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LORD HOWE RISE AREA, OFFSHORE AUSTRALIA: PRELIMINARY RESULTS OF A CO-OPERATIVE FEDERAL REPUBLIC OF GERMANY/AUSTRALIA GEOPHYSICAL SURVEY

by

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ABSTRACT

During October 1978 the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and the Bureau of Mineral Resources, under the auspices of the Federal Republic of Germany/Australia Science & Technology Agreement, conducted a co-operative survey of the central Lord Howe Rise area aboard the R/V Sonne. The main objectives were to examine the structure, geological evolution, and petroleum potential of the Lord Howe Rise. About 4000 line kilometres of multichannel seismic, gravity, and magnetic profiles were recorded. The survey lines were also extended across the Norfolk/West Norfolk Ridge, New Caledonia Basin, Middleton Basin, Lord Howe Basin, and Dampier Ridge.

The results of a preliminary seismic stratigraphic analysis based on the high-quality on-line monitor records, ties to DSDP Sites 207 and 208, and shallow refraction studies are discussed in this Report.

The Sonne survey has confirmed that numerous horsts and grabens underlie the western part of the Lord Howe Rise, but that there is no single sediment-filled depression resulting from rifting or pull-apart tectonics like that on the southern 'Atlantic-type' margin of Australia (Bremer, Great Australian Bight, and Otway Basins). The grabens probably trend north-northwest; they are each 30-40 km wide and of considerable but unknown length; and they are filled with 2000 m or more of pre-break-up (rift-fill) sediments. The horst and graben province extends westwards across the Middleton and Lord Howe Basins, where the basement appears to be more crystalline, and onto the Dampier Ridge, which is considered to be at least partly of continental origin. Within the sedimentary sequence on the northern Lord Howe Rise, pinnacle reefs appear to be built on and just above a ?Late Cretaceous 'break-up unconformity'. The New Caledonia Basin appears to be older than the Tasman Basin, and the eastern flank of Lord Howe Rise was probably the margin of the Australia-Antarctica supercontinent before Late Cretaceous time.

The overburden of post-break-up sediments on the Lord Howe Rise is probably too thin to have led to the maturation of any hydrocarbon source material within the marine transgressive rocks deposited just after break-up. However, sediments within the grabens, possibly mainly Cretaceous fluvial-deltaic deposits, may have some petroleum potential in the long term.

1. INTRODUCTION

Within the framework of a co-operative agreement in marine geoscience between the Federal Republic of Germany and Australia, the German research vessel R/V Sonne carried out geophysical investigations in the Lord Howe Rise area of the Tasman Sea between 20 October and 14 November 1978. Survey lines were run across the rise between latitudes 26° and 37°S (Fig. 1). The cruise, leg SO-7A, commenced in Suva on 19 October and ended in Brisbane on 15 November, and was the first part of an extensive survey near the Australian continental margin, which also included a geophysical survey of the Coral Sea margins and geological sampling off Western Australia. Scientists from the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, the Federal German Geological Survey), the Bureau of Mineral Resources (BMR), and the New Zealand Department of Scientific and Industrial Research (DSIR) took part in the cruise.

The measurements included 24-channel reflection seismic with digital and analogue recording, sonobuoy refraction seismic, gravity, magnetics, and bathymetry. About 4000 line kilometres of data were collected on the Norfolk and West Norfolk Ridges, New Caledonia Basin, Lord Howe Rise, Middleton Basin, Lord Howe Basin, and Dampier Ridge (Figs. 1 and 2). The ship's positions were determined by a 'Magnavox' integrated navigation system.

This Report, written in April 1979, summarises our knowledge of the Lord Howe Rise area before the survey, outlines the survey objectives, and provides a preliminary interpretation of the data. It points to problems which were apparent before the survey and some which have become apparent as a result of it. Possible solutions are offered for some of these problems, but further work - either more surveying, or more detailed interpretation making use of processed data and incorporating data from other sources - is required before many of them can be solved. This Report is based entirely on on-line data, comprising analogue seismic monitors, half-hourly gravity and magnetic values, and uncorrected ship's positions.

R/V Sonne

The research vessel Sonne is a converted stern trawler owned and managed by RF Reedereigemeinschaft, Forschungsschiffahrt GmbH, Bremen, Federal Republic of Germany. The dimensions of the ship (GRT2607, length 86.5 m, beam 14.2 m), and her cargo and bunker capacities, make her most suitable for the installation of a wide range of equipment for almost every type of oceanographic research, but especially for geological and geophysical studies. The ship is

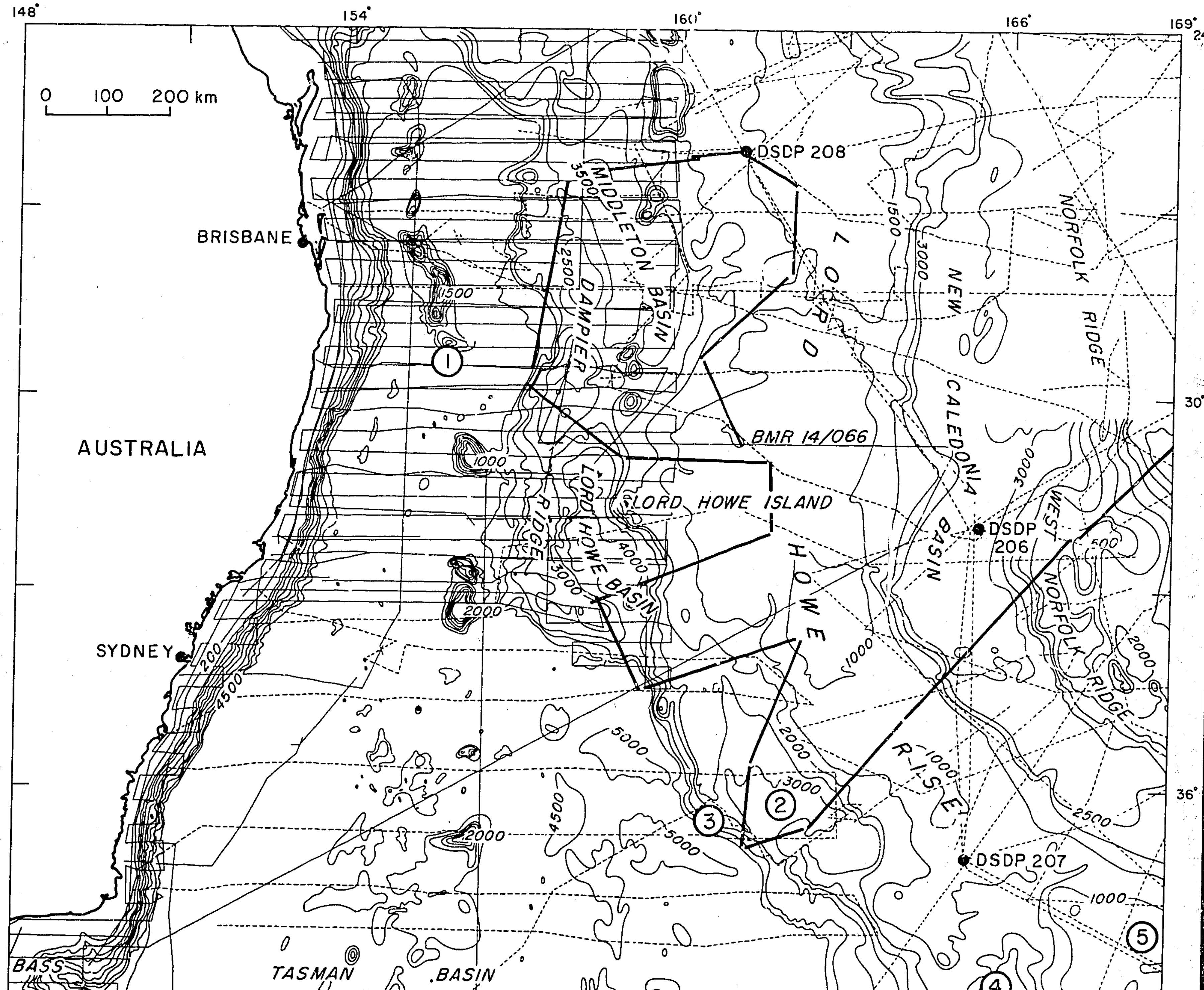

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Fig. 1. Bathymetry of the Tasman Sea region (after Ringis, 1972), and seismic reflection profiling tracks: BMR Continental Margin Survey lines (solid); BMR Line 14/066; *Sonne* SO-7 lines (heavy solid); lines from other surveys (broken). Numbered features are: (1) Tasmantid Seamount Chain, (2) Monowai Spur, (3) Monowai Sea Valley, (4) Bellona Gap, and (5) Challenger Plateau.

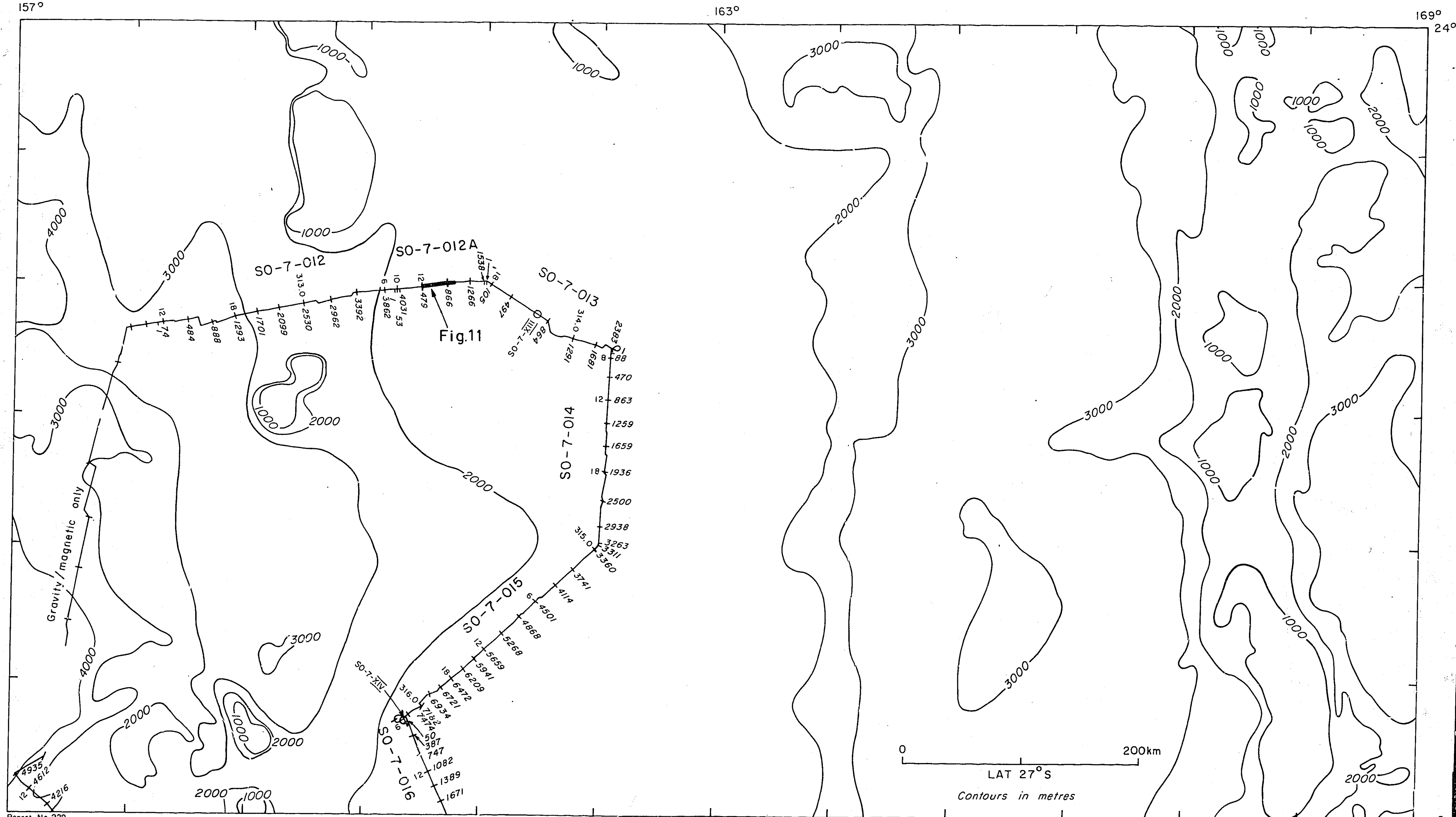

Fig. 2a. Tracks of Sonne cruise SO-7 superimposed on bathymetry from van der Linden (1968b, 1969). Uncorrected track shows position updates after satellite fixes. SO-7-012, etc. are shot-points. SO-7-XIII and XIV are sonobuoy refraction stations. Heavy line shows the location of the seismic profile illustrated in Figure 11.

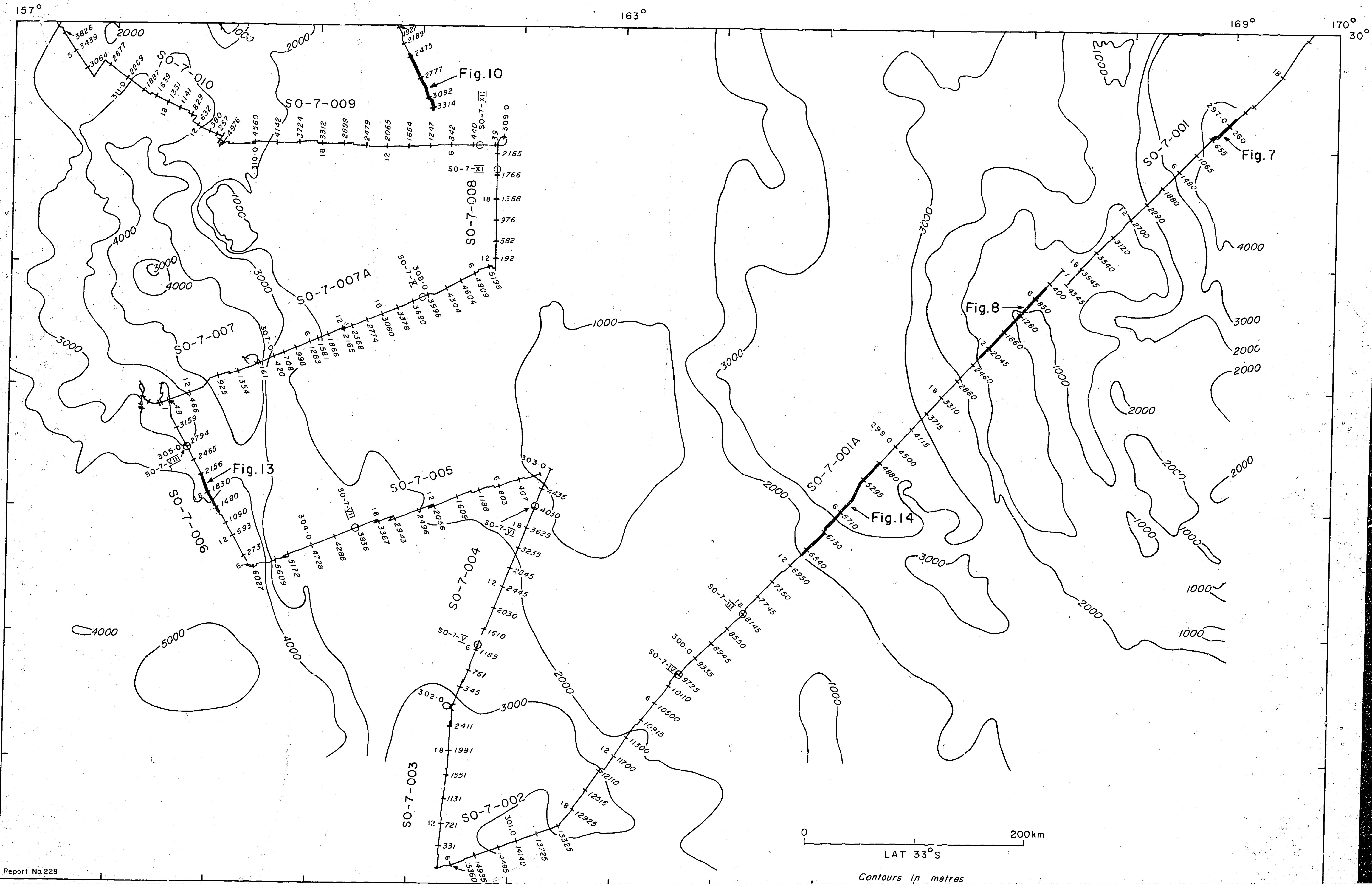

Fig. 2b. Tracks of Sonne cruise SO-7 superimposed on bathymetry from van der Linden (1968b, 1969) Uncorrected track shows position updates after satellite fixes. SO-7-005, etc. are shot-points; SO-7-VII, etc. are sonobuoy refraction stations. Heavy lines show the locations of seismic profiles illustrated in text figures.

equipped with an integrated satellite navigation system, narrow-beam echo-sounders and a deep-sea echo-sounder, and a deep-tow winch designed for dredging and sampling rocks and manganese nodules from the deep ocean floor.

Acknowledgements

The Federal German Ministry of Science and Technology provided the ship and funds for the co-operative studies off Australia. The Australian Department of Science and the Environment provided funds for a BMR geophysicist to participate in the data processing at BGR's facility in Hannover between May and September 1979.

2. PREVIOUS SURVEYS AND RESULTS

Geophysical surveys

Since the full extent and morphology of the Lord Howe Rise were first recognised in the early 1950s, several studies have been made of it, and many traverses have been run across it. Although the track coverage is large in total kilometres, it constitutes only a regional coverage in view of the very great size of the Rise. Added to this, most of the geophysical profiling (especially reflection seismic) carried out before 1970 is of poor quality. Before the Sonne survey, our understanding of the structure of the Rise came from the few seismic profiles which were of sufficiently good quality to reveal the deep sedimentary layers, and from two holes drilled as part of the Deep Sea Drilling Project (DSDP) in 1971 (see section 3).

The other useful geophysical data in the area covered by Sonne cruise SO-7A comes from four sources:

(i) United Geophysical Corporation in 1970 completed a seismic profiling track from Sydney, roughly eastwards to the West Norfolk Ridge, and passing just south of Lord Howe Island.

(ii) BMR in 1971 made two crossings of the central portion of the Lord Howe Rise in the M/V Lady Christine as part of the Continental Margin Survey (Fig. 1). Magnetic, gravity, multichannel seismic reflection profiling, and three sonobuoy refraction measurements were made along these lines.

(iii) Mobil Oil Corporation in 1972 surveyed the southeastern portion of the Lord Howe Rise in the R/V Fred H. Moore. Several lines were also run across the central and northern parts of the rise, and across the Norfolk Ridge. The data collected included high-resolution multichannel seismic, gravity, magnetics, and sonobuoy refraction. Some of the results of this survey have been published by Bentz (1974).

(iv) The Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) in Noumea, the Institut Français du Pétrole, and several other French petroleum companies (SNPA, ELF-ERAP, CFP) in 1972-73 made a magnetic and seismic survey (Austradec 1 & 2) of the northern part of Lord Howe Rise and Norfolk Ridge in the N/O Coriolis.

Details of all surveys in the Lord Howe Rise/Norfolk Ridge region have been compiled by Jongsma (1976) and these are tabulated in the Appendix.

Gravity and magnetic coverage in the region is similar to the seismic coverage. It provides a useful guide to basement structure, although it is probably too sparse for the production of meaningful contour maps.

Physiography

The Lord Howe Rise and the Norfolk/West Norfolk Ridge system are two submarine features which extend northwest from the New Zealand continental margin, then northwards along the eastern side of the Tasman Sea (Fig. 1). These features are separated from one another by the New Caledonia Basin. The Lord Howe Rise lies generally about 600 km off the east coast of Australia. Between latitudes 26° and 34°S it is separated from the Dampier Ridge to the west by the small Middleton and Lord Howe Basins. The Tasman Basin, which borders the narrow continental shelf off southeastern Australia, and the New Caledonia Basin have relatively flat floors at depths of around 4000-4500 m and 3000 m respectively. Both the Lord Howe Rise and the Norfolk Ridge are surmounted by islands and banks, but water depths along the crests of these features generally range from about 750 to 1200 m. The features are clearly outlined by the 2000 m isobath. The physiography of the region is made more complex by two northerly trending seamount chains: the Tasmantid Seamount Chain through the centre of the Tasman Basin, and the Lord Howe Island Chain along the western flank of the Lord Howe Rise.

The Lord Howe Rise extends from the Coral Sea region to New Zealand; it has a length of almost 2000 km and a width of about 300 km. Its northern end connects with a region of complex topography which includes features such as the Chesterfield Plateau, Kenn Plateau, Mellish Rise, and a northwest-trending feature named the Fairway Rise (Dubois & others, 1974). Southeastwards, the Lord Howe Rise connects with the Challenger Plateau (on the New Zealand continental margin). A 3000-m-deep depression called the Bellona Gap cuts into the Rise at about 39°S. Northwest of this (about 162°E, 36°S) lies a 3000-m-deep basin and flanking ridge which Eade & van der Linden (1977) have called the Monowai Sea Valley and Monowai Spur. The main body of the Rise is characterised by gentle relief, but it is bordered on the western flank by a zone of irregular foothills. The western edge generally has steeper slopes (up to 10°) than the eastern edge.

The Norfolk/West Norfolk Ridge system is a steep-sided feature about 75 km wide which extends from New Zealand to New Caledonia, a distance of 1600 km. The southern part of the Ridge, which is offset by the Vening-Meinesz Fracture Zone, is usually referred to as the West Norfolk Ridge. Its relief is much bolder than that of the Lord Howe Rise.

Crustal structure (based partly on Jongsma, 1976)

The crustal structure of the Lord Howe Rise and the Norfolk Ridge has been interpreted from seismic measurements (Officer, 1955; Shor, Kirk, & Menard, 1971) and the gravity field (Dooley, 1963; Woodward & Hunt, 1971). The gravity interpretation indicated that the Lord Howe Rise and Norfolk Ridge have crustal thicknesses of 26 km and 21 km respectively. In contrast, the crustal thickness under the Tasman Basin is of the order of 10 km, and under the New Caledonia Basin between 10 and 17 km. Shor & others (1971) showed that the Lord Howe Rise is largely composed of rocks with a P-wave velocity of 6.0 km/s, which is similar to values for the Australian continental crust. Rocks with a similar velocity are also present beneath the Norfolk Ridge. These results favour the interpretation that the Lord Howe Rise and probably Norfolk Ridge are fragments of continental crust.

Mutter & Jongsma (1978) computed the gravity response associated with the refraction model of Shor & others (1971) and showed that it gave a marked gravity gradient, unlike the relatively flat response on the BMR profiles and on profiles presented by Woodward & Hunt (1971). Using the refractors obtained by Shor & others, they presented a revised crustal model which satisfied the requirements of a flat gravity field. This showed a sharp division in both deep and shallow crustal structure of the Lord Howe Rise, which they considered lent support to the concept of a rift zone on the western side with associated crustal thinning and alteration.

Gravity data (based partly on Jongsma, 1976)

The published gravity data are sparse (Solomon & Biehler, 1969; Woodward & Hunt, 1971; Mutter & Jongsma, 1978), but generally indicate crustal thickening from the deep ocean basins to beneath the Lord Howe Rise. As for most ocean basins, the free-air anomaly over the Tasman Basin is negative but small. Over the Lord Howe Rise the free-air gravity anomaly is positive and up to 400 $\mu m.s^{-2}$ (40 mGal). Short-wavelength (less than 25 km) anomalies which cannot be accounted for by topography occur on the western flank of the Rise, and Woodward & Hunt (1971) have interpreted these as being due to intrusions of dense rock into the near-surface sediments. Over the eastern part of the Lord Howe Rise there are no short-wavelength anomalies, and the smooth topography is reflected in the gravity pattern. Bentz (1974) considered that the Bouguer gravity curves across the Lord Howe Rise are uneventful and generally reflect the crustal composition and thickness. The Bouguer gravity anomaly rises from 1000 $\mu m.s^{-2}$ (100 mGal) on the Lord Howe Rise to 2000 $\mu m.s^{-2}$ (200 mGal) over the New Caledonia Basin.

In the New Caledonia Basin the free-air gravity anomaly is largely negative (about -200 $\mu m.s^{-2}$, or -20 mGal) but small positive free-air anomalies (+200 $\mu m.s^{-2}$, or +20 mGal) are present in the central part. Over the edges of this basin there are steep gravity anomaly gradients.

The Norfolk Ridge has large gravity gradients over its flanks. The free-air anomaly rises to +750 $\mu m.s^{-2}$ (+75 mGal) over the central part of the ridge (Solomon & Biehler, 1969). According to Woodward & Hunt (1971) a large gradient in the gravity anomaly on the western flank of the West Norfolk Ridge can be simulated only if it is assumed that little or no sediment is present; indeed, the only appreciable thickness of sediment may occur in a graben on the top of the Ridge.

Magnetic data (based partly on Jongsma, 1976)

In the Tasman Basin, Hayes & Ringis (1973) identified linear northwest-trending magnetic anomalies disposed about a buried basement ridge, thus providing confirmatory evidence that the Tasman Sea was formed by seafloor-spreading processes - about 80 to 60 m.y. BP. In order to account for both the truncation of the magnetic anomaly pattern and their discovery that the crust adjacent to the east Australian margin is younger in the northern portion of the Tasman Sea than in the south, Hayes & Ringis (1973) suggested that an episode of crustal subduction had occurred. In order to test this controversial issue, Weissel & Hayes (1977) made a reappraisal of the spreading pattern and age identifications of the magnetic anomalies. Their results were largely consistent with the earlier work, but obviated the suggestion of a subduction episode. Their work implied that the oldest anomalies, 32 and 33, would be found within the Middleton and Lord Howe Basins. A recent reconstruction of the Lord Howe Rise and eastern Australia (Shaw, 1978) implies that strike-slip motion in the northern Tasman Basin was concurrent with accretion in the southern Tasman Basin during the early stages of opening from anomalies 33 to 32 (Fig. 16).

Over the Lord Howe Rise and the Norfolk Ridge the magnetic field is relatively quiet and generally reflects the relief of the basement rocks. According to Lapouille (1977), the Lord Howe Rise, Caledonia Basin, and Norfolk Ridge are characterised by large positive anomalies with wavelengths of about 100 km which may be readily correlated between adjacent profiles. He related these long-wavelength anomalies to broad variations in the nature and composition of basement; he modelled the major features of the magnetic field over the Lord Howe Rise as arising from blocks of basaltic material uplifted through sedimentary rocks (Lapouille, 1977). Superimposed on these large-scale features are short-wavelength anomalies; these can also be correlated between profiles in some places, and are related to the topography of the basement and to occurrences of basic intrusives or other magnetic rocks within the basement (Lapouille, 1977). Bentz (1974) has interpreted features of this type on the southern part of the Lord Howe Rise.

Over the Norfolk Ridge, extensive magnetic coverage (van der Linden, 1968a) shows a simple pattern of positive anomalies which trend northwest without steep gradients. In contrast the magnetics over the West Norfolk Ridge consist of a strong positive (+1500 nT) double-crested anomaly. Hochstein (1967) and van der Linden (1967) consider the anomalies to be due to a body of volcanics (basalts) overlying an older non-magnetic basement at a depth of 3000-4000 m.

Van der Linden (1967) described the New Caledonia Basin adjacent to the West Norfolk Ridge as being associated with a zone of smooth, negative magnetic anomalies. Overlying the basin adjacent to the Norfolk Ridge, Ravenne & others (1977) described a linear long-wavelength positive anomaly; they related it to a basement ridge which they called the Fairway Ridge. That part of the New Caledonia Basin between the Fairway Ridge and the Norfolk Ridge is associated with poorly defined low-amplitude magnetic anomalies, which Ravenne & others (1977) interpreted as indicating deep magnetic basement.

Volcanism and heat flow

Rhyolite flows intersected at DSDP Site 207 (see section 3) on the Lord Howe Rise have ages of 94 m.y. BP, or early Late Cretaceous (McDougall & van der Lingen, 1974). Late Pliocene volcanics of basaltic composition form Norfolk Island. Bentz (1974) considered that volcanism is still active on the Lord Howe Rise.

The only measurement of heat flow on the Lord Howe Rise (Grim, 1969) gave a value which is about twice normal for continents; this suggests that the Rise may be associated with an anomalous thermal regime.

Sedimentary structure

Continuous seismic reflection profiles over the Lord Howe Rise and Norfolk Ridge, collected before the Sonne survey, were adequate to show that throughout most of the area an undeformed sedimentary cover of variable thickness overlies folded and, in places, faulted older rocks. Over most of the southwestern Pacific there is a regional unconformity of middle Eocene to late Oligocene age (Burns & Andrews, 1973). DSDP results have shown that the duration of this break in sedimentation is variable, and is greatest on the Lord Howe Rise (see section 3). In seismic reflection profiles over the southern part of the Lord Howe Rise, Bentz (1974) has interpreted that Neogene sediments overlying the unconformity range in thickness from 260 to 400 m, which is in good agreement with thicknesses of Neogene sediments penetrated at DSDP Sites 207 and 208. Below the unconformity, Palaeogene to Upper Cretaceous sediments range in thickness from 950 to 1020 m according to Bentz (1974), but are much thinner over basement highs. Erratic variations in the thickness of Cainozoic sediments are probably due to the variable time-span of the Eocene/Oligocene unconformity, non-deposition or continuous erosion at active basement highs,

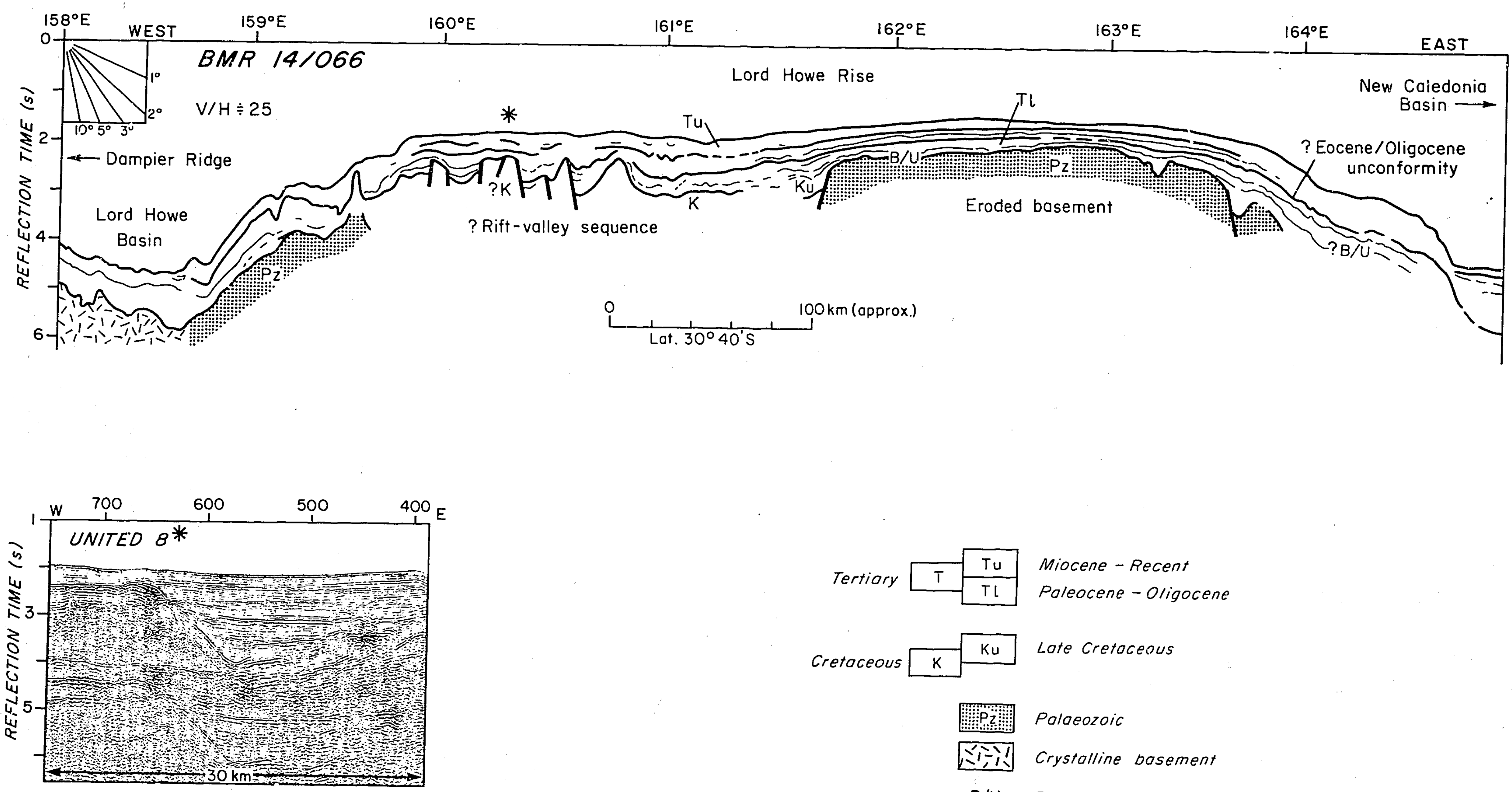

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Fig. 3. Structural profile across the Lord Howe Rise based on BMR Line 14/066 (after Willcox, 1981; location is shown in Fig. 1). Seismic detail is from near the centre of the 'rift-valley' (see asterisk) along Line 8 (reproduced with the permission of United Geophysical Corporation).

lateral depositional thickening, and slumping. The thickest sedimentary cover occurs within small basins or troughs, particularly on the western part of the Rise, where the oldest sediment-fill is of unknown but probably Cretaceous age. Thicknesses of up to 3000 m have been reported (Dubois & others, 1974) in the northern part of the Rise, and sediment-filled troughs are shown in interpretations of seismic profiles from the central area (Fig. 3; Jongsma & Mutter, 1978; Willcox, 1981). The BMR profiles show that relatively shallow planar basement is typical of the eastern half of the Rise, and that its internal acoustic properties are highly variable.

The sediment cover over the Norfolk Ridge is also variable. Shor & others (1971) reported sediments with a velocity of about 2.73 km/s and thickness of 1600 m at latitude 27°S, whereas Houtz & others (1967) found a very thin cover (less than 100 m) on the West Norfolk Ridge. Seismic profiling by Glomar Challenger shows that the sediment cover is less than 1000 m thick over the southern Norfolk Ridge and West Norfolk Ridge. Surveys over the Norfolk Ridge completed in recent years by ORSTOM (Noumea) and several French oil companies have delineated two elongate basins within the Norfolk Ridge in which the sediments are up to 3000 m thick. One of these basins occurs on the western flank of the Norfolk Ridge near New Caledonia, and the other is located between the West Norfolk Ridge and the Norfolk Ridge.

3. RESULTS OF THE DEEP-SEA DRILLING PROJECT AND GEOLOGICAL SAMPLING ON LORD HOWE RISE

The only direct knowledge that we have of the nature of the rocks forming Lord Howe Rise is provided by DSDP data, outcrop on Lord Howe Island, and dredging of one of the volcanic features described by Bentz (1974) on the southeastern side of the rise.

Data from three DSDP holes - Sites 206, 207, and 208 (Fig. 1) - are directly relevant to the Sonne survey. The following descriptions of the results of these drillholes are summarised from Burns & others (1973).

DSDP Site 206

Site 206 lies just east of a small elongate hill on the floor of the New Caledonia Basin at a water depth of 3196 m. The 734 m of sedimentary section penetrated consists of the following stratigraphic units:

Unit 1 (0-389 m) - early Miocene to ?late Pleistocene. Nannofossil ooze containing variable quantities of foraminifera and minor volcanic ash.
Unit 2 (389 to 614 m) - middle Oligocene to early Miocene. A semilithified sequence of clay nannofossil ooze passing downwards into clay-rich and rarely clay-bearing nannofossil ooze.
Unit 3 (614 to 677 m) - mid-middle Eocene to earliest late Eocene. Semi-lithified radiolaria-rich nannofossil calcic ooze.
Unit 4 (677 to 734 m) - early Paleocene to middle Eocene. Semilithified nannofossil calcic ooze and clay with minor chert (Fig. 4).

The early Paleocene sediments cored at this site contain some reworked latest Cretaceous material.

The sequence of calcareous oozes at Site 206, although fairly uniform, produces quite a diverse seismic picture in which the reflections rarely correlate well with lithologic breaks. In particular, the 'regional' late Eocene to middle Oligocene unconformity is not marked by a reflection at this site.

Palaeontological evidence indicates that since the Cretaceous the area has undergone a small amount of subsidence, but has always been in the bathyal zone above the calcium carbonate compensation depth.

DSDP Site 207

Site 207 is located in 1389 m of water on a structural high in the southern Lord Howe Rise northwest of the Bellona Gap. The 513-m section consists of the following stratigraphic units:

Unit 1 (0 to 142 m) - middle Miocene to Pleistocene. Foraminiferal-nannofossil ooze and nannofossil-foraminiferal ooze.
Unit 2 (142 to 309 m) - Paleocene to middle Eocene. Foraminiferal-nannofossil ooze to foraminifera-bearing nannofossil ooze and clay nannofossil ooze (or chalk), with subordinate siliceous foraminiferal-nannofossil ooze.
Unit 3 (309 to 347 m) - Maastrichtian. Glauconitic silty claystone (sandstone at the base).
Unit 4 (357 to 433 m) - Late Cretaceous. Rhyolitic (pumiceous) lapilli tuffs and vitrophyric rhyolite flows (fragmented in part).
Unit 5 (433 to 513 m) - Late Cretaceous or older. Vitrophyric rhyolite flows, fragmented in part (Fig. 4).

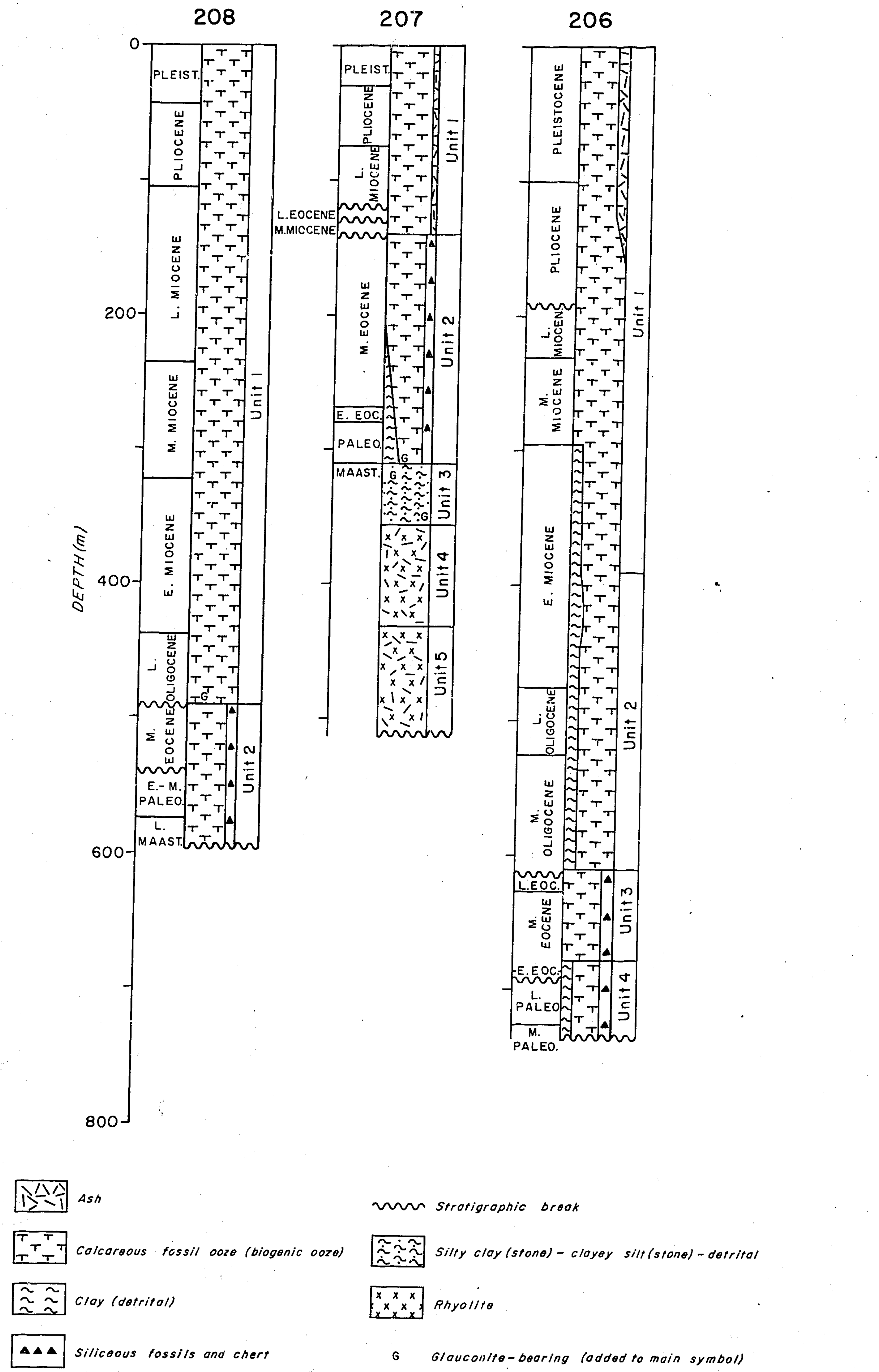

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Fig. 4. Generalised stratigraphic logs at DSDP Sites 206, 207 and 208 (after Burns & others, 1973)

The rhyolites from the base of Site 207 do not display unequivocal characteristics in favour of either a subaerial or subaqueous extrusive origin; however, van der Lingen (1973) has suggested that at least some of the rocks in unit 4 may be of subaerial or very shallow-marine origin. Rocks from unit 4 yielded a mean potassium-argon age of 94 m.y. (van der Lingen, 1973; McDougall & van der Lingen, 1974).

The sandy sequence at the base of unit 3 overlies the rhyolites and contains reworked rhyolitic detritus, and detritus from a granitic or metamorphic source. Many of the sand grains are well rounded, and Burns & others (1973) have suggested that the sequence formed as a result of strong currents transporting allogenic detritus to the site and locally reworking the underlying volcanics. The rarity of planktonic fossils in the silty claystone, which constitutes the rest of unit 3, indicated to Burns & others (1973) that it was probably deposited in a shallow-marine environment with restricted (non-oceanic) circulation.

The remainder of the rocks intersected at Site 207 are basically carbonate oozes, which were deposited well above the carbonate compensation depth. The 'regional' unconformity is between units 1 and 2, and separates late middle Eocene from early middle Miocene sediments.

Palaeontological evidence at this site indicates that from the Maastrichtian to the early Eocene there was a rapid increase in the depth of sedimentation, from relatively shallow water to a depth similar to that at the present day (1400 m).

DSDP Site 208

Site 208 is located in 1545 m of water just west of the crest of the northern Lord Howe Rise. The 504 m of section comprises the following stratigraphic units:

Unit 1 (0 to 488 m) - late Oligocene to late Pleistocene. Unconsolidated to semilithified foraminiferal-nannofossil ooze to foraminifera-rich nannofossil ooze.

Unit 2 (488 to 594 m) - Late Cretaceous to early middle Eocene. Siliceous-fossil-bearing nannofossil chalk to nannofossil-bearing radiolarite or diatomite. Calcic chalk occurs at the base of the unit (Fig. 4).

At this site the 'regional' unconformity is of middle Eocene to late Oligocene age and separates the foraminiferal-nannofossil ooze of unit 1 from the siliceous-fossil-bearing nannofossil chalk of unit 2.

Palaeontological evidence indicates that the sequence sampled was deposited under normal oceanic conditions, and that, except for a small amount of subsidence in the Late Cretaceous, water depths were always mid-bathyal. This, together with the near absence of clastic detritus led Burns & others (1973, p. 279) to suggest that the northern 'Lord Howe Rise has existed as a feature isolated from Australia since at least the Maastrichtian'.

DSDP Site 284

The results from DSDP Site 284 drilled in the Challenger Plateau have some relevance to this study as the plateau can be regarded as a southern extension to the Lord Howe Rise. The entire section of 208 m at this site consists of latest Pleistocene to late Miocene foraminiferal ooze. Apart from a minor unconformity in the mid-Pleistocene the sedimentation was continuous (Kennett & others, 1974).

Regional significance of the DSDP results

The DSDP results can be used to make a general reconstruction of the geological history of the region.

The results from Site 206 indicate that the New Caledonia Basin existed as an oceanic basin at least as far back as the early Paleocene. The presence of reworked Upper Cretaceous (Maastrichtian?) radiolarians near the base of the hole probably indicate that the Basin is even older.

The geological history of the Lord Howe Rise began with the eruption of rhyolites, possibly at or near sea level, 94 m.y. BP (McDougall & van der Lingen, 1974). This activity may have been related to the early separation of the Lord Howe Rise and Australia before the development of oceanic crust in the Tasman Sea at 80 m.y. BP (Hayes & Ringis, 1973). During the Maastrichtian the silty claystone intersected at Site 207 was deposited in a shallow-marine environment with restricted circulation. In the south, true oceanic conditions began in the middle Paleocene; the Rise continued to subside, reaching its present upper bathyal depth by the early Eocene. In the north, however, oceanic conditions prevailed in the Maastrichtian, and the Rise had reached upper bathyal depths by the latest Cretaceous. The Lord Howe Rise appears to have been stable along its length at about its present depth since the middle Eocene.

Outcrop on Lord Howe Island and Ball's Pyramid

Lord Howe Island and the nearby island of Ball's Pyramid are the only islands on the Lord Howe Rise; they form the southernmost part of a chain of volcanic features - the Lord Howe Island Seamount Chain - along the northwestern flank of the Rise. Game (1970) described the Lord Howe Island volcanics as typical alkali basalts, and distinguished at least three major eruptive periods, of which the youngest was isotopically dated as mid-Pliocene age (7.7 m.y. BP). He considered that the volcanism began as early as the mid-Tertiary and continued for 20 to 25 m.y. with no major change in its character.

Dredging on the southeastern Lord Howe Rise

Dredging on the flank of a volcanic feature described by Bentz (1974) near the southeastern margin of the Lord Howe Rise brought to the surface olivine basalts, gabbros, and a mixture of hyaloclastic breccias and biomicrites (Launay & others, 1977). The biomicrites contain deep-water planktonic foraminifera and shallow-water coral debris. Launay & others (1977) interpreted this assemblage to indicate that at sometime during the Palaeogene about 500 m of subsidence occurred, thus favouring the growth of corals on the top of the volcanic feature and the deposition of planktonic foraminiferal remains at its base. After the mid-Miocene, subsidence continued until the Lord Howe Rise reached its present depth of about 1500 m. This interpretation differs from that based on the DSDP results, which indicate that the Rise had subsided to its present depth by the middle Eocene.

4. EVOLUTIONARY MODEL FOR THE TASMAN SEA AND LORD HOWE RISE

The interpretation of data from DSDP Site 207 is in general accord with the spreading history of the Tasman Basin. According to McDougall & van der Lingen (1974) the rhyolites penetrated near the bottom of this site were extruded at or near sea level 94 m.y. BP, when Lord Howe Rise formed part of the Australian-Antarctic continent. This volcanism was probably associated with rifting processes which immediately preceded the earliest development of oceanic crust within the Tasman Basin (Hayes & Ringis, 1973) or possibly more precisely within the Middleton and Lord Howe Basins (Weissel & Hayes, 1977). The silty claystone of unit 3 indicates that restricted shallow-marine conditions became established shortly after break-up (80 m.y. BP) and that at least some detritus was derived from granitic and metamorphic source areas to the west (Burns & others, 1973). Oceanic conditions were quickly established, and throughout the seafloor-spreading episode (80-60 m.y. BP), the Lord Howe Rise rotated away from Australia (Shaw, 1978) and had subsided to bathyal depths by the early Eocene.

The widespread Eocene/Oligocene unconformity is considered by Burns & others (1973) to have been the result of a change in bottom-water circulation, which occurred when the Australian and Antarctic plates separated in the late Paleocene (55 m.y. BP; Weissel & Hayes, 1972).

Jongsma & Mutter (1978) have put forward an evolutionary model of the early rifting history of the Tasman Sea. In essence it suggests that the western half of the Lord Howe Rise and probably the whole of the Dampier Ridge are underlain by a former rift valley which developed in the Early Cretaceous, before the commencement of seafloor spreading in the Tasman Sea (Fig. 5a). When new oceanic crust broke through the rift valley, it was not along its axis as in most idealised models of rifting, but along its western boundary fault. They proposed such a model in order to account for a zone of apparent horst and graben structures along the western half of the Lord Howe Rise (see, for example, Fig. 3), and the lack of rift basins along the eastern seaboard of Australia. In a later paper, Mutter & Jongsma (1978) envisaged the fragmentation as resulting from a 3-branch rift system in which the Gippsland Basin formed a failed arm (Fig. 5b). This implies that pre-break-up Gippsland Basin sediments, mainly the Lower Cretaceous Strzelecki Group, may have equivalents beneath the Lord Howe Rise.

Several hypotheses have been advanced to explain the origin of the Norfolk Ridge and the New Caledonia Basin. These include the evolution of a complex arc system (Geze, 1963; Dubois & others, 1974), arc migration and the development of marginal basins (Karig, 1971; Packham & Falvey, 1971), and the creation of marginal basins caused by second-order adjustment at the edges of plates (Andrews & others, 1973). The presence of ophiolites on New Caledonia are believed to result from overthrusting of a fossil subduction zone. Whether the Norfolk Ridge was at one time also part of the Australian continental margin is at present not substantiated. However, the results of the DSDP drilling program support the conclusion that the basins and ridges in the region were formed by the end of the Mesozoic (Burns & others, 1973). The interpretation of the Sonne data sheds some light on the relative ages of the New Caledonia, Middleton, Lord Howe, and Tasman Basins.

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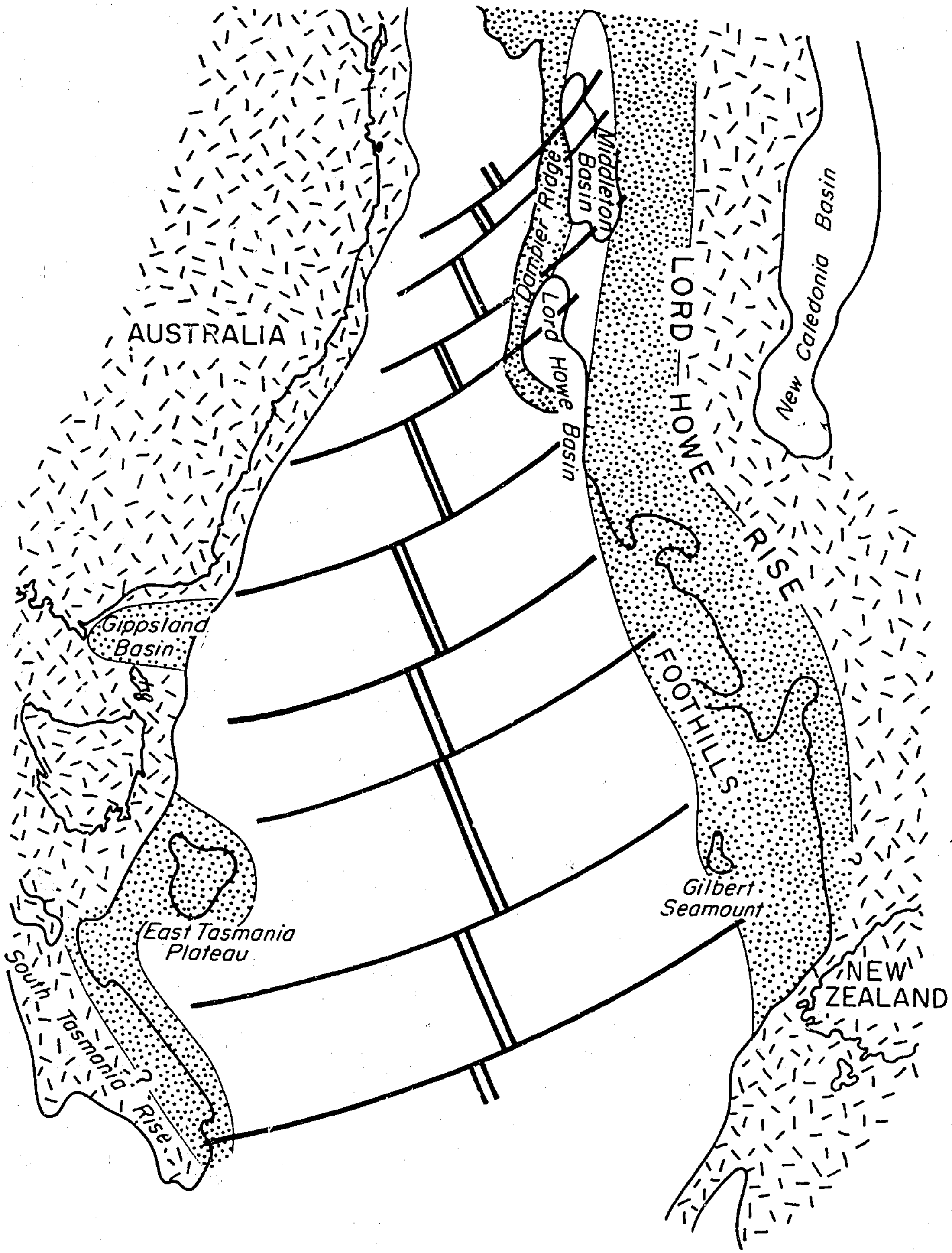

Fig.5a. Tectonic elements of the Tasman Sea region after Mutter & Jongsma (1978)

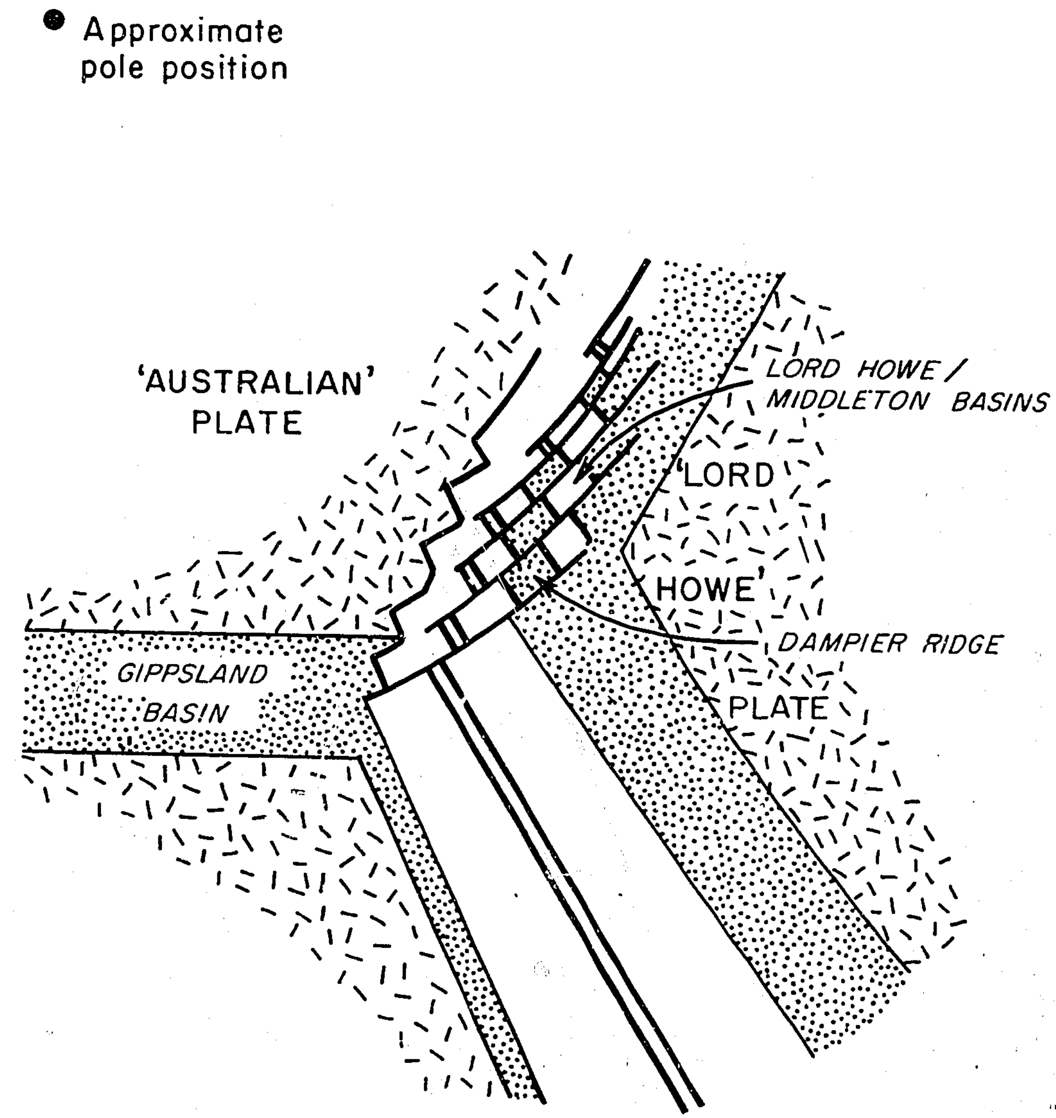

Fig.5b. Schematic diagram showing tectonic pattern of the Tasman Sea (after Mutter & Jongsma, 1978) reconstructed along the flow-lines of Weissel & Hayes (1977)

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5. OBJECTIVES OF THE SONNE SURVEY (CRUISE SO-7A)

Sonne cruise SO-7A was largely a survey of the western half of the Lord Howe Rise, although some lines also extended across the Norfolk Basin (east of the Norfolk Ridge), Norfolk/West Norfolk Ridge system, New Caledonia Basin, Middleton Basin, Lord Howe Basin, and Dampier Ridge. About 4000 km of 24-channel seismic, gravity, and magnetic profiles were obtained during the survey, and nine sonobuoys for shallow refraction studies were successfully deployed.

The principal objectives were:

(i) to add to the regional framework of geophysical data on the Lord Howe Rise, and in particular to obtain high-quality multichannel seismic reflection profiles;

(ii) to determine more about the geological history of the area and provide a high-resolution tie to DSDP Site 208;

(iii) to test the hypothesis of Jongsma & Mutter (1978) that the western half of the Lord Howe Rise was a Late Cretaceous rift-valley (pull-apart basin) associated with the Tasman Basin episode of rifting and break-up;

(iv) to further survey sediment-filled grabens which are indicated on BMR Lines 14/066 and 14/068 crossing the central part of the Rise, and to determine the lengths of these grabens;

(v) to test the seismic characteristics of the basement beneath the Lord Howe Rise and deduce its origin;

(vi) to determine the origin of the Middleton and Lord Howe Basins;

(vii) to determine whether the Dampier Ridge is of continental or oceanic origin;

(viii) to determine the relative age of the New Caledonia Basin with respect to that of the Tasman Basin; and

(ix) to obtain a high-resolution profile over the Norfolk Ridge.

6. SEISMIC INTERPRETATION

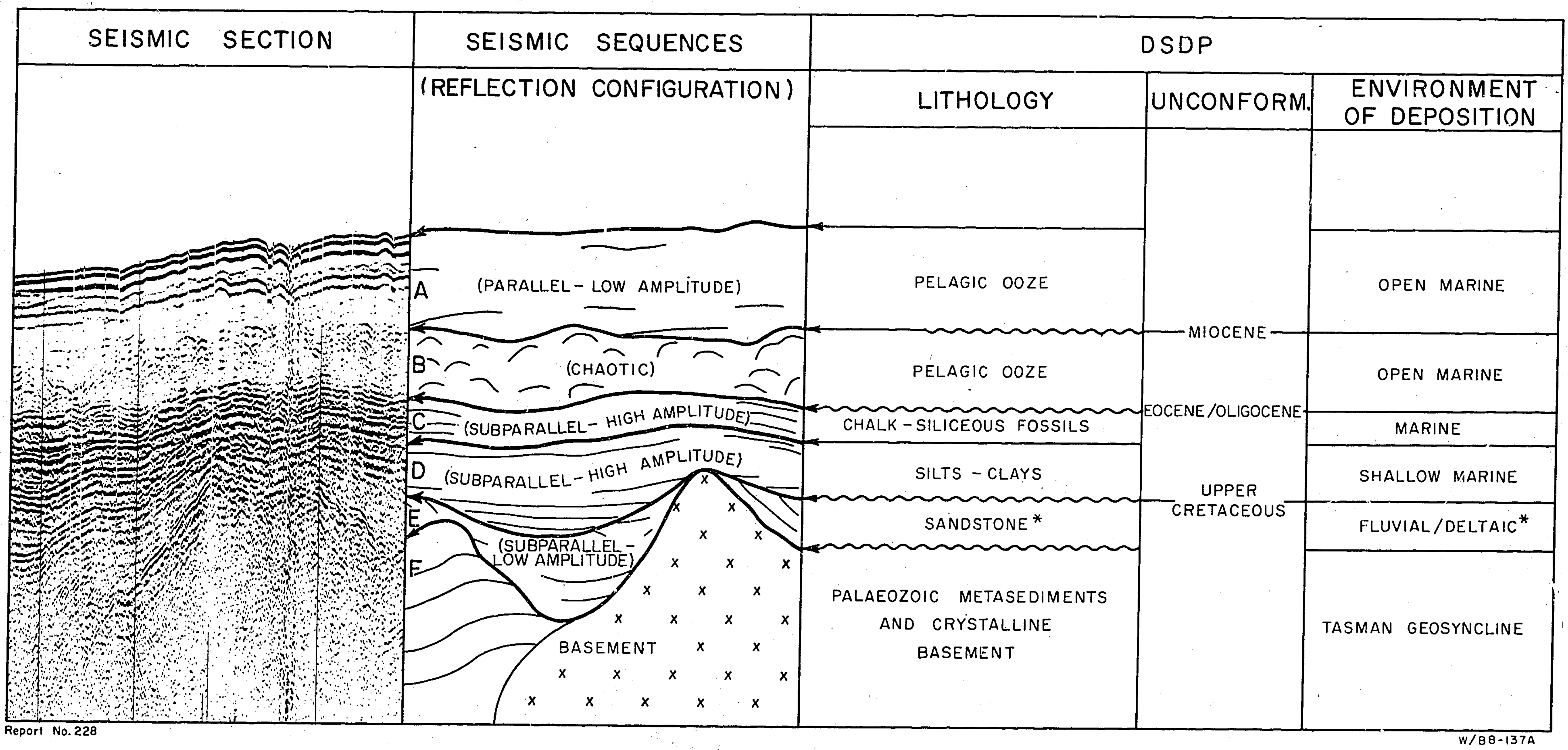
Most of the 4000 line kilometres of 24-channel digital seismic data recorded in the survey area is to be processed for detailed interpretation. The preliminary results discussed in this section are based on single-channel on-line monitor records which are generally of high quality. Good seismic penetration was achieved by fine tuning and precise depth control of the air-gun array, and by operating at 5 knots, or considerably less in rough seas, in order to reduce noise levels. Basement and intrabasement reflections were obtained over nearly all features, except for some deep grabens on the western part of the Lord Howe Rise. The apparent reverberations just below seabed on many profiles (see, for example, Fig. 11) are believed to result largely from real layering within the superficial sediments and not from bubble oscillations or multiples. Thus we have been able to pick with a fair degree of confidence the several closely spaced unconformities which occur near the base of the Tertiary. Sophisticated processing techniques, such as pulse-shortening deconvolution, should further improve resolution of these horizons.

Seismic stratigraphy: identification of depositional sequences

Several depositional sequences (Mitchum, Vail, & Thompson, 1977), each bounded by unconformities, have been distinguished on the reflection profiles across the Lord Howe Rise (Fig. 6). The internal configuration of sequences A to E is usually sufficiently characteristic for them to be identified on almost all parts of the Rise. In a few places additional sequences appear to be present (e.g., Fig. 10), but on some profiles these are obviously a result of sliding and slumping. Most sequences can be tentatively traced westwards across the Lord Howe Basin and onto the Dampier Ridge, and eastwards across the New Caledonia Basin; however, abrupt changes in the thicknesses of sediments on the flanks of the Rise cause correlation problems in some places.

The lithologies and environments of deposition at the DSDP sites appear to be consistent with those interpreted from the internal configuration of reflections for sequences A to E (Fig. 6). A good tie was made to DSDP Site 208 in the northern part of the area (Fig. 1), and an indirect tie was also made to DSDP Site 207 in the south, via profiles recorded by DSIR (New Zealand) using a relatively low-power air-gun source. The tie to Site 207 was less than satisfactory and somewhat ambiguous, mainly because the drill site is on a small basement high overlain by an attenuated sedimentary column.

Seismic stratigraphic sequence A exhibits parallel low-amplitude reflectors, and in places downlap onto the basal unconformity, which is considered to be of mid-Miocene age. It correlates with a deep-sea pelagic ooze penetrated in the drill sites. The underlying sequence B is characterised by a chaotic internal reflection configuration, erosional truncation of its upper surface, and often a concordant lower boundary. It is also a pelagic ooze, of mainly Oligocene to early Miocene age, and was probably deposited in turbulent bottom-water conditions. Such conditions are believed to have prevailed during the Eocene, after Australia and Antarctica had separated, and probably also resulted in the formation of the widespread Eocene/Oligocene unconformity.



* *Not penetrated in DSDP sites*

A *Seismic sequence identification*

Fig. 6. Seismic stratigraphy: depositional sequences on the Lord Howe Rise correlated with DSDP data.

Sequence C is characterised by subparallel high-amplitude events, which in places are discordant with those of the underlying sequence. The prominent increase in amplitude which occurs at the B/C interface (Fig. 6) correlates at the drill sites with what is little more than a slight increase in the siliceous content of the pelagic oozes. The sequence is of Eocene age.

Sequence D also shows a subparallel high-amplitude internal reflection configuration, generally erosional truncation at its upper boundary, and onlap at its base. It correlates with a sequence of shallow-marine silts and clays of Paleocene to Maastrichtian age, as intersected near the base of DSDP Site 207.

The internal reflection configuration of sequence E is subparallel; its top shows marked erosional truncation, and at its base reflectors lap onto basement. It forms the sediment-fill within grabens on the western part of the Lord Howe Rise, but is largely absent over the basement highs. The markedly erosional nature of the D/E unconformity indicates considerable subaerial or wave-base erosion, probably immediately before break-up in the Late Cretaceous. We thus regard the D/E interface as the break-up unconformity, formed in the Late Cretaceous at about anomaly 33 time. Although correlatives of sequence E have not been penetrated in either DSDP Sites 207 or 208, we infer from regional considerations that the sediments are probably of continental or shallow-marine origin, and of Cretaceous age.

The acoustic properties of sequence F and of the E/F interface are variable. Over large areas the sequence contains few coherent reflections and numerous diffractions, although folding, faulting, and clearly defined bedding are apparent in some places. On the western part of the Rise the sequence has been faulted into numerous horst-blocks, many of which are intruded along their bounding faults. On the flanks of the Rise and in the adjacent ocean basins it grades into, or is in faulted contact with, a diffracting basement which is probably of oceanic origin. The large range of refraction velocities (section 7) apparently associated with this sequence, and the large variation in magnetic response, also point to its complexity. Overall, the evidence suggests that it probably consists mainly of Palaeozoic metasediments which are essentially part of the Tasman Geosyncline of eastern Australia, although it may be a rift-sequence.

Sonne seamount

A previously unrecorded seamount (the Sonne Seamount, Fig. 7) was discovered in the southern Norfolk Basin just after the survey started. Based on the provisional navigation data, its apex lies roughly at latitude 30°47'S,

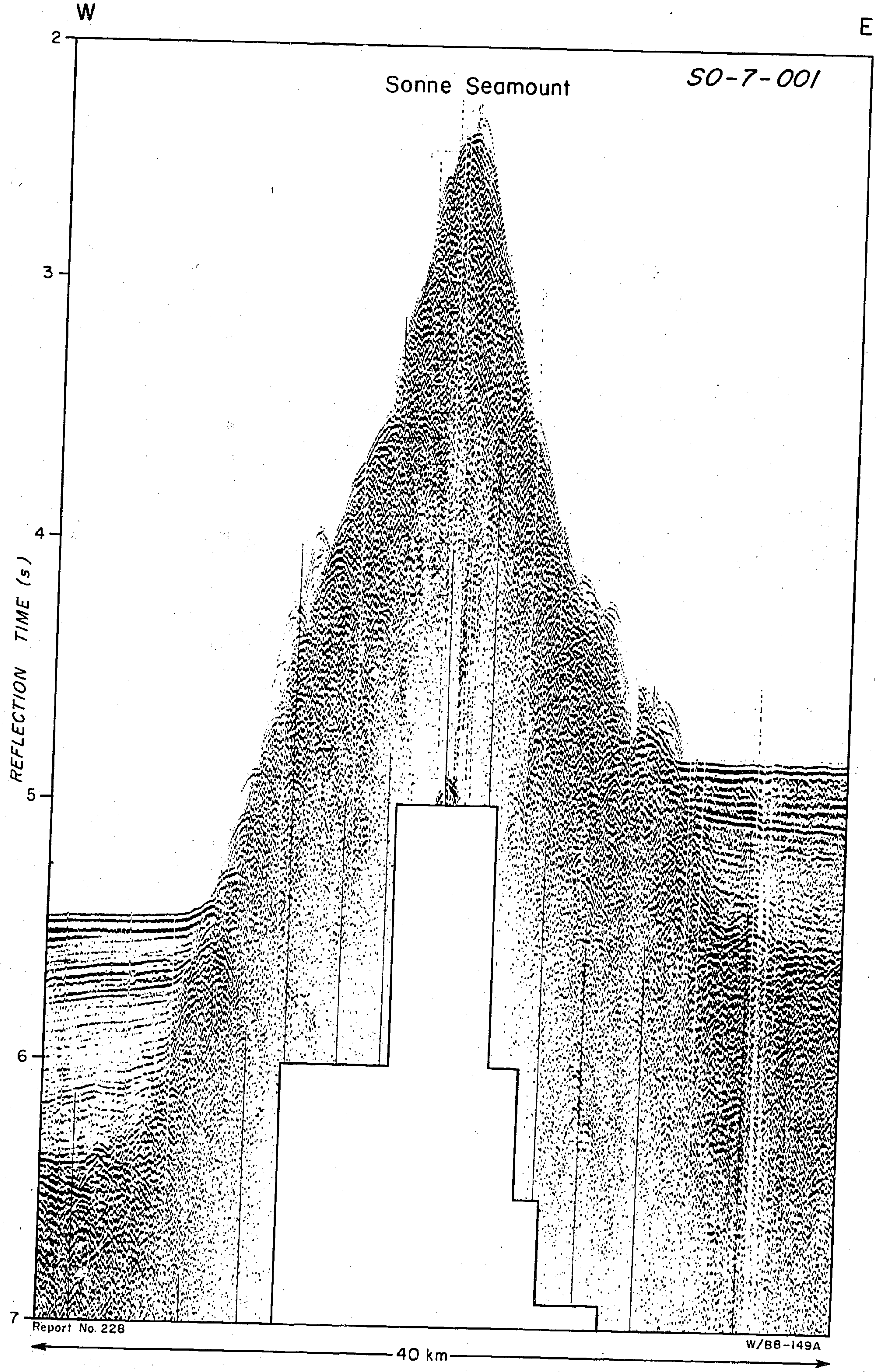


Fig.7. Seismic profile (single-channel on-line monitor record) of the Sonne Seamount, Norfolk Basin.

longitude 168°54'E on Line SO-7-001. The crossing was probably close to its peak, since there are few offside reflections from areas of more elevated sea-floor. The seamount has a basal extent of about 25 km, and rises 2800 m above the basement and 2200 m above the sea-floor. Its most elevated point on Line SO-7-001 has a reflection time of 2.44 s, which represents a water depth of about 1800 m.

Norfolk and West Norfolk Ridges

The Norfolk and West Norfolk Ridges were crossed on an east-west bathymetric high which appears to link them (Fig. 1; also see van der Linden, 1968b). The bathymetric high is the topographic expression of the Vening-Meinesz Fracture Zone.

Along profile SO-7-001 the Norfolk Ridge has a double ridge structure with an eastern peak at about 900 m and a western peak at about 600 m below sea level. A high-impedance contrast at the seabed is indicated by the ten multiples generated near the eastern peak. Weak layering within some parts of the ridge suggests that it is composed of metasediments or volcanics; the low-magnetic response indicates that metasediments are more likely.

The magnetic variations are more intense on Line SO-7-001A across the West Norfolk Ridge, indicating that the basement complex may contain a high proportion of volcanics. A probable volcanic outcrop occurs near the axis of the ridge, but sedimentary layering seems to be present on either side and is more than 2000 m thick on its eastern flank (Fig. 8). A prominent unconformity occurs within the section in the east and appears to continue westwards as the modern-day sea-floor. A thick wedge of sediment overlies this surface and is generally more uniformly stratified than the sediment beneath it. Recognisable within the wedge are at least two unconformities, of possible Eocene/Oligocene and mid-Miocene ages, and a mounded sequence which appears to have the external form of a deep-sea fan deposited perpendicular to the plane of the section.

Company lines across the central and southern parts of the Norfolk and West Norfolk Ridges show that the above features become more prominent farther south. The Norfolk Ridge has two peaks, and the data suggest that the ridge is composed mainly of sediments in which an intrusion or seamount causes the eastern peak. The West Norfolk Ridge is underlain by relatively planar basement, which has been downfaulted to form flanking grabens that contain at least 3000 m of sediment; in this respect it is similar to the Lord Howe Rise. The sediments in the grabens are prominently folded, which leads us to speculate that the area

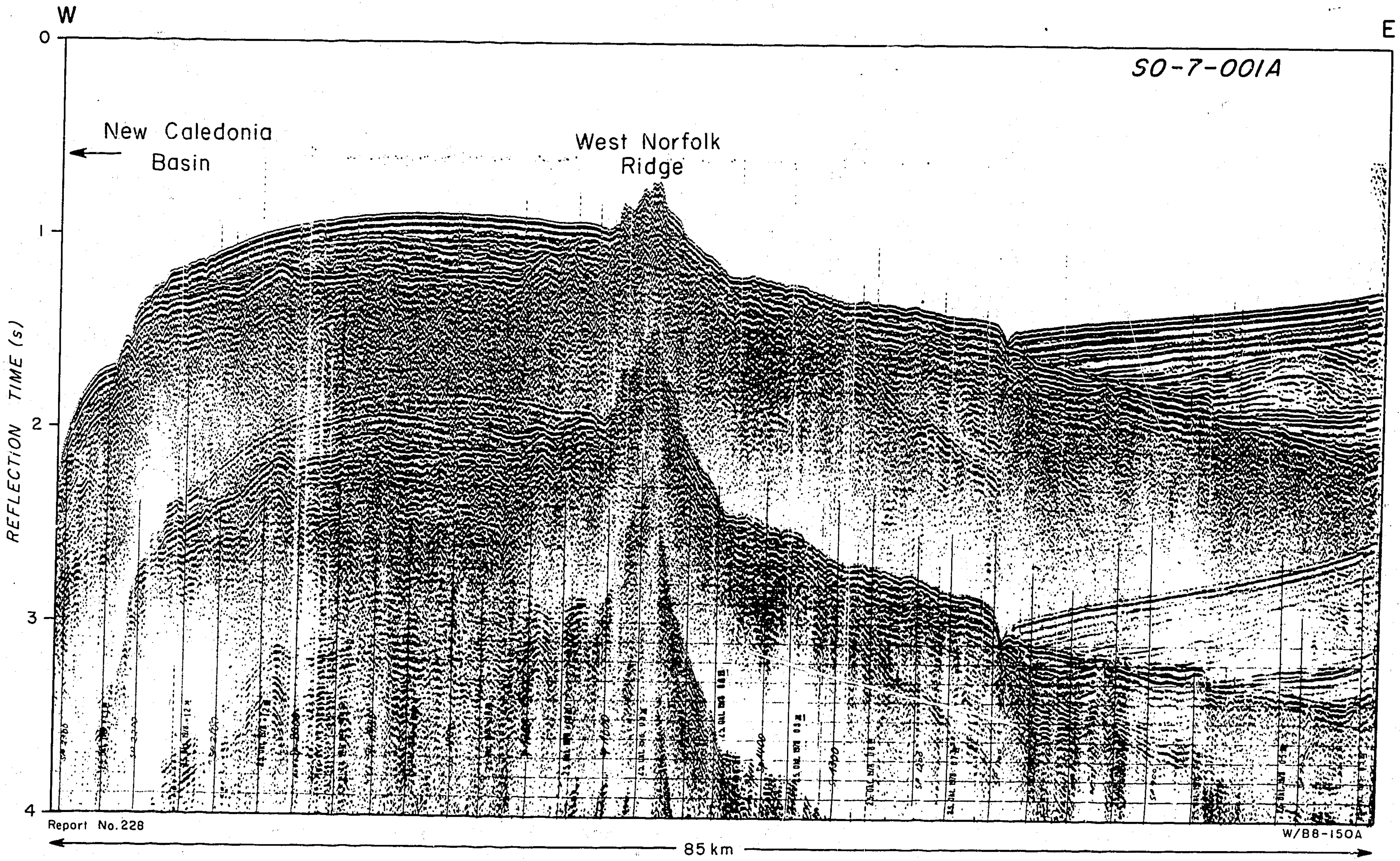


Fig. 8. Seismic profile across the West Norfolk Ridge (northern extremity).

was subjected to compressional stresses after the grabens had formed. East of the Norfolk Ridge, a relatively thin cover of more-recent sediments overlies a zone of steep westerly dipping reflectors which extend down to 3.8 s reflection time below the seabed.

Lord Howe Rise

Only the southernmost lines, SO-7-001A and 2, were planned to provide a complete crossing of the Lord Howe Rise, from the New Caledonia Basin to the Tasman Basin (Fig. 9). To the north, a further five lines were surveyed over the western flank of the Rise (Figs. 1 and 2) in order to investigate the horst and graben province described by Jongsma & Mutter (1978). The shipboard interpretation of all these lines is shown in Figure 15. Longitudinal tie-lines were also run between DSDP Site 208 in the north and BMR Line 14/066, which extends east-west about 40 km north of Lord Howe Island. Lines SO-7-007 and SO-7-012 extend across the Lord Howe and Middleton Basins respectively; and Lines SO-7-006 and SO-7-010 cross the Dampier Ridge.

The results indicate that in general terms there is some justification for dividing the Lord Howe Rise into an eastern province characterised by relatively elevated and eroded planar basement, and a western province dominated by horsts and grabens. However, this division is not nearly as clear-cut as indicated in the interpretations of BMR 14/066 given by Jongsma & Mutter (1978) and Willcox (1981; Fig. 3). Although an elevated planar basement province can be recognised on company lines which cross the northern part of the survey area, near DSDP Site 208, it is much narrower than farther south and is in places dissected by small grabens. In the far southeast, on Eltanin Line 34 (Davey, 1977, fig. 5), a narrow horst and graben province also seems to be present on the northeastern or New Caledonia Basin margin of the Challenger Plateau.

On Line SO-7-001A the eastern boundary of the Rise is marked by a major fault which apparently divides continental and oceanic basement (Figs. 9, 15). A wedge of sediment at least 2000 m thick, interpreted as sequence E (i.e., antedating the break-up of the Tasman Sea), extends across the eastern margin of the Lord Howe Rise and beneath the New Caledonia Basin. On its western flank, the elevated planar basement area is generally bounded by a major graben containing between 2000 and 4000 m of sediment.

The seismic sequence mapping and ties to the drill sites indicate that the interpreted break-up unconformity, probably of Late Cretaceous age, is almost continuous with the surface of the planar basement and several blocks to

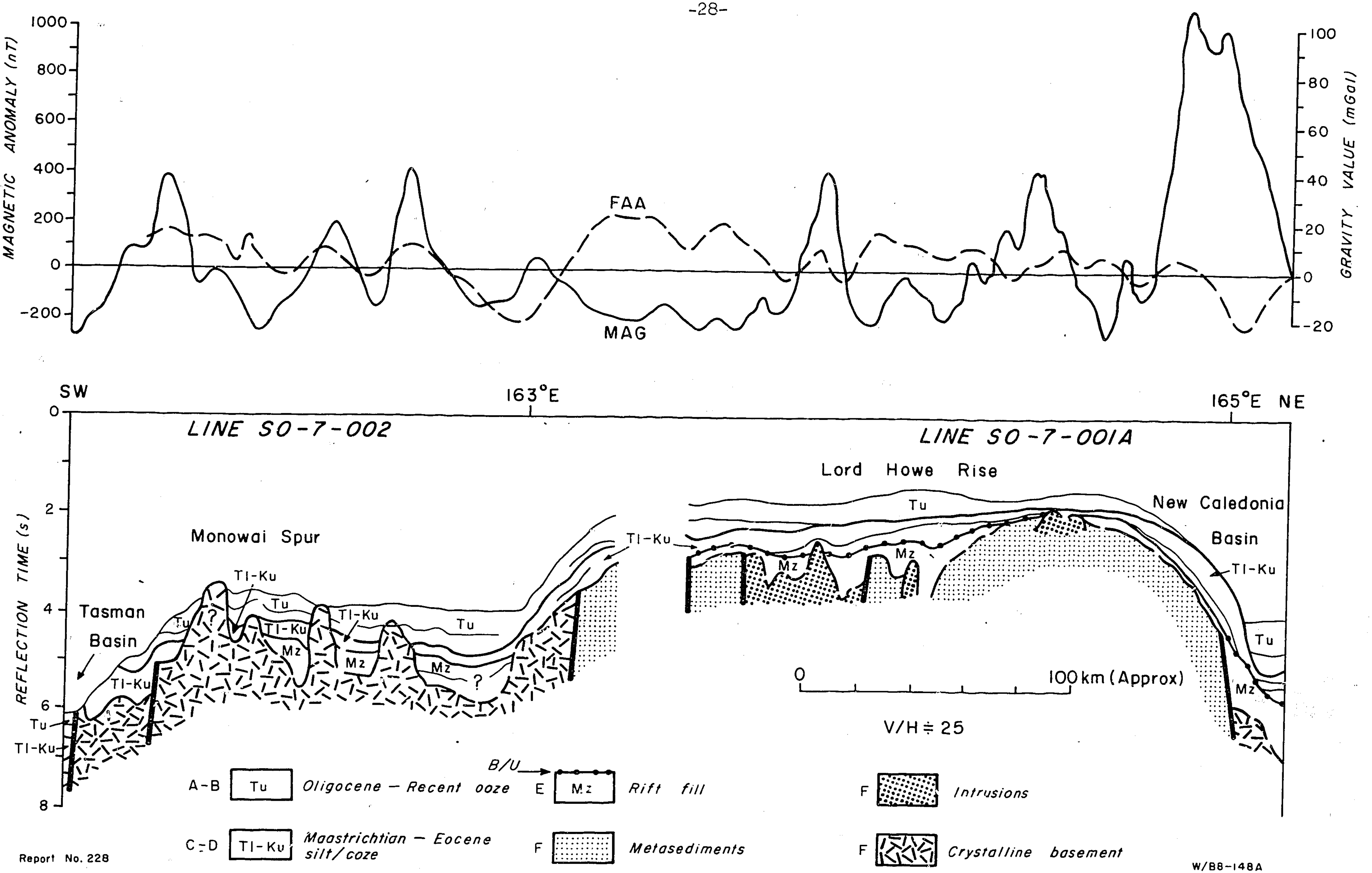


Fig. 9. Structural profile across the Lord Howe Rise based on Lines SO-7-001A and SO-7-002, showing seismic sequences (A-F), unconformities (B/U = break-up unconformity), apparent variation in basement types, free-air anomaly profile (FAA), and magnetic anomaly profile (MAG = total magnetic intensity - IGRF).

its west. Subaerial or wave-base erosion was probably occurring on these features just before break-up; they may have formed part of an ancient continental shelf, adjacent to which the eastern edge of the Lord Howe Rise was the continental slope. Structures within several of the blocks suggest that they are composed partly of old sediments which are probably part of the Palaeozoic Tasman Geosyncline.

Within the horst and graben province, intrusions are quite prominent, particularly along the fault planes bounding the horsts. Few faults extend beyond the break-up unconformity and many are confined only to the basement. The structural trends in this province are difficult to determine, as few features can be correlated between lines; however, where closely spaced lines are available, the trends seem to be north-northwesterly or northwesterly.

Many of the grabens contain probable continental or shallow-marine sediments of the pre-break-up sequence E. In the example shown in Figure 10, the basement is not apparent and the post-break-up sequences (A-D) have a thickness of at least 1.5s, or about 2000 m. Petroleum source rocks within the pre-break-up sequence, and marine source rocks deposited immediately after break-up, are probably buried deeply enough in this area to have reached maturity. The recorded high heat flow in the Lord Howe Rise region may have aided the maturation process.

In some areas 'reef-like' structures occur on and near the break-up unconformity (D/E). Figure 11 shows two such features: one on the break-up unconformity; and the other within sequence D, which laps on to the unconformity and is believed to be of shallow-water origin. Both features exhibit velocity pull-up and lateral facies variation, which are typical of reefs.

Middleton and Lord Howe Basins, and Dampier Ridge

Seismic sequences have been tentatively traced across the Middleton and Lord Howe Basins, and onto the Dampier Ridge. The character of the sequences appears to be largely maintained across the Lord Howe Basin, but their lateral continuity in the lower half of the section is broken by high-standing basement blocks (Fig. 12). In the Middleton Basin, the sequences are more difficult to trace across the relatively steep western margin of the Lord Howe Rise, and in places they change character within the Basin. The presence of additional sequences, probably resulting from slumping and the deposition of local sedimentary wedges from both the Lord Howe Rise and Dampier Ridge, further complicates the sedimentary structure.

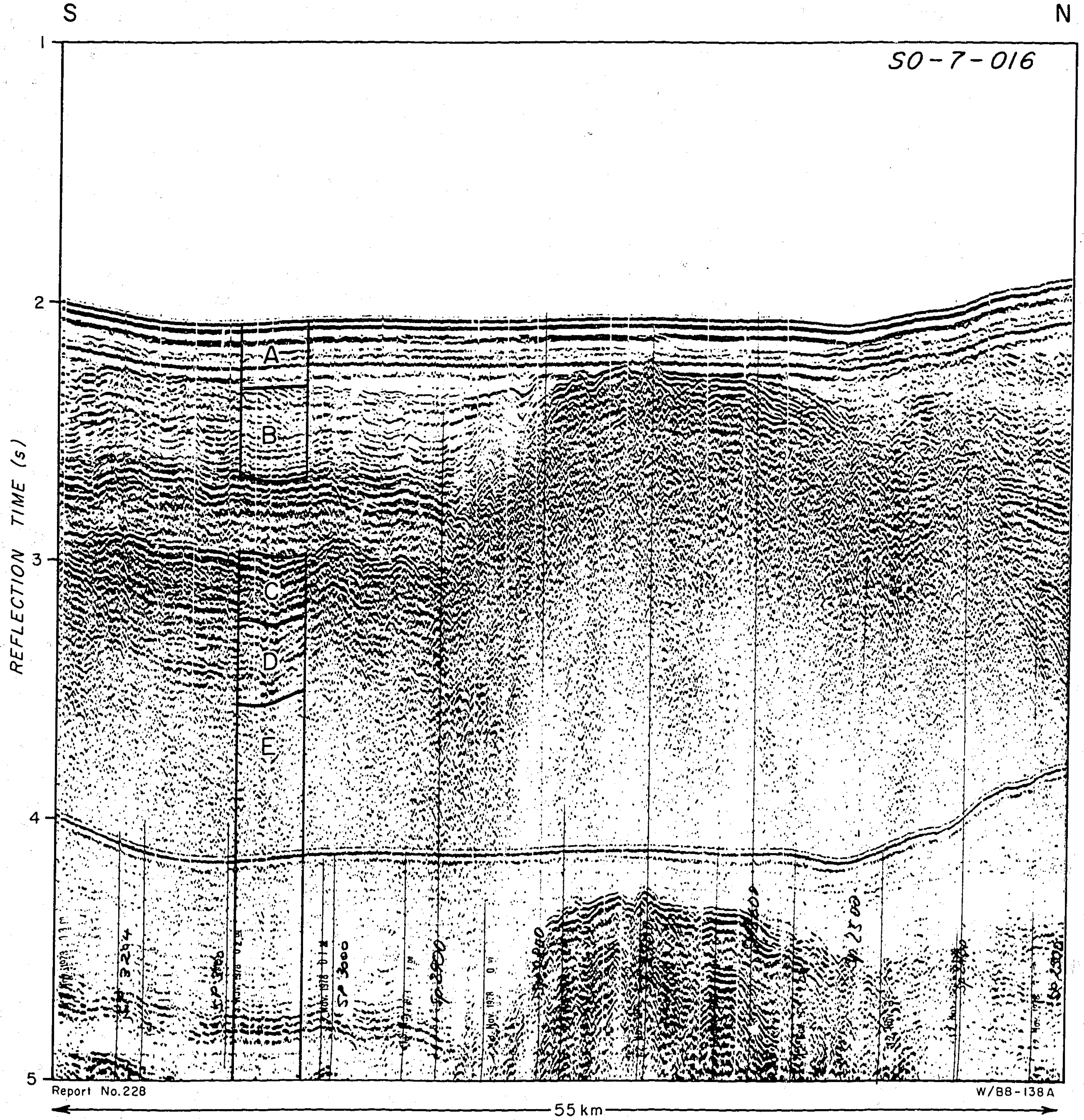


Fig. 10. Seismic profile showing horst and graben structures on the western flank of the Lord Howe Rise.

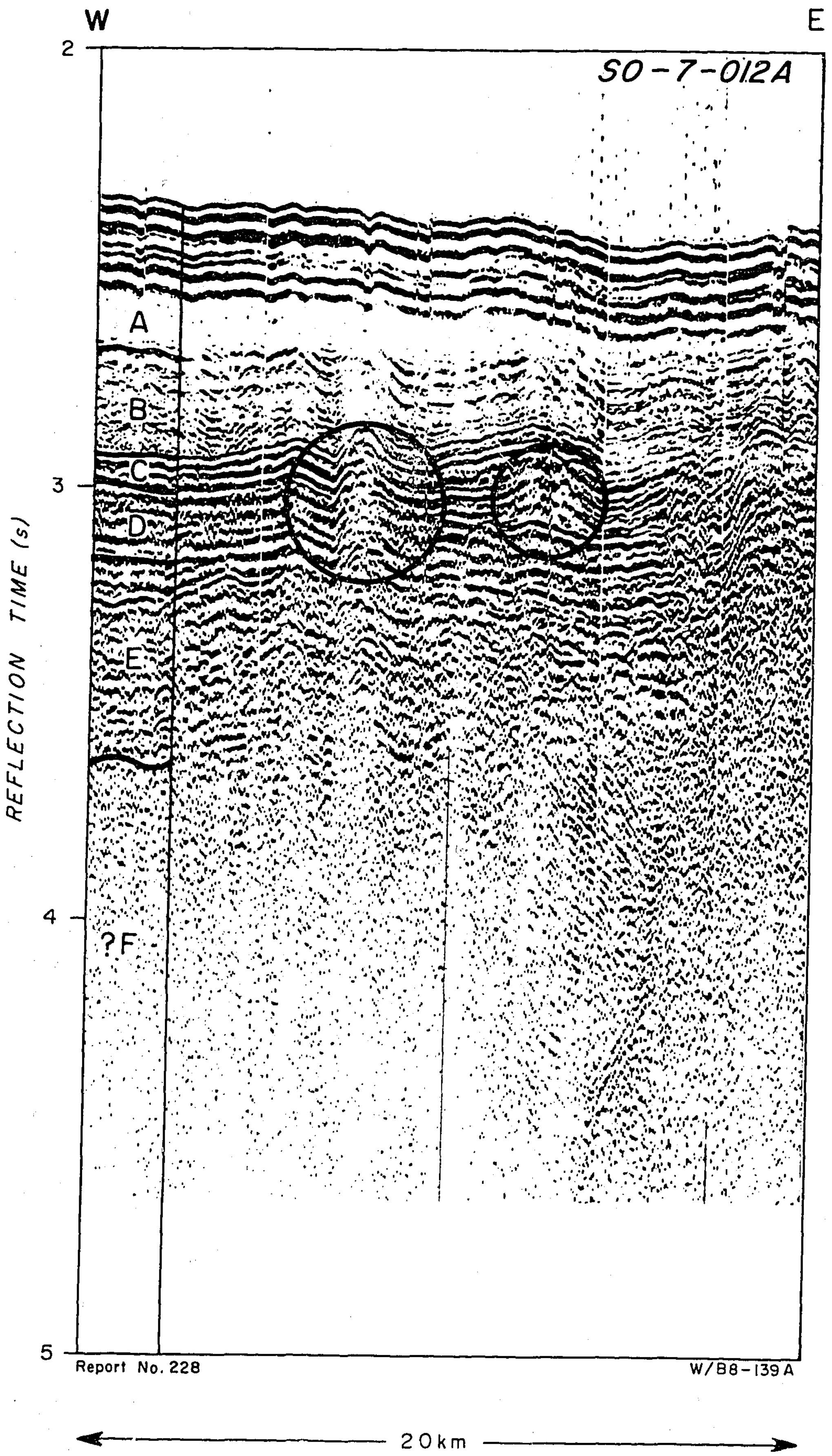


Fig.11. Seismic profile showing structures interpreted as pinnacle reefs built on or near the ?Late Cretaceous (D/E) break-up unconformity.

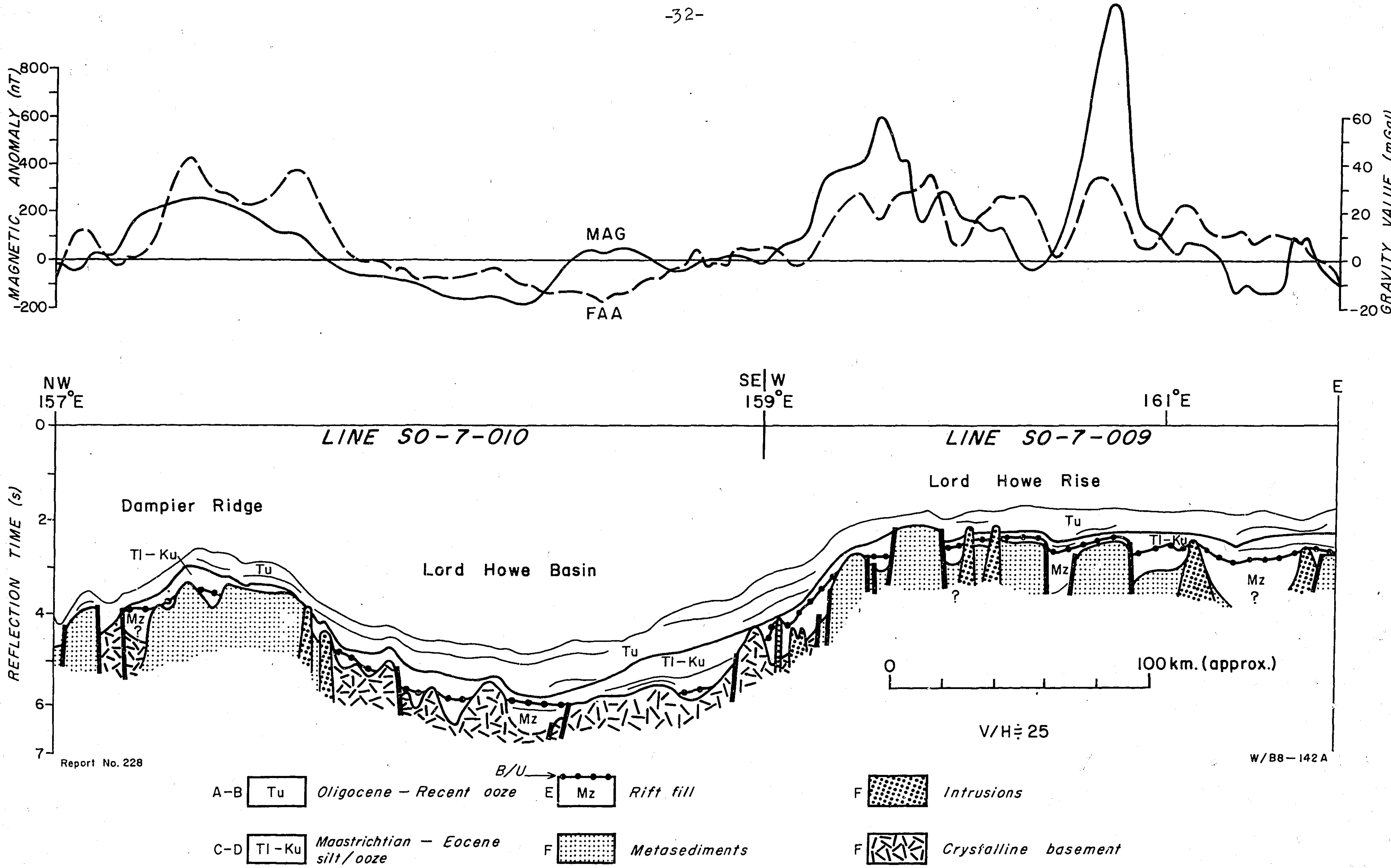


Fig.12. Structural profile across the Lord Howe Basin based on Lines SO-7-009 and SO-7-010, showing seismic sequences (A-F), unconformities (B/U = break-up unconformity), apparent variation in basement types, free-air anomaly profile (FAA), and magnetic anomaly profile (MAG=total magnetic intensity - IGRF).

The basement changes in character from the Lord Howe Rise westwards into the Lord Howe Basin and probably the Middleton Basin. Under the Lord Howe Basin it has fewer coherent events than the basement under the Lord Howe Rise, although it does not exhibit the numerous diffractions which are often associated with oceanic crust. In both basins it is block-faulted, and in the Middleton Basin there is a central graben about 15 km wide and more than 1000 m deep. The acoustic properties of the basement and the apparent lack of magnetic lineations in the Middleton and Lord Howe Basins suggest that these areas may be underlain by a thinned and altered continental crust. Basement blocks similar to those on the western Lord Howe Rise and in the Lord Howe Basin, and intrusive rocks, appear to be present on the Dampier Ridge, whose basement is about 500-1000 m lower than that of the Lord Howe Rise. Basement blocks to the west of the Lord Howe Rise show little sign of planation, indicating that the Lord Howe and Middleton Basins and the Dampier Ridge may have been below wave-base before break-up and the formation of the Tasman Basin. In these areas sediments within sequence E are probably of shallow-marine or marine origin.

Another important aspect of the preliminary interpretation of Line SO-7-010 (Fig. 12) is that the break-up unconformity separating sequences D and E on the Lord Howe Rise appears to extend across the Lord Howe Basin and onto the Dampier Ridge. If this unconformity was generated by a marine transgression over an erosion surface after break-up and emplacement of oceanic crust in the Lord Howe Basin, it should be continuous with the oceanic basement surface. Since it is not continuous with the basement of the Lord Howe Basin, either (i) the Lord Howe Basin (and probably also the Middleton Basin) is not underlain by oceanic crust, or (ii) the unconformity results from a slightly more recent episode of spreading, presumably within the Tasman Basin. If the entire area (Dampier Ridge, Lord Howe and Middleton Basins, and Lord Howe Rise) were a submerged continental margin before seafloor spreading of the Tasman Sea, any further subsidence after break-up may not have given rise to a well-defined break-up unconformity. The area may thus have had the form of a trough-bounded marginal plateau before break-up. Further studies using processed seismic data are obviously required to resolve these difficulties.

The western margin of the Dampier Ridge is shown by BMR and <u>Sonne</u> profiles to consist of steep northeast-trending segments alternating with less steep northwest-trending segments. The profile for Line SO-7-006 (Fig. 13) shows that the southern margin of the Dampier Ridge is also steep (greater than 6°). We infer, partly from consideration of the magnetic lineation pattern in

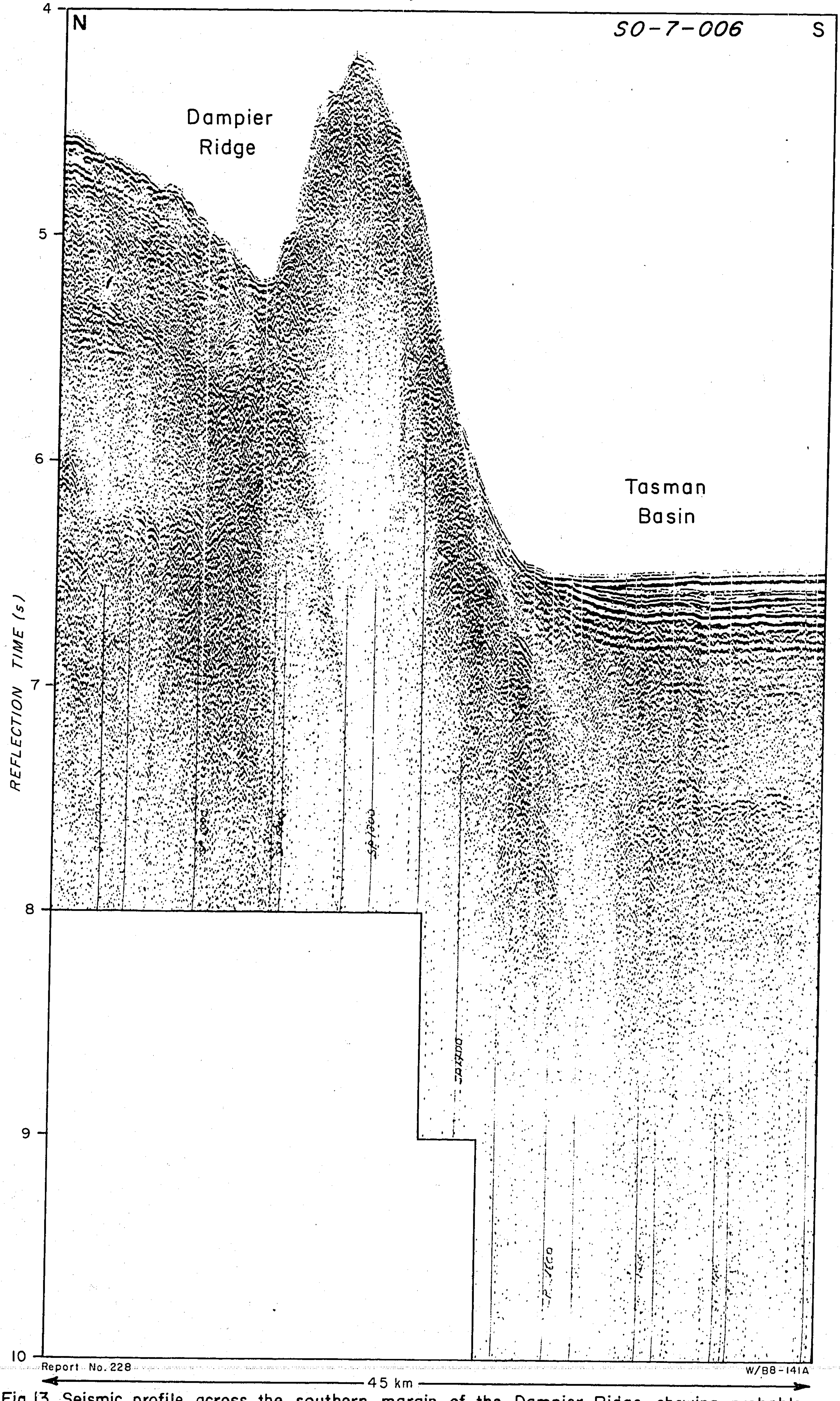


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Fig.13. Seismic profile across the southern margin of the Dampier Ridge showing probable intrusions (bathymetric peak) along a transform fault.

the Tasman Basin, that the steep segments were probably formed as a result of transform faulting, and the less steep segments as a result of rifting. The bathymetry indicates that this en-echelon pattern of rifted and transform segments, along similar northwesterly and northeasterly trends, may also be present along the margins of the Lord Howe Rise.

The profile for Lines SO-7-001A and 2 (Fig. 9) shows that a basin and ridge also flanks the western Lord Howe Rise in the south. These are the Monowai Sea Valley and Monowai Spur. The basement beneath the Monowai Sea Valley lies at a similar depth and has similar acoustic properties to that beneath the Lord Howe Basin, although its magnetic signature is more intense. The Monowai Spur, unlike the Dampier Ridge, appears to be composed entirely of crystalline basement. The structural trend, depths, and morphology of these features suggest that the Monowai Spur may be genetically related to the southern part of the Dampier Ridge, which appears to comprise a large proportion of crystalline rocks.

New Caledonia Basin

The New Caledonia Basin has an average water depth of a little over 3000 m, considerably less than the 4000-4500 m in the Tasman Basin. Most of this difference results from the sediment fill, which has 'time-thicknesses' of about 1-1.5s (probably 1000-1500 m) in the Tasman Basin and about 3s (probably in excess of 4000 m) in the New Caledonia Basin. In both basins the basement surface is evident at a reflection time of about 7s, but velocity considerations indicate that the basement is probably at least 1000 m deeper in the New Caledonia Basin. The greater depth of basement may indicate that the New Caledonia Basin is older than the Tasman Basin, although the effect of sediment loading needs to be considered.

On the basis of indirect seismic ties to DSDP Site 206 in the New Caledonia Basin, we have again been able to identify depositional sequences, each bounded by an unconformity. The upper four sequences correspond almost precisely in age with sequences A to D on the Lord Howe Rise (Fig. 14), and hence have been similarly named. In general, however, the sequences within the New Caledonia Basin have more internal reflectors than those on the Lord Howe Rise. Direct correlation of sequences A to D between the two areas is hindered by the steep gradient and thin section along the eastern edge of the Lord Howe Rise.

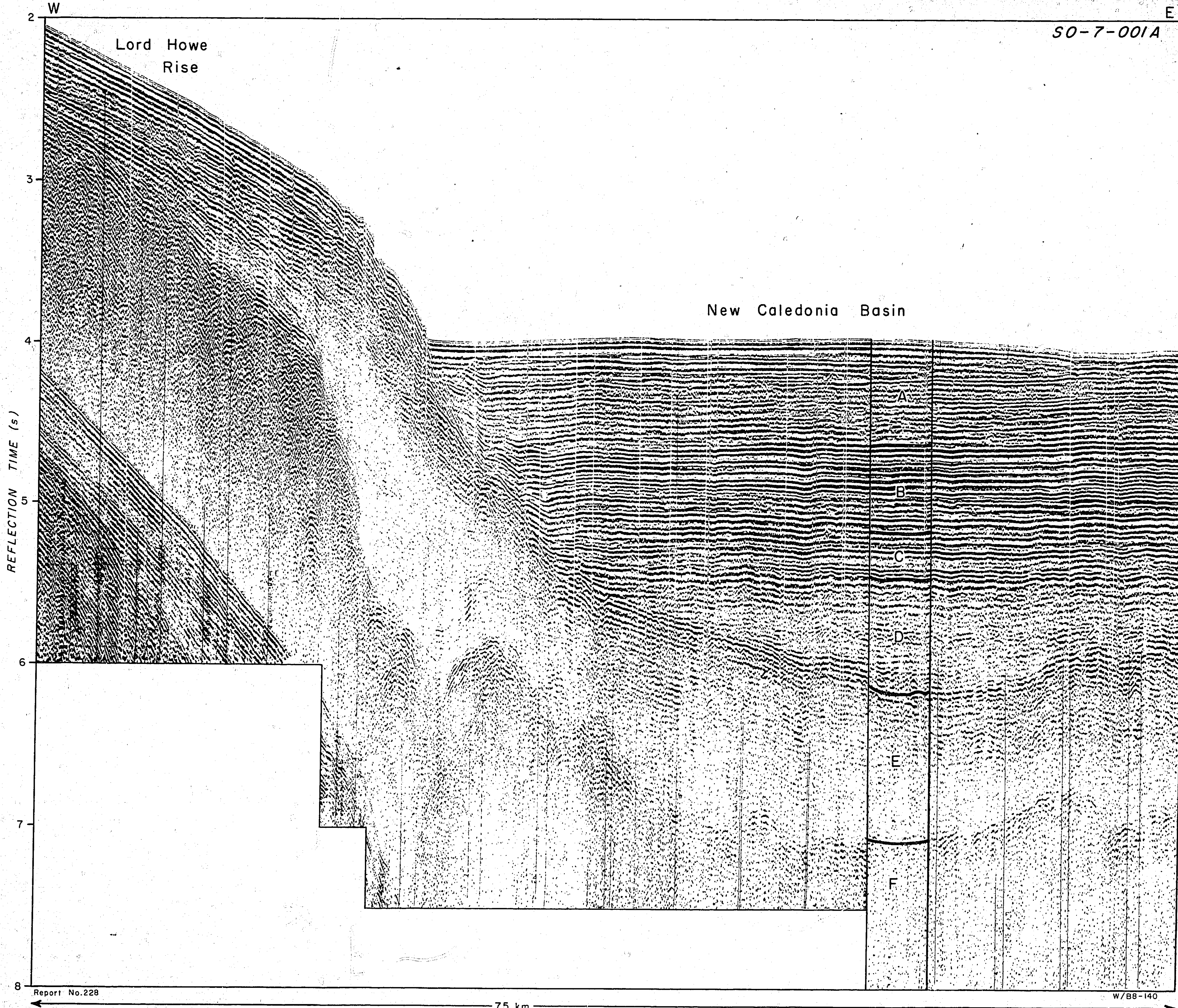

Fig.14. Seismic profile across the eastern flank of the Lord Howe Rise and the New Caledonia Basin. A marginal fault apparently juxtaposes continental and oceanic basement. The break-up unconformity on the Lord Howe Rise (D/E) appears to lie above oceanic basement in the New Caledonia Basin.

The lowermost sedimentary sequence was not penetrated at DSDP Site 206, but has been correlated tentatively with sequence E on the Lord Howe Rise, with which it appears to tie. This sequence forms an acoustically semitransparent sediment wedge which extends across the boundary fault separating continental crust on the Lord Howe Rise from oceanic crust beneath the New Caledonia Basin. It attains a thickness of at least 2000 m, and is probably composed of Cretaceous clastic sediments that were deposited on the ancient continental margin of the Australian-Antarctica supercontinent. Some company profiles across this margin show progradation within the sequence, similar to that which occurs around the margin of present-day Australia.

Correlation of this sediment wedge with sequence E implies that the New Caledonia Basin is older than the Tasman Basin. However, we know little of its exact age or mode of formation. It is interesting to note that the D/E unconformity surface within the New Caledonia Basin is gently folded and exhibits a well-defined onlap of sequence D. This may indicate that the Basin was affected during the Late Cretaceous by compressional forces similar to those that folded the graben sediments on the West Norfolk Ridge.

7. PRELIMINARY REFRACTION RESULTS

Figures 2a and 2b show the approximate locations at which sonobuoys were deployed to determine refraction velocities within the sedimentary section. Preliminary analyses of the monitor records have been made, and the velocity, thickness, and two-way time of the refraction intervals is given in Table 1. The calculations were based on a multilayer model in which all refractors were assumed to be horizontal (Dobrin, 1960).

These preliminary results, when plotted on to reflection profiles, indicate that the upper (Tertiary) sediments generally have refraction velocities ranging from about 2000 to 2400 m/s, although a superficial layer of velocity 1800 m/s is probably also present. (NB: 1500 m/s is the velocity of water.) The 'Lower Tertiary' and possibly 'Cretaceous' rift-fill sediments appear to have velocities in the range 2800 to 3600 m/s. Basement velocities are variable, but can be grouped into a lower range (about 4000-5000 m/s) which can probably be attributed to metasediments within a basement complex, and an upper range (5000 + m/s) which may result from volcanics and intrusions within the basement complex.

Processing of the refraction data is proceeding and should lead to more reliable picking and analysis of the velocities.

Table 1. Preliminary refraction velocities from sonobuoys (computed by L.A. Tilbury, BMR)

Sonobuoy III

'Velocity' layer	Intercept time(s)	Refraction velocity (m/s)	Thickness (m)	2-way time (s)
1	0.63	1500	888	1.17
2	2.08	1780	1019	2.31
3	2.71	3750	1367	3.04
4	3.32	5260	1679	3.68
5	-	6615	-	-

Sonobuoy IV

'Velocity' layer	Intercept time(s)	Refraction velocity (m/s)	Thickness (m)	2-way time (s)
1	1.25	1500	1258	1.68
2	2.69	2250	1379	2.90
3	-	4950	-	-

Sonobuoy V

'Velocity' layer	Intercept time(s)	Refraction velocity (m/s)	Thickness (m)	2-way time (s)
1	2.50	1500	2573	3.43
2	5.10	2190	2070	5.32
3	-	6230	-	-

Sonobuoy VI

'Velocity' layer	Intercept time(s)	Refraction velocity (m/s)	Thickness (m)	2-way time (s)
1	1.40	1500	1356	1.81
2	2.80	2370	1444	3.03
3	-	5020	-	-

Sonobuoy VII

'Velocity' layer	Intercept time(s)	Refraction velocity (m/s)	Thickness (m)	2-way time (s)
1	1.90	1500	2079	2.77
2	3.18	2060	1027	3.77
3	3.48	3122	(-122)*	(3.69)*
4	-	4864	-	-

Sonobuoy VIII

'Velocity' layer	Intercept time(s)	Refraction velocity (m/s)	Thickness (m)	2-way time (s)
1	3.92	1500	3237	4.32
2	5.29	3583	2595	5.77
3	-	5695	-	-

Sonobuoy X

'Velocity' layer	Intercept time(s)	Refraction velocity (m/s)	Thickness (m)	2-way time (s)
1	1.38	1500	1438	1.92
2	2.11	2160	731	2.59
3	2.55	2944	300	2.80
4	-	4450	-	-

'Velocity' layer	Intercept time(s)	Refraction velocity (m/s)	Thickness (m)	2-way time (s)
Sonobuoy XIII				
1	1.90	1500	1688	2.25
2	-	2800	-	-
Sonobuoy XIV				
1	1.63	1500	1630	2.17
2	2.30	2268	1541	3.53
3	3.00	2493	(-188)*	(3.38)*
4	3.18	3922	100	(3.43)*
5	-	4954	-	-

* Bracketed values have been generated by spurious refractions or by incorrect intercept times.

8. GRAVITY AND MAGNETIC DATA

Lines SO-7-001, 1A, and 2 together form the only complete crossing of the Lord Howe Rise and structural elements to its east. Profiles from the Norfolk Basin (east of the Norfolk Ridge) to the eastern slope of the Lord Howe Rise showed several features of interest, which are discussed below.

The Sonne Seamount, which rises 2800 m above the basement and 2200 m above the sea-floor, is characterised by a free-air anomaly of about 800 $\mu m.s^{-2}$ (80 mGal) peak amplitude, and a positive/negative magnetic anomaly of 500 nT peak to peak. Like many other seamounts, the Sonne Seamount does not appear to be isostatically compensated. The data collected from one crossing of the seamount are insufficient for constructing a geophysical model of it, but the ratio of magnetic-to-gravity anomaly is quite similar to that of the Derwent Hunter Guyot (Woodward, 1971) in the Tasman Sea, west of the Lord Howe Rise.

The <u>Sonne</u> profiles show a surprisingly small magnetic response over the Norfolk Ridge (about 200 nT), despite its considerable bathymetric expression, its associated free-air anomaly of more than 1000 $\mu m.s^{-2}$ (100 mGal) amplitude, and the presence of intrusive features as indicated on the seismic profile. Profiles presented by Lapouille (1977) to the north, and Woodward & Hunt (1970) to the south, show somewhat larger magnetic responses.

In contrast, the West Norfolk Ridge is characterised on the <u>Sonne</u> profiles by a narrow double magnetic anomaly of about 1500 nT peak to peak, and a positive free-air anomaly of 800 $\mu m.s^{-2}$ (80 mGal), decreasing sharply to a negative anomaly on the western side.

The crossing of the New Caledonia Basin from the Norfolk Ridge to the Lord Howe Rise intersects an Oceanographer line presented by Woodward & Hunt (1971) in the middle of the Basin, and the magnetic and gravity profiles from both lines are quite similar. The gravity data show negative anomalies on either side of the Basin, and a positive anomaly of 200 $\mu m.s^{-2}$ (20 mGal) amplitude in the centre. Woodward & Hunt (1971) considered that the positive anomaly was due to dense material in the upper layers of the crust. However, the seismic profile shows a basement high just west of the centre of the Basin, and we consider that this contributes significantly to the gravity high.

Figure 15 shows the gravity and magnetic profiles along Lines SO-7-001A and 2. The eastern edge of the Lord Howe Rise is characterised by a magnetic edge anomaly which rises to +1000 nT, and contrasts sharply with the broad negative anomaly of -400 nT in the New Caledonia Basin. This large positive/negative edge anomaly pair can be mapped along the strike of the structural elements southeastwards to the New Zealand continental shelf (Davey & Robinson, 1978).

At the southern end of Line SO-7-002 (Fig. 15), and even more noticeably at the southern end of SO-7-003, distinctive positive and negative magnetic anomalies occur over the Monowai Spur, and appear to be largely unrelated to basement structure. The Monowai system, which is parallel to the Lord Howe Rise, and the Dampier Ridge appear to be related in some way, and may be parts of a discontinuous ridge system broken by transform faults. However, the Dampier Ridge appears to be underlain by block-faulted continental basement, whereas the Monowai Spur is composed of crystalline rocks.

Within the horst and graben province underlying the western Lord Howe Rise, there is a general correspondence between basement structure and the gravity and magnetic anomalies. However, the ratio of the gravity-to-magnetic response varies considerably over different basement blocks, despite their similar acoustic properties, and may provide a means of determining the distribution of basement type.

Profiles across the western part of the Rise generally show a slightly more subdued magnetic field than that over the more elevated basement within the eastern part. Although the anomalies are commonly within $\pm$ 100 nT of the regional field, some individual anomalies of up to 1000 nT amplitude also occur. Mutter & Jongsma (1978) have speculated that a 'magnetic quiet zone' occupies the western part of the Rise, and that it results from altered continental (or rift-zone) crust underlying the horst and graben province. However, their hypothesis was based on only two BMR lines between about 30° and 34°S (Fig. 1).

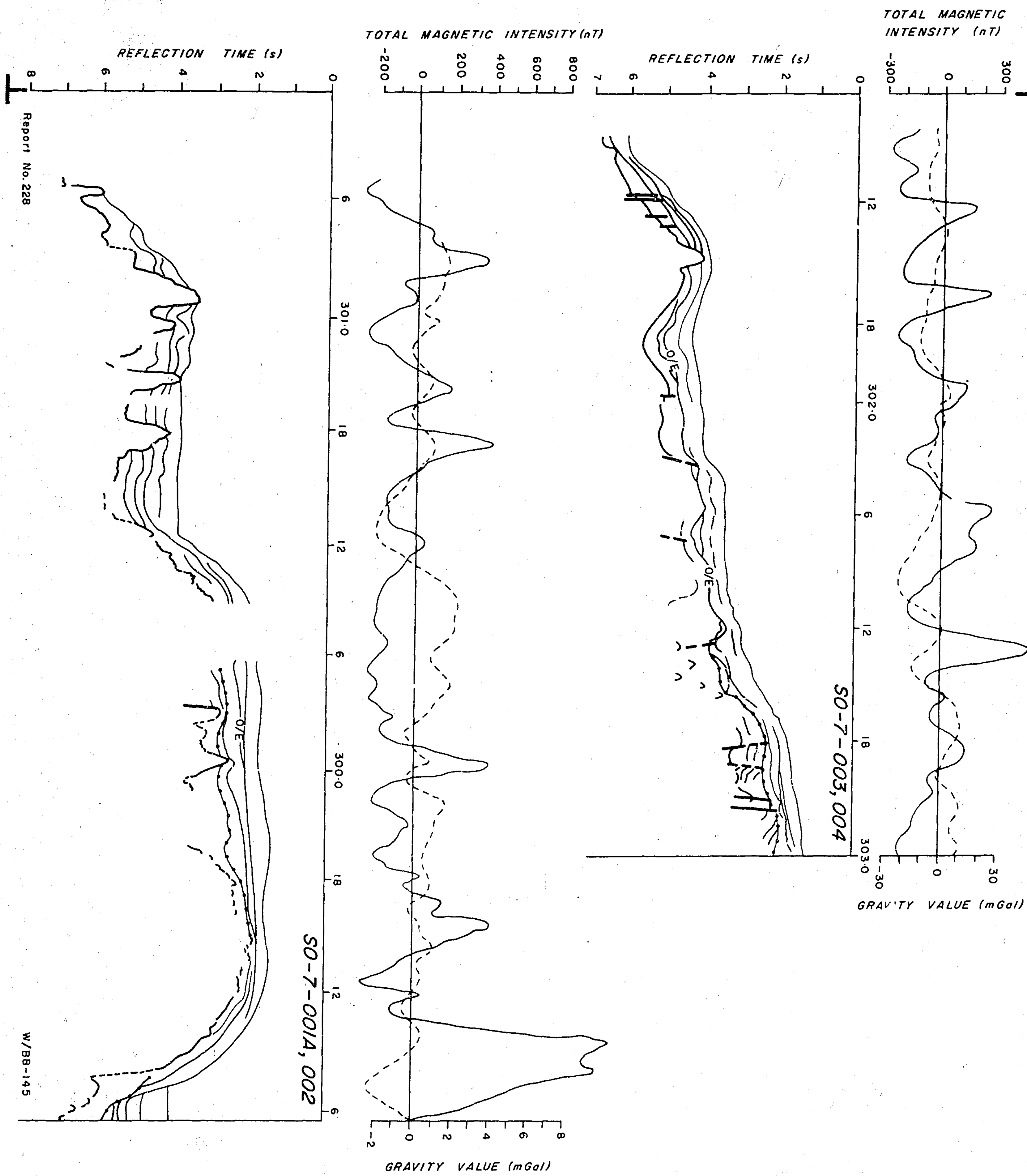

Fig. 15. Preliminary shipboard interpretation of selected seismic monitor records showing free-air anomaly profiles (dashed) and magnetic anomaly profiles (solid lines); locations are given in Fig. 2. The profiles are aligned on meridian 161° E. (Basement line heavy solid; break-up unconformity dotted; Eocene/Oligocene unconformity O/E).

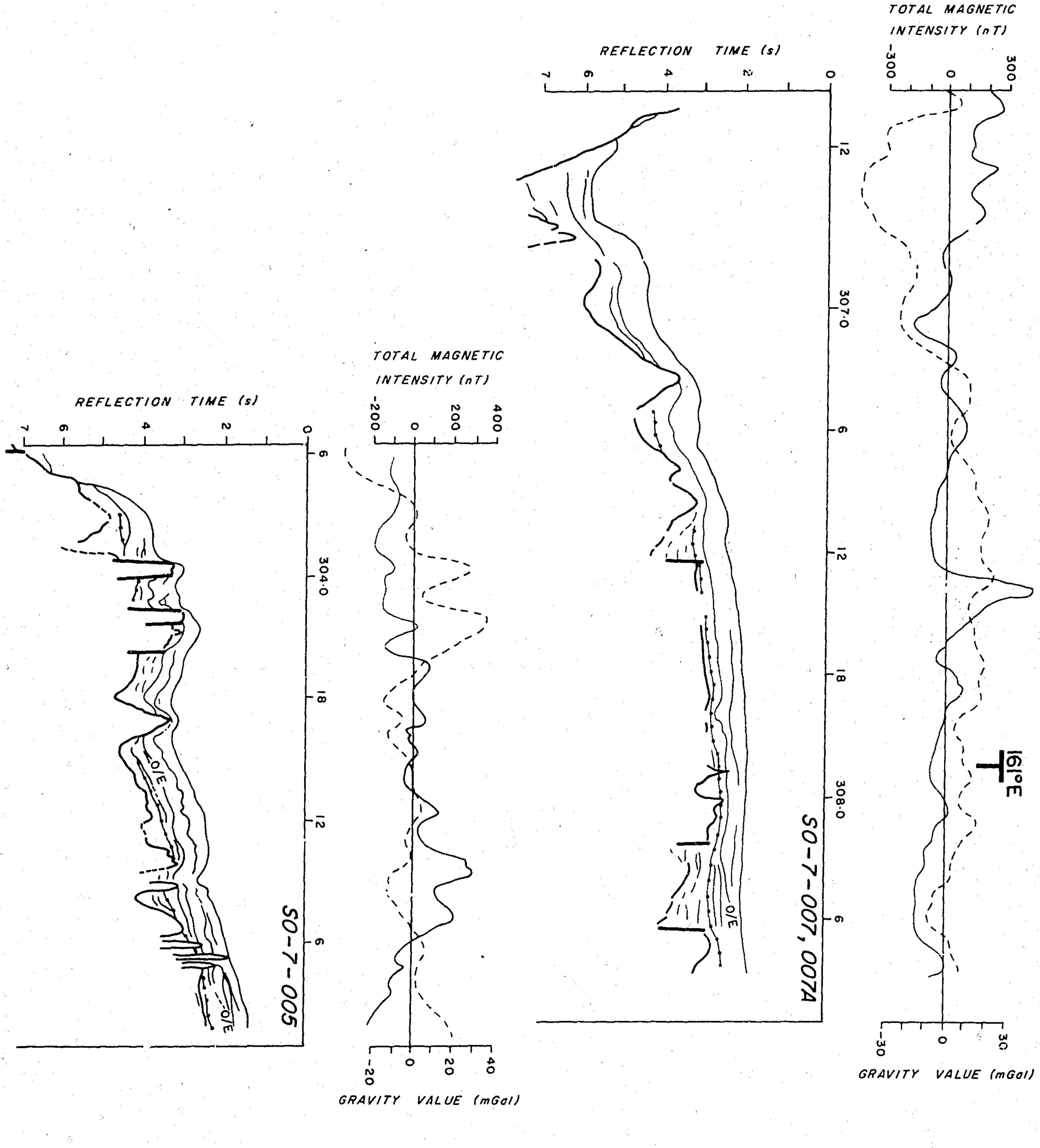

Fig. 15. (continued)

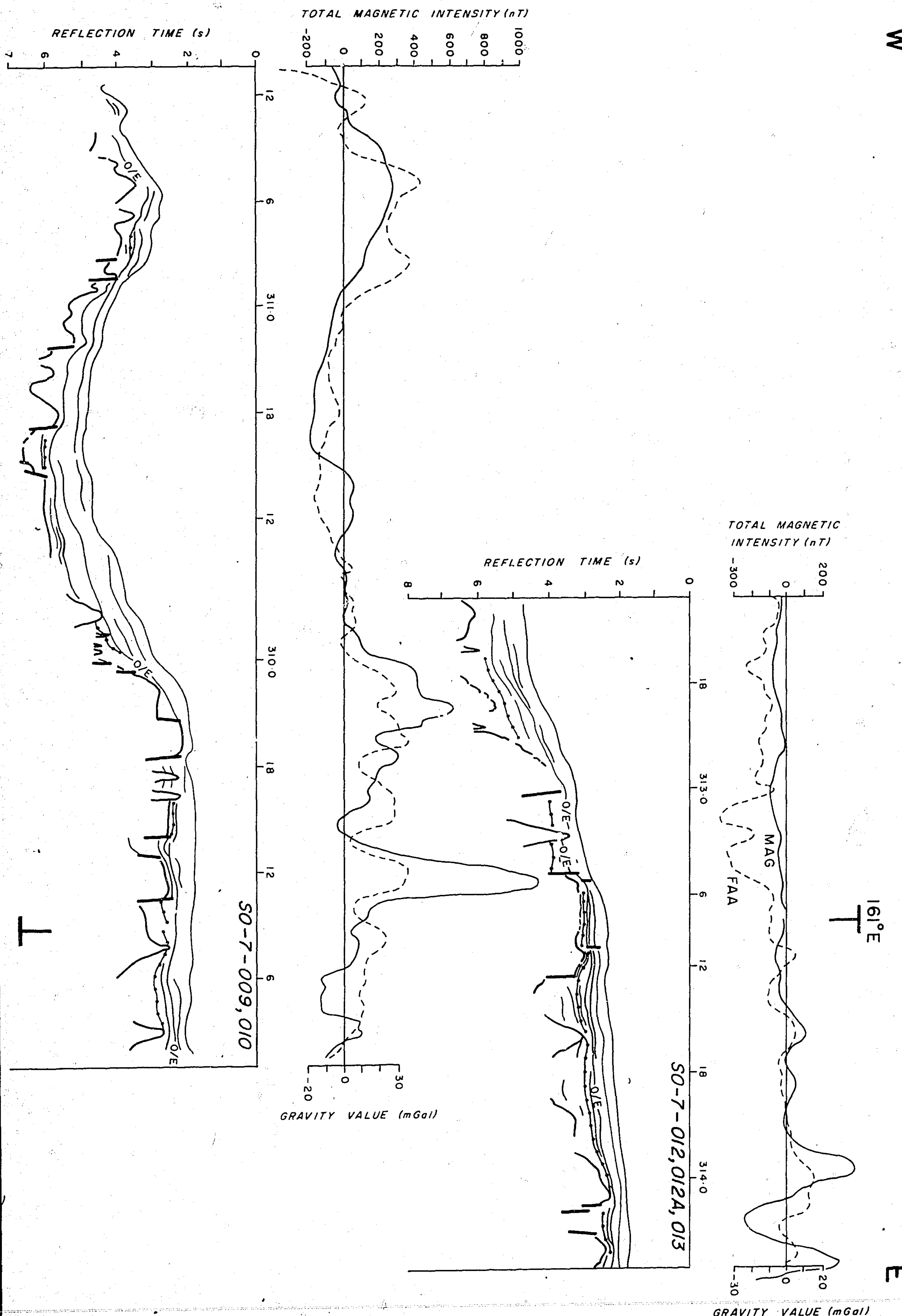

Fig. 15. (continued)

Although a zone of subdued magnetic field is apparent in several Sonne profiles between 26° and 34°S, it does not differ greatly from the field farther east, and could hardly be described as a 'magnetic quiet zone'.

The isolated large magnetic anomalies on the western part of the Rise do not obviously correlate with a particular basement type. Furthermore, their lack of correlation between the adjacent lines SO-7-005, BMR 14/066, BMR 14/068, and SO-7-009 and 10 show that they do not extend beyond 20-40 km or have any pronounced orientation.

Sonne profiles extend across the northern and southern edges of the Lord Howe Basin (SO-7-007, 009, and 010) and across the northern edge of the Middleton Basin (SO-7-012). Profiles over the Middleton Basin are particularly quiet, and in neither Basin is there any evidence of spreading anomalies as implied by Weissel & Hayes (1977, fig. 2).

In summary, the analysis of the gravity and magnetic data shows that:

(i) The gravity field reflects major relief of the faulted and intruded surface which forms the seismic basement.

(ii) The magnetic field over the western Lord Howe Rise is generally subdued, but its contrast with that over the eastern part of the Rise is not sufficient for it to be called a 'magnetic quiet zone'.

(iii) There is an apparent absence of edge anomalies in the gravity and magnetic fields at the western margins of the Lord Howe Rise and the Dampier Ridge.

(iv) No pronounced regional lineations are apparent in the gravity or magnetic fields, apart from the edge anomalies between the New Caledonia Basin and the adjacent structural elements.

The amount of high-quality data has not been increased sufficiently by the cruise for a meaningful regional analysis of magnetic and gravity data to be made, at least as far north as latitude 30°S.

9. CONCLUSIONS

The main conclusions which we can make from Sonne cruise SO-7A of the Lord Howe Rise area are as follows:

Lord Howe Rise

(i) There is some justification for dividing the Lord Howe Rise into an eastern province characterised by elevated planar basement, and a western province of horsts and grabens. However, this division is not clear-cut, since the area of planar basement becomes quite narrow in the north, and horsts and grabens occur on the northeastern flank of the southern Lord Howe Rise (Challenger Plateau). The horsts and grabens may lie within a mobile zone, possibly related to rifting which developed before the Tasman Sea basins formed. Jongsma & Mutter (1978) have described the zone as a rift-valley, but it lacks the development of major rift or pull-apart basins which occur on many other rifted margins.

(ii) The grabens appear to trend north-northwest or northwest, roughly parallel to spreading ridges in the Tasman Basin. They contain up to 3000 m of pre-break-up, probably Cretaceous sediment of continental or shallow-marine origin. The overburden of shallow-marine and pelagic sediment ranges in thickness from a few hundred metres to about 1000 m.

(iii) Widespread depositional sequences have accumulated in the Lord Howe Rise area. Their internal reflection configuration is compatible with their depositional history as deduced from DSDP results.

(iv) Probable reef structures are evident on the D/E break-up unconformity of Late Cretaceous age, and within the shallow-marine sequence immediately above it.

(v) Basement on the Lord Howe Rise exhibits very variable magnetic and acoustic properties, and is probably composed of Palaeozoic metasediments of the Tasman Geosyncline extensively intruded by volcanics.

Middleton and Lord Howe Basins, and Dampier Ridge

(vi) Horst and graben structures extend across the Middleton and Lord Howe Basins, and the Dampier Ridge. The Basins are probably underlain by crystalline basement which does not appear to have associated magnetic lineations as implied by Weissel & Hayes (1977) and may thus be continental. On the Lord Howe Rise, an unconformity of probable Late Cretaceous age is interpreted to be a break-up unconformity associated with spreading in the Tasman Sea; however, this unconformity is not continuous with basement in the Middleton and Lord Howe Basins, which implies that the Basins either were formed during an earlier period of spreading or are not underlain by oceanic crust.

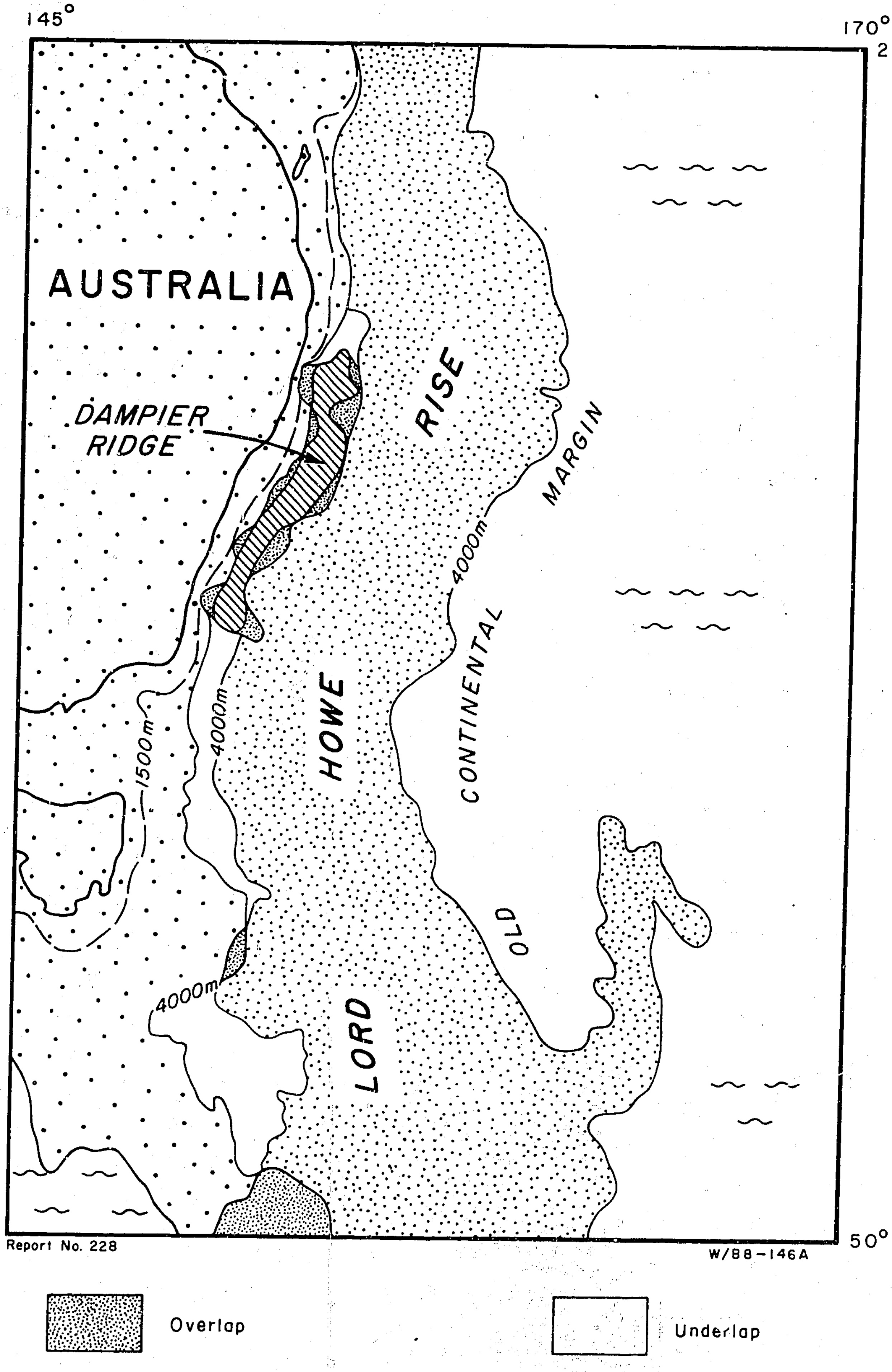

Fig. 16. The reconstructed positions of the Lord Howe Rise and the Dampier Ridge relative to the Australian plate for anomaly 33 time (72 to 76 m.y. BP), showing relative overlap and underlap; based on Shaw (1978)

(vii) Basement blocks similar to those beneath the western Lord Howe Rise underlie the Dampier Ridge, where, however, crystalline basement is also common. The Dampier Ridge must be largely of continental origin, but the anomalous position it occupies in reconstructions of the 'Lord Howe' and 'Australian' plates (see Figs. 5b & 16) is difficult to explain.
(viii) Basement blocks beneath the Middleton and Lord Howe Basins, and Dampier Ridge, have not been planated like those on the Lord Howe Rise. This implies that they were below wave-base before break-up, and hence that the Lord Howe Rise may have been a trough-bounded marginal plateau at that time.
(ix) The Monowai Sea Valley and Monowai Spur, in the southwest of the survey area, lie at similar depths to the Lord Howe Basin and Dampier Ridge respectively, and may be southerly extensions of these features.

New Caledonia Basin

(x) The eastern margin of Lord Howe Rise was once the margin of the Australian-Antarctic supercontinent, shedding sediment into the New Caledonia Basin. The New Caledonia Basin is thus older than the Tasman Basin.
(xi) Folding within the sediments of the West Norfolk Ridge and New Caledonia Basin may have resulted from compressional stresses generated in the Late Cretaceous.

Petroleum potential

(xii) In the horst and graben province, petroleum source rocks within the pre-break-up sequence, and in places in the marine sequence deposited immediately after break-up, are probably deeply buried enough to have reached maturity. The recorded high heat flow in the Lord Howe Rise area may have aided this process. However, the potential of the area is downgraded by the probable presence of volcanics. The thick wedge of sediment on the eastern flank of the Rise will have to be surveyed further before its petroleum potential can be assessed.

Further surveys and interpretation

Figure 17 illustrates schematically the areas where further work is required; the numbers refer to the following:
(1) A reconnaissance survey of the northern part of the Lord Howe Rise, covering the deeply submerged area north of the Middleton Basin, and extending onto the Kenn, Bellona, and Chesterfield Plateaus region farther north.

(2) A reconnaissance survey of the almost totally unknown area of the southern Lord Howe Rise and Challenger Plateau.

(3) A detailed study of the Monowai Sea Valley and Monowai Spur, to determine whether they are related to the Lord Howe Basin and Dampier Ridge.

(4) Further seismic interpretation, and possibly a detailed survey, to determine the extent and trend of the grabens on the western Lord Howe Rise and their relations to the margins of the Rise.

(5) Further seismic interpretation using all available data, and probably further surveying, to determine the structure, geological history, and petroleum potential of the ancient continental margin which is thought to lie along the eastern edge of the Lord Howe Rise.

(6) Geophysical interpretation of the West Norfolk Ridge, probably leading to further surveys.

(7) Detailed studies and surveys along the eastern seaboard of Australia, to identify rifted and transform segments of the margin and to locate any fragments of rift-basins left behind after spreading.

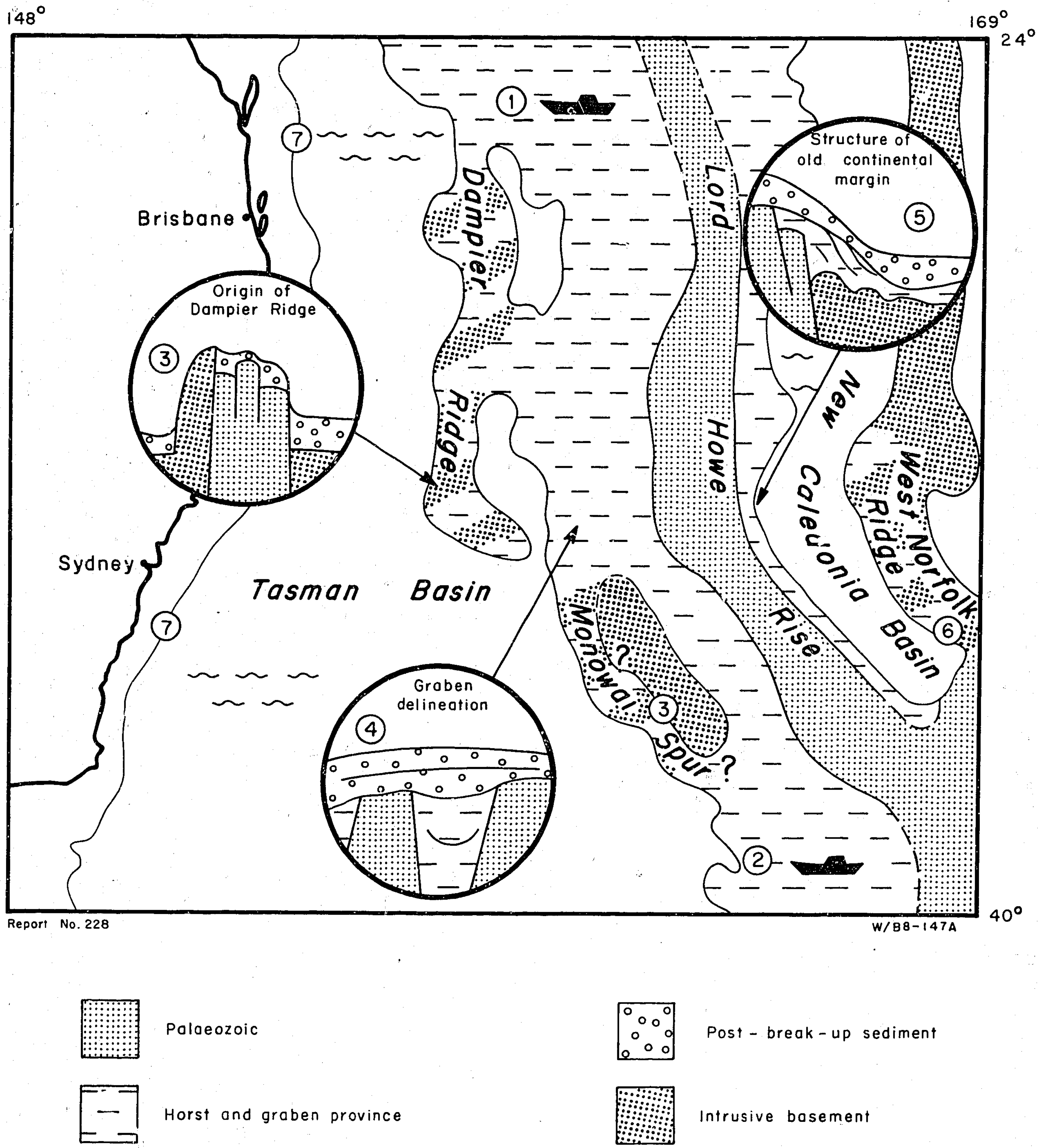

Fig. 17. Schematic map showing existing problems in the survey area and the need for further surveys. Numbers represent points discussed in the text.

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APPENDIX

Summary of survey vessels and types of data collected over the Lord Howe Rise and Norfolk Ridge (after Jongsma, 1976)

Vessel	Cruise	Date	Seismic	Gravity	Magnetics	Miscellaneous
ARGO	NOVA	1967	Airgun	Yes	Yes	Refraction
BERGALL		1949	No	Pendulum	No	
BURTON ISLAND (Deep Freeze)		1961	No	No	Yes	
CHALLENGER		1951	No	No	No	Refraction
CONRAD	C9	1964	Explosive	Yes	Yes	
CORIOLIS	C1	1971	Airgun	No	Yes	
CORIOLIS	C2	1971	Airgun	No	Yes	
CORIOLIS	AUSTRADEC 1	1972	Flexichoc	No	Yes	
CORIOLIS	AUSTRADEC 2	1973	Flexichoc	No	Yes	
ELTANIN	ELT 26	1966	Airgun	Yes	Yes	
ELTANIN	ELT 29	1967	Airgun	Yes	Yes	
ELTANIN	ELT 34	1968	Airgun	Yes	Yes	
ELTANIN	ELT 39	1969	Airgun	Yes	Yes	Sonobuoys
ELTANIN	ELT 47	1971	Airgun	Yes	Yes	Sonobuoys
FRED V.H. MOORE	MOBIL	1972	HI/FES & Airgun	Yes	Yes	Sonobuoys
GLOMAR CHALLENGER	DSDP 21	1971/72	Airgun	No	No	Sonobuoys, drilling
GLOMAR CHALLENGER	DSDP 29	1973	Airgun	No	No	Sonobuoy, drilling
HORIZON	NOVA	1967	Sparker	Yes	Yes	Refraction
KANA KEOKI		1971	Airgun Sparker	Yes	Yes	
KIMBLA	K3	1971	Airgun	No	Yes	
KIMBLA	K4	1971	Airgun	No	Yes	

APPENDIX - (Continued)

Vessel	Cruise	Date	Seismic	Gravity	Magnetics	Miscellaneous
LADY CHRISTINE	BMR 14/3	1971	Sparker	Yes	Yes	Sonobuoys
OCEANOGRAPHER		1967	No	Yes	Yes	
STRATEN ISLAND (Deep Freeze)		1960	No	No	Yes	
TARANUI		1966	No	No	Yes	
TARANUI		1967	No	No	Yes	
TELEMACHUS		1956	No	Pendulum	No	
UNITED GEOPHYSICAL		1970	Yes	Yes	No	
VEMA	V18	1962	Explosives	Yes	Yes	