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1976/36

A REVIEW OF THE GEOLOGY AND GEOPHYSICS OF MACQUARIE ISLAND AND THE MACQUARIE RIDGE COMPLEX

by

D. Jongsma

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CONTENTS

Tables

Figures

Plates

FOREWORD

Reviews have been made of the geology and geophysics of most of the Australian island territories. Other records in this series by the same author cover:

Record No. 1976/12	Lord Howe Rise and Norfolk Ridge
" " 1976/37	Christmas Island and Christmas Rise
" " 1976/38	The Cocos Islands and Cocos Rise
" " 1976/39	Queensland Plateau
" " 1976/40	Area of Mellish, Frederick, Kenn and Wreck Reef, and Cato Island.
" " 1976/41	Marion Plateau

SUMMARY

Macquarie Island is the emergent part of a submarine ridge system which runs south from the southern tip of New Zealand to the Pacific-Antarctic Ridge. The system is a complex of three discrete ridges with Macquarie Island on the central one. Trenches lie to the west of the northern and southern ridges and to the east of the central ridge. Part of the ridge system is at depths of less than 2000 m; the trenches reach depths of over 6000 m and the nearby ocean basins are at depths of 4500 m. Three 4000-m deep passages associated with structural offsets bisect the ridge.

The northern part of Macquarie Island is composed of gabbro, serpentinized peridotite masses and dolerite dyke swarms which are metamorphosed. In the southern part of the island the rocks are similar to those of the ocean floor and are composed of lavas and volcanic bre cias which are cemented by *Globigerina* ooze. The rocks of the island appear to have been formed at a spreading centre during the early Miocene and were uplifted to their present position during the Pliocene.

Prospectivity of the area is extremely low as no mineralization is either recorded or expected on the island, and the presence of only thin pelagic sediments on and near the ridge excludes the possibility of hydrocarbons having accumulated. The only possible economic potential lies in ferro-manganese deposits formed on the ocean floor near Macquarie Island. These are only marginally prospective at present, as they are poor in nickel, copper, and cobalt compared to the seabed nodules of the central Pacific.

INTRODUCTION

Macquarie Island (lat. $54^{\circ}30'$ - $54^{\circ}45'$S and long. $158^{\circ}57'$E) lies about 1000 km southwest of New Zealand and 1400 km southeast of Tasmania. The Antarctic continent is 1600 km to the south and its nearest neighbouring islands, the Auckland and Campbell Islands, lie 660 km to the northeast (Fig. 1). The island is 38 km long with its main axis running N. 15°E. Its maximum width is 5 km and it has an area of 117 km^2. There are two barren rocky islets close to the island: Judge and Clerk Island 14 km to the north, and Bishop and Clerk Island 32 km to the south. Macquarie Island is situated on the Macquarie Ridge, a narrow topographic high that extends from New Zealand southwards to connect with the South East Indian - Pacific - Antarctic Ridge system.

Macquarie Island was discovered on 11 July 1810, and from 1811 till about 1843 was a major source of oil and furs derived from sealing. Both Scott and Shackleton visited the island on their first expeditions, in 1901 and 1909 respectively. The first scientific station was established during the Australasian Antarctic Expedition led by Sir Douglas Mawson between 1911-1914. During the years 1912 and 1913, a party of five carried out comprehensive work on the meteorology, geology, and animal life of the island. In March 1948, the Australian Government via the Australian National Antarctic Research Expedition established a research station on Macquarie Island which is now in its 27th year of operation.

The Bureau of Mineral Resources (BMR) has recorded seismological data on Macquarie Island since 1950, and geomagnetic data since 1951.

INVESTIGATIONS

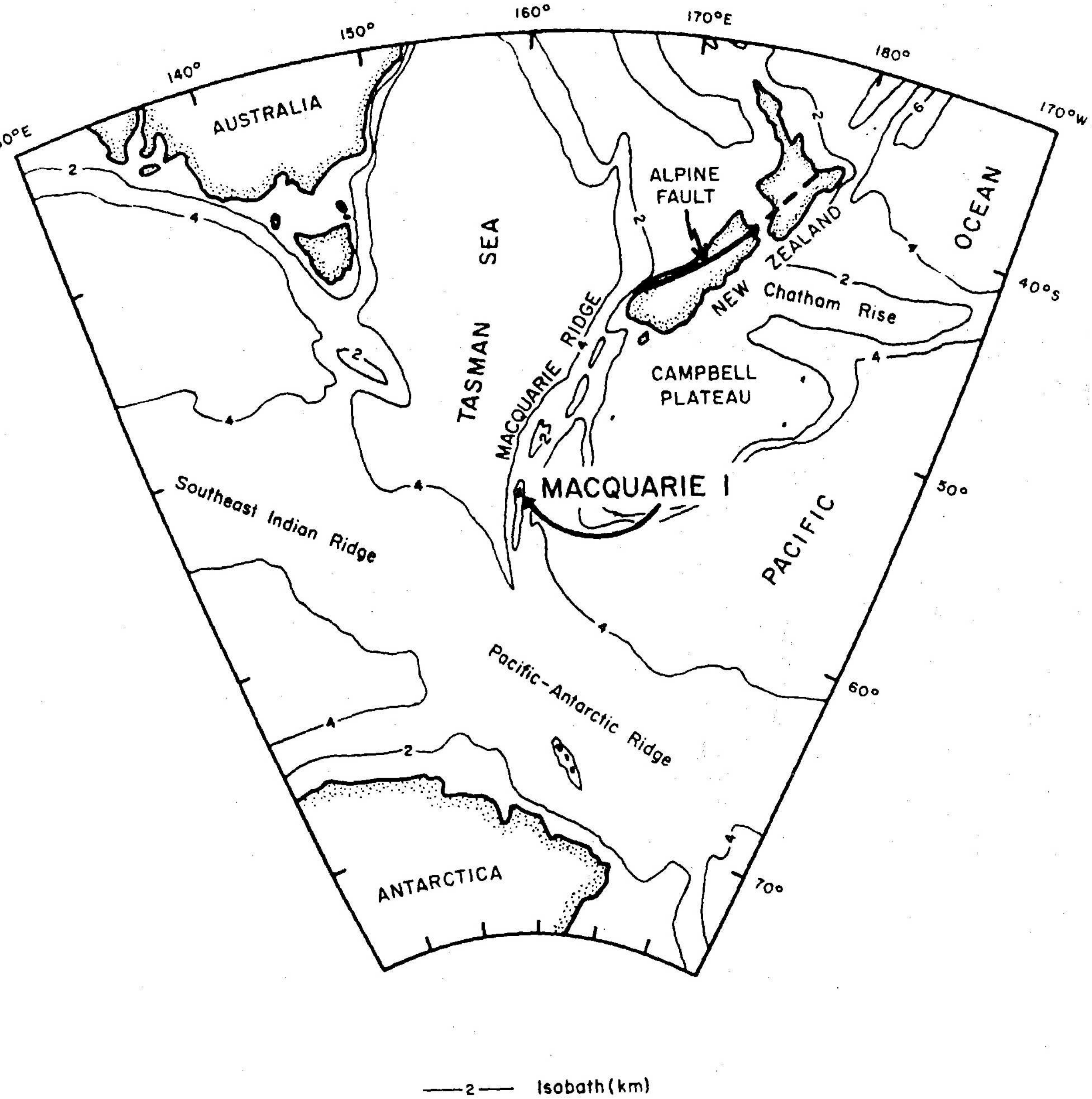
The earliest investigations of the geology of Macquarie Island were carried out by Blake during the Australasian Antarctic Expedition (Mawson, 1943). Some further observations were made in 1947 by Ivanac (1948). The morphology of the northern Macquarie Ridge was described by Brodie & Dawson (1965) mainly from data collected on the HMNZS Endeavour by the New Zealand Oceanographic Institute. Summerhayes (1967a, b, 1969) did an exhaustive study of the marine geology of the area during which a bathymetric map of the area on a scale of 1:1 000 000 was completed. The geology of the island and the petrology of rocks from it were studied by Varne et al. (1969) and Varne & Rubenach (1972). Rocks dredged from the Macquarie Ridge were investigated by Watkins & Gunn (1971). During 1970 a preliminary bathymetric map on a scale of 1:200 000 was published (Cullen, 1970).

The Macquarie Ridge is seismically active. Its conspicuous seismicity drew attention to the ridge and generated considerable speculation in the middle 1950s (Carey, 1958) on its origin, evolution, and relation to the processes of global tectonics (Le Pichon, 1968). In addition, the Macquarie Ridge provides the main barrier to the deep circumpolar flow of water around the Antarctic, and its growth and evolution must have had profound influence in modifying the patterns of polar circulation and ultimately the circulation of the entire world oceans (Gordon, 1972). Because of the ridge's importance to studies of global tectonics and oceanography, there has been a considerable amount of marine geophysical and geological research in this area over the last 7 years. Much of the information was published in Volume 19 of the Antarctic Research Series (Hayes, 1972) which contains bathymetric, gravity, sediment thickness, and magnetic anomaly maps. The results of early magnetic studies were published by Hatherton (1967, 1969). Marine magnetic profiles recorded by the Lamont-Doherty vessels <u>Eltanin</u> (in particular), <u>Vema</u>, and <u>Conrad</u> were analysed by Weissel & Hayes (1971, 1972). Seismic reflection profiles were presented by Houtz et al. (1971), Hayes & Talwani (1972), Hayes et al. (1972) and Christoffel & Van der Linden (1972). Houtz & Markl (1972) presented a sediment thickness map of the region and the sediments were discussed by Conolly (1972) and Watkins & Kennet (1971). The distribution of ferro-manganese deposits was studied by Goodell et al. (1971). A free-air gravity map of the ridge was produced by Hayes & Talwani (1972). Geophysical studies on Macquarie Island were described by Williamson & Rubenach (1972). Analyses of the earthquakes which occurred on or near the ridge were given by Johnson & Molnar (1972), Sykes (1967, 1970), Banghar & Sykes (1969), and Hamilton & Evison (1967). Heezen & Tharp (1972) and Goodell et al. (1973) and others have presented map showing the morphology and sediment distribution under the Southern Ocean; these are listed in Table 1. One drill site was occupied on the ridge (DSDP site 279) and another near the ridge (DSDP site 278) in March 1973, during Leg 29 (Fig. 10) of the Deep Sea Drilling Program (Kennet et al., 1974). The possible evolution of the Macquarie Ridge area and the major plate motions in the area discussed by Molnar et al. (1975).

MORPHOLOGY

The island morphology consist primarily of a narrow coastal plain and a steep-sided plateau with an average elevation of 350 m. The plateau is broken by hills which rise to 435 m in the central south (Cullen, 1970). There are numerous lakes on the island which are apparently of glacial or

FIG. 1



LOCALITY MAP

Record No. 1976/36

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periglacial origin. The coastal platform which fringes the island supports relict sea stacks, particularly in the north. Both raised beach deposits and fluvioglacial deposits have been found on the island. The fluvioglacial deposits and the lakes led Mawson (1943) to propose that an ice sheet, which supposedly originated from a foundered landmass to the west, over-rode and partly planated the island. Varne et al. (1969) showed that this concept is no longer tenable and that it is not known whether the topography is mainly a consequence of marine processes or of glacial processes.

The Macquarie Ridge is a narrow feature which runs from 60°S through Macquarie Island to the continental shelf of New Zealand at 46° (Fig. 2 and Pl. 1), where it terminates against the northeast-trending Resolution Ridge. Its morphology has been described by Brodie & Dawson (1965), Summerhayes (1969), and more recently by Hayes & Talwani (1972) whose data, taken mainly from the Lamont surveys, indicate that the morphology of the ridge is very complex. Ship tracks in the region are shown in Figure 3 and the bathymetric map of Plate 1 is based on data recorded along these traverses. Several topographic profiles across the ridge are shown in Figures 5a, b and c, and Figure 6. Much of the ridge is at depths of less than 2000 m and parts of the crest are shallower than 1000 m. The northern and southern parts of the ridge are bordered by trenches on their western sides (the Puysegur Trench and the Hjort Trench), and the central part is flanked by a trench on its eastern side (the Macquarie Trench). The Hjort and Macquarie Trenches are continuous over about 450 km with depths of over 6000 m and 5250 m respectively. The Puysegur Trench extends between 46°S and 49°S; it has length of about 320 km and depths of around 5800 m.

The Macquarie Ridge is bisected in three places by major deep-water passages (Fig. 4) which appear to coincide with offsets or dislocations of the ridge. The southern passage connects the Hjort and Macquarie trenches near 56°S and has a maximum depth of about 4500 m. The second break in the ridge is at 53.5°S but the passage is no deeper than 3500 m. At 50.5°S another passage is indicated although the ridge appears continuous at the 2700-m isobath level. A 90-km right-lateral offset of the ridge is observed here.

To the east of the southern Macquarie Ridge lies the Emerald Basin where water depths are around 4500 m. The northern part of the Ridge is separated from the Campbell Plateau by the Solander Trough. West of the Macquarie Ridge lies the Tasman Basin with depths of about 4200 m. The Tasman Basin is characterized by low sea-floor relief of about 400 m.

GEOLOGY

Macquarie Island is extensively faulted and is formed of basaltic lava flows, volcanic breccias and sediments, that are cut by many dolerite dykes (Fig. 7). Gabbros and serpentinites are found in the northern part of the island. Mawson (1943) first described the geology. He divided the rocks at the northern end of the island into an older basic group, metamorphosed to greenschist and/or amphibolite facies, and an unconformably overlying younger basic group consisting of pillow lavas, and pyroclasts cemented by Globigerina ooze. Mawson supposed that the island consisted of a fault-bounded horst rising above a much more extensive massif which is at present submerged. In contrast, Varne et al. (1969) and Varne & Rubenach (1972) have presented good evidence based on petrology and geochemistry, that the island is a piece of uplifted ocean floor. In their interpretation the 'older basic' rocks of Mawson are postulated to be younger than the overlying pillow basalts and appear to have been derived from deeper crustal levels. Summerhayes (1969) believed the Macquarie Ridge Complex to be an island arc, but the composition of the rocks is more typical of those formed at a spreading centre (Girod & Nougier, 1972).

Mawson suggested that the Globigerina ooze within the pyroclastics was of Miocene age. This was substantiated by Quilty & Wilcoxon (in Williamson & Rubenach, 1972) who determined an age of early to mid-Miocene for coccoliths within the ooze.

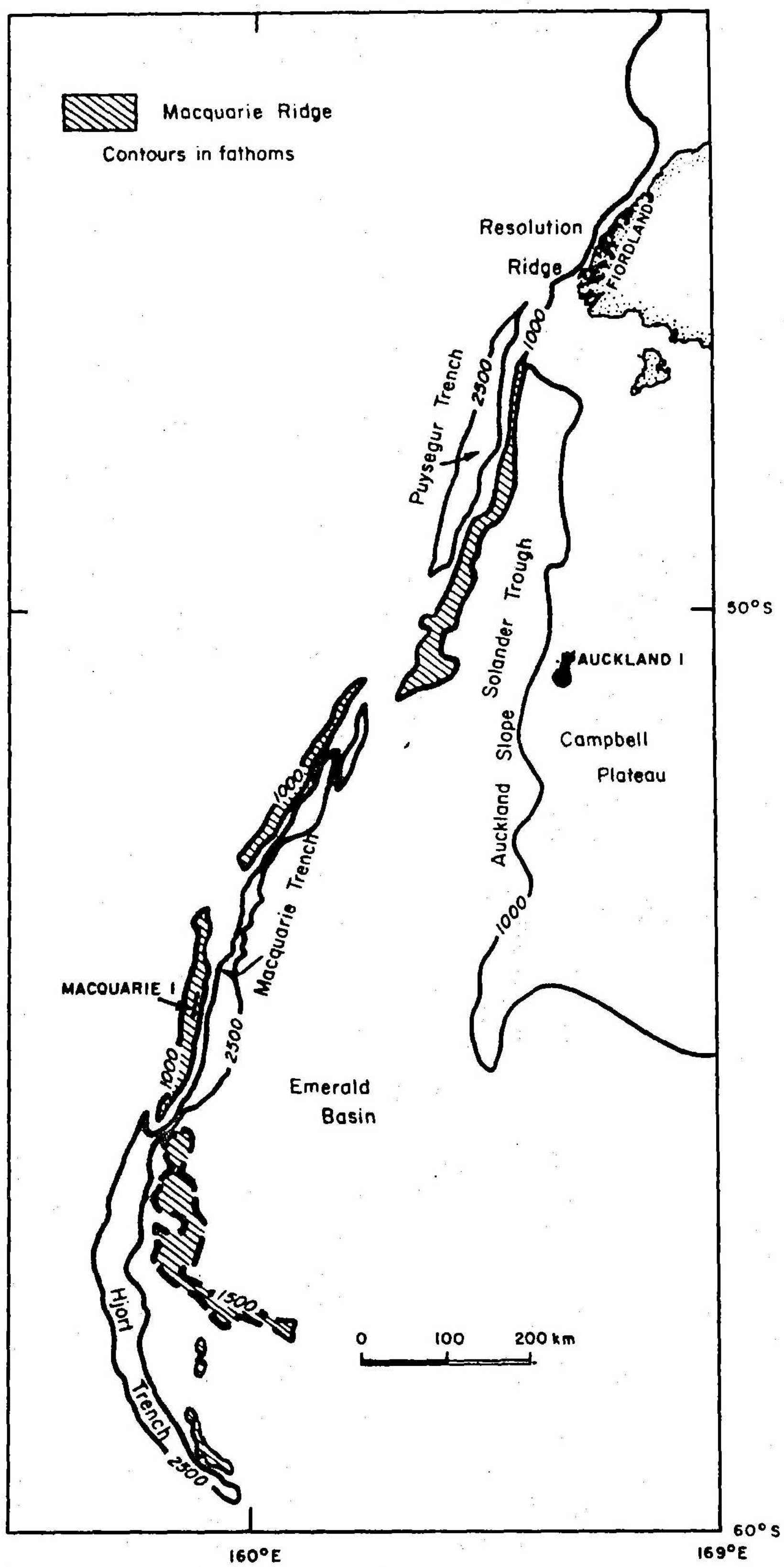
GEOPHYSICS

Gravity

The gravity field across Macquarie Island is described by Williamson & Rubenach (1972) from the results of a geophysical study on the island in the summer of 1970-71. Measurements were made at 59 localities using a Worden Gravimeter. A simple Bouguer gravity map (Fig. 8) shows a gradient of +5 mGal/km in a westerly direction. No significant local Bouguer anomaly features were observed on the island. Free-air gravity anomalies are consistent with those measured over the Macquarie ridge.

The gravity measurements over the Macquarie ridge complex were principally obtained aboard the Eltanin during cruises 34, 36, 37, 42 and 44,

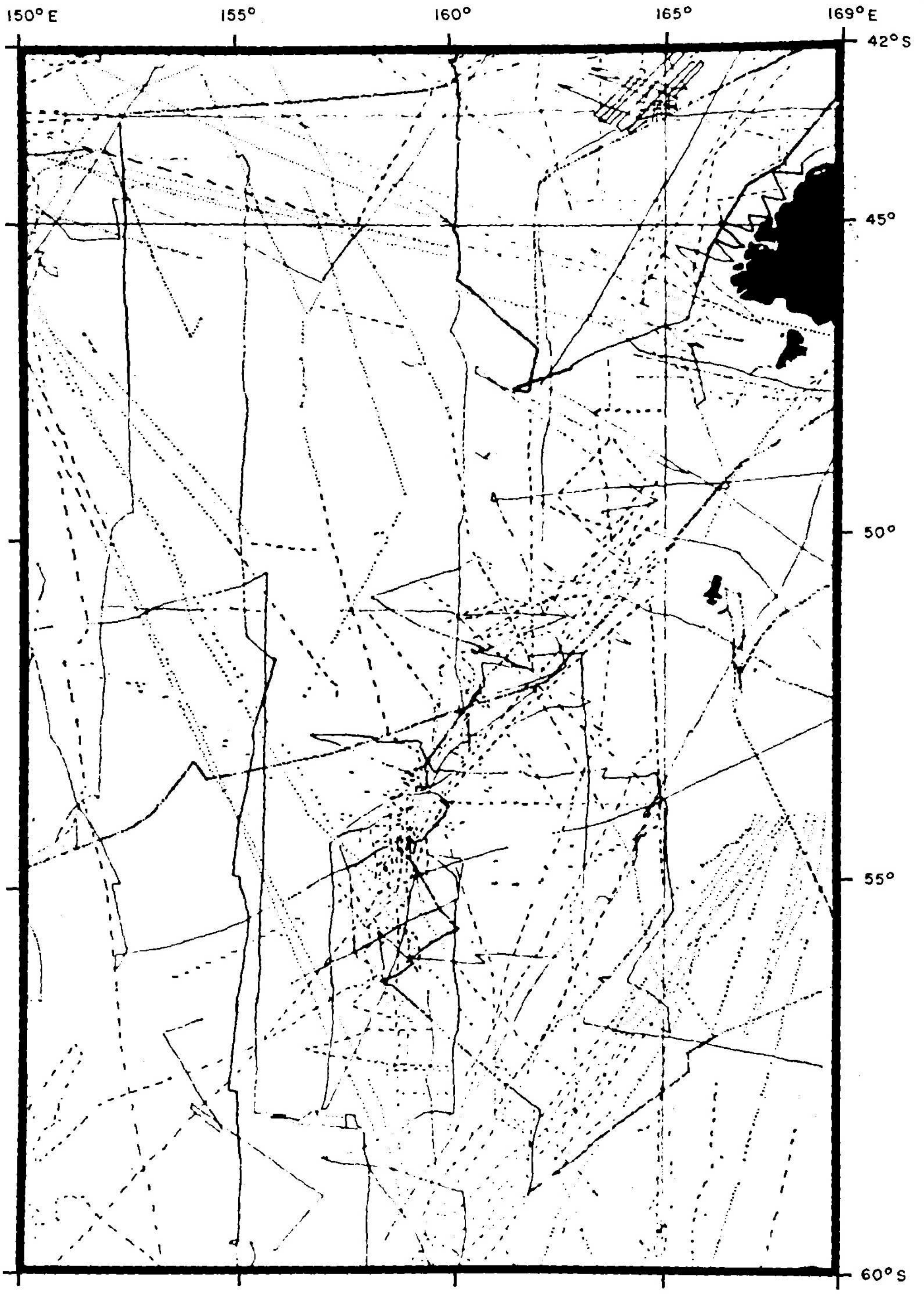
FIG. 2



SIMPLIFIED MORPHOLOGY OF THE MACQUARIE RIDGE

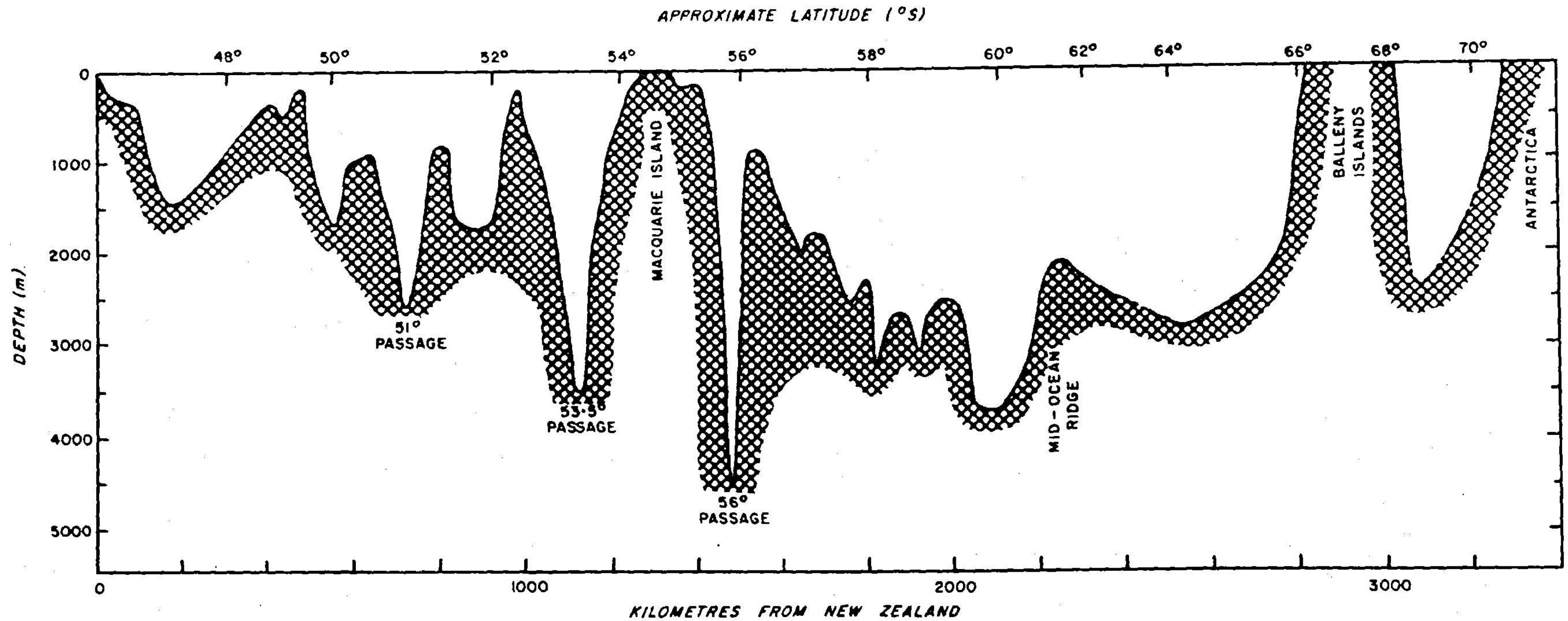
(After Hayes & Talwani, 1972)

FIG. 3



SHIPS TRACKS ALONG WHICH SOUNDING DATA WERE USED FOR PLATE I

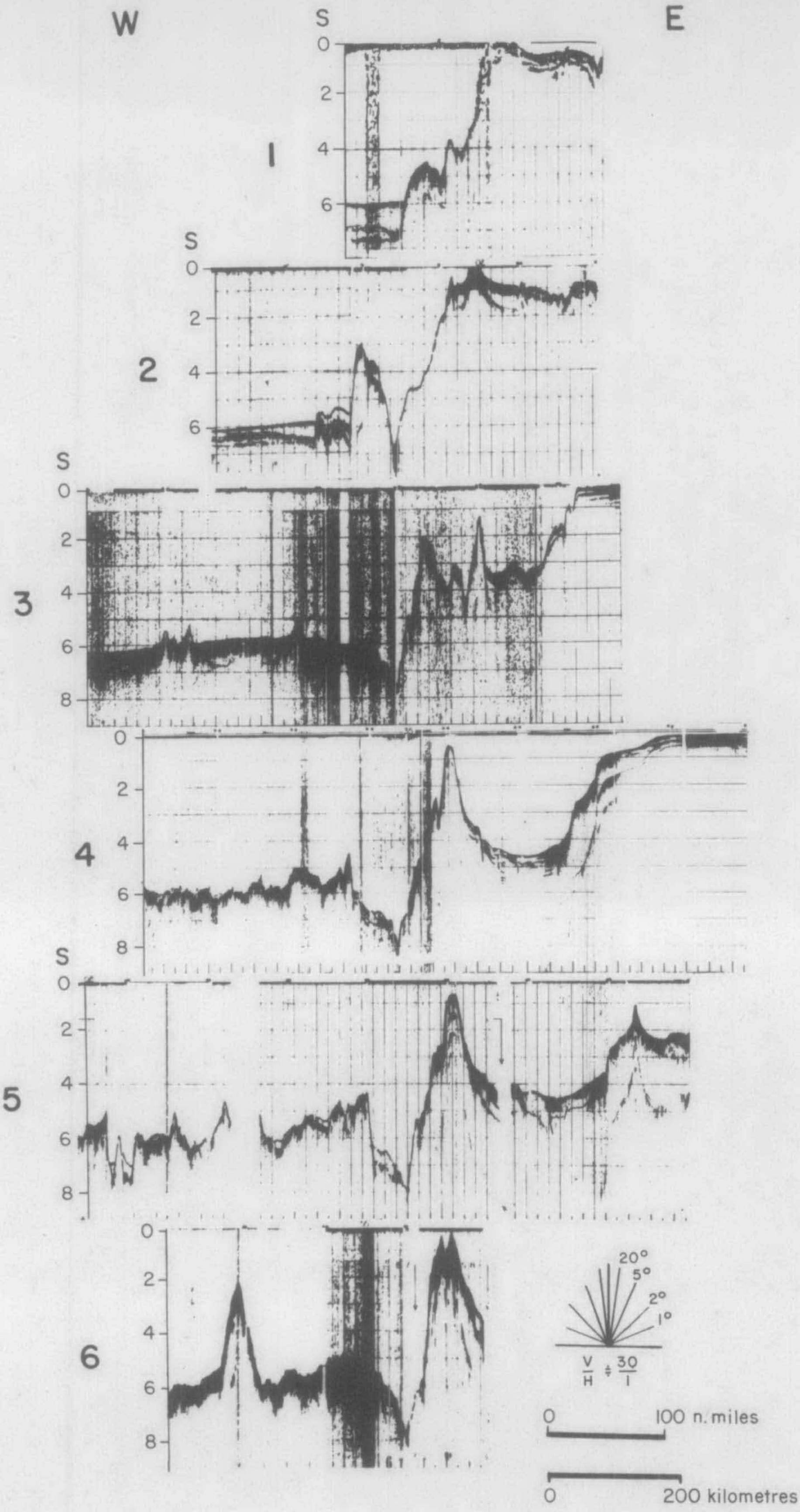
(After Hayes & Talwani, 1972)



SHALLOWEST PATH FROM NEW ZEALAND TO ANTARCTICA ALONG THE MACQUARIE RIDGE AND BALLENY ISLAND PLATFORM (After Gordon, 1972)

FIG. 4

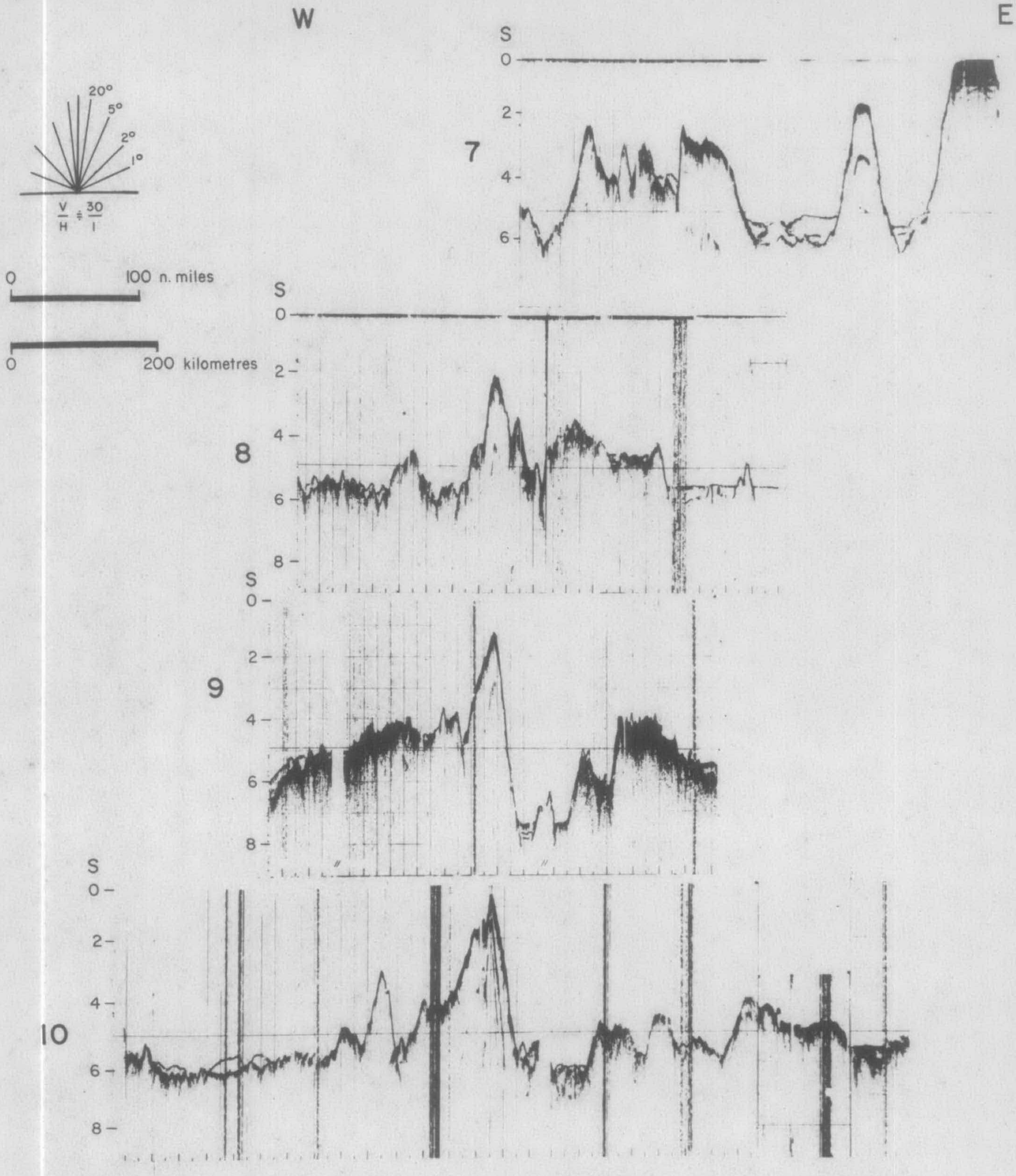
FIG. 5a



SEISMIC PROFILES. LOCATION SHOWN IN FIG. 6

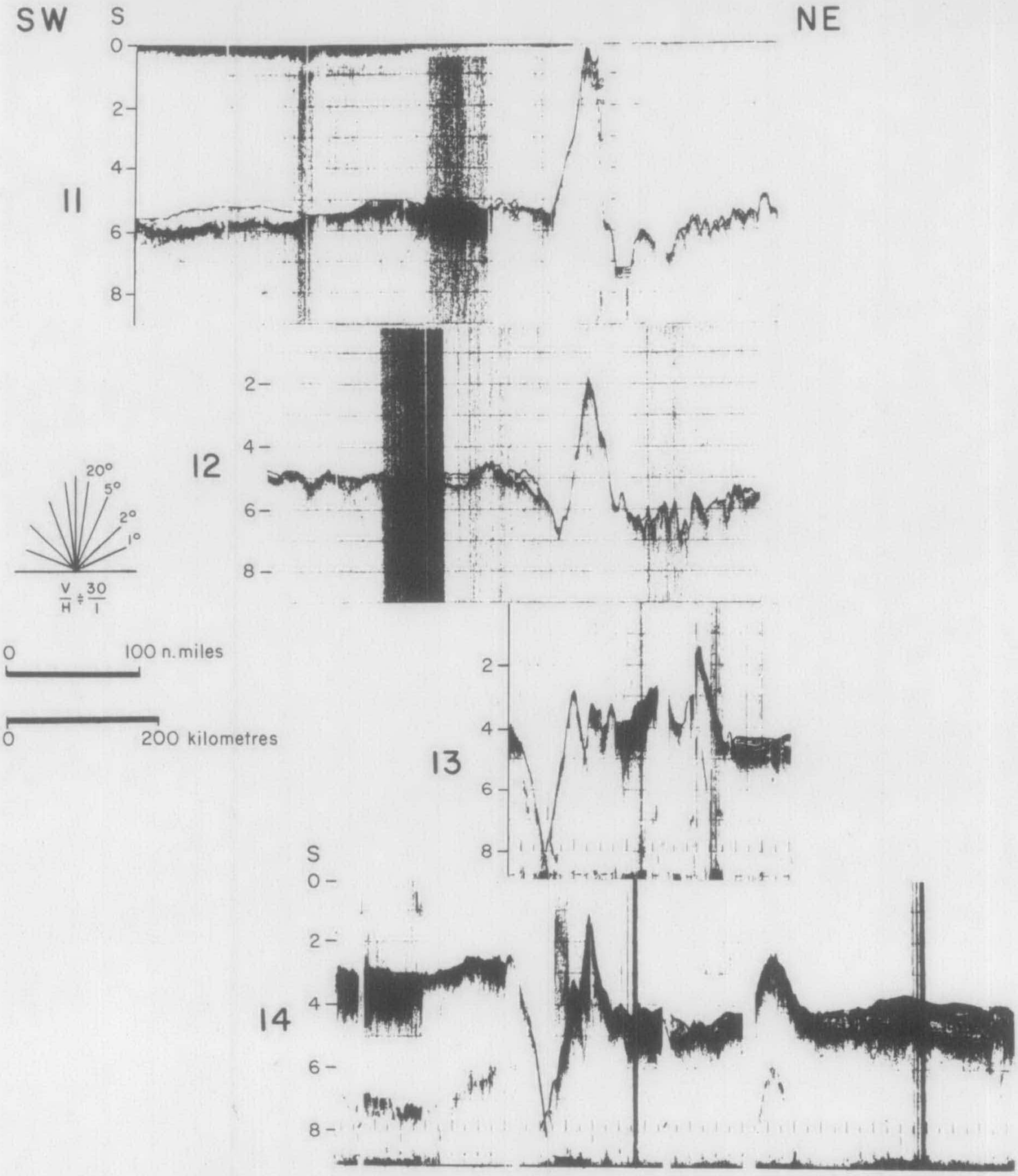
(After Hayes & Talwani, 1972)

FIG. 5b



SEISMIC PROFILES. LOCATION SHOWN IN FIG. 6

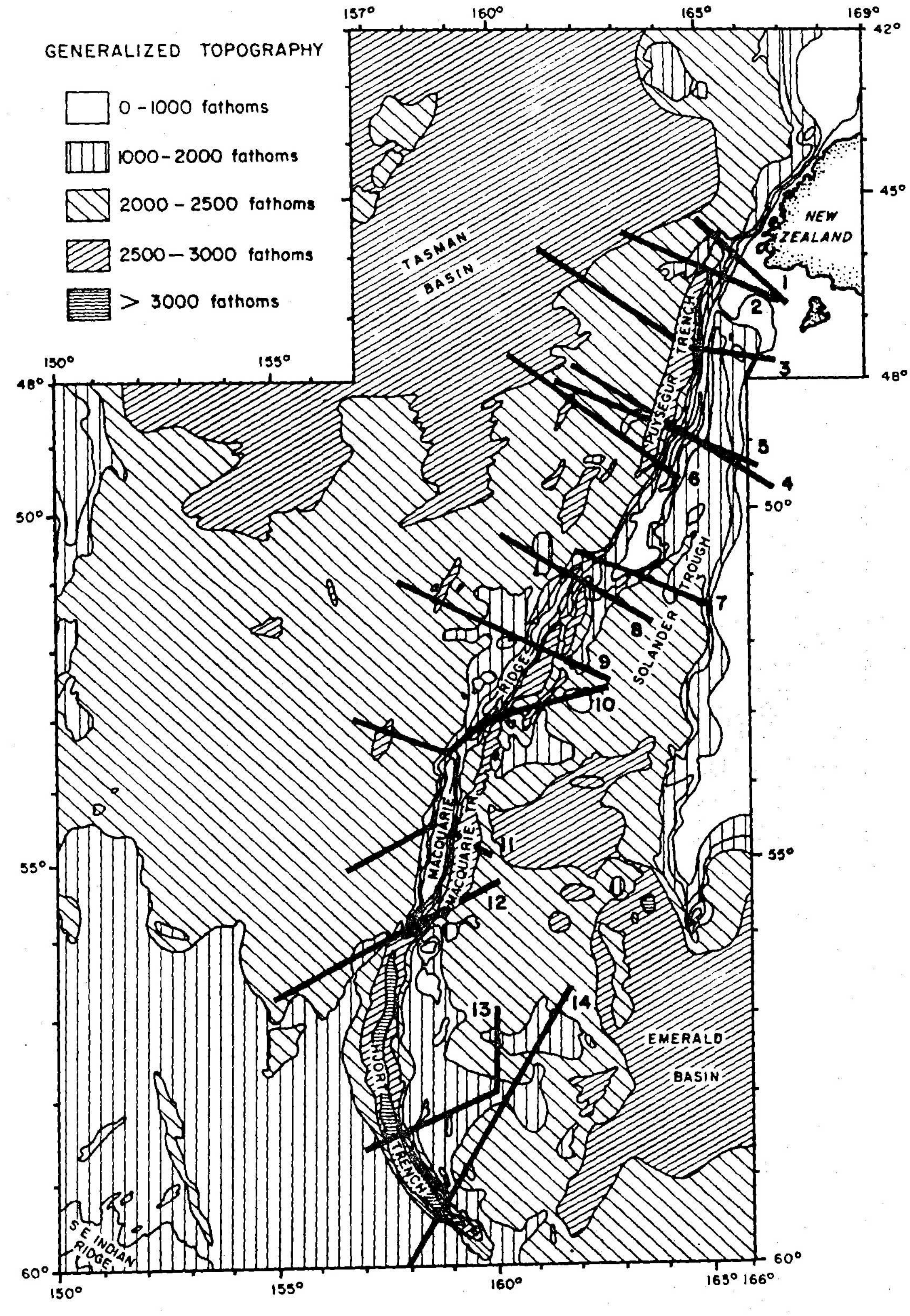
(After Hayes & Talwani, 1972)



SEISMIC PROFILES. LOCATION SHOWN IN FIG. 6

(After Hayes & Talwani, 1972)

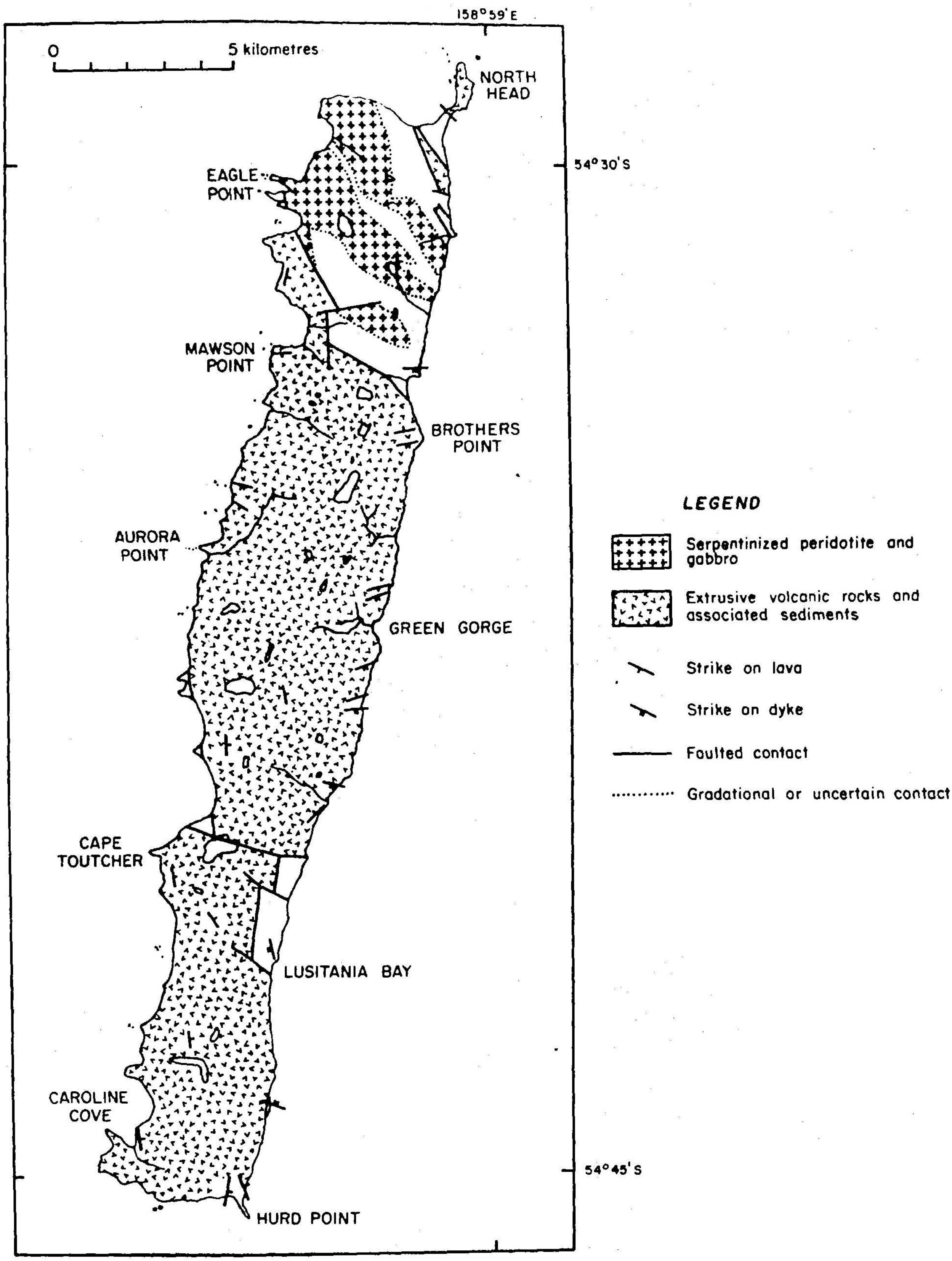
FIG. 6



LOCATIONS OF SEISMIC PROFILE SECTIONS SHOWN IN FIG. 5

(After Hayes & Talwani, 1972)

FIG. 7



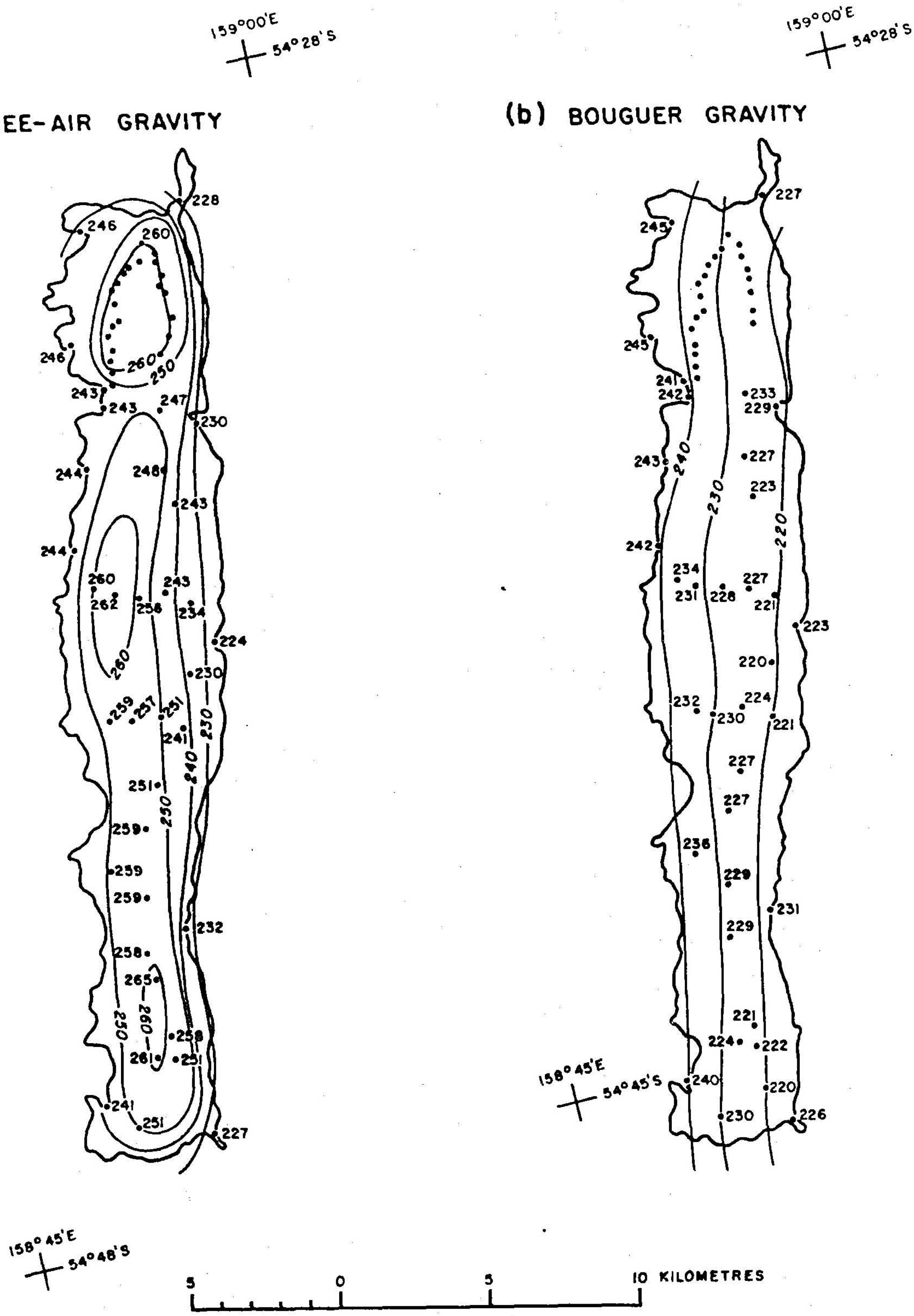
GEOLOGY OF MACQUARIE ISLAND

(After Varne & Rubenach, 1972)

ANT/B8-10A

Record No. 1976/36

FIG. 8



MACQUARIE ISLAND

(After Williamson & Rubenach, 1972)

and aboard the Robert D. Conrad during cruise 8 (Hayes & Talwani, 1972). The measurements were made using a Graf Askania Gss 2-25 sea gravimeter mounted on an Anschutz gyrotable. A free-air gravity anomaly map was produced from these measurements. In general the free-air anomalies reflect the topography. A free-air gravity high extends the entire length of the ridge complex, and local maxima of up to +150 mGal coincide with the three highest parts of the ridge crest.

Isostatic anomaly values over the ridge complex are large and contour trends are parallel to the ridge (Fig. 9). Values range from -100 mGal over the trenches to +100 mGal over the ridges. The anomalies are large at the northern and southern end of the complex compared with the central part. By analysis of the Bouguer anomalies, Woodward (1973) has shown that north of Macquarie Island the ridge and associated trenches are not on the whole reflected in the shape of the crust/mantle boundary; the ridge sits on a reasonably uniform crust of 10-15 km thickness. South of Macquarie Island the crust under the ridge is thought to be considerably thicker but insufficient data do not allow for model studies at present (Woodward, 1973).

MAGNETIC FIELD

The magnetic anomalies associated with the Macquarie Ridge complex are not yet well understood. Hatherton (1967) showed that the ridge is characterized by a large positive magnetic peak of amplitude 500 nT on which several shorter-wavelength peaks are superimposed. On Macquarie Island, magnetic contour trends are northwesterly to north-northwesterly, parallel with the regional strike of geologic features. The anomalies have average wavelengths of about 100 m and amplitudes of up to 1500 nT. Superimposed on them are anomalies of very short wavelengths with amplitudes of up to 500 nT, which are related to the degree of metamorphism of the basaltic and other volcanic rocks (Williamson & Rubenach, 1972).

To the west of the Macquarie Ridge magnetic anomalies are associated with roughly north-south sea-floor spreading from the Southeast Indian Ridge (Weissel & Hayes, 1972). Southeast of the Macquarie complex, magnetic lineations from about anomaly 25 to anomaly 32 and beyond have been described by Christoffel & Falconer (1973). These are adjacent to the southern slope of the Campbell Plateau. No lineations have yet been observed in the Emerald

Basin and the Solander Trough. A short sequence of magnetic lineations, close to and parallel with the central part of the Macquarie Ridge, was tentatively correlated from magnetic profiles by Hayes & Talwani (1972). However, the correlations are questionable and the nature of sea-floor spreading from the ridge, if any, is not known. The trenches flanking the ridge suggest the presence of subduction zones. However unlike most deep-sea trenches associated with subduction zones there is no decrease in the amplitude of the magnetic anomalies over the trenches in the Macquarie Ridge complex.

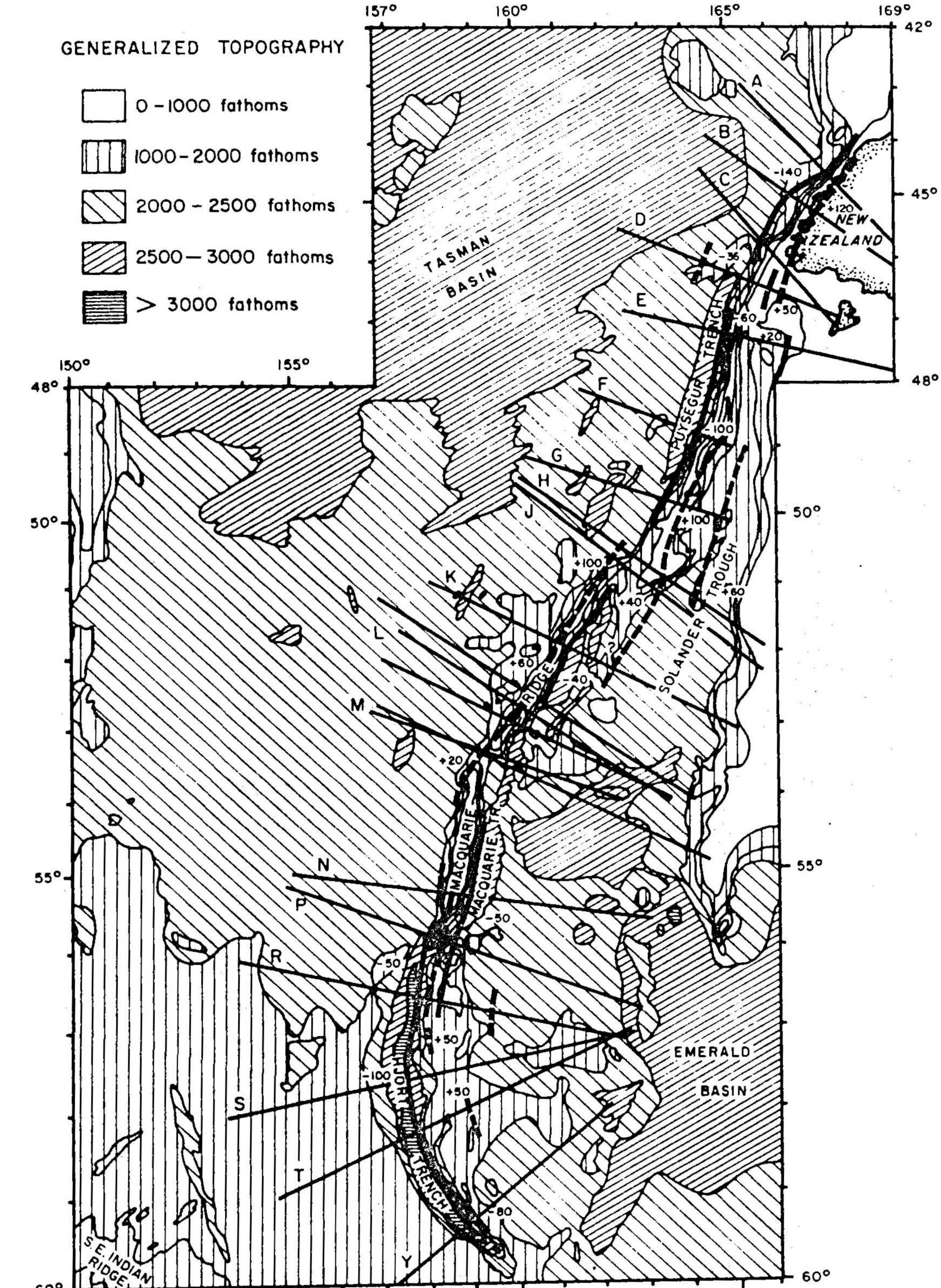
SEISMIC PROFILES AND SEDIMENT DISTRIBUTION

The sediment distribution in the region surrounding and including the Macquarie Ridge complex is variable (Houtz et al., 1971; Houtz & Markl, 1972). Selected profiles across the Macquarie ridge are shown in Figures 5a, b, and c. Most of the Macquarie Ridge complex is devoid of sediments, the only appreciable thicknesses being in the adjacent trench where the sediments are flat-lying and undisturbed. A sediment isopach map of the Macquarie Ridge area is shown in Figure 10. Between 2.5 and 3 km of turbidite sequences occur northwest of Auckland Island in the Solander Trough which has the appearance of a graben-like structure.

During leg 29 of the Deep Sea Drilling Project a hole (279, Fig. 10) was drilled on the northern Macquarie Ridge. The hole was in a water depth of 3381 m and penetrated through 13 m of Pleistocene foraminiferal ooze, an erosional surface, and 185 m of middle Miocene foram - nannofossil ooze. These sediments were deposited on a basement of vesicular basalt. The oldest sediments overlying this basement are of middle early Miocene age (20 million year) (Kennet et al., 1974).

The main reason for the lack of sediment on the Macquarie Ridge appears to be the presence of strong bottom currents caused by the Antarctic circumpolar flow of water. As a result of this current activity and the presence of submarine volcanism, ferro-manganese concretions have formed around Antarctica in a belt as much as 500 km wide and in fields to the north and south of this belt (Goodell et al., 1971, 1973; Watkins & Kennet, 1971; Summerhayes, 1969). Margolis (1974) has described the manganese deposits encountered during leg 29 of the Deep Sea Drilling Project. The deposits contain smaller copper and nickel concentrations than the deposits of the

FIG. 9



Axis of maxima of local Airy isostatic anomalies

Axis of minima of local Airy isostatic anomalies

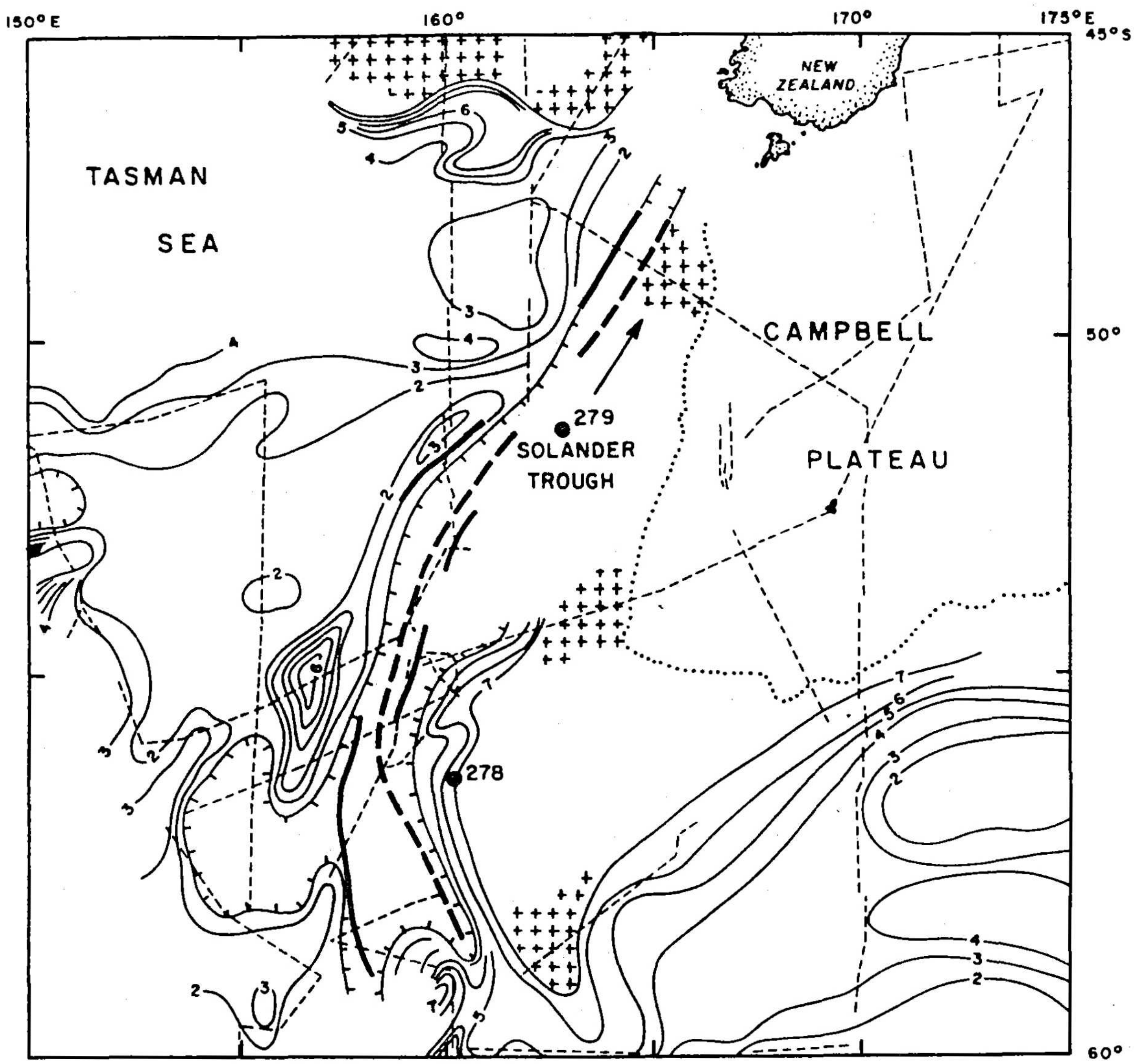
+100 Representative value at the axis (milligals)

D Examined profiles and key profiles

AXES OF MAXIMA AND MINIMA OF LOCAL AIRY ISOSTATIC ANOMALIES AND LOCATIONS OF PROFILES EXAMINED AND KEY PROFILES

(After Hayes & Talwani, 1972)

FIG. 10



LEGEND

Trench	Profiler track
Ridge crest	Sediment in excess of 1·0 sec.

Contour interval is 0·1 sec. of reflection time

SEDIMENT ISOPACH MAP OF THE MACQUARIE RIDGE AREA SHOWING LOCATIONS OF DSDP SITES 279 AND 278

(After Houtz & Markl, 1972)

Pacific Ocean and are therefore less important economically. Table 2 shows a comparison of elemental weight percentages in the ferro-manganese deposits of the Southern and Pacific Ocean.

Seismology, plate tectonics, and evolution

The Macquarie Ridge is an area of shallow earthquake activity. Most foci are no greater than 70 km deep. Six fault mechanisms have been determined near the ridge from first motions on seismographs (Banghar & Sykes, 1969; Sykes, 1970, 1967; Johnson & Molnar, 1972). The events studied are indicated in Figure 11 and they show that in the area of Puysegur Trench the Tasman Sea floor is being thrust eastwards beneath the Pacific floor. In the central part of the ridge, near Macquarie Island, there is strike-slip motion on a fault plane approximately parallel to the Macquarie Ridge. Around the Hjort Trench (57°S) faulting is compressional with a large component of strike slip according to Banghar & Sykes 1969, but extensional (normal) according to Johnson & Molnar (1972). However, the fault mechanism solutions for the Hjort Trench (123 on Fig. 11) on which these deductions were based relies on inadequate data. Hayes et al. (1972) predicted transform faulting parallel to the Hjort Trench from an analysis of the plate motions in this regions.

Since an early analysis of plate motions by Le Pichon (1968), in which the Macquarie Ridge was interpreted to form a compressive plate boundary with a large amount of transform movement, many models have been put forward to explain the observations. The ridge has been successively interpreted as a horst (Mawson, 1943), a branch of the mid-ocean ridge system (Ewing & Heezen, 1965), an island arc system (Summerhayes, 1969), and a transform fault.

The analysis of geophysical data collected up until now indicates that all three process namely, subduction, accretion, and transform movement are or have been active along the ridge since the start of its evolution (Hayes & Talwani, 1972; Hayes et al., 1972; Christoffel, 1971). This diversity is due at least partly to the close proximity of the ridge to the pole of relative motion between the Indian and Pacific Plates.

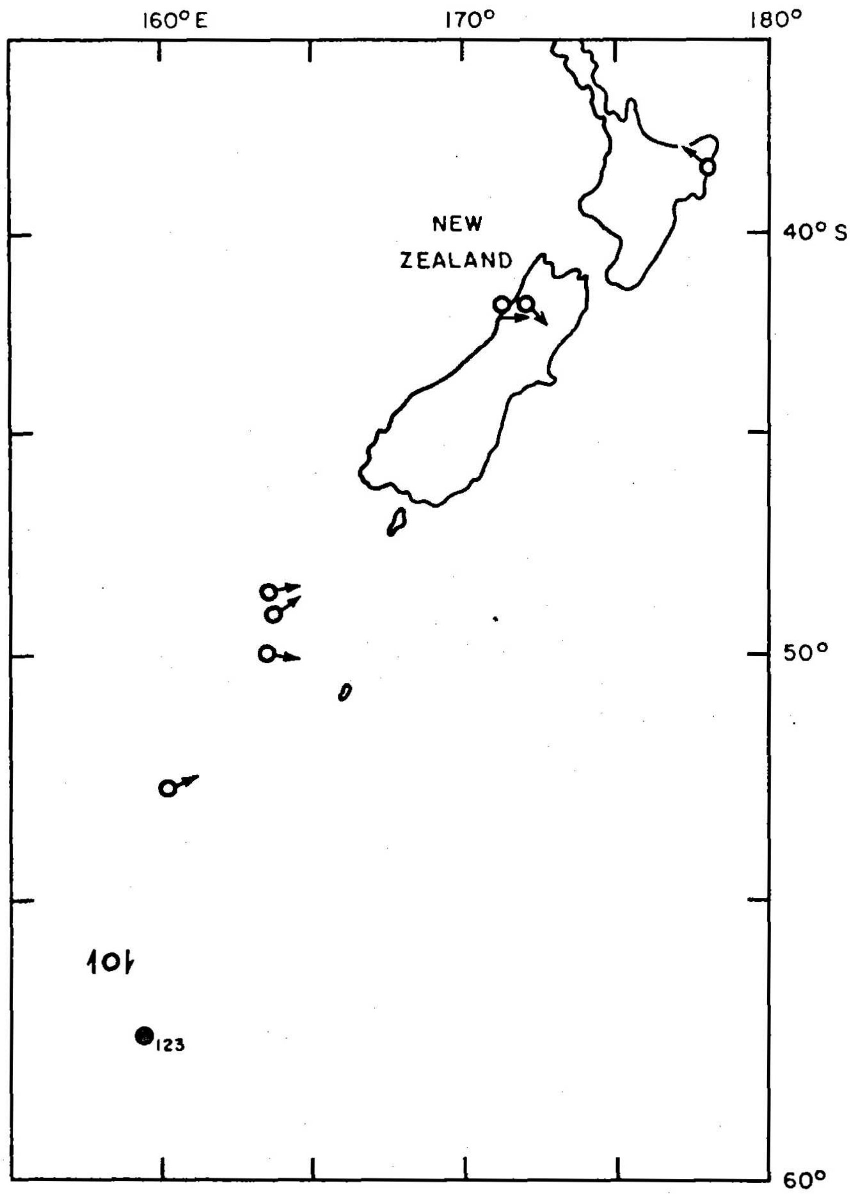
This evolution of the Macquarie Ridge is to a large extent the result of the various plate motions in the area. Reconstructions using marine magnetic anomalies of the plate boundaries for 10 m.y. ago and the present (Figs. 12 and 13a) confirm that the area of the Macquarie Ridge has been subject to a large component of thrust faulting in the north, principally right-lateral strike slip, and possibly some opening in the south (Molnar et al., 1975). Between 10 and 15 m.y. ago, the calculated plate motions indicate that spreading was active in the region (Figs. 13b and 14). It seems likely that the oceanic rocks of the ridge and Macquarie Island were formed during spreading in this period. With the onset of compression in the region after 10 m.y., the ocean floor was uplifted, probably in the Pliocene.

PROSPECTIVITY

The mineral economic potential of Macquarie Island is virtually nil No mineralization has been recorded on the island and it is unlikely that any will be found as mineralization is rarely associated with oceanic basalts and volcanics. The nature and sparsity of sediments on the Macquarie Ridge also excludes the possibility of any hydrocarbons being present in this area. Although a basin east of the southern Macquarie ridge contains about 1 km of sediment, the fairly recent origin of the sediments and their presumably pelagic nature does not favour the accumulation of hydrocarbons.

The only possible deposits of economic interest in the area are the ferro-manganese nodules. These, however, are generally poorer in metals such as copper and nickel than the nodules of the Pacific and are therefore of only marginal prospectivity.

FIG. 11



LEGEND

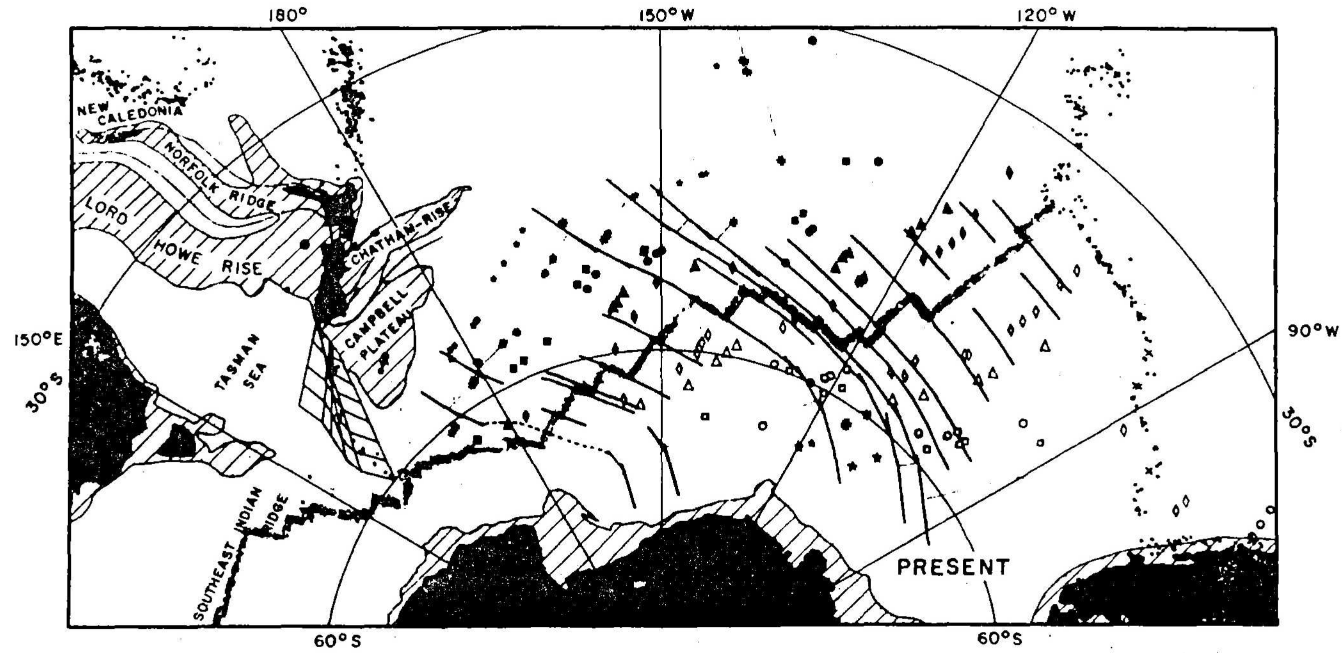
Thrust mechanism. Arrow shows direction of the slip vector

Strike-slip

123 Normal fault

LOCATIONS OF FOCAL MECHANISMS IN NEW ZEALAND AND THE MACQUARIE RIDGE (After Johnson & Molnar, 1972)

FIG. 12

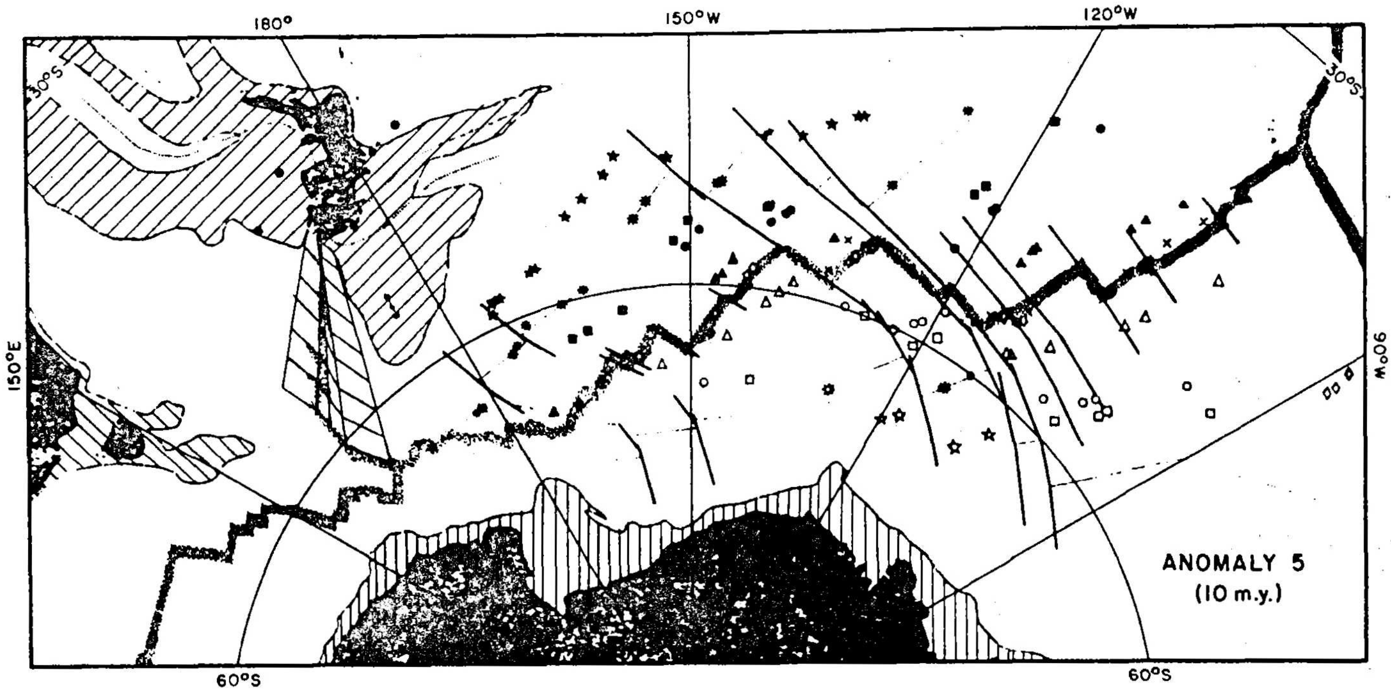


MAGNETIC ANOMALIES

×		Central anomaly	•	Earthquake epicentre
◊	♦	5	—	Fracture zone
△	▲	6		Amount of seafloor formed since 38 m.y. by Pacific – Indian spreading
○	●	13		
□	■	18	●—►—●	Amount of rigid rotation
✡	✱	25		
☆	★	31	▬	Active plate boundary

PRESENT CONFIGURATION OF CONTINENTAL FRAGMENTS, PLATE BOUNDARIES, FRACTURE ZONES AND MAGNETIC ANOMALIES IN THE SOUTH PACIFIC (After Molnar et al., 1975)

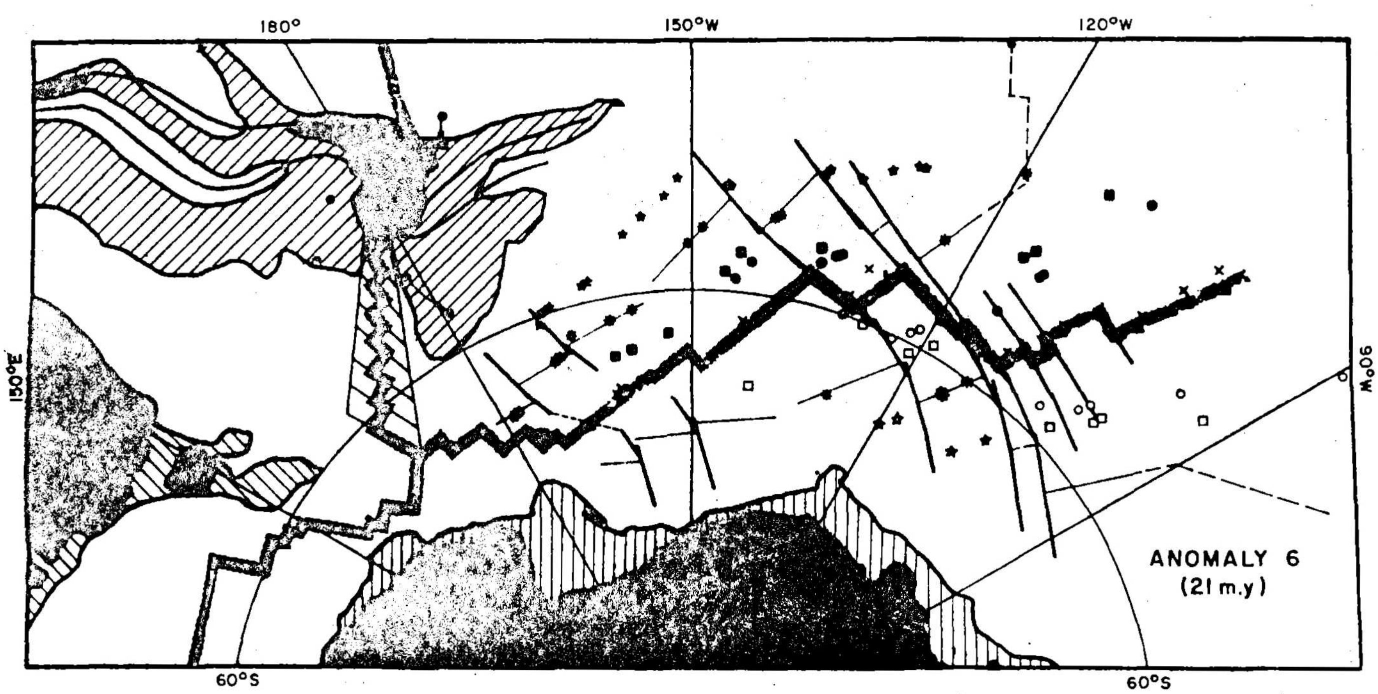
FIG. 13



13(a) CONFIGURATION OF SOUTH PACIFIC ABOUT 10 M.Y. AGO

SYMBOLS SAME AS FIG. 12

(After Molnar et al., 1975)

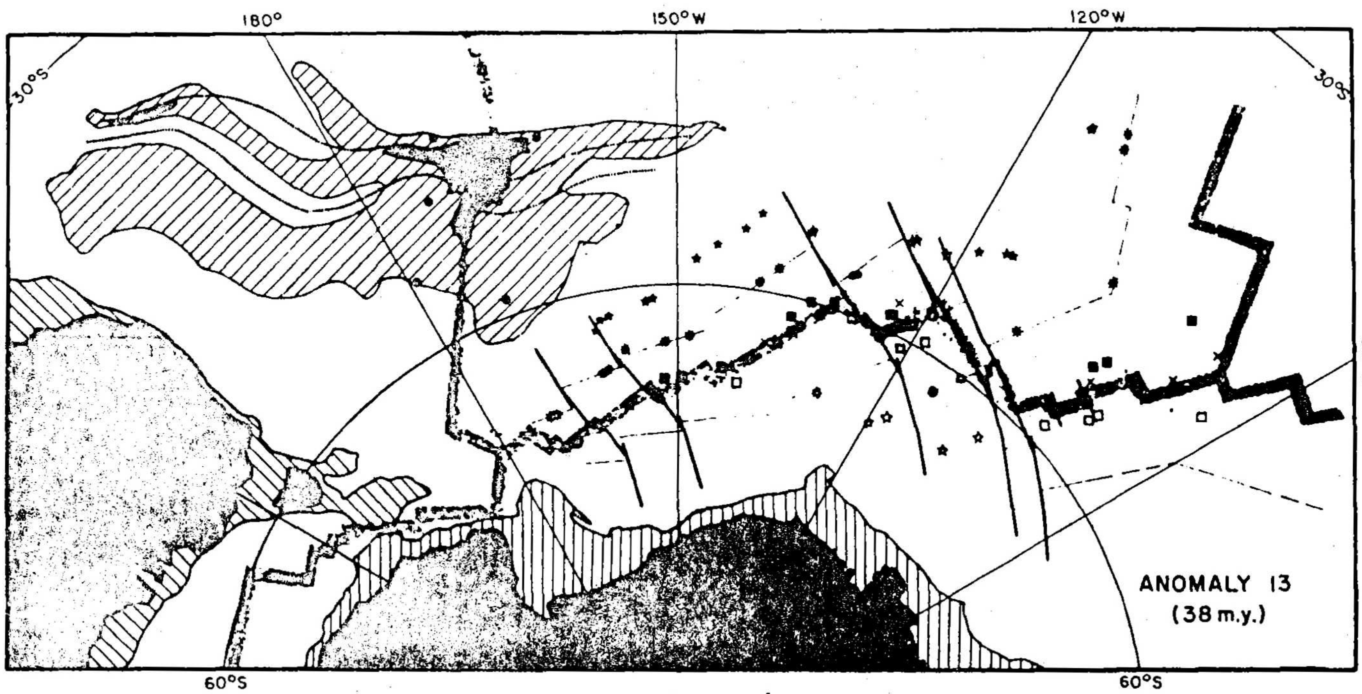


13(b) CONFIGURATION OF SOUTH PACIFIC ABOUT 21 M.Y. AGO

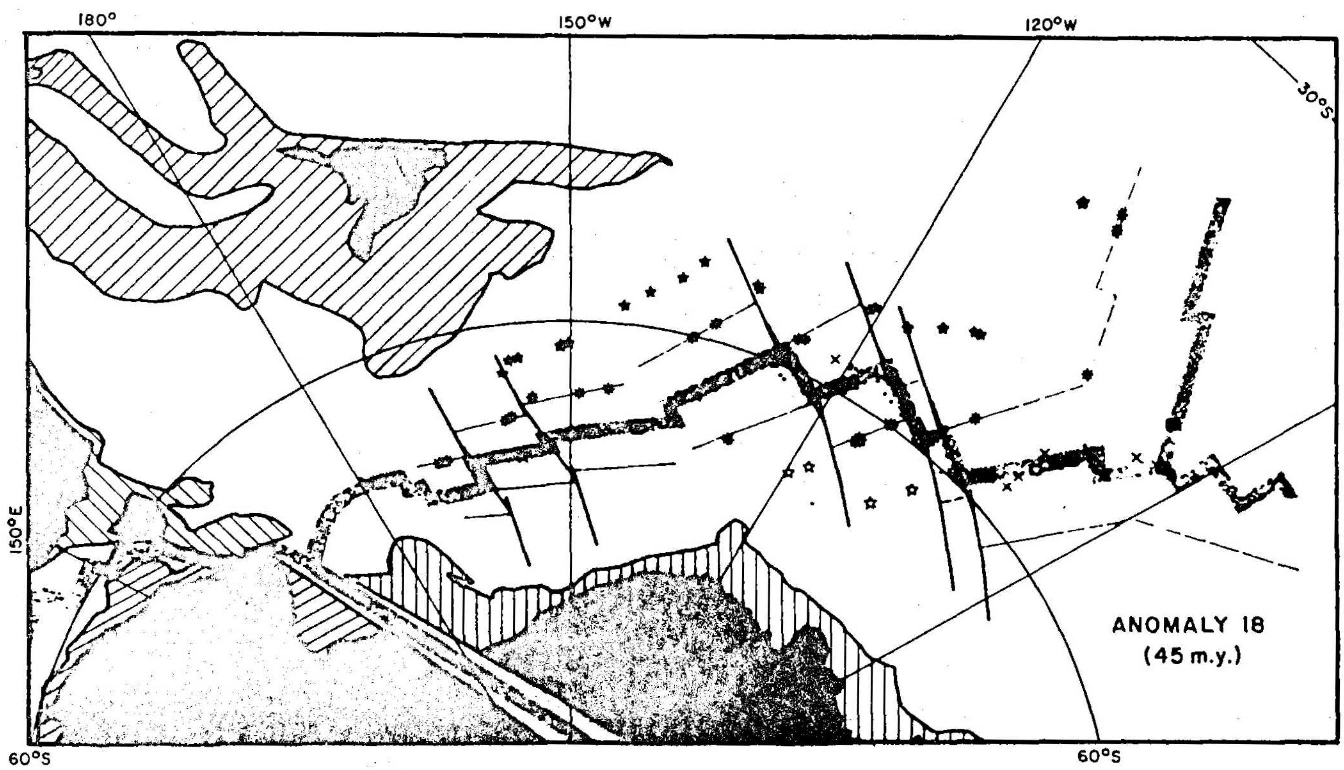
SYMBOLS SAME AS FIG. 12

(After Molnar et al., 1975)

FIG. 14



14(a) CONFIGURATION OF SOUTH PACIFIC ABOUT 38 M.Y. AGO.
SYMBOLS SAME AS FIG. 12
(After Molnar et al., 1975)



CONFIGURATION OF SOUTH PACIFIC ABOUT 45 M.Y. AGO.
PLATE BOUNDARY IN NEW ZEALAND IS NOT YET ACTIVE.
SYMBOLS SAME AS FIG. 12 (After Molnar et al., 1975)

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Table 1. MAPS COVERING THE MACQUARIE RIDGE AREA.

Bathymetry of the South Pacific - 1974 - J. Mammerickx, S.M. Smith,
I.L. Taylor and T.E. Chase

Scripps. Chart No. 17

Scale 1:3 630 000 at 30°

Bathymetry of the South Pacific - 1974 - D.E. Hayes, J.R. Conolly, and
J. Mammerickx

Scripps. Chart No. 16

Scale 1:3 630 000 at 30°

Bathymetry of the Southeast Indian Ocean - 1974 - D.E. Hayes and J.R. Conolly
Scale 1:4 000 000 at 46°

Macquarie Ridge complex - 1972 - D.E. Hayes and M. Talwani
Scale 1:2 000 000 at 57°Lat.

Macquarie Bathymetry - 1967 - Summerhayes C.P. 1:1 000 000

Macquarie Island Provisional Bathymetry - 1970 - Cullen, D.J. 1:200 000

Antarctic Map Folio Series Folio 16 1972 B.C. Heezen, and Tharp, 1972
Morphology of the earth in the Antarctic and Subantarctic

Plates		Polar Stereographic projection
1	Submarine and Subglacial Topography	1:15 000 000
2	Soundings and Earthquakes	1:15 000 000
3	Physiography and Tectonic Provinces	1:15 000 000

Antarctic Map Folio Series Folio 17 - 1973 - H.G. Goodell et al.,

9 Plates		Polar Stereographic Projection
1	Sediment collection localities	1:30 000 000
2	Surface Sediment Types	1:30 000 000
3	Ferro-manganese Deposits	1:30 000 000
4	Photographs of the sea floor	
5	Sediment Isopachs	
6,7,8,9.	Foraminifera and Diatom distribution	

Geophysical maps

Macquarie Ridge Complex — Hayes and Talwani 1972

Free-Air Anomalies — approx 1:5 000 000 at 46°

Magnetic Anomalies in the southeast Indian Ocean - Weissel and Hayes 1972

Bouguer Anomalies - Fig. 2. Woodward, D.J. 1973

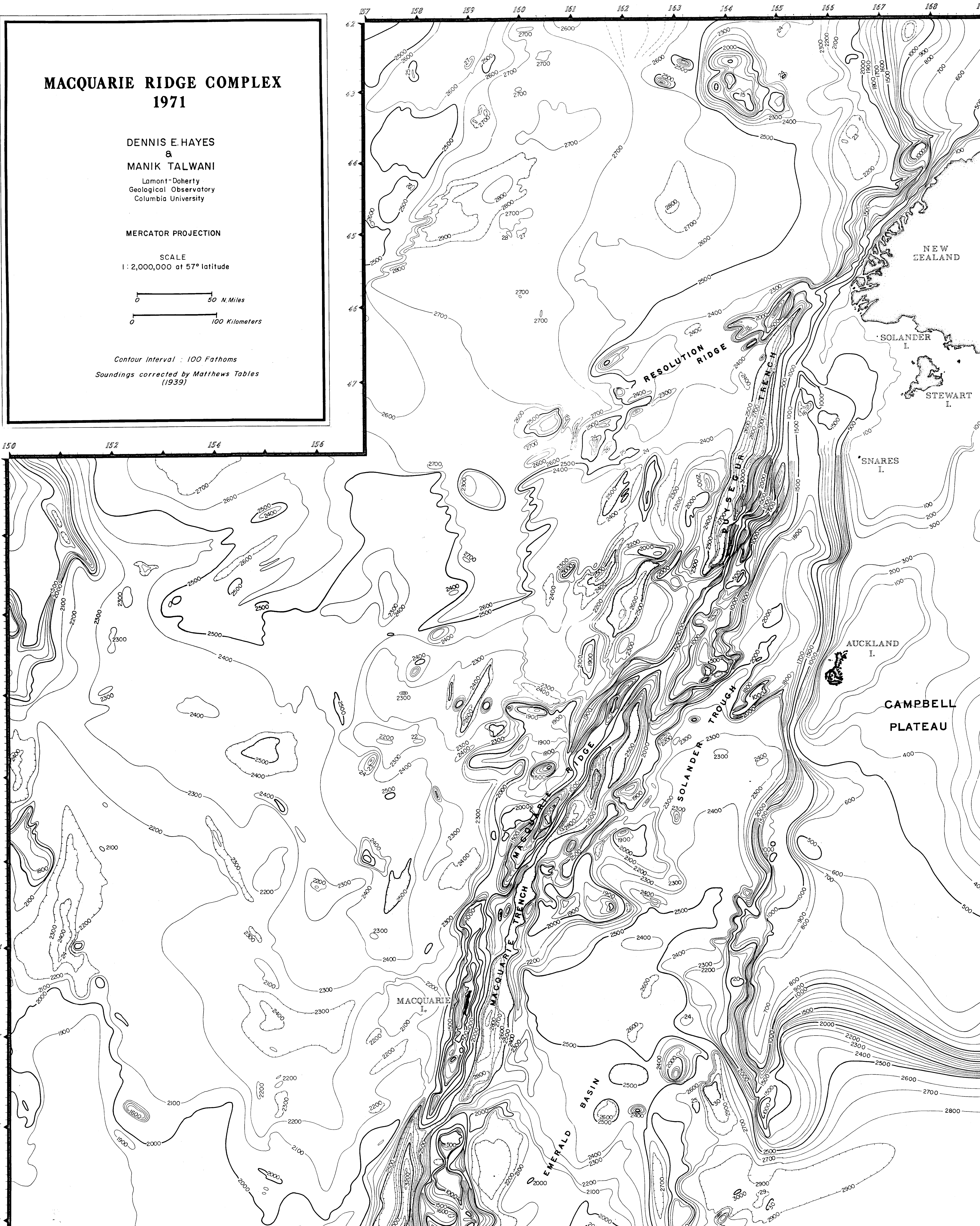
Sediment isopach map of the area between Australia and Antarctica - Houtz and Markl 1972.

Table 2.

Element	Southern Ocean		Pacific Ocean		
	Mean %	Standard Deviation	Maximum	Minimum	Mean
Iron	15.78	± 4.90	26.6	2.4	14.0
Manganese	11.69	± 7.73	50.1	8.2	24.2
Titanium	.64	± .27	1.7	0.11	0.67
Nickel	.45	± .38	2.0	0.16	0.99
Cobalt	.24	± .17	2.3	0.014	0.35
Copper	.21	± .15	1.6	0.028	0.53
Barium	.10	± .08	0.64	0.08	0.18
Strontium	.08	± .03	0.16	0.024	0.081
Zirconium	.07	± .05	0.12	0.009	0.063
Vanadium	.06	± .03	0.11	0.021	0.054
Zinc	.06	± .03	0.08	0.04	0.047
Molybdenum	.04	± .02	0.15	0.01	0.052
Water	14.60	± 5.80	39.0	15.5	25.8

Element weight percentages (water-free) in ferro-manganese concretions. Comparison of deposits in Southern Oceans with those of the Pacific. (After Goodell et al., 1971).

PLATE I



Geophysical Investigation of the Macquarie Ridge Complex by Dennis E. Hayes and Manik Talwani

Fig. 1. Bathymetry of the Macquarie ridge complex contoured in corrected fathoms. Sounding lines used in compiling the map are shown in Figure 2.

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