THE AGE AND DISTRIBUTION OF THE IGNEOUS ROCKS OF MACQUARIE ISLAND

by R. A. Duncan and R. Varne

(with one table and one text-figure)

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Basalts associated with the formation of the Macquarie Ridge have been radiometrically dated at between 9.7 Ma and 11.5 Ma, giving a Middle Miocene age in approximate agreement with the age indicated by fossils in intercalated sedimentary rocks but younger than suggested by the nearby sea-floor spreading anomaly pattern. (Ed.)

Key Words: igneous rocks, radiometric analysis, tectonic uplift, Macquarie Island.

INTRODUCTION

Macquarie Island is unique among islands of the major ocean basins in being composed of oceanic crust and marks the tectonic emergence above sea level of part of the Macquarie Ridge (Varne *et al.* 1969, Varne & Rubenach 1972). The latter is a narrow arcuate welt of ridges and trenches that runs southward from New Zealand to join the Indian-Pacific mid-ocean ridge system.

The first geological map of the island was produced by L. R. Blake, a surveyor with the 1911-1914 Australasian Antarctic Expedition led by Sir Douglas Mawson. Blake was killed in the First World War, and his map was published by Mawson in his account (the first) of the geological history of the island, also based on Blake's work (Mawson 1943). This assigned the rocks of the island to an older basic group of lavas, in places intensely folded, intruded by a group of peridotites and gabbros, with both groups, following a period of erosion which exposed the intrusive rocks, overlain unconformably by a younger basic group of pillow lavas and extrusive fragmental rocks. Mawson also tentatively suggested a Cretaceous age for the formation of the rocks of the island, by analogy with the timing of tectonic and magmatic activity in New Zealand.

More recent geological mapping, including that of Varne *et al.* (1969), Varne & Rubenach (1972), Christodoulou *et al.* (1984), Crohn (1986) and Lees (1987), generally confirms the lithological distributions recorded in Blake's map, but Mawson's stratigraphic column has been ques-tioned. Varne *et al.* (1969), who first showed that the island is formed from uplifted oceanic crust, pointed out that the older basic group described by Mawson (1943) is made up of dolerite dyke swarms and not of extrusive rocks. They also argued that the extrusive rocks of Mawson's younger basic group might be intruded by the dyke swarms, the gabbros and the serpentinised peridotites, and could therefore be the oldest rocks exposed on the island. Foraminifera from silicified oozes associated with pillow lavas were considered to be of Late Miocene or Pliocene age.

Varne & Rubenach (1972) presented new maps and geological data showing that Macquarie Island seems to be composed of a number of fault-bounded blocks, probably on all scales, derived from different layers of the oceanic lithosphere. This interpretation implies that all of the igneous rocks of the island could have been formed at much the same time, in a spreading zone in an oceanic environment, possibly the Indian-Antarctic spread-ing ridge. Poorly-preserved coccoliths recovered from oozes associated with North Head pillow lavas were identified by Quilty *et al.* (1973) as being of Early or Middle Miocene age.

Geochemical and geophysical data have supported the identification of Macquarie Island as uplifted oceanic crust. The basalts and dolerites are compositionally very like ocean-floor basalts from the Mid-Atlantic Ridge (Griffin & Varne 1980), and pillow lavas have magnetic properties which correspond well with those of ocean-floor basalts (Banerjee *et al.* 1974, Butler *et al.* 1976, Levi *et al.* 1978). A magnetic profile along the northern part of the island (Williamson 197 4) shows a broad anomaly which has been correlated with similar anomalies in marine magnetic profiles around the island, believed by Williamson *et al.* (1981) to be part of sea-floor spreading anomaly 7. Williamson (this volume) therefore suggests that the rocks of the island formed at the Indian-Antarctic spreading ridge at anomaly 7 time, about 27 Ma, considerably earlier than the palaeontological data suggest.

In this article, we briefly describe the geology of Macquarie Island, present a revised geological map, and provide the first radiometric determinations of the ages of Macquarie Island rocks.

THE GEOLOGY OF MACQUARIE ISLAND

The island is about 35 km long but less than 6 km wide, elongated northnorthwest along the axis of the Macquarie Ridge. It is topped by an elevated and undulating lake-studded summit plateau, best developed in the northern part of the island, which stands about 300 m above sea level and is cut off seaward by steep cliffs. A marked coastal platform with relict sea stacks occurs in places at the base of the cliffs on both sides of the island, with its greatest development at Handspike Point, where it is a kilometre wide and rises to an elevation of about 15 m above sea level (Mawson 1943).

Marine, glacial and other subaerial erosional processes may have all played a part in shaping Macquarie Island from the ridge as it rose. Varne *et al.* (1969) identified raised beach deposits at 200 m on the northern summit plateau of the island, but Colhoun & Goede (1974) and Löffler & Sullivan (1980) proposed that many landforms from this part of the island are of glacial origin. Some terraces in the northern part of the island may be relicts of periglacial activity, formed at a time when cooler climatic conditions favoured the operation of solifluction processes (Löffler *et al.* 1983). Others are associated with raised beach deposits that were apparently lifted to their present position by neotectonic processes (Varne *et al.* 1969, Selkirk *et al.* 1983, Ledingham & Peterson 1984). These raised beaches are not yet dated, but deposits resting upon them are young (Selkirk *et al.* 1983). It could be that the summit plateau was largely cut by marine erosion, either before renewed compression along the Macquarie Ridge uplifted it to its present position or when sea levels were higher, in the past.

The landscape has also been modified by recent faulting. Ledingham & Peterson (1984) described recent lineaments and fault lines: some apparently displace young topographical features and are associated with topographic depressions and lakes. These young lineaments and fault lines follow generally northerly trends, subparallel to the east and west coastlines of the island and to the general trend of the Macquarie Ridge. The Brothers fault line (fig. 1) and its northern continuation are the most prominent, but less distinct, apparently older, linear features trend northwest and southwest (Ledingham & Peterson 1984, plates 6 and 7).

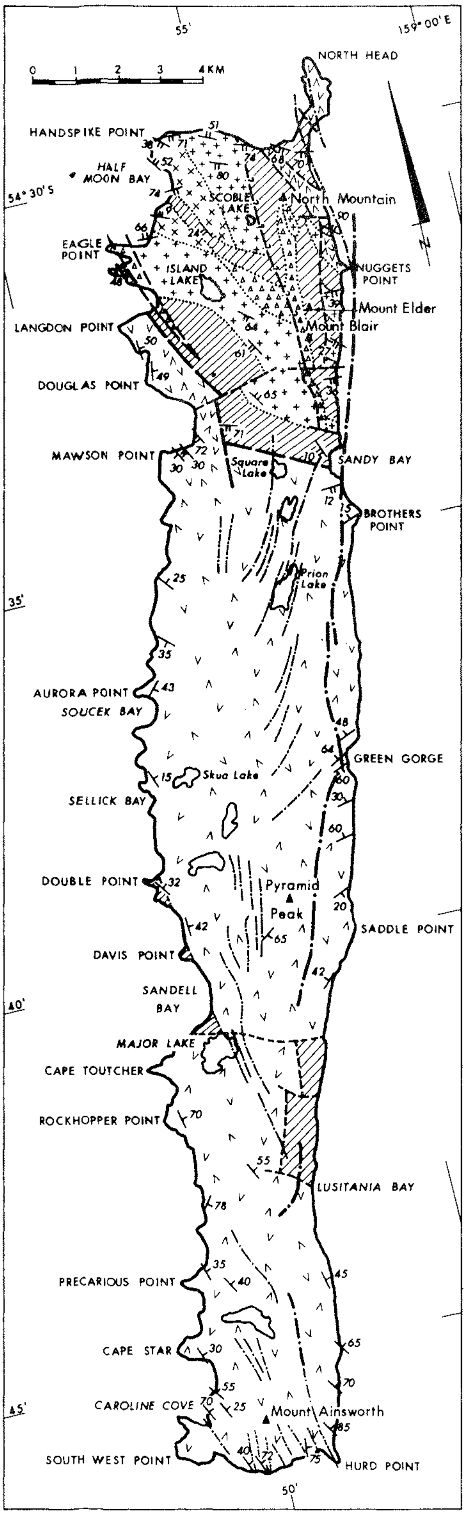
The northern part of Macquarie Island is formed mainly of intrusive igneous rocks, whereas the southern part is formed mainly of extrusive volcanic rocks and associated sedimentary rocks (fig. 1). The contact zone between the mainly intrusive rocks of the northern part of the island and the mainly extrusive rocks south of Bauer Bay and Sandy Bay follows a topographic depression, and corresponds in part with a northwest-trending fault zone that is marked by mylonites and flaser gabbros (Varne *et al.* 1969) and invaded by gabbroic veins, and therefore unlikely to be due to near-surface neotectonic movements. Other northwest-striking faults in the northern part of the island also appear to be older than the generally north-trending fault lines recorded by Ledingham & Peterson (1984).

The extrusive volcanic rocks are basaltic. Pillow lavas are common, and volcanic breccias, hyaloclastites, and massive lavas are also present (Mawson 1943, Varne & Rubenach 1972, Christodoulou *et al.* 1984, Crohn 1986). Thin lenses of volcaniclastic sediments, ranging from mudstone to conglomerate, tend to be associated with volcanic sequences which contain massive lavas, as at Mawson Point. Calcareous oozes occur between pillows, and are widely distributed although not abundant. Volcanic activity, therefore, occurred in a submarine setting, but the water depths at the time of deposition are unknown and may have ranged from deep to relatively shallow. Little is also known as yet of the volcanic successions or stratigraphy. An angular discordancy may occur

FIG. 1 — Interpretative geological map of Macquarie Island with superficial deposits omitted, compiled from the mapping of Varne et al. *(1969), Varne & Rubenach (1972), Griffin (1982), Christodoulou* et al. *(1984), Crohn (1986) and Lees (1987). The structural lineaments are from Ledingham & Peterson (1984).*

△	serpentinised peridotite	▨	dolerite dyke swarms
+	gabbro	×	layered gabbro
^	extrusive volcanics and associated sedimentary rocks		

—— / —— major/minor faults
—·— / —·— major/minor structural lineaments
········ gradational or uncertain contacts
⊥ / ⊥⊥ strikes on lavas/dykes



just east of Mawson Point (Varne & Rubenach 1972), although Lees (1987) has suggested that the variations in strike in the Mawson Point–Bauer Bay area are due to recent fault movement.

Two strike directions are commonly found in the volcanic and sedimentary rocks. South of Mawson Point and near Green Gorge, the dominant strike trends are westerly, but elsewhere they lie in the northwest quadrant. Dips range from shallow to steep, and are variable even in areas of constant strike. Narrow basaltic dykes cut the extrusive rocks. South of Brothers Point, dykes form as much as 40% of the coastal outcrop, but are generally less abundant elsewhere. The volcanic rocks may have been first tilted around axes that were near-horizontal and parallel to dyke bedding-plane intersections, causing variations in dip, and later rotated about vertical axes, causing variations in strike (Varne & Rubenach 1972, Williamson 1978).

Sheeted dyke complexes, composed of dipping series of parallel to subparallel dolerite dykes, occur mainly in the north of the island, associated with gabbros and peridotites, but are also exposed on the coasts north of Cape Toutcher and Lusitania Bay (fig. 1). Screens of gabbro, serpentinised peridotite, brecciated dolerite, and very rarely, pillow lava, have all been found within the dyke complexes, but no screens are identifiable over large areas.

Varne *et al.* (1969) reported that in the north of the island, the dykes are distributed around a near-horizontal axis trending 300°, with most dipping at about 50° to the west. They commented that the reversals in dyke dips were taken by Blake (see Mawson 1943) to be due to folding of originally-horizontal lava sheets. No systematic study has yet been made of the orientations of the dykes, of their thicknesses, or of the facings of their chilled edges. At Double Point, a transition may occur between extrusive rocks cut by many basaltic dykes into a sheeted dolerite dyke complex.

A recently-revised interpretative geological map of Macquarie Island, with superficial deposits omitted, is presented as figure 1. This map has been compiled from the mapping of Varne *et al.* (1969), Rubenach & Varne (1972), Griffin (1982), Christodoulou *et al.* (1984), Crohn (1986) and Lees (1987). In general, there is little outcrop inland on Macquarie Island, and the map is therefore more reliable along the coast. The maps of Crohn (1986) and Lees (1987), which are mainly of the northern part of the island, indicate areas where outcrop is relatively good.

South of Sandy Bay and Bauer Bay, this new version differs little from that of Varne & Rubenach (1972), other than in the addition of the structural lineaments discovered by Ledingham & Peterson (1984). Compared with earlier maps of the northern part of the island, the main difference lies in the incorporation of a north-trending fault, northwest of Sandy Bay, mapped by Lees (1987) in its southern part. Recent east-side-up movement has occurred along this fault, which runs near-parallel to the young structural lineaments of Ledingham & Peterson (1984). In the map, this fault is sketched as continuing northwards to Hasselborough Bay, along the eastern contact of the massive gabbro, but has not yet been located by field mapping. The northnorthwest-trending faults cutting the east coast between Nuggets Point and Buckles Bay may splay off the main north-trending offshore structural lineament drawn by Ledingham & Peterson (1984) and may also be young features.

PETROLOGY AND GEOCHEMISTRY OF THE IGNEOUS ROCKS OF THE ISLAND

Gabbros and peridotites are restricted to the northern third of the island. The peridotites are serpentinised; most were originally harzburgitic assemblages of olivine, orthopyroxene and spinel (Varne & Rubenach 1972) although dunite has been found as loose blocks (Mawson 1943) and may outcrop northwest of Sandy Bay (Lees, personal communication 1987). Layered sequences of gabbroic rock are exposed at Handspike Point and along Half Moon Bay (Varne & Rubenach 1972; Crohn 1986). At Handspike Point (fig. 1), olivine gabbro is common, although troctolite and dunite are the dominant rock types (Christodoulou *et al.* 1984). Several massive gabbro bodies are exposed along the north and east coasts, and gabbro probably underlies much of the plateau (fig. 1), although exposures there are poor.

Mawson (1943), Varne & Rubenach (1972), Cameron *et al.* (1981), Griffin & Varne (1980), and Griffin (1982) have described the petrography and chemical compositions of some basalts, dolerites and gabbros. Basalts and dolerites range from coarsely porphyritic to aphyric, and from almost wholly crystalline to almost wholly glassy. Many of the extrusive rocks have been altered and metamorphosed, although fresh glass is also widespread. Where alteration is slight, crystalline groundmasses are mainly composed of clinopyroxene, plagioclase, opaques, and recrystallised glass, with pseudomorphs after olivine and rare amphibole in relatively alkaline varieties (Griffin & Varne 1980).

On North Head, Mawson Point, and in the Pyramid Peak area (fig. 1), the rocks are relatively fresh, and at worst have suffered only the smectite-carbonate alteration that is characteristic of ocean-floor weathering. Rocks from these three locations have been radiometrically dated. Elsewhere basalts were metamorphosed to higher grades, and Griffin (1982) described a section from the south of the island where the volcanic succession is about 1.4 km thick, and passes from zeolite facies assemblages through to lower greenschist facies assemblages. Intense veining and alteration is associated with fault zones (Crohn 1986). The dolerites are compositionally similar to the basalts (Griffin & Varne 1980), but tend to be more altered, displaying a widespread replacement of primary mafic minerals by actinolite. However, plagioclase survives little-changed in the dolerites, as do their doleritic textures (Varne & Rubenach 1972, Banerjee *et al.* 1974, Griffin 1982). Locally the metamorphic grade in the dolerite dykes lies within the amphibole facies.

THE RADIOMETRIC AGES OF SOME MACQUARIE ISLAND ROCKS

Seven basaltic rocks were selected from the University of Tasmania Macquarie Island collection for radiometric analyses. Results are summarised in table 1; additional analytical details are available on request. All selected samples were well crystallised and compact (rare glass and vesicles) and showed the least low-temperature alteration in the collection.

K-Ar ages were determined for four whole rock samples and one hornblende mineral concentrate from a fifth sample. The hornblende is a fresh, primary igneous phase and its age (11.5±0.3 Ma) is the time of crystallisation of its host basalt. The measured ages for the whole rock samples range from 3.6 to 9.6 Ma. Based on the petrographic evidence for low temperature formation of K-rich zeolites and clays (samples 47959, 47977 and 60635) and higher temperature metamorphism (sample 38248) these ages are minimum estimates of the true crystallisation ages. Replicate analyses of one of the samples (47977) show that the ages are reproducible and may relate to the age of alteration, from 5.8 to 9.6 Ma. The youngest measured age (3.6 Ma) comes from the stratigraphically deepest sample (38248) and may reflect the addition of K to the rock during chemical exchange with seawater.

The $^{40}Ar/^{39}Ar$ experiments were undertaken to establish more reliable crystallisation and metamorphic ages for the basaltic rocks. Three samples (60635, 47977 and 38248) were investigated

TABLE 1

K-Ar and ^{40}Ar/^{39}Ar radiometric ages of basaltic rocks from Macquarie Island

Sample Identification*	**K-Ar ages****				**^{40}Ar/^{39}Ar ages****	
	% K	**Radiogenic ^{40}Ar ($\times10^{-11}$mol/g)**	**% Radiogenic Ar**	**Age ±1 σ (Ma)**	**Total Fusion Age (recombined)**	**Plateau Age**
38248 (Nuggets Point) — dyke	0.434	0.02748	5.9	3.6±0.3	6.9±0.7	6.5±0.5
47956 (Pyramid Peak) — dyke-hornblende separate	0.389	0.80696	36.0	11.5±0.3		
47959 (Pyramid Peak) — lava flow	0.464	0.54797	7.0	6.7±1.0		
47977 (Aerial Cove) — lava flow	0.999	1.01698 0.99950	7.6 7.6	5.8±0.8 5.7±0.8	9.2±0.4	9.7±0.3
60635 (Mawson Point) — lava flow	0.506	0.85452	6.7	9.6±0.9	13.4±0.3	11.5±0.3
60685 (Hurd Point) — dyke					7.2±0.6***	
60820 (Souchek Bay) — lava flow					6.7±0.3***	

* University of Tasmania collection numbers.

** Ages calculated using the following decay and abundance constants: $\lambda_\epsilon = 0.581\times10^{-10}$ yr^{-1}; $\lambda_\beta = 4.962\times10^{-10}$ yr^{-1}; ^{40}K/K = 1.167×10^{-4} yr^{-1} mol/mol.

*** not recombined.

using incremental heating methods (e.g. Walker & McDougall 1982) which reveal internally consistent "plateau" ages from the argon composition released in increasing temperature steps. Total fusion ages were calculated for these samples by recombining the individual step compositions; another two samples (60685 and 60820) were analysed in a single (total fusion) experiment. Samples 60635 and 47977 are from near the top of the section and exhibit zeolite facies metamorphism to cold sea-water alteration only. These show well-defined plateau ages at 11.5±0.3 and 9.7±0.3 Ma, respectively, which we interpret as original crystallisation ages. The older plateau age is identical to the K-Ar age of sample 47956 (11.5 Ma) which dates the oldest volcanic activity at Macquarie Island. The younger age dates the eruption of more alkalic flows which comprise North Head. Samples 38248, 60685 and 60820 are from the dyke swarm and lower pillow lava section and their ages reflect the end of greenschist metamorphism conditions. The age range, 6.5 to 7.2 Ma, records the time of closure of these rocks to diffusion of argon.

Griffin & Varne (1980) suggested that the coastal traverse from North Head, via Hasselborough Bay and Handspike Point to Eagle Point might represent a tilted section through ocean crust, with the extrusive rocks of North Head at the top, overlying dolerite dyke swarms and massive and layered gabbros, with serpentinised peridotites at the base. However, if volcanism at both Pyramid Peak and at North Head occurred at the Indian-Antarctic spreading ridge, this would imply a very low spreading rate of the order of 1 mm/yr.

A more reasonable interpretation is that the younger volcanism at North Head may have occurred away from the spreading axis. Off-axis seamount volcanism is observed in the Pacific Ocean (Batiza & Vanko 1984) and leads to the growth of submarine volcanoes, commonly located on or near transform faults, and ridge deflections. This would be compatible with the alkaline nature of the volcanism. Alternatively, the young north-trending lineaments and faults cutting the isthmus between North Head and Hasselborough Bay may mark the site of recent transcurrent movement along the Macquarie Ridge, throwing two diachronous sections of ocean crust against one another. The crustal section including North Head may terminate at the zone of major faulting between Bauer Bay and Sandy Bay. This could be in part the trace of an old fracture zone separating two segments of ocean crust.

SUMMARY

Macquarie Island is made up of fault-bounded blocks of oceanic lithosphere, planated by marine erosion as they were lifted and tilted during tectonic activity associated with the formation of the Macquarie Ridge. Radiometric ages for basalts range from 11.5 Ma to 9.7 Ma, broadly compatible with the Middle Miocene ages of fossils in intercalated sedimentary rocks, but younger than the age inferred from the sea-floor spreading anomaly pattern west of the Macquarie Ridge.

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