AUSTRALIAN NATIONAL ANTARCTIC RESEARCH EXPEDITIONS

A N A R E

R E S E A R C H

N O T E S

39

The geology and geomophology of Macquarie Island with special emphasis on heavy metal trace element distribution

P.W. Crohn

ANTARCTIC DIVISION
DEPARTMENT OF SCIENCE

ANARE RESEARCH NOTES (ISSN 0729-6533)

This series allows rapid publication in a wide range of disciplines. Copies of this and other ANARE Research Notes are available from the Antarctic Division. Any person who has participated in Australian National Antarctic Research Expeditions is invited to publish through this series. Before submitting manuscripts authors should obtain a style guide from:

The Publications Office
Antarctic Division
Channel Highway
Kingston
Tasmania 7150
Australia.

Published November 1986
ISBN: 0 642 09970 7

CONTENTS

FIGURES

TABLES

THE GEOLOGY AND GEOMORPHOLOGY OF MACQUARIE ISLAND WITH SPECIAL EMPHASIS ON HEAVY METAL TRACE ELEMENT DISTRIBUTION

by

P.W. Crohn
1 Durham Road
Surrey Hills, Victoria, Australia

ABSTRACT

New geological and geomorphological relationships established on Macquarie Island (54°38'S, 158°53'E) are discussed.

1. INTRODUCTION

Macquarie Island (54°38'S, 158°53'E) lies approximately 1500 km SSE of Tasmania and is 34 km long and 5.5 km wide at its broadest. It is composed mainly of basaltic rocks of possibly Miocene age, associated with dolerite dykes, gabbros and minor peridotites.

The long axis of Macquarie Island coincides with the alignment of the Macquarie Ridge. The Macquarie Ridge extends in a general SSW direction from the South Island of New Zealand and marks a zone of seismic activity. It is also associated with major linear gravity and magnetic anomalies.

Macquarie Island's geology and geomorphology were described by Mawson (1943). Varne, Gee and Quilty (1969) suggested that the rocks of the Island represented the products of igneous activity on a spreading mid-ocean ridge, but Hayes and Talwani (1972) considered that the Macquarie Ridge differed in some important respects from typical mid-ocean ridges, mainly because the dominant movement within this zone, by extrapolation from the New Zealand Alpine Fault, was considered to be one of lateral slip rather than ocean-floor spreading. More recently, studies have been conducted on the petrology of the Island by Varne and Rubenach (1972), Griffin and Varne (1980), and Griffin (1982); and on its geomorphology by Colhoun and Goede (1974) and Ledingham and Peterson (1984).

This study was undertaken between October 1983 and October 1984 and was specifically designed to provide information on a number of topics not fully covered by earlier research. These topics included geomorphology, with special emphasis on the evolution of composite landforms; general geology with special emphasis on field relations of the major rock groups; the sulphide occurrences; and trace element distributions, especially of heavy metals, in both mineralised and unmineralised rock types.

2. GEOMORPHOLOGY

The greater part of Macquarie Island consists of an undulating plateau 200 to 300 m above sea level, bounded by steep scarps on all sides. Isolated mountains rise above the plateau and, at Mount Hamilton, reach a maximum elevation of 433 m. At the extreme northern tip of the Island, a small isolated plateau remnant approximately 100 m above sea level forms Wireless Hill. Wireless Hill is connected to the rest of the Island by a low isthmus, 10 to 20 m above sea level. This isthmus is the site of the ANARE station. Some twenty lakes, and more than a hundred minor tarns are scattered over the plateau. Raised beaches are present around parts of the coastline (Figure 1).

Previous researchers have generally agreed in interpreting the plateau as part of an old peneplain, and the bounding scarps as evidence of relatively recent block faulting. There is also evidence that at least some parts of the Island's surface have been modified by glaciation, but the extent of this glaciation and its role in the formation of individual features, e.g. some of the lakes, has been subject to divergent interpretations.

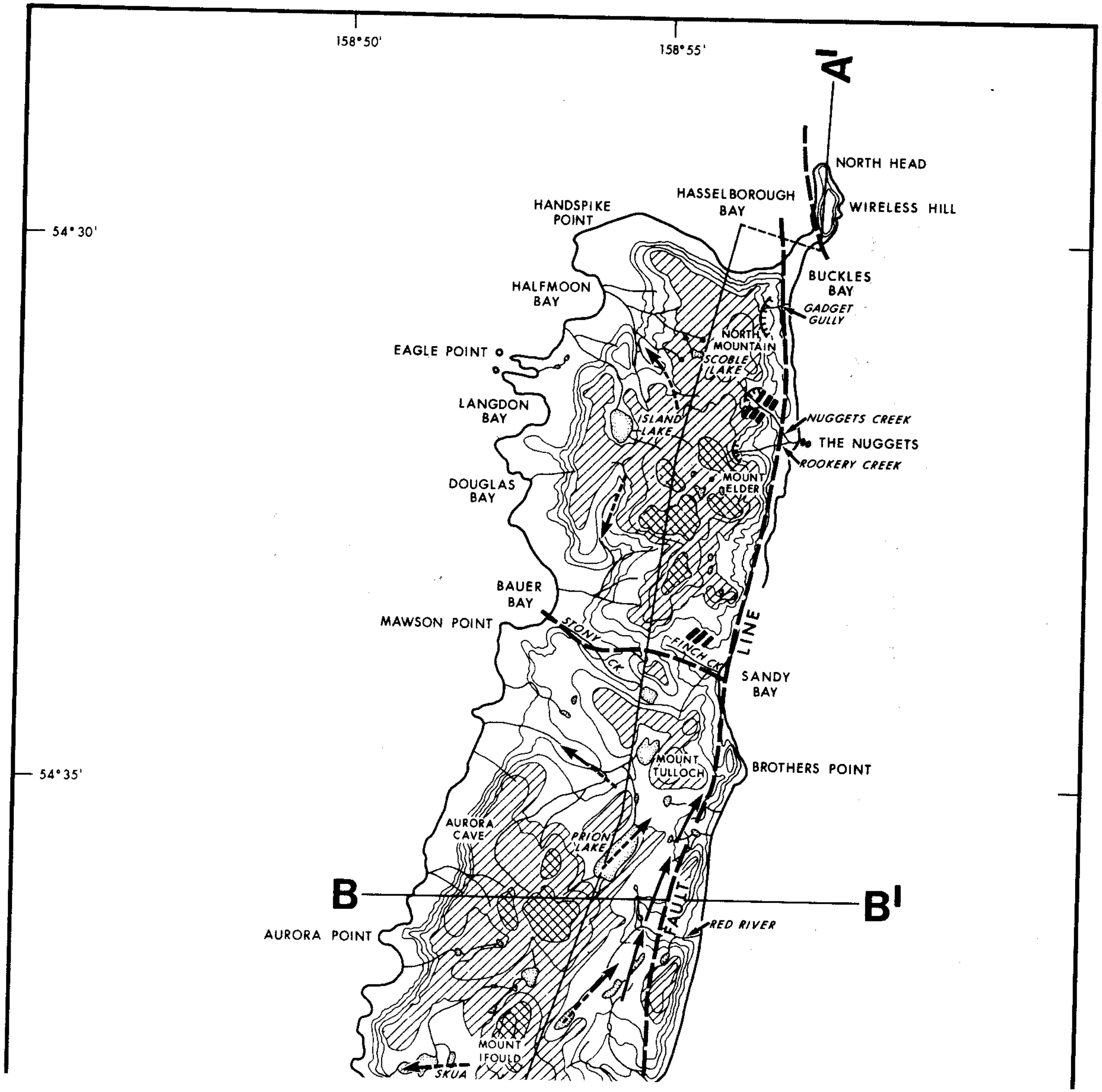
The peneplain remnant forming the plateau must have originated by sub-aerial erosion at a considerably lower elevation. Apart from being uplifted as a block, it has also undergone some warping or tilting, with average elevations ranging from 300 m in the Mount Hamilton - Mount Fletcher area to slightly less than 200 m west of Mount Tulloch. The low saddle between Finch Creek and Stony Creek, which also coincides with the major contact between intrusive rocks to the north and lavas to the south, marks a tectonic dislocation, north of which the plateau again rises to an average height of 250 m. Wireless Hill is also a tectonically discrete unit (Figure 2).

The exact location of the faults bounding the plateau cannot be determined as many lie some distance off-shore. However, the more linear nature of the east coast and the steeper slope of the sea floor on the eastern side of the Island (based on bathymetric data from Cullen 1970) suggest that vertical movement on this side of the Island may have been concentrated within a single major line or zone, while movement on the west side may have been more in the nature of a gentle warp or have been distributed over a number of parallel lines or zones (Figure 3).

Estimates of the area of the Island covered by ice at the time of maximum glaciation range from about 40% (Colhoun and Goede 1974) to 90% (Loeffler and Sullivan 1980). Ledingham and Peterson (1984) ascribed many features which other workers had considered of glacial origin, to raised beaches and block faulting. However, it appears that in many cases, individual topographic features can best be explained as the result of a complex interplay of tectonic and erosional processes.

Among the features most obviously related to glacial processes are a number of old glacial valleys. The most prominent extends 3.5 km northwards from the Pyramid Lake area to Green Gorge and is occupied in its lower portion by Sawyer Creek. It shows a classic U-shaped cross-section with stepped longitudinal profile, but its east wall coincides with a prominent tectonic lineament (named the Brothers Fault Line* by Ledingham and Peterson).

* not approved by the Antarctic Names and Medal Committee.


158°50'
158°55'
54°30'
54°35'
A'
B
B'
NORTH HEAD
WIRELESS HILL
HASSELBOROUGH BAY
HANDSPIKE POINT
BUCKLES BAY
HALFMOON BAY
GADGET GULLY
NORTH MOUNTAIN
SCOBLE LAKE
EAGLE POINT
LANGDON BAY
ISLAND LAKE
NUGGETS CREEK
THE NUGGETS
ROOKERY CREEK
MOUNT ELDER
DOUGLAS BAY
BAUER BAY
MAWSON POINT
STONY CK
FINCH CK
LINE
SANDY BAY
MOUNT TULLOCH
BROTHERS POINT
AURORA CAVE
PRION LAKE
FAULT
RED RIVER
AURORA POINT
MOUNT IFOULD
SKUA

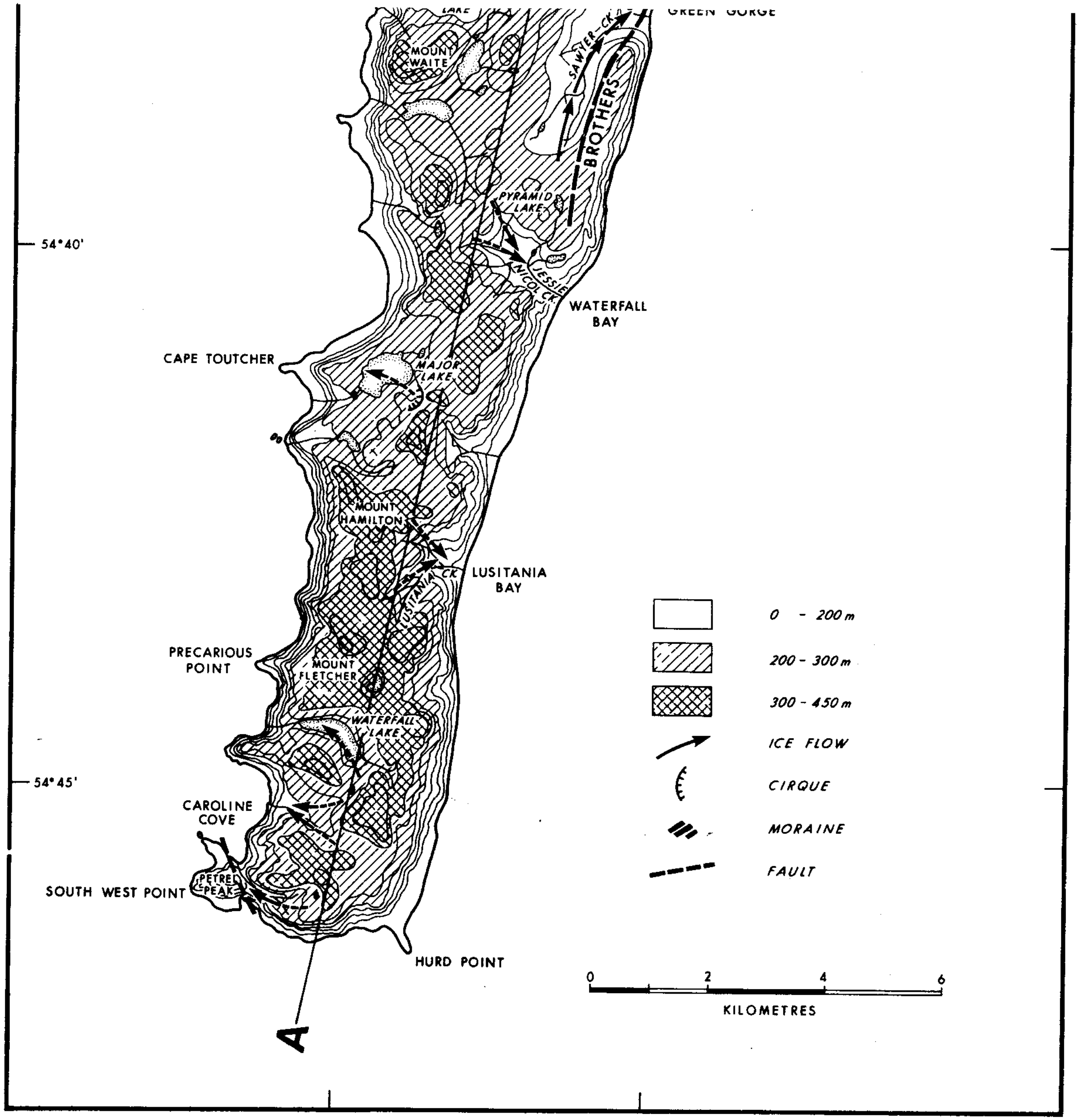


Figure 1. General geomorphology, structural lineaments and major glacial features of Macquarie Island.

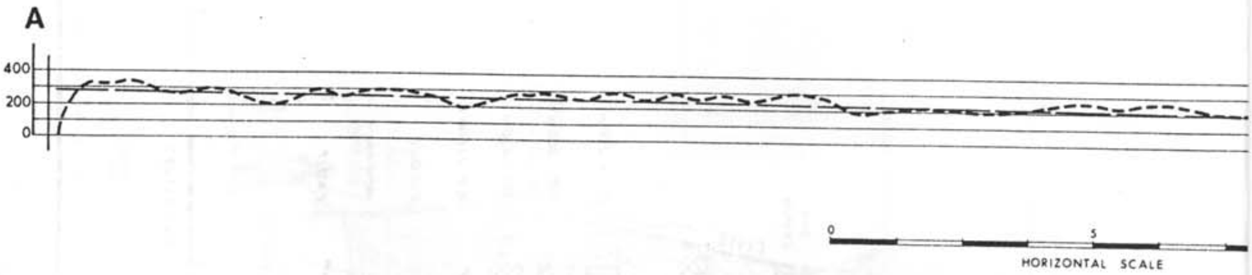


Figure 2. Longitudinal section of Macquarie Island.

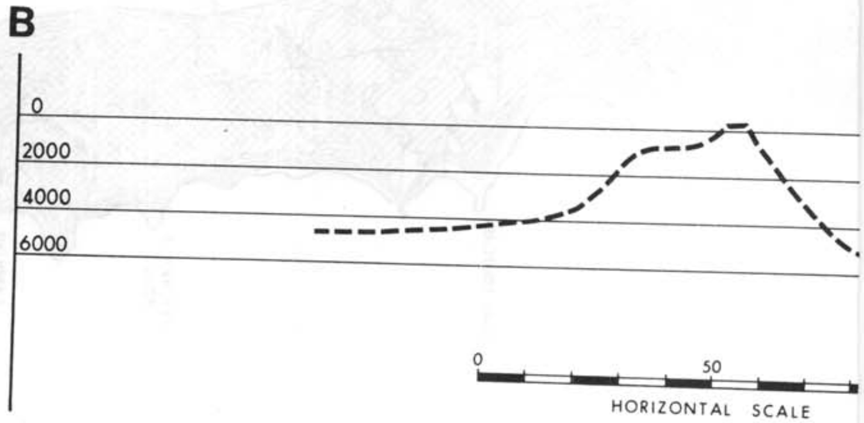
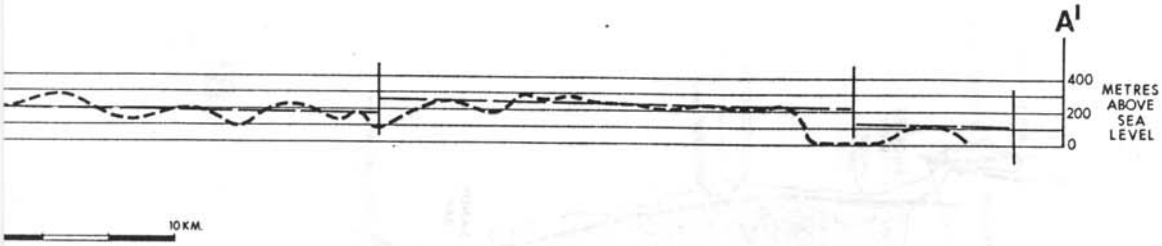
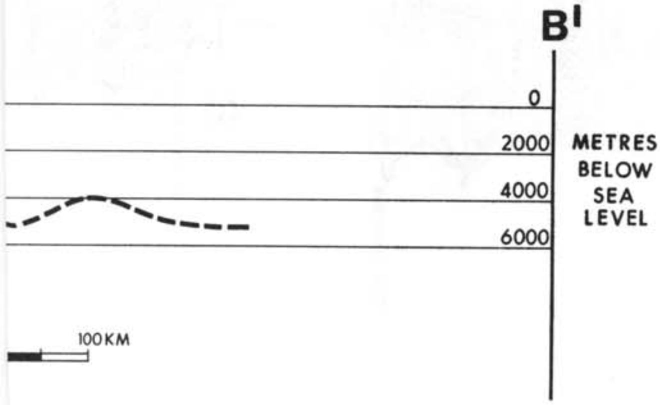


Figure 3. Section along 54°36' south.


A'
400
200
0
METRES
ABOVE
SEA
LEVEL
10 KM.


B'
0
2000
4000
6000
METRES
BELOW
SEA
LEVEL
100 KM

The most recent movement on this fault, east block up, post-dates the development of the glacial valley, but the close coincidence of the valley and fault line shows that the zone of weakness associated with this lineament probably helped to originally localise the valley.

North of Green Gorge, another glacial valley which debouched near Mount Tulloch follows the same alignment, with the Brothers Fault Line again forming its east wall. The close coincidence of these alignments again suggests that a zone of weakness along this fault line was responsible for controlling the development of the glacial valley. However, the valley is crossed from west to east by the middle portion of Red River which has captured the headwaters of a north-north-easterly flowing stream draining the small lake east of Mount Ifould. This stream originally followed the trend of the old glacial valley. Also, 2 km north of Red River, a small unnamed stream, draining another lake within the old glacial valley, has cut a small gorge through the uplifted block east of the fault (Ledingham and Peterson 1984), and is thus antecedent to it. The most recent east-block-up movement on the Brothers Fault Line thus not only post-dates the major period of glaciation, but also the development of the post-glacial fluvial drainage system.

Similar complex interactions may be responsible for many of the other twenty or more lakes and more than a hundred minor tarns scattered throughout the plateau.

Cirques are fairly widespread and vary considerably in degree of development and state of preservation. Some of the better examples are at Gadget Gully, Nuggets and Rookery Creeks, and above Major Lake. The cirque at the head of Gadget Gully is of particular interest. The present steep middle portion of the gully is actively cutting back into the floor of the cirque. Rejuvenation of the stream must therefore be a post-glacial event. If the cirque glacier, consonant with others on the Island, was developed at about the present height, i.e. about 150 m above sea level, the absolute movement responsible for the development of the scarp and the rejuvenation of the stream has been east-block down, rather than west-block up, and must have truncated the old glacial valley draining the cirque.

Old glacial valleys can be traced to within less than 50 m of sea level at Sandy Bay and Green Gorge, and between 50 and 100 m at Lusitania Bay and Waterfall Bay. There are also indications of remnants of old glacial valleys extending southerly from Island Lake and westerly at Skua Lake. At all these locations there is a notable opening of the valleys in their middle sections, apparently corresponding to the levels at which tributaries to the original glaciers joined the main streams. Ledingham and Peterson would ascribe most of these features to old beach levels, and refer to them as terraces. However, there are uninterrupted scarps higher than these level sections in adjacent areas, and many of these 'terraces' occur in re-entrants without direct exposure to the coast. It is therefore difficult to visualise any sequence of events by which old beach levels could make more than a very minor contribution to the present topography of the more elevated parts of the Island.

However, at a lower level, a major raised beach 10 to 20 m above sea level extends intermittently from Handspike Point to Aurora Point with minor similar occurrences elsewhere on the Island, e.g. Hurd Point. These represent a very recent phase of uplift, which may however be unrelated to the major movements responsible for the elevation of the plateau.

The general sequence of events leading to the development of the Island's present configuration may therefore be outlined as follows:

1. An undulating mature surface developed by processes of subaerial erosion at a low to moderate elevation above the then prevailing sea level.

2. A large block, extending for an appreciable distance east and west of the present limits of the Island, was uplifted to an elevation comparable to that of the present plateau.

3. Glaciation occurred, affecting most or all of the present plateau surface. Major glacial valleys, as well as local cirques and moraines developed. At least some of these glacial valleys were aligned on structural zones of weakness related to major pre-existing fault lines.

4. Following the end of glaciation, fluvial drainage was re-established over the whole area, with many streams following the old glacial valleys. Some of the existing lakes probably occupy over-deepened rock basins and moraine-dammed valleys dating from this period, but others may owe their origin to minor faulting associated with events 5 and 7 (Ledingham and Peterson 1984).

5. Faulting to downthrow the blocks east and west of the present Island occurred. The post-glacial age of these movements is shown by the truncation of glacial valleys, e.g. Gadget Gully. Separate movements to account for the discontinuity at the Sandy Bay - Bauer Bay gap and for the lower elevation of the plateau remnant at Wireless Hill may date from the same period.

6. As a result of these movements the streams draining the plateau were rejuvenated in their lower portions and cut their valleys into the plateau. Some developed sharp knick points, while others captured the headwaters of less favourably situated streams, as at Red River.

7. Fault movements continued, e.g. on the Brothers Fault Line where the most recent movement, east-block up, post-dates the establishment of the present river system.

8. The final movements have been those responsible for the present beach terraces at elevations of 10 to 20 m above sea level, best developed in the Handspike Point - Eagle Caves area, which may still be in progress, but not necessarily related to the major movements responsible for the scarps of the Island.

3. GEOLOGY

Basaltic lavas and associated pyroclastics and minor intercalated sedimentary rocks occupy most of the Island south of a line joining Sandy Bay and Bower Bay (Figure 4). Intrusive rocks including dolerite dykes, gabbros and peridotites predominate in the north. Contacts between the two major groups are not generally well exposed and are thought to be predominantly faulted.

Recent research into the various groups of rocks has been heavily biased towards laboratory studies (Varne and Rubenach 1972, Griffin and Varne 1980). Emphasis in this study has been given to field relations, and an attempt has been made to re-interpret some aspects of the Island's geology in the light of this evidence.

3.1 BASALTIC SEQUENCE

Basaltic lavas occupy most of the Island south of a line joining Bauer Bay and Sandy Bay, as well as Wireless Hill and the northern part of The Isthmus, the west coast between Bauer Bay and Langdon Bay, and several small areas at and north of The Nuggets. Pillow lavas are the most characteristic form, with particularly good examples at Green Gorge, Langdon Point and the coast north of Brothers Point. Individual pillows vary considerably in size, and average 0.5 to 1.0 m in diameter. However, in areas examined in detail, notably the northern part of The Isthmus, Mawson Point, the coast north of The Nuggets and the Caroline Cove area, agglomerates make up a significant part of the sequence and typically contain sub-rounded to sub-angular fragments with a maximum diameter of 10 mm to over 150 mm.

Finer-grained sedimentary material is less abundant. It ranges from calcareous material packing inter-pillow spaces, e.g. north of Brothers Point, to siltstones and tuffaceous sandstones which form isolated occurrences at Mawson Point, in the lower part of Lusitania Creek and on the coast west of the hut at Caroline Cove (Section 3.3).

The lavas are generally porphyritic and/or amygdaloidal to varying degrees, with phenocrysts in places to 10 mm. Calcic plagioclase are the dominant phenocrysts, followed by clino-pyroxene, rare olivine and occasionally analcite. The same minerals, together with alteration products - chlorite, sericite, clino-zoisite and zeolites - and minor magnetite, generally make up the bulk of the matrix.

Rocks collected during this study include medium-grained, even-grained types (35425^{+}, 35426 in the Garden Cove area), moderately porphyritic types (35420, 35421 in the northern part of The Isthmus, Hasselborough Bay side, and 35437 from The Nuggets area), and samples containing more then 50% by volume of phenocrysts (35472 from Buckles Bay foreshore, 35478 from Lusitania Bay, 35518 from Hurd Point).

Rocks showing amygdaloidal texture generally also show more extensive alteration as well as minor quartz-carbonate veining (35477 from Lusitania Bay, 35513 from the Brothers Point area, 35519 from Green Gorge).

$^{+}$Registered numbers, Geology Department, University of Melbourne collection.

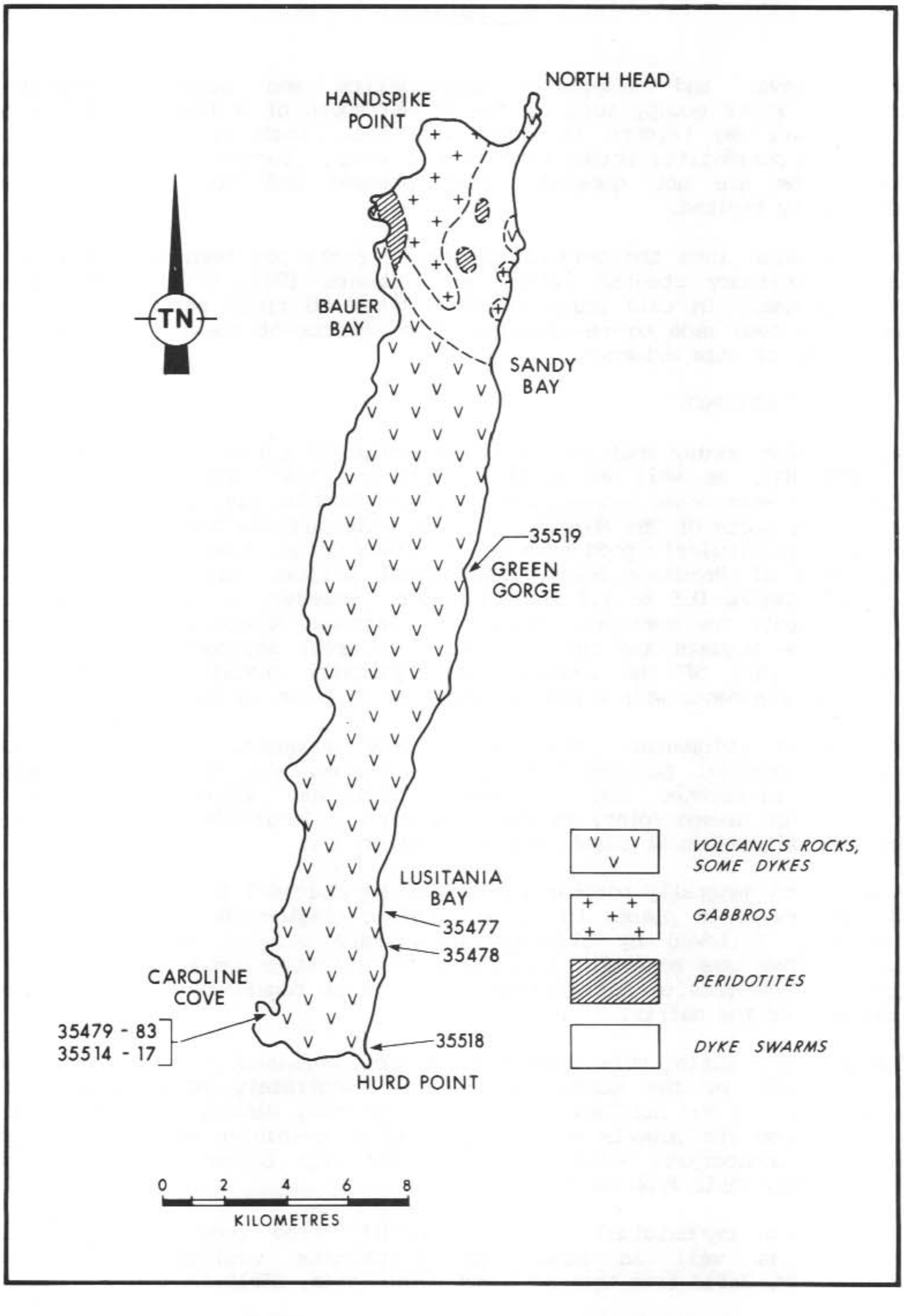


Figure 4. Generalised geology.

In some instances they appear to be associated with areas of better than average development of pillow structures. Other rocks showing evidence of veining and/or alteration occur adjacent or close to major shear zones or zones of mineralisation (35438, 35439 from the vicinity of The Nuggets, 35482, 35483 from Caroline Cove, 35499 from Langdon Bay).

Basalts containing significant amounts of sulphides (mostly pyrite) have only been noted at Caroline Cove (Section 4.1).

3.2 AGGLOMERATES

Agglomerates range from medium to relatively coarse textured, with fragments in places up to 150 mm across. Most of the fragments consist of basalt similar to that in near by flows, or else of crystal fragments similar to the phenocrysts in the flows (35422, 35423 from the northern part of The Isthmus, Hasselborough Bay side, 35432, 35433 from the east coast between The Isthmus and The Nuggets). Veining and alteration have again affected some of the rocks (35424 from the north part of The Isthmus, 35440 from the coast towards The Nuggets). Some agglomerates in the Caroline Cove area have suffered pyritisation, although usually to a lesser extent than the near by lavas.

3.3 SEDIMENTARY ROCKS

Sedimentary material other than agglomerates, occurs at several localities in small quantities interbanded with volcanics.

At Mawson Point, reddish-brown shale (35512) and fine-grained siltstone (35511) occur in a sub-horizontal layer about 300 mm thick and a few metres in lateral extent. Underneath is fine-grained sandstone, about 1 m thick, composed largely of material similar to that making up the nearby basalts, mainly felspar, clino-pyroxene and magnetite grains and fragments (35506). Beneath the fine-grained sandstone is a slightly coarser-grained unit of similar composition with the addition of fragments of fine-grained basalt and minor carbonates (35507), which in turn grades downwards into agglomerate with fragments up to 100 mm across.

On the foreshore north of Brothers Point calcareous sedimentary material, consisting of foraminiferal remains in a fine-grained matrix of carbonates, clay minerals and iron oxides (35509), occurs in the interstices of a pillow lava.

On the foreshore of Caroline Cove, about 400 m west of the hut, a banded sequence of fine-grained sediments about 2 m thick strikes 330° and dips vertically, interbanded with lavas. The rock consists of occasional felspar grains and ? foraminiferal remains in a fine-grained matrix of ? clay minerals and iron oxides (35514).

A minor occurrence of sedimentary rocks was also noted in the lower portion of Lusitania Creek, but was not examined in detail.

Quilty at al. (1973) described Globerigina ooze from two locations north of The Isthmus near Tottan Head and Catch-Me Point, to which they ascribed a Miocene age. These occurrences were not located during the author's study, but appear similar to that described here from Brothers Point.

3.4 DOLERITE DYKES

Dolerite dykes cut the gabbros in the Langdon Bay - Half Moon Bay area and occupy extensive areas on the plateau and the east coast north of Sandy Bay (Figure 5). They have been described as dyke swarms by previous researchers. Some dykes have also been described as cutting the lava sequences. They are, however, frequently very similar to the lavas in general appearance. In isolated outcrops, in the absence of pillows or agglomeratic phases, there is little to differentiate the two groups, except that fine-grained, even-grained types commonly occur in the dykes, whereas they are rare or almost non-existent among the lavas.

In the Half Moon Bay area numerous dykes, some more than 10 m across, cut the gabbro, while other petrologically identical material occurs as inclusions within the gabbro, also on occasions as bodies more than 10 m across.

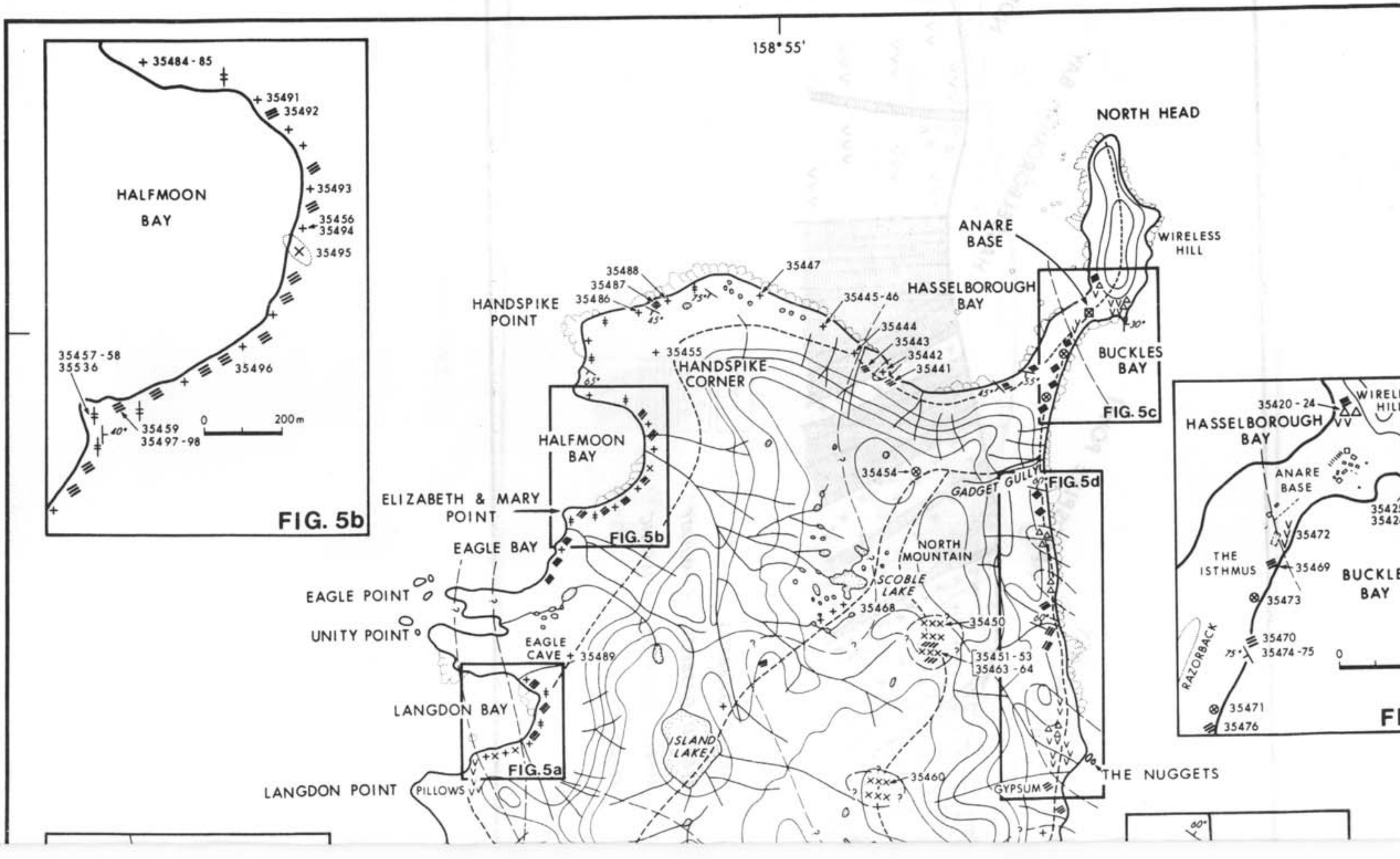
Rocks collected during this study include a number of fine-grained, even-grained types (35431, 35434, 35435 from the east coast between The Isthmus and The Nuggets, 35441 from the southern foreshore of Hasselborough Bay, 35466, 35467 from the northern part of the plateau, 35459, 35496 from Half Moon Bay) which have no equivalent among the lavas. The moderately to strongly porphyritic types are very similar to some of the lavas in general appearance (35427, 35429, 35430, 35436 from the east coast between The Isthmus and The Nuggets, 35453 from the northern part of the plateau, 35475 from the foreshore of Buckles Bay). Plagioclase is again predominant among the phenocrysts, followed by clino-pyroxene.

Some degree of alteration is commonly present. It may be of two types. One is similar to that noted in many lavas and is represented by sericitisation of the felspars and the development of chloritic aggregates, clino-zoisite and ? zeolites in the matrix, occasionally associated with minor quartz-calcite veining.

The other is marked by the development of pleochroic green-brown amphibole, in places rimming or replacing clino-pyroxene, or less commonly forming large poikilitic crystals which may also be pseudomorphing clino-pyroxene (35427, 35429, 35431, 35434 from the east coast between The Isthmus and The Nuggets, 35470, 35475 from the foreshore of Buckles Bay). However, no development of green-brown amphibole was noted in basalts occurring close to the dyke swarm near Brothers Point (35513) or at Garden Point (35426). This appears to be in contrast to the conclusions of Varne and Rubenach (1972), who considered that there was no decrease in metamorphic grade at the contact between dyke swarms and extrusive rocks, either in the Sandy Bay - Bauer Bay area, or in the Buckles Bay - North Head area.

On the other hand, a comparable development of pleochroic amphibole was noted in a dyke rock cutting the layered gabbro at Elizabeth and Mary Point (35459) and in an inclusion of similar material within the same gabbro (35458), suggesting that the metamorphism responsible for this amphibole may be a function of proximity to the gabbro intrusives rather than a regional effect.

Sulphide occurrences within dyke rocks were noted from the foreshore of Buckles Bay, from an isolated occurrence at Langdon Bay and from the northern portion of the plateau alongside the overland track to Bauer Bay (Section 4.1).



158° 55'
NORTH HEAD
WIRELESS HILL
ANARE BASE
HASSELBOROUGH BAY
BUCKLES BAY
FIG. 5c
HANDSPIKE POINT
HANDSPIKE CORNER
35488
35487
35486
35447
35445-46
35444
35443
35442
35441
35455
HALFMOON BAY
FIG. 5b
ELIZABETH & MARY POINT
EAGLE BAY
EAGLE POINT
UNITY POINT
EAGLE CAVE
35489
LANGDON BAY
FIG. 5a
LANGDON POINT
PILLOWS
35454
GADGET GULLY
FIG. 5d
NORTH MOUNTAIN
SCOBLE LAKE
35468
35450
35451-53
35463-64
ISLAND LAKE
35460
GYPSUM
THE NUGGETS
HALFMOON BAY
35484-85
35491
35492
35493
35456
35494
35495
35496
35457-58
35536
35459
35497-98
40°
0
200m
FIG. 5b
35420-24
HASSELBOROUGH BAY
ANARE BASE
35472
THE ISTHMUS
35469
35473
RAZORBACK
35470
35474-75
35471
35476
BUCKLES BAY
0

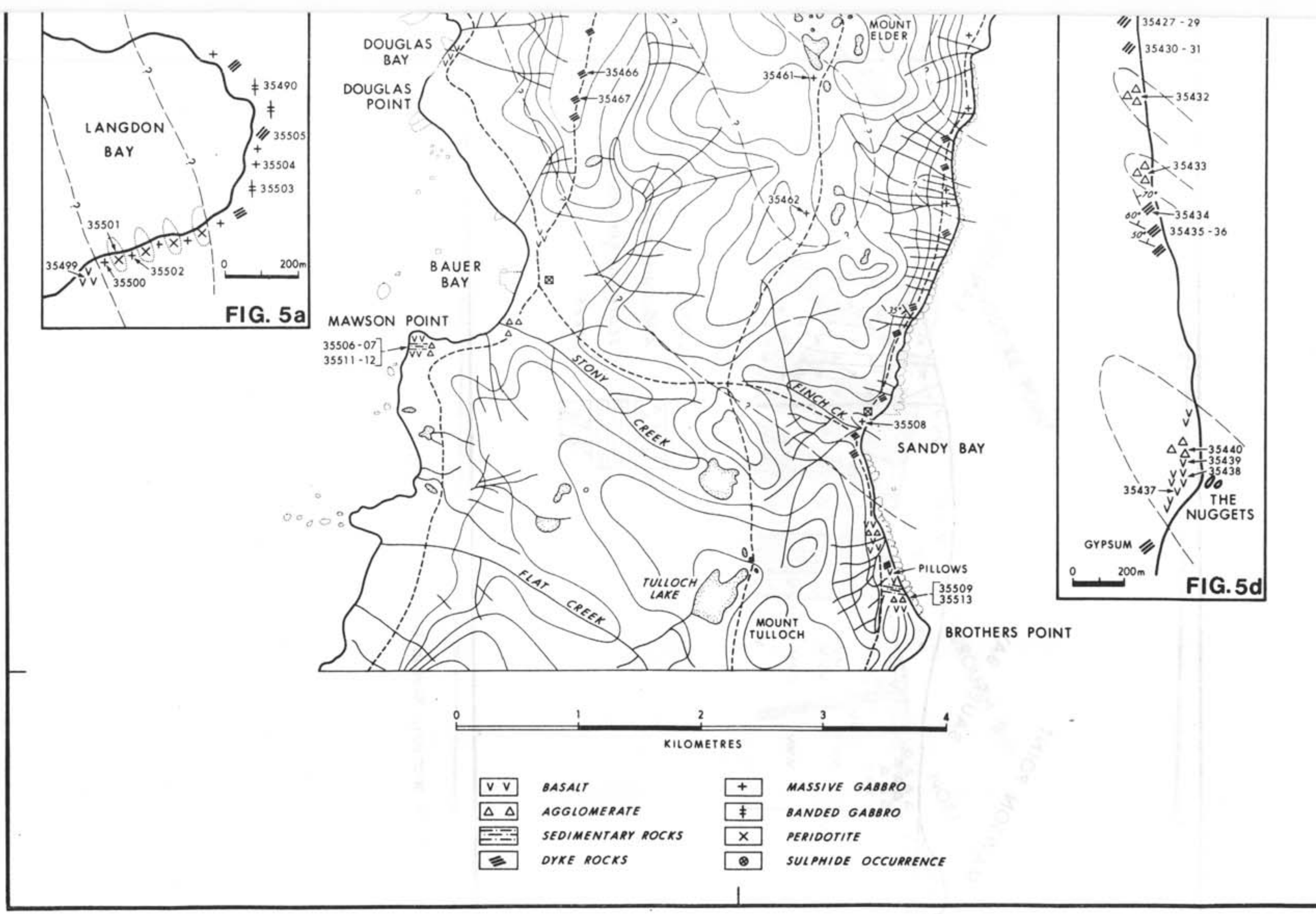


Figure 5. Northern geology and sample locations.

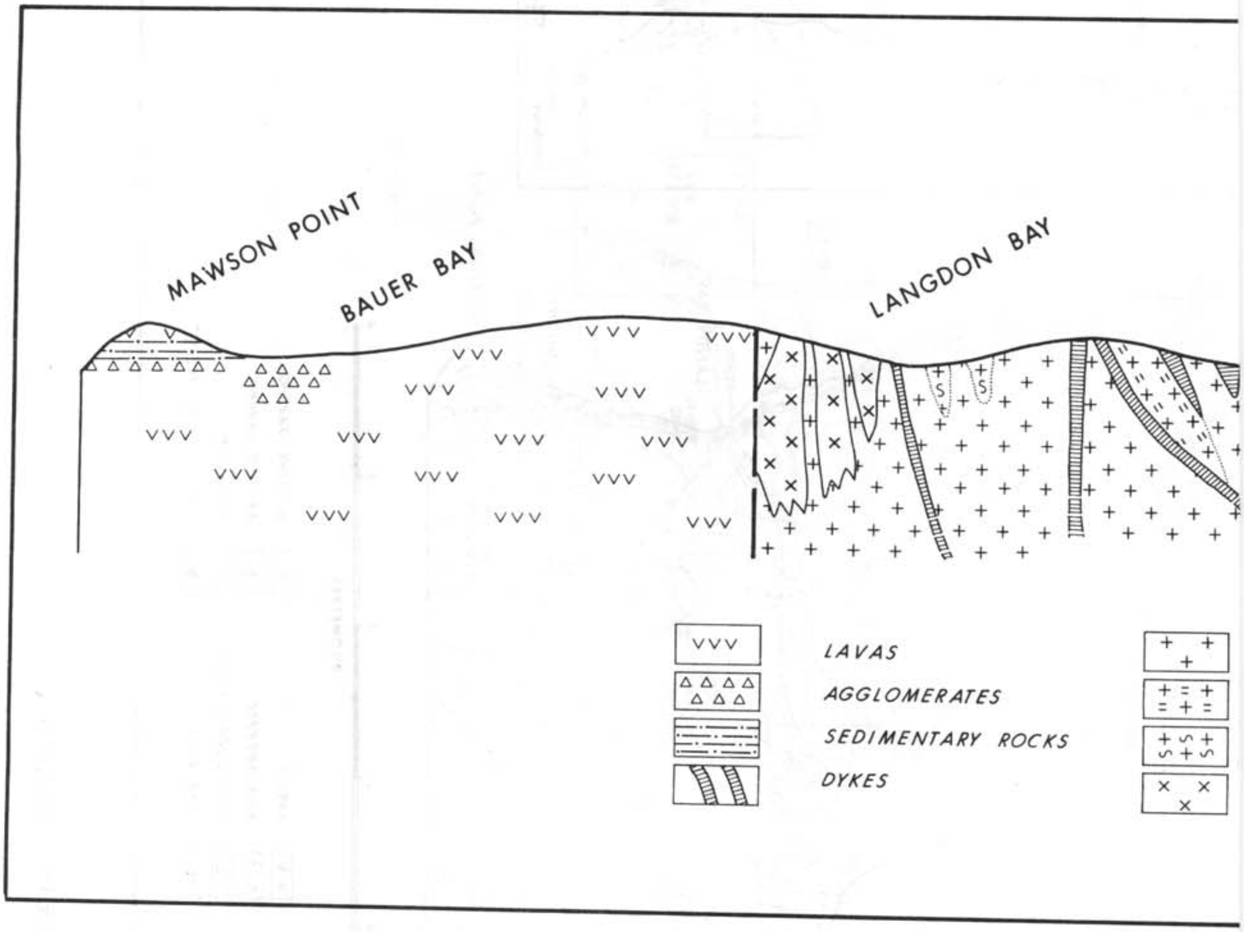
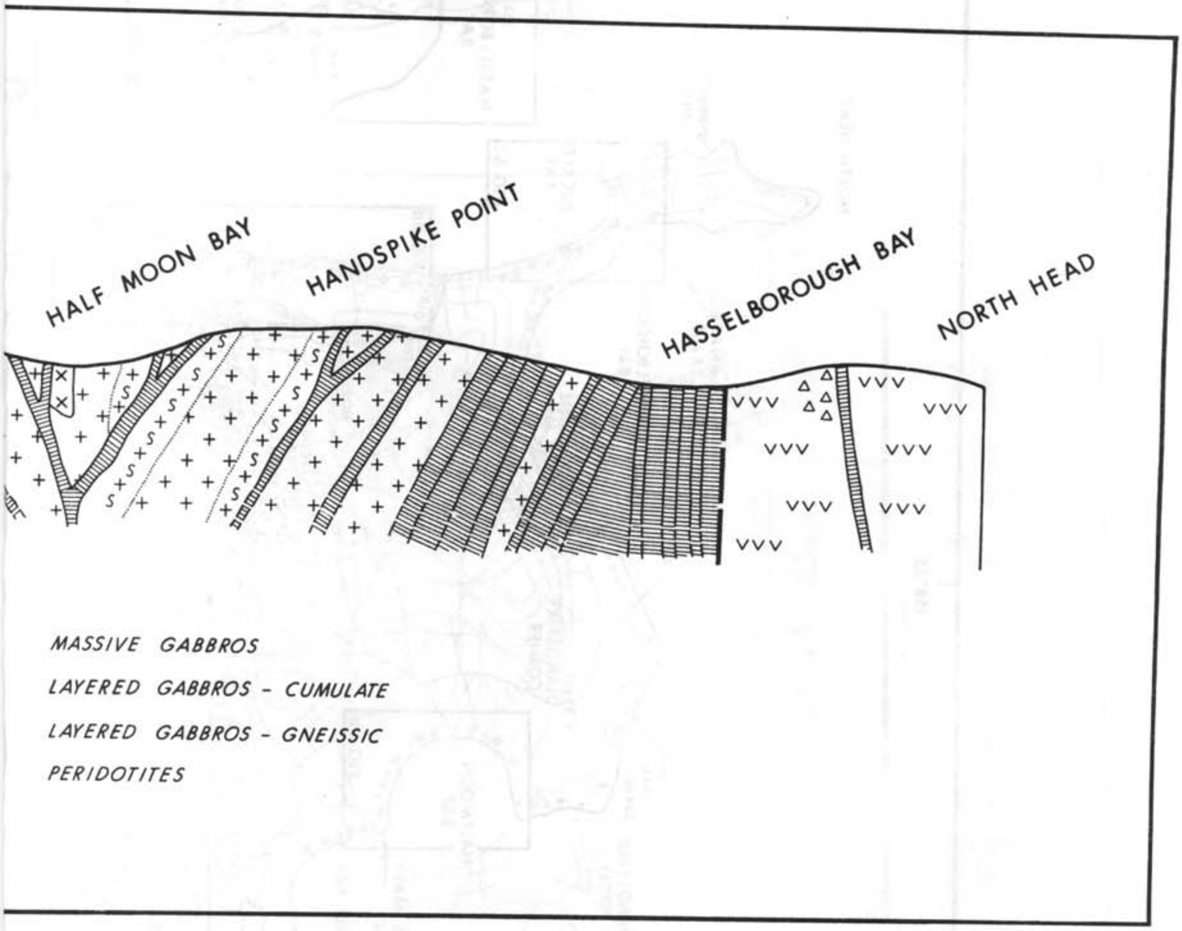


Figure 6. Generalised section, Mawson Point to North Head.



HALF MOON BAY
HANDSPIKE POINT
HASSELBOROUGH BAY
NORTH HEAD
MASSIVE GABBROS
LAYERED GABBROS - CUMULATE
LAYERED GABBROS - GNEISSIC
PERIDOTITES

3.5 GABBROS

Gabbros occupy the north-west of the Island between Handspike Corner and Langdon Bay, the adjacent plateau area, and a number of smaller areas on the east coast between Sandy Bay and The Nuggets (Figure 5).

Some of the best exposures are along Half Moon Bay where both massive and layered gabbros are complexly associated with dolerite dykes, and the southern portion of Langdon Bay where pegmatitic gabbro is intrusive into peridotite and is locally associated with felspar-prehnite rock.

Isolated outcrops on the plateau near Scoble Lake and Island Lake and to the south-west of Mount Elder may be continuous with the occurrences on the west coast, although their boundaries have not been traced on the ground. The intermittent good exposures on the east coast between Sandy Bay and The Nuggets are similar in general appearance to the massive phases at Half Moon Bay and Handspike Point.

The majority of the gabbro occurrences are medium to coarse-grained roughly equigranular rocks, composed essentially of plagioclase and clino-pyroxene (35444, 35447 from the foreshore between The Isthmus and Handspike Point, 35455 from Handspike Corner, 35468 from the northern portion of the plateau, 35484 from Half Moon Bay, 35486 from Handspike Point). Slightly finer grained rocks were noted from the foreshore between The Isthmus and Handspike Point (35443, 35445), possibly representing a marginal phase of the gabbro.

Alteration with the development of chloritic and sericitic aggregates was noted in some rocks (35493 from Half Moon Bay), while others showed evidence of shearing, ranging from localised (35461 from the northern part of the plateau), to pervasive (35446 from the foreshore between The Isthmus and Handspike Point).

Minor greenish amphibole, ? replacing clino-pyroxene, occurs in a rock from the foreshore between The Isthmus and Handspike Point (35442), and brown amphibole in a rock from Sandy Bay (35508). Major development of amphibole is restricted to the pegmatitic phase of the gabbro which is widespread in Langdon Bay (35500, 35502). At this locality it is intrusive into peridotite. The pegmatitic phase contains crystals of both plagioclase and amphibole in excess of 50 mm and is locally associated with minor occurrences of highly felspathic rocks, in part prehnitised (Section 3.7).

Layering is present in a number of the gabbro occurrences, but there is no large homogeneous unit of layered gabbro as suggested by the maps compiled by Varne and Rubenach (1972), Griffin and Varne (1980) or Christodoulou et al. (1984).

Layering is best developed along a 200 m stretch of coastline at Elizabeth and Mary Point (erroneously called Eagle Point by Christodoulou), where it is the result of alternating bands of contrasting mineral composition, generally from a few millimetres to about 20 mm thick (35457). Some of these bands are rich in olivine, which elsewhere in the gabbros is subordinate or absent. A few consist entirely of plagioclase and olivine (troctolite - Section 3.6). This layering must largely be a primary feature and was described as cumulate by Griffin and Varne (1980), although Varne now considers it more likely to be a result of selective crystallisation in situ (pers. comm.). However, the rocks have also been subject to movement during the final stages of consolidation as they show evidence of deformation on both small and medium scales, the latter including truncation of layered zones, from a few centimetres to several metres thick, against adjacent zones.

Less pronounced banding has been noted in rocks from Langdon Bay, Half Moon Bay and Handspike Point. In these areas banded phases alternate with others which show no banding, and differences between adjacent layers are largely due to variations in texture rather than mineral contents. This is particularly marked in the Langdon Bay area, where augen and schlieren structures are locally strongly developed (35490, 35503), and the layering is obviously of predominantly deformational origin.

The attitude of the layering and/or banding shows considerable variation, with moderate easterly dips at Elizabeth and Mary Point contrasting with generally steeper south-south-westerly dips in the northern portion of Half Moon Bay and around Handspike Point.

Relations of the gabbros with the dyke rocks are complex, and the relative ages of the rocks cannot generally be determined. At Elizabeth and Mary Point some dykes cut across the layering of the gabbro (35459), while other occurrences are generally conformable to the layering and are thought to represent inclusions in the gabbro (35458). Some occurrences of dyke rocks in the massive phases of the gabbro can be seen to have lenticular outlines, and are therefore also thought to be inclusions (35485 from Half Moon Bay, 35488 from Handspike Point). The actual contact between dyke rocks and gabbros often show strong cataclastic structures (35491, 35498 from Half Moon Bay). Similar relations have been noted by Christodoulou et al. (1984) from the east coast south of The Nuggets.

Mineralisation in the gabbros is restricted to the sporadic occurrence of disseminated sulphides, almost entirely pyrite, e.g. in rocks from Handspike Point, the northern portion of the plateau, the Eagle Cave area and Sandy Bay (Section 4.1).

The major new conclusions relating to the gabbros thus concern the distribution and origin of the layered phases which have resulted from two different processes. At Elizabeth and Mary Point, magmatic processes have resulted in a layered gabbro (35457) closely associated with troctolite. It can be traced along the foreshore for about 200 m. However, near Handspike Point and in Langdon Bay, layering in the gabbro is essentially due to post-consolidation movements, with the development of augen structures and strong cataclastic structures (35490, 35503). In these areas there is a close association between layered and massive phases of the gabbro.

3.6 TROCTOLITES

The troctolites are essentially plagioclase - olivine rocks. Good examples of layered troctolites, with layers distinguished mostly by the proportion of the two major constituents, are restricted to the vicinity of Elizabeth and Mary Point (35536) where they are interbanded with layered gabbros. The olivine in these rocks is altering to serpentinous aggregates, and the plagioclase is extensively sericitised.

The only other occurrence of comparable rocks seen during this study is about half way along the Half Moon Bay foreshore. It is a small outcrop consisting of rocks composed of serpentinised olivine and aggregates of clay minerals, ? after plagioclase (35456, 35494). It is not layered and its relationship with near by gabbros and dyke rocks was not established.

3.7 FELSPAR - PREHNITE ROCKS

A single example of a felspar-prehnite rock was collected from the northern part of Langdon Bay (35504) where it forms veins and small irregular masses closely associated with pegmatitic gabbro, which itself is intrusive into peridotite.

3.8 PERIDOTITES

Peridotites have been noted along the southern foreshore of Langdon Bay, on the plateau between North Mountain and Mount Elder, and on the foreshore of Half Moon Bay. The Langdon Bay occurrence has been reported by previous researchers to extend to the Eagle Point area, but this area was not visited during this study.

In each area the rocks consist essentially of olivine and ortho-pyroxene, with the olivine generally showing alteration to serpentinous aggregates. The ortho-pyroxene, which locally shows poikilitic texture and may attain a size of up to 50 mm, is relatively unaltered.

At Langdon Bay the peridotite occurs in a belt about 500 m wide, forming bodies from 20 to about 50 m across (35501), alternating with about equal amounts of pegmatitic gabbro, which are intrusive into the peridotite.

The occurrences on the plateau are generally similar in texture and composition (35450, 35451, 35460), but also include some strongly sheared phases with extensive slickensides (35452), tremolite and ? talc veining (35463) and manganese staining (35454). The more northerly occurrence is closely associated with dyke rocks; most of the contacts appear to be faulted, but some dykes cut across the peridotites. Gabbros also occur in the general area, but were not seen in contact with the peridotites.

The only other occurrence seen during this study was a small isolated body between troctolite to the north and fine-grained dyke rocks to the south about half-way along the foreshore of Half Moon Bay (35495). Its contact relations with the adjoining rocks have not been established.

These observations suggest that a revision is required of two aspects of previous accounts.

Firstly, it is clear that earlier maps showing a large body of apparently homogeneous peridotite in the Langdon Bay area represent a considerable over-simplification. Good exposures on the foreshore show discrete blocks of peridotite, generally from 10 to about 50 m across, separated by comparable widths of pegmatitic gabbro. Some contacts are faulted, but where relationships are exposed, the gabbro is invariably intrusive into the peridotite.

Secondly, the field relations of the peridotite occurrences throws considerable doubt on the supposed position of these rocks at the base of the ophiolite sequence, as postulated by Griffin and Varne (1980). The pegmatitic amphibole-rich and locally felspathic gabbro intruded into the Langdon Bay peridotite is indicative of a volatile-enriched and mobile and therefore a high level phase of the gabbro complex. Similarly, the small, strongly sheared peridotite occurrences between North Mountain and Mount Elder are in contact with parts of the dyke swarm with some dykes intruding the peridotite, again indicating a position high in the overall sequence.

3.9 OTHER RECORDED ROCK TYPES

Previous researchers have recorded a number of rock types some of which were not observed during this study. Others are thought to be local variants of the groups described previously.

Some phases of the gabbro were described as eucrites by Mawson (1943); felspathic phases of the gabbro were referred to as anorthosite by Varne and Rubenach (1972); olivine-rich variants of the gabbro were variously described as allivalites and harrisites by Mawson (1943) and as wehrlites by Griffin and Varne (1980); while the peridotites have also been referred to as harzburgites by Mawson (1943), Griffin and Varne (1980) and Varne and Rubenach (1972). Norites and dunites were recorded by Mawson (1943) and Varne and Rubenach (1972).

3.10 CONCLUSIONS

The overall structure of Macquarie Island has been interpreted by Griffin and Varne (1980) as a typical ophiolite sequence, involving (from top to bottom) pillow lavas, dyke swarms, massive gabbros, layered gabbros, recrystallised gabbros and peridotites. The upper parts of the sequence were thought to be affected by metamorphism of zeolite to lower amphilbolite grade, related mainly to depth of burial. Results of this study suggest that this may require some modification.

1. The highest grade of metamorphism, involving the development of pleochroic green-brown amphilbole, is restricted to parts of the dyke swarm and may be related to the proximity of the gabbro intrusives (not necessarily exposed at the present surface), rather than depth of burial.

2. The unit described as layered gabbros is not a homogeneous occurrence. Obvious layering of magmatic origin is restricted to a small area at Elizabeth and Mary Point. Other occurrences of less strongly layered gabbro have been noted from Handspike Point, from the northern portion of Half Moon Bay and from northern and central Langdon Bay. They are of deformational rather than magmatic origin, and are closely associated with petrologically similar phases which do not show layering (Figure 5).

3. Dolerites occur both as cross-cutting dykes and as irregular inclusions in the gabbros, particularly in the Half Moon Bay area. Both phases have locally undergone amphibole facies metamorphism, indicative of an overlap in time between the intrusion of the gabbro and the dolerites, as previously noted by Christodoulou et al. (1984).

4. The peridotite occurrence at Langdon Bay consists of roughly equal proportions of peridotite and pegmatitic gabbro locally rich in amphibole, which is considered a high level phase of the gabbro complex and which intrudes the peridotite. This relationship is in direct contradiction to

the position of the peridotite below the entire gabbro sequence as postulated by Griffin and Varne (1980) and Christodoulou et al. (1985). The rather less well exposed occurrences of peridotite on the plateau between Mount Elder and North Mountain appear to be largely faulted against dolerites and possibly against gabbros. They are cross cut by some of the dykes, which again suggests that the peridotites occupied a position high in the ophiolite sequence at the time of intrusion of the gabbros and dolerites.

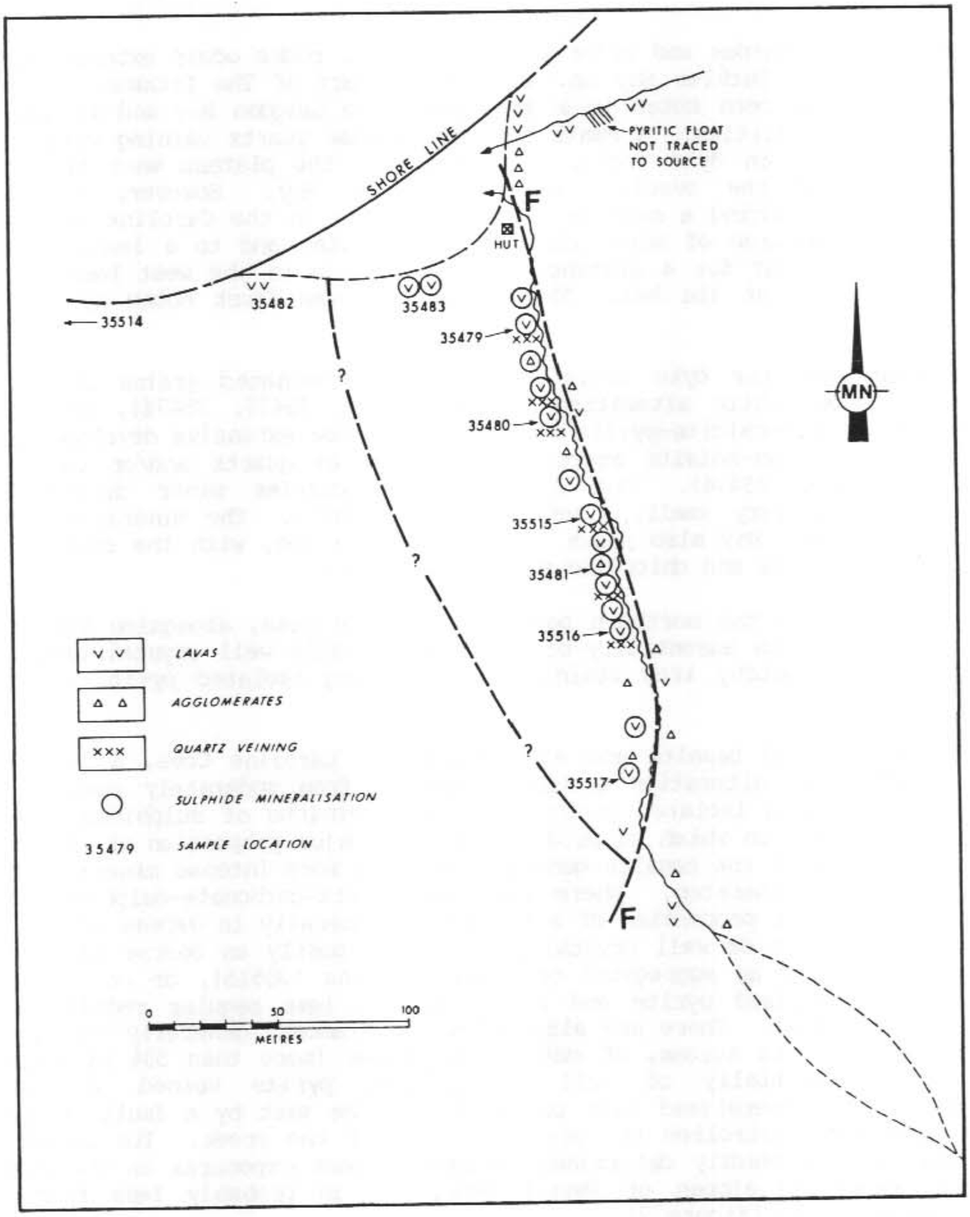


Figure 7. Caroline Cove area geology and sample locations.

4. SULPHIDE AND GYPSUM OCCURRENCES

4.1 SUPLPHIDE OCCURRENCES

Sulphide occurrences are widespread and usually small. They range from disseminated grains in otherwise only slightly altered rocks, through minor quartz-carbonate-sulphide veining, to a single occurrence of locally massive sulphides.

Disseminated sulphides and minor veining in dyke rocks occur extensively on the foreshore of Buckles Bay on the southern part of The Isthmus. Smaller occurrences have been noted in a dyke rock from Langdon Bay and in gabbros from several localities. A small area of intense quartz veining with minor sulphides, again in dyke rocks, also occurs on the plateau west of Gadget Gully alongside the overland track to Bauer Bay. However, the only occurrence approaching a massive concentration is in the Caroline Cove area where good exposures of mineralisation in basalts, and to a lesser extent agglomerates, occur for a distance of about 250 m in the west bank of the creek debouching at the hut. This occurrence was first noted by Griffin (1982).

At Buckles Bay, the dyke rocks containing disseminated grains of pyrite generally show little alteration (35470, 35473, 35475, 35476), but those containing quartz-calcite-pyrite veining often show extensive development of chlorite and clino-zoisite aggregates as well as quartz and/or carbonate mosaics (35469, 35474). One specimen also carries minor disseminated chalcopyrite as very small, discrete grains (35471). The mineralised dyke rock from Langdon Bay also shows extensive alteration, with the development of calcite, epidote and chloritic aggregates (35505).

The occurrence on the northern portion of the plateau, alongside the Bauer Bay track, consists essentially of vuggy and locally well crystallised vein quartz showing patchy iron staining and carrying isolated pyrite crystals (35454).

In the mineralised basalts and agglomerates at Caroline Cove, a generally higher degree of alteration prevails, ranging from moderately sheared and altered rocks with isolated grains and minor veinlets of sulphides (35516, 35517), to others in which sulphides make up a major proportion of the whole rock (35479), with the basalts generally showing more intense mineralisation than nearby agglomerates. Where discrete quartz-carbonate-sulphide veins are developed, the proportion of sulphides is generally in excess of 10% and typically consists of well crystallised pyrite, partly as coarse individual grains and partly as aggregates of smaller grains (35515), or occasionally of well crystallised pyrite and less abundant, less regular reddish-brown sphalerite (35480). There are also a few occurrences, generally only a few hundred millimetres across, of massive sulphides (more than 50% by volume) consisting essentially of well crystallised pyrite veined by quartz (35481). This mineralised zone is bounded to the east by a fault or shear zone which has controlled the present course of the creek. Its extent to the west is not readily determined because of poor exposures on the steep, heavily vegetated slopes of Petrel Peak, but is probably less than the north-south extent (Figure 7).

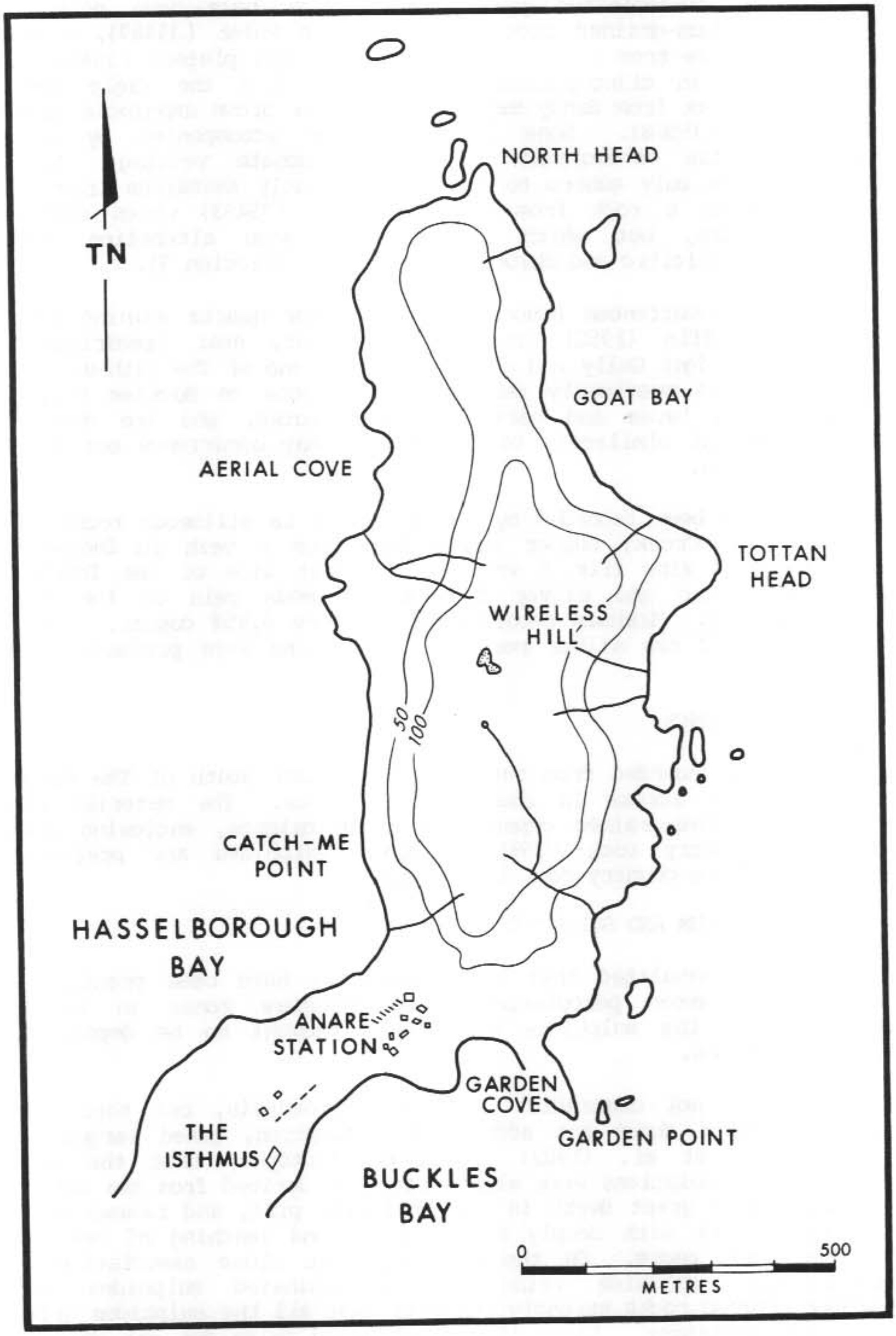


Figure 8. Wireless Hill - North Head area, showing localities mentioned in text.

Occurrences of disseminated pyrite in gabbros have been noted in an even-grained medium-grained rock from Handspike Point (35487), a slightly finer-grained phase from the northern portion of the plateau (35462), a rock slightly richer in clino-pyroxene than usual from the Eagle Cave area (35489), and a rock from Sandy Bay which contains brown amphibole as well as clino-pyroxene (35508). None of these are accompanied by extensive alteration or the development of quartz-carbonate veining. It is of interest that the only gabbro to show significantly anomalous trace element concentrations is a rock from Half Moon Bay (35493) which contains no visible sulphides, but which has suffered some alteration with the development of sericitic and chloritic aggregates (Section 5).

Other sulphide occurrences associated with minor quartz veining have been recorded by Griffin (1982) from Douglas Point, near Precarious Point, Lusitania Bay, Gadget Gully and at the northern end of The Isthmus (which is distinct from the previously mentioned occurrence on Buckles Bay). They occur partly in lavas and partly in dyke rocks, and the descriptions indicate a general similarity to the Buckles Bay occurrence but on a very much smaller scale.

Minor copper has been recorded by Mawson (1943) in siliceous rocks from the head of Rookery Creek; copper and silver from a vein in Gadget Gully; copper, lead and zinc from a vein on the west side of The Isthmus; and copper, lead, zinc and silver from a siliceous vein on the shore of Hasselborough Bay. Maximum recorded values were 6.95% copper, 3.08% lead, 1.98% zinc and 13 ozs silver per ton. The veins were probably less than 50 mm wide.

4.2 GYPSUM OCCURRENCE

Gypsum has been recorded from the east coast just south of The Nuggets as veins to 100 mm across in sheared dyke rocks. The material consists essentially of fine-grained gypsum and minor calcite, enclosing scattered remnants of country rock (35510). Minor sulphides are preferentially associated with the country rock inclusions.

4.3 ORIGIN OF GYPSUM AND SULPHIDES

Griffin (1982) postulated that the gypsum may have been precipitated by descending sea water percolating along fracture zones in the rocks, contrasting with the sulphides which were thought to be deposited from ascending solutions.

This study does not contradict Griffin's hypothesis, but there must be considerable doubt about his additional suggestion, based largely on the work of Cocker et al. (1982) on oxygen isotopes, that the ascending sulphide-bearing solutions were also originally derived from sea water which has percolated to great depth in the ophiolite pile, and re-ascended after heating by contact with deeply buried rocks and leaching of heavy metals from these same rocks. On the contrary, the close association of the quartz-carbonate sulphide veins with disseminated sulphides in only moderately altered rocks strongly suggests that all the sulphides originated from similar processes. Since the disseminated sulphides are most readily accounted for as normal products of crystallisation from a magma containing minor amounts of sulphur, it would therefore appear more likely that the quartz-carbonate-sulphide veins also originated from constituents contained in the original magma and concentrated during the final stages of crystallisation. This is supported also by the distribution of heavy metal trace elements in the unmineralised rocks (Section 5).

In summary, pyrite is the dominant sulphide in all samples collected. The only other sulphides present in significant amounts in a few samples are sphalerite and chalcopyrite.

All the sulphide occurrences noted in this study appear to be the products of late-stage hydrothermal activity. By contrast with the gypsum, which may well have been precipitated from sea water percolating downwards through the ophiolite sequence, the sulphides and associated quartz and carbonate gangue are thought to have resulted from the concentration of volatile constituents in the original magma.

	Sample Number	Co	Cr	Cu	Ni	V	Zn	Pb	As	Location
Basalt	35420	44	177	70	96	178	80	36	2	North end of The Isthmus
	35426	56	373	49	81	250	97	53	-	Garden Cove
	35518	34	141	36	93	159	55	51	-	Hurd Point
	35513	56	296	54	192	262	83	39	-	Coast north of Brothers Point
	35438	42	216	51	121	190	74	58	-	Coast north of The Nuggets
Basalt w. sulphides	35479	49	185	207	98	243	5250	34	3	Caroline Cove
	35516	60	208	85	120	290	1310	36	-2	Caroline Cove
Agglomerate	35433	47	195	62	149	183	76	49	-	Coast north of The Nuggets
Dyke Rocks	35427	53	283	4	82	277	40	48	-2	Coast north of The Nuggets
	35429	36	313	9	80	175	39	64	-	Coast north of The Nuggets
	35475	44	557	4	231	167	131	44	-	Buckles Bay foreshore
	35434	51	134	16	84	281	60	37	-	Coast north of The Nuggets
Dykes w. sulphides	35469	46	82	6	79	276	180	36	-2	Buckles Bay foreshore
	35470	52	160	93	82	291	101	43	-2	Buckles Bay foreshore
	35471	46	173	2270	125	186	2780	29	-2	Buckles Bay foreshore
	35505	50	52	86	63	276	86	40	-2	Langdon Bay
Gabbro	35444	35	321	19	131	153	55	45	2	Coast between The Isthmus and Handspike Point
	35461	34	235	77	151	218	51	34	-	Northern part of plateau
	35500	38	154	55	103	258	69	49	-	Langdon Bay
	35493	48	644	264	315	49	68	44	-2	Half Moon Bay
	35442	26	114	3	68	144	138	41	-	Coast between The Isthmus and Handspike Point
Gabbro w. sulphides	35508	45	50	66	70	267	84	37	-2	Sandy Bay foreshore
Amphibolite	35458	54	13	8	39	222	50	44	-	Half Moon Bay
Troctolite	35536	57	1430	37	591	42	63	33	-2	Half Moon Bay
Peridotite	35451	102	709	9	1720	53	88	21	-2	Northern part of plateau
	35460	104	817	5	1765	65	88	22	-	Northern part of plateau
Prehnite Rock	35504	18	46	4	81	143	19	46	2	Langdon Bay
Qtz.-sulphide veins	35454	5	50	626	12	51	373	360	-2	Northern part of plateau
	35480	42	53	73	36	53	3580	32	2	Caroline Cove
	35515	158	17	165	46	32	39	51	6	Caroline Cove
Massive sulphides	35481	70	22	12	48	24	46	58	-2	Caroline Cove
Gypsum	35510	6	16	8	17	23	32	27	2	Coast south of The Nuggets
Sandstone	35506	53	139	103	75	303	152	44	3	Mawson Point
Calcareous sediment	35509	19	25	40	61	36	46	31	-	Coast north of Brothers Point
Siltstone	35511	60	153	122	88	289	163	43	-	Mawson Point

All values in parts per million.

Table 1. Trace element contents of representative samples.

	Number of Samples	Na	K	Mg	Ca	Fe	Al	Ti	Ba	Sr	Zr	Mn	Co	Cr	Cu	Ni	V	Zn	Pb	As
		%						ppm												
Basalts	6	2.0	0.6	4.5	8.0	4.1	8.9	6760	640	210	100	950	45	230	60	125	210	75	45	2
Basalts w.sulphides	2	1.8	0.08	5.1	1.6	9.8	6.6	8100	930	65	100	2150	55	195	150	110	270	3200	40	3
Dyke Rocks	4	1.6	0.2	5.0	8.5	5.5	9.0	5050	760	130	70	1040	45	320	8	120	220	65	50	2
Dykes w.sulphides	4	1.6	0.08	4.5	6.3	6.2	9.0	6900	290	130	65	1700	50	115	600	85	250	1000	35	2
Gabbros	5	1.3	0.2	6.0	9.3	3.5	9.3	2040	1200	160	25	850	35	300	80	150	160	75	40	2
Troctolite	1	0.4	0.1	13.4	7.2	3.2	8.6	230	610	85	10	600	57	1430	37	590	40	60	33	2
Peridotites	2	0.01	0.01	26.5	0.02	5.3	0.3	40	5	2	18	840	100	760	7	1740	60	90	21	2
Qtz.-sulphide veins	4	-	-	-	-	17.0	-	630	500	35	35	65	70	35	220	35	40	1000	125	3
Gypsum	1	-	-	-	-	0.3	-	220	10	200	10	140	6	15	7	17	23	30	27	2

Table 2. Trace and selected major element values of major rock types.

5. TRACE ELEMENT DETERMINATIONS

Trace element determinations (for Cu, Pb, Zn, Co, Ni, Cr and V) were carried out by ICP at Geology Department, University of Melbourne on thirty-six samples. The samples comprised six basalts, one agglomerate, four dyke rocks, five gabbros, one amphibolite, one troctolite, two peridotites, one prehnite rock and three samples of sedimentary rocks intercalated with the volcanics, as well as twelve samples of mineralised material (two pyritised basalts, four dyke rocks, one gabbro, three sulphide-bearing quartz veins, one sample of massive sulphides and one of gypsum with minor sulphides). Twenty of the samples were also analysed for gold by solvent extraction/atomic absorption at AMDEL, and for arsenic by XRF at both Melbourne University and AMDEL (Table 1).

The highest copper value (2270 ppm) was noted in a mineralised dyke rock from Buckles Bay. The only other values in excess of 100 ppm were from a mineralised basalt at Caroline Cove, a quartz sulphide vein occurrence on the northern part of the plateau, and an apparently unmineralised but possibly hydrothermally altered gabbro from Half Moon Bay. However, the most striking feature is the very low copper concentration of less than 20 ppm in all the unmineralised dyke rocks and in two samples of gabbro from the marginal phase of the plutonic complex. They contrast with an average of about 60 ppm in the volcanics and the remaining gabbros. The hypabyssal rocks and the marginal phase of the gabbro have therefore been severely depleted in copper, possibly by removal as an immiscible sulphide phase prior to consolidation. As no indication of major sulphide concentrations with copper enrichment have been noted in the currently exposed rocks, such concentrations must lie below the present surface or have been carried to the originally upper parts of the sequence and removed by erosion. The peridotites and the felspar-prehnite rock also show very low copper values.

Zinc values in excess of 1000 ppm (maximum 5250 ppm) have been recorded in three mineralised samples from the Caroline Cove area and in one mineralised dyke rock from Buckles Bay. Values in unmineralised rocks generally fall within the range 50 to 150 ppm and show no significant variation between major groups of rocks.

Lead values generally fall between 30 and 60 ppm, with only one anomalous value (360 ppm) in a sample of quartz-sulphide vein material from the northern part of the plateau. The peridotites, (at 21 and 22 ppm respectively) have the lowest concentrations of any rock group, and it is notable, that with the single exception quoted above, mineralised rocks are not enriched in lead compared to their unmineralised counterparts.

Cobalt values also generally fall within the range 30 to 60 ppm, with a peak value of 158 ppm in a mineralised sample from Caroline Cove and above-average values of 102 and 104 ppm in the peridotites. Values less than 10 ppm were recorded in a sample of gypsum from The Nuggets area and in quartz-sulphide from the northern part of the plateau. With the single exception noted above, mineralised samples are not significantly enriched in cobalt.

Nickel values generally fall within the range 80 to 200 ppm with maximum values of 1720 and 1760 ppm in the peridotites. Other above-average values are 591 ppm in the troctolite and 315 ppm in a gabbro from Half Moon Bay.

None of the mineralised samples contain above-average nickel values, and several are significantly lower in nickel than the average unmineralised rocks.

Chromium values generally fall within the range 150 to 300 ppm, with a maximum of 1430 ppm in the troctolite. Other high values are 709 and 817 ppm in the peridotites, 644 ppm in a gabbro from Half Moon Bay and 557 ppm in a dyke rock from Buckles Bay. The mineralised rocks are not enriched in chromium, and several, particularly from the Caroline Cove area, are signficantly lower in chromium than the average of the unmineralised rocks.

Vanadium values also generally fall within the range 150 to 300 ppm, with a maximum of 303 ppm in a sandstone from Mawson Point. The troctolite, peridotites, and some of the mineralised samples from Caroline Cove have significantly below-average values.

Arsenic is consistently low, ranging from less than 2 ppm to 6 ppm (average between AMDEL and University of Melbourne determinations), including all the mineralised samples. Gold was less than 0.05 ppm in all samples tested.

Other elements determined at the University of Melbourne included Ti, P, Li, Be, Ba, Sr, La, Ce, Sm, Eu, Gd, Yb, Zr, Nb, B, Ga, Mn, Ag, Cd and Mo.

Titanium gave very low values in peridotites (48 and 53 ppm) and troctolite (230 ppm) compared to the basalts and dyke rocks (generally 4000 to 9000 ppm) and intermediate values (average 2000 ppm) in gabbros.

Cerium gave maximum values of 2220 ppm in calcareous sediment from Brothers Point and 1770 ppm in gypsum from The Nuggets area, compared to values in the range 20 to 200 ppm in most other rocks.

Zircon values generally fell in the range 10 to 30 ppm in gabbros and periodites, compared to 40 to 120 ppm in basalts and dyke rocks.

Barium, strontium and niobium all gave significantly lower values in the peridotites than in the basalts and dyke rocks.

Gallium gave a maximum of 77 ppm in a sample of massive sulphides from Caroline Cove.

Silver, cadmium and molybdenum showed no significant differences between major rock groups. Maximum values for silver and molybdenum were recorded in gypsum from The Nuggets area. Maximum values for cadmium were recorded in mineralised samples from Caroline Cove.

In summary, trace and minor element distributions in unmineralised rocks generally follow expected trends. Compared to the basalts and dyke rocks, the troctolite and peridotites show notably higher Cr and Ni values and a slight increase in Co, but lower Cu, V, Pb, Ti, P, Ba, Sr, Zr, and Nb. The gabbros show considerable individual variation, but generally are closer to the basalts and dyke rocks than to the troctolite or peridotites (Table 2).

The mineralised rocks generally show above background zinc and cadmium values. High copper values are rather erratically distributed, and only one sample shows a significant enrichment in lead and one in cobalt. Nickel and chromium are generally lower in the mineralised rocks than in their unmineralised counterparts, while vanadium is unaffected in the pyritised basalts and dyke rocks, but is low in the quartz-sulphide veins and massive sulphides.

Copper is markedly depleted in all the unmineralised dyke rocks and some of the gabbros, indicating a stripping of copper from a large part of the parent magma prior to consolidation, possibly in an immiscible sulphide phase. Also, arsenic is unexpectedly low in all the mineralised samples, showing no significant increase over the unmineralised rocks, indicative of an almost complete absence of arsenic in the mineralising solutions.

This trace element distribution provides a further argument against Griffin's hypothesis (1982) that the present distribution of sulphides throughout the ophiolite complex is the result of transport by circulating sea water. According to Griffin's hypothesis, this water had entered the complex from above and picked up heavy metals whilst percolating through pore spaces within the rocks, and had subsequently reprecipitated these materials as sulphides while reascending through the complex. However, if this were so, the process should also have affected other mobile elements, notably zinc. It is much more likely, therefore, that sulphide occurrences on Macquarie Island are the product of late magmatic mineralising fluids.

ACKNOWLEDGMENTS

The ICP determinations were carried out by Mr P. Hannaker, and the XRF by Mr M. Haukka at the Department of Geology, University of Melbourne.

Dr P. Quilty, Dr R. Varne and Dr E. Colhoun examined the manuscript and contributed a number of comments.

REFERENCES

Christodoulou, C., Griffin, B.J. and Foden, J. (1984). The geology of Macquarie Island. ANARE Research Notes Number 21. Antarctic Division, Kingston.

Cocker, J.D., Griffin, B.J. and Muehlenbachs, K. (1982). Oxygen and carbon isotope evidence for seawater-hydrothermal alteration of the Macquarie Island ophiolite. Earth and Planetary Science Letters 6:112-122.

Colhoun, E.A. and Goede, A. (1974). A reconnaissance survey of the glaciation of Macquarie Island. Papers and Proceedings of the Royal Society of Tasmania 108:1-19.

Cullen, D.J. (1970). Macquarie Island bathymetry. Island Chart Series, 1:200 000. New Zealand Oceanographic Institute, Department of Scientific and Industrial Research.

Griffin, B.J. (1982). Igneous and metamorphic petrology of lavas and dykes of the Macquarie Island ophiolite complex. Unpublished Ph.D. Thesis, University of Tasmania.

Griffin, B.J. and Varne, R. (1980). The Macquarie Island ophiolite complex: mid-Tertiary oceanic lithosphere from a major ocean basin. Chemical Geology 30:285-308.

Hayes, D.E. and Talwani, M. (1972). Geophysical investigation of the Macquarie Ridge complex. In: D.E. Hayes (Ed). Antarctic Oceanology, II, the Australian-New Zealand Sector. Antarctic Research Series, American Geophysical Union 19:211-234.

Ledingham, R. and Peterson, J.A. (1984). Raised beach deposits and the distribution of structural lineaments on Macquarie Island. Papers and Proceedings of the Royal Society of Tasmania 118:223-235.

Leoffler, E. and Sullivan, M.E. (1980). The extent of former glaciation on Macquarie Island. Search 11:246-247.

Mawson, D. (1943). Macquarie Island, its geography and geology. Australasian Antarctic Expedition, 1911-14. Scientific Reports, Series A, Volume V. Government Printing Office, Sydney.

Quilty, P.G., Rubenach, M. and Wilcox, J.A. (1973). Miocene ooze from Macquarie Island. Search 4:163-164.

Varne, R., Gee, R.D. and Quilty, P.G. (1969). Macquarie Island and the cause of oceanic linear magnetic anomalies. Science 166:230-233.

Varne, R. and Rubenach, M.J. (1972). Geology of Macquarie Island and its relationship to oceanic crust. In: D.E. Hayes (Ed). Antarctic Oceanology, II, The Australian-New Zealand Sector. Antarctic Research Series, American Geophysical Union 19:251-266.