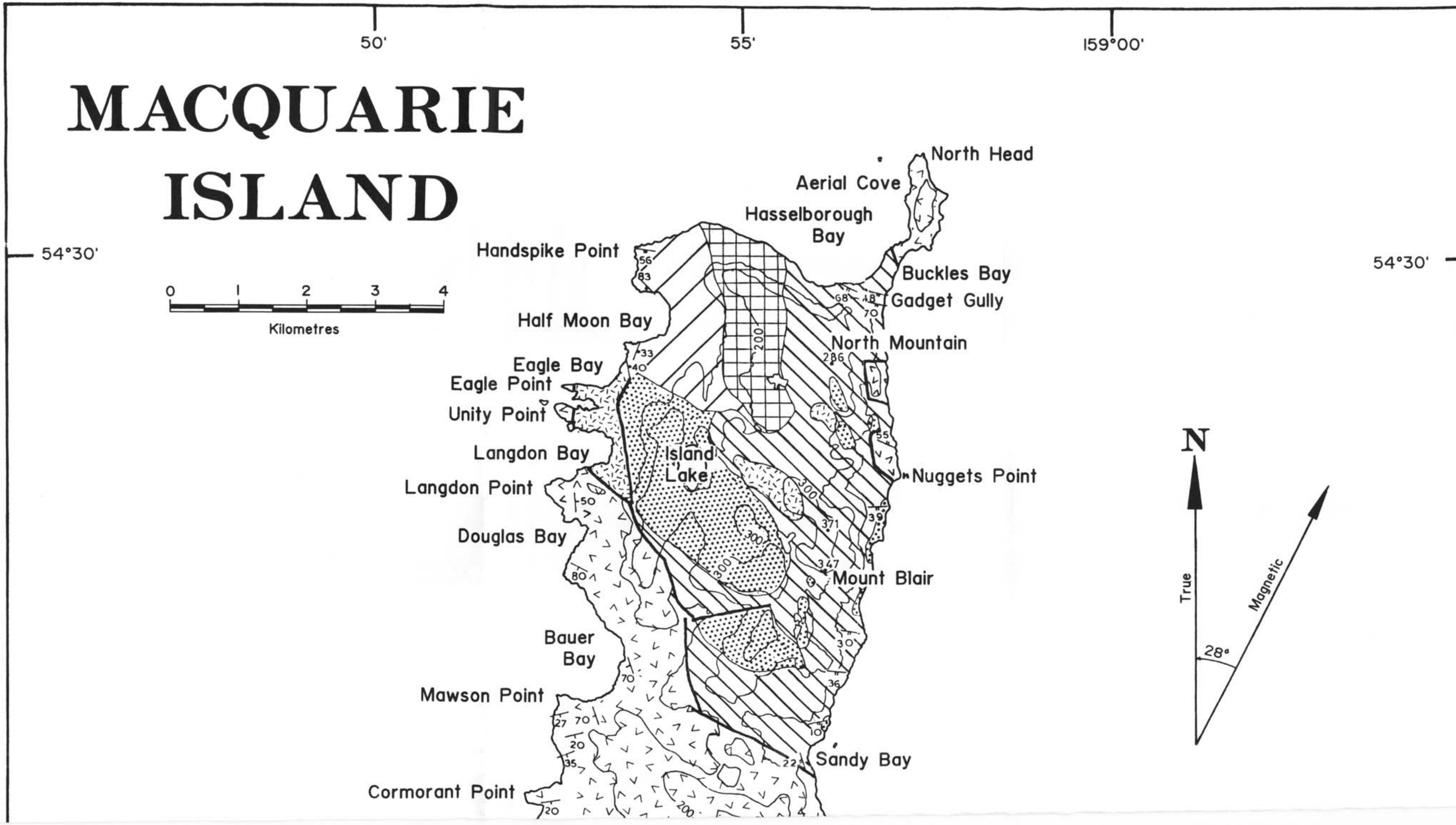
MACQUARIE ISLAND




35'
35'
40'
40'
Brothers Point
Aurora Point
Soucek Bay
Sellick Bay
Green Gorge
Double Point
Pyramid Peak
Davis Point
Saddle Point
Sandell Bay
Cape Toutcher
292
284
341
374
347
422
371
283
340
300
200
100
15
25
80
35
43
48
64
60
30
32
42
20
65
PILLOW BASALTS
DOLERITE DYKES
UPPER LEVEL GABBRO
SEQUENCE OF LAYERED GABBRO
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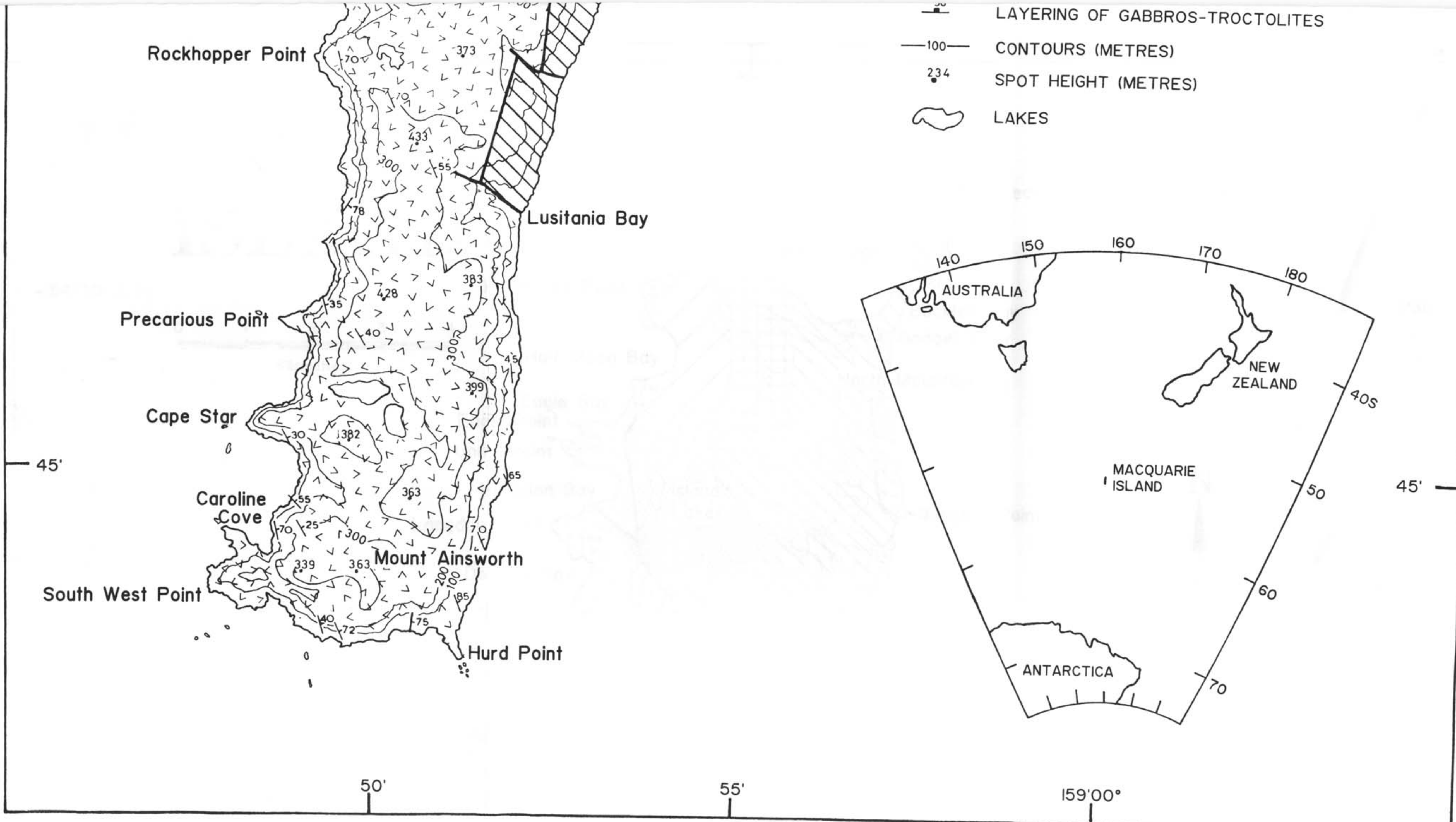

Figure 1. Map of Macquarie Island showing major geologic structures.

(To accompany ANARE Research Note Number 21)

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21

The Geology of Macquarie Island

C. Christodoulou, B.J. Griffin and J. Foden

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THE GEOLOGY OF MACQUARIE ISLAND

by

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ABSTRACT

The various rock lithologies present on Macquarie Island are described in detail together with their mode of occurrence and field relations. The four predominant rock types are pillow basalts, dolerite dykes, troctolites and gabbros, and ultramafics (mainly harzburgite). This sequence represents a section through the earth's oceanic crust. The dominant structural geological feature is faulting at any scale. Faulting also controls the evolution of the Macquarie Ridge complex, of which the uppermost part is the Island. It is concluded that the sequence of rock units present on Macquarie Island generated at the Australian-Antarctic spreading ridge.

1. INTRODUCTION

The earth's crust is of two distinct types: continental and oceanic. In the past three decades geologists have discovered that these differ significantly in both age and chemical composition.

The understanding of the important role of the oceanic crust in the geologic evolution of the earth arose in the 1950s and 1960s when the elegant theory of plate tectonics was formulated. Interpretation of the magnetisation and age variation of the rocks of the ocean floor led to an understanding of the distribution of earthquakes and volcanoes, the motion of crustal plates, and of the global distribution of mineral deposits.

Studies of the ocean floor and the rocks that occur there revealed several interesting features. The so-called mid-ocean ridge systems, submarine mountain ranges formed in the central axis of the major ocean basins, were found to represent the major physiographic features on the earth's surface. These are now known to represent the site of upwelling of magma from depth, the locality where the oceanic crust is formed and the locus of lateral spreading of the crust towards the continent. The oceanic crust, or lithosphere, is not completely detached from the uppermost layers of the earth's mantle. In fact, mantle layers accompany the oceanic crust movements and probably represent zones which produced a substantial amount of melt.

Assemblages of mafic and ultramafic igneous rocks, generally found as sheet-like, fault-bounded bodies in the orogenic zones at the margins of continental plates, are known as ophiolite complexes. These were considered to represent old oceanic crust or lithosphere generated at mid-ocean ridges, emplaced in the continental margin by tectonic processes. Continuous production at the spreading ridge results in the migration of the solidified lithosphere towards continental margins and subsequent emplacement into the continental shelf or recycling down to the mantle. A section through an ophiolite complex reveals the following stratigraphy from top to bottom:

Sediments - volcaniclastic material - pillow lavas
Sheeted dolerite dykes - massive gabbros
Gabbroic-troctolitic-ultramafic cumulates
Peridotite (harzburgite with tectonic fabric)

Such a section is present in the northern part of Macquarie Island and similar sections have been inferred through drilling in the present oceanic lithosphere. Consequently ophiolite complexes are considered to represent a good analogue for study of the earth's crust beneath oceans.

Recent detailed studies of several on-land ophiolites suggest that many complexes have not been formed at typical mid-ocean spreading systems, but in different tectonic settings, perhaps in back-arc basins. However, Macquarie Island is recognised unequivocally to have been formed at a major oceanic ridge and is still a component of the oceanic crust. Its present aerial exposure is attributed to faulting and uplift.

A significant aspect of the geology of ophiolites is the presence of ore deposits. These include the strata-bound massive sulphide deposits and podiform chromite deposits. The former are iron rich copper sulphide deposits precipitated on the sea bed, in association with pillowed basalts and oceanic sediments, by hydrothermal discharge. Such deposits are found on Cyprus and have been mined since historical times.

The massive chromite deposits occur at the uppermost level of the periodites and are known as podiform chromite deposits. They are irregular in shape and rich in either chromium (metallurgical type) or aluminium (refractory type). There are another three kinds of ore deposits accompanying ophiolite complexes; magnesite, asbestos and lateritic ores. Magnesite deposits are perhaps the most important as they seem to have been formed during the obduction of the ophiolites onto the continental margin.

1.1 PREVIOUS WORK

The magnetic properties of the various rock types and especially the pillow basalts have been investigated in detail by several workers (Williamson and Rubenach 1972, Williamson 1978, Butler et al. 1975 and 1976). The paleomagnetic studies in the region of Macquarie Island give an age of 27 m.y. for the spreading ridge where Macquarie Island originated (Williamson 1974). On the other hand, studies of calcareous ooze associated with pillow basalts in North Head suggest an Early Miocene age of approximately 20 m.y. (Quilty et al. 1973).

The geology of Macquarie Island has been studied by Varne et al. (1969) and Varne and Rubenach (1972). Petrological studies of the pillow lavas and the sheeted dyke complex have been carried out by Varne and Rubenach (1972) and Griffin and Varne (1980), and a more detailed treatment of the igneous petrology as well as the metamorphism of the volcanic sequence and the dolerite dyke swarm was presented by Griffin (1982).

1.2 LOCATION AND TECTONIC SETTING

Macquarie Island is situated approximately 1100 km south-south-west of New Zealand, on the Macquarie ridge system. The Macquarie ridge has a complicated morphology and represents a region of the underthrusting of the Australian plate beneath the Pacific plate. To the east of the ridge there is a deep depression, the Macquarie Trench. Earthquakes are frequent along the ridge system and their study indicates that normal and thrust faults predominate. Macquarie Island is believed to be part of the Australian plate according to paleomagnetic studies (Williamson 1978), and to have been generated during the Early Miocene (Quilty et al. 1973).

2. GENERAL GEOLOGY

Description and field relations of the various rock-types are outlined in this section. The various rock units described are: the volcanic sequence, the dyke-swarm complex, the upper level gabbro, the sequence of layered troctolites-gabbros, the peridotites, and the several gabbroic bodies. A geological map is presented in Figure 1.

2.1 THE VOLCANIC SEQUENCE

The sequence is composed of pillow lavas, massive lava flows and volcaniclastic sediments. It is the most widespread unit on Macquarie Island and is the dominant exposed rock type to the south of a line drawn between Bauer Bay and Sandy Bay, apart from a small area of dolerite dykes around Lusitania Bay. To the north of the Bauer Bay - Sandy Bay line volcanic rocks occur at Douglas Point, Langdon Point, Eagle Point on the west coast and North Head and Nuggets Point on the east coast.

The sequence is, in decreasing abundance, predominantly pillow basalts, followed by massive paraconglomerate, lithicwackes and reddish mudstones, massive lava flows, hyaloclastic breccias and oozes.

The pillow lavas are well exposed in many outcrops, for example at North Head, at Eagle Point and around Green Gorge. The size of pillows varies considerably between outcrops, but is relatively uniform within individual outcrops (Plate 1). The pillows are elliptical in cross section and lobate in oblique section. Cross sections range from more than 0.1 m to 1.0 m, whereas the lateral extent varies from 0.5 m to 9.0 m.

The degree of packing of the pillow lavas is inconsistent. Closely packed pillows with virtually no interstitial material give way to loosely packed pillows with up to 30% interstitial material. Interstitial material can be either hyaloclastite breccias or reddish mudstones and calcareous ooze. Due to the lack of internal deformation of pillows the only occurrences of dynamic metamorphism are observed adjacent to fault zones. Ropy surfaces, contraction cracks filled with interstitial sediment, and glassy rims are well preserved. Rapid cooling produced the 'chilled' (glassy) selvedges and induced the contraction cracks, which in turn have allowed fluid percolation. The penetration of these fluids results in the alteration of the pillow lavas and the development of secondary minerals, in particular zeolites as either veins or as amygdule fillings.

Massive lava flows are best exposed at Mawson Point. Here one lava flow which has a maximim thickness of 6 m overlies pillow lava and shows ropy surfaces. An interesting feature is the complete absence of feeder dykes to both pillow and massive lavas, although there are exposures of thick lava sections, such as the 100 m high section at Langdon Point. A plausible explanation is that pillows were built up by material provided by other pillows and not by feeder dykes having roots deep in the crust. In this way generation of pillows by extrusion of material from narrow fissure zones can augment the pillow lava pile extensively. However, the size of individual pillows would always be a function of the rate of the extruded material and the slope of the extrusive surface.

In hand specimen the lavas are usually fine grained, but they range from glassy to medium grained. Mostly they are porphyritic. Phenocryst phases include plagioclase, in greatest abundance, followed by olivine, pyroxene and some spinel. The common colouration of basalts is grey-brown reflecting extensive degrees of weathering or alteration. The freshest samples have a blue-grey colour at lower grades of metamorphism and a grey-green at higher grades.

The volcaniclastic sediments occur as interstitial material, as intercalated lenses and as massive units to the pillow lavas. The interstitial material can be hyaloclastic breccia, calcareous ooze or reddish mudstones. The hyaloclastic breccia is the most abundant and is encountered at Aerial Cove and near Pyramid Peak. It is composed of volcanic glass fragments, commonly 2-5 cm in section. The glass fragments are angular and not welded. Because of

Plate 1. Section through a pillow lava outcrop. Note the variable shapes and sizes of pillows.

Plate 2. Synsedimentary load structures well developed in siltstones; sediments intercalated with pillow lavas at Mawson Point.

alteration, the margins of the fragments have a yellowish colour, with relatively fresh dark brown to black interiors showing a vitreous lustre. Calcareous ooze is found in North Head as thin intercalations to pillows often associated with breccias and at Pyramid Peak, as small irregular lenses. It is fine grained, yellow to pinkish-grey in colour and usually well baked. Examination of the foraminifera and radiolaria in the Globigerina ooze suggest a depth of deposition between 2000 and 4000 m and a probable recent age (F. Chapman in Mawson 1943). On the other hand a study of coccoliths in this ooze (Quilty et al. 1973) indicates a Miocene age. The reddish-brown mudstones which fill the interstices of pillows are silicified and owe their colouration to the presence of iron hydroxides.

The intercalated lenses and the massive units consist essentially of volcanic detritus; the former range from siltstone to volcanic conglomerate, whereas the latter is predominantly volcanic breccia. The intercalated sediments occur as small lenses, up to 2 m thick and are well exposed at Mawson Point. Their lateral extent cannot be assessed accurately, but one lens at Mawson Point extends for about 60 m. The finer grained sediments, siltstones and lithicwackes, show bedding which is defined by pale yellow laminae, occasionally truncated and covoluted (Plate 2). Grading within the lenses, from siltstone or mudstone to volcanic conglomerate, is not uncommon.

The volcanic breccias are lenses of various thickness and occur in several places. The best outcrops are at Mawson Point where the lenses reach a thickness of 15 m, whereas further to the north at Douglas Point they are 2 to 3 m thick. An outcrop of lens at Mount Ainsworth is about 10 m thick. These volcanic breccias consist of angular clasts (lava fragments) with sizes between 50 and 150 mm. The clasts are set in a matrix, the size of which varies from mudstone to siltstone. The degree of packing is highly variable.

2.2 THE DYKE SWARM COMPLEX AND THE UPPER LEVEL GABBRO

The dyke swarm complex outcrops at several localities on the Island, but the best exposures are along the coastline. Among the best outcrops are those at Hasselborough Bay, Gadget Gully, Nuggets Point, Sandy Bay, Lusitania Bay and to the east of Mount Blair.

The upper contact of the dyke swarm is not clearly defined. However, parallel dolerite dykes crosscut pillow lavas and as Varne and Rubenach (1972) noted there is no continuous gradation between these dykes and the dyke swarm. It was also noted by Varne and Rubenach that these dolerite dykes cut the associated volcaniclastic sediments at acute angles to the bedding planes, suggesting inclined intrusion of the dolerite dykes.

The internal structure of the dyke swarm has been described by Varne and Rubenach (1972) and Griffin (1982). The principal characteristic is that dykes intrude amongst other dykes forming parallel sheets. The dykes show chilled margins facing the same direction. The width of dykes ranges from 0.1 to 1.0 m; however the width of individual dykes is not constant as they thin and swell irregularly. Another characteristic is that the dykes commonly have porphyritic central zones grading to aphyric ones and then passing to the chilled margins. The most abundant phenocryst phase is plagioclase. The size of plagioclase phenocrysts decreases from the centre of the dyke towards the chilled margins. The structure of the dykes and the distribution of the phenocryst phases suggest slow cooling and a relatively plastic environment of formation.

Plate 3. Gabbroic material (in dyke-fashion) penetrating dolerites and penecontemporaneously displaced, south of Nuggets Point.

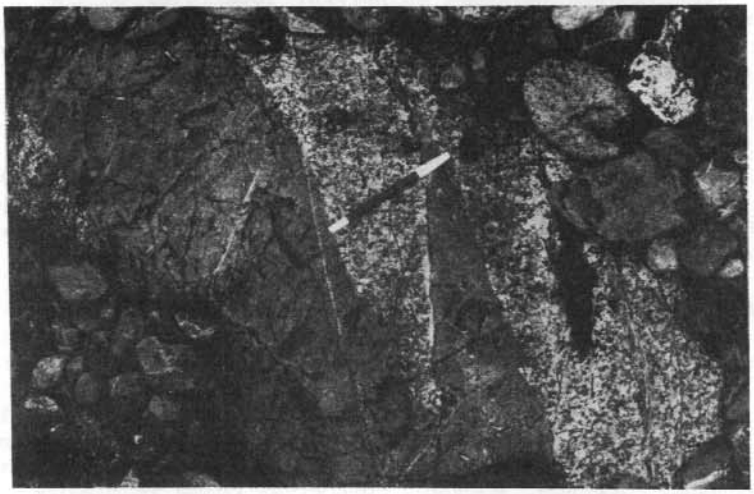

Plate 4. Mutual intruding relation of gabbroic and doleritic material, at the base of the dolerite dyke-swarm complex, 1 km south of Nuggets Point.

In hand specimen, fresh dolerite is a dark grey colour with the white plagioclase phenocrysts standing out. However, all the dykes have also been affected by secondary alteration resulting in a sequential increase of greenish tints, representing the incoming of chlorite and hornblende. Zeolites are also present in veins and aggregates and in narrow quartz veins, often containing sulphides.

Stratigraphically beneath the dolerite dyke swarm a massive gabbroic body appears. The boundary between these two units is a mutually intrusive zone which is encountered along Hasselborough Bay and between Nuggets Point and Sandy Bay. Gabbroic screens have been found in the dyke swarm at Hasselborough Bay and Gadget Gully. They are usually lobate and conformed with the direction of dykes. Gabbroic dykes and veins also penetrate parallel sets of dolerite dykes (Plate 3) or form a complex network within the dolerite dykes. The mutually intrusive character of the two rock units is best shown in Plate 4 which suggests a rather plastic environment and near-solidus temperatures for the melts which generated the dolerite dykes and the gabbroic screens and dykes.

Tabular plagiogranite(?) lenses occur within this zone. They are exposed to the south of Nuggets Point and have a lateral extent of less than 1 m. They consist of quartz and altered plagioclase. Their position within the sequence is suggestive of derivation from later stage differentiated liquids.

The upper level gabbro itself is massive, grey-green and consists of only two primary minerals, plagioclase and clinopyroxene. Secondary minerals have been developed but not all of them are identifiable in the field; however, amphibole (tremolite), epidote and minor zeolites were identified. Dolerite dykes intrude throughout the extent of the gabbro exposure, the most common being 20 to 100 mm wide.

2.3 THE LAYERED SEQUENCE OF TROCTOLITES-GABBROS

This unit is exposed around Handspike Point and along Half Moon Bay to Eagle Point. A fault disrupts the sequence in the middle of Half Moon Bay. To the north of this fault the layering strikes north-west and dips at about 60° towards the south-west whereas to the south it strikes north-south and dips tend towards east-north-east. However, the layering is not consistent even in single outcrops, changing in less than 2 m. At Eagle Point, predominant rock types are plagioclase-dunite, troctolite and minor anorthosite. Around Handspike Point, olivine-gabbro dominates the outcrop, but minor gabbro, troctolite, anorthosite are also present. The different rock types have been named according to their modal mineralogy as shown in Figure 2. Norites and hypersthene-gabbros reported by Varne and Rubenach (1972) are absent throughout the layered sequence.

Layering is a typical feature of large continental mafic intrusive complexes (stratiform complexes) and is also present in the lower crustal sequences of many ophiolites. 'Rhythmic layering' is the most common type of layering found in ophiolite plutonic sequences. The layered troctolites at Eagle Point do not show rhythmic layering. They display a different style with combinations of olivine and plagioclase-rich layers. The style of layering can only be classified as 'intrusive' indicating the relationship between adjacent sets of layers and clearly not due to crystal settling processes.

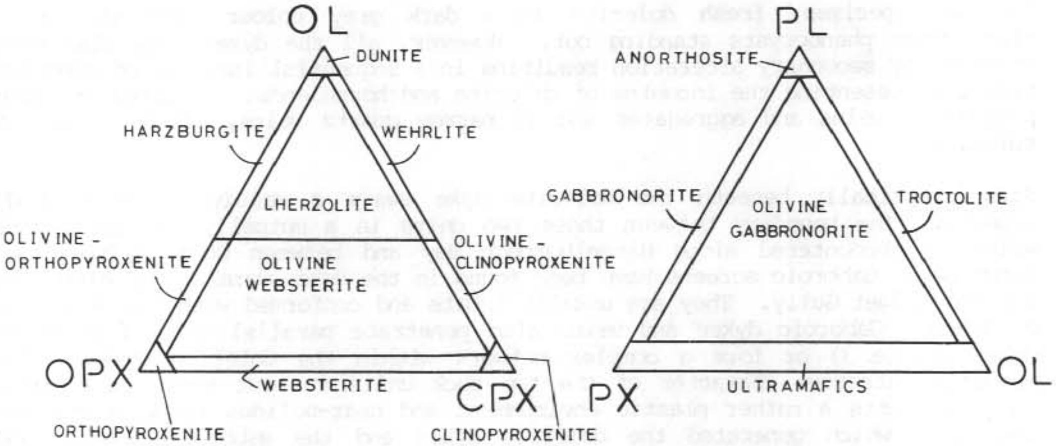

Figure 2. Classification of mafic and ultramafic plutonic rocks (according to IUGS Subcommission on the Systematics of Igneous Rocks).

The layers themselves range from thin (0.1 to 0.2 m) to medium-thick (less than 1.0 m). They can be best described as 'modally graded', but normal or reverse grading is obscured. 'Grain size graded' and 'texturally graded' layers are not present. Other kinds of layers present in ophiolitic layered sequences are not encountered here either. The modal variation of minerals is the fundamental criterion for the recognition of layers, and this is clearly shown in Plates 5, 6 and 7. The lateral continuity of layers is very restricted; single layers do not extend for more than 2 m. They laterally vary to a rock with different mineral proportions or form wedges disappearing after a few tens of centimetres. The contacts between adjacent layers are almost always sharp, although gradational contacts have been observed in a few instances. Small scale faulting with a displacement of a few tens of centimetres is preserved as well (see Plate 5). The angles between the fault plane and the layering range from 65° to 24°. The style of dragged layers suggests a highly plastic environment.

In hand specimen, the olivine is always replaced, in part or wholly, by serpentine, thus showing black colour instead of the typical olive-green of fresh olivine. Plagioclase is usually unaltered, but when replaced by secondary minerals greenish tints are developed, this being more evident in the plagioclase dunites.

Along Half Moon Bay the outcrop is discontinuous and in places is dominated by dolerite dykes. The dykes show no relationship to the internal stratigraphy of the layered sequence and crosscut the layering at variable oblique angles. Very rarely they intrude parallel to the layering. The thickest dykes are plagioclase-phyric and show progressive reduction of the phenocryst grain size from centres to margins, with eventual disappearance of the phenocrysts near the margins.

The olivine-gabbros are best exposed around and to the south-east of Handspike Point. Pyroxene substitutes for olivine and there is progressive increase of the pyroxene-olivine ratio, till olivine disappears entirely. In outcrop the olivine-gabbros have a greenish colouration due to the incipient replacement of pyroxene by secondary amphibole. The style of layering and the characteristic of layers are similar to those described above for the troctolites. The only new feature is observed in the gabbros, where tabular plagioclase and prismatic pyroxene are aligned parallel to the plane of layering. 'lineate lamination' is the term applied to this fabric. The anorthosites, occurring as thin layers between gabbros, show planar lamination. At Handspike Point a 900 mm thick melanocratic layer, in which olivine and pyroxene account for more than 80%, has sharp contacts and an acute angle to the layering defined by the planar lamination of the adjacent olivine-gabbro.

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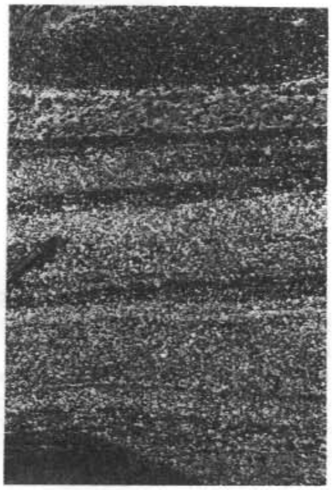

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Plate 5. Small scale drag faulting in layered troctolites, Eagle Bay.
Plate 6. Olivine plagioclase variations outlining the style of layering, northern tip of Eagle Bay.
Plate 7. Intrusive character of layering as shown on a boulder in Half Moon Bay.
Plate 8. A melanocratic layer intrudes poorly layered olivine gabbro, Half Moon Bay. The layering of olivine gabbro is at an angle to the plane of emplacement of the melanocratic layer.

The principal characteristic of layering in this area is the intrusive contacts among adjacent sets of layers. The layers always have been sharp contacts which are disturbed and disrupted. A few styles of this notable feature are shown in Plates 7 and 8. It is suggested that such layering cannot be developed by any normal crystallisation and subsequent settling event, but can be attributed to multiple cycles of intrusion and re-intrusion of new magma.

3. PERIDOTITES

The peridotitic rocks in Macquarie Island are harzburgites. The main outcrop is at Langdon Bay and Eagle Point. Minor harzburgite bodies occur on the plateau, but are extensively serpentinised. Much smaller bodies are found as inclusions in dolerite dykes. The harzburgite consists of enstatite and serpentised olivine. In outcrop, the rock is black with pale green enstatite crystals standing out and reflecting the light on cleavage planes. Chromite is present as accessory mineral (approximately 2%), but can be observed only under the microscope.

The predominant feature of the outcrops is small scale faulting, which has caused displacement of adjacent blocks along curved fault surfaces. The blocks show variable width from less than 0.1 m to a maximum of 2.0 m. Development of chrysotile fibres on the fault planes is very common, as is the formation of much thicker serpentinite slabs along major fault zones present at Unity Point. A consequence of this close-spaced faulting is that no fabrics (foliations and lineations) can be identified in the field, as opposed to other ophiolitic harzburgite sequences where enstatite foliation and chromite lineation are observable and measurable in the field. The orientation, however, of these fault planes does not show any consistency.

At Eagle Point the harzburgite shows compositional banding, the orientation of which is well conformed with the layering orientation of the troctolites at Eagle Point. The layers consist of different amounts of olivine and enstatite and are less than 100 mm thick. Enstatite-rich layers are as thin as 5 mm and do not maintain constant thickness. Unfortunately, the outcrop is of very limited extent (less than 20 m).

Gabbroic dykes and veins are present throughout the harzburgite exposure at Langdon Bay. Their orientation does not form a uniform pattern. They possess various styles and may be bent, folded, disrupted or confined to the prominent small scale fault pattern of the harzburgite. The primary minerals have been replaced by secondary phlogopite, prehnite and epidote. The grain size varies from fine to coarse. The mode of occurrence suggests that they represent partially molten material generated from, or introduced by, residual upper mantle rock which was subjected to plastic deformation.

4. GABBROIC BODIES

Several gabbroic bodies outcrop on the plateau and along the east coast. The largest ones are the gabbro unit around Island Lake and the unit to the north-west of Sandy Bay. Four gabbroic bodies are exposed between Sandy Bay and Nuggets Point on the east coast. A few smaller gabbroic bodies are scattered throughout the northern third of the island (e.g. the body to the south of North Mountain).

The massive gabbro unit around Island Lake is the largest. The exposure, however, is poor and the rocks highly altered. The gabbro is medium to coarse grained with pyroxene crystals reaching 40-50 mm in length. Screens of fine grained gabbro are included in the coarser rock. In hand specimens pyroxene shows the effects of alteration, becoming progressively grey-green as is replaced by horn blende or tremolite. Plagioclase is relatively fresh but is itself replaced by a mixture of epidote-clinozoisite and hydrous garnet. Prehnite also replaces plagioclase. Dolerite dykes are common, but their usual width does not exceed 200-300 mm. Along the west slopes, the gabbro develops foliation, and a zone of cataclasite is revealed. The cataclasite is a fine grained recrystallised rock that shows spectacular slickensided surfaces dipping south-west. The same gabbro continues to the coast where it is exposed in a few places interbanded with the harzburgite at Langdon Bay and Eagle Bay. Foliation is well developed but no prominent orientation was found. The foliation is defined by the rearrangement of pyroxene and plagioclase to form distinct layers. Spindle-like pyroxene crystals of larger size are enveloped by the foliation outlined by the parallel arrangement of smaller pyroxene and plagioclase crystals. Both pyroxene and plagioclase are replaced by amphibole (and/or phlogopite) and prehnite respectively. The development of cataclasite zones and foliated gabbro, which is very similar to a mylonite, respresents a major dynamothermal event during which the harzburgite has moved upwards relative to the gabbro.

The gabbroic body to the north-west of Sandy Bay is a massive, medium- to coarse-grained gabbro-olivine gabbro, without any evident structure in the field. When fresh it is dark grey to black, but usually it is altered to some degree with the pyroxene showing incipient uralitisation. Olivine is usually inconspicuous in hand specimens. Dolerite dykes, less than 100 mm thick, cut across the gabbro and are always aphyric.

The gabbroic exposures along the east coast are very similar to the two gabbroic bodies described before, being mainly massive and structureless. They are nested in dolerite dykes, but their contacts are obscured by the lack of exposure. About 1 km north of Sandy Bay there is a small body with the gabbro showing subophitic texture in hand specimens. This texture is very similar to that of dolerites, although much coarser. This gabbro therefore could represent a transitional rock type between the dolerite dykes and the overlying massive gabbros.

The gabbro bodies occurring on the plateau are very altered. They do not show any structure and are always found in dolerite dykes. The small gabbroic unit to the south of North Mountain is altered and weathered out. In hand specimen, the gabbro is grey-green with occasional screens of more fresh dark grey material. Zeolites in veins and patches are also present marking a lower degree of metamorphism.

5. CONCLUSIONS

The series of rocks outcropping on Macquarie Island, is the same as that dredged from the ocean floor. This, together with palaeomagnetic and petrologic evidence, argues for an origin at a spreading ridge in a major ocean and subsequent uplifting of the island due to interaction of the Indian-Australian and Pacific plates. The island is faulted on all scales and many of these faulted blocks are tilted relative to each other. The rocks are relatively fresh along the coastline but weathered on the plateau. The basalts, dolerite dykes and the upper level gabbros have also suffered ocean-floor metamorphism and this is responsible for the development of secondary mineral assemblages, principally zeolites, tremolite, epidote, prehnite and sulphides.

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