gateway Ridge, the metasomatized tonalites and breccia dykes on the Joubin Islands and with the patches and veins of trondhjemitic porphyry in the Altered Assemblage. They appear to be a part of the metasomatic process and are discussed further on p. 58.

Many of the small inclusions (N.151.1) on the two peninsulas carry elongated prisms of hornblende (1.0–2.0 mm.; α' = pale yellow, γ' = green-brown), which may be fresh or partially replaced by aggregates of olive-green biotite. Albite-oligoclase forms ragged laths and anhedral crystals between the laths, the latter carrying more epidote. Small areas of quartz between the laths have replaced the plagioclase and form optically continuous groups over relatively large areas (2.0–3.0 mm.). Epidote is common and sphene is an accessory.

The centres of the large inclusions (N.153.1) have equant crystals of albite-oligoclase (1.0–2.0 mm.) packed with small blebs of quartz and flakes of green-brown biotite. Larger biotite crystals (0.2 mm.) occur outside the plagioclase, while quartz surrounds and has replaced the plagioclase. Accessories include epidote, allanite and apatite.

The rock is similar in composition and texture to the metasomatized tonalite on the islands west of Dream Island (p. 41). Farther north, peninsula (*3*) (Fig. 14) is composed entirely of unaltered tonalite of the Andean Intrusive Suite. It is probable that the included material on the two peninsulas originated as tonalite and was subsequently altered during the formation of the Cape Monaco Granite.

2. *Peninsula opposite Gerlache Island*

A number of outcrops separated by steep ice slopes occur on the peninsula. The country rock is Cape Monaco Granite and is cut by feldspathic bands. Associated with the bands are dark inclusions in which porphyroblastic quartz and feldspar crystals are characteristic. Only two basic dykes were observed cutting the granite.

In general the country rock (N.160.1) is similar to the type granite. Large tabular crystals of plagioclase (2.0–3.0 mm.) have normal-oscillatory zoning from An_{30} to An_{12}. Some of the crystals show patchy sericitization and contain optically continuous blebs of quartz. The quartz crystals reach a size of 4.0 mm., but average approximately 2.0 mm. But in contrast with the type granite the crystals of perthite are almost as large as those of plagioclase and there is no finer-grained phase. The ferromagnesian material forms few but relatively large crystals, most of which are biotite with some chlorite. Iron ore altered to leucoxene and epidote is associated with the chlorite. Apatite is an accessory.

The feldspathic veins (N.160.3) are equigranular (approx. 1.0 mm.) with quartz, perthite and albite-oligoclase as the essential minerals, and odd flakes of brown biotite (1.0 mm.) associated with a little chlorite and iron ore. The plagioclase includes areas of small epidote grains and is surrounded and replaced by perthite and quartz. The latter has a typical Cape Monaco Granite form, surrounding and penetrating the feldspar.

Inclusions are similar to those described from the Joubin Islands (p. 45). The matrix is composed of narrow oligoclase laths (0.5 mm.) rimmed by potash feldspar and separated by quartz. Both brown biotite and small twinned crystals of hornblende (α' = pale yellow, γ' = blue-green) occur but iron ore is scarce. The quartz and plagioclase porphyroblasts (2.0–3.0 mm.) are rounded and occur either alone or in groups. Those of plagioclase have a faint oscillatory zoning, are packed with flecks of sericite and epidote, and also include small crystals of biotite and hornblende similar to those in the matrix. Blebs and stringers of quartz may also occur within the plagioclase but the cores of the crystals are usually comparatively clear oligoclase.

3. *Between Hamburg and Perrier Bays*

The rocks forming the peninsulas and islands between the two bays have a coarse spotted appearance due to the large number of dark inclusions set in a paler country rock. The inclusions increase in number to the north-west and the outer islands are composed entirely of the dark rock.

The country rock (N.162.1) is of Cape Monaco Granite type but where the inclusions are abundant the typical large quartz crystals are absent, although large crystals of plagioclase remain. Perthite is abundant and there is a larger proportion of ferromagnesian material as clots of chlorite (deep blue interference colours) and iron ore. Where the granite is virtually free of inclusions it has regained its characteristic appearance with large crystals of both quartz and plagioclase. Quartz veins but no aplitic or feldspathic veins have been recorded.

The inclusions are rounded and vary in diameter from a few inches to 6 ft. Around their margins large porphyroblasts of plagioclase are developed and they are surrounded by an obviously mixed zone as much as 6 in. wide. They differ from those previously described (p. 45, see above) in the relative abundance of green hornblende which forms poikilitic crystals full of quartz. Some of these crystals have centres of brown hornblende.

Veins (N.163.1) from the country rock are coarser than both the country rock and the inclusions which they penetrate. Large crystals of plagioclase, quartz and perthite (3.0–4.0 mm.) are separated either by large clusters of ferromagnesian minerals, in which deep green hornblende predominates over brown biotite, or by separate subhedral crystals of biotite and hornblende up to 1.5 mm. long. The large plagioclase crystals occur separately or in groups. They have fine albite twin lamellae and are zoned from a core of An_{30} to a band of An_{42} which changes gradually to a margin of An_{17}. They contain patches of sericite and optically continuous blebs of quartz. The large crystals of quartz and perthite enclose small groups of plagioclase, biotite and hornblende.

4. *Cape Bayle*

An isolated outcrop on the shore at Cape Bayle (N.167.2) is a coarse granodiorite with numerous small inclusions, varying from microscopic clots to inclusions 12 in. across. In the granodiorite large crystals of plagioclase (7.0 mm.) are surrounded by crystals of quartz and potash feldspar (3.0–4.0 mm.). The plagioclase has normal-oscillatory zoning from An_{45} to An_{16} and includes blebs of quartz and patches of severe sericitization. Hornblende (α' = yellow, γ' = rich green) forms large but scattered subhedral crystals up to 4.0 mm. long, which are full of rounded patches of altered plagioclase, iron ore and blebs of quartz. Brown biotite forms smaller flakes partially altered to chlorite. A microscopic patch with a concentration of these dark minerals represents one of the smaller inclusions.

D. Discussion

The Cape Monaco Granite occupies a narrow belt approximately 5 miles wide and about 40 miles long, elongated parallel to the Graham Land axis. Long vertical faults, trending parallel to the Graham Land axis and associated with the margins of members of the Andean Intrusive Suite, have already been described from the east coast of Anvers Island and the Graham Coast (p. 37). It is suggested that the Cape

Monaco Granite may have developed along another similar fault parallel to the north-west of Anvers Island.

The margins of the granite are extremely irregular. In fact, it may form a series of isolated or semi-isolated areas within the belt described rather than one continuous mass. In only one area is the contact straight and there it follows an older tonalite/volcanics contact (p. 46).

The granite is a structureless mass with marginal facies formed by the metasomatism of earlier rocks (p. 47). In composition and texture it varies considerably; in the type locality alone it varies from a porphyritic (or porphyroblastic) granodiorite to a more even-textured alkali-granite. From the order of crystallization (large crystals of plagioclase and quartz, followed by quartz and potash feldspar) and the apparent porphyroblastic growth of the quartz it is concluded that the alkali-granite has developed from the granodiorite by metasomatism. Evidence for considering the earlier oscillatory-zoned andesine-oligoclase crystals as porphyroblasts is found in the volcanic inclusions, in which similar crystals are developed as porphyroblasts close to their margins with the granite. It is considered unlikely that phenocrysts in a magma and porphyroblasts in an inclusion would both possess the same faint but frequently repeated oscillatory zoning (p. 47). It is more satisfactory to consider both the crystals in the granite and those in the inclusions as porphyroblasts, formed by the same metasomatic process.

Potash feldspar has been used by Tuttle (Tuttle and Bowen, 1958) as a means of classifying granites and of separating high temperature from low temperature granites. Tuttle considers the presence of perthite indicates a high temperature granite which has crystallized from a comparatively dry magma so that recrystallization and complete exsolution has not been possible.

The potash feldspar of the Cape Monaco Granite is normally in small ill-defined crystals, the optical properties of which it has not been possible to determine. Most, however, have a rather vague perthitic structure and in one rock indistinct microline twinning is present. Well-developed perthitic structures are confined to aplite veins and to the varieties of the granite north of Gerlache Island. It is suggested that in these rocks this structure is not a result of exsolution but rather a result of replacement of plagioclase by potash feldspar.

Older rocks surrounding the Cape Monaco Granite have been metasomatized by the introduction of silica, soda and potash. The metasomatism was more extensive in rocks above than in those adjacent to the granite (p. 26). In the light of the available evidence it seems probable that the Cape Monaco Granite represents the culmination of this metasomatism rather than its source. The area of metasomatism was controlled by a regional fault zone formed during the intrusion of the Andean Intrusive Suite, which would form a natural path for rising volatiles.

VII. THE ALTERED ASSEMBLAGE

THE rocky peninsulas and small islands along the south-west coast of Anvers Island between Dream Island and Janus Island are composed of an unusual assemblage of rock types which possess, in addition to their great variety, many similarities to the hybrid rocks developed along the western margins of the Cape Monaco Granite. The principal types are described and the relations of one type to another are followed.

A. THE PRINCIPAL ROCK TYPES

1. *The dioritic rock*

The dioritic rock is typically developed across the base of the peninsula leading to Norsel Point (Fig. 17). The normal rock (N.3.2) is dark grey and fine- to medium-grained with plagioclase crystals up to 3.0 mm. long and a few ragged crystals of pale green hornblende separated by smaller crystals of quartz and sheaves of actinolite. Iron ore is associated with the actinolite and apatite is a common accessory. The plagioclase is basic andesine with margins of albite-oligoclase. Faint oscillations in the zoning are often present and the patchy extinction is due to enclosed quartz blebs, each of which is surrounded by a narrow albite-oligoclase rim.

As in other members of the Altered Assemblage variability is characteristic. Large areas of a variety paler than that described above have a finer grain-size, a higher quartz percentage and a tendency to vein

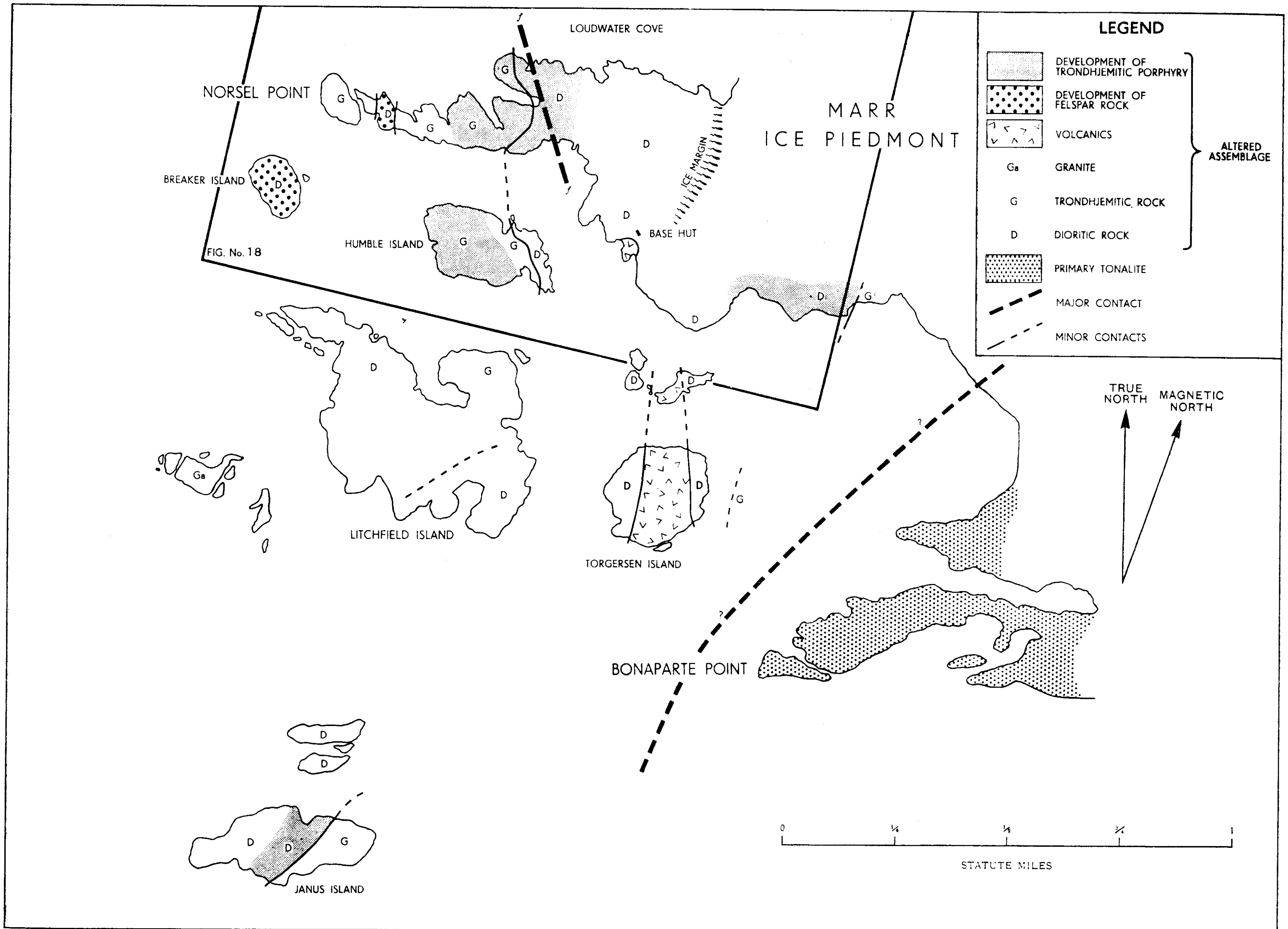


FIGURE 17
Geological map of the Arthur Harbour area.

and replace the normal variety. Pale yellow patches (N.18.1), from a fraction of an inch to many feet in diameter, are rich in epidote, quartz and albite-oligoclase but poor in actinolite. Denser varieties (N.184.1) with less quartz and smaller feldspar crystals than the normal variety, and in which actinolite forms nearly 50 per cent of the rock are also common, particularly south-east of the base hut and on Torgersen Island.

On Norsel Point, Humble Island and Janus Island the dioritic rock is intruded by the trondhjemitic rock. On Torgersen Island it is in contact with a belt of brecciated volcanics and here the boundaries are faulted and complex, the general appearance being that of volcanics cutting the dioritic rock. However, dykes very similar to the dioritic rock cut the marginal volcanics. On Janus Island and along the shore section south-east of the base hut the dioritic rock grades into the trondhjemitic porphyry which is developed close to the contact with the trondhjemitic rock. On Breaker Island the feldspar rock has developed within a dense variety of the dioritic rock.

2. *The trondhjemitic rock*

A zone of trondhjemitic rock which crosses the centre of the peninsula leading to Norsel Point also crops out on Humble Island and on the north-east corner of Litchfield Island. A similar but slightly coarser rock forms the east end of Janus Island.

The hand specimen (N.25.1) is a pale medium-grained rock rich in quartz and poor in dark minerals. Microscopic study reveals quartz and albite-oligoclase with minor quantities of chlorite, epidote and iron ore, most of which is included in the feldspar. Twinning and zoning in the albite-oligoclase is normally obscured by the enclosed grains but in occasional crystals the quantity of chlorite and iron ore is reduced and the epidote is concentrated into large crystals leaving the rest of the feldspar clear. Such feldspars are frequently subhedral and possess well-developed albite twin planes. On Janus Island the trondhjemitic rock (N.116 1) contains minor quantities of acicular hornblende, brown biotite and sphene. Narrow stringers of potash feldspar and blebs of quartz also occur within the albite-oligoclase. In all cases the quartz extinction is irregular.

On Norsel Point, Humble Island and Janus Island the trondhjemitic rock intrudes the dioritic rock and at the first two localities it contains numerous veins and patches of the trondhjemitic porphyry. On Janus Island such material is notably absent from the trondhjemitic rock but it is present in the nearby dioritic rock.

3. *The trondhjemitic porphyry*

On Norsel Point and Humble Island the trondhjemitic rock contains patches and veins of trondhjemitic porphyry. Occasionally the porphyry is sharply defined but more usually it occurs as vague areas merging into the country rock.

The matrix of the porphyry (N.1.1) is composed of interlocking quartz and albite grains (approx. 0.1 mm.) with traces of potash feldspar. Small clusters of green biotite flakes with iron ore and epidote are present and specks of epidote occur in the plagioclase. In the matrix are set large crystals (0.5–3.0 mm.) of quartz and albite, both of which are frequently euhedral. Under ordinary light the large plagioclase crystals can barely be distinguished from the matrix. Veinlets of epidote cross the rock. In another specimen (N.24.1) epidote is much more common in both the matrix and the albite while calcite occurs in the matrix (Plate VIc).

There are a number of interesting details concerning the large crystals of quartz and albite: the larger ones tend to show the best developed crystal faces; those of quartz are often cracked in an hexagonal pattern with stringers of albite or matrix enclosed along the cracks, and the crystal faces of both the quartz and plagioclase reveal under high power a tendency to send out tiny apophyses into the surrounding matrix.

Narrow veins of trondhjemitic porphyry are described on p. 47 from the peninsulas north of Cape Monaco where they are associated with a marginal facies of the Cape Monaco Granite. In each case the textural evidence points to the development of the large crystals after the crystallization of the matrix. The trondhjemitic porphyry and the feldspar rock are the youngest members of the Altered Assemblage.

4. *The feldspar rock*

The feldspar rock occurs very locally at the extremity of Norsel Point and on Breaker Island (Fig. 18). It develops as coarse patches and stringers within a much darker, fine-grained rock (Plate IIIc) and consists

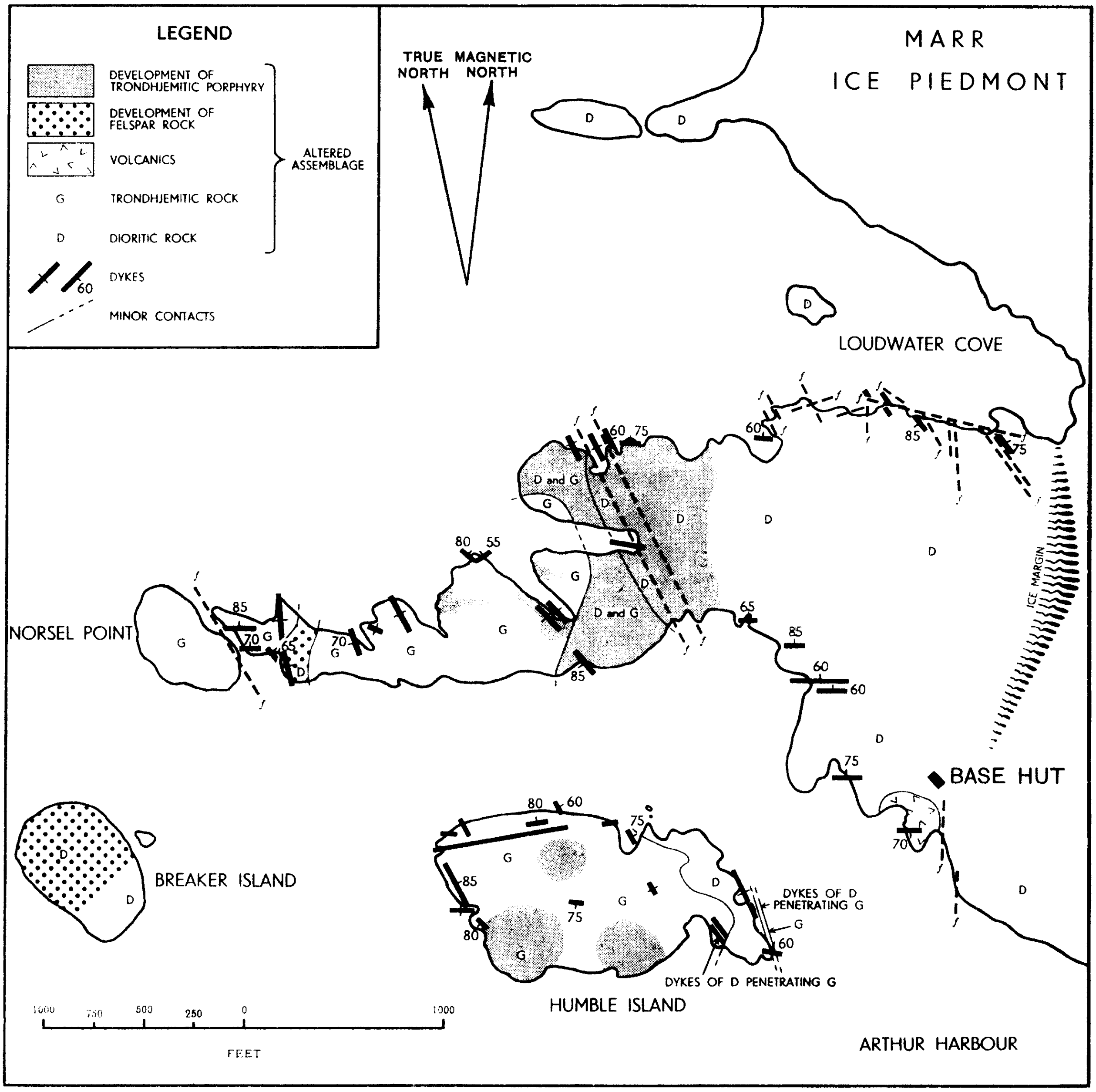


FIGURE 18
Geological map of Norsel Point and Humble Island.

merely of large (1.0–3.0 mm.), closely packed, subhedral crystals of plagioclase surrounded by finer material. Both in the field and under the microscope it is clear that the feldspar has developed as porphyroblasts in the finer rock.

The darker, finer-grained rock (N.188.1) has a groundmass of small quartz and plagioclase crystals with areas of granular epidote and platy to acicular crystals of actinolitic hornblende within which are relics of a primary hornblende (α' = yellow, γ' = olive-green) and a pyroxene. Skeletal crystals of ilmenite associated with leucoxene and sphene are numerous and apatite is a common accessory. The rock is similar to basic varieties of the dioritic rock.

In the development of the plagioclase porphyroblasts (N.185.1, N.187.1) the new crystals are first recognizable as large areas of uniform extinction. Thereafter the new plagioclase proceeds to eject the included groundmass material, some of which collects into zones parallel to the crystal faces which also develop at an early stage (Plate VId). The zones may be the origin of the oscillatory zoning so often associated with the oligoclase porphyroblasts. Intricate albite and pericline twinning is a feature of some porphyroblasts from the earliest stages.

In its most developed form the feldspar rock consists of closely packed oligoclase porphyroblasts, the majority still spongy with quartz inclusions and separated by areas of a quartz/feldspar matrix. The dark minerals are much reduced in quantity and consist of small grains of chlorite, actinolitic hornblende and iron ore with occasional specks of biotite. Epidote and sphene are also present.

5. *The volcanic rocks*

Rocks of indisputable volcanic origin form a small zone running approximately north – south across the centre of Torgersen Island and into the group of islands to the north. Another small outcrop on the rock promontory below the base hut may be a continuation of this zone subsequently faulted out of position. On a small island at the head of Wylie Bay (Fig. 1) pale volcanic rocks occur with a darker and coarser dioritic rock.

On Torgersen Island the rock is broken into large loose angular blocks by innumerable shatter planes, while on a smaller scale there are angular fragments discernable in the hand specimen (N.102.1). Pyrite is associated with extensive iron staining. Microscopic examination reveals broken fragments of acid andesine and indistinct angular rock fragments set in a fine matrix composed essentially of plagioclase and hornblende. The great majority of the rock fragments have a similar mineral assemblage but vary in texture and mineral proportions. Many carry plagioclase phenocrysts in a fine matrix with recognizable plagioclase laths. The hornblende (α' = pale yellow, γ' = green with a faint blue tinge) normally forms stumpy prisms orientated parallel to the plagioclase laths but ragged crystals also occur. Minor quantities of quartz, iron ore and biotite are present, the latter occurring with hornblende as tiny crystals within the plagioclase.

The volcanic rock from Wylie Bay (N.230.1) is a tuff containing crystal and rock fragments in a fine granoblastic matrix. Most of the crystal fragments are of fresh unzoned medium andesine. The rock fragments tend to merge with the groundmass but distinctive trachytic textures are occasionally observed. The matrix is composed of quartz, untwinned plagioclase, biotite and iron ore with sheaves of anthophyllite.

B. Field Relations

1. *Janus Island*

On Janus Island, at the entrance to Arthur Harbour, a sharp contact separates the trondhjemitic rock on the east from a darker and exceptionally variable dioritic rock on the west (Fig. 17). A younger dyke crosses the contact at right angles. The same contact passes just to the east of Torgersen Island and is exposed again in the cliff section south-east of the base hut. Farther to the south-east normal tonalite of the Andean Intrusive Suite forms Bonaparte Point but the boundary between the trondhjemitic rock and the tonalite is not exposed.

Evidence from Janus Island alone is inconclusive but on Norsel Point (p. 55) it is clear that the trondhjemitic rock is younger than the dioritic rock. Inclusions in the trondhjemitic rock on Janus Island are fairly common and zones of slight crushing are frequent. A thin section of a pink inclusion from the eastern tip of the island (N.116.3) reveals a fine-grained garnet-plagioclase-quartz-hornfels, in which are comparatively large crystals of sphene and epidote. Iron ore and specks of a green ferromagnesian mineral, probably chlorite, occur as accessories. The garnet is yellow and forms approximately 30 per cent of the rock. The untwinned plagioclase has a refractive index greater than that of balsam. This rock is similar to the highly altered volcanic inclusions in the southern tonalite mass on the Joubin Islands (p. 18, 19). Another smaller inclusion (N.200.1) in the trondhjemitic rock a few feet from the contact consists of small interlocking biotite and albite-oligoclase crystals with a considerable quantity of apatite.

The dioritic rock 600 ft. west of the contact contains areas of a paler variety which veins and replaces it. Quartz-epidote patches similar to those in the dioritic rock of Norsel Point are abundant. Under the microscope the normal type (N.118.1, N.193.1; Plate VIe) is composed essentially of plagioclase, quartz, actinolitic hornblende and iron ore. The quartz and plagioclase form indistinct crystals full of actinolite needles and the plagioclase is also packed with small cubic magnetite crystals. Actinolitic hornblende forms both ragged crystals (0.5–1.0 mm.) with acicular margins and innumerable needles which penetrate all the other minerals. Accessory apatite is present. In some specimens (N.193.1) epidote and sphene are abundant, while in others (N.118.1) these minerals are absent and small brown flakes of biotite replace the amphibole.

Thirty feet from the contact the paler variety of the dioritic rock is more abundant and has a distinct tendency to flow around streaked out inclusions of the darker type (Plate IIId). Its texture is now porphyritic (or porphyroblastic). All gradations between the darker inclusions (N.200.5) and the paler variety (N.200.4) are present. The plagioclase crystals in the darker rock become smaller and more indistinct while those of quartz become more obvious and apatite forms comparatively large crystals. Moving into the paler variety, the plagioclase is replaced by a very fine, pseudocataclastic quartz/feldspar matrix with larger euhedral grains of magnetite and skeletal rods of ilmenite surrounded by biotite. All the amphibole is acicular. In this matrix are set large clear euhedral crystals of quartz and equally large but vague crystals of albite-oligoclase speckled with groundmass material (Plate VIf).

A dyke of trondhjemitic porphyry (N.200.3), which runs close and parallel to the contact with the trondhjemitic rock, appears to represent the final stage in the alteration of the dioritic rock and its sharp boundaries indicate a high degree of fluidity. While similar to the typical trondhjemitic porphyry already described, this example contains a higher proportion of quartz in the matrix and the euhedral porphyroblasts of plagioclase frequently enclose substantial groups of epidote. Another interesting feature is an irregular vein composed of large quartz and plagioclase crystals, which is contemporaneous with the porphyroblasts.

A thin section cut across the trondhjemitic rock/dioritic rock contact (N.200.2) shows the dioritic rock to have a distinctive cataclastic appearance in which the fragmentary nature of the large quartz crystals is particularly marked. Small veins of this material penetrate the trondhjemitic rock.

Thus the dioritic rock grades into the trondhjemitic porphyry which shows signs of having been very fluid. Each stage in the development of this porphyry from the dioritic rock is clearly displayed. It must have involved the addition of silica and soda and, apparently, the remobilization of the original rock first into a plastic material then into a more fluid material capable of forming independent dykes with sharp intrusive contacts.

The late development of the quartz and albite porphyroblasts has been demonstrated in similar veins from north of Cape Monaco (p. 47). More evidence is found in the present example, in which some of the porphyroblasts are linked to each other by a contemporaneous vein of large quartz and albite crystals.

It is suggested that the dioritic rock has been subjected to intense localized metasomatism involving the introduction of silicon and sodium in a volatile state. Along zones where this process has been most intense the metasomatized rock has been mobilized.

2. *Norsel Point*

Another trondhjemitic rock/dioritic rock contact crosses the peninsula leading to Norsel Point from north to south, and continues southwards across the eastern end of Humble Island (Fig. 18). On Norsel Point there is a broad zone of mixing between the two types in which innumerable blocks of the dioritic rock, mainly rounded and partially digested, are surrounded by the trondhjemitic rock. In places the forceful intrusion of the trondhjemitic rock between the joint planes of the dioritic rock can be demonstrated (Fig. 19).

Within the trondhjemitic rock, the trondhjemitic porhyyry becomes more abundant towards the contact. Indeed, it frequently appears to form a contact facies of the trondhjemitic rock where it grades into the dioritic rock. The latter is severely shattered by faults and for 100 yd. east of the contact it is unusually pale owing to an increase in quartz and epidote. The formation of this material is probably analogous to the formation of trondhjemitic porphyry across the contact and both varieties are similarly shaded in Figs. 17 and 18.

On Humble Island there are fewer complications. The trondhjemitic rock sends large veins into the dioritic rock and the trondhjemitic porphyry is absent from the contact zone. Farther west, however, the porphyry is abundant throughout the trondhjemitic rock. On the eastern extremity of the island broad veins of trondhjemitic rocks cutting the dioritic rock are, in turn, cut by bands of the dioritic rock (Fig. 20). Again, on the contact, dykes of the dioritic rock penetrate the trondhjemitic rock. The field evidence is indisputable and it must be concluded that both rock types were mobile at the same time.

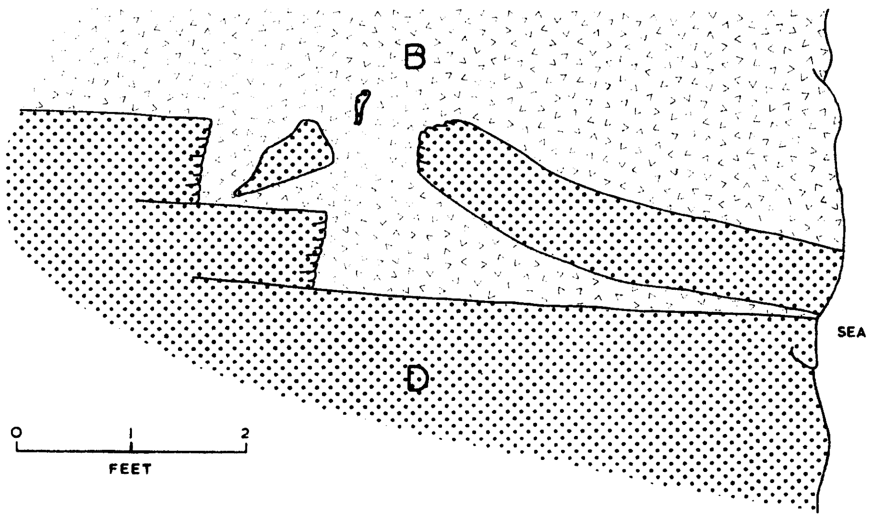


FIGURE 19
Field sketch of the trondhjemitic rock intruding the dioritic rock, Norsel Point. B = trondhjemitic rock, D = dioritic rock.

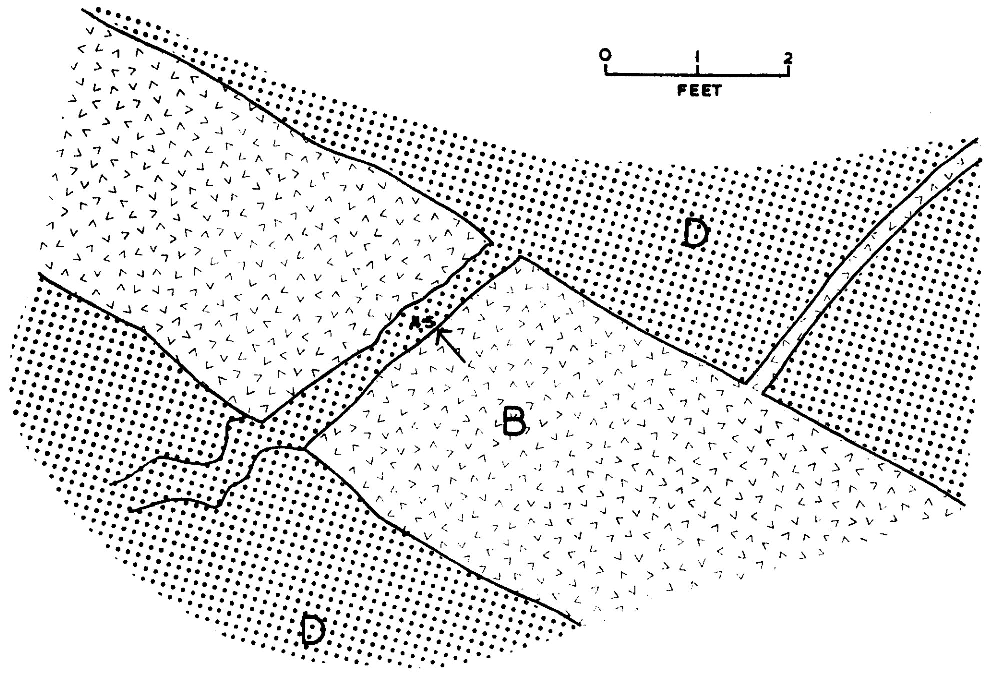


FIGURE 20
Dyke of trondhjemitic rock cutting dioritic rock and itself being cut by a vein of the dioritic rock, Humble Island. B = trondhjemitic rock, D = dioritic rock.

3. *Wylie Bay*

On a small isolated island in the centre of Wylie Bay a small boss-like mass of granite has developed in the variable paler and darker dioritic rocks of the Altered Assemblage. The mass is cut by veins of aplite and porphyry, and the latter extend into the country rock. The contact of the mass may be sharp or graded, the porphyry frequently forming a marginal facies which veins the country rock. Around the mass there is no evidence of pressure or physical distortion so the granite appears to have formed by replacement rather than displacement.

This granite (N.262.1) is of Cape Monaco type. Subhedral albite crystals (2.0 mm.) are surrounded by a crude quartz/orthoclase intergrowth which, with other quartz crystals, forms a finer-grained matrix. A few quartz crystals, however, reach a size greater than that of the albite. Occasional groups of small biotite, hornblende and iron ore crystals are also present.

The dark country rock farthest from the granite mass (N.263.1) is similar to the actinolite-rich rock of Arthur Harbour (e.g. N.193.1), the actinolite needles and sheaves apparently developing through a finer irregular quartz/plagioclase groundmass. Occasional much larger porphyroblasts of plagioclase packed with iron ore and other groundmass material are present.

Four feet from the margin of the granite mass (N.262.6) the plagioclase porphyroblasts are more abundant and better developed. The quantity of ferromagnesian material is smaller, biotite is as plentiful as actinolite and the proportion of iron ore has increased.

This rock grades into the porphyry developed around the contact (N.262.5), which is similar in most respects to the trondhjemitic porphyry of Arthur Harbour. Differences, however, include larger and more irregular crystals of quartz and quartz/feldspar intergrowths, the presence of occasional large euhedral hornblende crystals and some hornblende and iron ore in the matrix. Within the granite the porphyry veins (N.262.4) include minor quantities of hornblende, biotite, iron ore and accessory apatite.

Veins of aplite (N.262.2) are confined to the granite and are similar to others in the Cape Monaco Granite. Small interlocking grains of quartz and sodic plagioclase are separated by narrow stringers of orthoclase. Along their margins the veins become slightly porphyritic, the finer matrix sending short apophyses into the granite.

Thus the most obvious points regarding the relation of the Cape Monaco Granite to the Altered Assemblage which emerge from a study of this small island are:

i. A lack of evidence for forceful intrusion.
ii. The granite contacts may be sharp or graded.
iii. The members of the Altered Assemblage show a progressive change from the darker dioritic rock through a paler variety with large plagioclase porphyroblasts to merge finally with the trondhjemitic porphyry, which frequently forms the marginal facies of the granite.
iv. This gradation towards the granite is similar to the gradation from the dioritic rock to the trondhjemitic porphyry described from Janus Island (p. 54).
v. The trondhjemitic porphyry forms a direct link between the Cape Moncao Granite and the Altered Assemblage.

It is noteworthy that the granitic rocks on Dream Island and on the small island immediately southwest of Litchfield Island contain considerable quantities of perthitic feldspar and crude intergrowth structures, although they lack the coarseness of the Cape Monaco Granite. They may be considered as intermediate between the trondhjemitic rock of the Altered Assemblage and the Cape Monaco Granite.

C. Discussion

The complicated nature of the geology of the Altered Assemblage is illustrated in Figs. 17 and 18 in which it has been necessary to use two types of symbol, the one representing the original rocks and the other their more extreme metasomatic derivatives. Thus the dioritic rock and the trondhjemitic rock are original rocks altered by metasomatism, but the feldspar rock and the trondhjemitic porphyry are derivatives of these rocks, which owe their separate identity to the metasomatism.

It is probable that the dioritic rock developed by the growth of plagioclase and hornblende in a finer-grained rock rich in actinolite and iron ore. The rock on the west end of Janus Island probably represents an early stage in the alteration process and it has much in common with the Upper Jurassic Volcanics which crop out on Spume Island (p. 12).

The dioritic rock is intruded by the trondhjemitic rock in a manner which leaves little doubt that the latter entered as a magma. Yet, its composition and texture strongly support the supposition that metasomatism has played a major part in its formation. Furthermore, on Humble and Janus Islands there are minor examples of the reverse relationship of the dioritic rock intruding the trondhjemitic rock. These apparent contradictions can be resolved if the contacts are regarded as ghost structures modified by later metasomatism affecting a wide area. The contacts within the Altered Assemblage have much in common with the tonalite/volcanics contacts described from the Outcast and Joubin Islands. In addition, the trondhjemitic rock on Janus Island is similar in composition and to some extent in texture to the metasomatized tonalite on the Joubin Islands (p. 41). It is suggested that the dioritic rock and the trondhjemitic rock are the metasomatized equivalents of the Upper Jurassic Volcanics and the tonalites of the Andean Intrusive Suite respectively.

Perhaps the most surprising feature of the trondhjemitic porphyry is its development from the dioritic rock in one place and from the trondhjemitic rock in another. In each case, however, it occurs close to the trondhjemitic rock/dioritic rock contact.

The porphyry is believed to represent a more intense form of the silica/soda metasomatism apparent in the trondhjemitic and dioritic rocks. Its frequent association with the contact between these two rocks might be explained by the presence of contact faults. Faulting is typical of the volcanics/tonalite contacts elsewhere (p. 10, 15) and would provide convenient channels for the rise of volatile material. In contrast, the feldspar rock has developed only in the dioritic rock and does not appear to have been influenced by older structures (Plate IIIc).

A metasomatic origin for the Cape Monaco Granite has already been suggested on p. 50. There is a close similarity between the marginal facies of the Cape Monaco Granite and the more extreme examples of metasomatism in the Altered Assemblage. In the granite the metasomatism appears to have involved the introduction of silicon and sodium first and silicon and potassium later (p. 50). That of the Altered Assemblage, however, involved the introduction of only silicon and sodium. In other words, the Altered Assemblage appears to represent an early stage in a large-scale metasomatic process which culminated in the formation of the Cape Monaco Granite.

VIII. THE GEOCHEMISTRY OF THE ANDEAN ROCKS

EIGHT new chemical analyses, representative of the Andean rocks in the Anvers Island area, are given. They include a primary gabbro and a primary tonalite of the Andean Intrusive Suite, three associated hybrid rocks and a granodiorite, all collected from the Wauwermans Islands. Another is the Cape Monaco Granite and the last is a trondhjemitic porphyry of the Altered Assemblage.

The analyses, both complete and recalculated on a water-free basis, are given in Table X. They are also plotted on triangular variation diagrams with the co-ordinates (Fe″ + Fe‴) — Alk — Mg and

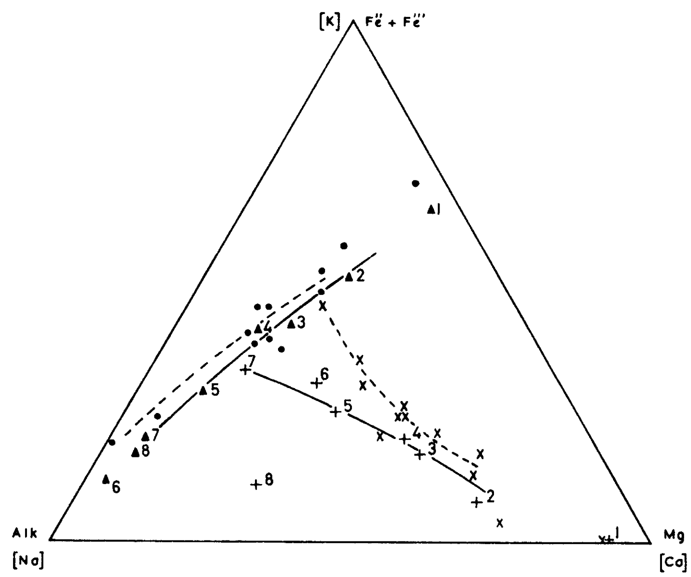


FIGURE 21

Variation diagrams (Fe″ + Fe‴) — Alk — Mg and K — Na — Ca showing the new analyses of rocks from the Anvers Island area (Table X) in relation to the rocks of the Andean Intrusive Suite of Graham Land (Adie, 1955).

● = (Fe″ + Fe‴) — Alk — Mg (Adie, 1955); × = K — Na — Ca (Adie, 1955).
▲ = (Fe″ + Fe‴) — Alk — Mg (Hooper); + = K — Na — Ca (Hooper).

Dashed lines are Adie's curves drawn through the analyses of the Andean Intrusive Suite; solid lines represent curves through the new analyses of the Anvers Island rocks.

K — Na — Ca (Fig. 21). Curves have been drawn through the plotted points in order to facilitate comparison with twelve analyses of rocks from the Andean Intrusive Suite of Graham Land (Adie, 1955).

Adie has stated that the Andean Intrusive Suite of Graham Land is calc-alkaline and, in particular, he has compared it with the calc-alkaline volcanic series from the East Central Sierra Nevada (Nockolds and Allen, 1953). He has concluded that the two most basic rocks analysed are crystal accumulates of the parental magma, while the remainder represent the liquid line of descent from that magma. His curves are reproduced in Fig. 21.

In the (Fe″ + Fe‴) — Alk — Mg diagram the Anvers Island rocks fall on a line which is parallel and close to that for the Andean Intrusive Suite but which is persistently richer in magnesium relative to total iron and total alkalis. The difference is small and, in itself, is of doubtful significance. In the K — Na — Ca diagram, however, the contrast is much greater, for not only are the Anvers Island rocks persistently richer in sodium relative to potassium and calcium, but the divergence towards sodium increases with acidity so that the curve is concave towards the sodium apex.

Only three previous chemical analyses of Andean rocks from the Anvers Island area are available. Two are of gabbro and fall in the areas of the triangular variation diagrams (Fig. 22) in which the Andean

TABLE X

NEW CHEMICAL ANALYSES OF THE ANDEAN ROCKS OF ANVERS ISLAND

	1	2	3	4	5	6	7	8	
SiO_2	41.57	53.06	56.22	62.11	67.89	72.64	72.79	78.36	SiO_2
TiO_2	1.12	0.93	1.02	0.66	0.40	0.22	0.34	0.26	TiO_2
Al_2O_3	22.55	17.68	17.40	16.88	15.82	15.78	13.49	11.31	Al_2O_3
Fe_2O_3	4.30	2.19	2.22	2.99	1.65	0.07	1.15	0.74	Fe_2O_3
FeO	6.30	6.65	4.58	2.71	1.81	1.07	0.92	0.48	FeO
MnO	0.22	0.21	0.18	0.11	0.07	0.04	0.05	n.d.	MnO
MgO	7.61	5.04	3.94	2.39	1.50	0.74	0.80	0.50	MgO
CaO	14.11	9.43	7.39	5.92	3.87	2.70	1.56	2.20	CaO
Na_2O	1.07	3.36	4.01	3.69	4.22	3.79	4.53	4.52	Na_2O
K_2O	0.06	0.97	2.00	2.01	2.39	2.62	2.61	0.73	K_2O
H_2O+	0.75	0.70	0.75	0.55	0.28	0.21	0.96	0.35	H_2O+
H_2O-	0.05	0.04	0.02	0.02	0.10	0.06	0.17	0.04	H_2O-
P_2O_5	0.06	0.06	0.25	0.13	0.10	0.02	0.22	n.d.	P_2O_5
CO_2	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	nil	CO_2
TOTAL	99.80	100.32	99.98	100.17	100.10	99.96	99.59	99.49	TOTAL
	ANALYSES LESS TOTAL WATER (Recalculated to 100)								
SiO_2	42.01	53.29	56.66	62.37	68.09	72.87	73.94	79.08	SiO_2
TiO_2	1.14	0.93	1.03	0.66	0.40	0.22	0.35	0.26	TiO_2
Al_2O_3	22.79	17.76	17.54	16.95	15.87	15.83	13.70	11.41	Al_2O_3
Fe_2O_3	4.34	2.20	2.24	3.00	1.65	0.07	1.17	0.75	Fe_2O_3
FeO	6.36	6.68	4.62	2.72	1.81	1.07	0.93	0.48	FeO
MnO	0.22	0.21	0.18	0.11	0.07	0.04	0.05	—	MnO
MgO	7.69	5.06	3.97	2.40	1.50	0.74	0.81	0.50	MgO
CaO	14.25	9.47	7.45	5.94	3.88	2.71	1.58	2.22	CaO
Na_2O	1.08	3.37	4.04	3.70	4.23	3.80	4.60	4.56	Na_2O
K_2O	0.06	0.97	2.02	2.02	2.40	2.63	2.65	0.74	K_2O
P_2O_5	0.06	0.06	0.25	0.13	0.10	0.02	0.22	—	P_2O_5
	NORMS								
Q	—	1.68	4.44	17.94	23.82	33.12	32.64	44.28	Q
C	—	—	—	—	—	1.83	0.92	—	C
or	0.56	5.56	11.68	11.68	13.90	15.57	15.57	4.45	or
ab	7.86	28.30	34.06	30.39	35.63	31.96	38.25	38.25	ab
an	56.99	30.30	23.63	23.91	17.24	13.34	6.12	8.34	an
ne	0.57	—	—	—	—	—	—	—	ne
di	10.66	13.41	8.99	3.77	0.89	—	—	1.94	di
hy	—	15.14	10.53	5.92	4.82	3.62	2.00	0.40	hy
ol	14.66	—	—	—	—	—	—	—	ol
mt	6.26	3.25	3.25	4.41	2.32	—	1.62	0.93	mt
il	2.13	1.82	1.98	1.22	0.76	0.46	0.61	—	il
hm	—	—	—	—	—	—	—	0.16	hm
cc	0.01	—	—	—	—	—	—	—	cc
Plag. comp.	An_{90}	An_{56-40}	An_{55-34}	An_{50-30}	An_{50-22}	An_{46-18}	An_{23-10}	An_{0-5}	*Plag. comp.*

TABLE X—*continued*

NEW CHEMICAL ANALYSES OF THE ANDEAN ROCKS OF ANVERS ISLAND

	1	2	3	4	5	6	7	8	
	RECALCULATED AS ELEMENTS (Weight per cent)								
Si	19.6	24.9	26.5	29.1	31.8	34.1	34.5	36.9	Si
Al	12.1	10.5	10.3	10.0	9.4	8.4	8.1	6.7	Al
Fe'''	3.0	1.5	1.5	2.0	1.1	—	0.8	0.5	Fe'''
Mg	4.6	3.1	2.4	1.4	0.9	0.4	0.5	0.3	Mg
Fe''	4.9	5.2	3.6	2.1	1.4	0.8	0.7	0.4	Fe''
Na	0.8	2.5	3.0	2.7	3.1	2.8	3.4	3.4	Na
Ca	10.2	6.8	5.3	4.2	2.8	1.9	1.1	1.6	Ca
K	0.1	0.8	1.7	1.7	2.0	2.2	2.2	0.6	K
Ti	0.7	0.6	0.6	0.4	0.2	0.1	0.2	0.2	Ti
Mn	0.2	0.2	0.1	0.1	0.1	—	—	—	Mn
P	—	—	0.1	—	—	—	0.1	—	P
O	43.8	44.1	44.6	46.1	47.1	49.1	48.1	49.3	O
Fe	59	51	42	41	29	14	20	17	Fe
Mg	35	24	19	14	11	7	6	6	Mg
Alk	6	25	39	45	60	79	74	77	Alk
Ca	93	67	53	49	35	28	16	29	Ca
Na	7	25	30	31	40	41	51	60	Na
K	0	8	17	20	25	31	35	11	K

1. N.137.1 Olivine-gabbro, Pardoner Island, Wauwermans Islands.
2. N.124.1 Gabbro-diorite, Chaucer Island, Wauwermans Islands.
3. N.136.1 Tonalite, Tangent Island, Wauwermans Islands.
4. N.132.1 Tonalite, small island south-west of Prioress Island, Wauwermans Islands.
5. N.126.1 Granodiorite, Prioress Island, Wauwermans Islands.
6. N.137.3 Granodiorite vein penetrating gabbro, Pardoner Island, Wauwermans Islands.
7. N.145.1 Cape Monaco Granite, Gossler Islands.
8. N.200.3 Trondhjemitic porphyry, Janus Island, Arthur Harbour.

(Analyses by P. R. Hooper)

Intrusive Suite of Graham Land is indistinguishable from the Anvers Island rocks. The third, a quartz-diorite from Port Lockroy, Wiencke Island, falls on the curve joining the new analyses of Anvers Island rocks in the K — Na — Ca diagram.

The Anvers Island curves are not only similar to those drawn through the plotted analyses of the intrusive rocks of Patagonia (Fig. 22) but are also similar to those for the lavas of the Lesser Antilles and the lavas of Crater Lake and Mount Shasta (Nockolds and Allen, 1953, p. 105). From this comparison a purely magmatic origin for the Anvers Island rocks might be postulated, despite the field and microscope evidence, with, presumably, a parent magma of a composition similar to that suggested by Adie for the Andean Intrusive Suite of Graham Land. Against this hypothesis are the following facts:

i. The number of plotted analyses is too small for the construction of a reliable curve.
ii. There is a marked difference between the trend of the Anvers Island rocks and that of the Andean Intrusive Suite of Graham Land.
iii. It is necessary to omit the trondhjemitic porphyry (analysis No. 8) from these considerations.

The chemical evidence for concluding that the trondhjemitic porphyry is not magmatic is convincing, yet the field evidence links it firmly to the marginal facies of the Cape Monaco Granite.

Taking all the available evidence into account, it is difficult to accept that all the Andean rock types in the Anvers Island area have developed by differentiation during crystallization from a single parent magma. The primary gabbro (Table X, No. 1) and the primary tonalite (No. 3) may be regarded as members of the Andean Intrusive Suite of Graham Land, the former representing a heterogeneous magmatic mush resulting from crystal accumulation. The primary tonalite has a distinctly higher Na/K ratio than its equivalent in the Andean Intrusive Suite of Graham Land and it is probable that, despite its primary structures, it has suffered some of the subsequent alteration which has produced the hybrid rocks. It does in fact contain some textural features (e.g. a sieve structure in the pyroxene and replacement of plagioclase by quartz) which are considered typical of that process (p. 30, 38).

From the field and microscope evidence it has been concluded that the basic hybrid (No. 2) was formed by the addition of aplitic material to the primary gabbro (No. 1), and that the acid hybrid (No. 4), the

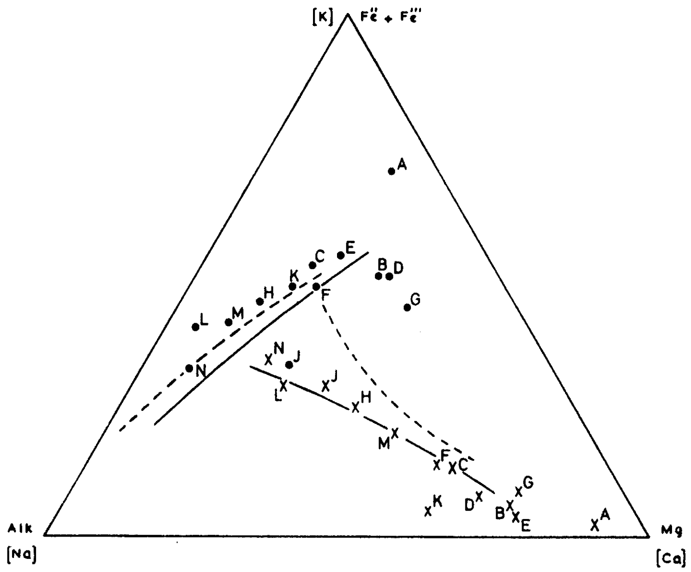


FIGURE 22

Variation diagrams (Fe″ + Fe‴) — Alk — Mg and K — Na — Ca showing the curves drawn through the analyses of the Andean Intrusive Suite of Graham Land (dashed line) and the Anvers Island rocks (solid line; Fig. 21) in relation to previous analyses of Anvers Island rocks and Andean rocks of Patagonia.

● = (Fe″ + Fe‴) — Alk — Mg.
× = K — Na — Ca.

A. Gabbro, Bob Island (Pelikan, 1909).
B. Gabbro, Anvers Island (Pelikan, 1909).
C. Quartz-diorite, Port Lockroy, Wiencke Island (Barth and Holmsen, 1939).
D. Essexite-gabbro, Rio Pinto (Quensel, 1912).
E. Uralitized hornblende-gabbro, Puerto Angosto (Bodman, 1916).
F. "Essexite", Cerro Cagual (Quensel, 1912).
G. Bronzite-orthoclase-gabbro, Cerro Payne (Quensel, 1912).
H. Quartz-bearing andendiorite, San Antoniotal (Stelzner, 1885).
J. Quartz-bearing andendiorite, Yuncantal (Stelzner, 1885).
K. Quartz-diorite, Hoste Island (Bodman, 1916).
L. Granite, Puerto Angosto (Nordenskjöld, 1905).
M. Quartz-mica-diorite, Quarenta Dias (Bodman, 1916).
N. Andengranite (hornblende-bearing biotite-granite), Yuncantal (Stelzner, 1885).

[For analyses A and B, *see* Adie, 1955, Table VI, Nos. 3 and 16; for analyses D-N, *see* Adie, 1955, Table IX, Nos. 1-10]

granodiorite (No. 5) and the associated aplite vein (No. 6) were formed by the addition of similar material to the primary tonalite (No. 3) (p. 38). This is consistent with the chemical analyses and is best illustrated in the K — Na — Ca diagram. The straight line joining analysis No. 2 with No. 1 and that joining Nos. 6, 5 and 4 with No. 3 both imply an increase in aplitic material which has a higher Na/K ratio than would be expected from the normal magmatic differentiation of the Andean Intrusive Suite. The Cape Monaco Granite (No. 7) shows a similar but more striking divergence from the magmatic trend.

In the K — Na — Ca diagram the trondhjemitic porphyry (No. 8) stands alone and this, in itself, is good evidence for concluding that this rock type owes its origin to some process other than magmatic differentiation. Both this rock and the Cape Monaco Granite have normative quartz + orthoclase + albite exceeding 80 per cent of the total and may be plotted on a triangular diagram with the co-ordinates normative quartz — orthoclase — albite (Fig. 23). Both rocks fall outside the triangle containing normal granites (Tuttle and Bowen, 1958, p. 128) and this again supports the view that both rocks are of metasomatic origin.

From the field and microscope study it was concluded that the trondhjemitic rocks represent extreme cases of an early stage in a metasomatic process which culminated in the formation of the Cape Monaco Granite (p. 58). In Fig. 23 the trend from trondhjemitic porphyry to Cape Monaco Granite may be extended to enter the field of normal granites. Indeed, the analysed specimen of Cape Monaco Granite

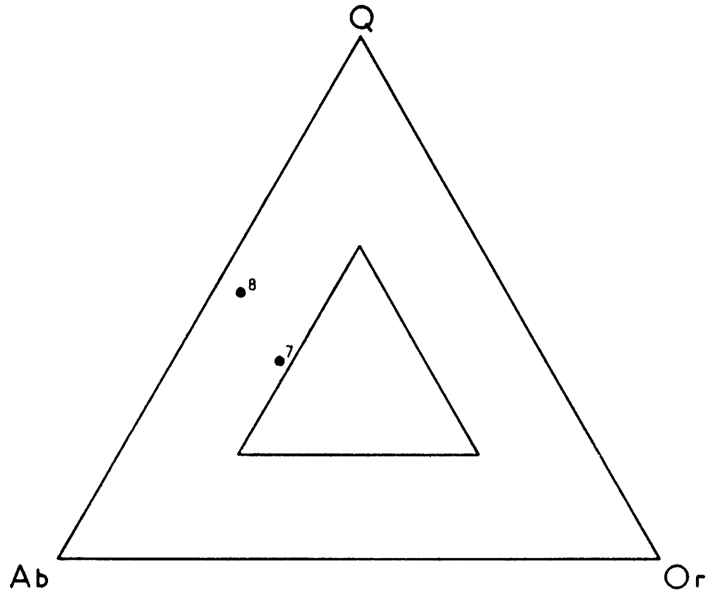


FIGURE 23
Triangular diagram of normative quartz-orthoclase-albite showing the respective positions of the trondhjemitic porphyry (Table X, No. 8) and the Cape Monaco Granite (Table X, No. 7) in relation to the triangle enclosing normal granites (after Tuttle and Bowen, 1958).

(N.145.1; p. 42) represents the earlier pseudo-porphyritic variety of the granite and it is probable that an analysis of the more equigranular variety would fall within the field of normal granites where it might well prove indistinguishable from one of magmatic origin.

The metasomatic process

The chemical evidence, then, is consistent with the metasomatic hypothesis suggested by the field and microscope study.

It is probable that in the process envisaged the material available for metasomatism in any one place is controlled by the nature of the original metasomatizing material, the distance of the metasomatizing material from its origin and the nature of the rocks through which the material has already passed. In addition, the material accepted during metasomatism is controlled by the nature of the host rock.

In the Anvers Island area metasomatism has involved the introduction of silicon accompanied by either sodium or potassium or both in each case examined. It is concluded that the original metasomatizing material was rich in these three elements.

Whatever the physical state of the metasomatizing material it is likely that some of its constituents will move faster than others under certain conditions. On Anvers Island this is reflected in the trondhjemitic nature of the Altered Assemblage and in the order of formation of the minerals of the Cape Monaco Granite. In each case silicon and sodium entered in advance of potassium and hence the silicon and sodium were capable of moving faster or farther from the source than the potassium. The trondhjemitic rocks of Arthur Harbour crop out at a considerable distance from the nearest exposure of Cape Monaco Granite and towards the granite their potassium content increases. Those rocks in which the trondhjemitic tendency is strongest formed along older contacts where faults might have been expected. It is concluded that the silicon and sodium were capable of moving up these older fractures faster than the potassium. The latter, entering more slowly, altered the trondhjemitic rocks towards the Cape Monaco Granite. Within the Cape Monaco Granite it has been concluded (p. 45) that the plagioclase porphyroblasts formed first with quartz and that the potash feldspar developed later.

The time lag between the introduction of silicon and sodium and the introduction of potassium is not always so noticeable. Thus in the hybrid rocks associated with the primary gabbros and tonalites of the Andean Intrusive Suite the introduced material has a smaller Na/K ratio than the trondhjemitic porphyry. Apparently in this case the potassium has almost kept pace with the silicon and sodium.

Surface evidence suggests that the rocks through which the metasomatizing material passed were either tonalites and gabbros of the Andean Intrusive Suite or andesitic rocks of the Upper Jurassic Volcanics. The chemical differences between these rocks are not likely to play a significant part in the trend of the metasomatism.

On the triangular variation diagram with the co-ordinates K — Na — Ca (Fig. 21) the metasomatic process envisaged can be traced as follows. The approximate position of the average primary rock will be close to analysis No. 2. In the most extreme case of sodium entering in advance of potassium the composition would move towards the sodium apex, and somewhere in the region of the trondhjemitic porphyry (No. 8) it is probable that the host rock would become saturated with sodium. Any further metasomatism would involve the addition of potassium and the trend would be towards the Cape Monaco Granite (No. 7).

In those cases where the time lag between the introduction of sodium and potassium was smaller the trend would be less convex towards the sodium apex, trending along a line intermediate between the extreme case just described and the trend of the Andean Intrusive Suite. In all cases the final product would be a normal granite. If conditions were such that sodium and potassium were added in proportions identical to those in the original material, then the trend in the K — Na — Ca variation diagram would be a straight line probably running close to the curve of the Andean Intrusive Suite.

Regarding the physical properties of the metasomatizing material the following points appear relevant:

i. The relative ease with which the metasomatizing material penetrated upwards as opposed to sideways (p. 26).

ii. Its tendency to follow earlier planes of weakness such as fault planes (p. 49, 58).

iii. Its ability of metasomatize, brecciate and, in extreme cases, remobilize the country rock.

Examples of the last process which occur throughout the area are listed below:

a. On the "*F*" group of the Joubin Islands, Upper Jurassic Volcanics have been metasomatized and frequently brecciated. Euhedral porphyroblasts of quartz and albite are typically developed (p. 21).

b. Breccia dykes occur on island *G1* of the Joubin Islands, where angular fragments of volcanic rock have been formed and the whole mobilized to intrude metasomatized volcanics. Two points of interest are the fine-grained margins caused, at least in part, by shearing and the association of fragments less metasomatized than the country rock with euhedral quartz crystals which are a result of the metasomatism (p. 26).

c. On Gateway and Bull Ridges, in an area apparently dissociated from the Cape Monaco Granite, large zones of mylonitized rock cut through the Andean intrusives and associated hybrid rocks. The mylonite has been recrystallized and apparently metasomatized to a coarse microcline-granite, the texture of which is very similar to that of the Cape Monaco Granite (p. 40).

d. The trondhjemitic porphyry occurs in marginal zones of the Cape Monaco Granite and in the Altered Assemblage. This rock type has been formed by intense silica-soda metasomatism of earlier rocks; it frequently possesses cataclastic features and in many cases has been remobilized to form sharp-sided veins. Euhedral porphyroblasts of quartz and albite are a typical feature of the trondhjemitic porphyry (p. 47).

It is concluded that the metasomatizing material and particularly the early silicon-sodium-rich material was in an active volatile state, capable in extreme cases of brecciating the country rock and remobilizing it, sometimes with the remobilized fragments still in a solid state.

IX. THE POST-ANDEAN VOLCANICS

In the north-east corner of Anvers Island a narrow flat-topped ridge, approximately 4,000 ft. high and forming part of the Osterrieth Range, runs from the Mount Français massif to Ryswick Point, descending in nearly vertical walls to Fournier Bay on the one side and to the Gerlache Channel on the other (Fig. 1). The ridge is formed of a post-Andean volcanic succession not less than 4,000 ft. thick. Most of the area is inaccessible on foot and only two outcrops were reached.

The conspicuous layering lies approximately horizontal except where it approaches the Mount Français massif. Here it sweeps upwards to rest at a high angle against the Andean rocks.

Over 2,000 ft. of the succession are exposed in the cirque wall at the head of William Glacier (Fig. 10), where it is bordered on either side by Andean intrusives. The dip of the layers in the exposed section varies from zero at the centre to 30° near both contacts. The contacts are sharp; that to the south-east dips at 45° to the north and a small part of it is accessible although partly obscured by ice and frozen mud. Here the layers sweep evenly up to the intrusives without dislocation.

Specimens were collected from three layers in the succession. Two of these are thick and composed of coarse tuff, whereas the third, which separates the other two, is an aphanitic tuff only 1 in. thick. Two large fragments from the coarse tuff were also collected. One is volcanic material and the other is an Andean granodiorite. All the specimens were collected within 2 ft. of the contact.

Lavas of the same unaltered appearance were collected from an isolated outcrop at 6,000 ft. on the southern shoulder of Mount Français (Fig. 10). Narrow, deep red zones of weathering, assumed to follow bedding planes, dip approximately 70° south, away from the concealed contact. On Bull Ridge, at the bottom of this shoulder, another contact between the volcanics and the Andean rocks dips approximately 45° north.

A. Petrology

The aphanitic tuff (N.90.1) from William Glacier cirque is a pale chocolate colour in the hand specimen and breaks with a conchoidal fracture. Some crystallinity is visible under a lens along the bottom millimetre. A thin section cut across the layer reveals a marked gradation from a cryptocrystalline rock at the top to a microcrystalline base in which feldspar and pyroxene fragments reach a size of 0.1 mm. The bottom millimetre has alternate fine and very fine bands parallel to the base. Recognizable crystal fragments are of plagioclase (labradorite and perhaps bytownite), clinopyroxene and iron ore with small areas of secondary haematite. The rock is a crystal tuff with basaltic affinities.

The coarse thick layers above and below the aphanitic layer are lithic tuffs in which all the smaller rock fragments are angular and of volcanic origin. In the hand specimen the first layer (N.90.2) is a grey compact rock. Under the microscope the larger crystal fragments are seen to be of olivine ($2V\gamma = 95°$*), clinopyroxene ($2V\gamma = 55° \pm 3°$), iron ore and anorthite (An_{90}). They are angular and vary in size from the cryptocrystalline to 0.4 mm. Those of plagioclase are often spongy, the irregular inclusions being composed of an opaque material which is probably glass with iron ore.

The rock fragments vary in size up to 3.0 mm. The majority contain phenocrysts similar to the crystal fragments in the groundmass, namely olivine, pyroxene, plagioclase and iron ore of which the first three are euhedral. Some fragments, however, lack olivine and have a higher percentage of a plagioclase which is strongly zoned (e.g. core $An_{62} - An_{30}$ margin). The most abundant type of rock fragment has large phenocrysts of plagioclase, iron ore and olivine. Those of plagioclase are up to 1.0 mm. long, zoned from a core of An_{70} to a margin of An_{56} and are spongy with rounded or elongated inclusions of pale brown glass. These are associated with rather smaller phenocrysts of plagioclase (An_{51}), olivine, clinopyroxene and iron ore, all of which are set in a pale brown glass. The groundmass of other rock fragments varies from a pale brown glass to entirely opaque material while the phenocrysts of olivine and plagioclase vary in their relative abundance. The overall composition of the tuff is basaltic.

The second lithic tuff (N.90.3) is a less compact, more weathered specimen with occasional rock fragments reaching 10.0 mm. The fragments are coloured red, blue or yellow. Under the microscope it differs from the previous specimen mainly in its lack of olivine, higher percentage of plagioclase and the devitrification of the groundmass material.

However, the crystal fragments are of approximately the same size (0.4 mm.). Those of plagioclase are often spongy and, although the composition is variable, a typical crystal has a core of An_{88} zoned to a margin of An_{62}. In the most abundant type of rock fragment small (0.1 mm.) zoned plagioclase laths predominate, often with a trachytic texture. Clinopyroxene ($2V\gamma = 56° \pm 2°$) occurs as much larger euhedral phenocrysts in some and as smaller anhedral crystals associated with iron ore in others. One large trachytic fragment with very small pyroxene and iron ore crystals between the feldspar laths has a matrix of pale brown glass. The zoned plagioclase has a relatively small extinction angle and is probably

* The 2V measured over γ (4 crystals) averaged 92° and those measured over α (4 crystals) averaged 97°. Tomkieff (1939), Johnston (1953) and Wyllie (1959) have described a similar discrepancy.

andesine at the core with an oligoclase margin. The rim of the fragment is devitrified. Most of the rock fragments have a red stain due to the presence of secondary haematite. Again, the composition of these tuffs is probably basaltic but they contain many andesitic fragments.

The volcanic inclusion (N.89.2) collected from the coarse tuffs is a grey aphanitic rock carrying feldspar and iron ore phenocrysts. Under the microscope it is holocrystalline with a trachytic texture. After feldspar, iron ore is the most abundant mineral in the groundmass and a third is a pigeonitic augite ($2V\gamma = 31° \pm 3°$) sometimes with a core of more normal augite ($2V\gamma = 54° \pm 3°$). Small laths of plagioclase in the groundmass have a composition of An_{36} but other feldspar crystals have a refractive index lower than balsam. The orientated feldspar phenocrysts are plagioclase with oscillatory zoning between labradorite and oligoclase. Small iron ore phenocrysts pseudomorph pyroxene and occasionally possess a chlorite core. The rock is probably a trachyandesite.

The inclusion of Andean granodiorite (N.88.2) in the coarse tuff is a dark grey rock of medium grain-size with a smoothed exterior. Under the microscope it is seen to consist mainly of interlocking grains (0.1 – 0.5 mm.) of plagioclase, potash feldspar and quartz with approximately 20 per cent of ferromagnesian minerals. A few of the plagioclase crystals are larger (up to 2.0 mm.), have cores of An_{68} and include small crystals of biotite, iron ore and chlorite. The normal crystals of plagioclase are fresh and have an equant form with cores between An_{40} and An_{50}. The twinned part of the crystals is zoned normally to An_{34} and outside this is an untwinned border of oligoclase against the quartz and potash feldspar.

The ferromagnesian minerals are hornblende ($2V\alpha = 66° \pm 3°$; $\gamma{:}c = 15° \pm 2°$), biotite and iron ore with a little chlorite replacing the biotite. Relics of clinopyroxene ($2V\gamma = 52° \pm 4°$) form the centres of some hornblende crystals. These dark minerals are normally anhedral and poikilitic with bold margins. The rock is a granodiorite by composition but may have suffered some degree of recrystallization.

The lava from high on the southern shoulder of Mount Français (N.218.1) has a red crust of spheroidal weathering more than an inch thick. The rock is porphyritic and the phenocrysts of plagioclase, clinopyroxene and hypersthene make up 50 per cent of the rock. Some of the plagioclase phenocrysts are as much as 2.0 mm. long and possess oscillatory zoning between An_{85} and An_{68}, the two compositions alternating several times between the core (An_{85}) and the margin (An_{68}). The clinopyroxene has $2V\gamma = 52° \pm 2°$ and extinction angle $\gamma{:}c = 42° \pm 3°$. The groundmass is holocrystalline and andesitic, consisting of laths of andesine and pyroxene with grains of iron ore. The red weathering appears in thin section as translucent red haematite filling the numerous fractures through both the groundmass and the phenocrysts. The rock is a porphyritic hypersthene-augite-andesite.

B. Discussion

Specimens collected within 2 ft. of the contact show no alteration beyond slight devitrification and the formation of haematite, both of which may be attributed to normal weathering. This, together with the presence of considerable quantities of unaltered volcanic glass may be regarded as confirmation of the meagre field evidence that the succession is, in fact, younger than the Andean rocks.

Pyroclastic rocks appear to predominate in the middle part of the succession where a trachyandesite forms an inclusion in lithic tuffs which are predominantly basaltic. Towards the top of the succession a hypersthene-augite-andesite is recorded. The high percentage of anorthite in the plagioclase, both in the crystal fragments of the tuffs and the phenocrysts of the hypersthene-augite-andesite, is most marked. This may be compared to a similar phenomenon in the Andean rocks. Finally, the extreme freshness of the rocks collected should be emphasized.

Post-Andean volcanic rocks have been described from the South Shetland Islands immediately to the north and from the James Ross Island group off the north-east coast of Graham Land. The age of the latter (the James Ross Island Volcanics) is Middle Miocene (Andersson, 1906; Adie, 1953), while in the South Shetland Islands post-Andean volcanicity probably commenced early in the Miocene and continued until the last century (Hawkes, 1961*b*, p. 2, 25).

Correlation is difficult on the evidence available but it is suggested that the Anvers Island succession compares more favourably with that of the South Shetland Islands than with that of the James Ross Island group. In particular the presence of hypersthene-augite-andesite and the very basic plagioclase may be quoted. Both are typical of the South Shetland Islands succession but neither have been recorded from the James Ross Island group. In the South Shetland Islands true olivine-basalts were not extruded before the

Pliocene (Hawkes, 1961*a*, Table I, p. 2), hence the fresh olivine-bearing basaltic tuffs of Anvers Island probably belong to this period. This correlation is tentative and should not be over emphasized.

The structure of the post-Andean succession on Anvers Island is interesting. The steep opposed contacts indicate that the volcanics were deposited in deep, steep-sided valleys already hewn from the Andean intrusive rocks. One such valley appears to have run from the north-east tip of Anvers Island up towards Mount Français, while a narrow continuation extended around to the south of Mount Français, reaching, perhaps, to a higher peak behind. The steep sides of the valleys suggest a glacial origin.

The marked increase in the dip of the volcanics towards the sides of these valleys implies considerable settling of the material after deposition. This effect increases from the middle parts of the succession where the layers only sweep up to 30°, to those at 6,000 ft. where the dip reaches 70°. This in turn suggests a considerable proportion of pyroclastic material, as already indicated by the few specimens collected.

X. THE GEOLOGICAL HISTORY OF ANVERS ISLAND AND ITS RELATION TO GRAHAM LAND

THE oldest rocks exposed in the Anvers Island area are a succession of andesitic lavas and tuffs of Upper Jurassic age. The succession is more than 4,000 ft. thick and probably covered most of the area when it was extruded. At present they are seldom preserved far from the Andean intrusions and are usually highly altered.

Volcanic rocks of Upper Jurassic age have been recorded on the east coast of Graham Land from Trinity Peninsula to the Oscar II Coast (Adie, 1953) and down the entire length of the west coast of Graham Land from the South Shetland Islands to Alexander Island (Gourdon, 1906; Ferguson, 1921; Tyrrell, 1921, 1945; Adie, 1953; Bayly, 1957; Hawkes, 1961*a*).

On the east coast of Graham Land Adie has recorded rhyolites and associated tuffs followed by a series of quartz-plagioclase-porphyries. In the South Shetland Islands the volcanics are predominantly andesitic with only a small proportion of basaltic and rhyolitic rocks (Hawkes, 1961*a*, Table I, p. 2). Bayly has described andesitic rocks associated with a group of acid volcanics from the Danco Coast. From the west coast of Adelaide Island Tyrrell (1945) has described quartz-plagioclase-porphyries and Adie (1953) has also described andesites and rhyolites from the Marguerite Bay and George VI Sound areas. The predominantly andesitic nature of the west coast volcanics is clear. The metasomatized volcanics of the Joubin Islands have certain similarities to the quartz-plagioclase-porphyries described both by Tyrrell and Adie, and to the acid volcanics of the Danco Coast.

On Wiencke Island the succession is severely faulted but it is not folded, having a dip of less than 10°. Similarly, on the Outcast Islands that part of the volcanic succession farthest from the Andean tonalite is only gently folded and the folds appear to be related to the tonalite intrusion. It is apparent, therefore, that post-Jurassic orogenic folding is absent in the Anvers Island area.

A similar absence of folding is described by Bayly (1957) from the Danco Coast. The maximum dip Adie (1953) recorded in the Jurassic Volcanics on the east coast of Graham Land is 26°, and in this and other instances where the dip is recorded it appears to be constant in one direction. Thus it seems probable that post-Jurassic orogenic folding is also absent from the northern part of the Graham Land peninsula.

In the late Cretaceous or early Tertiary the undisturbed Upper Jurassic Volcanics were intruded by gabbros and tonalites of the Andean Intrusive Suite. Around the intrusions the volcanics were pushed back and contact metamorphosed in wide aureoles. Faulting played a major part in the intrusive process and it is probable that regional faults, tangential to a number of Andean bosses and parallel to the curved axis of Graham Land, were formed at this time. Associated with these is a secondary group of faults which are almost perpendicular to the Graham Land axis. Vertical movement along these faults is suggested as the prime cause of the uplift of the Graham Land peninsula in the Anvers Island area and the Palmer Archipelago.

Similar large faults, parallel to the Graham Land axis, have been recorded from both the Hope Bay area and the east coast of Graham Land, from George VI Sound in the south-west (Knowles, 1945, p. 135) and from the Graham Coast.* Oppenheim (1947) has drawn attention to similar structural features in the western cordilleras of the South American Andes.

* Personal communication from Dr. R. Curtis.

On Wiencke Island, where these faults displace the Upper Jurassic Volcanics, cataclastic metamorphism, sometimes amounting to mylonitization, has resulted. Severe hydrothermal alteration, associated with the last phases of the Andean intrusions, is concentrated along the fault zones, thus emphasizing the close association between the faulting and the intrusive process. Much of the vertical movement along the faults, however, must be of much later date, as the post-Andean peneplain of Graham Land (Holtedahl, 1929) now stands between 4,000 and 6,000 ft.

During some period subsequent to the emplacement of the Andean Intrusive Suite but prior to the eruption of the post-Andean volcanic succession (Miocene to Recent) many of the Upper Jurassic Volcanics and the gabbros and tonalites of the Andean Intrusive Suite were altered by regional metasomatism. In general, the metasomatic process involved the introduction of silicon, sodium and potassium in varying proportions. The addition of such material to the primary gabbros and tonalites has produced a series of hybrid rocks with textural and chemical characteristics distinct from those of the primary intrusives. In the more extreme cases the quantity of acid material added was apparently enough to produce a rock of granodiorite composition with a peculiar texture of broken and rewelded crystals caused by limited remobilization to a thick crystal mush.

At other localities the metasomatic material streamed upwards in a volatile state, frequently following older fault planes associated with the earlier intrusions. In such cases sodium and silicon entered in advance of potassium to form trondhjemitic rocks. Extreme examples of silicon/sodium metasomatism again resulted in local remobilization. Further additions of potassium and silicon transformed the trondhjemitic rocks to Cape Monaco Granite. This body, as now exposed, forms a narrow belt along the north-west coast of Anvers Island and it is suggested that its shape was controlled by an earlier regional fault zone associated with the emplacement of the Andean Intrusive Suite. Similarly, the Altered Assemblage of metasomatic rocks, possibly underlain by Cape Monaco Granite, forms a broad zone, trending at an angle to the granite zone, which may be related to the second group of faults associated with the Andean Intrusive Suite.

Study of the Andean rocks of Graham Land has not led previous workers to postulate a regional metasomatism. Adie (1955) has concluded that all the rocks he studied from the Andean Intrusive Suite of the Graham Land peninsula were derived by differentiation during crystallization from a single parent magma. However, he does mention the addition of some silicon, sodium and potassium to Upper Jurassic rhyolites on the east coast.

Barth and Holmsen (1939) have suggested that the Anvers Island area formed part of a downwarp during the time the Andean rocks were intruded. The resultant rise in temperature melted the Upper Jurassic Volcanics to form, first, the volcanic breccias and then a dioritic (tonalitic) magma. The gabbro-adamellite suite was then formed by differentiation during crystallization of this new magma.

More recently, Bayly (1957) has suggested widespread autometasomatism as an explanation for the petrology of the acid volcanic rocks of the Danco Coast. He also discussed the possibility of external metasomatism accompanied by remobilization. The present author believes that the rocks of the Danco Coast and those of Anvers Island have much in common. The relation of these two areas to the rest of Graham Land, however, raises a new and interesting problem.

Many small dykes, mainly of a basic composition, intrude the rocks associated with the Andean Intrusive Suite in the Anvers Island area. Some can be associated with the post-Andean volcanic succession. The dykes will be described in a later report.

The post-Andean volcanic rocks are exposed in the north-east corner of Anvers Island where they fill deep valleys eroded in the Andean rocks. Predominantly pyroclastic, they include basaltic tuffs, hypersthene-augite-andesites and trachyandesites. Post-Andean volcanics have been described from the north-east coast of Graham Land (the James Ross Island Volcanic Group; Adie, 1953) and from the South Shetland Islands (Hawkes, 1961*a*, *b*). The James Ross Island Volcanic Group is composed principally of olivine-basalts of Miocene age and neither hypersthene-augite-andesites nor trachyandesites have been recorded. The post-Andean volcanics of the South Shetland Islands, however, range in age from Miocene to Recent and include both hypersthene-augite-andesites and trachyandesites in addition to basalts. The Anvers Island Post-Andean volcanic succession is therefore tentatively correlated with that of the South Shetland Islands.

XI. ACKNOWLEDGEMENTS

THE field work was carried out from the Falkland Islands Dependencies Survey base on Anvers Island between March 1955 and March 1957 with the assistance and friendship of the other members of the Survey at the base. I am grateful to Mr. J. P. Wylie for drawing the nine geological maps under the direction of the Directorate of Overseas Surveys at Tolworth, and to Dr. D. C. Goldring for assistance in the field during January 1957 and for the use of his field notes.

My thanks are due to Professor F. W. Shotton for making available the laboratory facilities for this study, to Dr. R. J. Adie for advice and helpful criticism during the preparation of the manuscript, and to other members of the Falkland Islands Dependencies Survey geological research group at Birmingham University for discussions on the work.

The photomicrographs were prepared by Mr. L. W. Vaughan.

XII. REFERENCES

ADIE R. J. 1953. *The Rocks of Graham Land.* Ph.D. thesis, University of Cambridge, 259 pp. [unpublished.]

———. 1954. The Petrology of Graham Land: I. The Basement Complex; Early Palaeozoic Plutonic and Volcanic Rocks. *Falkland Islands Dependencies Survey Scientific Reports*, No. 11, 22 pp.

———. 1955. The Petrology of Graham Land: II. The Andean Granite-Gabbro Intrusive Suite. *Falkland Islands Dependencies Survey Scientific Reports*, No. 12, 39 pp.

———. 1957*a*. Geological Investigations in the Falkland Islands Dependencies before 1940. *Polar Rec.*, **8**, No. 57, 502–13.

———. 1957*b*. The Petrology of Graham Land: III. Metamorphic Rocks of the Trinity Peninsula Series. *Falkland Islands Dependencies Survey Scientific Reports*, No. 20, 26 pp.

ANDERSON, C. A. 1933. Volcanic History of Glass Mountain, Northern California. *Amer. J. Sci.*, **226**, No. 155, 485–506.

ANDERSSON, J. G. 1906. On the Geology of Graham Land. *Bull. geol. Instn Univ. Upsala*, **7**, 19–71.

ARÇTOWSKI, H. 1900*a*. Géographie physique de la région antarctique visitée par l'expédition de la Belgica. *Bull. Soc. belge Geogr.*, **24**, No. 1, 93–175.

———. 1900*b*. Sur l'ancienne extension des glaciers dans la région des terres découvertes par l'expédition antarctique belge. *C.R. Acad. Sci., Paris*, **131**, No. 9, 479–81.

———. 1901. Sur les glaciers et la géologie des terres découvertes par l'expédition antarctique belge et sur les glaces du Pôle Sud. *C.R. 8th Int. geol. Congr.*, Paris, 1900, **8**, Pt. 1, 380.

BARTH, T. F. W. *and* P. HOLMSEN. 1939. Rocks from the Antarctandes and the Southern Antilles. Being a description of rock samples collected by Olaf Holtedahl 1927–28, and a discussion of their mode of origin. *Sci. Res. Norweg. antarct. Exped.*, No. 18, 64 pp.

BATTEY, M. H. 1955. Alkali Metasomatism and the Petrology of Some Keratophyres. *Geol. Mag.*, **92**, No. 2, 104–26.

BAYLY, M. B. 1957. The Geology of the Danco Coast, Graham Land (Charlotte Bay to Andvord Bay). *Falkland Islands Dependencies Survey Preliminary Geological Report*, No. 1, 33 pp. [unpublished.]

BODMAN, G. 1916. Petrographische Studien über einige antarktische Gesteine. *Wiss. Ergebn. schwed. Südpolarexped.*, Bd. 3, Lief. 15, 100 pp.

FERGUSON, D. 1921. Geological Observations in the South Shetland Islands, the Palmer Archipelago and Graham Land, Antarctica. *Trans. roy. Soc. Edinb.*, **53**, Pt. 1, No. 3, 29–55.

GOODSPEED, G. E. 1959. Some Textural Features of Magmatic and Metasomatic Rocks. *Amer. Min.*, **44**, Nos. 3–4, 211–50.

GOURDON, E. 1905. Les roches éruptives grenues de la Terre de Graham recueillies par l'expédition antarctique du Dr. Charcot. *C.R. Acad. Sci., Paris*, **141**, No. 24, 1036–38.

———. 1906. Les roches microlithiques de la Terre de Graham recueillies par l'expédition antarctique du Dr. Charcot. *C.R. Acad. Sci., Paris*, **143**, No. 3, 178–80.

———. 1907. Sur un microgranite alcalin recueilli sur la Terre de Graham par l'expédition antarctique du Dr. Charcot. *C.R. Acad. Sci., Paris*, **144**, No. 22, 1224–26.

———. 1908. *Géographie physique, Glaciologie, Pétrographie des Régions visitées par l'Expédition Antarctique Française commandée par le Dr. Charcot, 1903–05*, 214 pp., Paris.

———. 1917. *Minéralogie, Géologie: Deuxième Expédition Antarctique Française (1908–10) commandée par le Dr. Charcot*, pp. 1–10, Paris.

HAWKES, D. D. 1961*a*. The Geology of the South Shetland Islands: I. The Petrology of King George Island. *Falkland Islands Dependencies Survey Scientific Reports*, No. 26, 28 pp.

———. 1961*b*. The Geology of the South Shetland Islands: II. The Geology and Petrology of Deception Island. *Falkland Islands Dependencies Survey Scientific Reports*, No. 27, 43 pp.

HESS, H. H. 1941. Pyroxenes of Common Mafic Magmas, Pts. 1 and 2. *Amer. Min.*, **26,** No. 9, 515–35; No. 10, 573–94.

HOLTEDAHL, O. 1929. On the Geology and Physiography of Some Antarctic and Sub-antarctic Islands. *Sci. Res. Norweg. antarct. Exped.*, No. 3, 172 pp.

JOHNSTON, R. 1953. The Olivines of the Garbh Eilean Sill, Shiant Isles. *Geol. Mag.*, **90,** No. 3, 161–71.

KNOWLES, P. H. 1945. Geology of Southern Palmer Peninsula, Antarctica. *Proc. Amer. phil. Soc.*, **89,** 132–45.

MISCH, P. 1949. Metasomatic Granitization of Batholithic Dimensions. Pt. I; Pt. II. Static granitization in Sheku area, northwest Yunnan (China); Pt. III. Relationships of synkinematic and static granitization. *Amer. J. Sci.*, **247,** No. 4, 209–45; No. 6, 372–406; No. 10, 376–705.

NOCKOLDS, S. R. 1954. Average Chemical Compositions of Some Igneous Rocks. *Bull. geol. Soc. Amer.*, **65,** No. 10, 1007–32.

———. *and* R. ALLEN. 1953. The Geochemistry of Some Igneous Rock Series. *Geochim. et Cosmoch. Acta*, **4,** 105–42.

NORDENSKJÖLD, O. 1905. Die krystallinischen Gesteine der Magellansländer. *Wiss. Ergebn. schwed. Exped. Magell.*, Bd. 1, Lief. 6, 175–240.

OPPENHEIM, V. 1947. Structural Evolution of the South American Andes. *Amer. J. Sci.*, **245,** No. 3, 158–74.

PELIKAN, A. 1909. Petrographische Untersuchung der Gesteinsproben. *Résult. Voy. Belgica*, Teil I, 1–49.

QUENSEL, P. D. 1912. Geologisch-petrologische Studien in der patagonischen Cordillera. *Bull. geol. Instn Univ. Upsala*, **11,** 1–114.

SISTEK, D. 1912. Petrographische Untersuchungen der Gesteinsproben. *Résult. Voy. Belgica*, Teil II, 1–20.

STELZNER, A. 1885. *Beiträge zur Geologie und Palaeontologie der Argentinischen Republik*, 329 pp., Berlin.

STEWART, D. 1945. Preliminary Report on Some Intrusives of the Melchior Islands, Antarctica. *Proc. Amer. phil. Soc.*, **89,** 146–47.

———. 1947. Rocks of the Melchior Islands, Antarctica. *Proc. Amer. phil. Soc.*, **91,** 229–33.

TOMKIEFF, S. I. 1939. Zoned Olivines and their Petrogenetic Significance. *Miner. Mag.*, **25,** No. 164, 229–51.

TURNER, F. J. *and* J. VERHOOGEN. 1951. *Igneous and Metamorphic Petrology*, McGraw-Hill Book Company Inc., New York.

TUTTLE, O. F. *and* N. L. BOWEN. 1958. Origin of Granite in the Light of Experimental Studies in the System $NaAlSi_3O_8 — KAlSi_3O_8 — SiO_2 — H_2O$. *Mem. geol. Soc. Amer.*, No. 74, 153 pp.

TYRRELL, G. W. 1921. A Contribution to the Petrography of the South Shetland Islands, the Palmer Archipelago, and the Danco Land Coast, Graham Land, Antarctica. *Trans. roy. Soc. Edinb.*, **53,** Pt. 1, No. 4, 57–79.

———. 1945. Report on Rocks from West Antarctica and the Scotia Arc. '*Discovery*' *Rep.*, **23,** 37–102.

WYLLIE, P. J. 1959. Discrepancies between Optic Axial Angles of Olivines Measured over Different Bisectrices. *Amer. Min.*, **44,** Nos. 1–2, 49–64.

Printed in England under the authority of HER MAJESTY'S STATIONERY OFFICE
By F. MILDNER & SONS, LONDON

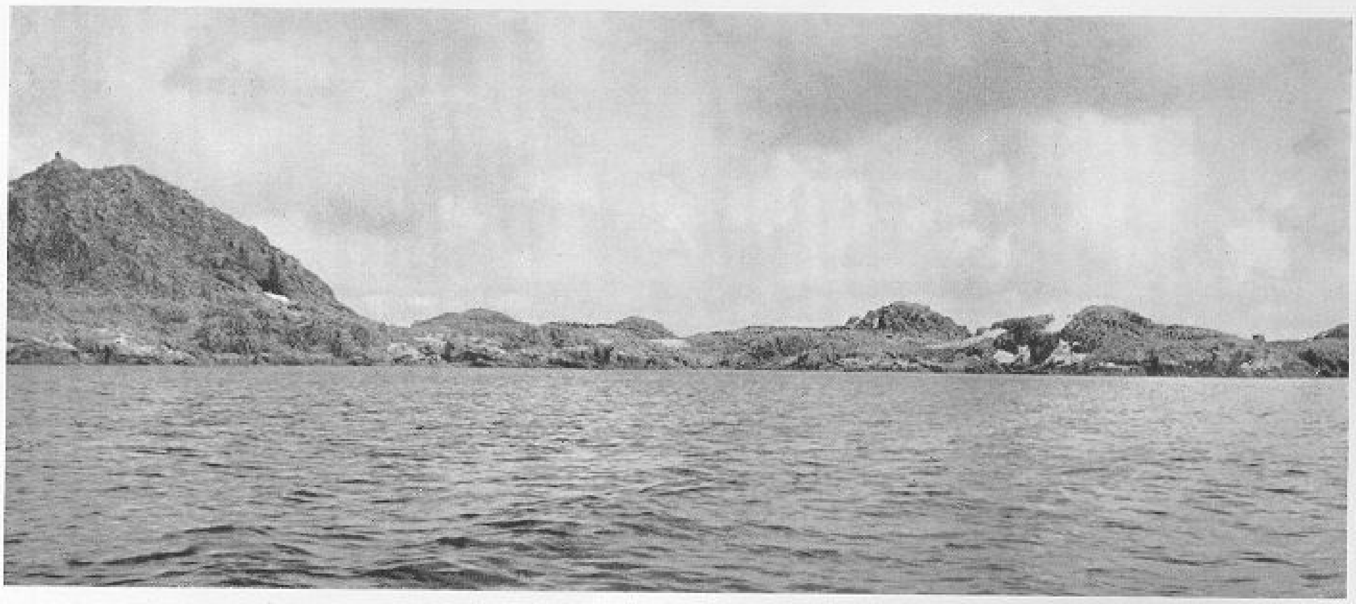
(51246) Wt. P25257/32 K6 10/60

PLATE I

a. Aerial view of north-east Anvers Island from the east. Mount Français is on the left and the layered character of the post-Andean volcanics can be seen in the right foreground.

b. Dream Island from the east. A sea cave can be seen in the rock tower on the left of the photograph, above the wave-cut platform.

a



b

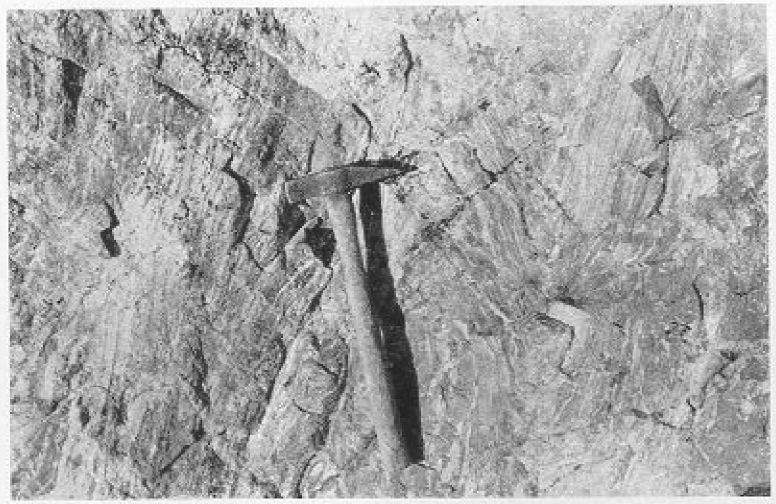
PLATE II

a. Contorted banding in thermally metamorphosed and metasomatized volcanics from the centre of island *G1*, Joubin Islands.

b. Vertical banding in gabbro, island 2 miles south-east of Arthur Harbour.

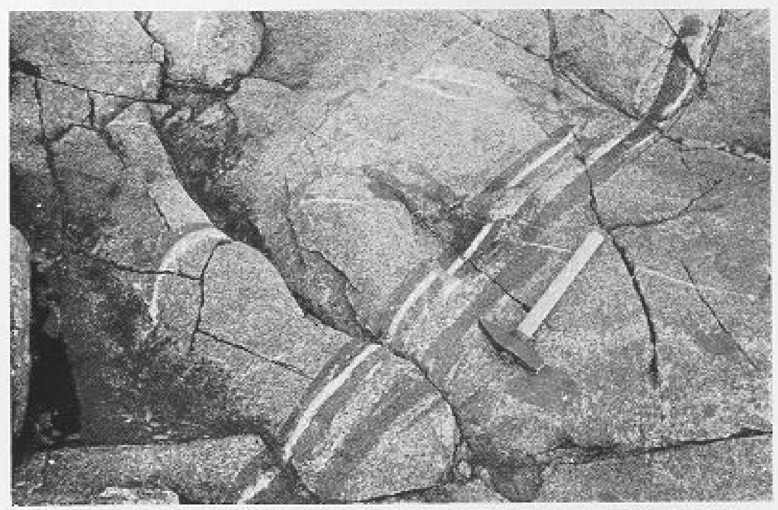
c. Dislocated bands in gabbro, island 2 miles south-east of Arthur Harbour.

d. Partially digested inclusions separated by an acid variety of the hybrid country rock, Wauwermans Islands (N.129.2).

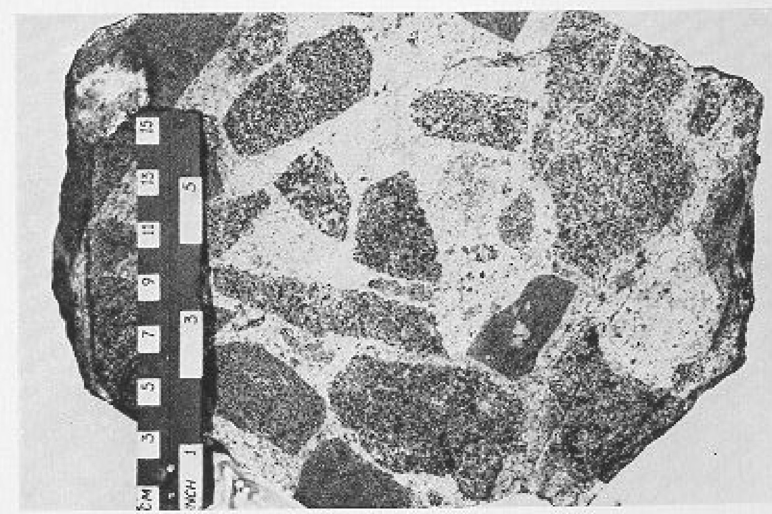


a

b



c



d

PLATE II

PLATE III

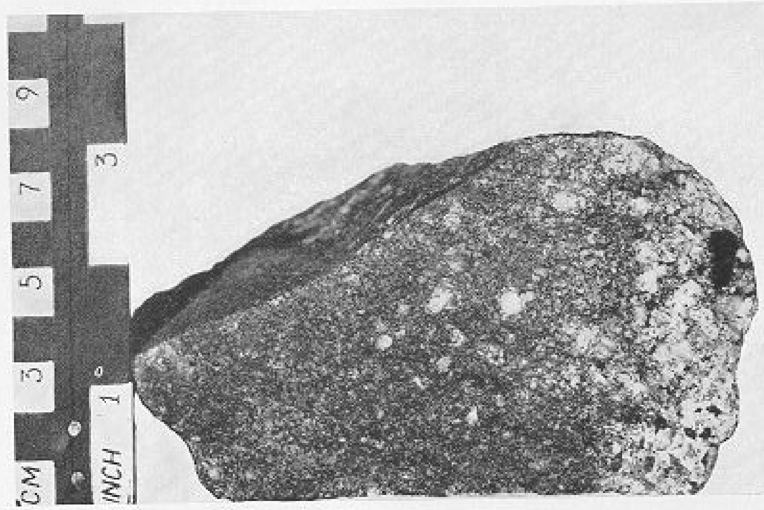
a. Development of quartz and plagioclase porphyroblasts in a dark inclusion in the Cape Monaco Granite, island *D1*, Joubin Islands (N.295.3).

b. Irregular contact between the Cape Monaco Granite (left) and an Andean tonalite boss (right). Small dark inclusions, typical of the marginal facies of the tonalite boss, can be seen in the lower half of the photograph.

c. The irregular formation of the feldspar rock as patches and stringers within the darker dioritic rock, Norsel Point.

d. Plastic flow of the paler (remobilized) material in the dioritic rock, Janus Island.

PLATE III



a

b

c

d

PLATE IV

a. Altered andesitic tuff showing the development of a felted mass of acicular hornblende crystals, Zone I, Outcast Islands (N.252.1; ordinary light; × 70).

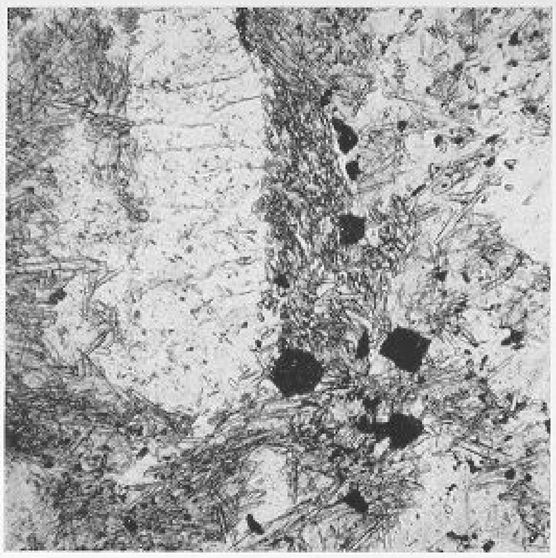
b. Recrystallized tuff showing the development of anthophyllite in a quartz-plagioclase groundmass, Zone II, Outcast Islands (N.257.1; ordinary light; × 40).

c. Sillimanite crystals associated with oligoclase, cordierite and pyrrhotite from a large volcanic inclusion in tonalite, island *A4*, Joubin Islands (N.425.2; ordinary light; × 40).

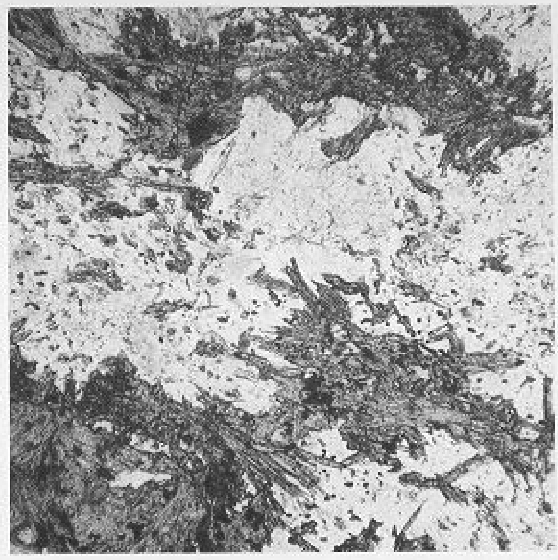
d. Spherulite composed of radiating ellipsoidal forms of quartz and alkali-feldspar centred on an euhedral albite crystal in the metasomatized volcanics, western tip of island *F5*, Joubin Islands (N.410.2; X-nicols; × 14).

e. Euhedral porphyroblasts of andalusite and cordierite, the latter showing typical interpenetrating twins, in the metasomatized volcanics, island *F1*, Joubin Islands (N.290.1; X-nicols; × 40).

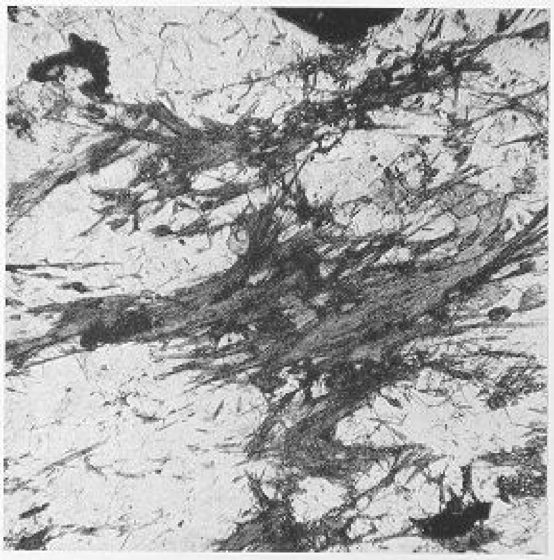
f. Breccia dyke, showing the shear zone which separates the coarse central part of the dyke from the finer marginal part. The quartz crystal in the top left corner is euhedral; island *G1*, Joubin Islands (N.279.1; ordinary light; × 40).



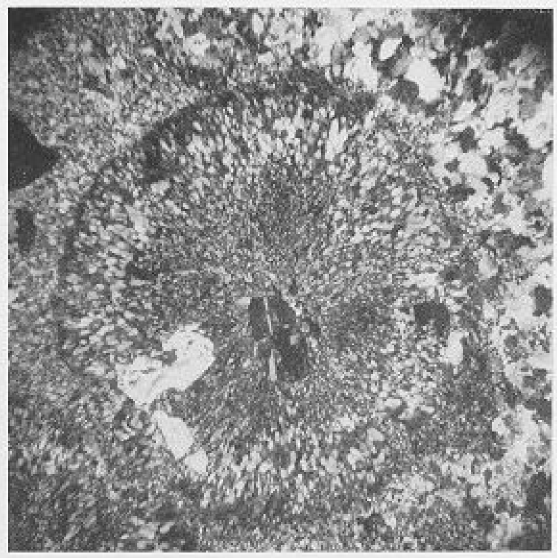
a



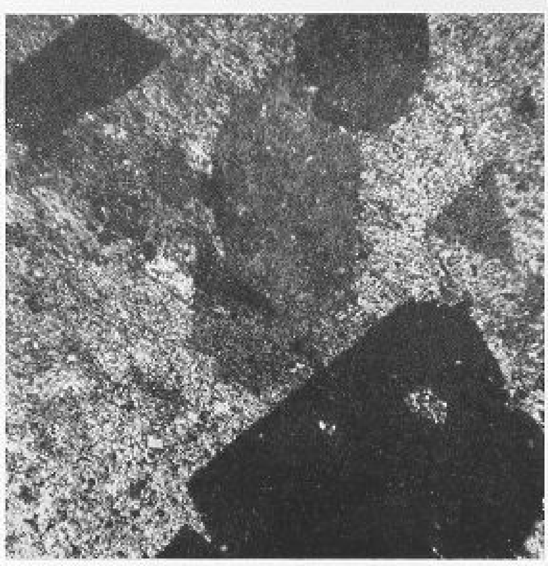
b



c



d



e

f

PLATE V

a. Typical sieve structure. Pyroxene crystals have been partially replaced by single crystals of hornblende. Iron ore, formed during the alteration, has collected in large masses outside the pyroxene crystals; north-east tip of Host Island, Wauwermans Islands (N.122.1; X-nicols; × 40).

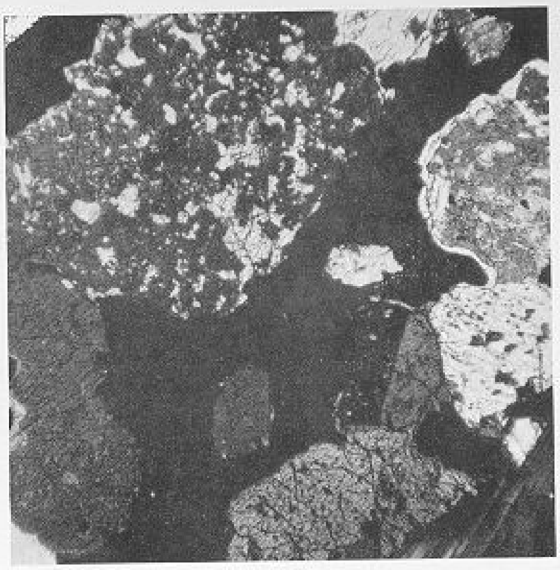
b. Granodiorite showing broken oscillatory zoning in the plagioclase crystals, Prioress Island, Wauwermans Islands (N.47.2; X-nicols; × 40).

c. Early stage in the development of a plagioclase porphyroblast (in the centre of the field) in a recrystallized mylonite, north end of Gateway Ridge (N.48.5; X-nicols; × 12.5).

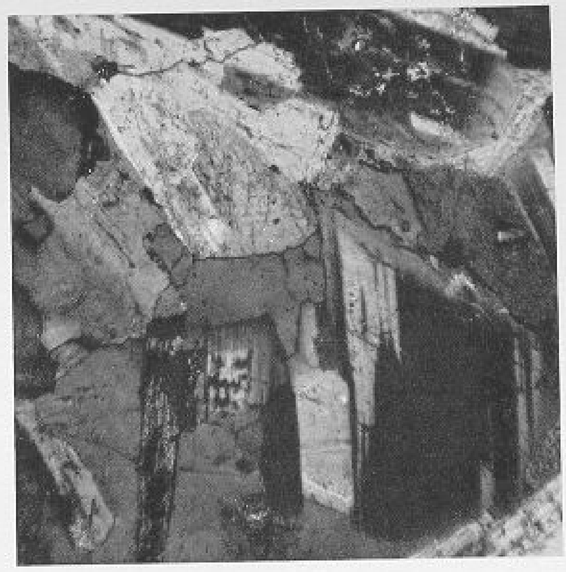
d. Later stage in the development of a plagioclase porphyroblast, showing faint oscillatory zoning, in a recrystallized mylonite, north end of Gateway Ridge (N.51.1; X-nicols; × 12.5).

e. Early stage in the development of a quartz porphyroblast, showing a ragged group of quartz crystals with similar but not identical orientation, in a recrystallized mylonite, Bull Ridge (N.212.1; X-nicols; × 12.5).

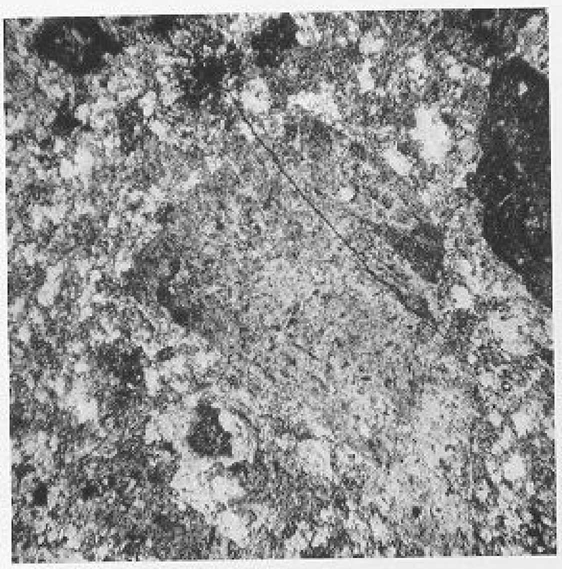
f. Later stage in the development of a quartz porphyroblast. The porphyroblast is full of inclusions, has undulose extinction and sends apophyses into the surrounding rock, Bull Ridge (N.219.1B; X-nicols; × 12.5).



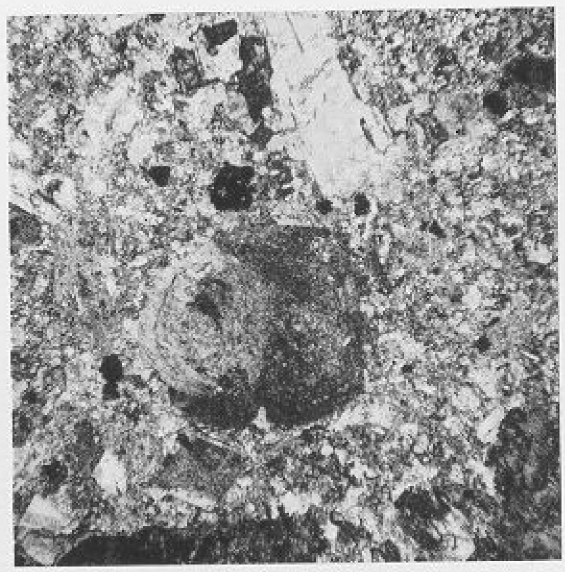
a



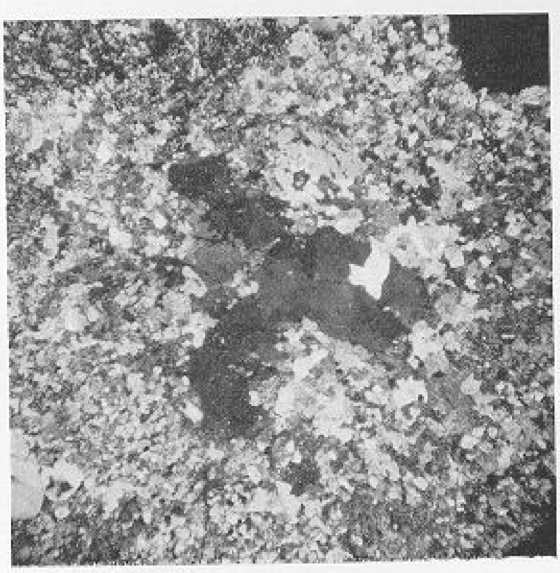
b



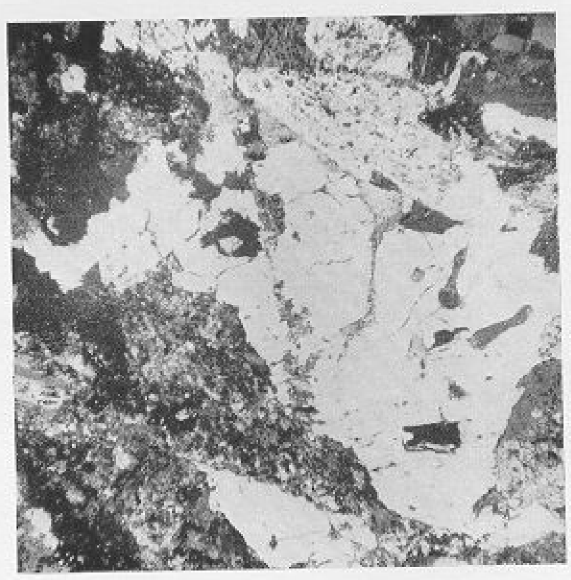
c



d



e



f

PLATE VI

a. Pseudo-porphyritic facies of the Cape Monaco Granite, showing the large porphyroblasts of oscillatory-zoned oligoclase separated by finer crystals of quartz and potash feldspar, Gossler Islands (N.141.4; X-nicols; × 30).

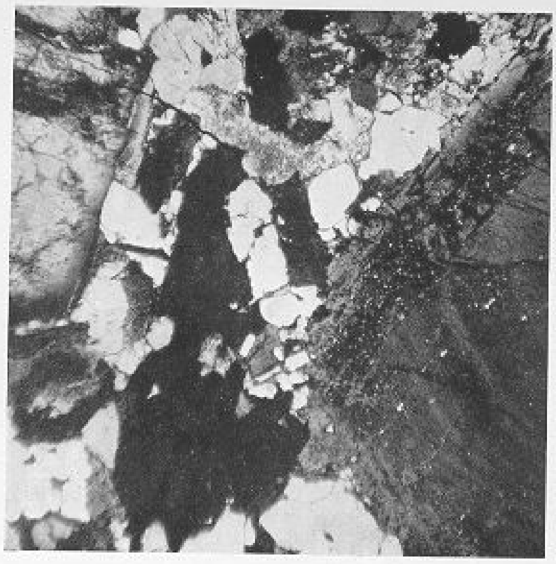
b. Equigranular facies of the Cape Monaco Granite, Cape Monaco (N.147.2; X-nicols; × 30).

c. Trondhjemitic porphyry showing the development of euhedral quartz and albite porphyroblasts in a finer quartz-albite groundmass, Humble Island (N.24.1; X-nicols; × 30).

d. The development of plagioclase porphyroblasts in the feldspar rock, Breaker Island. Note twinning, euhedral tendency and zones of included material parallel to the crystal faces (N.188.1; X-nicols; × 30).

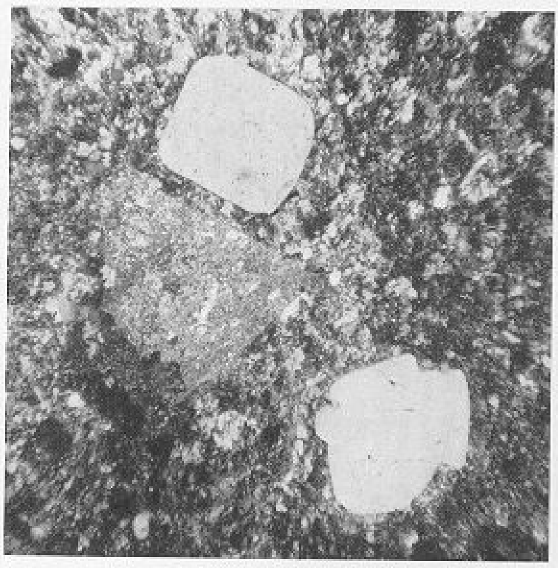
e. Dioritic rock, Janus Island (N.193.1; ordinary light; × 30).

f. Dioritic rock remobilized to a plastic state, Janus Island. Note the quartz and albite porphyroblasts which are clearly defined under crossed nicols (N.200.4; ordinary light and X-nicols; × 30).



a

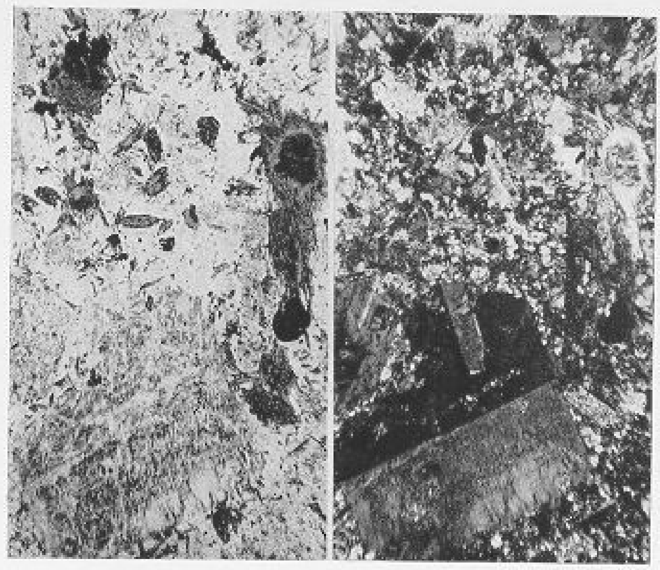
b



c

d

e



f