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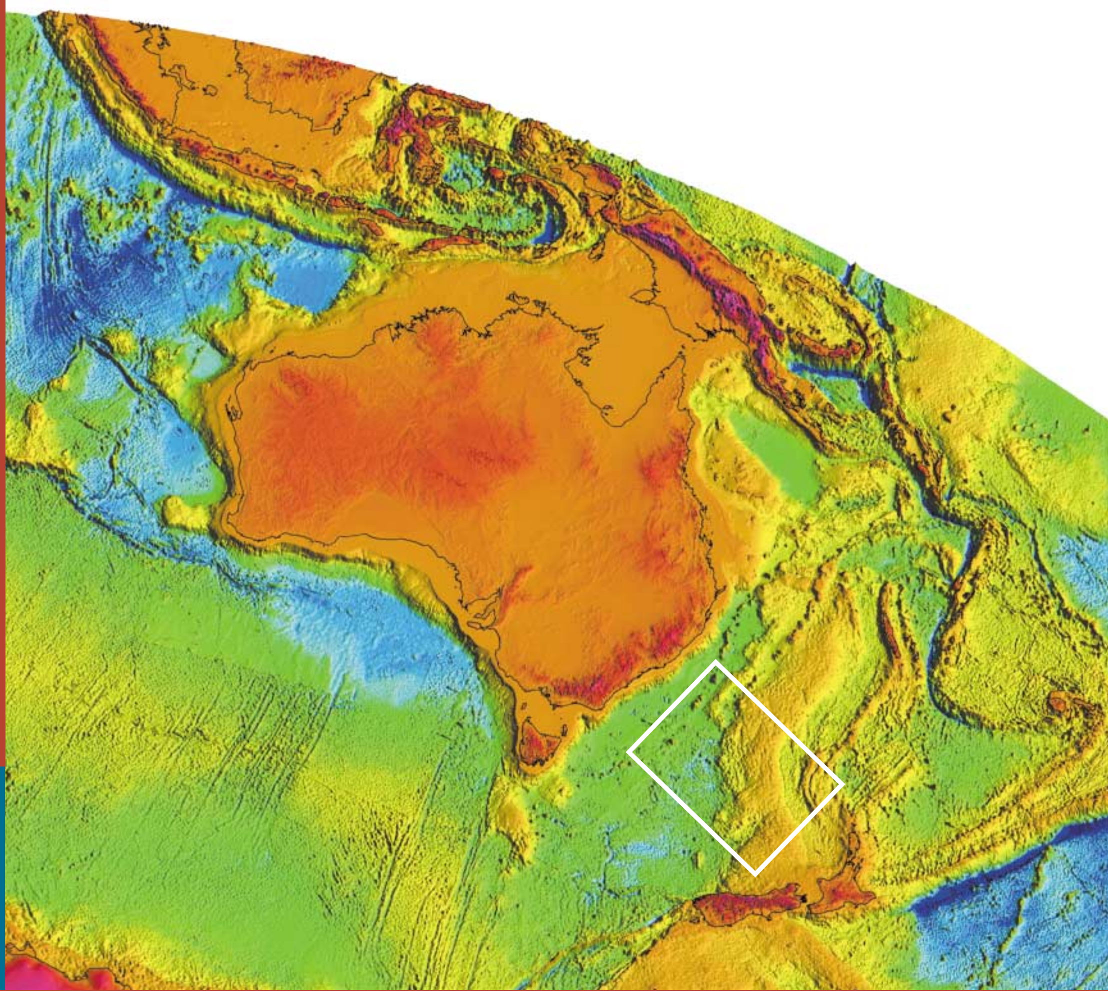

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GEOLOGICAL FRAMEWORK OF THE SOUTHERN LORD HOWE RISE AND ADJACENT AREAS

H.M.J. Stagg, M.B. Alcock, I. Borissova & A.M.G. Moore

Petroleum and Marine Division, Geoscience Australia,
GPO Box 378, Canberra, ACT 2601
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CONTENTS

The data and the interpretations based on that data contained in this report are not necessarily indicative or representative of the final information that might be used by Australia to support the location of the outer limit of the continental shelf beyond 200 nautical miles.

EXECUTIVE SUMMARY

Analysis of the extent of Australia's legal continental shelf under the United Nations Convention on the Law of the Sea (UNCLOS) has shown that there are nine areas of 'extended Continental Shelf' that extend beyond the 200 mile Australian Exclusive Economic Zone (AEEZ). One of these areas includes the physiographic and geologic province of the Lord Howe Rise and the adjacent oceanic ridges and basins, east of Australia. The geological framework of the region has been interpreted from conventional seismic and deep-penetration seismic, crustal refraction velocities, potential field, heat-flow, and geological samples from scientific and exploration drilling and from seabed dredging and coring.

The Lord Howe Rise extends north for more than 1600 km from the Challenger Plateau, west of New Zealand, to southwest of New Caledonia in water depths generally greater than 1000 m. The rise is underlain by continental crust which detached from eastern Australia during the margin breakup that led to the formation of the oceanic Tasman Basin from 85-52 Ma. While the rise has long been recognised as having long-term hydrocarbon potential as a frontier province, interpretation of all the available regional data sets shows that potentially prospective sedimentary basins underlie it for much of its length.

The rise is 400-500 km in width and comprises four sub-parallel provinces that extend for most of its length. From east to west, these provinces comprise:

- Shallow, planated, probable Palaeozoic basement of the *Lord Howe Platform*, overlain by a few hundred metres of mainly Cainozoic siliceous and carbonate oozes. To the east, the basement of the New Caledonia Basin is about 4 km deeper and of uncertain crustal affinity, while the western boundary of the platform is defined by a sharp Cretaceous hinge.

- A central rifted province adjacent to the Lord Howe Platform and characterised by a series of poorly-defined basement blocks, normally down-faulted to the west, with 2-4 km of Upper Cretaceous and Cainozoic syn- and post-rift section. This province includes the *Moore Basin* in the south and the *Faust Basin* in the north.

- A western rift province which is separated from the central rift by a broad fault zone across which basement is down-faulted to the west. Basement and water depths are considerably deeper than in the central rift, and the syn- and post-rift sediments are considerably thicker. This province includes the *Monowai Basin* in the south and the *Capel Basin* in the north. In the vicinity of Lord Howe Island, the central and western rifts cannot be separated, and the combined rift has been referred to as the Gower Basin.

- A western bounding complex ridge system of known continental origin. In the north, the *Dampier Ridge* is separated from the western rift province by the Lord Howe and Middleton Basins, which may be underlain by highly extended lower

continental crust. Further south, where extension is less extreme, the *Monowai Ridge* forms an intact outer margin to the Monowai Basin.

Regional-scale crustal lineaments, interpreted from satellite gravity and seismic data, are important in the evolution of the region. These lineaments are aligned along two main trends: NE-SW, parallel to the Cretaceous-early Cainozoic Tasman Basin spreading direction, and NW-SE, roughly perpendicular to the convergence direction between the Australian and Pacific Plates in the late Cainozoic. The NE-SW lineaments have been particularly important in influencing the present-day regional structure, and have segmented the Lord Howe Rise into a southern province, which includes the Monowai Basin and Ridge, and the Moore Basin; a central province, which includes the southern Dampier Ridge, Lord Howe Basin and Gower Basin; and a northern province, which includes the central and northern segments of the Dampier Ridge, Middleton Basin, Capel Basin and Faust Basin.

This study confirms the long-term hydrocarbon potential of the Lord Howe Rise region, both for conventional and unconventional hydrocarbons. The most prospective areas are the central and western rift provinces of Lord Howe Rise (Moore and Monowai Basins), the eastern flank of Lord Howe Rise, adjacent to the New Caledonia Basin, and possibly in the New Caledonia Basin itself, where the sediment thickness reaches 3.5 s TWT (*ca* 4+ km).

Despite the lack of wells and other rock samples in the region, structural and palaeogeographic considerations suggest that hydrocarbon source rocks may be present, particularly in Late Cretaceous syn-rift sediments. A favourable restricted marine environment may also have prevailed in the restricted half-grabens on the western Lord Howe Rise, and in the New Caledonia and Reinga Basins. Hydrocarbon traps may exist against the boundary faults and as smaller structures within the depocentres. Interbedded shales and pelagic oozes may provide a regional seal.

High-quality seismic data and satellite synthetic aperture radar (SAR) imagery indicate possible direct hydrocarbon indications. Bottom simulating reflectors (BSRs) are observed in seismic reflection data on the northeast and southwest flanks of Lord Howe Rise and may indicate the presence of gas hydrate. In the northeast, the general coincidence of the BSR with the western updip flank of the Fairway Basin may indicate a thermogenic component to the gas hydrates. Also, in this area, some evidence for low-level oil slicks and films on SAR imagery, combined with seismic evidence for fluid migration through the sedimentary section, may indicate that active hydrocarbon generation is taking place. While non-conventional hydrocarbon resources cannot currently be exploited, their interpreted presence suggests that hydrocarbons may be currently being generated. If such hydrocarbons are of thermogenic, rather than biogenic origin, this significantly upgrades the hydrocarbon prospectivity of the region.

1. INTRODUCTION

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) defines a nation's legal seabed and subsoil jurisdiction as extending throughout its Continental Shelf (Fig. 1; Appendix 1)[1]. Where the continental margin of a nation extends beyond 200 nautical miles, the outer limit of the "legal" Continental Shelf is defined by a series of rules contained within Article 76 of UNCLOS (United Nations, 1983). The rules require definition of the foot of the continental slope, knowledge of sediment thickness and good bathymetric information defining the 2500 m bathymetric contour. The Continental Shelf must be defined, at least, every 60 nautical miles around the parts of the margin extending beyond 200 nautical miles, and thus in these areas a comprehensive seismic and bathymetric database, together with a detailed understanding of the continental margin geology, is essential to optimising the area of the extended Continental Shelf.

A preliminary analysis of the extent of Australia's legal Continental Shelf under UNCLOS (Symonds & Willcox, 1989), including the EEZ around the Australian Antarctic Territory, indicated that it could be at least 14.8 million square kilometres in area - nearly twice the area of the continent and one of the world's largest. Nine areas of Continental Shelf extend beyond the 200 nautical mile Australian Exclusive Economic Zone (AEEZ). Geoscience Australia has the responsibility for ensuring that Australia has the necessary technical information to fully define its Continental Shelf under UNCLOS. Geoscience Australia has decided to adopt a 'safe minimum' approach to Continental Shelf definition in which bathymetric and seismic data are acquired, or compiled, on profiles spaced about 30 nautical miles apart over areas of margin extending beyond the AEEZ. Internal Geoscience Australia assessments indicated that further data collection and analysis was needed in about six of the eight areas extending beyond the AEEZ. One of the areas requiring such analysis was the Lord Howe Rise and Norfolk Ridge, surrounding Lord Howe and Norfolk Islands in the Tasman Sea, where Australia has very large potential extended Continental Shelf (Fig. 1; Symonds et al., 2001).

This report presents the geological framework information relevant to consideration of Australian extended Continental Shelf over the southern Lord Howe Rise, south of Lord Howe Island.

1.1 Limits of the Study Area

The AEEZ and the extended Continental Shelf in the vicinity of Lord Howe and Norfolk Islands are complex in their morphologic and geologic definition and large in

[1] The 'Legal Continental Shelf' ('LCS'), defined by a complex series of rules or formulae, is quite distinct from the geomorphic continental shelf as understood by a marine scientist. The LCS includes the geomorphic continental shelf, the continental slope, marginal plateaus and sometimes the continental rise and the inboard edge of deep ocean basins.

area. In addition to the rules to be applied under UNCLOS Article 76, boundaries also require negotiation with New Zealand to the southeast. Boundaries have already been negotiated with France to the north and northeast. Because of these boundary complexities, and because of the large area encompassed by the Lord Howe Rise and its environs (more than 4 million km^2, or more than half the area of the Australian landmass), the Geoscience Australia geological framework study has been split into southern and northern sectors, with this report focussing on the southern area.

2. BACKGROUND

While this study concentrates on the geological framework of the southern sector of the Lord Howe Rise and adjacent basins and ridges, the framework cannot be understood without reference to the regional geology of the wider area of the southwest Pacific and eastern Australia. Therefore, this report is both spatially and temporally wide-ranging. Spatially, it covers the area ranging from New Zealand in the south to New Caledonia in the north, and from eastern Australia in the west to the Tonga-Kermadec Trench in the east. The time range covered extends from the Palaeozoic to the Recent, although concentrating mainly on the Cretaceous and Cainozoic periods.

The present-day rises, ridges and basins of the Lord Howe Rise region are generally interpreted to comprise mainly continental fragments that detached from the eastern margin of Australia during the latest Jurassic and Cretaceous rifting episode that led to the formation of the Tasman and New Caledonia Basins. These continental fragments were themselves composed of terranes that accreted to the eastern edge of the Australian carton in the Palaeozoic and early Mesozoic. The region has passed through the full gamut of continental margin development, from compression and accretion, through passive margin extension, breakup and seafloor spreading, to the present-day convergence and subduction setting. While both compression and extension have generally taken place in an approximately east-west direction, the azimuths of relative motion between plates and microplates has varied widely through time. The resultant geology is complex.

While the Lord Howe Rise and its companion features have been known for many years, and a number of scientific papers have been written on the region, most of these papers have concentrated on the geology of localised areas and very little has been written on the regional geology and tectonic evolution. This report aims to redress this shortcoming by providing an integration of the relevant existing knowledge with an interpretation of new data sets.

2.1 Physiography

Although the Lord Howe Rise constitutes the major physiographic feature in the region, there are a number of other significant sub-parallel rises, ridges and basins in the region (Fig. 2; Plate 1). The following section summarises the main physiographic characteristics of these elements.

The Lord Howe Rise extends from the eastern Coral Sea, southwest of New Caledonia, in the north, to the Bellona Trough in the south. The Bellona Trough separates the Lord Howe Rise from the Challenger Plateau which abuts the South Island of New Zealand. At about 2500 km in length and with a width of 450-650 km, the combined Lord Howe Rise – Challenger Plateau province has a total area of about 1 500 000 km^2, approximately 50% greater than the area of the North West Shelf, including its marginal plateaus, and comparable with the area of the state of Queensland.

The NW-trending northern segment of Lord Howe Rise merges with a region of complex topography, which includes features such as the Chesterfield Plateau, Kenn Plateau, Mellish Rise and the NW-trending Fairway Ridge (Dubois et al., 1974). The central segment of the rise trends north-south for some 1100 km from about 24-34°S. The southernmost segment of the rise again trends NW-SE, and is separated from the Challenger Plateau adjacent to the New Zealand continental margin by the 3000 m deep, N-S trending Bellona Trough at about 39 °S (Fig. 2; Plate 1).

Excluding the islands and banks of the N-S trending Lord Howe seamount chain on the western flank of the rise, the rise is shallowest in the east. Here crestal water depths generally range from 1000-1500 m. The western flank of the rise is morphologically complex. Along the N-S trending, central segment of the rise, the Dampier Ridge (crestal water depths of 2000-2500 m) is separated from the rise by the 3000-4000 m deep Lord Howe and Middleton Basins (Fig. 2; Plate 1). In the south, the western flank of the rise is formed by the NW trending Monowai Sea Valley, at about 3000 m depth, and the slightly shallower Monowai Spur to the southwest.

Lord Howe Rise is separated from eastern Australia by the Tasman Basin and the Cato Trough. This ocean basin is triangular in outline, narrowing from about 1100 km in the south, between Tasmania and New Zealand, to about 150 km in the north, southeast of the Marion Plateau (Fig. 2; Plate 1). The basin floor lies at water depths of about 4800-5100 m, and varies from quite flat to extremely rugged, depending on the presence of fracture zones. The Tasman Sea is notable for the presence of the linear N-S trending Tasmantid seamount chain, which extends from the northern Tasman Sea to about 37°S, where it appears to bifurcate. These seamounts have relief of up to 2500 m above the seabed and some of them have planated summits (guyots), indicating that they have been subaerially exposed in the past.

To the east of Lord Howe Rise, lies the sub-parallel New Caledonia Basin (Fig. 2; Plate 1). This basin extends for about 2000 km from the continental margin of the North Island of New Zealand to southwest of New Caledonia. As with the Lord Howe Rise, there are NW-SE trending segments in the north and south, separated by a N-S trending central segment. The basin has strong linearity, with an average width of about 150 km. The base of the basin is generally very flat-lying, at a depth of about 3000 m.

The eastern flank of the New Caledonia Basin is bounded by the Norfolk Ridge system, a complex series of ridges and basins that extends for some 1600 km from the northern tip of New Zealand to New Caledonia (Fig. 2; Plate 1). In the south, it comprises the NW trending West Norfolk Ridge, Wanganella Basin, Wanganella Ridge, Reinga Basin and Reinga and South Maria Ridges, with water depths generally ranging from 300-1000 m on the ridges to 1500-2000 m in the intervening basins.

This segment is bound to the northeast by the large-scale, NW-trending scarp of the Vening Meinesz Fracture Zone (VMFZ; Plate 2). The northwest extension of the VFMZ separates the southern part of the Norfolk Ridge system from the N-S trending Norfolk Ridge proper. The N-S trending segment of the Norfolk Ridge is steep-sided and only about 70 km in width. Crestal water depths average 1000 m, and Norfolk Island is the only exposed portion of the ridge. The western flank of the ridge is punctuated by a chain of seamounts that are prominent in the satellite gravity data (Plate 2).

To the east of Norfolk Ridge lies the complex province which includes the North and South Norfolk Basins, Kingston and Bates Plateaus, Three Kings Ridge, South Fiji Basin, and the Tonga-Kermadec Trench and its associated volcanic ridges (Bernardel et al., 2002; Fig. 2; Plates 1 & 2). These features have derived from complex processes related to the collision of the Australian and Pacific Plates and will not be described further here.

2.2 Data Sets Used in the Study

2.2.1 Bathymetry

The principal bathymetric dataset used in this study was the gridded, levelled bathymetric dataset of Petkovic & Buchanan (2002), which combined a number of sources of bathymetric data, including single-beam and swath ship-acquired bathymetric data, and the 2 arc-minute predicted bathymetry of Smith et al. (1997) derived principally from the satellite altimeter gravity dataset. The gravity field accurately reflects sea-floor topography in the 15-160 km wavelength band, except for areas with large sediment thicknesses. Large-scale bathymetric features are generally isostatically compensated and do not correlate with the gravity field, except at their boundaries. Smith & Sandwell (1994) developed an algorithm to predict depth from the satellite gravity, ground-truthing their model with ship-acquired data. Predicted bathymetry can be helpful in studies of remote areas, where ship-acquired bathymetric data are sparse. In the Petkovic & Buchanan (2002) grid, ship-acquired bathymetric data were merged with the 2 arc-minute dataset so that areas without ship-acquired gridded data were filled with predicted bathymetry values. Figure 2 shows the Petkovic & Buchanan (2002) grid for the Lord Howe Rise region and uses a hill shading technique to highlight the bathymetric features.

Contour bathymetric data have been used as a backdrop for displaying survey lines and interpretation results. We used contours from a digital version of the General Bathymetric Chart of the Oceans (GEBCO; Jones et al., 1997; Fig. 3).

2.2.2 Seismic Reflection

The Lord Howe Rise is a 'frontier area' for commercial hydrocarbon exploration, which is generally the principal stimulus to the acquisition of reflection seismic data. Therefore the acquisition of seismic data in the region has generally been on irregular grids and at infrequent intervals. A few commercial spec seismic survey lines have been acquired over the Gower Basin on the central Lord Howe Rise in recent years.

The principal data sets that have been acquired since the early 1970s include (Appendix 2; Fig. 4; Plates 2, 3):

United Geophysical Corporation (1970): The United Geophysical Corporation acquired a seismic survey in a roughly east-west orientation from Sydney, to the Norfolk Ridge, passing south of Lord Howe Island. The data are of good quality for their vintage, but only paper copies are available for interpretation.

Mobil (1972): Mobil acquired 3-fold data as part of a world-wide reconnaissance program (Bentz, 1974). The seismic data are of excellent quality for the vintage (1972) and show good resolution of sedimentary structure and acoustic basement on the Lord Howe Rise and West Norfolk Ridge. The data were collected on a series of zig-zag lines running generally east-west from the crest of Lord Howe Rise through the New Caledonia Basin and onto the West Norfolk Ridge. The data have not been migrated and only paper copies of the data are available

Shell International (1972): Two lines (P705 and P706) from the Shell MV *Petrel* roving reconnaissance survey in the Australian region have been used for this study. The data are of poor quality and are only slightly superior to a normal near trace display. The data were only available on paper and were not used extensively in this study.

BMR[2] Continental Margins Surveys 12, 14 & 15 (CGG, 1975): Survey 12 was recorded along a grid of E-W lines from the continental shelf on the Australian margin to the Tasman Basin at a regular 20 mile (~35 km) spacing. These data were complemented by regional tie-lines collected on surveys 14 and 15. Survey 14 also acquired three lines on Lord Howe Rise. The seismic data were recorded with a sparker source and are generally only available in analogue form. While the data are of generally poor quality compared to modern multichannel seismic data, they are valuable in the correlation of major geological structures in areas where there are no modern alternatives.

BGR Sonne 7 (1978): The Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, of the then Federal Republic of Germany) collected approximately 4000 km of 24-channel seismic, magnetic and gravity data over the Lord Howe Rise, New Caledonia Basin, Norfolk and West Norfolk Ridges, Middleton and Lord Howe Basins and the Dampier Ridge (Willcox et al., 1981). The survey was a cooperative venture between BGR and the Bureau of Mineral Resources (BMR). Basic data processing was carried out; however, the resultant data are of inferior quality by modern standards. Some of the data were migrated at a later date but are still generally of only fair quality. The data did not contribute significantly to this study.

BGR Sonne 36 (1985): BGR/BMR acquired 3660 km of seismic data on an ENE-WSW oriented grid over the Lord Howe Basin and adjacent Lord Howe Rise (Roeser

[2] BMR (Bureau of Mineral Resources) is a former name of Geoscience Australia, from its founding in 1946 to 1993. From 1993-2001, the organisation was named the Australian Geological Survey Organisation (AGSO).

& Shipboard Party, 1985), concentrating on the Gower Basin (Willcox & Symonds, 1990). The data were processed during 1999 and are of very good quality, with excellent resolution of basement topography and internal sedimentary character. These data were used in the interpretation of tectonic elements on the Lord Howe Rise, but were not interpreted in detail.

AGSO Survey 46 (1985): Approximately 1030 km of 24-fold conventional seismic data were acquired along four parallel lines, southeast of Lord Howe Island (Whitworth, Willcox et al., 1985). The data are only of fair quality and were of limited value to this study.

AGSO Survey 114 (1992): Approximately 3190 km of good-quality deep-seismic data were acquired by AGSO on the *Rig Seismic* in 1992 over the Lord Howe Rise, New Caledonia Basin and Norfolk Ridge / Reinga Basin (Marshall et al., 1994). The survey comprised two major transects and one shorter line oriented ENE-WSW, two NNW-SSE strike lines and several shorter lines that tie the survey to DSDP Sites 207 and 592. As seems to be the norm in the region, intra-basement reflections are rarely imaged and Moho was not imaged in either the Tasman or New Caledonia Basins.

AGSO Survey 125 (1994): Approximately 3200 km of geophysical data were acquired between New Zealand and the South Tasman Rise by the French research vessel *l'Atalante* on a transit that crossed the Challenger Plateau and Tasman Basin. These data included 3-fold high-speed seismic data.

AGSO Survey 177 (1996): Survey 177 was a joint Australia-New Zealand deep-seismic survey acquired by AGSO on the *Rig Seismic* in 1996 over the western flank of the Lord Howe Rise and adjacent Tasman Basin, and east of Norfolk Ridge, primarily for UNCLOS purposes (Ramsay et al., 1997). A total of 5714 km of data were acquired. The data are of excellent quality, with good resolution of sedimentary sequences, but little penetration beneath basement.

AGSO Survey 206 (1998): Survey 206 was a joint Australian-French deep-seismic survey acquired by AGSO on the *Rig Seismic* in 1998 (Bernardel et al., 1999). 4564 km of high-quality data were recorded over the northern Lord Howe Rise, New Caledonia Basin and Norfolk Ridge system along four lines, of which three are oriented ENE-WSW, while the fourth is oriented N-S along the axis of Lord Howe Rise. Line 206-4 is a 2000 km long transect that extends from the New Hebrides Trench subduction zone, across the New Caledonia Basin, Lord Howe Rise and Tasman Basin, to the passive continental margin of eastern Australia. The data were used in the interpretation of tectonic elements on the northern Lord Howe Rise, but were not interpreted in detail.

Surveys 114 and 177 were the primary seismic data sets used in this study.

2.2.3 Velocity Data

Sedimentary and crustal refraction velocity data are available from a number of sources, summarised below (Appendix 3; Fig. 4; Plates 3, 4).

Shor et al. (1971) discussed the acquisition and analysis of refraction data recorded with explosives sources by the Scripps Institution of Oceanography vessels *Ragi* and *Horizon* in 1967 in the southwest Pacific. A total of 17 reversed and 6 unreversed profiles were recorded, mainly in the northern half of the study area, between the Tonga-Kermadec Trenches and the northern Tasman Sea. While the majority of stations recorded basement and mantle arrivals, there is little velocity detail in the sedimentary section.

Houtz (1974) tabulated refraction solutions for sonobuoys recorded by Lamont-Doherty Geological Observatory *Eltanin* cruises 42-44 and 53 in the Southern Ocean. The only data of direct relevance to this study were six stations recorded in the southern Tasman Sea, of which three were in the vicinity of DSDP Site 283. The *Eltanin* data have limited detail in the sedimentary section, and did not record Moho arrivals; however, they do give some detail of the basement velocity structure.

Bentz (1974) tabulated the refraction solutions for eight sonobuoy stations recorded by the Mobil Oil Corporation's research vessel *Fred H. Moore* in 1972, using an airgun source. Unfortunately, positional data are only available for four of these stations. The stations were recorded on the southern Lord Howe Rise, northern Challenger Plateau, and in the southern New Caledonia Basin, and used an airgun source. Velocity solutions were derived for the sedimentary section and for shallow basement at all stations.

Willcox et al. (1981) tabulated preliminary refraction velocities computed for nine sonobuoys recorded with an airgun array source by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) research vessel *Sonne*, during survey SO-7A on the west-central Lord Howe Rise in 1978. Eight of these stations recorded basement velocities.

Ramsay et al. (1997) reported on a number of sonobuoy refraction stations recorded during AGSO Survey 177 using an airgun array source. These stations are located on the southeast flank of the Tasman Sea, southern Lord Howe Rise, and in the southern New Caledonia Basin. These sonobuoys have been analysed for this report.

Onshore velocity data from southeast Australia have been compiled by Collins (1988), and pertinent data have also been included in Appendix 3.

2.2.4 Potential Field Data

In recent years, shipboard gravity data has largely been supplanted by high-resolution satellite gravity data sets (eg Sandwell & Smith, 1997). These data are collected by satellites carrying radar altimeters measuring the shape of the ocean surface along tracks 3-4 km apart. Variations in the sea surface shape are caused by very small changes in the earth's gravitational field. For instance, a seamount 2000m high and having a radius of about 20 km will produce a 2 m high perturbation at the ocean surface.

The accuracy of the modern satellite-mounted radar on a satellite is very high: 10-15 km in horizontal resolution and 0.03 m in vertical resolution. Data collected by the European Space Agency ERS-1 (Exact Repeat Mission) and recently declassified data from the US Navy Geosat altimeter have provided detailed measurements of sea surface height over the oceans. Continuous profiles of geoid height from different satellites, collected over many years, were combined to produce high resolution maps of the marine gravity field. Sandwell & Smith (1992) developed a method to convert geoid height measurements into images of free-air gravity anomaly. Testing the accuracy of this method through comparisons with shipboard gravity measurements has shown agreement with the ship data to within 5 milligals. Gravity datasets produced by this technique are now available from National Geophysical Data Center (NGDC).

A 2 arc-minute satellite gravity dataset (Sandwell & Smith, 1992) has been downloaded from the National Geophysical Data Centre web site and processed through ERMapper to produce gravity images (Figs 5, 6; Plate 2). Such images are particularly valuable to the geological interpretation of remote frontier areas, such as the Lord Howe Rise, where shipboard data are both sparse and unevenly spaced.

2.2.5 Geological Samples.

Geological samples within the study area are extremely limited in number and come from only a few sources. The locations of the most important samples are shown in Figure 4 and Plates 3 & 4. The sources include:

Exploration wells:

The only oil exploration well which directly ties to the seismic data interpreted in this study is Wainui-1, drilled by Shell BP in 1981 in the Taranaki Basin, offshore New Zealand. The well penetrated Cainozoic and Upper Cretaceous sediments before reaching basement at 3890 m sub-sea. Wainui-1 was plugged and abandoned as a dry well.

Deep Sea Drilling Program:

Three legs of the Deep Sea Drilling Project (DSDP) have drilled wells that are relevant to this study. Leg 21 (Burns, Andrews et al., 1973) drilled Sites 203 to 210, of which Site 206 in the new Caledonia Basin, and Sites 207 and 208 on the Lord Howe Rise have been used here. Leg 29 (Kennett, Houtz et al., 1974) drilled Sites 275 to 284; Site 283 in the southwest Tasman Basin and Site 284 on the Challenger Plateau were used here. Leg 90 (Kennett, von der Borch et al., 1986) drilled Sites 587 to 594 on the Lord Howe Rise, Challenger Plateau and Chatham Rise. However, these sites were drilled primarily for palaeoceanographic purposes and are of limited value to this study.

Seabed samples from dredging and coring:

The locations and depths of seabed dredge and core sites relevant to this study are shown on Plates 3 & 4 and are listed with a description in Appendix 4. Their tectonic province location is given here, and the geological aspects are treated in the 'Stratigraphy' section below.

While a large number of seabed samples have been recovered since the lat 1960s, most of them consisted of surficial sediments. Only those samples of value to a geological framework study have been included here.

USNS *Eltanin* took cores and samples from seabed in the Tasman Sea during its traverses of the area in the late 1960s and early 1970s as part of the Lamont-Doherty Geological Observatory Survey of the World Ocean (Talwani, 1975). The *Eltanin* samples generally comprised Quaternary oozes.

Survey SO-36A of the RV *Sonne* (Bundesanstalt fur Geowissenschaften uni Rohstoffe; BGR) recovered five cores and two dredges from the central Lord Howe Rise (Roeser & Shipboard Party, 1985). The dredges were key samples for this study and were taken from the Dampier Ridge (McDougall et al., 1994) and the apparent westward extension of the Vening Meinesz Fracture Zone.

Dredge samples were taken from the West Norfolk Ridge and adjacent features by the RV *Akademik M.A. Lavrentyev* on Cruise RE9302 of the New Zealand Institute of Geological and Nuclear Sciences (IGNS) in 1993 (Herzer & Zhu, 1993; Zhu & Symonds, 1994). Dredge sample RE9302-5-2 was taken from the western margin of the West Norfolk Ridge adjacent to the New Caledonia Basin, while dredge RE9302-6-1 was taken about 40 km to the east-northeast, on the Norfolk Ridge. Two samples (G-1 and RE9302-7-2) were taken from the Wanganella Ridge.

The New Zealand department of Scientific and Industrial Research (DSIR) also recovered granite in a dredge (no. P44932 in the petrology collection of the New Zealand Geological Survey) from the western flank of the Challenger Plateau (Tulloch et al., 1991).

The ORSTOM research organisation (New Caledonia) recovered dredge samples from the Norfolk Ridge, Wanganella Ridge and Reinga Basin area during Cruise GEORSTOM III SUD (Monzier & Vallot, 1983; Herzer et al., 1997). Dredge sample GO349D was recovered from a pinnacle, possibly a part of the Norfolk Ridge, immediately east of the Wanganella Ridge. Dredges GO351D g and GO350D-5 were recovered from each side of the Vening Meinesz Fracture Zone.

2.2.6 Heat-flow Data

Heat-flow data are particularly sparse in the study area, with the only data available coming from seven stations in the Tasman Basin and on the western Lord Howe Rise (Grim, 1969) and from Deep Sea Drilling Project (DSDP) Sites 206 and 583 in the New Caledonia Basin and northern Lord Howe Rise, respectively. These results are contained in Appendix 5, and their significance is discussed later in this report.

2.3 Previous Studies

Despite the vast area encompassed by the Lord Howe Rise, Tasman Basin, New Caledonia Basin and the Norfolk Ridge system, the number of papers dealing with the geological evolution of the region is quite limited. These papers can be broadly divided into five broad categories. *viz.*:

- *Regional interpretations* – eg Stagg et al. (1999); Willcox et al. (2001); Blevin (2001); Bernardel et al. (2002);

- *Interpretations of local features and basins* – eg Gower Basin (Roeser & Shipboard Party, 1985; Willcox & Sayers, 2001); Dampier Ridge (McDougall et al., 1994); Reinga Basin (Herzer et al., 1997); Challenger Plateau (Tulloch et al., 1991; Wood, 1991); New Caledonia Basin (Ravenne et al., 1977; Uruski & Wood, 1991); Fairway Ridge (Ravenne et al., 1977; Lafoy et al., 1994); Norfolk Ridge (Eade, 1988);

- *Results of Deep Sea Drilling Project* – (DSDP) Legs 21 (Burns, Andrews et al., 1973), 29 (Kennett, Houtz et al., 1974) and 90 (Kennett, von der Borch et al., 1986).

- *Interpretations of the Tasman Basin spreading history* – eg Ringis (1972), Hayes & Ringis (1973), Weissel & Hayes (1977), Shaw (1978) and Gaina et al. (1998). The comprehensive work of Gaina et al. (1998) is summarised later in this section.

- *Interpretations of the regional and tectonic setting* – eg Walley & Ross (1991; Fig. 7); Walley (1992); Powell (1996); Symonds et al. (1996); Norvick et al. (2001); Sutherland et al. (2001).

2.3.1 Seafloor Spreading in the Tasman Sea

Hayes & Ringis (1973) were the first workers to identify seafloor spreading magnetic anomalies in the Tasman Sea, when they interpreted a complete set of anomalies from 33o (33 'old') to 24. They described the opening of the Tasman Basin in terms of a two-plate model, but also considered the possibility of subduction to account for the truncated pattern of magnetic anomalies adjacent to southeast Australia. Weissel & Hayes (1977) reinterpreted the magnetic anomalies and calculated finite poles of rotation based on these anomalies. They concluded that subduction of Tasman Basin crust at the east Australian margin was not necessary as an extension of the two-plate model described the evolution of most of the basin quite well. Shaw (1979) interpreted magnetic anomalies north of 30^{o}S in the Tasman Basin, based on new magnetic data, and argued that the morphology of the northern Tasman Basin could only be explained by strike-slip motion and not by a simple pull-apart mechanism as suggested by Weissel & Hayes (1977).

Gaina et al. (1998) have revised plate tectonic reconstructions for the opening of the Tasman Basin based on a compilation of all the available magnetic data and satellite gravity data. This interpretation of the breakup of the Tasman Basin is considerably more complex than previous authors have interpreted. They showed that Tasman Sea spreading cannot be modelled as a simple two-plate spreading system and they identified a number of microplates (Fig. 8) that were active during breakup and spreading. This complex microplate history was accompanied by several changes in spreading azimuth, and involved several failed rifts, and is described in some detail below, summarised from their paper.

Seafloor spreading was initiated in the southern Tasman Sea (84 Ma) as a result of rifting between the Challenger Plateau and the middle Lord Howe Rise. A brief left-lateral transtension phase led to the formation of the Bellona Trough, which contains Cretaceous sediments (Wood, 1993), before the onset of spreading in the Tasman Basin. Following this event the Challenger Plateau attached to the middle Lord Howe Rise and the combined structures separated from Australia. Magnetic lineations identified between the Challenger Plateau and the Gilbert Seamount Complex (84–77

Ma) correspond to the next episode of spreading resulting in about 250 km of oceanic crust being emplaced between these structures. At about 77 Ma the spreading stopped and Gilbert Seamount, which was previously attached to the South Tasman Rise, transferred to the Challenger Plateau. As will be noted later in our interpretation, it is possible that the crust between the Gilbert Seamount and Challenger Plateau is either highly-extended continental crust, or an amalgam of continental and oceanic crust.

At the same time, a short period of seafloor spreading occurred between Australia and the East Tasman Plateau. The South Tasman Rise, comprising eastern and western parts separated by a transform fault, started moving slowly southward relative to Australia, resulting in extension between Tasmania and the South Tasman Rise and in E-W seafloor spreading between the South Tasman Rise and East Tasman Plateau.

In the north, extension between northern Lord Howe Rise and the Dampier Ridge (then attached to Australia) led to the formation of Lord Howe and Middleton Basins, beginning at about 84 Ma. It is unclear whether these basins are floored by oceanic crust or (more likely) by highly-extended continental crust. Prior to 79 Ma the southern Dampier Ridge became attached to the northern Lord Howe Rise following rift or ridge propagation from the Lord Howe Basin into the Tasman Sea. As a consequence, transtension was set up between the southernmost two blocks of the Dampier Ridge. This motion ceased when the second block of the ridge became attached to the northern Lord Howe Rise, which in turn set up strike-slip motion between the two central blocks of the Dampier Ridge. At 72 Ma, after short-lived transtension between the northern Dampier Ridge and the fragment immediately to the south, the entire Dampier Ridge became attached to the Lord Howe Rise and rifting in the Lord Howe and Middleton Basins ceased. The last stage of rift propagation at about 62.5 Ma separated the Chesterfield Plateau from Australia and established a continuous spreading centre through the length of the Tasman Sea. At the same time, the central and northern Lord Howe Rise blocks became attached after 260 km of left-lateral strike-slip motion between them.

In the reconstructions, it is apparent that spreading in the northern Tasman Sea was highly oblique. This accounts for the observation that the Australian continental margin in this area is very narrow and steep and largely devoid of sediments.

Tasman Basin spreading ceased between 56 and 52 Ma following a slowing of the spreading rate. This event reflects a major change in plate driving forces.

An aspect of the Gaina et al. (1998) interpretation that is worthy of comment is their estimates of the half-spreading rates. From 83 to 79 Ma (chron 33o), the half spreading rate is only 4 $mm.a^{-1}$, which means that the Tasman Basin only opened by about 30 km during this time. At 79 Ma, the spreading increased more than five-fold to a more 'normal' rate of 22 $mm.a^{-1}$, which was maintained until 56 Ma, shortly before spreading ceased, when the rate slowed to 16 $mm.a^{-1}$. Gaina et al. do not suggest any reasons for the major increase in spreading rate.

2.3.2 Models of Rifting and Breakup

Of the models that have been developed to explain the evolution of the Lord Howe Rise region, the most important are those developed by Jongsma & Mutter (1978) and Etheridge et al. (1989).

Jongsma & Mutter (1978) built upon earlier models of continental margin formation (eg Falvey, 1974), which envisioned the formation of a rift valley through a protracted period of tectonism and extension emanating from the centre of a rift valley system. Seafloor spreading was interpreted to start near the centre of the rift valley, if extension proceeded far enough. This process was interpreted to account for the presence of normally faulted blocks which, at that time, were interpreted to form beneath conjugate continental margins.

In their interpretation of the small amount of data then available on Lord Howe Rise, Jongsma & Mutter (1978) reported that the western half of Lord Howe Rise was underlain by faulted rough basement topography, disturbed overlying sediments and a relatively subdued magnetic field, while the eastern half of the rise was underlain by a smooth basement surface, thin and undisturbed overlying sediments, and a high-frequency, high amplitude magnetic field. In contrast, the continental margin of eastern Australia has an unusually steep continental slope, with little evidence of the tectonism associated with rift valley development.

From these observations, they concluded that the final breakup occurred along the western boundary of the rift valley. In this model, the major portion of the rift valley remained as part of Lord Howe Rise, forming the western rift province. They further suggested that, in the north, a westward jump of the seafloor spreading axis from the Middleton and Lord Howe Basins to the west across the Dampier Ridge caused a similar removal of rift valley structures from the eastern Australian margin.

Etheridge et al. (1989) applied models of continental margin formation via crustal detachments (eg Lister et al., 1986) to the separation of the Dampier Ridge - Lord Howe/Middleton Basins - Lord Howe Rise - New Caledonia Basin - Norfolk Ridge complex from Australia. They proposed that the southeast Australian margin formed an upper plate margin, with the uplift of the eastern Australian Highlands taking place prior to breakup, whereas the highly structured western flank of Lord Howe Rise (including Dampier Ridge) formed the complementary lower plate margin (Fig. 9). This lower plate margin is interpreted to be underlain by an undulating detachment. The headwall at the eastern end of this detachment may have been located somewhere to the east of Norfolk Ridge, and possibly near the former pre-Cretaceous continent-ocean boundary, while to the west it plunges beneath eastern Australia. The differences in crustal thickness, structure and subsidence history across the region are interpreted to have resulted from horizontal and vertical variations in the partitioning of extension. Some of the complexity may also have resulted from the presence of multiple, branching detachments and/or ramp-flat detachments, all with a westerly dip (Lister et al., 1986).

Bradley (1993) adapted this detachment model to the development of the offshore Sydney Basin; this adaptation will be examined later in this report.

There are two important implications of the detachment model:

- The crust beneath the New Caledonia and Lord Howe / Middleton Basins is interpreted to be highly-attenuated continental crust, with no evidence of the emplacement of oceanic crust in either basin;

- Seafloor spreading was initiated along the inboard edge of an internal rift basin, in the region where the detachment dipped into the mantle lithosphere, and was associated with the melting that produced the underplating of southeastern Australia.

3. STRATIGRAPHY

Our knowledge of the stratigraphy of the Lord Howe Rise region is based on:

- Deep Sea Drilling Project Sites 206 (New Caledonia Basin), 207-208 and 588-592 (Lord Howe Rise), 284 and 593 (Challenger Plateau) and 283 (Tasman Basin);
- dredged and cored seabed samples (eg Willcox et al., 1981; Roeser & Shipboard Party, 1985; Herzer et al., 1997); and
- Wainui-1 oil exploration well in the Taranaki Basin on the northern New Zealand continental margin and at the southeastern end of the New Caledonia Basin.

The locations of the wells and the key dredge and core samples on the southern Lord Howe Rise are shown in Plates 3 & 4. Selected lithostratigraphic columns are shown in detail in Plate 5. Well geology is summarised in Figures 10-17.

3.1 Chrono-stratigraphy

The stratigraphy is summarised below in order of age of deposition, followed by a description of the volcanic rocks. The summary is based largely on the DSDP reports for the sites in the area (Burns, Andrews et al., 1973; Kennett, Houtz et al., 1974; Kennett, von der Borch et al., 1986). Plate 6 displays the regional stratigraphy, with the main tectonic events and the seismic horizons. It is clear that in this oceanic environment, some widespread unconformities are due to changes in oceanography, rather than to tectonic events.

3.1.1 Basement and near-basement rocks

Dredge station GO357D1 of ORSTOM Cruise 3 (Launay et al., 1977; Willcox, 1980) from the eastern flank of the southern Lord Howe Rise, recovered olivine basalt with gabbroic intrusions, and hyaloclastic breccias. Seismic data indicates that these volcanic deposits have been extruded on to basement, but basement rocks have not been recovered from the Lord Howe Rise. However, dredging of the Dampier Ridge, on the western flank of the central Lord Howe Rise, has recovered small fragments of granite, gabbro and sandstone (McDougall et al., 1994). Dating of the igneous samples yielded ages in the range of 250-270 Ma (mid-Permian; McDougall et al., 1994), 170-190 million years prior to the opening of the Tasman Basin. Taken together, this evidence strongly suggests a continental origin for the Dampier Ridge.

In the Tasman Basin, Site 283 encountered pillow lavas near the bottom of the hole, and these are interpreted to be the top of the oceanic basement.

3.1.2 Mesozoic

Two DSDP sites and some ORSTOM dredge hauls recovered pre-Tertiary sediments. DSDP Sites 207 and 208, both located west of the crest of Lord Howe Rise, penetrated Upper Cretaceous sediments. These are described in section 3.2.2 on the central rift province.

3.1.3 Cainozoic

DSDP Site 206 in the New Caledonia Basin reached TD in Middle Paleocene nannofossil ooze. The oldest Tertiary sediments cored are Early Paleocene, but these were not recovered from the base of the hole. This age inversion is attributed to post-depositional slumping in a deep basinal setting. On the southern Lord Howe Rise, DSDP Site 207 encountered Middle Paleocene shallow marine carbonate oozes overlying Cretaceous claystones, while Site 208 in the north recovered a complete Lower to Middle Paleocene marine section with siliceous microfossils.

Early Eocene regional unconformity
This unconformity spans the earliest Eocene at DSDP Site 207 on the Lord Howe Rise; the time break is shortest at this location. The unconformity is also recorded at Site 206 in the New Caledonia Basin, where the hiatus extends from the Late Paleocene to the Early Eocene, despite the basinal setting. The unconformity is also present at Site 208 on the northern Lord Howe Rise. It is absent, however, at Site 593 on the Challenger Plateau, 'suggesting that the bottom currents that eroded the regional hiatus in [the] Tasman Sea did not extend that far to the east' (Nelson et al., 1986).

Eocene
DSDP Site 207 recovered Lower Eocene carbonates above the early Eocene regional unconformity. Benthonic foraminifera indicate a very rapid increase in water depth between the Late Cretaceous and the Early Eocene.

Late Eocene to Oligocene regional unconformity
There is disagreement about the time extent and the cause of this unconformity, which is reflected in its nomenclature. The unconformity was documented on DSDP Leg 21 by Edwards (1973). Bentz (1974) referred to it as the Neogene/Paleogene unconformity, while Kennett et al. (1975) identified it as the intra-Oligocene regional unconformity, and Nelson et al. (1986) referred to it as the Paleogene-Neogene regional unconformity.

The time span of the hiatus is highly varied. At Site 206 in the New Caledonia Basin, it extends from 33-43 Ma BP (Kennett, von der Borch et al., 1986), and separates latest Middle Eocene from mid-Oligocene carbonates. At Site 592, less section is missing, and there are separate Late Eocene and Oligocene unconformities rather than a single long hiatus. The largest hiatus is at DSDP Site 207, where late Middle Eocene carbonate ooze is overlain by early Middle Miocene carbonate ooze. According to early estimates (Burns, Andrews et al., 1973), the unconformity at this site extends from 46 to 13 Ma. In later estimates (Kennett, von der Borch et al., 1986), the oldest Neogene above the unconformity is dated at 15.5 Ma, and at Site 592, not far distant in the same structural province, it is dated at 20 Ma. The Upper Eocene to mid-Oligocene is also missing at Site 208, on the northern Lord Howe Rise.

Martini & Jenkins (1986) and Kennett et al. (1972) interpret the Late Eocene to Oligocene hiatus as probably resulting from bottom current activity, rather than from tectonics. However, Bentz (1974) correlated the unconformity with a change in tectonics from an episode of rifting to subsequent subsidence. Eade (1988), in discussing the Norfolk Ridge system, refers to the hiatus as the 'Regional Unconformity', separating a folded and faulted Paleogene section from overlying slumped deposits. He interpreted the unconformity to be produced by an Eocene global plate tectonic event, and not due to current action. Van de Beuque et al. (2002) have noted the widespread occurrence of the unconformity, and the associated peneplanation visible on seismic regional profiles, indicating subaerial erosion and a possible tectonic origin. It may be that the unconformity is initiated by a tectonic event, and then the hiatus is further extended temporally by non-deposition and possibly erosion due to current action in some localities (eg Site 207), while older Neogene sediments are present elsewhere.

Mid-Oligocene to Pleistocene
The entire section of this age is present at DSDP Site 206 in the New Caledonia Basin, where it comprises one of the most complete known sequences of Neogene planktonic foraminifera and calcareous nannofossils.

3.1.4 Volcanic Rocks

Volcanic rocks of a range of ages form a significant component of the geology of Lord Howe Rise.

Lord Howe Island and the nearby Ball's Pyramid, the only subaerial exposures of the Lord Howe Rise, are composed of alkali basalts. At least three major periods of eruption are recognised, beginning in the mid-Tertiary or earlier, while the youngest volcanics are dated at around 7.7 Ma, in the Late Miocene (Game, 1970). The composition of the volcanics is almost standard for oceanic islands, but with a bias toward 'circum-oceanic' basalts.

On the northern Lord Howe Rise, little trace of volcanic activity has been found by drilling, other than some siliceous detritus in DSDP Site 209. However, to the south, DSDP Site 207 sampled volcanic ash, and the site reached TD in pumiceous lapilli tuffs and rhyolite flows erupted above, or very near, sea level. These volcanics are dated at about 94 Ma (Cenomanian), approximately 10 my prior to the onset of seafloor spreading in the Tasman Sea. Bentz (1974) interpreted seismic data on the southern Lord Howe Rise to show the presence of eruptive volcanics in a number of locations.

Dredging by the French GEORSTOM III survey in 1975 (Launay et al., 1977) on the eastern flank of the southern Lord Howe Rise recovered olivine basalts, gabbros and a mixture of hyaloclastic breccias and biomicrites. Fossils recovered from the biomicrite suggest a mid-Miocene or younger age.

As noted previously in this report, dredging has recovered granite and gabbro, dated as mid-Permian (250-270 Ma) from the Dampier Ridge, west of the central sector of Lord Howe Rise.

DSDP Site 593, on the Challenger Plateau, cored 16.4 m of altered and hydrated volcanogenic deposits, which were the only relatively thick non-biogenic lithology cored on Leg 90 (Nelson et al., 1986). These volcanics were dated, from planktonic fauna in the surrounding bathyal chalk, as being emplaced near the Eocene/Oligocene boundary. The timing of eruption and the oceanic setting indicate that the volcanics were not a direct product of rifting or the opening of the Tasman Basin.

Trace quantities of volcanic shards are the major component of terrigenous material at the DSDP sites on and near the Lord Howe Rise, and pale green laminae found throughout the Neogene carbonates are thought to be altered volcanic ash layers from regional sources, mainly in New Zealand (Gardner et al., 1986). Volcanic glass and laminae interpreted as altered volcanic ash increase in quantity in the Early and Middle Miocene and in the Quaternary.

3.2 Stratigraphy of the Major Provinces.

3.2.1 Tasman Basin

Although USNS *Eltanin* surveyed the region during the late 1960s and early 1970s, taking seabed samples along some transits, only soft surficial sediments (mainly Quaternary oozes) were recovered. DSDP Site 283, in the southwest Tasman basin, sampled 588 m of sediments above altered pillow basalt. While an age consistent with magnetic anomaly 32 (*ca* 73 Ma) was expected, the overlying Early Paleocene claystone is 10-15 Ma younger than this (Kennett, Houtz et al., 1974). The age discrepancy appears to be the result of non-deposition.

The Late Eocene to Late Pliocene is also missing at Site 283. As the underlying sediments are unconsolidated, the absence of sediments of this age is attributed to non-deposition rather than to erosion. The Plio-Pleistocene succession above the Eocene-Pliocene hiatus is less than 15 m thick.

By the Early Paleocene, Site 283 lay at a depth greater than the silica and calcium carbonate compensation depths, and diatoms and calcareous nannofossils are not found until the Late Eocene, at which time the Tasman Sea may have shoaled. The sedimentary section in the Tasman Sea can be summarised as: terrigenous silt and clay overlying oceanic basement, succeeded by siliceous ooze and calcareous chalk and ooze (Kennett, Houtz et al, 1974).

3.2.2 Lord Howe Rise

From east to west the Lord Howe Rise is segmented longitudinally into the shallow planated basement of the Lord Howe Platform, the Central Rift (primarily the Moore

Basin), and the deeper Western Rift (Monowai Basin and Monowai Ridge). These structural subdivisions are discussed in detail later in this report.

Lord Howe Platform.

Seabed sample GO357D1 of ORSTOM Cruise 3 (Launay et al., 1977; Willcox et al., 1980) was dredged from the flank of a pinnacle on the southwest part of the platform, on Mobil seismic line 72-109. The pinnacle was not a basement exposure but a younger volcanic edifice. The recovered samples included subaqueously extruded olivine basalt, gabbroic intrusions in the basalt, with olivine and pyroxene, and hyaloclastic breccias and biomicrites, with foraminifera of mid Miocene age and coral debris. The basalt contains an abnormally low silica content (34%). The coral debris indicates that the water depth in the area was shallow during the Miocene eruption of the basic volcanics than the present 700+ m. Miocene volcanics are part of the eruptive episode that formed Lord Howe Island and Ball's Pyramid.

Central Rift (Moore Basin, Gower Basin)

DSDP Site 207, in the Central Rift on the southern Lord Howe Rise, and Site 208 to the north, both penetrated Cretaceous rocks. Site 207 encountered glauconitic silty claystones of Maastrichtian age above basal volcanics. These claystones were deposited in a shallow marine environment with non oceanic circulation.

Site 208 drilled through the Tertiary-Cretaceous boundary succession and reached TD in latest Maastrichtian fossiliferous nannofossil chalk of normal oceanic affinity. The absence of clastics at the site indicates an oceanic setting for the central Lord Howe Rise since at least the Maastrichtian.

Western Rift (Monowai Basin)

There are no wells or samples in this province.

3.2.4 Challenger Plateau

Granite dredged from the southwestern margin of the plateau (Tulloch et al., 1991) indicates its continental origin. DSDP Site 593, drilled on the plateau, intersected 16.4 m of Eocene/Oligocene volcanogenic sandstones, one of the strongest indications of volcanic activity drilled anywhere in the region. The volcanic influence is attributed to the proximity of the dredge site to the 'Lalitha Pinnacle', an apparent shield volcano identified in seismic data (Nelson et al., 1986). The volcanogenic sediments are underlain by nannofossil chalks, indicating that the Challenger Plateau, as with the Lord Howe Rise, lay in a deepwater oceanic setting at the time of emplacement.

3.2.5 New Caledonia Basin

DSDP Sites 206 (Leg 21) and 591 (Leg 90) were drilled in the New Caledonia Basin. Site 206 reached TD in calcareous oozes of probable Early Paleocene age, while Site 591 reached TD in Miocene sediments. The biostratigraphic succession of nannofossil oozes in Site 206 above the Eocene/Oligocene regional unconformity is notably complete, while the Paleogene section is disrupted by slumping, with mid-Paleocene underlying Early Paleocene near the base of the hole. The regional Early Eocene unconformity was also present at Site 206 (although it cannot be tied to seismic profiles, because of the slumping), and it seems to have been in a deepwater setting since at least the Paleocene, with oceanic biogenic deposits dominating the section.

Seismic line TL-01, along the axis of the basin, ties Site 206 in the north to Wainui-1 oil exploration well in the Taranaki Basin on the northern margin of New Zealand. It is apparent that the basins are structurally and stratigraphically continuous.

3.2.6 Taranaki Basin

The stratigraphy of the Taranaki Basin (Fig. 2) is well documented from the many oil exploration wells that have been drilled (eg King & Thrasher, 1996). The nomenclature and age of the New Zealand series and stages, and their relationship to the international system, are displayed in Plate 6.

The 7-8 km thick, mainly Late Cretaceous to Early Miocene Taranaki Basin is underlain by igneous and metamorphic basement rocks of eastern Gondwana. From the Middle Miocene, the basin underwent inversion, accompanied by regression as the terrestrial input from New Zealand began to dominate sedimentation.

While the oldest sediments in the basin are pre-rift deltaics of probable early Cenomanian age found locally in the north, the first widespread sedimentation comprises the Rakopi Formation of the Late Cretaceous Pakawau Group. These early rift conglomerates, sandstones, carbonaceous shales and minor coals were derived mainly from the area now occupied by the Challenger Plateau to the west. These deposits are succeeded by Paleocene and Eocene late-rift and post-rift basin-fill fluvial and coastal sands, shelf muds and marine shales of the Kapuni and Moa Groups. These are in turn overlain by the Oligocene and Lower Miocene Ngatoro Group which comprises continental slope carbonates and slope fan turbidites deposited during a major marine as the basin subsided eastward in a foreland flexure, with the subsidence outstripping sediment supply.

An influx of volcaniclastics in the Middle Miocene (the Mohakitino Formation of the Wai-Iti Group, deposited on the bathyal muds of the Manganui Formation), marked the onset of a new tectonic and sedimentary regime that progressively affected sedimentation in the Eastern Mobile Belt of the basin from the Middle Miocene onward. This resulted in the deposition, from easterly sources, of submarine fan sands, and shelf sands and muds in a progressively shallowing basin. The giant westward-prograding foresets of the Rotokare Group reflect the massive influx of clastics during the latest Miocene and the Plio-Pleistocene caused by the uplift of the North Island to the east of the Taranaki Fault.

Important hiatuses and unconformities include the near top Cretaceous, the Early Eocene, and the Late Eocene/Oligocene. These broadly correlate with the major unconformities interpreted on the Lord Howe Rise and in the New Caledonia Basin to the north, and also with unconformities in the southwest Pacific.

Until the Middle Miocene, the geological history of the Taranaki Basin is closely reflected in the basin and ridge complex to the northwest (discussed below). It is only with the massive influx of sediments from the east in the Miocene to Pliocene that the geology of these two areas significantly diverges.

3.2.7 West Norfolk Ridge, Wanganella Trough, Wanganella Ridge, Norfolk Ridge, Reinga Basin

There is no well information in this area, and knowledge of the stratigraphy is derived solely from seabed sampling. Dredge samples were taken from this complex of ridges, troughs and basins by the RV *Akademik M.A. Lavrentyev* on Cruise RE9302 of the New Zealand Institute of Geological and Nuclear Sciences in 1993 (Herzer & Zhu, 1993; Zhu & Symonds, 1994.). ORSTOM also recovered dredge samples in the Norfolk Basin and Wanganella Ridge area during Cruise GEORSTOM III SUD (Monzier & Vallot, 1983; Herzer et al., 1997).

Dredge sample RE9302-5-2, on the western margin of the West Norfolk Ridge adjacent to the New Caledonia Basin, recovered carbonaceous sandstone and mudstone of Mangaotanean (Turonian) age derived from a granite bedrock source (Herzer et al, 1997). Dredge sample RE9302-6-1, some 40 km to the east-northeast on the ridge recovered Early Miocene limestone. Two samples from the Wanganella Ridge (G-1 and RE9302-7-2) recovered Early and Middle Miocene sediments.

Dredge GO349D, located on a pinnacle lying immediately to the east of the Wanganella Ridge (possibly a part of the Norfolk Ridge), recovered volcanogenic sandstone. GO348D-6 on the Norfolk Ridge, just south of 30^{o}S, recovered Lower Oligocene to Lower Miocene limestone. GO351D-g, just off the Norfolk Ridge in the Reinga Basin, recovered Middle Eocene mudstone breccia. GO350D-5, about 100 km to the southeast on the southern side of the Vening Meinesz Fracture Zone, recovered Upper Paleocene-Lower Eocene argillaceous limestone.

R/V Sonne Survey SO-36 in 1985, recovered a dredge sample (SO-36-63) from the edge of a bathymetric depression interpreted to be the western end of the Vening Meinesz Fracture Zone (Roeser & Shipboard Party, 1985). The dredge recovered manganese nodules containing pebbles of sandstone, limestone, phyllite and granite (Roeser & Shipboard Party, 1985).

4. SEISMIC SEQUENCES

4.1 Introduction

Seismic sequences on the Lord Howe Rise have previously been described by Willcox et al. (1980) and in the Reinga Basin by Herzer et al. (1997). Most recently, Willcox & Sayers (2001) have reported on an interpretation of the seismic stratigraphy for the Gower Basin region of the central Lord Howe Rise. The Gower Basin is the only part of the Lord Howe Rise that is covered by a regional grid of fair- to good-quality seismic reflection profiles (*Sonne* SO36A survey and AGSO *Rig Seismic* Survey 46). The sequence nomenclature adopted by Willcox & Sayers (2001) and their proposed ages are contained in the following table:

Table 1: Seismic megasequences & proposed ages (after Willcox & Sayers, 2001)

Megasequence	Proposed age of basal unconformity
GB1	?Miocene
GB2	?
GB3	Oligocene
GB4	Early Eocene
GB5	?Maastrichtian
GB6	Santonian / Campanian
GB7	?
GB8	?
GB10	New England Fold Belt equivalents
GB11	intra-basement

In this report, we have interpreted similar seismic sequence ages to those in Table 1, and have also incorporated the work of Herzer et al. (1997). Seismic sequences and facies are illustrated by reference to Plates 7-9, while a full listing of the horizons and units that were mapped in the study is contained in Appendix 6.

There are major changes in the character and range of depositional sequences between the Lord Howe Rise, Tasman Basin and New Caledonia Basin; consequently, the seismic sequence characteristics will be discussed separately for each area. Extrusive and intrusive volcanics and volcanogenic sediments are widespread, and their seismic characteristics will be discussed at the end of this section.

Lord Howe Rise sequences have been interpreted both in survey 114 and 177 data and also in the early 1970s Mobil, United Geophysical and Shell International data. They have been tied to DSDP Site 207 (Burns, Andrews et al., 1973) at the intersection of lines 114/06 and 114/07 and to DSDP Site 592 (Kennett, von der Borch et al., 1986) at the intersection of lines 114/07 and 114/08.

Depositional sequences on the Lord Howe Rise are broadly divided into pre-rift, syn-rift and post-rift sequences. From east to west the rise is segmented longitudinally into the shallow planated basement of the Lord Howe Platform, the Central Rift province (primarily the Moore Basin), and the deeper Western Rift province (Monowai Basin and Monowai Ridge). These structural subdivisions are discussed in detail later in this report.

4.2 Lord Howe Rise

4.2.1 Pre-rift (pre-Cenomanian) basement

Pre-rift rocks have been included in the general category of 'basement' beneath the Lord Howe Rise. However, in recognition of the varying basement character throughout the region, basement has been subdivided according to those character variations, which in turn reflect different tectonic elements. The basement reflectors (eg Plate 8, line 114-02) include ***plan*** (Lord Howe Platform), ***crif*** (Central Rift Province) and ***wrif*** (Western Rift Province).

Beneath the Lord Howe Platform, the seismic character of the pre-rift section varies considerably, from seismically transparent to well-layered, folded and faulted. Fine-scale layering and structuring can in places be identified for up to 1s TWT (*ca* 3 km) into basement. Below this level, faint crustal fabrics can be identified down to depths of about 10s TWT (*ca* 30 km); however, the fabric is not sufficiently consistent to allow mapping of crustal provinces. The basement section probably comprises Palaeozoic rocks of the New England Fold Belt and its equivalents. DSDP Site 207, recovered rhyolites, tuffs and flows of Cenomanian age (94 Ma) from within seismic basement, indicating that Cretaceous volcanic basement is difficult to distinguish from Palaeozoic fold belt rocks in seismic data.

Beneath the Central and Western Rift provinces, the top of the pre-rift section comprises a series of distinct to poorly-defined fault blocks. Within this basement, reflectors are rarely observed, other than in isolated cases in the Monowai Basin. However, it is likely that the basement rocks are similar to those beneath the Lord Howe Platform, with the absence of coherent reflections being due to the extensive faulting.

A fourth basement (***bech***) type has been identified beneath the Bellona Trough / Challenger Plateau at the southern end of Lord Howe Rise. Very little seismic data is available in this area and the only information on basement comes from a Carboniferous granite sample that was dredged from a basement horst on the western margin of the plateau (Tulloch et al., 1991).

Interpreted lithologies: Palaeozoic New England Fold Belt equivalents; volcanics.

4.2.2 Cenomanian – Campanian (syn-rift; cen – camp)

(Equivalent to Gower GB7-10 of Willcox & Sayers, 2001)

This sequence comprises syn-rift fill in the grabens of the Western and Central Rifts and onlaps the underlying basement (eg Plate 8, line 114-02). In the deeper parts of the rifts, the syn-rift section covers the pre-rift blocks completely. The sequence is at least 0.2 s TWT thick, and is characterised by sub-parallel, low-amplitude reflections, generally of low continuity. The lower boundary is onlapping or concordant, while the upper boundary (***camp***) is typically erosional. As the underlying basement blocks are frequently obscured by interpreted volcanics, the geometry of this sequence is often valuable for determining fault geometries. This sequence has not been sampled on the Lord Howe Rise, and is dated by analogy with the Gippsland Basin and by reference to the Tasman Basin spreading history.

Interpreted lithologies: continental to paralic clastics.

4.2.3 Post-rift Sequence 1 (Campanian – Lower Eocene; camp – maas – eocl)

(Equivalent to Gower GB5-6 of Willcox & Sayers, 2001)

The first post-rift sequence initially fills in the topographic lows in the underlying Campanian (breakup) unconformity, but becomes widespread by the Eocene, eventually onlapping the shallowest parts of the Lord Howe Platform (eg Plate 8, line 114-02). The seismic character of the oldest part of the sequence is very similar to the underlying syn-rift section, and the base of the section is often difficult to distinguish. Reflection continuity and amplitudes increase in the younger part of the section. The top of the sequence is a highly reflective erosional surface, often showing signs of compression, and the Early Eocene unconformity (***eocl***) is the most prominent and consistent unconformity throughout the region. Within this sequence, an Masstrichtian unconformity has been identified on some lines.

Interpreted lithologies: shallow marine silty claystone.

4.2.4 Post-rift Sequence 2 (Lower Eocene – Oligocene; eocl – olig)

(Equivalent to Gower GB4 of Willcox & Sayers, 2001)

This sequence is composed of strong, sub-parallel high-continuity reflections in the lower part of the section with amplitude decreasing in the upper part of the section (eg Plate 8, line 114-02). High-amplitude reflections are more characteristic of the Central and Western Rifts where the older part of the sequence is present, whereas on the Lord Howe Platform only the low-amplitude part of the section is present. The sequence is disrupted by widespread small-scale faulting which rarely penetrates the base of the sequence. The sequence is of more uniform thickness (0.2-0.3 s TWT, decreasing into the Tasman Basin) than the underlying sequences, reflecting an open marine environment. The Oligocene unconformity (***olig***) marks a regional change in ocean circulation following the final separation between Australia and Antarctica.

Interpreted lithologies: foraminiferal-nannofossil ooze and chert.

4.2.5 Post-Oligocene (post-rift; post-olig)

(Equivalent to Gower GB1-3 of Willcox & Sayers, 2001)

The lower part of this sequence is distinguished by parallel, high-amplitude reflections, while the amplitude decreases upwards (eg Plate 7, line LHRNR-E). Faulting also decreases upwards in the sequence. The sequence ranges from 0.1-0.5 s TWT in thickness (*ca* 100-500 m), and usually thins on to the planated basement. Within the lower part of this sequence, a persistent minor unconformity of probable Middle Miocene age has been interpreted on several lines.

Interpreted lithologies: foraminiferal-nannofossil ooze.

4.3 Tasman Basin

Tasman Basin seismic sequences have been identified mainly in the Survey 177 data. Seismic horizons have been tentatively tied, via lines 125-2 and 125-3 to DSDP Site 283 (Kennett, Houtz at al., 1974) in the southwestern Tasman Sea. All post-breakup sequences equivalent to those on Lord Howe Rise have been identified (eg Plate 8, line LHRNR-G); however, their seismic characteristics in this area are somewhat different.

4.3.1 Oceanic basement

Tasman Basin oceanic crust is invariably very rugged with up to 1.5 s TWT (*ca* 1500 m) of relief at the highly reflective upper surface being observed in many areas (eg Plate 8, line LHRNR-G). The internal basement character is generally reflection-free, except on the eastern flank of the basin where steeply dipping, cross-cutting reflectors are sometimes seen. These reflectors may be the product of very slow early seafloor spreading; alternatively, they may also be the expression of highly extended continental crust (eg Plate 8, line LHRNR-H). While there are occasional hints of Moho reflections at about 10 s TWT, the base of the crust is generally not recorded.

Interpreted lithology: oceanic crust.

4.3.2 Campanian – Upper Eocene (camp - eocl – eocu)

The main part of the sedimentary section in the Tasman Basin comprises thick Campanian to Upper Eocene sediments. The oldest part of the section is restricted to localised areas of deep basement, for example adjacent to DSDP Site 283. The section generally contains low-amplitude, parallel reflectors of high continuity that have been folded and eroded in the Late Eocene. The upper part of the section is broken by numerous small faults.

Interpreted lithologies: terrigenous silty clay.

4.3.3 Upper Eocene – Oligocene (eocu – olig)

This sequence is represented by sub-parallel low-amplitude reflections with significantly less faulting than in the underlying section. The Oligocene unconformity (***olig***) is well defined with younger sediments onlapping the unconformity in isolated depocentres and draping over palaeo-highs.

Interpreted lithologies: silty clay and diatom ooze.

4.3.4 Post-Oligocene (post-olig)

The post-Oligocene section is generally very thin, ranging from almost absent to about 0.3 s TWT (*ca* 300 m) in thickness in palaeo-lows where it onlaps the Oligocene unconformity. The sequence exhibits parallel, low-amplitude reflectors with no evidence of deformation.

Interpreted lithologies: zeolitic clay.

4.4 New Caledonia Basin

Seismic sequences in the southern New Caledonia Basin have been interpreted along line TL-01 (Survey 177) along the axis of the basin, which ties in the south to Wainui-1 well in the Taranaki Basin on the New Zealand continental margin, and in the north to DSDP Site 206 (Burns, Andrews et al., 1973; Plate 9) in the central New Caledonia Basin. Regional dip lines from surveys 114 and 177 have been tied to line TL-01 (Plate 8, lines 114-02, 114-04; Plate 7, line LHRNR-J).

4.4.1 Basement

Acoustic basement in the New Caledonia Basin cannot readily be classified as being either oceanic or continental. In the central part of the basin, it is a relatively flat-lying and highly reflective interface that varies from smooth to very rugged. Apparent basement highs with relief of up to 2 s TWT (*ca* 2.5 km) are not obviously related to basement tectonics, and some of these may be due to massive sediment slumping, as at DSDP Site 206. Beneath the eastern flank of the basin, basement has been strongly overthrust from the east, and the location of the basement surface is unclear.

Interpreted lithologies: unknown; possibly crystalline lower continental crust with some basic volcanics if basin has not proceeded to seafloor spreading; otherwise may contain oceanic crust.

4.4.2 Pre-Lower Eocene (ncb – eocl)

The Late Cretaceous to Lower Eocene sequence onlaps basement and is characterised by complex internal structuring with strong parallel reflectors in the upper part of the section and weaker and more chaotic reflections in its lower part. There is distinct channelling in different parts of this section indicating current erosion and reworking of sediments. The sequence varies from 0.2-1.5 s TWT in thickness (*ca* 200-2000 m).

The entire sequence has been compressed, faulted and folded, with the bounding Early Eocene unconformity being the most prominent reflector in the basin.

Interpreted lithologies: nannofossil ooze.

4.4.3 Lower Eocene – Oligocene (eocl – olig)

As with the corresponding sequence on the Lord Howe Rise, this sequence is characterised by sub-parallel, low-amplitude reflectors. However, in contrast to the Lord Howe Rise, the Oligocene unconformity is not prominent. The average thickness is 0.2-0.3 s TWT (*ca* 2-300 m). The sequence is draped or onlapping at its basal (Early Eocene unconformity), while the upper boundary is mildly erosional.

Interpreted lithologies: radiolarian and nannofossil ooze.

4.4.4 Oligocene – Lower Miocene (olig – miol)

As with the underlying sequence, the Early Miocene section is generally thin and characterised by sub-parallel, low-amplitude reflectors. On the eastern flank of the basin, the sequence has been compressively deformed and eroded at the time of the emplacement of the Northland Allochthon in New Zealand. The bounding Early Miocene unconformity is a strong and continuous event that can be traced for some distance up-dip onto the Lord Howe Rise.

Interpreted lithologies: nannofossil ooze.

4.4.5 Lower Miocene - Recent (miol – miou – wb)

The Lower to Middle Miocene section is 0.2 to 0.3 s TWT thick (*ca* 2-300 m) and is characterised by consistently sub-parallel, medium-amplitude reflectors. The Upper Miocene and younger section is up to 1 s TWT (*ca* 1000 m) thick and is characterised by higher frequency, higher continuity, sub-parallel reflectors. The Miocene section is also characterised by many small buildups, particularly in the south. The origin of the buildups is not clear, and they could be either carbonate or volcanic in origin.

Interpreted lithologies: nannofossil ooze, chalk, volcanic ash.

4.5 Western Norfolk Ridge and Reinga Basin

For completeness, we will include a summary of the seismic stratigraphy of the West Norfolk Ridge and Reinga Basin. Seismostratigraphic interpretation in this region is based only segments of lines 114/02 and 114/04 and partly on line TL01 (survey 177). Therefore, most sequences have been identified from the detailed interpretation of Herzer et al. (1997), which was based on good-quality, industry seismic reflection data for the southeastern end of Reinga Basin, tied to petroleum exploration wells in the Taranaki Basin.

4.5.1 Pre-Campanian sequence (equivalent to pre-camp)

This sequence corresponds to sequence *Cre2* of Herzer et al. (1997). It is characterised by chaotic reflections similar to those in the basement. The basal boundary with basement is frequently not identified, whereas the upper boundary of the sequence is a strong reflector which can be mis-identified as basement. Consequently, neither the thickness of Cretaceous section nor its geometry can be determined. This sequence corresponds to the first phase of rifting on the Pacific-facing sedimentary margin, when extensional structures were filling with terrestrial sediments, including coal measures.

Interpreted lithologies: terrestrial sediments, including coal measures.

4.5.2 Campanian – Maastrichtian (equivalent to camp-maas)

This sequence (*Cre1* of Herzer et al., 1997) is found mostly within tilted fault blocks; however, in places it also onlaps basement highs. The sequence is characterised by low-amplitude reflectors and corresponds to open marine clastic deposits, including shelf sands, bathyal muds and redeposited greensands. The upper bounding Maastrichtian unconformity is a high-amplitude reflector that is prominent in relation to the weakly reflective sequences above and below.

Interpreted lithologies: open marine clastic deposits, including shelf sands, bathyal muds and redeposited greensands.

4.5.3 Maastrichtian – Lower Eocene (equivalent to maas-eocl)

This sequence (*Pal2* of Herzer et al., 1997), characterised by low- to medium-amplitude, sub-parallel events, infills residual Cretaceous grabens and onlaps basement horst blocks. The sequence was deformed by folding in the Neogene, and reverse and wrench faulting. The thickness is fairly uniform at about 0.5-0.7 s TWT (*ca* 500-800 m). Rocks of this sequence were dredged on the nearby Norfolk Ridge and on the fault scarps of the Reinga Ridge, with siliceous mudstone and fine-grain limestone being recovered, indicating deposition in paralic to bathyal environments. There are indications of westwards deltaic progradation.

Interpreted lithologies: paralic to bathyal sediments, including limestone.

4.5.4 Lower Eocene – Oligocene (equivalent to eocl-olig)

This part of the section (*Pal1* of Herzer et al., 1997) is similar is seismic character to the underlying sequence. It is uniformly 0.2-0.3 sec TWT (*ca* 2-300 m) thick and it was deformed at the same time as the underlying sequence. The upper boundary of the sequence is a high-amplitude regional reflector, which is tied to wells in the Taranaki Basin where it correlates with the base of the Oligocene carbonates.

Interpreted lithologies: paralic to bathyal sediments, including limestone.

4.5.5 Oligocene – Lower Miocene (equivalent to olig-miol)

In the Reinga Basin, this sequence is variable in thickness (0.2-0.4 s TWT; *ca* 2-400 m), being ponded in regional depressions and thinning over residual, basement cored highs. It is characterised by sub-parallel, low-amplitude reflectors and the upper boundary is a distinct regional reflector. The sequence was deformed in the Miocene following the obduction of the Northland Allocthon. In New Zealand, this sequence is characterised by volcaniclastics, and it is expected that similar sequences will be present to the northwest.

Interpreted lithologies: mainly volcaniclastics.

4.5.6 Lower to Upper Miocene (equivalent to miol-miou)

This sequence is typically a basin sag-fill in the Reinga Basin, and onlaps underlying tilted sequences on the eastern flank of the Wanganella Ridge, which was uplifted in the Middle Miocene. In the central part of the Reinga Basin it is characterised by low-amplitude reflectors and is 0.1-0.15 sec TWT thick (*ca* 100-150 m). The sequence has not been sampled;, however, it has been suggested that the sequence comprises mostly clastics deposited in pelagic and hemipelagic environment (Herzer et al., 1997). The upper bounding Late Miocene unconformity is generally recognisable as one of a number of closely spaced, medium-amplitude reflectors with low-amplitude reflectors above and below.

Interpreted lithologies: pelagic and hemipelagic clastic sediments.

4.5.7 Post-Upper Miocene (equivalent to post-miou)

The Pliocene-Pleistocene sequence is characterised by low-amplitude, sub-parallel to incoherent reflectors. It reaches a maximum thickness of about 1 s TWT (*ca* 1-1.2 km) in the Reinga Basin, and comprises pelagic and hemipelagic drift sediments. In the northwestern part of the basin, the sequence is thinner, either due to erosion or to reduced deposition rates. Dredging of this sequence has recovered bathyal oozes.

Interpreted lithologies: bathyal oozes.

4.6 Volcanic Facies

Volcanics have been widely identified in the Lord Howe Rise region, both through sampling (eg Lord Howe Island; DSDP Site 207; dredging) and through the interpretation of seismic data. Volcanics were emplaced in a wide range of settings from the Late Jurassic to the Pliocene.

4.6.1 Upper Jurassic – mid-Cretaceous (rift volcanics)

Other than at DSDP Site 207 (eg Plate 9, lines 114-06, 114-07), volcanics of this age have not been sampled directly and their presence is inferred in seismic data partly by extrapolating from the widespread volcanics in eastern Australia. Examples of volcanics of this age in Australia include volcanogenic sediments shed westwards into the Surat and Maryborough basins in the Middle Jurassic (~165 Ma); the Whitsunday volcanics (120-100 Ma); volcanogenic sediments of the Eumeralla Formation (Otway Basin), Otway Group (Bass Basin) and Strzlecki Group (Gippsland Basin); intrusives / extrusives in the Boobyalla Sub-basin and in northeast Tasmania; and intrusions along the southeast coast. It is likely that equivalent volcanics are present beneath Lord Howe Rise, as volcanogenic sediments, intrusions and extrusions, including the Cenomanian rhyolites drilled at Site 207.

Interpreted lithologies: rhyolite and other acid to intermediate volcanics.

4.6.2 Upper Cretaceous (breakup volcanics)

Volcanics of this phase are interpreted to be widespread. They include:

- interpreted basalt flows overlying highly extended continental crust beneath the eastern flank of the Tasman Basin (Plate 8, line LHRNR-H);
- a possible Seaward-Dipping Reflector Sequence (SDRS; Plate 8, line LHRNR-G); and
- extensive flows, intrusions and volcaniclastic sediments associated with the final stages of rifting in the Central and Western Rifts.

This phase of volcanism appears to have continued for some period after Tasman Basin breakup, with volcanic sills being interpreted in the oldest sedimentary section overlying oceanic crust.

Interpreted lithologies: basalt.

4.6.3 Eocene-Oligocene

DSDP Site 593, on the western flank of the Challenger Plateau, recovered lithified volcanogenic sandstones, mudstones and breccias from within chalks, that were interpreted to emanate from the ‘Lalitha pinnacle’, a now buried 500 m-high volcanic shield (Nelson et al., 1986). These volcanics were emplaced rapidly at bathyal depths close to the Eocene/Oligocene boundary (~36-37 Ma) and were interpreted to be the product of off-rift volcanism that was related to regional extension and the formation of a major western New Zealand rift system. Seismic evidence suggests that volcanic centres of similar age and character are widespread on the southern Lord Howe Rise and Challenger Plateau.

Interpreted lithologies: basalt.

4.6.4 Late Cainozoic (hotspot volcanism)

A prominent feature of the Lord Howe Rise region is the presence of hotspot volcanism in the form of the Tasmantid and Lord Howe seamount chains. These parallel, N-S trending chains of seamounts extend from the northern end of the rise and Tasman Basin, where they have been dated at ~24 Ma (Queensland Seamount), to the southern Tasman Sea, where they have been dated at 6.4 Ma (McDougall & Duncan, 1988). A third, less well-developed chain appears to have been emplaced beneath the central Lord Howe Rise. The typical form of these volcanics is as large-scale seamounts and guyots (up to 70 km across and with more than 5 km of relief above basement; eg Plate 8, line LHRNR-F), to small-scale pinnacles on the Lord Howe Rise which may either be buried in the sedimentary section or protrude above the seabed (eg Plate 9, line 114-09). The generally thin sedimentary cover on the southern Lord Howe Rise makes it difficult to distinguish the Eocene-Oligocene volcanism from the late Cainozoic volcanism.

Interpreted lithologies: basalt.

4.7 Other Seismostratigraphic Units

Beneath the western flank of the Lord Howe Rise, a prominent 'bottom simulating reflector' (BSR) has been identified (Fig. 18). This is manifest as a moderate amplitude reflector that cuts across sedimentary structures and sequences at an average depth of about 0.4 s TWT below the seafloor. The origins of BSRs and the implications for the resource potential of the Lord Howe Rise are discussed later in this report.

5. STRUCTURE & SEDIMENT DISTRIBUTION

5.1 Introduction

While the structure of the Lord Howe Rise region has been discussed in a number of papers since the mid-1970s, most of these have either been based on sparse, low-quality data (eg Jongsma & Mutter, 1978), or they have concentrated on localised areas within the region where more detailed data sets were available (eg Bentz, 1974; Willcox et al., 1980; Zhu & Symonds, 1994; Herzer et al., 1997). The interpretation summarised in this report and in Willcox et al. (2001) is the first time that that the regional structure has been interpreted based all the available data sets.

The basis for this discussion of the structure and sediment distribution of the Lord Howe Rise region is the tectonic provinces that are summarised at regional and sub-regional scales in Figures 19 & 20. More detailed tectonic elements in the study area are shown in Figure 21. These tectonic provinces have been compiled from interpretation of the seismic, bathymetric and satellite gravity data. The regional sub-division of tectonic provinces is based on the main structural entities of the region, and includes:

Lord Howe Rise

Challenger Plateau & Bellona Trough

Tasman Basin

New Caledonia Basin

West Norfolk Ridge & Reinga Basin

Each of these provinces can be further subdivided on the basis of internal structural style and segmentation imposed by regional-scale tectonic lineaments. The dominant azimuths of these regional-scale tectonic lineaments are NE-SW (pre-Oligocene, largely related to Tasman Sea spreading) and NW-SE (post-Eocene, largely related to convergent tectonics). These lineaments will be discussed in more detail later in this chapter.

5.2 Lord Howe Rise

Mutter & Jongsma (1978) divided the Lord Howe Rise into an eastern 'stable platform' (corresponding to the Lord Howe Platform of this report), and a western 'rift zone'. Jongsma & Mutter (1978) extended this interpretation to conclude that the Lord Howe Rise and Australia separated through non-axial breaching of the Tasman Sea.

In this study, we interpret the Lord Howe Rise to be divided into tectonic provinces both longitudinally and latitudinally. The longitudinal divisions are on the basis of structural style, broadly following the divisions outlined by Jongsma & Mutter

(1978), and subsequent authors. The new data available to this study enable us to refine our understanding of the structure of those longitudinal divisions which effectively extend for up to 2000 km along the rise. The latitudinal segmentation of the LHR is largely determined by the locations of the major fracture zones in the Tasman Sea and their apparent influence on structures on the Lord Howe Rise and will be discussed later.

From east to west, the Lord Howe Rise is divided into the planated basement province (referred to here as the 'Lord Howe Platform'), the central rift province, and the western rift province. While the boundaries of the planated basement province are sharp, the boundary between the central and western rift provinces is broad and cannot be unequivocally defined. The rift provinces appear to correspond to the 'sedimentary sag basin' and 'outer rise' in a schematic illustration of a breakup model for the Sydney Basin, adapted by Bradley (1993, fig. 10) from Lister & Etheridge (1989, fig. 7.3.4) and Lister et al. (1991), and are illustrated here as Figure 22.

5.2.1 Lord Howe Platform

The Lord Howe Platform (Fig. 23) generally underlies the shallowest part of the rise in water depths from 1000-1300 m, and extends from the boundary with the Bellona Trough / Challenger Plateau at about 37°S, to at least 23°S, in the north, a distance of at least 1600 km. The average width of the platform is less than 100 km along most of its length, with a maximum width of about 200 km east-northeast of Lord Howe Island.

The internal seismic character of the basement ranges from entirely reflection-free to low-amplitude reflections showing extensive layering and structuring, suggesting that it comprises in part Palaeozoic fold belt sediments and meta-sediments, correlating with either New England or Lachlan Fold Belt rocks of eastern Australia. DSDP Site 207, at the southern end of the province, recovered Cenomanian rhyolitic lapilli tuffs and vitrophyric rhyolite flows from within the acoustic basement (Burns, Andrews et al., 1973; McDougall & van der Lingen, 1974). These volcanics cannot be distinguished from the interpreted Palaeozoic basement and their areal extent and thickness is uncertain. Refraction velocities in the range of 5.26-5.95 $km.s^{-1}$ (Appendix 3) are consistent with a Palaeozoic and/or volcanic composition.

The sedimentary section overlying basement at Site 207 comprises 38 m of glauconitic silty claystone (sandstone at the base), overlain by 167 m of Paleocene to Middle Eocene and 142 m of carbonate oozes (Burns, Andrews et al., 1973). A major hiatus in the Oligocene can be traced in wells and seismic data throughout the Lord Howe Rise region. The Cainozoic section is ubiquitous across the Lord Howe Rise, and thickens westwards into the central rift province and eastwards into the New Caledonia Basin.

Gravity modelling by Zhu & Symonds (1994) and refraction stations reported by Shor et al. (1971) indicate crustal thicknesses in the range 29-34 km for the Lord Howe Platform, suggesting that the original crust has only undergone minimal thinning during pre-breakup rifting.

The margins of the platform are structurally distinctive. The eastern flank is marked by a 40-50 km-wide zone of major faulting into the New Caledonia Basin. Throws on the faults are up to 4 km and, while most of the faulting is downthrown into the basin, on at least one line (114-4; Plate 8), there is pronounced reverse faulting indicating localised compression. Willcox et al. (1980, fig. 7) interpreted the eastern flank of the Lord Howe Rise to be a remnant pre-Maastrichtian continental margin.

The western flank of the platform is characterised by a sharp basement hinge and a flanking half-graben, which is faulted on its western margin (eg Plate 8, line 114-04. This half-graben is up to 20 km wide, and contains about 2 km of interpreted Cretaceous sediments that are generally folded and eroded, indicating compression in the latest Cretaceous or earliest Tertiary. This structure can be unambiguously traced for at least 400 km along the flank of the platform beneath the southern Lord Howe Rise and probably marks a major underlying crustal boundary. On line 114/4, this structure also coincides with a distinct change in the fabric of the underlying crust.

5.2.2 Central and Western Rift Provinces

With the high-quality data now available, the 'rift zone' of Mutter & Jongsma (1978) can structurally be divided into two longitudinal provinces – the Central Rift and the Western Rift. The boundary between these provinces is not clear cut; however, in small-scale seismic sections in which gross structures are more evident, there is an obvious distinction between them (eg Plate 8, line 114-02). This division into two parallel rift provinces, which are sub-parallel to the Lord Howe Platform, appears to be a valid distinction along much of the length of the Lord Howe Rise.

The Central Rift (Fig. 24) underlies the western half of the bathymetric culmination of the Lord Howe Rise and is approximately 150 km wide. It is separated from the Lord Howe Platform by the long and narrow half graben referred to previously, and from the Western Rift by a broad fault zone across which basement is downfaulted to the west by about 2s TWT (*ca* 3 km).

The Central Rift is characterised by a series of basement blocks, normally down-faulted to the west. The average basement depth is about 3s TWT (*ca* 3 km), which is about 1 s (1-1.5 km) deeper than the basement beneath the Lord Howe Platform, indicating greater crustal thinning beneath the Central Rift. This is supported by the gravity modelling of Zhu & Symonds (1994), who show a crustal thickness of about 20 km in this zone, and refraction station N16 of Shor et al. (1971) which gave a crustal thickness of 18 km beneath the northern Lord Howe Rise (Appendix 3). This zone has been referred to as the Moore Basin by Stagg et al. (1999).

Within the Central Rift, the tops of the basement blocks are typically ill-defined, even where the overlying sedimentary cover is relatively thin. We interpret that volcanics, presumably of Cretaceous age, are a significant component of the rift fill and are possibly also included in the tops of the rift blocks (ie pre-rift volcanics).

The Western Rift (Fig. 25) is principally identified beneath the Monowai Sea Valley and Monowai Spur which together form a subsided western flank to the Lord Howe Rise; we have named this depocentre the Monowai Basin. Strongly faulted and intruded basement lies at depths of 3.5-5.5s TWT (*ca* 3-5 km), up to 2 km deeper than in the central Rift, suggesting even greater crustal thinning than beneath the Central Rift and Lord Howe Platform. This is again supported by the gravity modelling of Zhu & Symonds (1994) which interprets a crustal thickness of slightly less than 20 km beneath the Monowai Basin on line 114-4. This zone has been referred to as the Monowai basin by Stagg et al. (1999).

The outer (western) flank of the Monowai Basin is a structural high, forming the bathymetric Monowai Spur. Basement beneath this spur is typically 1-1.5 s TWT (*ca* 1-2 km) shallower than that beneath the basin. It is likely that the Monowai Basin and the Monowai Spur are correlatives of the Lord Howe and Middleton Basins and their outer high, the Dampier Ridge. In this interpretation, extension in the Lord Howe and Middleton Basins proceeded much further than it did in the Monowai Basin, with the possible (though unlikely) emplacement of some incipient oceanic crust in the northern basins. If this correlation is valid, then it follows that pre-breakup extension, and perhaps the earliest phase of Tasman Basin spreading, were concentrated between the Dampier Ridge and Lord Howe Rise in the north and west of the 'Dampier Ridge' (ie the Monowai Spur) in the south. The location of this jump in the locus of extension corresponds to the major boundary between the central and northern Lord Howe Rise blocks interpreted in the reconstruction of Gaina et al. (1998).

As with the Central Rift, the basement blocks underlying the Monowai Basin are frequently indistinct; again, we suggest that this is due to the presence of extensive volcanics within the sedimentary fill and possibly incorporated into the blocks prior to the onset of rifting. On one line (LHRNR-G; Plate 8) we have interpreted a 'seaward-dipping reflector sequence' (SDRS). The presence of SDRS is often used to classify a continental margin as being 'volcanic' as opposed to 'non-volcanic'. While the eastern margin of Australia should perhaps not be designated a 'volcanic margin' (as for example the northwest Australian margin is), there is no doubt that the emplacement of volcanic rocks have been a major factor in the development of the margin.

5.3 Challenger Plateau & Bellona Trough

The Bellona Trough appears to be the structural feature that separates the Lord Howe Rise from the Challenger Plateau; this is reinforced by the Tasman Sea reconstructions of Gaina et al. (1998). Only a small amount of geophysical and geological data is available from these features (including lines 125-2 and NZ-A, available to this study), and the only publications of significance are those of Nelson et al. (1986), Tulloch et al. (1991) and Wood (1991, 1993).

DSDP Site 593, on the western flank of the plateau, adjacent to the Bellona Trough, drilled 571 m of apparently continuous Late Eocene to Quaternary pelagic ooze with virtually no terrigenous influences, but did not reach acoustic basement. The site was located about 3 km from 'Lalitha pinnacle', a buried volcanic shield. Nelson et al.

(1986) analysed volcanogenic deposits at the Eocene/Oligocene boundary in the well, and interpreted submarine basaltic volcanism and associated re-deposition was widespread in the southeast Tasman Sea during the Late Eocene to Early Oligocene. Tulloch et al. (1991) described a granite sample dredged off a basement block on the western margin of the plateau. Dating of zircon fractions from the sample yielded a 335 +/- 7 Ma age of crystallisation (Carboniferous). The granite was subsequently brecciated and hydrothermally altered at 95 Ma (Cenomanian).

Wood (1993) mapped the available seismic data over the Challenger Plateau and interpreted five main seismic horizons – basement, and within sedimentary rocks of late Cretaceous, Late Eocene, Oligocene and Early Pliocene age. He noted that the plateau has a core in the northwest, from which basement descends steeply into the Tasman Basin (west) and into the New Caledonia Basin (northeast), but more gently beneath the rest of the plateau to the southeast.

Line 125-2, a high-speed shallow seismic line recorded on the *L'Atalante* (location in Fig. 4), provides a valuable transect of the northern part of the Challenger Plateau. Here the plateau has prominent rift structures on the eastern flank with more than 2.5 s TWT (*ca* 3 km) of rift and post-rift sediments being present. The prominent Late Eocene unconformity can be traced from the tie to line TL-01 in the New Caledonia Basin on to the plateau, where it onlaps basement near the plateau crest. The western half of the plateau crest is underlain by a narrow zone of planated basement, similar in appearance to the Lord Howe Platform. This basement is overlain by about 200-300 m of post-Eocene pelagic ooze.

West of the Challenger Plateau, structuring is complex. Sediments thicken westward into the Bellona Trough; however, basement is not identifiable and the total sediment thickness is uncertain, although it is probably at least 2 s TWT (*ca* 3 km). The Bellona Trough is probably fault-bounded, at least on the eastern flank, but the geometry of the faults is not clear. The nature of the crust to the west of the Bellona Trough is also unclear. The interpretation of satellite gravity data (Plate 2) and other data (Plate 4) indicates slightly different structural trends and characteristics on each side of the Bellona Trough, implying somewhat different basement and crustal characteristics. Gaina et al. (1998) interpreted the Bellona Trough to be a rift that formed during a short-lived period of left-lateral transtension between the Challenger Plateau and the Lord Howe Rise.

5.4 Tasman Basin

A number of high-quality seismic lines available to this study provide clear images of the crust and sedimentary fill of the Tasman Basin (Fig. 26). These lines are supplemented by a single high-speed seismic line (125-2) recorded during a joint Australian-French swath-mapping survey by the *L'Atalante*. This line, for which accurate navigation data are currently not available, extends from the North Island of New Zealand, across the New Caledonia Basin, northernmost Challenger Plateau, Bellona Trough and Tasman Basin, to DSDP Site 283 in the southwest Tasman Basin and the South Tasman Rise. While the data are only of fair quality, they provide an valuable trans-Tasman tie to Site 283.

DSDP Site 283 was drilled west of the extinct spreading ridge on crust slightly younger than about anomaly 31 (*ca* 68 Ma) in the interpretation of Gaina et al. (1998). (Note that, in the DSDP initial report (Kennett, Houtz et al., 1974), the site was interpreted to be located at anomaly 32, corresponding to about 71 Ma on the time scale of Cande & Kent (1995). Basement was directly overlain by earliest Paleocene silty claystone that is several million years younger than the basement (Kennett, Houtz et al., 1974). In the initial report for Site 283, which gave the age difference as about 13 Ma, this discrepancy was ascribed to dislocations along nearby fracture zones and/or mis-identification of weak magnetic anomalies. However, the *L'Atalante* seismic data, which clearly image the top of oceanic basement, show that Site 283 was drilled on a terrace of shallow basement. The adjacent, deeper basement contains an additional ~300 m of sediment above basement which is not present at Site 283. We therefore believe that the age discrepancy between basement and the oldest sediments is due to non-deposition on a current-swept high at the drill site.

Five main episodes of the basin history were distinguished at Site 283 (Kennett, Houtz et al., 1974):

1. Deposition of terrigenous silty clay in an oxygenated abyssal plain with restricted circulation in the Paleocene.
2. Non-deposition in the Early Eocene to earliest Middle Eocene, followed by deposition of terrigenous silty clay in the Middle Eocene.
3. Deposition of silty clay and nannofossil-bearing diatom oozes in the Late Eocene.
4. Non-deposition from the Late Eocene to the middle Pliocene-Pleistocene.
5. deposition of very thin zeolitic clays in the ?Late Plio-Pleistocene.

Analysis of sonobuoy refraction records from the vicinity of DSDP Site 283 by Houtz (1974) reveals a somewhat unusual velocity structure for oceanic crust, with a 'typical' oceanic layer 3 velocity of about 6.8 $km.s^{-1}$ apparently being absent. Instead, three sonobuoys produced high layer 3 velocities of 7.05 to 7.37 $km.s^{-1}$, while a fourth sonobuoy gave a low velocity of 6.2 $km.s^{-1}$. While there is no obvious reason for these anomalous crustal velocities, we note that the stations were located between and adjacent to the major Cascade and Bellona Fracture Zones which offset oceanic crust laterally by 100 and 200 km, respectively. It is possible that the anomalous velocities are a function of volcanism along these fractures. Shor et al. (1971) reported a reversed refraction line recorded in the northern Tasman Basin (stations N12 and

N13; Appendix 3; Plates 2 & 3). Again, a 'normal' oceanic layer 3 is absent and a thick layer with an anomalously low velocity of 5.6 $km.s^{-1}$ overlies the mantle.

Basement in the Tasman Basin is extremely rugged and lies at depths of 6.6 - 8 s TWT (*ca* 5-7 km). The rugged surface of the basement appears to have three causes: the original oceanic crust emplacement process; the presence of many rugged fracture zones; subsequent magmatic intrusions and extrusions; and Cainozoic reactivation, including volcanism, which has produced both normal and reverse faulting with throws of more than 1 km in places.

The internal character of the Tasman oceanic crust is generally reflection free, except for some isolated locations adjacent to the Lord Howe Rise (eg Plate 8, profile LHRNR-G), where the lower crust contains strong, cross-cutting reflections. Such lower oceanic crust structuring has also been identified at other locations on the Australian margin, including the Argo Abyssal Plain (Stagg & Symonds, 1995) and the Cuvier Abyssal Plain (Sayers et al., 2002). Previous interpretations of such structuring have generally ascribed them to structural deformation in a setting of low magma supply (eg Mutter & Karson, 1992) and low spreading rate. Gaina et al. (1998, fig. 2) interpret a very slow half-spreading rate of 4 $mm.a^{-1}$ for pre-anomaly 33 spreading, which may explain the highly structured deep crust.

The boundary between Tasman Basin oceanic crust and the thinned continental crust of the Western Rift of the Lord Howe Rise is frequently ill-defined, and it is possible that we are dealing with a zone of mixed oceanic (or magmatic) and continental crust, in a similar style to the northwestern margin of the Exmouth Plateau. This difficulty in interpretation is particularly evident on line LHRNR-H (Plate 8) at the southern end of Lord Howe Rise. Gaina et al. (1998) interpret the continent-ocean boundary (COB) at approximately SP 4100 on this profile, and seafloor spreading anomalies 34y and 33o at about SPs 4500 and 4900, respectively. However, our interpretation of the seismic data on this line is that the basement comprises tilted fault blocks bounded by low-angle listric faults as far west as SP 5200, and true oceanic crust can only be identified oceanwards of this point. We further interpret that volcanic flows have largely filled in the depressions between the blocks, producing a strong horizontal reflector through which the uppermost corners of the blocks protrude. These volcanics are probably the products of the earliest stages of seafloor spreading and therefore, as with the northwest Exmouth Plateau margin (Stagg et al., 2002), we may be dealing with a zone of highly thinned continental crust which is overlain by oceanic volcanic flows. If this interpretation is correct, then the magnetic anomaly identification of Gaina et al. (1998) may still be correct.

The sedimentary fill of the eastern Tasman Basin is interpreted, as at DSDP Site 283 to comprise thick sequences of Paleocene to Early Eocene and Middle to Late Eocene pelagic sediments, overlain by a thin and irregularly distributed sequence of Miocene and younger sediments. Internal reflector configurations indicate that strong bottom currents have been an important factor in controlling sediment distribution throughout the development of the Tasman Basin.

5.5 New Caledonia Basin

The geology of the New Caledonia Basin has been interpreted by a number of authors, including Shor et al. (1971), Burns, Andrews et al. (1973), Bentz (1974), Ravenne et al. (1977), Eade (1988), Lafoy et al. (1994), and Zhu & Symonds (1994). However, these authors have generally only had limited access to the modern data sets that are now available, particularly the latest satellite gravity and the deep-seismic data. The interpretation in this section will mainly be based on the satellite gravity data, two dip lines across the basin (114-2 and 114-4; Plate 8) and a 1000+ km-long strike line (TL-01; Plate 9; Fig. 27) that ties Wainui-1 exploration well in the Taranaki Basin on the northern margin of New Zealand to DSDP Site 206 in the south-central New Caledonia Basin.

Wainui-1 (Figs 16 & 17) penetrated 3725 m of Upper Cretaceous and Cainozoic sediments before reaching basement. More than three-quarters of this section was Miocene and younger in age. The well provides an invaluable tie of the sedimentary section in the southern New Caledonia Basin. DSDP Site 206 is located on the flank of an apparent major basement high (Fig. 11) some 1000 km northeast of Wainui-1. However, the section penetrated at Site 206 was exclusively sedimentary, comprising more than 730 m of middle Paleocene and younger nannofossil ooze with variable amounts of foraminifera and volcanic ash (Burns, Andrews et al., 1973), with no basement rocks encountered. Therefore the 'basement high' at Site 206 is therefore due to massive slumping of Cretaceous/Cainozoic sediments which has totally destroyed the internal reflection character. Consequently, Site 206 is of minimal value as a stratigraphic tie for the southern New Caledonia Basin.

On the basis of seismic and satellite gravity data, the New Caledonia Basin can be divided into three distinct sectors (Fig. 28):

> The ***southern sector*** extends from the northern margin of New Zealand to about 30-31°S, where it is terminated by the extension of the NW-SE trending Vening Meinesz Fracture Zone. The southern sector trends northwest for most of its length, changing to a northerly trend at its northern end, and has an average width of about 120 km.
>
> The ***central sector*** extends from the extension of the NW-SE trending Vening Meinesz Fracture Zone in the south to the NE-SW trending Barcoo-Elizabeth-Fairway Lineament in the north. The central sector trends north-south and has an average width of about 250 km.
>
> The ***northern sector*** extends from the Barcoo-Elizabeth-Fairway Lineament in the south to about 19°S in the north. The northern sector trends slightly west of north in the south, changing to northwest in the vicinity of New Caledonia. The average width of the deepest part of the basin is about 130 km.

This report focuses on the southern sector.

A cross-section through the Tasman Basin, Lord Howe Rise and New Caledonia Basin gives a misleading impression that the New Caledonia Basin is structurally shallow, compared to the Tasman Basin. This impression is largely the result of the large sediment thickness and shallower water depths in the New Caledonia Basin. The sediment thickness averages 3 s TWT (*ca* 4 km, based on sonobuoy refraction velocities), compared with 1-1.5 km in the Tasman Basin, while water depths are typically about 3200 m, compared to 4500-5000 m in the Tasman Basin. However, the basement depth in the New Caledonia Basin ranges from 5.8-7.4 s TWT along line TL-01, corresponding to an average depth of about 6 km, which is comparable to the basement depth in the Tasman Basin.

The seismic character of basement along the length of the southern sector shows considerable variation. Basement is generally rugged, with isolated areas that have been intensely structured, either through later volcanic intrusion or through thrusting (Plate 8, line 114-4). As is the case at DSDP Site 206, some of the apparent basement structuring may be due to intense deformation of the sedimentary section (eg Plate 9, line TL-01, SPs 10200-10800), possibly due to reactivation of older basement structures. A major basement boundary can be identified at the southern end of the basin (Plate 9, line TL-01, SPs 3500-5000), where the thick sedimentary section of the Taranaki Basin onlaps the basement of the New Caledonia Basin. However, the basement beneath the outer Taranaki Basin cannot be identified, and hence the nature of the boundary, including the crustal types involved, cannot be interpreted.

In combination with the basement character, the similar basement depths in the two basins make it tempting to suggest that the New Caledonia Basin is floored by a narrow strip of oceanic crust, despite the lack of identifiable seafloor spreading magnetic anomalies. However, this interpretation is not strongly supported by gravity modelling (Zhu & Symonds, 1994) or by seismic refraction data, both of which indicate a crust which is neither unmistakably oceanic nor continental.

Moho depths computed from gravity modelling in the southern sector of the basin (Zhu & Symonds, 1994) are around 17-18 km, giving an average thickness of 12 km for the crystalline crust, approximately twice that of 'normal' oceanic crust. Moho depths computed from refraction probes in the northern New Caledonia Basin (Shor et al., 1971) are in the range 10.4-16.9 km. While these are nearer to the expected Moho depth for oceanic crust, there are significant structural differences along the length of the basin; for instance reflection Moho is clearly visible on transects of the northern sector, whereas it is not observed in the south. It would therefore be expected that the crustal type is also variable.

A number of refraction probes are available in the southern sector of the basin, on or near to line TL-01. These include two stations recorded by Mobil (107B and 108; Bentz, 1974), and four stations which were recorded during Survey 177 (Appendix 3). The sedimentary section at these stations comprises up to 1 km of sediments with velocities around 2 $km.s^{-1}$, overlying 3-4 km of sedimentary rocks with velocities of 2.8-4.5 $km.s^{-1}$. Basement velocities are unusual and variable. At the two Mobil stations, the deepest interpreted velocity was 5.4 $km.s^{-1}$, which is compatible with oceanic layer 2. However, these sonobuoys were recorded almost 30 years ago, and the quality of the refraction data is not known. These velocities were not recorded on the survey 177 stations, and we consider that there existence is dubious. The survey 177 stations recorded basement velocities of 6.26, 6.57, 6.58 and 6.98 km.s^{-1}, while two of these stations also recorded shallow basement velocities of about 6 km.s^{-1}.

Based on the available information, we do not believe it is possible to unequivocally define the crust in the New Caledonia Basin as being either thickened oceanic or thinned continental.

As noted above, the sedimentary section in the New Caledonia Basin is very thick, with up to 4 km of sediment being present. There are some difficulties in accurately interpreting unconformity ages in the New Caledonia Basin, due to the deformation of the sedimentary section and/or volcanic intrusions, and also because of rapid sequence thickness variations across the outer margin of the Taranaki Basin. Despite these difficulties we are confident that our dating of the unconformities in the New Caledonia Basin is broadly correct. In gross terms, three major sequence packages can be seismically identified. From oldest to youngest, these are:

?Uppermost Cretaceous to Lower Eocene: This sequence onlaps and fills the rugged basement surface and comprises both well-layered intervals and low seismic amplitude intervals. There are strong indications of current scouring adjacent to basement highs, and volcanics are also interpreted within the section. The average thickness of the sequence is about 1 s TWT (*ca* 1.7 km). The upper surface of the sequence exhibits strong relief that is largely due to Eocene compression which is the major tectonic event expressed in the basin. We interpret this structuring to coincide with the cessation of spreading in the Tasman Sea and a likely plate boundary readjustment. It is likely that this section was laid down in a gradually deepening environment contemporaneously with Tasman Sea spreading. The basement-focussed scouring was probably due to strong current action in a long narrow trough prior to the onset of full oceanic circulation.

Middle Eocene to Lower Miocene: This onlapping sequence is an average of 0.3 s TWT thick (*ca* 500 m), and attains a maximum thickness of about 0.8 s TWT (*ca* 1.3 km) in the vicinity of Site 206. The sequence exhibits generally low reflectivity, although the regional Oligocene unconformity does appear as a relatively high amplitude and continuous reflector.

Lower Miocene and younger: This sequence, which contains a number of unconformities that can be traced for varying distances along the axis of the basin, provides a thick (average 1.5 s TWT, *ca* 1.4 km), flat-lying blanket of pelagic sediments throughout the basin. The internal reflector character is high amplitude and high continuity with mainly parallel reflectors, with many reflectors being traced uninterrupted for hundreds of kilometres. In the southern end of the basin, in particular, this sequence contains many small-scale anomalous features which may be interpreted as volcanic intrusions, diagenetic effects, or submarine channels.

5.6 West Norfolk Ridge & Reinga Basin

The Norfolk Ridge system extends northwards from the Northland region of the North Island of New Zealand to New Caledonia, and marks the western boundary of the major region of deformation behind the Tonga-Kermadec Trench (see, for example, Bernardel et al., 2002). In this report, we will restrict our interpretation to the southern end of the ridge system, south of the NW-SE trending Vening Meinesz Fracture Zone (VMFZ). This interpretation is based primarily on two deep-seismic lines (114-2 and 114-4; Plate 8) and the work of Herzer et al. (1997).

The southern end of the Norfolk Ridge system comprises a series of northwest-trending thrust ridges and intervening sedimentary basins. from southwest to northeast, these comprise the West Norfolk Ridge, Wanganella Basin, Wanganella Ridge, Reinga Basin, and the contiguous Reinga and South Maria Ridges. Some previous interpretations (Ravenne et al., 1977, 1982) concluded that the West Norfolk Ridge connect with the Fairway Ridge. However, satellite gravity and predicted bathymetry data strongly support the Norfolk Ridge and West Norfolk Ridge being the same original structure which has later undergone 100+ km of dextral offset along the VMFZ.

The crustal structure of the northern sector of the Norfolk Ridge has been interpreted from refraction velocities by Shor et al. (1971), while Zhu & Symonds (1994) and Herzer et al. (1997) have carried out gravity modelling across the West Norfolk Ridge – Reinga Basin end of the ridge system. These studies indicated a crustal thickness greater than 20 km beneath the Norfolk Ridge in the north and as much as 30 km beneath the West Norfolk Ridge in the south, thinning to 16-25 km beneath the Reinga Basin, Taranui Sea Valley and Wanganella Trough. These crustal thicknesses are consistent with thinned continental crust.

Herzer et al. (1997) have tied a grid of seismic data (including AGSO lines 114-2 and 114-4) to petroleum exploration data on the New Zealand continental shelf and carried out a detailed seismic stratigraphic analysis. In the absence of contrary information, we accept their dating of the sequences on lines 114-2 and 114-4 (Plate 8). Their work indicated that the Reinga Basin was originally formed by up to 35-40% crustal thinning in the Cretaceous. Within the basin, they interpreted two Cretaceous sequences above an older Mesozoic basement. The lower sequence is apparently terrestrial and may include both pre- and syn-rift sub-sequences. These sequences are overlain by Paleocene and Eocene that were deposited during post-rift thermal subsidence in generally quiescent conditions. A strong unconformity, combined with an Oligocene condensed sequence, separates the Paleogene and Neogene sediments. Sedimentation in the Neogene records infill from several different directions, including the north and west as well as from New Zealand. In the Early and Middle Miocene, sediment accumulated in clastic wedges and ponded sub-basins. In the Late Miocene, this changed to sedimentation in drifts flanked by scours, with the change reflecting the end of tectonism, a reduction in clastic sediment supply and the establishment of throughgoing oceanic currents as the ridges subsided. This pattern of sedimentation persists today.

5.7 Crustal Segmentation of the Lord Howe Rise Region

Regional-scale crustal lineaments are interpreted to be an important factor in the present-day structural divisions of the Lord Howe Rise region (Stagg et al., 1999). These lineaments are aligned along two principal trends: northeast-southwest, related to Cretaceous-early Cainozoic Tasman Sea spreading; and northwest-southeast, related to the collision between the Australian and Pacific Plates in the late Cainozoic. The northeast-southwest lineaments are the more important in the structural segmentation of the Lord Howe Rise, and are described in some detail here.

The Tasman Sea, Lord Howe Rise and the northern New Caledonia Basin appear to be segmented along strike by a series of NE-SW trending crustal-scale lineaments (Fig. 28). From south to north we identify the following segments, which are grouped into two large-scale provinces:

Southern Province:

> Challenger Segment – bounded by the Resolution plate boundary to the south and the broad zone between the Cascade and Bellona Fracture Zones to the north;
>
> Monowai Segment – bounded by the Cascade / Bellona Fracture Zones to the south and the Bass Fracture Zone to the north;
>
> Gower Segment – bounded by the Bass Fracture Zone to the south and the Barcoo-Elizabeth-Fairway Lineament to the north.

Northern Province:

> Middleton Segment – bounded by the Barcoo-Elizabeth-Fairway Lineament to the south and the Brittania Fracture Zone to the north;
>
> Nova Segment – bounded by the Brittania Fracture Zone to the south and the Cato Fracture Zone and Cato Trough to the north;

Several of the names used above (Cascade, Bellona, Brittania Fracture Zones; Barcoo-Elizabeth-Fairway Lineament) are used for the first time here.

The most important of these boundaries is that between the southern and northern provinces – what we have referred to as the Barcoo-Elizabeth-Fairway Lineament (BEFL). This major crustal lineament is a major gravity feature and has structural expression as:

- the boundary between the relatively 'normal' seafloor spreading in the south Tasman Sea and the strongly oblique spreading in the north Tasman Sea;

- an offset in the Dampier Ridge and the major offset between the Lord Howe and Middleton Basins;

- a 130 km offset in the western edge of the Lord Howe Platform, with commensurate northward narrowing of that province;

- probable southward termination of the Fairway Trough and Fairway Ridge; and

- a northwards constriction of the New Caledonia Basin and accompanying change in structural style of that basin

There are significant differences between the segmentation outlined above, and that interpreted by Gaina et al. (1998), largely on the basis of interpretation of magnetic profiles, satellite gravity and reconstruction considerations. In particular:

- The major boundary interpreted by Gaina et al. (1998) between the central and northern Lord Howe Rise blocks (Fig. 8), along which they interpret 260 km of left-lateral strike slip motion from the onset of extension until about 63 Ma, corresponds to our minor boundary between the Monowai and Gower Segments and the southwards termination of the Dampier Ridge. This study points to a problem with the Gaina et al. interpretation in that there is no seismic indication of a major crustal boundary beneath the main part of the Lord Howe Rise which would separate the central and northern blocks.

- The major crustal boundary in our interpretation (the BEFL) is only interpreted as a minor boundary between the two central Dampier Ridge blocks by Gaina et al. (1998).

The second set of lineaments are oriented northwest-southeast and are restricted to the eastern half of the region. They are primarily represented by the *en echelon* Vening Meinesz Fracture Zone, northwest of the North Island of New Zealand, and by the parallel Cook Fracture Zone, some 600-700 km to the north, and will not be described further here as they appear to have little impact on the structuring of the Lord Howe Rise.

6. GEOLOGICAL EVOLUTION

6.1 Introduction

This chapter uses, as a framework, previous published studies of the geological evolution of eastern Australia and the adjacent oceanic provinces. This is expanded with the structural and stratigraphic interpretation of this study.

The geological evolution of the Lord Howe Rise region can be described in terms of the pre-Tasman Basin rifting evolution (ie approximately pre-120 Ma); Tasman Basin rifting, breakup and spreading (approximately 120-52 Ma); and post-Tasman Basin spreading (post-52 Ma). The evolution during the first of these phases produced the 'basement' to the Lord Howe Rise and other associated continental fragments. However, as the data used in this study do not add to our understanding of this period, we will therefore rely on the interpretations of previous workers, such as Veevers (1985), Stephens et al. (1996), Korsch & Totterdell (1996), Fielding (1996), Powell (1996), Symonds et al. (1996), Korsch et al. (1997) and Veevers (2000).

Table 2: Tectonic events in the Lord Howe Region (after Symonds et al., 1996, modified according to Norvick et al., 2001).

Age	***Regional tectonic events***	***Lord Howe Rise tectonics***
Barremian-Cenomanian (120-95 Ma)	Late syn-rift sag in SE Australia; extrusives and intrusives in Gippsland	Start of extension on western Lord Howe Rise
Cenomanian-Turonian (95-90 Ma)	Volcanism ceases; basin inversion; parts of eastern Highlands uplifted.	Extension, rift basin development
Turonian - Paleocene (90-60 Ma)	Breakup and start of sea-floor spreading on the southern margin. Seafloor spreading in Tasman Basin commences in south and migrates northwards. Seafloor spreading in Coral Sea commences at ~62 Ma.	Subaerial rhyolite flows and gradual subsidence
Paleocene-Eocene (63-55 Ma)	End of sea-floor spreading in the Tasman Basin and Coral Sea (~53 Ma). Middle Eocene (~45 Ma) change in pole and faster spreading.	Increased subsidence Late Paleocene-Early Eocene unconformity and compression on North LHR. Late Eocene volcanism.
Late Eocene - Oligocene (55-38 Ma)	Collision along northern Australian margin. New Caledonia basin - ophiolite obduction in Late Eocene	Eocene-Oligocene unconformity and widespread deformation of sediments
Oligocene - Miocene (38-24 Ma)	Convergence along Norfolk ridge system. E. Miocene obduction of Northland Allochthon	Subsidence; E. Miocene volcanism; M. Miocene unconformity.

6.2 Pre-Tasman Basin Rift

The eastern half of Australia is composed of the Tasman Fold Belt System, a composite orthotectonic orogenic region of Neoproterozoic to Triassic age composed of a foredeep and four orogenic belts which differ in the timing of their cratonisation, becoming younger from west to east (Scheibner & Basden, 1996). From west to east the fold belts comprise:

- the Kanmantoo Fold Belt, occupying western Tasmania, western Victoria and western New South Wales;
- the Thomson Fold Belt, which occupies much of western and central Queensland;
- the Lachlan Fold Belt, which occupies much of central New South Wales, central and eastern Victoria and eastern Tasmania; and
- the New England Fold Belt, which underlies southeast Queensland and northeast New South Wales.

The elongate, latest Carboniferous to Triassic Sydney-Bowen Basin overlies the boundary between the Lachlan / Thomson Fold Belts and the New England Fold Belt. The basin evolved during the Permian from a rift basin in a general back-arc region into a foredeep of the New England Fold Belt. The Sydney Basin continues offshore beneath the continental shelf, but any continuation onto the Lord Howe Rise is conjectural. Offshore, the Sydney Basin comprises the 'offshore Syncline', an offshore extension of the Newcastle Syncline, an offshore extension of the New England Fold Belt, and the 'offshore Uplift' (Alder et al., 1998). The offshore Uplift is suggested by Alder et al. to be part of the Currarong Orogen of Veevers (1985), who postulated that it was the remnant of a NE-SW trending orogen underlying the present continental shelf.

The prolonged period of convergent tectonism in eastern Australia culminated in the Middle to Late Triassic with the docking of the Gympie Province in Queensland. Subsequently, a 5000 km-long rift system developed, the remnants of which now extend from the Gulf of Papua in the north to the southern end of the South Tasman Rise in the south. This rift system, referred to here as the 'Eastern Rift System', was up to 1000 km in width (Symonds et al., 1996) and is comparable in scale with the Southern Rift System (Stagg et al., 1991) which developed contemporaneously between the southern margin of Australia and Antarctica. The eastern flank of the Eastern Rift System subsequently became the Lord Howe Rise and associated continental fragments of the Tasman Sea and southwest Pacific (eg Norvick et al., 2001)..

The Maryborough Basin, and similar coastal basins in northeast Australia, developed in the Late Triassic to Middle Jurassic as epicratonic downwarps within a foreland setting following the docking of the Gympie Province with the New England Orogen. In the north, in New Guinea, rifting in the Triassic to Early Jurassic led to margin development, breakup and seafloor spreading in the Middle to Late Jurassic. To the south, in the Middle Jurassic (175 +/- 18 Ma), the tholeitic Tasmanian dolerite province formed as part of a long, linear flood basalt belt within Gondwana that stretched from southern Africa, through Antarctica to Tasmania and probably represents the initial stages of Gondwana breakup. The Middle Jurassic magmatic belt normally shown to terminate in the Tasmania area could have extended further north along eastern Australia with its remnant now lying beneath Lord Howe Rise.

6.3 Tasman Basin Rifting, Breakup and Spreading

When the rises, ridges and basins of the Tasman Sea are reconstructed against the eastern Australian margin, the principal alignments are (Fig. 19):

- Far northern Lord Howe Rise with the Maryborough and Nambour Basins;

- Northern Lord Howe Rise (including Damper Ridge; Middleton Basin; Faust and Capel Basins) with the New England Fold Belt and the northern margin of the Sydney Basin;

- Central Lord Howe Rise (including southern Dampier Ridge, Lord Howe Basin and Gower Basin) with the Sydney Basin, the Lachlan Fold Belt or the Currarong Orogen (Veevers, 1985; Alder et al., 1998), and the Gippsland Basin. Mutter & Jongsma (1978) envisaged the Gippsland Basin forming a failed arm of a rift at a triple junction;

- Southern Lord Howe Rise (including the Moore and Monowai Basins and Monowai Ridge) with the eastern margin of Tasmania; and

- Challenger Plateau and Bellona Trough with the East Tasman Plateau and eastern South Tasman Rise.

In the Late Jurassic to Early Cretaceous the overall tectonic setting of the margin was still largely convergent with the plate boundary lying to the east of the Lord Howe Rise/Norfolk Ridge system. In the Middle Jurassic (<165 Ma), large volumes of volcanogenic sediments were deposited in the Surat and Maryborough Basins; these sediments were probably derived from a magmatic arc lying east of the present coastline. The latest phase of this magmatism (135-95 Ma) has been associated with the Whitsunday-Proserpine-Grahams Creek volcanic belt which is thought to have formed in an extensional/transtensional setting (Ewart et al., 1992). At the same time, NW-SE directed extension might have commenced in the Queensland and Townsville Basins. Further south, the Late Jurassic to Early Cretaceous saw major intracontinental extension in the complex Southern Rift System, which extended from southwest Australia, through the Great Australian Bight and Otway Basins (with a splay forming the Bass and Gippsland Basins), to the west and south of Tasmania to the South Tasman Rise.

In the Aptian, the tectonic setting of eastern Australian changed abruptly from a compressional to an extensional regime. The culmination of the convergent regime is represented by the widespread deformation, metamorphism, uplift, erosion and calc-alkaline volcanism of the Rangitatat II Orogeny (110-105 Ma) in New Zealand and the Neo-Cimmerian Orogeny in New Caledonia. This change of tectonic style has been attributed to the collision of the spreading ridge between the Pacific and Phoenix Plates with the subduction zone.

In the Lord Howe Rise region, this NE- to NNE-directed extension is reflected in graben development throughout the central and western rifts, Lord Howe and Middleton Basins, Western Norfolk Ridge and New Caledonia Basin, the west coast of New Zealand (including the Taranaki Basin), Challenger Plateau, parts of the Campbell Plateau, Bounty Trough and Chatham Rise. In the case of Lord Howe Rise, it is likely that extension was initially distributed evenly across the central and western rifts, with the two provinces later being separated by a major fault system (the Monowai Fault System). Later extension appears to be concentrated in the western rift, as indicated by the increased crustal thinning beneath this rift.

Through the Barremian-Cenomanian (120-95 Ma) the southeast Australian basin system (Otway, Bass and Gippsland) was filling with late-rift to sag-phase volcanogenic sediments of the Eumeralla Formation, the Otway group and the upper Strzlecki Group (Wonthaggi Formation). The composition and provenance of these sediments indicate that they were derived from an Aptian-Albian volcanic province, which is presumably now beneath Lord Howe Rise. This province may have formed as a result of transitional to extensional/transtensional magmatism along the line of incipient Tasman Sea breakup, represented by 100-90 Ma age mafic to intermediate intrusions along the southeast Australian coast, subaerial to very shallow marine 94 Ma rhyolites and tuffs from DSDP Site 207 on the southwestern Lord Howe Rise, and the main phase (120-100 Ma) of the Whitsunday-Proserpine volcanics off northeast Australia. Seismic data indicate that volcanics of this age are probably extensive throughout the rift provinces of Lord Howe Rise. Extensive magmatism in the southern part of the Eastern Rift System could be explained by the presence of mantle plumes, such as the Balleny hotspot.

In the Late Cretaceous (Cenomanian), tectonism of variable style occurred throughout the eastern Australian and New Zealand/New Caledonia region. In the northeast it was represented by regional uplift and compression in onshore basins, folding in the Maryborough Basin, a syn-rift pulse in the Townsville Basin and the end of convergence in New Caledonia. Further south there was uplift and denudation in a zone parallel to the southeastern Australian margin at about 100-80 Ma and on the margins of Bass Strait at 95-90 Ma.

The Cenomanian tectonism has been interpreted as being accompanied by breakup and start of the slow NNW-SSE spreading between Australia and Antarctica. This period was marked by:

- major subsidence in the southern Otway basin;
- wrench style basin development along the west Tasmanian margin and western South Tasman Rise;
- the start of NE-SW extension in the southeast Bass Basin;
- extension and inversion in the Gippsland Basin; and

– the start of the main episode of rifting on the east South Tasman Rise and along the east Australian margin and the margins of Lord Howe Rise.

This might also have been the time of maximum extension in the New Caledonia Basin. Our interpretation indicates that pre-Tasman Basin breakup sediments (ie pre-Campanian) overlie basement on the western flank of that basin.

Recent work in the Great Australian Bight (Sayers et al., 2001), indicates that spreading between Australia and Antarctica did not start until the Campanian (~80 Ma), coinciding with the onset of spreading in the Tasman Basin. This revised estimate of the onset of spreading is approximately 15 million years younger than previously accepted ages for this event. Breakup of the Tasman Basin was accompanied by another pulse of volcanism, reflected by the possible presence of an SDRS in the Monowai Basin, by lava flows interpreted to overlie extended continental blocks on the eastern margin of the Tasman Basin, and by apparent volcanics associated with the final stages of rifting in the Central and Western Rifts.

While the Tasman Sea / Coral Sea spreading from 84-52 Ma was clearly the main episode of seafloor spreading off eastern Australia, there is some evidence of older Gondwana breakup further east. This evidence includes: ?Albian (~102 Ma) oceanic crust forms the Northland Allocthon of New Zealand; New Caledonia ophiolites (presumed older than 80-100 Ma); the MORB-type basalt of the west coast of New Caledonia that probably formed during the initiation of the New Caledonia Basin in the Coniacian-Campanian (<89 Ma); seismic evidence from the New Caledonia Basin; and the regional considerations of Korsch & Wellman (1988).

Rifting and magmatism associated with Tasman Sea breakup occurred along the west coast of New Zealand (Laird, 1994). The West Coast and Taranaki Basins were initiated during the Campanian-Maastrichtian by oblique NNE to NE extension which utilised the existing Albian transfer faults. This transtensional rift system may have linked divergence in the New Caledonia Basin to the Tasman spreading ridge.

6.4 Cainozoic convergent tectonics

In the Eocene there was extension in the New Zealand region and convergence in New Caledonia. An east-dipping subduction zone formed along the Norfolk Ridge, followed by Early to Middle Eocene opening of back-arc basins northeast of New Caledonia. From the late Middle Eocene to Early Oligocene convergence increased and spreading in these marginal basins ceased. The newly formed oceanic crust was obducted from the northeast on to New Caledonia.

In the ***Late Eocene to mid Oligocene***, convergent tectonism extended along the whole eastern margin of Australia from New Guinea to New Zealand. This new convergent regime caused basin inversion and reactivation through the Mesozoic extensional terrane off Eastern Australia, manifest as Early Eocene inversion in the Cato Trough, and compression on the northeast flank of Lord Howe Rise, in the southern New Caledonia Basin and in the Boobyalla Sub-basin of the Bass Basin. This compression was accompanied by widespread volcanism at bathyal depths on the southern Lord Howe Rise.

In the ***Mid-Oligocene***, the plate boundary moved away from New Caledonia to north of the Solomon Islands. The transform margin or rift system was still present throughout western New Zealand. The South Fiji Basin began to open as a back-arc basin to an arc along either the Three Kings Rise or the Colville-Lau Ridge. Spreading in this basin continued until about 26 Ma.

In the ***Early Miocene***, (~23 Ma) the plate boundary began to propagate through New Zealand as a convergent boundary. There was a transform motion along the Vening Meinesz Fracture Zone associated with the dextral shear between the two halves of the North Island. These movements were initiated by Neogene clockwise rotation of the subduction system.

Further south the plate boundary became a zone of dextral transcurrent movement marking the inception of the Alpine Fault. Immediately south of the Alpine Fault, an east-dipping subduction zone developed along the line of the future Macquarie Ridge. In the Late Miocene (10 Ma), oblique compression along the Alpine Fault caused uplift of the Macquarie Ridge.

Throughout the Miocene, the Australian Plate was moving northwards over hotspots that produced the Lord Howe and Tasmantid seamount chains.

In the ***Pliocene*** (5 Ma), the subduction system (including eastern North Island of New Zealand and the associated arc) rotated further clockwise. The Haruaki inter-arc basin (between Northland and Coromandel) and the Havre Trough opened and the active arc moved eastwards to the Kermadec Ridge. Continued rotation of the subduction system led to an increasing obliquity of compression on the Alpine Fault. In the far north of the region, the Loyalty Ridge began to collide with the New Hebrides arc.

From 1 Ma onwards, the Kermadec arc propagated through the North Island as the Taupo Volcanic Zone followed by opening of the Taupo back-arc basin. Dextral transpression along the Alpine fault then brought the two halves of South Island to their present position.

7. RESOURCE POTENTIAL

7.1 Hydrocarbons

Willcox et al. (1980) undertook a regional assessment of the hydrocarbon prospectivity of the Lord Howe Rise. This assessment, which is still largely relevant, has been taken further by Symonds & Willcox (1989) who assessed the hydrocarbon prospectivity of areas beyond the EEZ. As no petroleum exploration has taken place in the southern Lord Howe Rise region, any assessment of the hydrocarbon potential must be based on samples acquired for scientific purposes, interpretation of seismic data, and comparisons with basins in eastern Australia and the northern margin of New Zealand that were formerly adjacent (Sydney and Gippsland Basins) or are now contiguous (Taranaki Basin).

7.1.1 Relevant eastern Australian and New Zealand basins

The Palaeozoic to Triassic Sydney Basin has generally been assumed to have only fair hydrocarbon potential. While it contains more than 5000 m of marine and non-marine sediments, and having been targeted by several rounds of exploration, no offshore wells have been drilled despite occurrences of oil and gas onshore (Alder et al., 1998). Potential source and seal sequences occur extensively within both Early Permian marine shales and siltstones and Early and Late Permian coal measure sequences. Although the Sydney basin is perceived to lack suitable reservoirs, Alder et al. (1998) speculate that the west-facing flank of the offshore Uplift would have been subject to marginal and shallow marine, wave-base, barrier and strand bar deposition during the Early Permian, conditions that are known in the onshore to favour better reservoir development. In addition to structural traps formed through compression, Alder et al. also identified several new structural targets created during the Cretaceous rifting of the Tasman Basin, including some that are considered to be well-placed with regard to source rock and reservoir development.

The Gippsland Basin was, until the 1990s, Australia's premier oil province. The Cenomanian to Eocene, non-marine to shallow marine Latrobe Group sediments contain both the only mature hydrocarbon source in the continental fine-grained sediments of the Late Cretaceous and the prime reservoir units in sediments of mostly Tertiary age. The top of porosity in the basin is at or near the top of the Latrobe Group and this is where 90% of the basin's original oil reserves are found (Esso Australia Ltd, 1988). The regional seal to the hydrocarbon traps is provided by the Seaspray Group and in particular by the basal Lakes Entrance Formation, predominantly an Oligocene marl. Some fields (eg Kipper and Sunfish) have been sealed by volcanics (either extrusive or shallow intrusive) in the Late Cretaceous (Mebberson, 1989). A variety of structural and stratigraphic traps are recognised, with the most productive fields being found in large-scale NE-SW trending anticlines formed by compression in the Eocene and later.

The onshore and offshore Taranaki Basin (King & Thrasher, 1996), on the western margin of New Zealand at the southern end of the New Caledonia Basin, is currently New Zealand's only commercial hydrocarbon province, with the bulk of production coming from the offshore Maui Field. The Taranaki Basin contains up to 9 km of Cretaceous to Quaternary sedimentary rocks, which include a range of known and potential source and reservoir rocks. The Maui Field consists of two broad anticlinal closures formed by Miocene compression with hydrocarbons being reservoired in stacked Paleocene to Eocene marginal marine to terrestrial sandstones (Funnell et al., 2001). The Deepwater Taranaki Basin is also recognised as having some hydrocarbon potential (Stagpoole et al., 2001), with potential source rocks in Cretaceous rift sediments, reservoirs that include Cretaceous transgressive shoreline sands and turbidite sands, and Cainozoic siltstone and carbonate rocks providing the seal.

7.1.2 Heat-Flow

Heat-flow is one of the factors that influence hydrocarbon generation in a basin. Heat-flow data are sparse in the Lord Howe Rise region. The data listed in Appendix 5 and shown in Figure 4 and Plates 3 & 4 are derived from surficial sediment thermal gradient measurements published by Grim (1969) and from DSDP Sites 206 (Burns, Andrews et al., 1973) and 587 (Kennett, von der Borch et al., 1986). Both these methods of measuring heat-flow are subject to multiple sources of error and caution must be used in over-interpreting the results, particularly where there is only a few measurements in a large area. In a detailed heat-flow study of the Exmouth Plateau off northwest Australia, Swift (1990) shows that pore fluid convection produces large, short-wavelength variations in heat-flow that are typically much larger than variations due to tectonic effects.

While accepting that the variation in heat-flow values must be treated with caution, some general comments can be made on the heat-flow distribution in the Lord Howe Rise region.

Four measurements in the northern sector of the Tasman Sea average 55 $mW.m^{-2}$, slightly less than the world-wide average of about 60 $mW.m^{-2}$, but somewhat higher than results reported for ocean basins elsewhere, where lower heat-flow values have generally been ascribed to the lower proportion of radioactive elements in oceanic crust compared to continental crust. As these stations lie astride the Tasmantid Seamounts hotspot trace, the higher than expected values may be due to residual elevated heatflow due to that hotspot which is now interpreted to underlie the southern Tasman Sea at approximately 40.4°S, 155-156°E. The only other deep-ocean heat-flow measurement is a value of 58 $mW.m^{-2}$ computed at DSDP Site 206, in the southern sector of the New Caledonia Basin.

Three heat-flow measurements are available on Lord Howe Rise. At the northern end of the rise, a single value of 57 $mW.m^{-2}$ was obtained at DSDP Site 587, in a location that appears to correspond to an extension of the eastern planated basement province. This value is very close to the world-wide average. Grim (1969) derived two values of 100 and 97 $mW.m^{-2}$ from the southern end of the Lord Howe Basin and the western rift province of the southern rise, respectively. These values are 60-70% higher that the world-wide average and, if representative, have important implications for petroleum prospectivity, as the sediment thickness on the western half of the Lord Howe Rise is, in many cases, marginal for the generation of hydrocarbons.

The cause of this high heat-flow is uncertain. As rifting in the Tasman Sea culminated at around 95-80 Ma, it is unlikely that there are any residual heating effects from that process. Also, the continental crust beneath the western Lord Howe Rise has been considerably thinned (to about 18-20 km), which should reduce the component of heat-flow due to the decay of radioactive elements. A third possibility is that, as with the heat-flow measurements in the Tasman Sea, the elevated values could be due to residual heat from the trace of the hot spot that produced the Lord Howe Rise seamount chain. Both the heat-flow stations lie south of Lord Howe Island, where volcanism has been dated at 6.4-6.9 Ma (McDougall & Duncan, 1988).

7.1.3 Western Lord Howe Rise

The western Lord Howe Rise has been recognised as a potential hydrocarbon province since the mid-1970s, although it has never been actively explored. None of the DSDP wells penetrated the syn-rift section in any of the rifts, and an assessment of the hydrocarbon prospectivity is still largely dependent on an understanding of the regional palaeogeography and on comparisons with the formerly adjacent Australian continental margin. The conjugate portion of the Australian margin includes the New England Fold Belt, the postulated Currarong Orogen (Veevers, 1985; Alder et al., 1998) or the Lachlan Fold Belt, the Permian to Triassic Sydney Basin, and the Cretaceous to Cainozoic Gippsland Basin. Of these elements, Sydney Basin equivalents may be present beneath the western Lord Howe Rise, but if they are present, they probably form part of the seismic / economic basement.

Source, reservoir and seal

The structural characteristics and sediment fill of the central and western rifts have been described previously in this report. In many depocentres the interpreted Cretaceous section is quite thick (more than 2000 m). We have no direct evidence of depositional environments that prevailed in these depocentres prior to the Maastrichtian. However, based on the observations made on Atlantic-type margins, Symonds & Willcox (1989) suggested that the early sediment fill could be predominantly fluvio-lacustrine. Wave-base erosion and planation of some horst blocks indicates that in the Late Cretaceous the western Lord Howe Rise was still at shallow water depths, with deposition restricted to the grabens. DSDP Site 207 (Burns, Andrews et al., 1973) confirms that restricted shallow marine silts and clays of Maastrichtian age overlie the horst blocks. These sediments may contain suitable organic material, but they are unlikely to have been buried deeply enough to reach thermal maturity.

The reconstruction of the Gippsland Basin against the southwestern Lord Howe Rise (Monowai Basin) has been used to suggest that a potential hydrocarbon province may be present (Willcox et al., 1980; Symonds & Willcox, 1989). Willcox (1981) noted that most of the major hydrocarbon discoveries in the Gippsland Basin is reservoired at the top of the Latrobe Group, below the Eocene-Oligocene unconformity. Sequences corresponding to the lower part of the Latrobe Group (Golden Beach and Emperor Sub-groups; Bernecker & Partridge, 2001) may be present in grabens on the western Lord Howe Rise.

Potential reservoir rocks on the western Lord Howe Rise may be present in the form of interbedded sandstones in fluvial and shallow-marine sequences, while pelagic oozes could provide a regional seal. Volcanic rocks are interpreted to be present in both the pre-rift and syn-rifts sections. The effect of volcanics on the quality of reservoirs is not known, but they may provide effective seals, as in some fields in the Gippsland Basin.

Source rock maturity

In most places on Lord Howe Rise, the Late Cretaceous section is overlain by less than 1000 m of overburden, which is probably insufficient to produce source rock maturity, unless the heat flow has been abnormally high. However, the deepest rift basins in the western rift zone contain up to about 3000 m of sediment, which may be sufficient to generate hydrocarbons. If the high heat-flow values (60-70% higher than average, as noted previously) recorded at the southern end of Lord Howe Basin and in northern end of the Monowai Basin are representative of the southern Lord Howe Rise, then Cretaceous source rocks in grabens may have reached thermal maturity.

As was noted previously in this report, bottom-simulating reflectors (BSRs) have been observed on a line (114-9) in the northern part of the Monowai Basin, while some flat spots have also been observed. If these BSRs are due to the presence of gas hydrates, and if those gas hydrates are thermogenic, rather than biogenic, then this would indicate that active hydrocarbon generation is taking place. The potential for both conventional and unconventional hydrocarbon resources is discussed in section 7.2.

Petroleum plays and traps

Symonds & Willcox (1989) identified several potential petroleum plays with different trap types, including fold and wrench-related anticlines, fault blocks, stratigraphic traps and possible diapiric traps. Any hydrocarbons generated within the grabens may have been trapped against the bounding faults, while further structural traps may have been created by folding and faulting within the graben fill. Hydrocarbons could also have migrated upwards and been trapped in possible cool-water carbonate buildups and sealed by pelagic oozes.

This study shows that regional compressional tectonism commencing in the Early Eocene has caused reactivation and reversal of many faults. This compression appears to have been localised in many areas, probably due to the relative orientation of compression azimuths and pre-existing structures or general structural grain. However, the currently available regional seismic data do not permit any detailed analysis of these trends. This compression-related structuring might have affected hydrocarbon plays either by creating new traps through, for example, fault-propagation folds, or by breaching pre-existing traps.

7.1.4 Eastern flank of Lord Howe Rise

Source, reservoir and seal

The eastern flank of Lord Howe Rise has been interpreted to be an ancient seaboard of the Australian-Antarctic supercontinent (Willcox et al., 1980). A considerable thickness of probable Late Cretaceous clastic sediment (up to 2500 m), derived mostly from the Lord Howe Platform, was deposited across this margin above a narrow rift. Depositional environments in this rift may have been favourable for both the deposition and preservation of sediments with suitable hydrocarbon generative potential.

Source rock maturity

Because of the thick post-Cretaceous section present in the New Caledonia Basin, it is possible that source rocks will be mature. The only heat-flow stations in the basin indicate that heat-flow of 57-58 $mW.m^{-2}$ is close to the world-wide average.

Petroleum plays and traps

Structuring within the eastern rift province is complex and varied in style, including both normally faulted blocks and compression/thrust structures which may have provided suitable traps for generated hydrocarbons. There is also a possibility of stratigraphic traps being developed where reservoirs pinch out against the basement of the Lord Howe Platform, with seals being provided by Cainozoic pelagic oozes.

7.1.5 New Caledonia Basin

Source, reservoir and seal

DSDP Site 206 provides the only samples from the sedimentary section in the deep-water part of the basin; however, this well did not penetrate the pre-Cainozoic section and hence source and reservoir quality can only be inferred from the structural setting and by comparisons with other areas. The southeastern end of the basin connects with the Taranaki Basin in New Zealand waters, a proven hydrocarbon province which has positive implications for the New Caledonia Basin. The basin contains up to 4000 m of sedimentary rocks, and the basal 1500-1700 m of this section has been interpreted as being of Cretaceous age. The basin appears to have been structurally enclosed with restricted circulation until at least the end of the Cretaceous. During this time, it can be expected that both terrestrial and shallow marine sediments were deposited. It is likely that any potential source rocks would have been preserved. As noted above for the eastern flank of the Lord Howe Rise, the depth of burial and regional heat-flow may be sufficient for the generation of hydrocarbons.

The Cretaceous section is overlain by a considerable thickness of Cainozoic oozes which may have provided a suitable regional seal.

Source rock maturity

High-quality seismic data and satellite synthetic aperture radar (SAR) imagery indicate possible direct hydrocarbon indications beneath the eastern flank of Lord Howe Rise, in the north (Exon et al., 1998; Symonds et al., 1999). Bottom simulating reflectors (BSRs) observed in seismic reflection data on the northeast (and southwest) flanks of Lord Howe Rise may indicate the presence of gas hydrate (see section 7.2). In the northeast, the general coincidence of the BSR with the western updip flank of the Fairway Basin may indicate a thermogenic component to the gas hydrates. Also, in this area, some evidence for low-level oil slicks and films on SAR imagery, combined with seismic evidence for fluid migration through the sedimentary section, may indicate that active hydrocarbon generation is taking place. Should suitable source rocks also be present in the southern sector of the New Caledonia Basin, then it is reasonable to assume that generation is also taking place, although no BSRs have been observed.

Petroleum plays and traps

The Cretaceous and early Palaeogene section has been affected by at least two phases of compressive tectonism in the Early Eocene and the Miocene. In particular, the Early Eocene compression has produced strong relief at that level which may have produced suitable anticlinal traps, albeit in very deep water (*ca* 3000 m).

7.1.6 West Norfolk Ridge

Little is known of the sedimentary sequences of the West Norfolk Ridge. The hydrocarbon prospectivity of this area is discussed briefly in Symonds & Willcox (1989). The western part of the western Norfolk Ridge is underlain by up to 3000 m of sediment. These sediments are possibly similar to those infilling the rift basins of Lord Howe Rise (Symonds & Willcox, 1989). However, sediments on the West Norfolk Ridge have been folded, which may have hydrocarbon plays that are less developed on the Lord Howe Rise. A thick sedimentary sequence (at least 1500 m) containing mounded and prograding facies underlies the northern end of the Wanganella Trough. This sequence might be a deltaic sequence deposited in the trough during subaerial erosion and planation of the northern West Norfolk Ridge.

Between the northern end of the West Norfolk Ridge and the southern end of the Norfolk Ridge, the Taranui Sea Valley is underlain by another basin with a thick sedimentary section. The basin contains up to 4000 m of faulted and folded sedimentary rocks in a graben setting. The structural style of the basin suggests wrench tectonics, and could indicate that sediments were deposited in a dextral strike-slip zone, which was responsible for the offset of the Norfolk Ridge. This area is also potentially prospective for petroleum.

7.1.7 Reinga Basin

Source, reservoir and seal

The hydrocarbon potential of the Reinga Basin has been analysed by Herzer et al. (1997). The Reinga Basin lies seaward of the hydrocarbon-producing Taranaki and prospective Northland regions. In the Taranaki Basin, source rocks are mainly represented by Cretaceous and Palaeogene coal measures and possibly marine shales. Tying of the seismic sequences into the Reinga Basin and dredging of coal measures and marine organic shale facies (samples RE9302-5 and GO351D, respectively) indicate that the basin may contain source rocks similar to those in the Taranaki Basin.

The most common reservoir rocks are likely to be terrestrial and paralic sandstone facies of the Cretaceous sequences. Similar facies might also be expected in Palaeogene sequences. While reservoir characteristics of the Neogene sequences are unknown, turbidite sands are likely to be present in areas with high sedimentation rates, for instance adjacent to the Reinga Ridge and in the east of the Wanganella Sub-basin. Early Miocene turbidites contain a significant volcanoclastic component, which could degrade reservoir quality. Carbonate-rich facies are probably common at all stratigraphic levels.

Seals could be provided by marine mudstones, shales, limestones and altered volcanoclastics.

Petroleum plays and traps

Potential traps, including anticlines, fault blocks, drape structures, unconformities, onlaps and combinations of these, have been recognised (Herzer et al., 1997) in seismic data.

Source rock maturity

The maturity of potential source rocks is largely unknown. According to the interpretation of Herzer et al. (1997), Reinga Basin Cretaceous and Palaeogene terrestrial and shallow marine sediments have probably been buried deeply enough to have generated hydrocarbons. A Late Cretaceous marine shale (GO351D-a) recovered from a degraded Miocene fault scarp in the extreme northwest of the area contained extractable hydrocarbons of maturity equivalent to a vitrinite reflectance of Ro 0.6%. Thermal modelling using the properties of rocks recovered from dredges RE9302-5 and GO351D suggests that hydrocarbon generation and expulsion should have occurred in many parts of the basin.

7.1.8 Non-conventional Hydrocarbon Resources

Exon et al. (1998) have reported a 'bottom-simulating reflector' (BSR) that extends over an area of at least 25 000 km^2 of the eastern flank of the northern Lord Howe Rise and adjacent New Caledonia Basin at water depths of 1500-3600 m. BSRs generally indicate an interface between overlying sediment containing methane hydrate (a frozen crystalline mixture of methane and water) and underlying sediment containing bubbles of free methane gas. The depth of the BSR of 520-600 m below sea bed, as inferred from seismic reflection profiles, is consistent with this interpretation, given the expected thermal gradient for the region. BSRs have also been identified on the western flank of the northern Lord Howe Rise, where it descends into the Middleton Basin, and in the northern part of the Monowai Basin in this study.

These observations constitute the first compelling evidence for methane hydrate deposits in waters off Australia. If confirmed, the deposits could represent an immense accumulation of natural gas in an unexpected open-ocean location within both French and Australian seabed jurisdiction. More details of the origins of gas hydrates and BSRs are contained in Chapter 8 of this report.

7.1.9 Summary

This study confirms that the southern Lord Howe Rise region has long-term hydrocarbon potential, both for conventional and unconventional hydrocarbons. The most prospective areas are the central and western rift provinces of Lord Howe Rise (Moore and Monowai Basins), the eastern flank of Lord Howe Rise, adjacent to the New Caledonia Basin, and possibly in the New Caledonia Basin itself, where the sediment thickness reaches 3.5 s TWT (*ca* 4+ km).

Despite the lack of wells and other rock samples in the region, structural and palaeogeographic considerations suggest that hydrocarbon source rocks may be present, particularly in Late Cretaceous syn-rift sediments. A favourable restricted marine environment may also have prevailed in the restricted half-grabens on the western Lord Howe Rise, and in the New Caledonia and Reinga Basins. Hydrocarbon traps may exist against the boundary faults and as smaller structures within the depocentres. Interbedded shales and pelagic oozes may provide a regional seal.

While non-conventional hydrocarbon resources (methane hydrates) cannot currently be exploited, their interpreted presence suggests that thermogenic hydrocarbons may be currently being generated in the region. This significantly upgrades the regional hydrocarbon prospectivity.

7.2 Minerals

At present, very little is known about the non-petroleum mineral resource potential of the Lord Howe Rise region. The only such resources likely to be of any long-term economic interest are manganese nodules and crusts (which normally include nickel, copper and cobalt).

Symonds & Colwell (1992) have reported sampling results of a survey by the BGR research vessel *Sonne* (Roeser & Shipboard Party, 1985). On this survey, dredging on a major NW-SE structural lineament about 250 km northeast of Lord Howe Island recovered Mn/Fe nodules containing pebbles of sandstone, quartzite, coralline and ?algal limestone, phyllite and granite. A large block of shallow water calcarenite / calcirudite thickly encrusted by Mn/Fe was also recovered. The presence of intercalated mineralised layers within a complex stratigraphy of dark and dense Mn/Fe crusts may indicate that hydrothermal activity was associated with the structural zone (Roeser & Shipboard Party, 1985).

Bolton et al. (1986) reported several samples from the southwest pacific, one of which (sample SP29) came from the northwest margin of the Reinga Basin on the eastern flank of the Norfolk Ridge. These samples were unusual in that they contained grains of silver and gold in their native form.

8. DISCUSSION

A number of issues of scientific importance have arisen from this study. In the following discussion, we outline some of these issues.

8.1 Geometry of post-breakup continental fragments

The geometry of the continental fragments that separated from eastern Australia during Tasman basin spreading is notable for its consistency. Lord Howe Rise / Dampier Ridge, New Caledonia Basin and the Norfolk Ridge system comprise sub-parallel strips of continental or possibly hybrid crust that are narrow in relation to their length and of approximately consistent width for more than 2000 km. Changes in trend along their length are also closely reflected between features.

The question arises as to what regional crustal-scale processes have caused this remarkable continuity over such a long distance? It is tempting to suggest that the post-breakup configuration of continental fragments is a function of the geometry of accretion in eastern Australia during the Palaeozoic and Mesozoic. However, maps of the present-day structural entities of eastern Australia (eg Scheibner & Basden, 1996, fig. 3.1), while showing a general north-south orientation of the fold-belts and sedimentary basins do not show a comparable linearity to that observed on the Lord Howe Rise. We therefore conclude that the consistency is mostly a product of the extension and breakup mechanism, rather than of the pre-breakup crustal fabric.

8.2 Importance of SW-NE and SE-SW crustal-scale lineaments

Satellite gravity data, in conjunction with careful mapping of the limited seismic data, indicate that crustal-scale lineaments have played an important role in the present-day structures of the region. While the segmentation of the Lord Howe Rise by NE-SW trending lineaments is quite interpretive, we are confident that the Barcoo-Elizabeth-Fairway Lineament is a major crustal feature that has produced structural dislocations in the Tasman Basin, Lord Howe Rise / Dampier Ridge, and the New Caledonia Basin.

The SE-NW crustal lineaments are similarly prominent, particularly in the eastern part of the study area. The Vening Meinesz Fracture Zone is a very strong lineament which has produced much of the present-day physiography at the southern edge of the Norfolk Ridge system. While SE-NW trending lineaments have had less effect on the structuring of the Lord Howe Rise, there are suggestions in the satellite gravity (and the predicted bathymetry) and in seismic data that the VMFZ may have a structural continuation across the Lord Howe Rise, and possibly as far as the Australian continent. We note that Roeser & Shipboard Party (1985) referred to a sampling target (dredge SO-36-63; Appendix 4) being located at an '… embayment within the Lord Howe Rise marking the westward end of the Vening Meinesz Fracture Zone', indicating that they also believed that the VMFZ continued on to Lord Howe Rise.

8.3 Seismic vs magnetic interpretations and Tasman Basin crust

As noted previously in this report (section 5.6), there is a significant discrepancy between the segmentation of structural elements interpreted here and the arrangement of microplates proposed by Gaina et al. (1998), which was based on the interpretation of magnetic anomalies, combined with satellite gravity determination of fracture zones and the continent-ocean boundary. The principal problem is with Gaina et al.'s major boundary south of the Dampier Ridge, which they required to fully close the southern part of the Tasman Basin. We believe that the integrated interpretation presented in this report means that there are aspects of the magnetics-derived spreading history that are not yet explained.

The difference in interpretations may arise from mis-identification of some of the crust at the margins of the Tasman Basin which has conventionally been interpreted as oceanic crust emplaced during a period of very slow spreading (presumably also a period of low magma supply). Some seismic data (eg our interpretation of part of line LHRNR-H) suggests that this crust may be either highly extended continental crust, or possibly an amalgam of slow-spreading oceanic crust with continental fragments. If this interpretation is correct, then this continental material needs to be incorporated into the closure of the Tasman Basin derive its pre-breakup configuration and the early stage of very slow spreading identified by Gain et al. (1998) may not exist.

8.4 Crust beneath Lord Howe/Middleton Basins and New Caledonia Basin

In some interpretations, the New Caledonia Basin (eg Sutherland et al., 2001, fig. 5) and possibly also the Lord Howe and Middleton Basins (eg Jongsma & Mutter, 1978; Norvick et al., 2001, fig. 7b) have been interpreted to have formed through the emplacement of 'normal' oceanic crust. While we have not presented an interpretation of the Lord Howe and Middleton Basins as part of this study, there is little support in the available seismic data for an oceanic origin for these basins.

However, interpretation of the crustal type in the New Caledonia Basin is still equivocal. As noted previously in this report, reflection and refraction seismic, gravity and magnetic data do not strongly support either continental or oceanic origins of the basement. This is consistent with the interpretation of Etheridge et al. (1989) that the southern segment of the New Caledonia Basin is floored by lower continental crust that has been unroofed by a regional, sub-horizontal detachment.

8.5 Spatial and Temporal Distribution of Volcanic Rocks

As has been noted previously in this report, volcanism has been an important factor in the development of the Lord Howe Rise region and is both temporally and spatially wide-ranging. This volcanism is manifested in a number of divergent styles and as several different compositions. Without extensive drilling, we can only speculate on the effects of volcanism on the hydrocarbon prospectivity.

The most important volcanic phases can be summarised as:

8.5.1 Early to mid Cretaceous (ca 120-95 Ma)

From the Barremian to the Cenomanian, the Otway, Bass and Gippsland basins in southeast Australia were filling with late-rift to sag-phase, slightly alkaline volcanogenic sediments, which were thought to have an eastern provenance. The composition and provenance of these sediments has led to the conclusion that they were derived from an Aptian-Albian volcanic arc to the east of the Gippsland basin, possibly now beneath Lord Howe Rise (Jones & Veevers, 1983; Hill et al., 1995a; Hill et al., 1995b). However, Symonds et al. (1996) believe that the volcanogenic sediments are most likely the result of transitional, extensional / transtensional magmatism along the line of incipient Tasman Sea breakup. On Lord Howe Rise, there is direct evidence of this volcanic phase in DSDP Site 207 which penetrated subaerial to shallow marine rhyolite tuffs and flows.

Interpretation of the seismic data indicates that equivalent volcanics and volcanogenic sediments are widespread on the southern Lord Howe Rise where they are either incorporated into the acoustic basement or in the base of the syn-rift fill. This volcanic phase is unlikely to have had much impact on the hydrocarbon potential as it mostly pre-dates the sequences of hydrocarbon interest.

8.5.2 Late Cretaceous (ca 85-80 Ma)

While volcanics of breakup age have not been sampled directly, their presence is inferred to be widespread on the basis of seismic data. These volcanics include an interpreted Seaward-Dipping Reflector Sequence in the Monowai Basin; interpreted basalt flows overlying highly-extended continental crust beneath the southeastern flank of the Tasman Basin; and extensive flows, intrusions and volcaniclastic sediments associated with the final stages of rifting in the central and western rifts. The volcanism appears to have continued for some millions of years after breakup, with sills being interpreted in the deepest sediments in the Tasman Basin.

It is likely that this phase of volcanism has had an impact on hydrocarbon prospectivity in the region, particularly in the western rift, through increased transient heat-flow and impacts on potential reservoirs.

8.5.3 Eocene-Oligocene (37-36 Ma)

Basaltic volcanics were emplaced rapidly at bathyal depths close to the Eocene/Oligocene boundary. These were interpreted to be the product of off-rift volcanism that was related to regional extension and the formation of a major western New Zealand rift system (Nelson et al., 1986). Seismic data suggests that volcanics of this age are largely restricted to the southern end of Lord Howe Rise and the Challenger Plateau. Their impact of heat-flow and the quality of potential hydrocarbon reservoirs is likely to be relatively minor.

8.5.4 Miocene (24-6 Ma)

Miocene and younger basaltic volcanism is reflected by the linear, N-S trending hotspot trails of the parallel Tasmantid and Lord Howe seamount chains which extend for at least 2000 km from the northern Lord Howe Rise and Cato Trough to the southern Tasman Sea. These seamount chains are located in the central Tasman Basin and along the western flank of Lord Howe Rise. It is likely that more minor expressions of this volcanic phase are also present on the main part of Lord Howe Rise where narrow intrusions have penetrated the sediments and are frequently exposed as small pinnacles at the sea floor.

While the Miocene volcanics have strong gravity and seismic expression, their extent appears to be very localised and they do not appear to have greatly disturbed the sedimentary section. We therefore believe it is likely that the major impact on the hydrocarbon potential will have been the late heat-flow pulse associated with their emplacement.

In the Norfolk Ridge-Reinga Basin region, a field of shallow intrusions and extrusions occurs near the Wanganella Ridge in the northwestern part of the Reinga Basin. These features are seen cutting through the Miocene sediments of the East Wanganella Sub-Basin, some of them being expressed in the bottom topography as well.

The volcanic bodies decrease in size away from the ridge. They appear to have diapir-like shape with undisrupted reflectors underneath. However, there is some evidence of their igneous origin. A small peak on the seafloor, which seem to belong to one of the diapiric bodies was dredged (GO353) and Late Pliocene intraplate alkaline basalts and hyaloclastites were recovered there (Monzier & Vallot, 1983). Some hyaloclastites were also recovered at dredge site GO349 on a prominent peak 100 km north of GO353 (Herzer et al., 1997).

8.5.5 Summary

Volcanic rocks, in the form of extrusions, intrusions and volcaniclastics have been an important component of the geological evolution of the Lord Howe Rise region for much of the time from the Jurassic to the Miocene. As well as the practical problems in interpreting the seismic data, these volcanics may also have a strong, though as yet unquantifiable, influence on the hydrocarbon potential. These influence, both negative and positive, include:

- damage to reservoirs (negative);
- damage to existing hydrocarbon accumulations (negative);
- provision of a late heat-flow pulse, in the case of the Miocene volcanics, possibly enhancing maturation which would otherwise be vary marginal in view of the general thickness of the overburden (positive);
- extrusions and shallow intrusions can provide a seal, as in the case of several Gippsland Basin fields (positive);
- volcaniclastics can provide good-quality reservoirs (positive).

8.6 Bottom-simulating Reflectors

8.6.1 Distribution and origin

At the northern end of line 114-09 we have identified a prominent bottom simulating reflector (BSR) – a high amplitude reflector that is discordant with geological structures and sequences – at a constant depth of about 0.4 sec below the seafloor (Fig. 18). It occurs at water depths of 2500-3000 m in two locations extending about 25 and 12 km along the line.

Anomalous seismic reflectors that intersect bedding reflectors mimicking seafloor topography may indicate the presence of natural gas hydrates in continental margin sediment (eg Singh et al., 1993). The position of the reflector coincides with the transition boundary at the base of the gas hydrate zone. BSRs mark the interface between higher sonic velocity in hydrate-cemented sediment above and lower sonic velocity in uncemented sediment below. The seismic reflection from the base of gas hydrate zone is generally characterised by a negative impedance contrast and large reflection coefficients.

BSRs have also been interpreted in seismic data from the flanks of the northern Lord Howe Rise (Exon, et al., 1998). The extent, depth and character of this reflector is different from the one we observed on line 114/09. It occurs in the area with water depths 3000-4000 m at about 0.7 sec below the seafloor and extends for up to 220 km. On line LHRNR-B, the BSR is identified as a zone of high-amplitude reflectors, with the main reflector corresponding to a negative impedance contrast. Calculation of the predicted transition boundary for the eastern Lord Howe Rise and in the New Caledonia Basin based on the recorded thermal gradients (Exon, et al., 1998) shows that it is consistent with the observed BSR depth of 0.7 s TWT below seabed.

Direct evidence of gas hydrates is provided by sampling in 14 oceanic locations (the landward wall of the Mid-America trench off Mexico and Guatemala, on the Blake Outer Ridge off the southeastern US and others), shallow sediment coring (six locations) and ODP drilling (nine locations) in various regions of the world (Kvenvolden & Barnard, 1983; Kvenvolden, 1995). Where solid gas hydrates have been sampled the gas is composed mainly of methane accompanied by carbon dioxide. Molecular and isotopic composition of hydrocarbons indicates that most of methane is of biological origin. The gas was probably produced by the bacterial alteration of organic matter buried in sediment. Under appropriate regime of pressures and temperature natural gas can interact with water to form solids in which water molecules form a rigid lattice of cages each containing a molecule of natural gas. These deposits are called gas hydrates. There are two types of known gas hydrates: Structure I and Structure II. Structure I gas hydrates are most common and are characterised by cages with body-centred packing, allowing to include in their structure such gases as methane, ethane, carbon dioxide and hydrogen sulphide. Diamond packing in Structure II results in cages being larger and they can include larger molecules, such as propane and isobutane. As a result of the packing gas hydrates in shallow reservoirs can have more methane per unit volume than can be contained as free gas in the same space.

The occurrence of gas hydrates is controlled by a combination of temperature, pressure, gas composition and ionic impurities in the water. In oceanic sediment gas hydrates occur where bottom water temperatures approach $0^{o}C$ and water depths exceed about 300 m. The lower limit of gas hydrate occurrence is determined by geothermal gradient, the maximum lower limit being about 2000 m below the seafloor.

Gas hydrates occur worldwide, but because of the pressure-temperature and gas volume variations they are restricted to two regions: polar and deep oceanic. Gas hydrates are most commonly found in slope and rise sediments, where cold bottom water is present.

Gas in hydrate deposits may come from bacterial decomposition of organic matter in shallow sediment or from thermogenic processes deeper in the sediment pile (Claypool & Kaplan, 1974; Kvenvolden, 1995). Sediment is organic-poor at DSDP sites on the central rise (Kennett, von der Borch et al., 1986), tending to favour a thermogenic origin for at least some of the hydrates. Also, in the northeast, the general coincidence of the BSR with the southern part of a structural depression and depocentre, the Fairway Basin, may indicate a thermogenic component to the gas hydrates. Such gas could be being generated in older, rift-related and organic-rich sediments in the basins, and migrating up-dip onto the Lord Howe Rise, perhaps in part beneath a seal of early-forming hydrates (Exon et al., 1998).

Satellite synthetic aperture radar (SAR) imagery recently acquired over the potential gas hydrate zone beneath the northeastern Lord Howe Rise provided evidence for some low-level oil slicks above the eastern (?western) New Caledonia Basin. SAR anomalies interpreted as natural oil films normally unrelated to hydrocarbon generation occur over the eastern Lord Howe Rise in association with seismic evidence for fluid migration. Together, these data provide further evidence for hydrocarbon generation and active migration to the seafloor (Symonds et al., 1999).

The distribution and general characteristics of the BSRs on the Lord Howe Rise, and their relationship to gas hydrate deposits, cannot be established without additional research, including analysis of the seismic signal, further seismic surveying and direct sampling of the water column and shallow sediments. Ongoing studies at the University of Texas Institute of Geophysics indicates that some of the BSRs have a positive polarity indicating a velocity increase. Such BSRs cannot be explained by a velocity decrease associated with free gas beneath gas hydrate-bearing sediments at the base of gas hydrate stability (BGHS). The DSDP results indicate that other phenomena that may cause BSRs of this type, such as an Opal to Opal-CT transition and a chalk to limestone transition, are unlikely to be operative in this region. Alternative explanations that are being investigated are that the BSR is either produced from the top of a thin gas hydrate layer at the BGHS, probably without free gas beneath, or from the base of a hydrate layer associated with little or no free gas.

8.6.2 Resource Potential

Recent interest in gas hydrates as potential future energy resource is associated with their energy density in comparison to conventional gas deposits and worldwide distribution along continental margins. Although naturally occurring gas hydrates have been recognised since the 1960s, the technology is not currently available to make the deposits economically viable.

Over the past decade, several methods of recovering methane from gas hydrates have been proposed, however their resource potential will be recognised only when it can be shown that the energy required to release methane from the hydrate is significantly less than the thermal energy of methane that can be recovered from the gas hydrate deposit. Circulation of warm surface water into gas hydrate deposits and horizontal drilling techniques provide possible future approaches to their exploration. Free gas trapped beneath the gas hydrate represents another exploration possibility, however the ability of gas hydrates to act as a seal has not been investigated sufficiently.

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APPENDIX 1: 1982 UNITED NATIONS CONVENTION ON THE LAW OF THE SEA (UNCLOS)

Article 76 : Definition of the continental shelf

1. The continental shelf of a coastal State comprises the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend up to that distance.

2. The continental shelf of a coastal State shall not extend beyond the limits provided for in paragraphs 4 to 6.

3. The continental margin comprises the submerged prolongation of the land mass of the coastal State, and consists of the seabed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor with its oceanic ridges or the subsoil thereof.

4. (a) For the purposes of this Convention, the coastal State shall establish the outer edge of the continental margin wherever the margin extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by either:

   (i) a line delineated in accordance with paragraph 7 by reference to the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 per cent of the shortest distance from such point to the foot of the continental slope; or

   (ii) a line delineated in accordance with paragraph 7 by reference to fixed points not more than 60 nautical miles from the foot of the continental slope.

   (b) In the absence of evidence to the contrary, the foot of the continental slope shall be determined as the point of maximum change in the gradient at its base.

5. The fixed points comprising the line of the outer limits of the continental shelf on the seabed, drawn in accordance with paragraph 4 (a) (I) and (ii), either shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured or shall not exceed 100 nautical miles from the 2,500 metre isobath, which is a line connecting the depths of 2,500 metres.

6. Notwithstanding the provisions of paragraph 5, on submarine ridges, the outer limit of the continental shelf shall not exceed 350 nautical miles from the

baselines from which the breadth of the territorial sea is measured. This paragraph does not apply to submarine elevations that are natural components of the continental margin, such as its plateaux, rises, caps, banks and spurs.

7. The coastal State shall delineate the outer limits of its continental shelf, where that shelf extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by straight lines not exceeding 60 nautical miles in length, connecting fixed points, defined by coordinates of latitude and longitude.

8. Information on the limits of the continental shelf beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured shall be submitted by the coastal State to the Commission on the Limits of the Continental Shelf set up under Annex II on the basis of equitable geographical representation. The Commission shall make recommendations to coastal States on matters related to the establishment of the outer limits of their continental shelf. the limits of the shelf established by a coastal State on the basis of these recommendations shall be final and binding.

9. The coastal State shall deposit with the Secretary-General of the United Nations charts and relevant information, including geodetic data, permanently describing the outer limits of its continental shelf. The Secretary-General shall give due publicity thereto.

10. The provisions of this article are without prejudice to the question of delimitation of the continental shelf between States with opposite or adjacent coasts.

APPENDIX 2: DETAILS OF SEISMIC SURVEYS

Survey	Mobil
Contractor	Mobil
Vessel	*Fred Moore*
Year	1972
Streamer length (m)	500
Seismic channels	6
Sample rate / rec. length (ms)	Analogue / 6000
Group length/interval (m)	unknown / 330 feet (100 m)
Shot interval (s)*	12
Recording fold	3
Cable depth (m)	11 m
Source type / power or volume	Air Guns
Nominal vessel speed (kn)	8
Primary navigation	unknown
Secondary navigation	unknown
Tertiary navigation	unknown
Primary echo-sounder	unknown
Secondary echo-sounder	unknown
Magnetic data	yes
Gravity data	yes

Survey	United
Contractor	United Geophysical Corporation
Vessel	*Unknown*
Year	1970
Streamer length (m)	unknown
Seismic channels	24
Sample rate / rec. length (ms)	4 / 7000
Group length/interval (m)	? / 70
Shot interval (m)	unknown
Recording fold	
Cable depth (m)	unknown
Source type / power or volume	3 air guns / 4.6 litres
Nominal vessel speed (kn)	5
Primary navigation	unknown
Secondary navigation	unknown
Tertiary navigation	unknown
Primary echo-sounder	unknown
Secondary echo-sounder	unknown
Magnetic data	no
Gravity data	no

Survey	12, 14, 15
Contractor	Compagnie General de Geophysique / Bureau of Mineral Resources
Vessel	*Lady Christine*
Year	1972
Streamer length (m)	1000
Seismic channels	6
Sample rate / rec. length (ms)	analogue / continuous
Group length/interval (m)	50 / 200
Shot interval (m)	50
Recording fold	6
Cable depth (m)	10
Source type / power or volume	sparker / 120 kJ
Nominal vessel speed (kn)	7-9
Primary navigation	Transit Satnav + Marquardt sonar doppler
Secondary navigation	Transit Satnav + Chernikeef paddle log
Tertiary navigation	Transit Satnav + pressure log
Primary echo-sounder	Elac
Secondary echo-sounder	seismic
Magnetic data	yes
Gravity data	yes

Survey	Roving Reconnaissance Seismic (P)
Contractor	Shell Internationale Petroleum Maatschappij N.V.
Vessel	*Petrel*
Year	1971
Streamer length (m)	2400
Seismic channels	24
Sample rate / rec. length (ms)	4 / 6000
Group length/interval (m)	50 / 100
Shot interval (m)	50
Recording fold	24
Cable depth (m)	15
Source type / power or volume	airgun array / 6.4 litres
Nominal vessel speed (kn)	6
Primary navigation	Transit Satnav + Marquardt sonar doppler
Primary echo-sounder	Not known
Magnetic data	yes; analogue only
Gravity data	yes; analogue only

Survey	SO-7A
Contractor	BGR / BMR
Vessel	*Sonne*
Year	1978
Streamer length (m)	2400
Seismic channels	24
Sample rate / rec. length (ms)	
Group length/interval (m)	
Shot interval (m)	
Recording fold	24
Cable depth (m)	
Source type / power or volume	
Nominal vessel speed (kn)	
Primary navigation	Transit Satnav + sonar doppler
Secondary navigation	
Tertiary navigation	
Primary echo-sounder	
Secondary echo-sounder	
Magnetic data	yes
Gravity data	yes

Survey	SO-36A
Contractor	BGR / BMR
Vessel	*Sonne*
Year	1985
Streamer length (m)	2400
Seismic channels	24
Sample rate / rec. length (ms)	
Group length/interval (m)	
Shot interval (m)	
Recording fold	24
Cable depth (m)	
Source type / power or volume	Airgun array / 25.6 litres
Nominal vessel speed (kn)	5
Primary navigation	Transit Satnav and sonar doppler
Secondary navigation	GPS
Tertiary navigation	
Primary echo-sounder	
Secondary echo-sounder	
Magnetic data	yes
Gravity data	yes

Survey	46
Contractor	AGSO
Vessel	*Rig Seismic*
Year	1984
Streamer length (m)	2400
Seismic channels	48
Sample rate / rec. length (ms)	2 / 8000
Group length/interval (m)	50 / 50
Shot interval (m)	50
Recording fold	24
Cable depth (m)	7
Source type / power or volume	2 8.2l Bolt Guns /16.4l
Nominal vessel speed (kn)	5
Primary navigation	Transit Satnav + Magnavox sonar doppler
Secondary navigation	Transit Satnav + Raytheon sonar doppler
Tertiary navigation	none
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	no

Survey	114
Contractor	AGSO
Vessel	*Rig Seismic*
Year	1992
Streamer length (m)	4800
Seismic channels	192
Sample rate / rec. length (ms)	2 / 16000
Group length/interval (m)	25 / 25
Shot interval (m)	50
Recording fold	48
Cable depth (m)	10
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (kn)	5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Transit Satnav + Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	125 (*Tasmante*)
Contractor	AGSO
Vessel	*L'Atalante*
Year	1994
Streamer length (m)	300
Seismic channels	6
Sample rate / rec. length (ms)	4 / 5000
Group length/interval (m)	50 / 50
Shot interval (m)	50
Recording fold	3
Cable depth (m)	12
Source type / power or volume	2 x GI guns / 4.92 litres
Nominal vessel speed (kn)	10
Primary navigation	differential GPS
Secondary navigation	GPS
Tertiary navigation	
Primary echo-sounder	SIMRAD Dual EM12 multibeam
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	177
Contractor	AGSO
Vessel	*Rig Seismic*
Year	1996
Streamer length (m)	4000
Seismic channels	320
Sample rate / rec. length (ms)	4 / 16000
Group length/interval (m)	12.5 / 12.5
Shot interval (m)	50
Recording fold	40
Cable depth (m)	10
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (kn)	5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	206
Contractor	AGSO
Vessel	*Rig Seismic*
Year	1998
Streamer length (m)	3000 nominal*
Seismic channels	240 nominal*
Sample rate / rec. length (ms)	4 / 16000
Group length/interval (m)	12.5 / 12.5
Shot interval (m)	50
Recording fold	35 (maximum)
Cable depth (m)	10
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (kn)	5.5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

** Due to difficulties with the streamer several different streamer lengths were used*

APPENDIX 3: VELOCITY DATA

Locations

Sonobuoys

Station	*Latitude*	*Longitude*	*Water depth*	*Reference*
1E53	-43.116667	160.053333	5.0	Houtz (1974)
2E53	-43.160000	159.835000	4.94	Houtz (1974)
4E53	-43.326667	159.251667	4.93	Houtz (1974)
6E53	-44.041667	154.438333	4.87	Houtz (1974)
8E53	-43.735000	154.071667	4.71	Houtz (1974)
9E53	-43.186667	155.225000	4.47	Houtz (1974)
N1	-22.483333	168.250000		Shor et al. (1971)
N2	-21.650000	168.500000		Shor et al. (1971)
N3	-21.866667	171.316667		Shor et al. (1971)
N4	-21.683333	172.250000		Shor et al. (1971)
N5	-23.533333	171.800000		Shor et al. (1971)
N6	-23.900000	170.833333		Shor et al. (1971)
N7	-24.300000	167.433333		Shor et al. (1971)
N8	-23.150000	167.250000		Shor et al. (1971)
N9	-23.516667	165.633333		Shor et al. (1971)
N10	-23.000000	164.950000		Shor et al. (1971)
N11	-24.066667	161.883333		Shor et al. (1971)
N12	-27.100000	155.866667		Shor et al. (1971)
N13	-27.783333	156.100000		Shor et al. (1971)
N14	-27.666667	158.900000		Shor et al. (1971)
N15	-28.400000	159.250000		Shor et al. (1971)
N16	-28.250000	161.533333		Shor et al. (1971)
N17	-28.416667	163.183333		Shor et al. (1971)
N18	-27.883333	166.083333		Shor et al. (1971)
N19	-26.933333	166.166667		Shor et al. (1971)
N20	-27.150000	167.333333		Shor et al. (1971)
N21	-26.683333	167.616667		Shor et al. (1971)
N22	-26.966667	168.183333		Shor et al. (1971)
N23	-27.616667	169.000000		Shor et al. (1971)
N24	-29.500000	176.000000		Shor et al. (1971)
N25	-29.916667	176.766667		Shor et al. (1971)
N26	-31.500000	179.333333		Shor et al. (1971)
N27	-32.566667	179.333333		Shor et al. (1971)
N28	-32.550000	179.750000		Shor et al. (1971)
N29	-31.950000	179.933333		Shor et al. (1971)
N30	-33.016667	-179.550000		Shor et al. (1971)
N31	-34.200000	-179.883333		Shor et al. (1971)
N32	-34.083333	-178.083333		Shor et al. (1971)
N33	-34.700000	-178.350000		Shor et al. (1971)
C5	-13.600000	174.933333		Shor et al. (1971)

C6	-18.983333	177.566667		Shor et al. (1971)
C7	-21.916667	178.550000		Shor et al. (1971)
C8	-19.616667	-174.900000		Shor et al. (1971)
C9	-19.950000	-172.550000		Shor et al. (1971)
C10	-20.500000	-173.333333		Shor et al. (1971)
C11	-20.033333	-173.116667		Shor et al. (1971)
Mobil-106				Bentz (1974)
Mobil-107A	-37.172694	168.859694	1350	Bentz (1974)
Mobil-107B	-36.310139	169.367306	2300	Bentz (1974)
Mobil-108	-36.302389	168.213306	2500	Bentz (1974)
Mobil-109	-36.310194	165.552111	1100	Bentz (1974)
Mobil-113			1500	Bentz (1974)
Mobil-114A				Bentz (1974)
Mobil-114B				Bentz (1974)
SO7-III	-34.8146	164.2712	890	Willcox et al. (1981)
SO7-IV	-35.2824	163.6635	1260	Willcox et al. (1981)
SO7-V	-35.1366	161.6393	2570	Willcox et al. (1981)
SO7-VI	-33.9913	162.1841	1360	Willcox et al. (1981)
SO7-VII	-34.1603	160.4587	2080	Willcox et al. (1981)
SO7-VIII	-33.3513	158.7184	3240	Willcox et al. (1981)
SO7-X	-32.2869	161.0544	1440	Willcox et al. (1981)
SO7-XIII	-26.2463	161.3383	1690	Willcox et al. (1981)
SO7-XIV	-29.2616	160.4001	1630	Willcox et al. (1981)

Velocity Analyses Southwest Pacific, Tasman Sea & Eastern Australia

1E53

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.86	5.0	6.67
5.15	5.67	7.4
7.10	7.78	8.2

2E53

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.60	4.94	6.58
4.65	6.03	7.43
7.05	7.53	8.07

4E53

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.84	4.93	6.57
1.99	5.3	6.98
4.90	5.76	7.44

6E53

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.75	4.87	6.49
5.19	5.5	7.21
7.37	7.54	8.0

8E53

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.73	4.71	6.28
2.20	5.23	6.88
5.50	5.63	7.24

9E53

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.05	4.47	5.96
4.80	5.51	6.97
6.20	7.66	7.87

Mobil-106

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.8	-	-
5.58	-	-

*

Mobil-107A

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	o
1.65	1.35	1.8
2.67	1.86	2.42
2.86	2.7	3.05
3.09	3.21	3.41
5.25	4.72	4.41

*

Mobil-107B

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.6	2.3	3.07
1.7	2.44	3.25
3.38	3.42	4.40
3.83	4.69	5.15
3.92	6.19	5.93
5.4	7.01	6.35

*

Mobil-108

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.6	2.5	3.33
1.79	2.6	3.46
2.09	2.88	3.77
2.64	3.29	4.16
2.99	4.02	4.71
4.98	5.75	5.87
5.43	6.56	6.20

Mobil-109

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.8	1.1	1.47
2.345	1.36	1.76
5.31	2.4	2.65

Mobil-113

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.6	1.5	2.0
1.87	1.57	2.09
2.73	1.77	2.30
3.87	2.8	3.05
5.06	3.01	3.16
6.8	3.62	3.40

Mobil-114A

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.6	-	-
1.67	-	-
2.15	-	-
4.8	-	-
5.145	-	-
5.36	-	-

Mobil-114B

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.6	-	-
1.73	-	-
2.59	-	-
3.33	-	-
3.85	-	-
4.07	-	-
5.69	-	-

SO7-III

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.78	0.89	1.17
3.75	1.91	2.31
5.26	3.28	3.04
6.62	4.96	3.68

SO7-IV

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.25	1.26	1.68
4.95	2.64	2.90

SO7-V

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.19	2.58	3.43
6.23	4.65	5.32

SO7-VI

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.37	1.36	1.81
5.02	2.8	3.03

SO7-VII

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.06	2.08	2.77
3.12	3.11	3.77
4.86	?	?

SO7-VIII

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
3.58	3.24	4.32
5.7	5.4	5.77

SO7-X

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.16	1.44	1.92
2.94	2.17	2.59
4.45	2.47	2.80

SO7-XIII

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.8	1.69	2.25

SO7-XIV

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	1.63	2.17
2.27	1.63	2.17
2.49	3.17	3.53
4.95	?	?

177-TL01-1

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.0	1.92	2.56
2.93	2.36	3.0
3.43	3.21	3.58
4.34	3.31	3.64
4.54	5.48	4.64
6.0	6.98	5.3
6.98	8.78	5.9

177-TL01-2

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.0	2.61	3.48
2.76	2.89	3.76
3.9	4.05	4.6
5.97	6.51	5.86
6.58	8.55	6.48

177-TL01-3

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.0	2.94	3.92
3.96	3.82	4.8
5.48	4.34	5.06
6.26	7.29	6.14

177-TL01-4

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.0	3.15	4.2
2.99	4.07	5.12
4.16	4.61	5.48
4.28	5.17	5.75
4.84	5.92	6.1
6.57	7.32	6.68

177-NZ-A-1

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
2.0	4.77	6.36
3.19	5.09	6.68
3.6	5.73	7.08
6.3	6.3	7.4
6.94	9.45	8.4

PFI08

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.80	0.0	0
5.85	5.00	1.72
6.10	7.00	2.05
6.12	11.00	3.36
6.10	13.50	4.18
6.50	15.00	4.66
6.80	25.00	7.66
7.00	34.50	10.42
7.80	39.00	11.63
8.12	41.50	11.95
8.14	60.00	16.5

PFI09

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
4.70	0.00	0
4.90	2.00	0.83
5.75	3.20	1.33
5.90	6.50	2.46
6.35	8.00	2.95
6.37	11.00	3.90
6.36	17.00	5.78
7.00	20.00	6.68
7.02	22.00	7.25
6.70	23.00	7.54
6.72	27.00	8.73
7.18	32.00	10.17
7.70	41.00	12.59
8.04	43.50	13.23
8.05	60.00	17.33

PFI10

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.60	0.0	0
5.75	2.00	0.35
5.80	2.50	0.53
5.95	3.30	0.80
5.96	5.50	1.54
5.80	7.00	2.05
6.00	14.50	4.59
6.30	16.00	5.08
6.60	26.50	8.33
6.80	28.00	8.78
7.10	33.00	10.22
7.20	40.00	12.18
7.60	42.50	12.85
7.95	43.00	12.98
7.97	50.00	14.74
7.60	52.00	15.25
7.62	60.00	17.36
8.00	63.00	18.13
8.02	70.00	19.87

PD002

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
4.90	0.00	0
6.04	5.50	2.24
6.52	6.60	2.61
7.86	24.60	8.13
7.86	30.00	9.50

PD004

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
6.04	0.00	0
6.52	21.20	7.02
7.86	41.80	13.34
7.86	45.00	14.15

PR104

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.95	0.00	0
8.00	25.00	8.4
8.00	100.00	27.15

PMU01

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
6.15	0.00	0
6.17	20.00	6.49
6.75	20.30	6.59
6.77	35.00	10.94
7.98	35.30	11.02
8.00	75.00	20.95

PMU02

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
6.15	0.00	0
6.75	20.00	6.50
7.98	35.00	10.95
8.36	100.00	27.24
8.23	120.00	32.02
8.72	190.00	49.03
8.72	225.00	57.06

PJ001

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
6.00	0.00	0
6.01	20.00	6.66
8.00	30.00	9.52
8.01	50.00	14.49

PPI01

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.60	0.00	0
6.40	3.40	1.21
6.62	4.30	1.50
7.15	13.30	4.21
6.98	27.00	8.06
7.38	34.10	10.04
7.40	42.00	12.18

PRI01

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.86	0.00	0
7.95	24.80	8.46
7.95	40.00	12.29

PRI02

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.55	0.00	0
5.72	8.00	2.88
6.00	14.50	5.16
7.80	23.80	8.26
8.24	35.40	11.23
7.50	45.00	13.56

N1

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	2.09	2.79
3.48	3.38	3.99
5.16	5.18	5.02
5.95	7.18	5.80
6.92	9.98	6.74
8.04	18.02	9.06

N2

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	2.20	2.93
3.48	3.22	3.88
5.16	5.42	5.15
5.95	9.02	6.54
6.92	14.62	8.42
8.04	20.10	10.01

N3

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
3.28	2.73	3.64
5.49	4.00	4.41
6.53	5.60	5.00
7.83	9.20	6.10

N4

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
3.28	2.57	3.43
5.49	3.89	4.23
6.53	5.99	5.00
7.83	7.99	5.61

N5

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	4.49	5.99
4.42	4.95	6.41
6.82	7.05	7.36
8.13	15.05	9.71

N6

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	4.07	5.43
4.42	5.17	6.45
6.82	6.37	6.99
8.13	12.37	8.75

N7

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.96	1.01	1.35
4.02	2.08	2.44
4.89	3.88	3.34
6.17	7.28	4.73
6.73	11.18	5.99
7.74	21.28	8.99

0

N8

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.96	0.87	1.16
4.02	1.86	2.17
4.89	3.06	2.77
6.17	6.36	4.12
6.73	17.96	7.88

N9

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	3.60	4.80
3.20	4.72	5.84
4.95	6.22	6.78
6.02	7.82	7.43
6.83	9.12	7.86
8.11	12.82	8.94

N10

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	3.62	4.83
3.20	4.72	5.85
4.95	6.02	6.66
6.02	7.42	7.23
6.83	9.32	7.86
6.83	14.32	9.32

N11

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	1.03	1.37
4.26	1.86	2.15
6.19	3.06	2.71
6.99	3.86	2.97

N12

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.42	4.77	6.36
5.58	6.47	7.76
7.85	11.17	9.45

N13

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.42	4.80	6.40
5.58	6.39	7.71
7.85	9.69	8.90

N14

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	3.43	4.57
3.62	4.49	5.56
5.29	6.89	6.89
6.86	7.99	7.30
7.80	17.49	10.07

N15

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	3.41	4.54
3.62	5.30	6.30
5.29	6.20	6.80
6.86	9.60	8.09
7.80	10.90	8.47

N16

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	1.64	2.19
3.90	2.05	2.57
5.95	3.75	3.44
6.82	11.75	6.13
8.03	18.85	8.21

N17

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	1.17	1.56
3.90	1.47	1.84
5.95	2.37	2.30
6.82	15.57	6.74
8.03	28.97	10.67

N18

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	3.56	4.75
3.74	4.53	5.65
5.07	6.33	6.61
6.36	7.83	7.20
6.92	9.53	7.74
7.98	16.93	9.88

N19

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	3.59	4.79
3.74	4.64	5.76
5.07	5.84	6.41
6.36	7.14	6.92
6.92	9.24	7.58
7.98	10.34	7.90

N20

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.73	0.78	1.04
4.53	2.42	2.24
5.95	8.02	4.71
6.73	10.72	5.62

N21

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.73	1.03	1.37
4.53	2.65	2.56
5.95	8.25	5.03
6.73	15.55	7.49

N22

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	3.25	4.33
3.97	3.99	5.02
6.05	5.89	5.98
7.04	7.99	6.67
8.17	11.49	7.67

N26

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.33	1.71	2.28
5.14	3.15	3.52
6.20	5.85	4.57
7.00	8.25	5.34
8.06	20.05	8.71

N23

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	2.99	3.99
3.97	3.88	4.81
6.05	5.18	5.47
7.04	7.48	6.23
8.17	15.38	8.47

N27

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.33	2.33	3.11
5.14	3.73	4.31
6.20	5.13	4.86
7.00	9.23	6.18
8.06	14.03	7.55

N24

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	4.29	5.72
6.02	5.43	6.78
6.90	6.73	7.21
8.26	10.04	8.17

N28

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	3.63	4.84
4.39	4.14	5.31
6.62	5.44	5.91
8.46	13.04	8.20

N25

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	4.28	5.71
3.50	5.22	6.58
6.90	6.42	7.27
8.26	12.62	9.06

N29

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	2.80	3.73
4.39	3.95	4.80
6.62	5.95	5.71
8.46	8.65	6.53

N30

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.81	0.68	0.91
5.42	2.17	1.97
6.92	9.07	4.51
8.13	19.07	7.40

N31

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.81	2.49	3.32
5.42	5.23	5.27
6.42	9.03	6.67
8.13	16.23	8.92

N32

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	8.37	11.16
5.54	8.38	11.17
7.84	13.98	13.19

N33

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
2.15	7.60	10.13
5.54	8.44	10.91
7.84	10.34	11.60

APPENDIX 4: KEY GEOLOGICAL SAMPLE STATIONS IN DEEP WATER

Sample No.	*Latitude*	*Longitude*	*Depth (m)*	*Greatest age*	*Location, lithology and environment*
GO357D	35 37.2’ S	165 46.8’ E			Lord Howe Platform; olivine basalt, gabbro, hyaloclastic breccia with mid-Miocene forams (from Willcox et al, 1980)
SO36-57KD	31 51.9’ S	157 22.7’ E	2550	mid Permian	Dampier Ridge; granite, gabbro, sandstone
SO36-63KD	28 34.4’ S	163 00.6’ E	1700		Lord Howe Platform; sandstone, quartzite, coralline and ?algal limestone, phyllite and granite
CH8701	42 46’ S	166 48’ E	3000	Carboniferous	Challenger Plateau; granite.
GO348D-b	30 07.2’ S	167 29.8’ E	900-1400	vL.Olig-vE.Mio	Norfolk Ridge; coquina with volcanic lithics, shallow open marine, photic zone to >100m
GO347D	30 28.5’ S	168 05.4’ E	1840-2300		Norfolk Ridge; calcareous mudstone
U566 1-3	35 05’ S	169 10’ E	979	?vL.Olig – lE.Mio	West Norfolk Ridge; bioclastic, bryozoan limestone, oceanic, shoal
RE9302-5-2	34 00.65’ S	166 57.5’ E	1270-2250	eL.Cret	West Norfolk Ridge; coal measures, carbonaceous mudstone, lower coastal plain
RE9302-6-1	33 54.43’ S	167 22.89’ E	700-735	vL.Olig-E.Mio	West Norfolk Ridge; bioclastic bryozoan limestone, bored and replaced by foraminiferal limestone, bathyal (age and depth ranges common to both limestones).
RE9302-7-2	33 33.65’ S	167 39.32’ E	650-900	vL.Olig-mE.Mio	Wanganella Ridge; foraminiferal limestone, bathyal
RE9302-2-6	33 07.59’ S	170 54.85’ E	1875-1950	mE.Mio	Vening Meinesz FZ; micrite infilling cracks in basalt, oceanic bathyal, calm
GO350D-5	32 21.8’ S	169 08.5’ E	1600-3400	L.Pal-E.Eo-M.Eo	Vening Meinesz FZ; ?argillaceous limestone, cataclasite, planktonic
GO351D-g	31 52.9’ S	168 17.2’ E	900-2500	M.Eo	Vening Meinesz FZ; mudstone breccia, bathyal >1000m (age and depth of matrix fauna only)
RE9302-1-1 to –4	33 00.66’ S	171 42.42’ E	2500-2700	?vL.Olig-E.Mio, ?lE.-?eM.Mio	Three Kings Ridge; calcareous volcanic sandstone, shoal, lapilli tuff, lower bathyal, rapidly deposited
U579	31 51.5’ S	171 57.6’ E	2109	late Paleogene? Olig?	Three Kings Ridge; calcareous fine sandstone, oceanic, bathyal or deeper
GO353D	33 01’ S	167 50.9’ E	1870-1530		Reinga Basin; hyaloclastic breccia, palagonite and ‘bubble’ lava, pyroxene, olivine inclusions

APPENDIX 5: HEAT-FLOW DATA

Station	*Latitude*	*Longitude*	*Heat-flow ($mW.m^{-2}$)*	*Reference*
TASMAN-1	-31.565000	153.555000	54.0	Grim (1969)
TASMAN-2	-31.620000	154.233333	64.5	Grim (1969)
TASMAN-3	-31.508333	155.016667	54.4	Grim (1969)
TASMAN-4	-31.471667	156.208333	47.3	Grim (1969)
TASMAN-5	-31.508333	156.905000	44.4	Grim (1969)
TASMAN-6	-33.156667	159.450000	100.0	Grim (1969)
TASMAN-7	-33.376667	161.613333	96.7	Grim (1969)
DSDP-206	-32.012500	165.452500	57.8	Burns, Andrews et al. (1973)
DSDP-587	-21.197833	161.333167	56.9	Kennett, Houtz et al. (1974)

APPENDIX 6: INTERPRETED SEISMIC HORIZONS

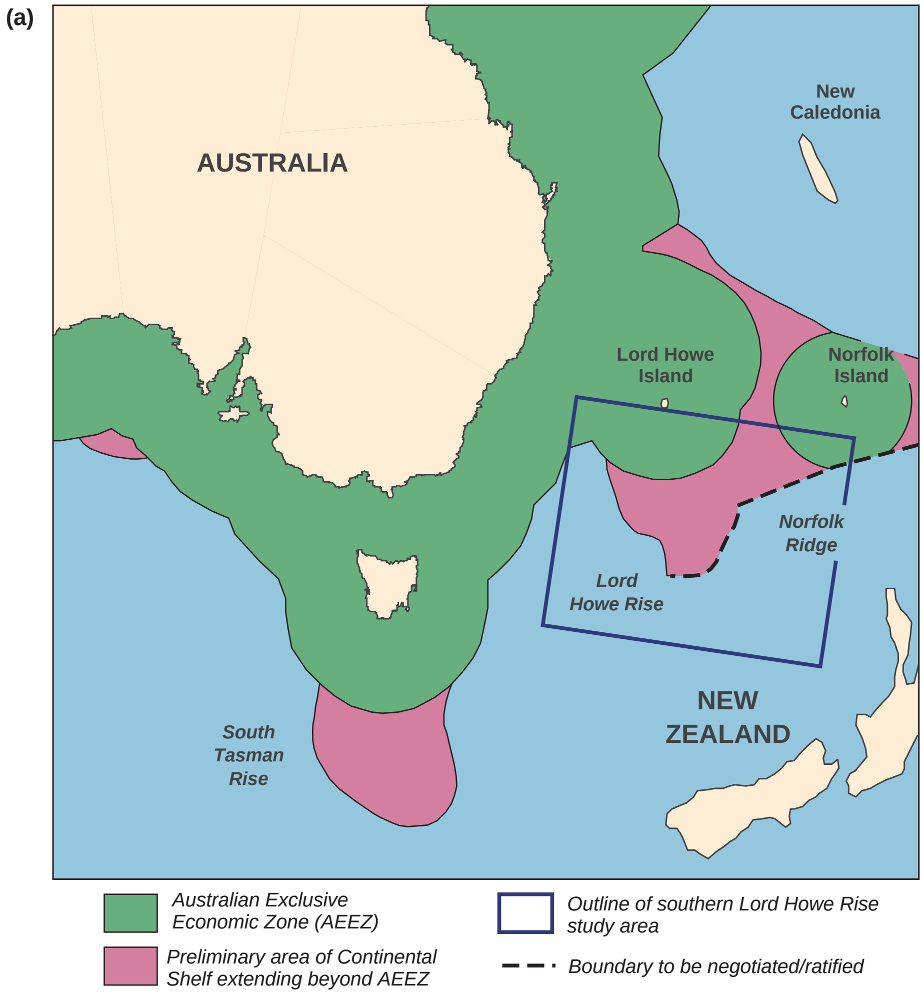
Seismic Horizon	*Description*
wb	water bottom
bsr	bottom-simulating reflector
miou	Upper Miocene
miom	Middle Miocene
miol	Lower Miocene
olig	Oligocene
eocu	Upper Eocene
eocl	Lower Eocene
maas	Maastrichtian
camp	Campanian (Tasman Sea breakup)
cen	Cenomanian
plan	planated basement – Lord Howe Platform
erif	rifted basement – eastern margin Lord Howe Rise
bech	rifted basement – Bellona-Challenger province
crif	rifted basement – central Lord Howe Rise
trif	rifted basement – Tasman Basin
wrif	rifted basement – western Lord Howe Rise
ncb	basement – New Caledonia Basin
tara	Taranaki Basin basement
vmio	Miocene volcanics
veoc	Eocene – Oligocene volcanics
vcam	Campanian (breakup) volcanics
vcen	Cenomanian volcanics
tsdr	top Seaward Dipping Reflector Sequence (SDRS)
bsdr	base SDRS
lay2	top oceanic crust layer 2 (volcanic basement)
moho	Moho

FIGURES & CAPTIONS

1. (a) The main marine jurisdictional zones off eastern Australia; study area shown by box. (b) Marine jurisdictional zones contained in the 1982 United Nations Convention on the Law of the Sea (modified from Symonds et al., 2001).
2. Bathymetric image of the Tasman Sea and southwest Pacific showing the study area for this report (solid box). Bathymetry based on the gridded data set of Petkovic & Buchanan (2002).
3. Bathymetry of the study area based on the GEBCO data set. Contour interval 500 m.
4. Locations of seismic lines, DSDP sites, sample stations, heat-flow stations and refraction stations used in this study. Short highlighted sections of seismic lines (with numbers) refer to figures in this report. Bathymetry contour interval 1000 m.
5. Satellite gravity image of eastern Australia and the western Pacific. Also shown are the Australian and New Zealand Exclusive Economic Zones and the outlines of the major basins (after Symonds et al., 2001).
6. Satellite gravity image of the Lord Howe Rise region. The study area is south of 30^{o}S.
7. Plate evolution of the western Pacific since 100 Ma (after Walley & Ross, 1991).
8. Magnetic lineations and microplates in the Tasman Sea, interpreted by Gaina et al. (1998). Magnetic anomaly identifications are shown in Plate 4.
9. Detachment model describing the formation of the eastern Australian margin and the basins and ridges of the Lord Howe Rise region (after Etheridge et al., 1989).
10. Stratigraphic column at DSDP Site 206, New Caledonia Basin (adapted from Burns, Andrews et al., 1973).
11. Seismic profile at DSDP Site 206, New Caledonia Basin. Key to interpreted seismic horizons is contained in Appendix 6.
12. Stratigraphic column at DSDP Site 207, southern Lord Howe Rise (adapted from Burns, Andrews et al., 1973).
13. Seismic profile at DSDP Site 207, southern Lord Howe Rise. Key to interpreted seismic horizons is contained in Appendix 6.
14. Stratigraphic column at DSDP Site 208, northern Lord Howe Rise (adapted from Burns, Andrews et al., 1973).
15. Stratigraphic column at DSDP Site 283, western Tasman Basin (adapted from Kennett, Houtz et al., 1974).
16. Stratigraphic column at Wainui-1, Taranaki Basin, offshore New Zealand.
17. Seismic profile at Wainui-1, Taranaki Basin, offshore New Zealand. Key to interpreted seismic horizons is contained in Appendix 6.
18. Bottom-simulating reflector (BSR) in the Monowai Basin (line 114-9). Location shown in Figure 4.

PLATES

7. Interpreted seismic sections: sheet 1.
8. Interpreted seismic sections: sheet 2.
9. Interpreted seismic sections: sheet 3.



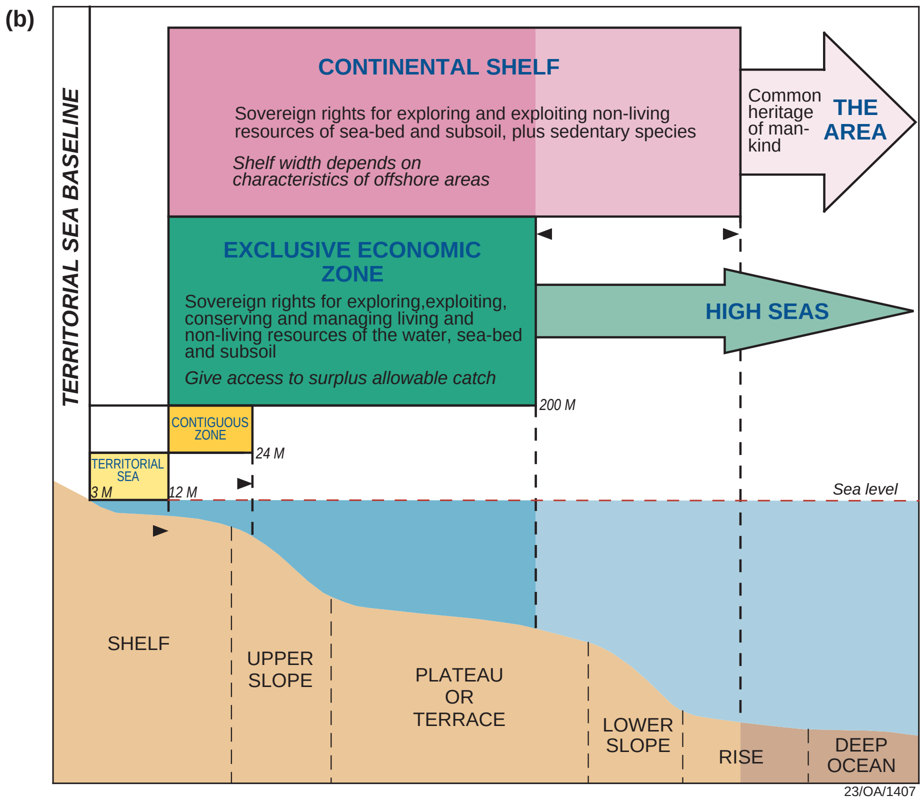


Figure 1. (a) The main marine jurisdictional zones off eastern Australia; study area shown by box. (b) Marine jurisdictional zones contained in the 1982 United Nations Convention on the Law of the Sea (modified from Symonds et al., 2001).

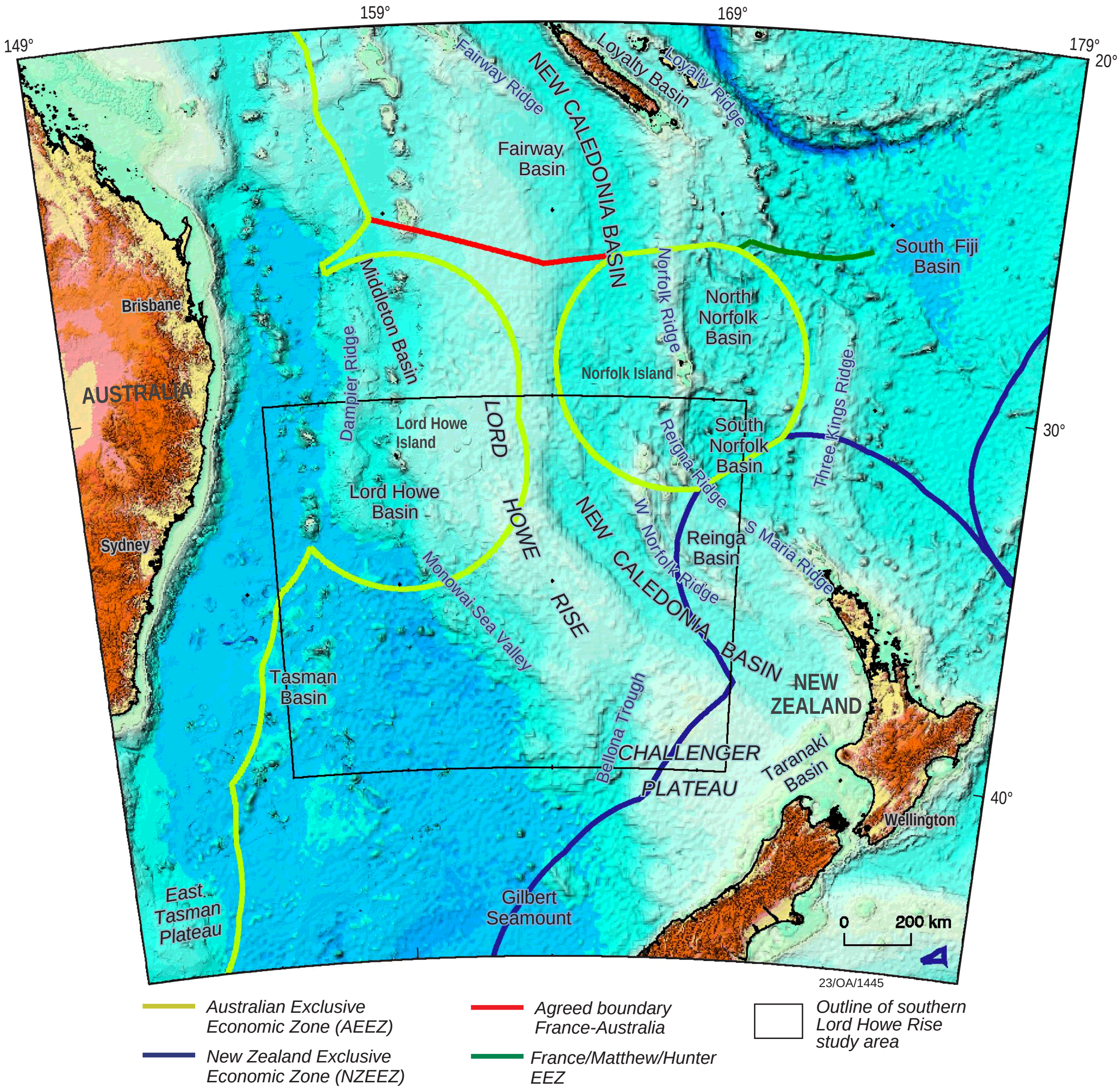
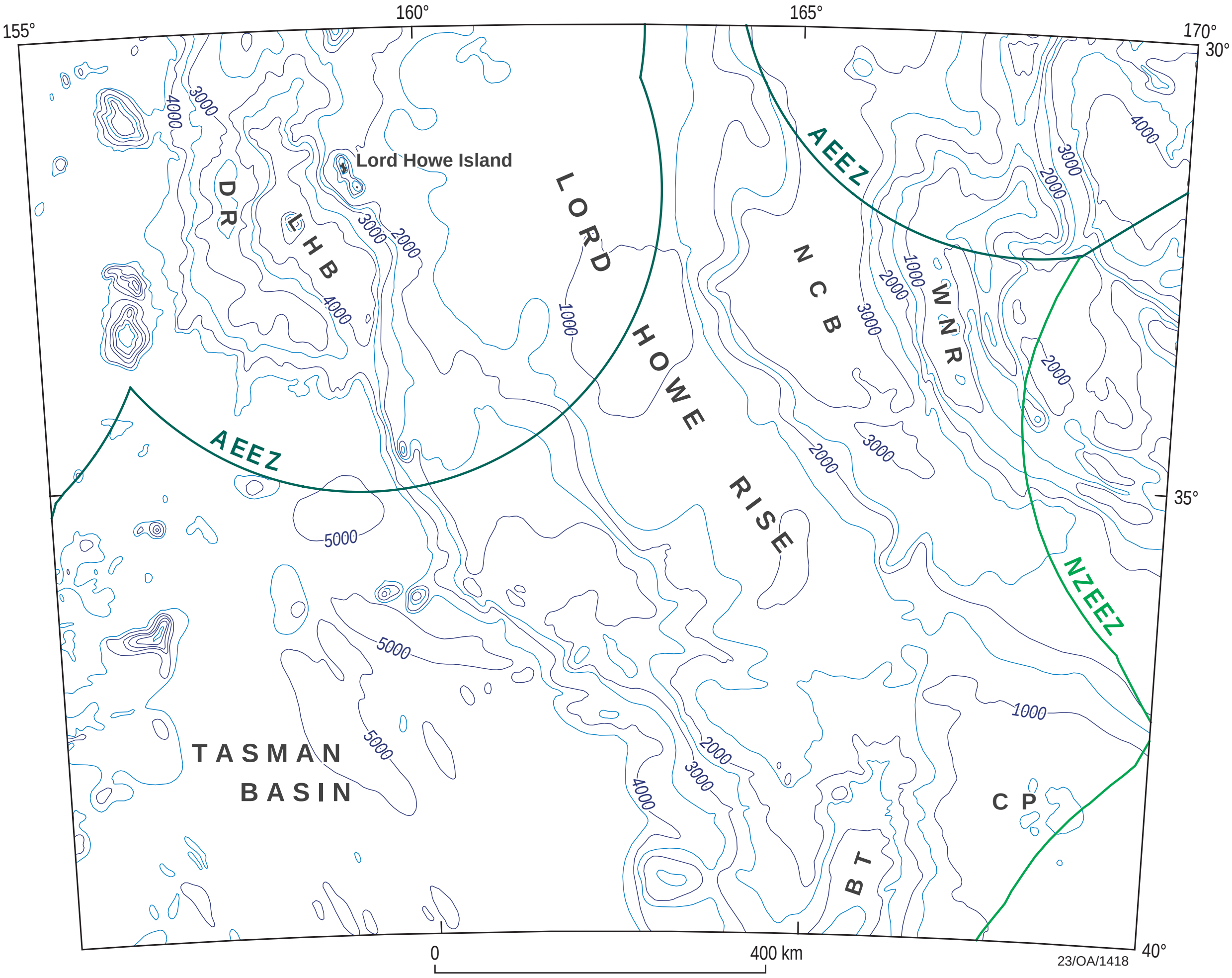
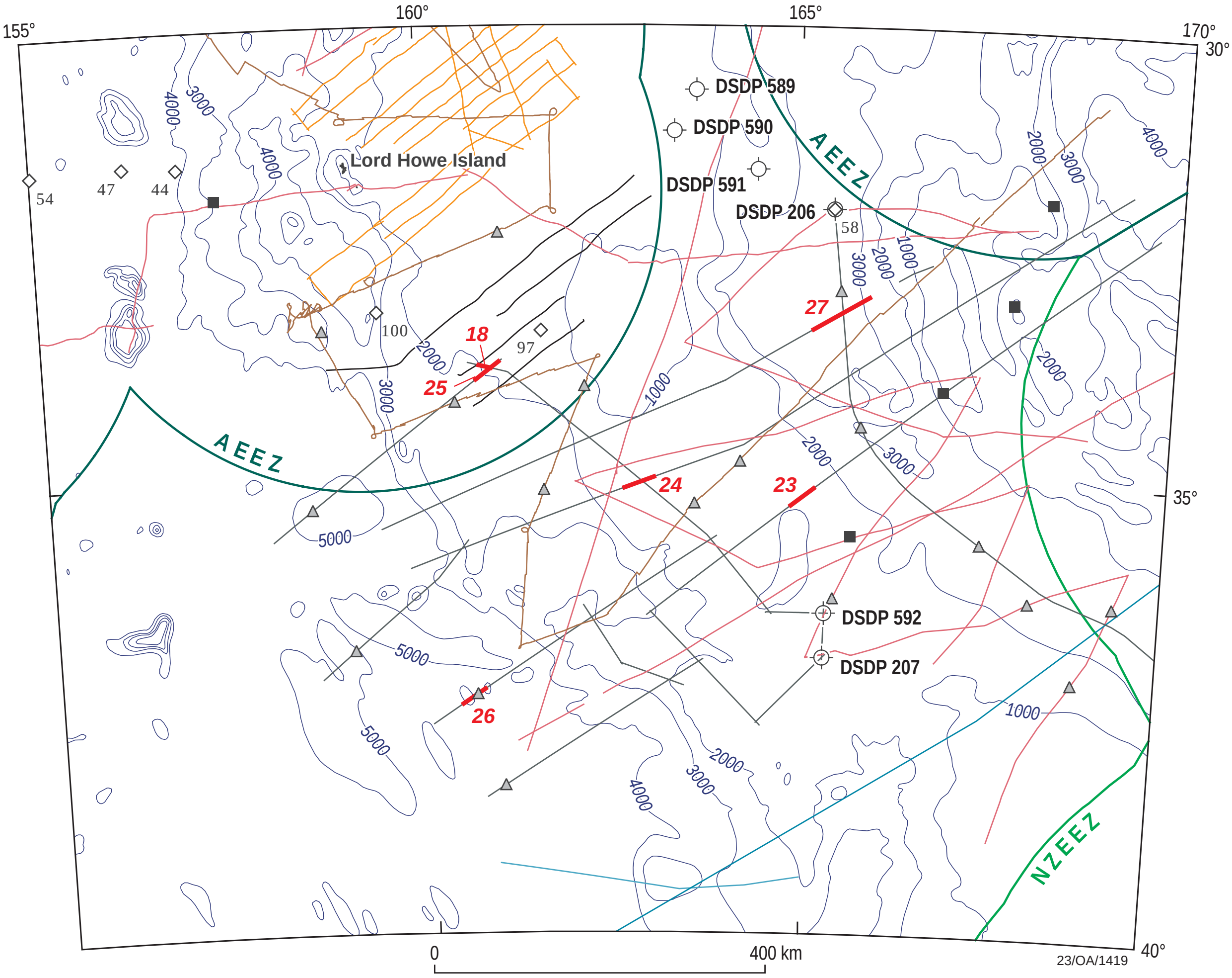


Figure 2. Bathymetric image of the Tasman Sea and southwest Pacific showing the study area for this report (solid box). Bathymetry based on the gridded data set of Petkovic & Buchanan (2002), and Smith et al., (1997)



AEEZ	Australian Exclusive Economic Zone
NZEEZ	New Zealand Exclusive Economic Zone
BT	Bellona Trough
CP	Challenger Plateau
DR	Dampier Ridge
LHB	Lord Howe Basin
NCB	New Caledonia Basin
WNR	West Norfolk Ridge

Figure 3. Bathymetry of the study area based on the GEBCO data set. Contour interval 500 m.



SEISMIC SURVEYS

Geoscience Australia Surveys 114, 177

Geoscience Australia Survey 46

Geoscience Australia Survey 125 (l'Atalante)

BGR (Germany) Survey SO-36A

BGR (Germany) Survey SO-7

Shell *Petrel*, United, Mobil

STATIONS

DSDP site

Seabed sample

58 *Heatflow station with value (mW.m^{-2})*

Sonobuoy refraction station

AEEZ Australian Exclusive Economic Zone

NZEEZ New Zealand Exclusive Economic Zone

Figure 4. Locations of seismic lines, DSDP sites, sample stations, heat-flow stations and refraction stations used in this study. Short red highlighted sections of seismic lines (with numbers) refer to figures in this report. Bathymetry contour interval 1000 m.

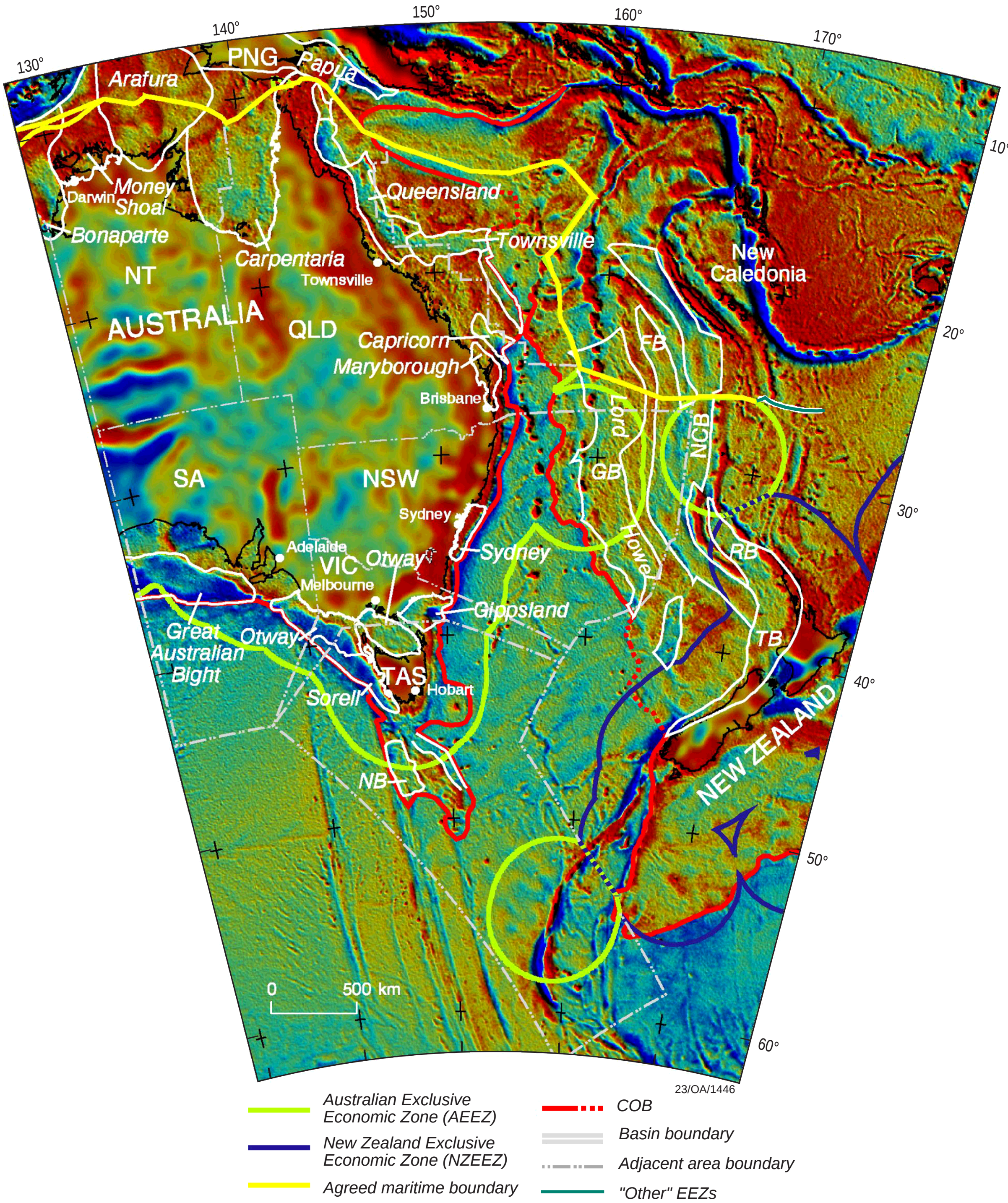


Figure 5. Satellite gravity image of eastern Australia and the western Pacific. Also shown are the Australian and New Zealand Exclusive Economic Zones and the outlines of the major basins (after Symonds et al., 2001)

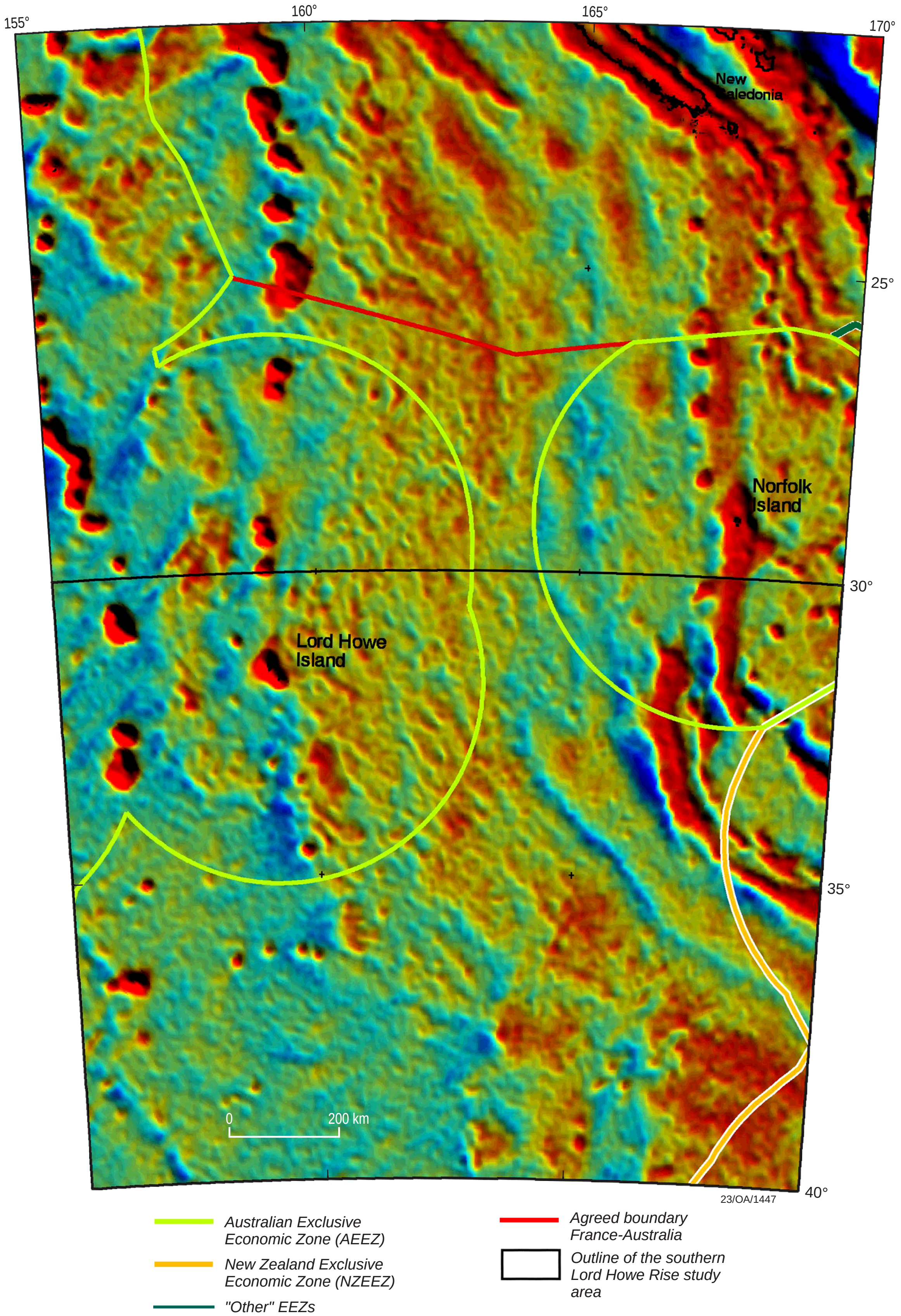
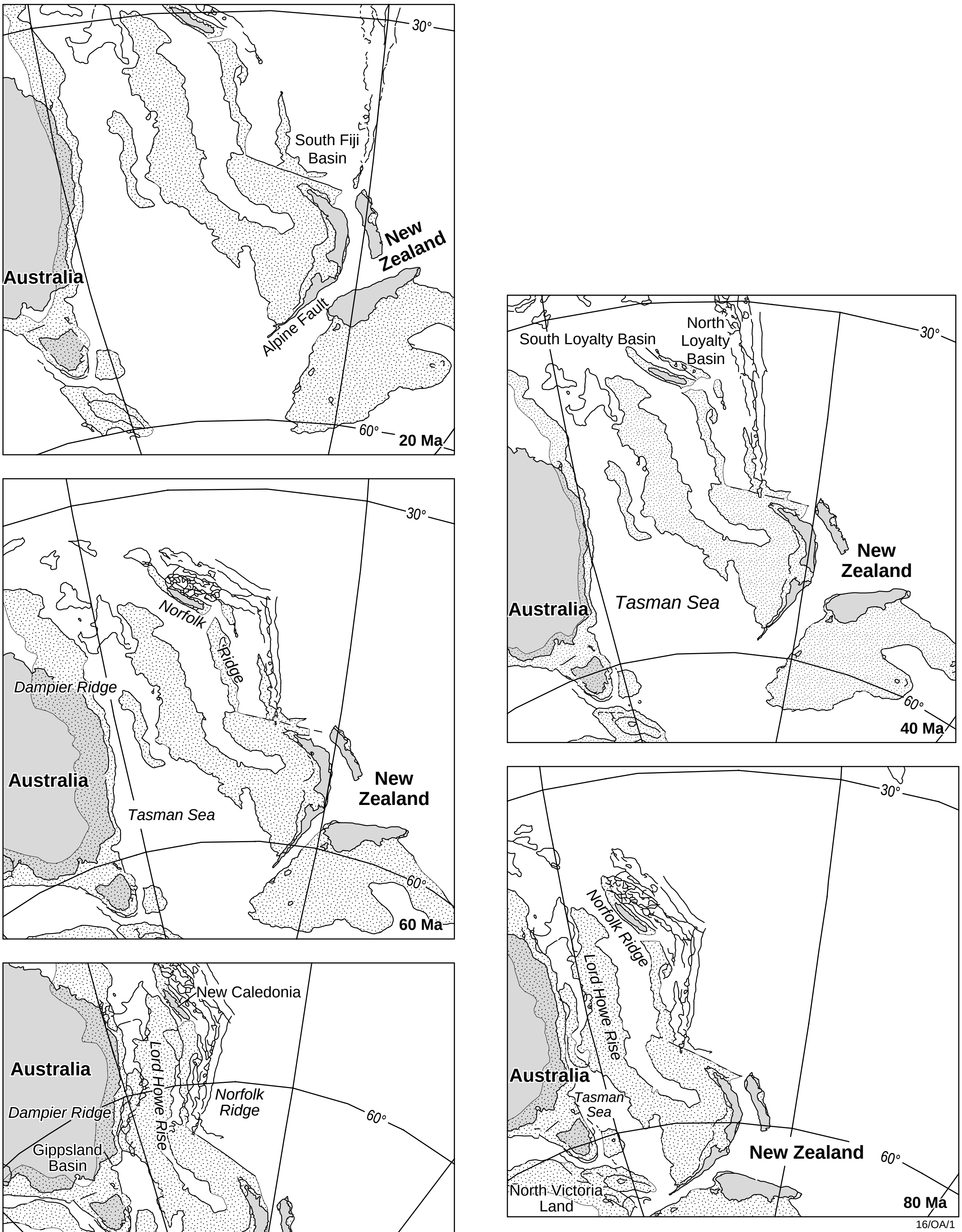
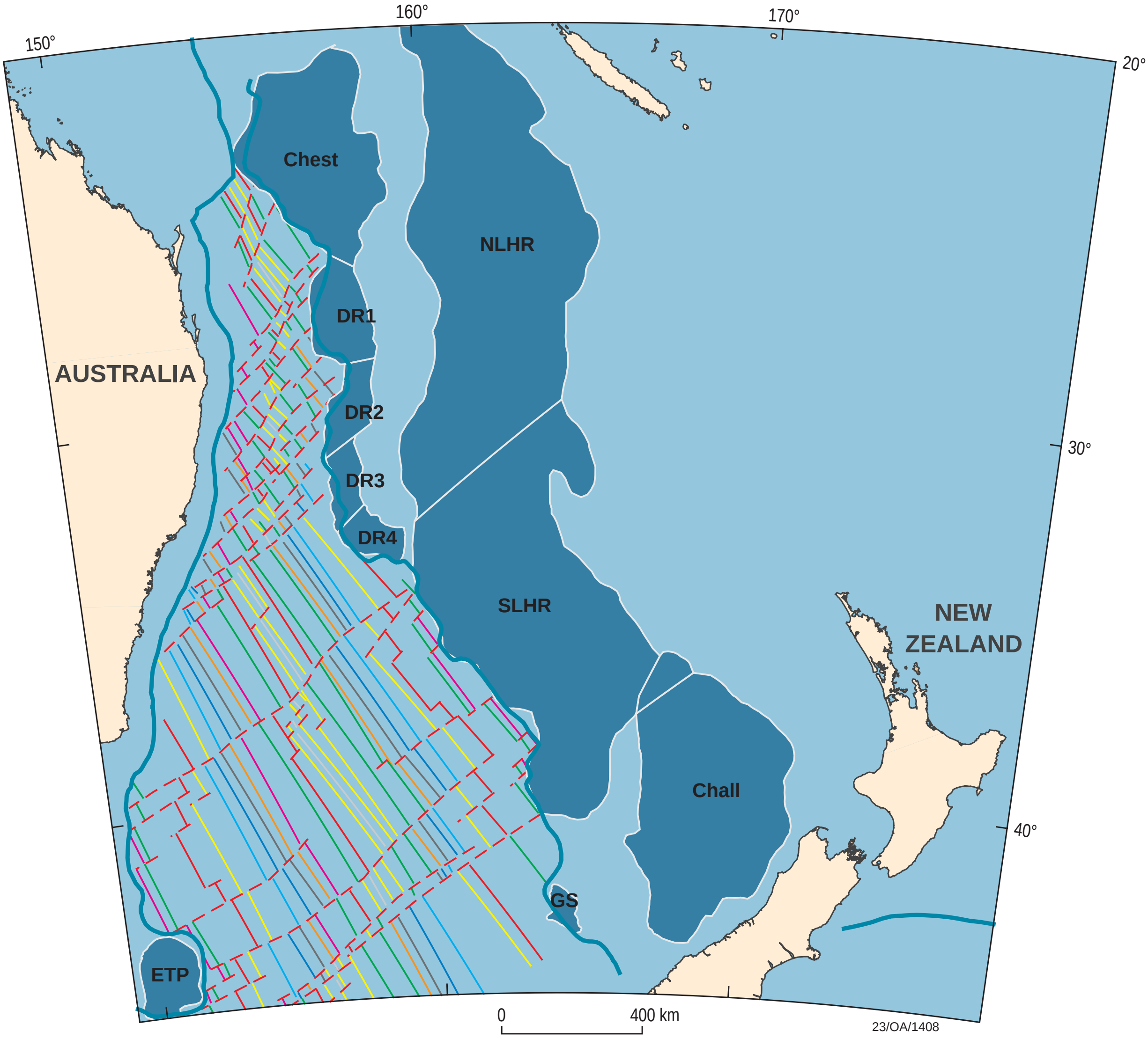


Figure 6. Satellite gravity image of the Lord Howe Rise region. The study area is south of 30°S.



Adapted from Walley & Ross (1991)

Figure 7. Plate evolution of the western Pacific since 100 Ma (after Walley & Ross, 1991).



Chall Challenger Plateau
Chest Chesterfield Plateau
DR1 - DR4 Dampier Ridge
ETP East Tasman Plateau
GS Gilbert Seamount
NLHR northern Lord Howe Rise
SLHR southern Lord Howe Rise

Figure 8. Magnetic lineations and microplates in the Tasman Sea, interpreted by Gaina et al. (1998). Magnetic anomaly identifications are shown in Plate 4.

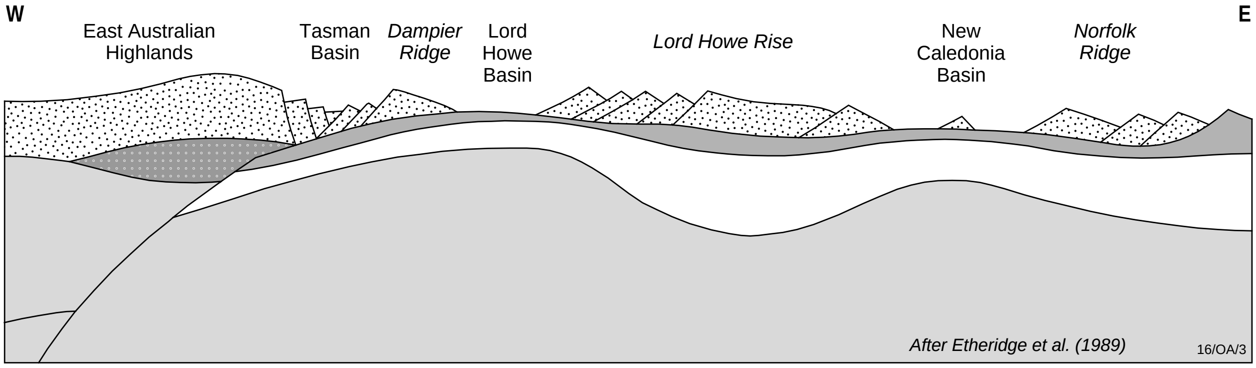


Figure 9. Detachment model describing the formation of the eastern Australian margin and the basins and ridges of the Lord Howe Rise region (after Etheridge et al., 1989).

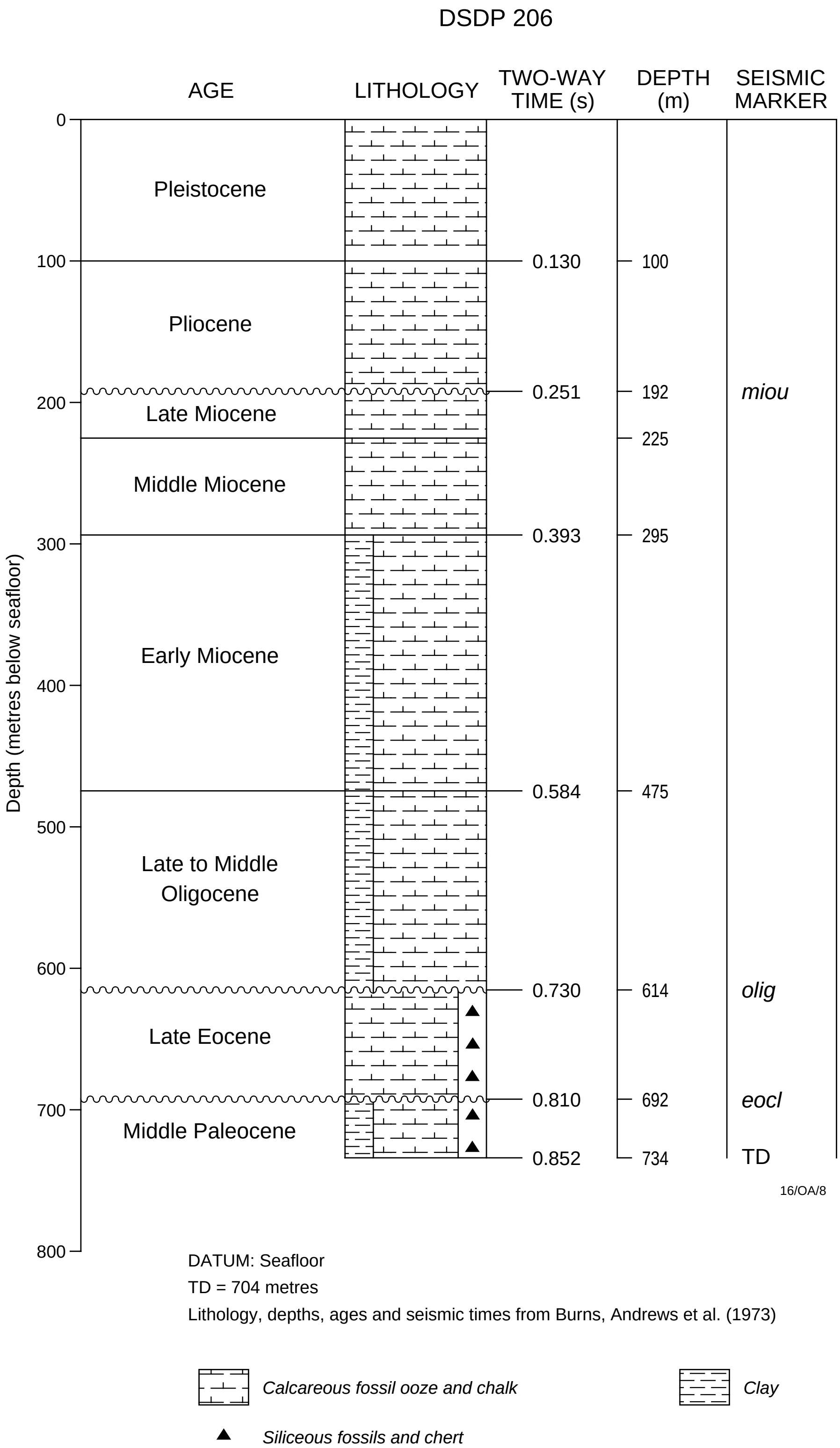


Figure 10. Stratigraphic column at DSDP Site 206, New Caledonia Basin (adapted from Burns, Andrews et al., 1973).

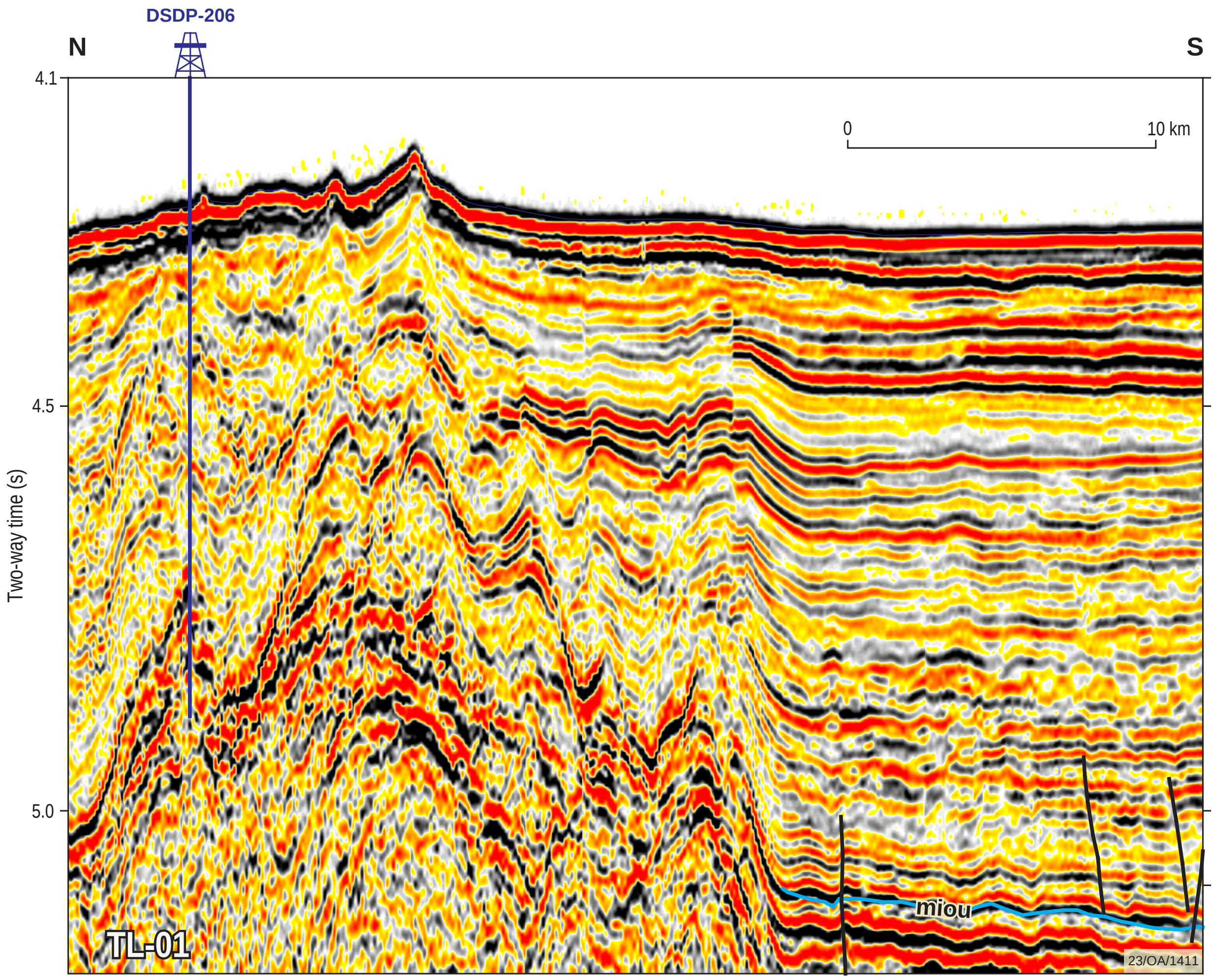


Figure 11. Seismic profile at DSDP Site 206, New Caledonia Basin. Key to interpreted seismic horizons is contained in Appendix 6.

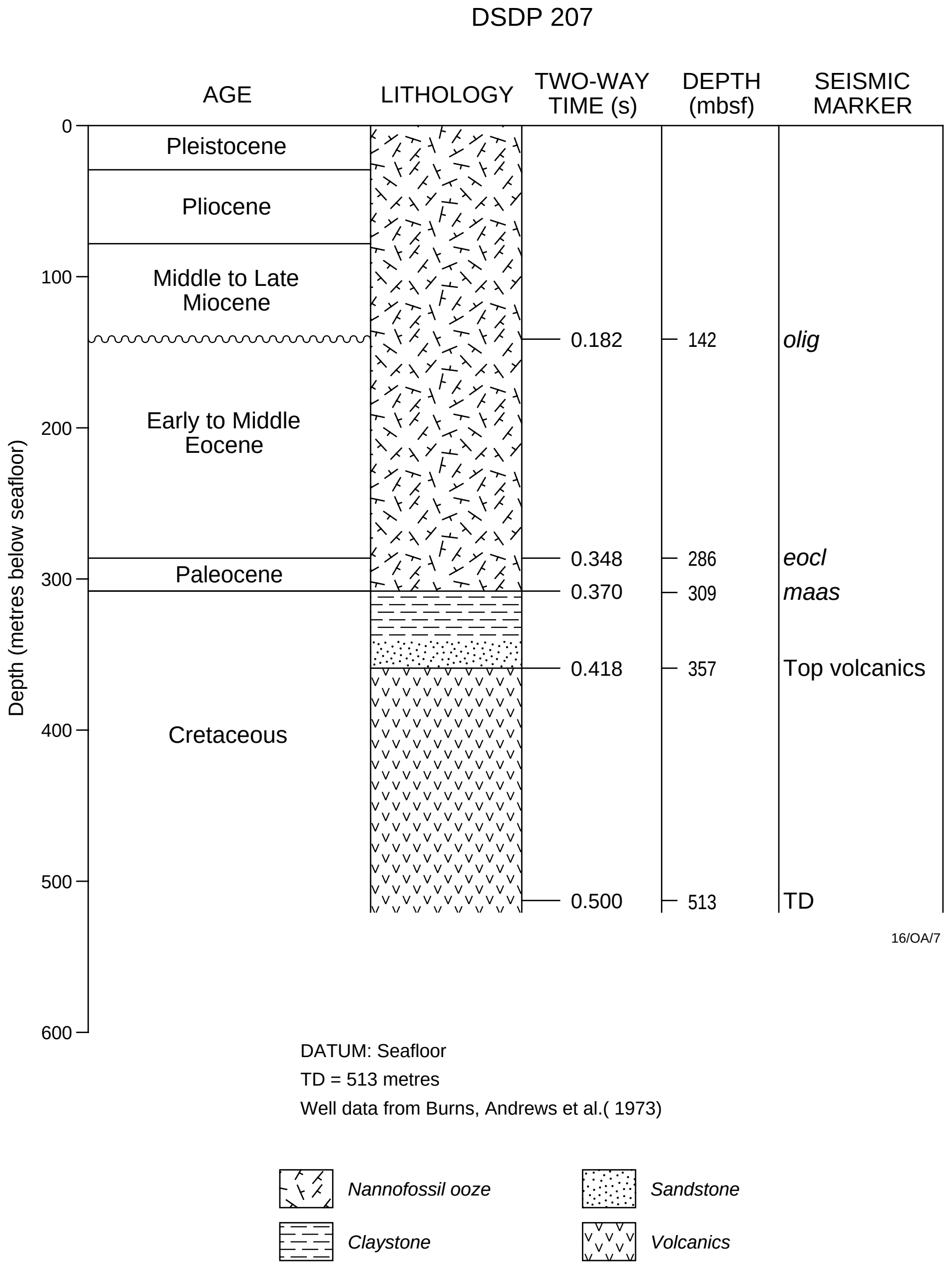


Figure 12. Stratigraphic column at DSDP Site 207, southern Lord Howe Rise (adapted from Burns, Andrews et al., 1973).

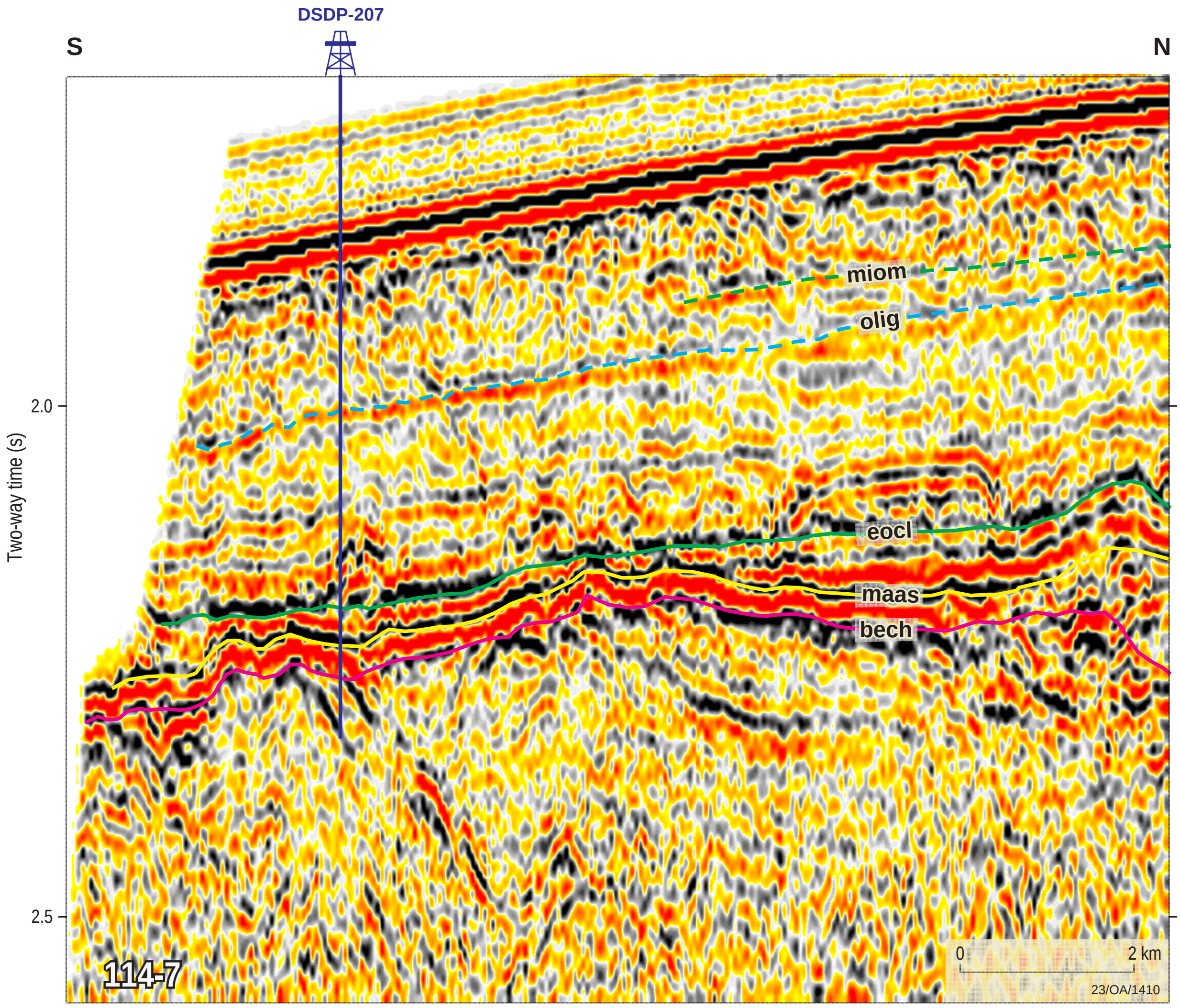


Figure 13. Seismic profile at DSDP Site 207, southern Lord Howe Rise. Key to interpreted seismic horizons is contained in Appendix 6.

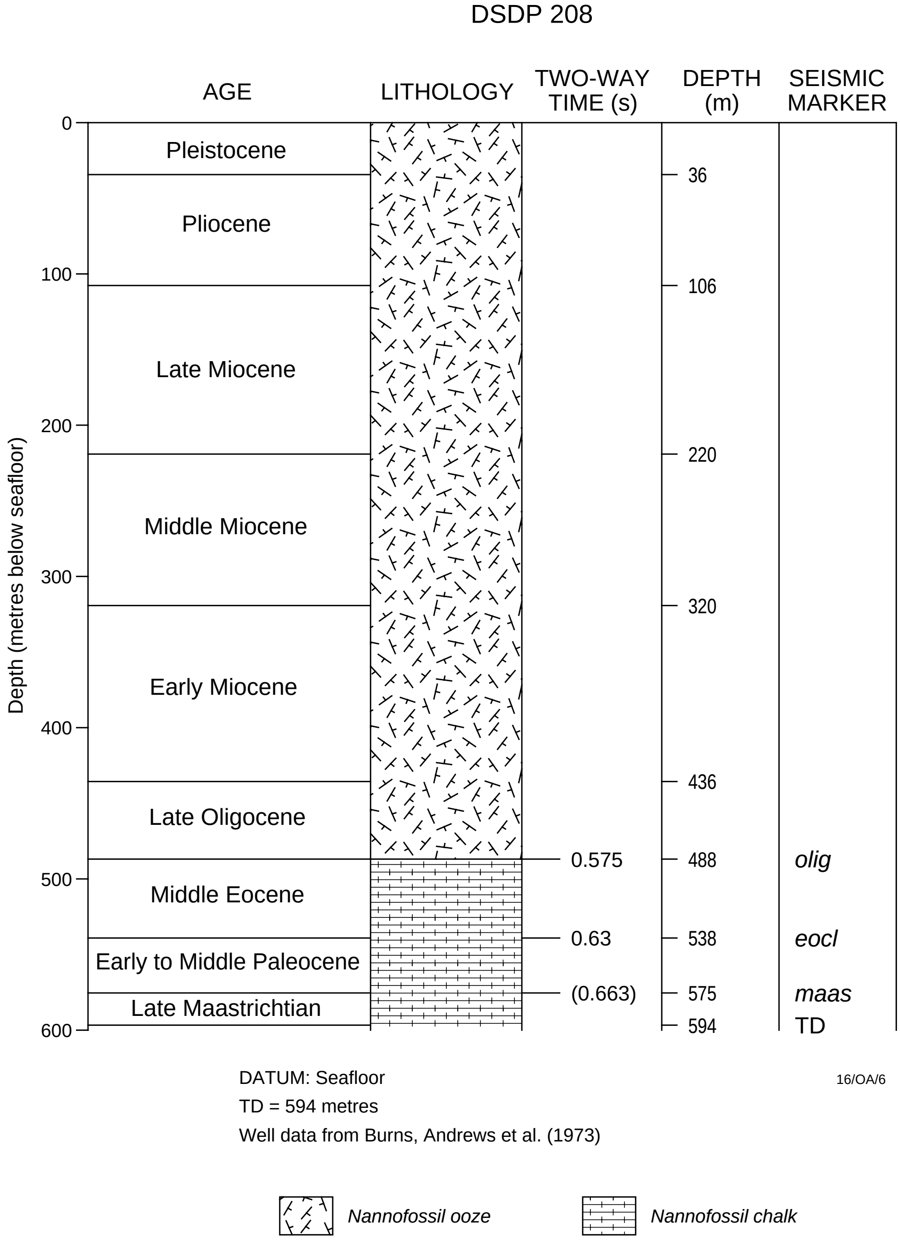


Figure 14. Stratigraphic column at DSDP Site 208, northern Lord Howe Rise (adapted from Burns, Andrews et al., 1973).

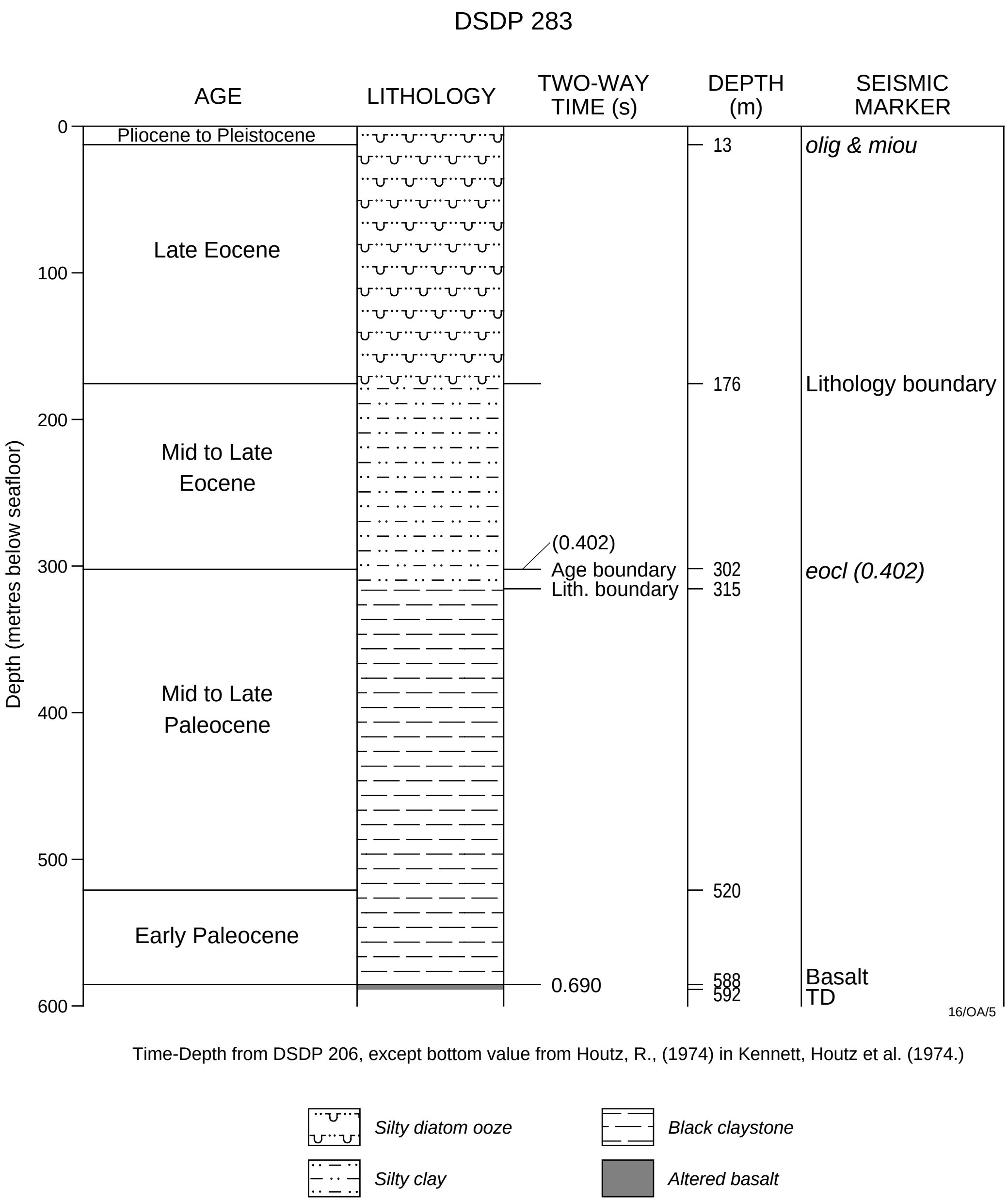


Figure 15. Stratigraphic column at DSDP Site 283, western Tasman Basin (adapted from Kennett, Houtz et al., 1974).

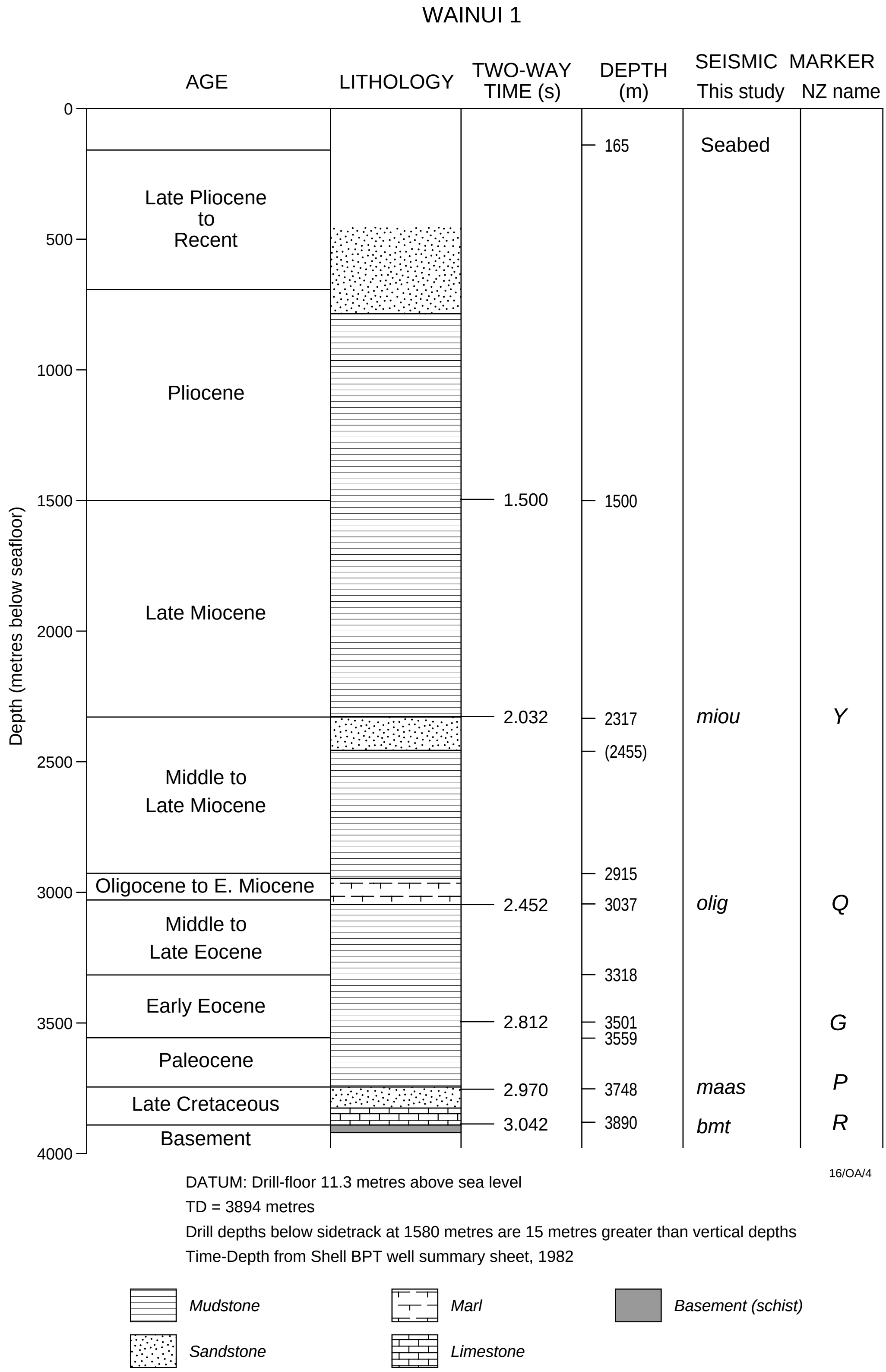


Figure 16. Stratigraphic column at Wainui-1, Taranaki Basin, offshore New Zealand.

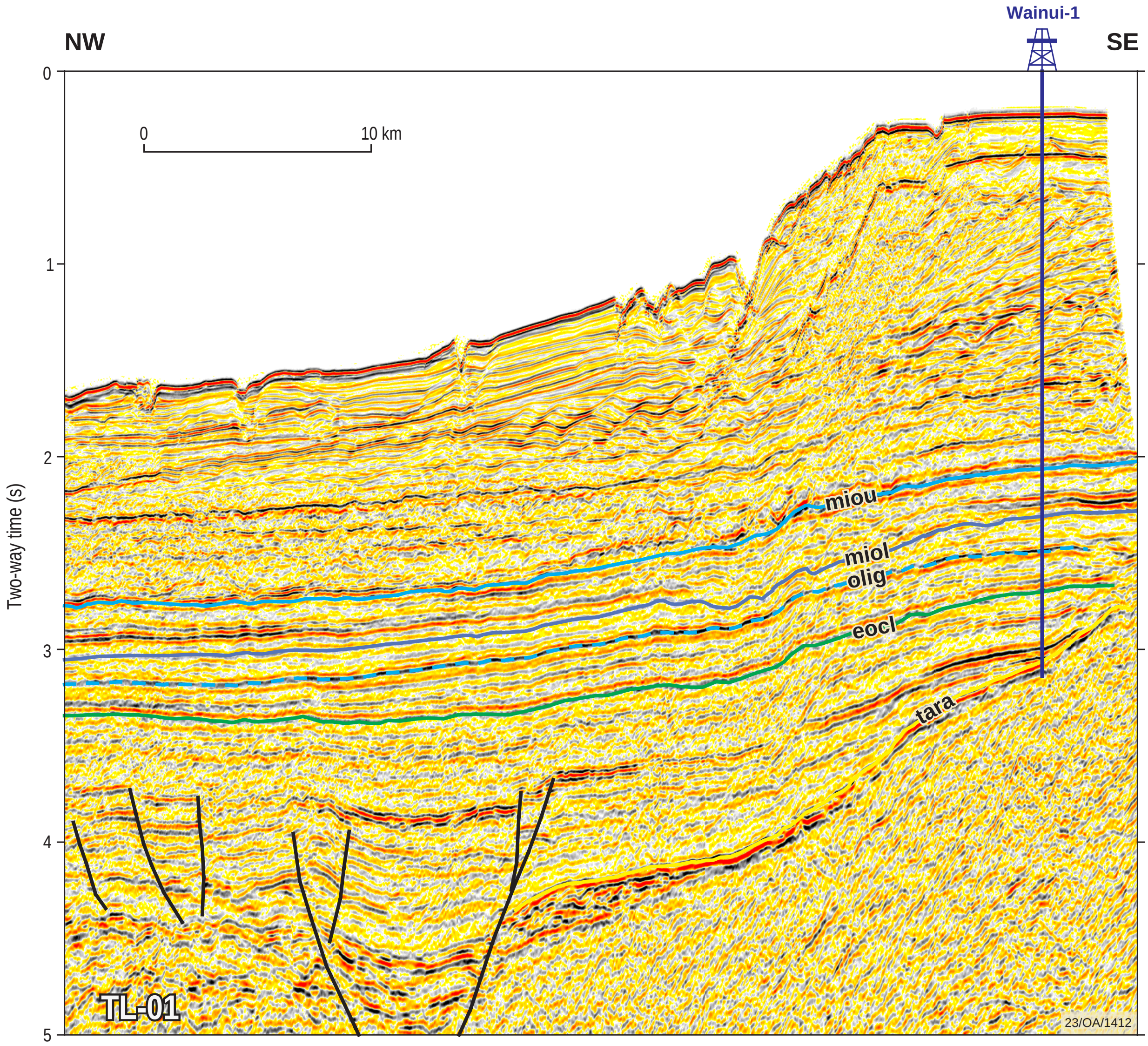


Figure 17. Seismic profile at Wainui-1, Taranaki Basin, offshore New Zealand. Key to interpreted seismic horizons is contained in Appendix 6.

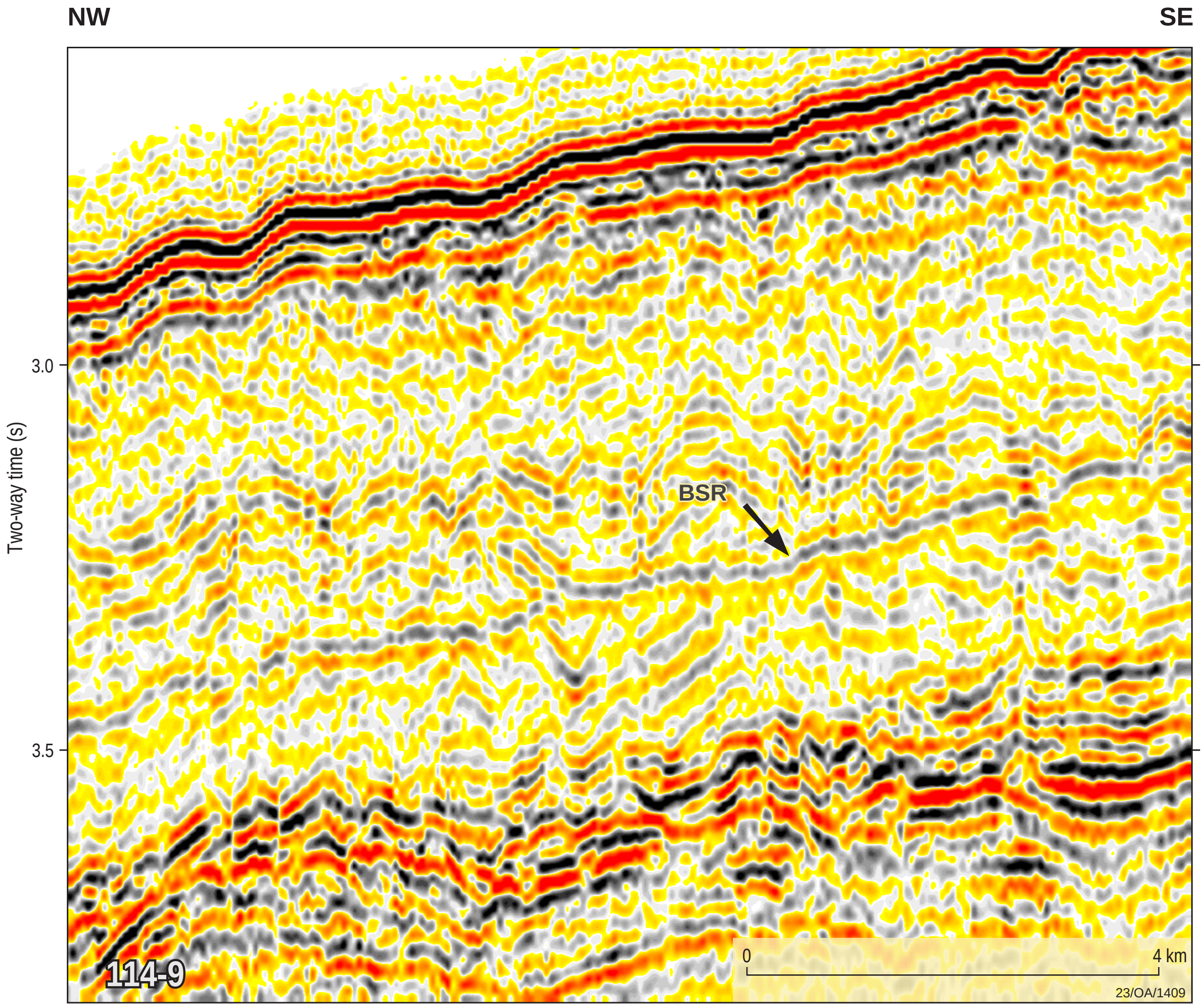


Figure 18. Bottom-simulating reflector (BSR) in the Monowai Basin (line 114-9). Location shown in Figure 4.

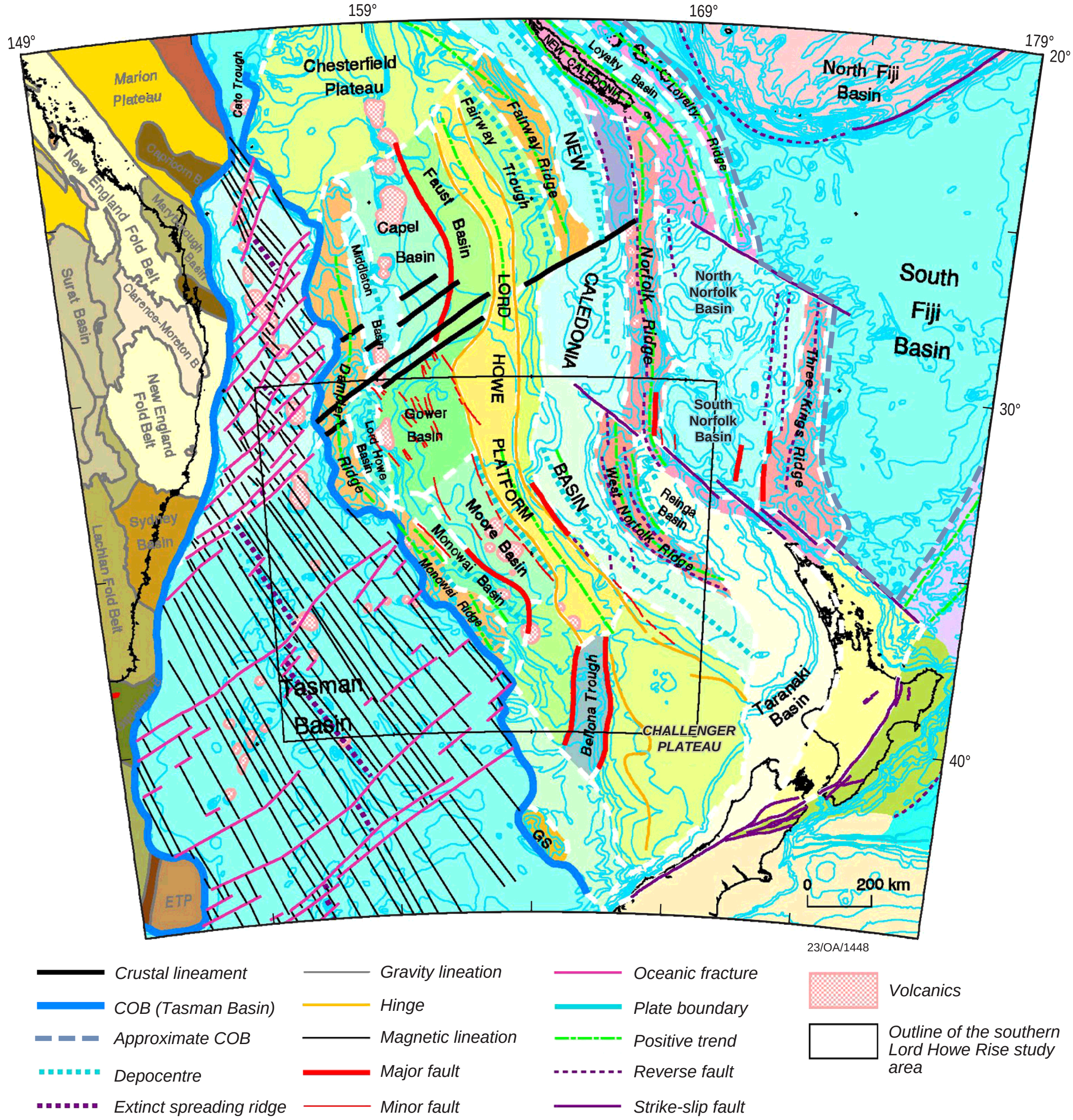


Figure 19. Tectonic provinces of the Lord Howe Rise region and eastern Australia (after Stagg et al., 1999). COB is only shown on the margins of the Tasman Basin and the South Fiji Basin.

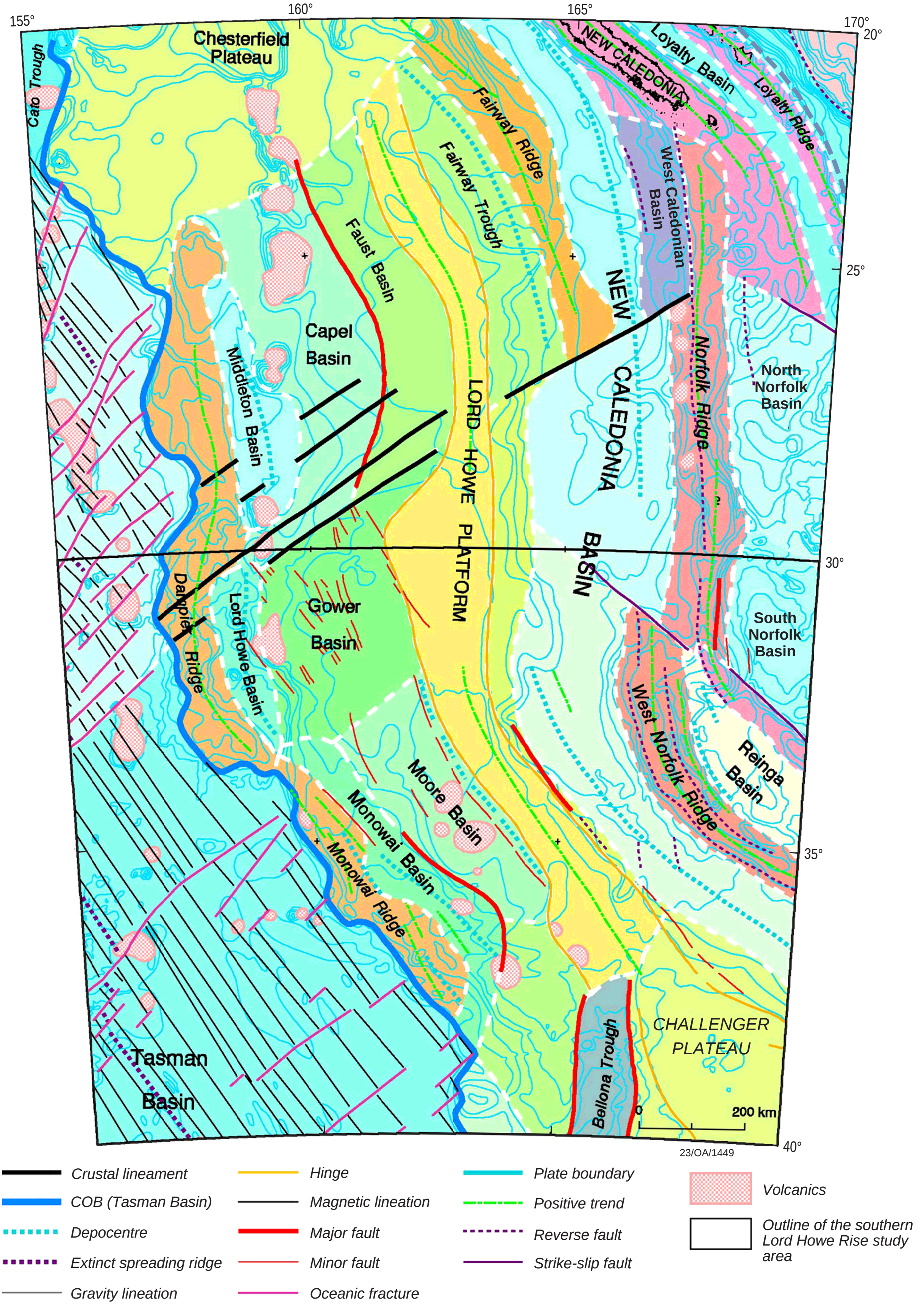


Figure 20. Tectonic provinces of the Lord Howe Rise and adjacent basins (modified from Stagg et al., 1999). COB is only shown on the margins of the Tasman Basin and Loyalty Ridge.

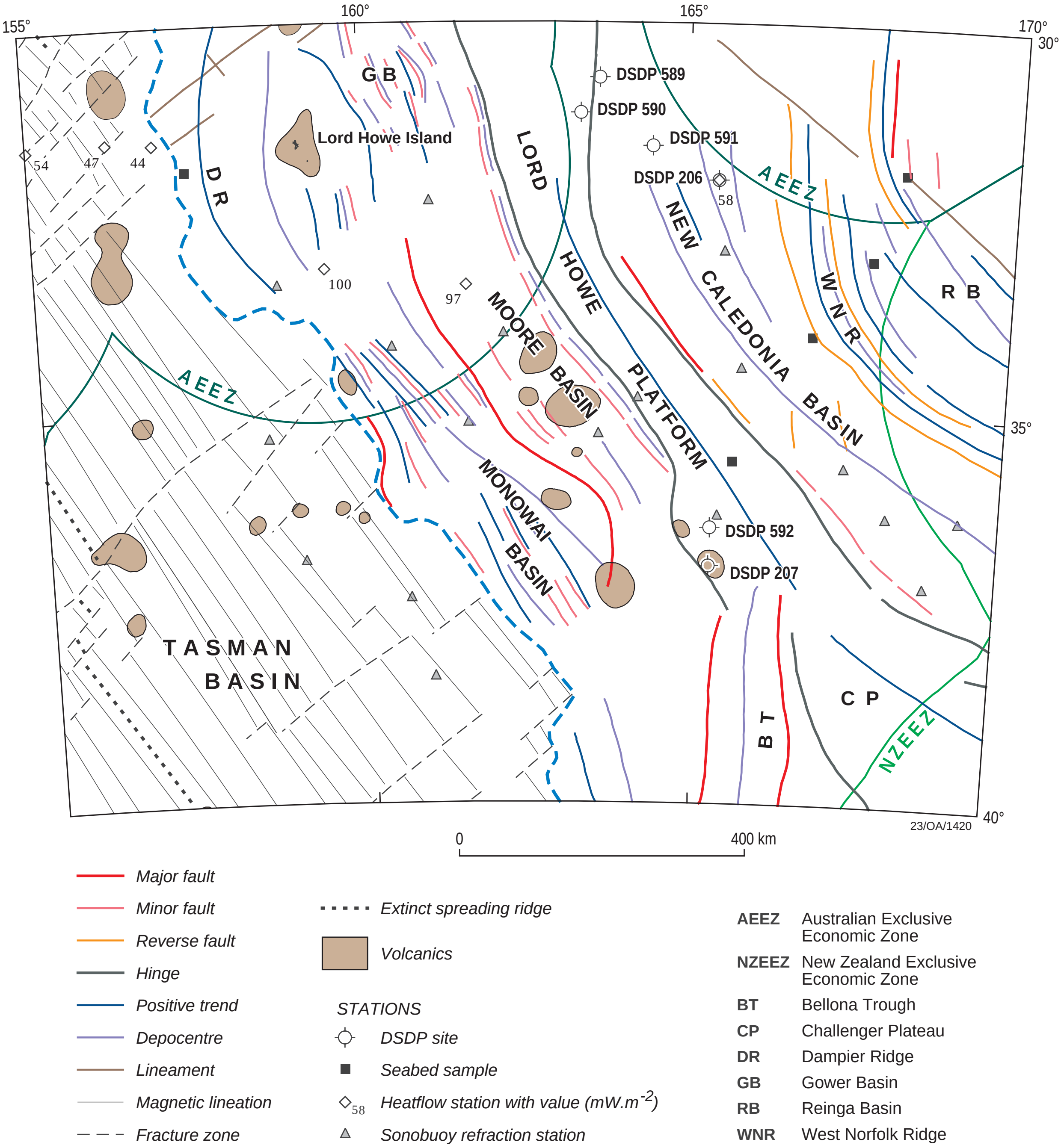


Figure 21. Tectonic elements of the southern Lord Howe Rise.

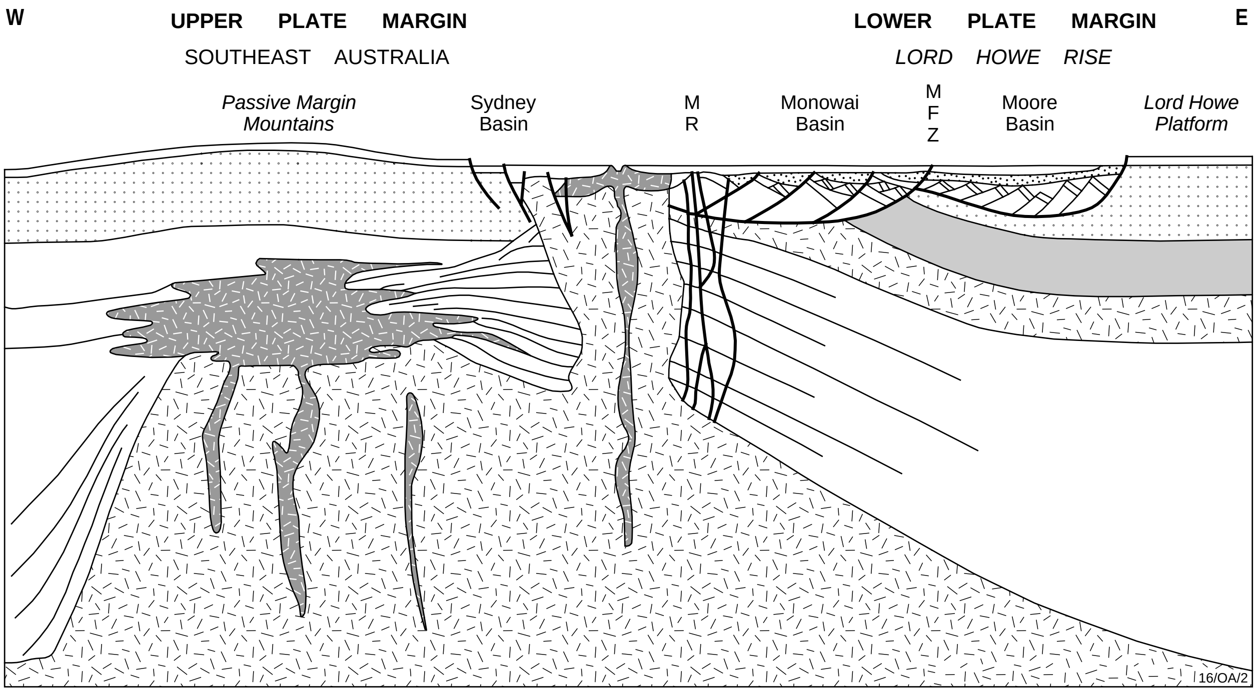


Figure 22. Possible model for the formation of eastern Australia, Tasman Basin and Lord Howe Rise (adapted by Bradley (1993, fig. 10) from Lister & Etheridge, 1989, fig. 7.3.4, and Lister et al., 1991). MR - Monowai Ridge; MFZ - Monowai Fault Zone

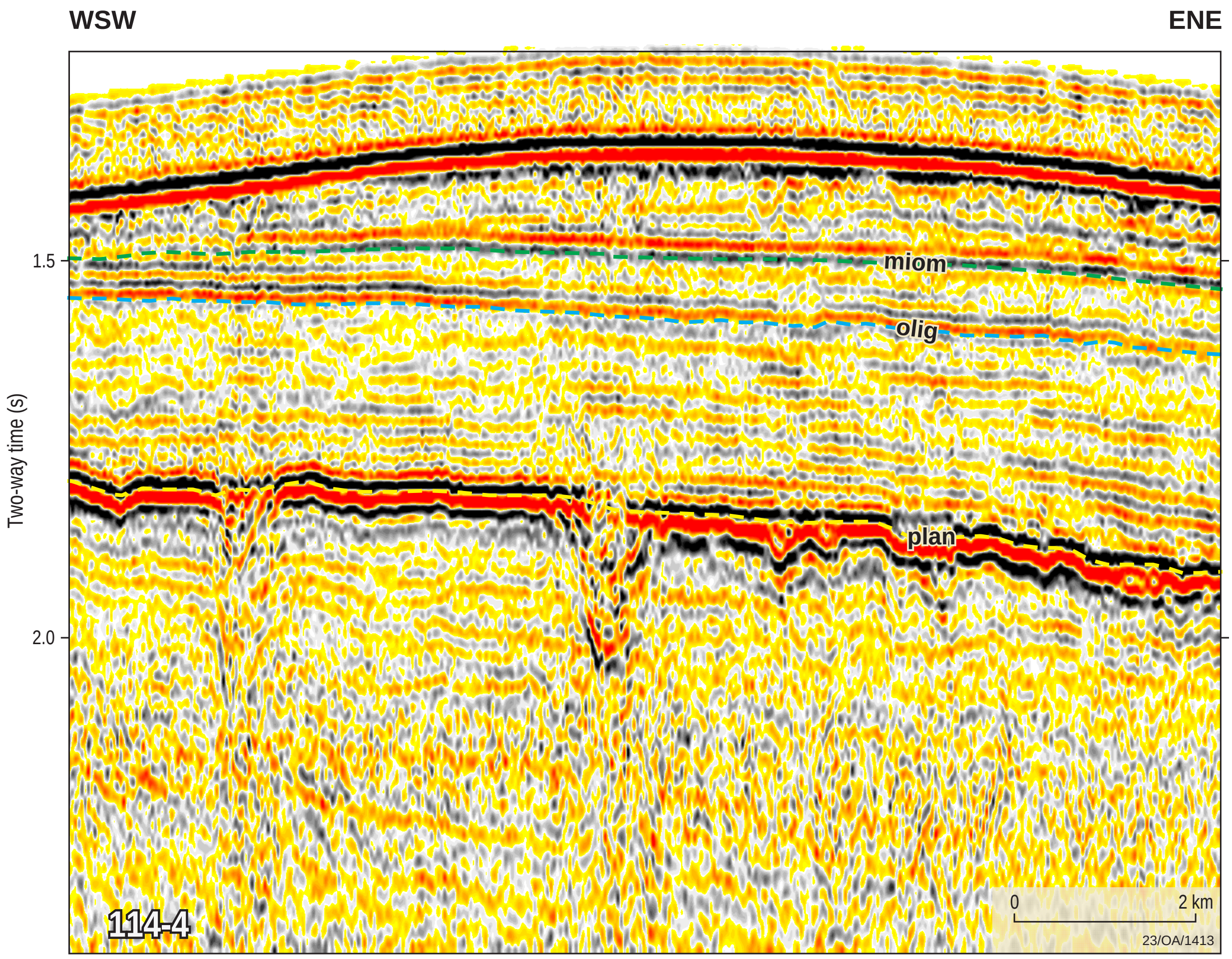


Figure 23. Seismic profile from the Lord Howe Platform (line 114-4), showing planated basement and the thin sedimentary section. Location shown in Figure 4. Key to interpreted seismic horizons is contained in Appendix 6.

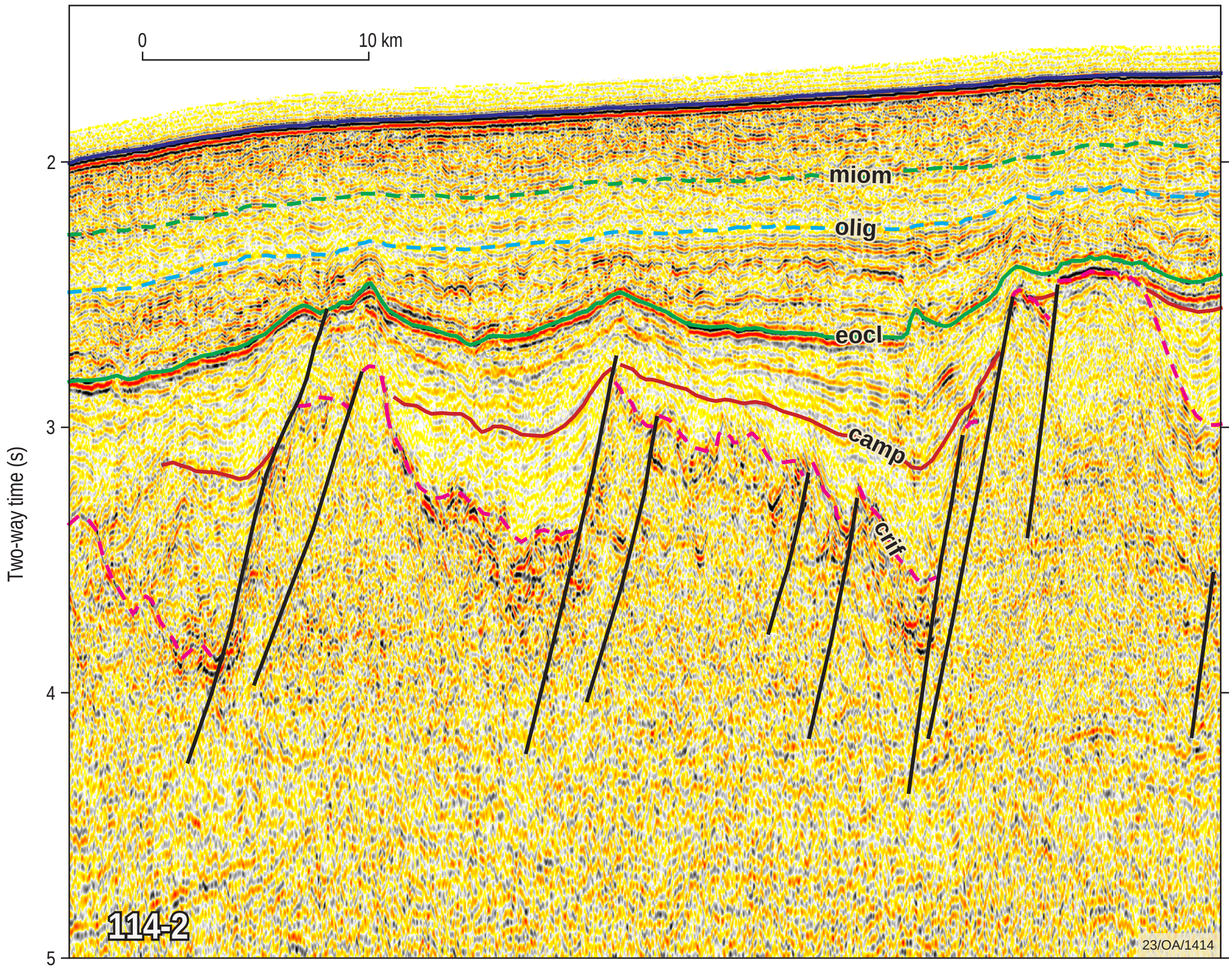


Figure 24. Seismic profile from the Central Rift province (Moore Basin), Lord Howe Rise (line 114-2). Location shown in Figure 4. Key to interpreted seismic horizons is contained in Appendix 6.

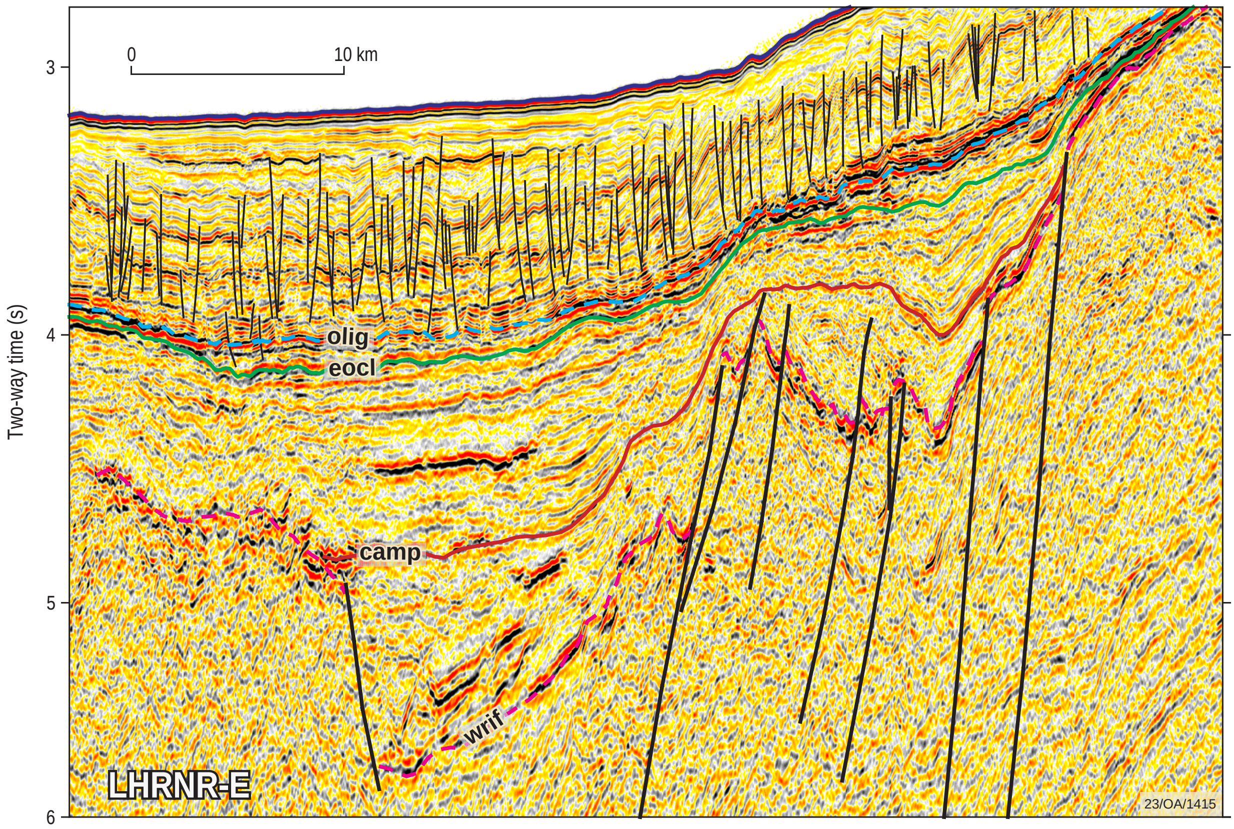


Figure 25. Seismic profile from the Western Rift province (Monowai Basin), Lord Howe Rise (line LHRNR-E). Location shown in Figure 4. Key to interpreted seismic horizons is contained in Appendix 6.

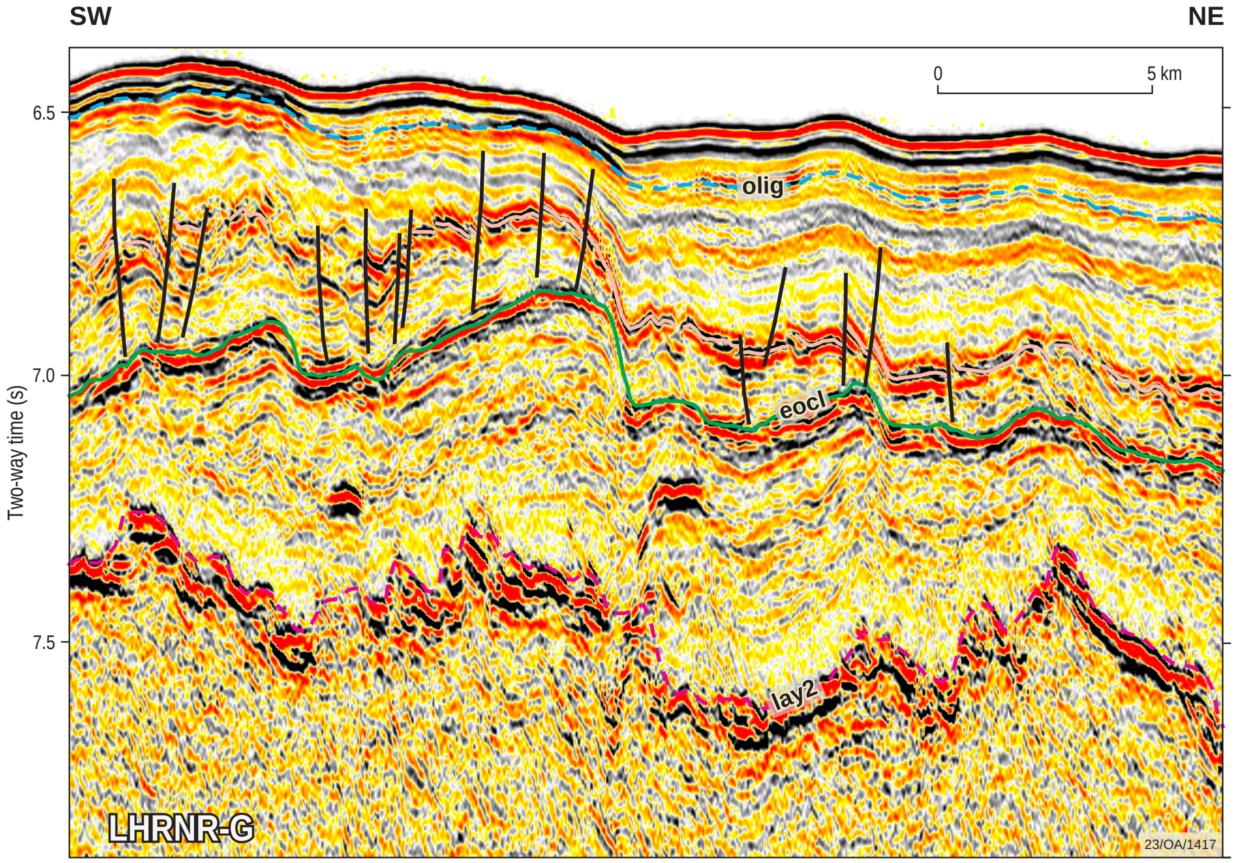


Figure 26. Seismic profile from the eastern flank of the Tasman Basin (line LHRNR-G). Location shown in Figure 4. Key to interpreted seismic horizons is contained in Appendix 6.

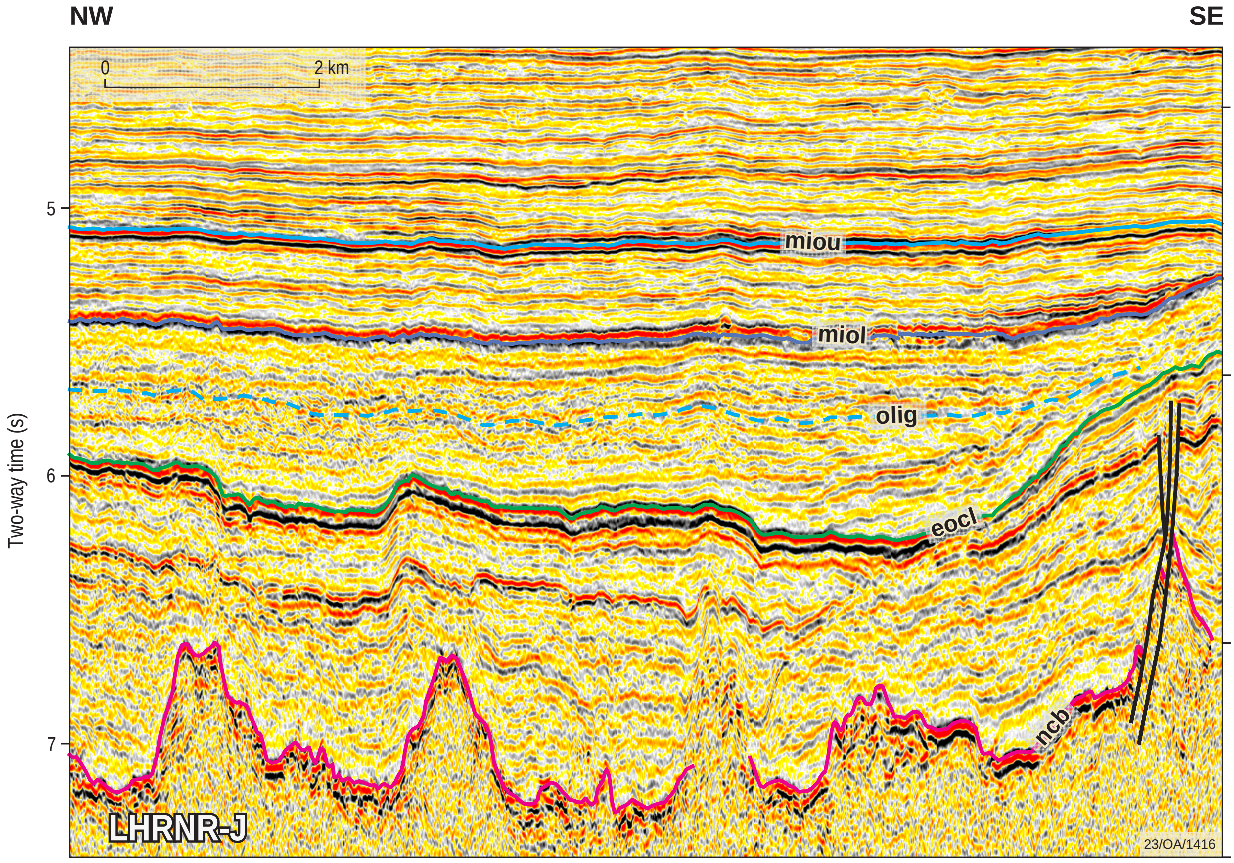
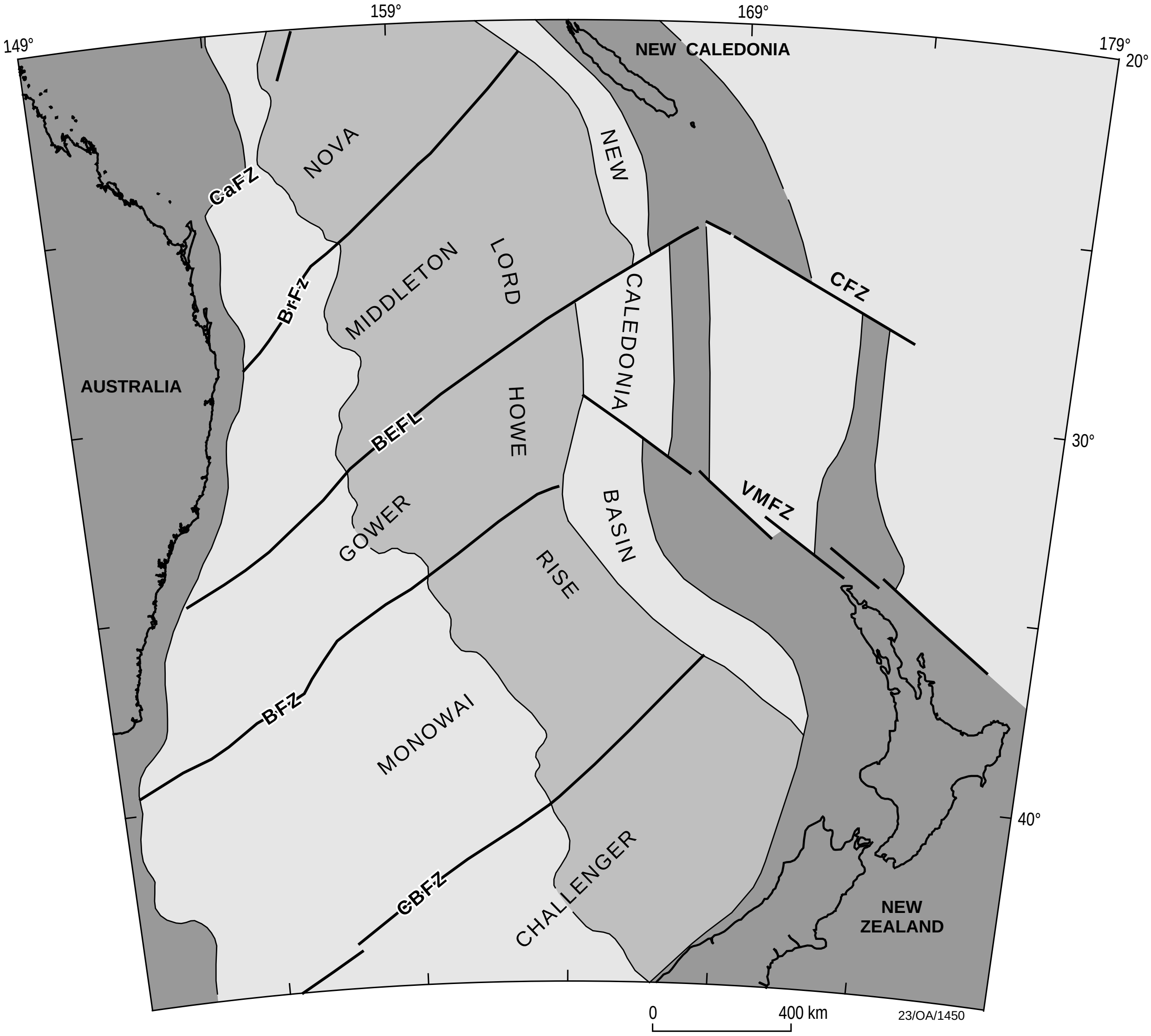
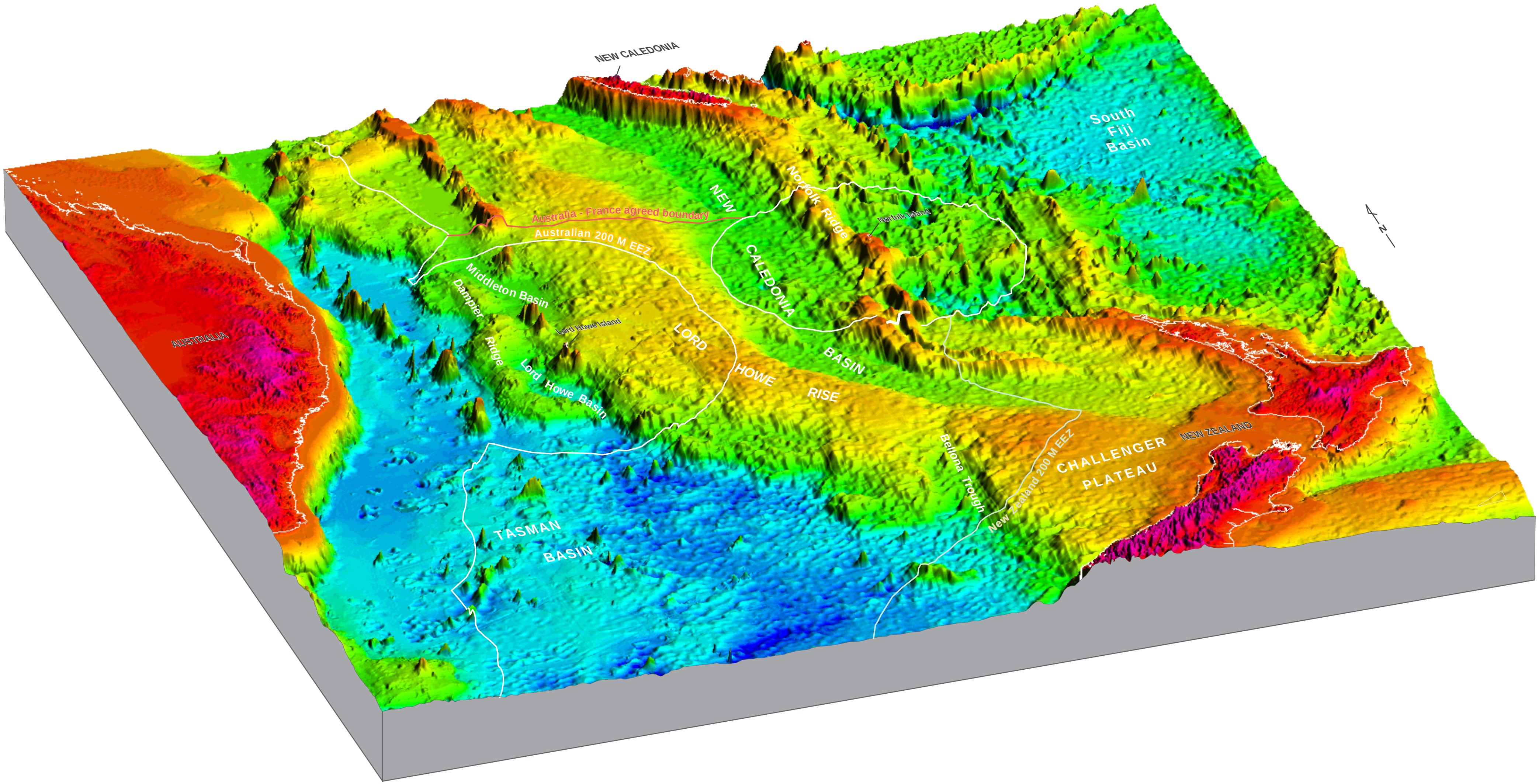


Figure 27. Seismic profile from the southern New Caledonia Basin (line LHRNR-J). Location shown in Figure 4. Key to interpreted seismic horizons is contained in Appendix 6.



BEFL *Barcoo-Elizabeth-Fairway Lineament*
BFZ *Bass Fracture Zone*
BrFZ *Brittania Fracture Zone*
CaFZ *Cato Fracture Zone*
CBFZ *Cascade-Bellona Fracture Zones*
CFZ *Cook Fracture Zone*
VMFZ *Vening Meinesz Fracture Zone*

Figure 28. Crustal segmentation of the Lord Howe Rise region.



High resolution plot files of Plates 1-9 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .JPEG on this CD

Geoscience Australia - Law of the Sea Project

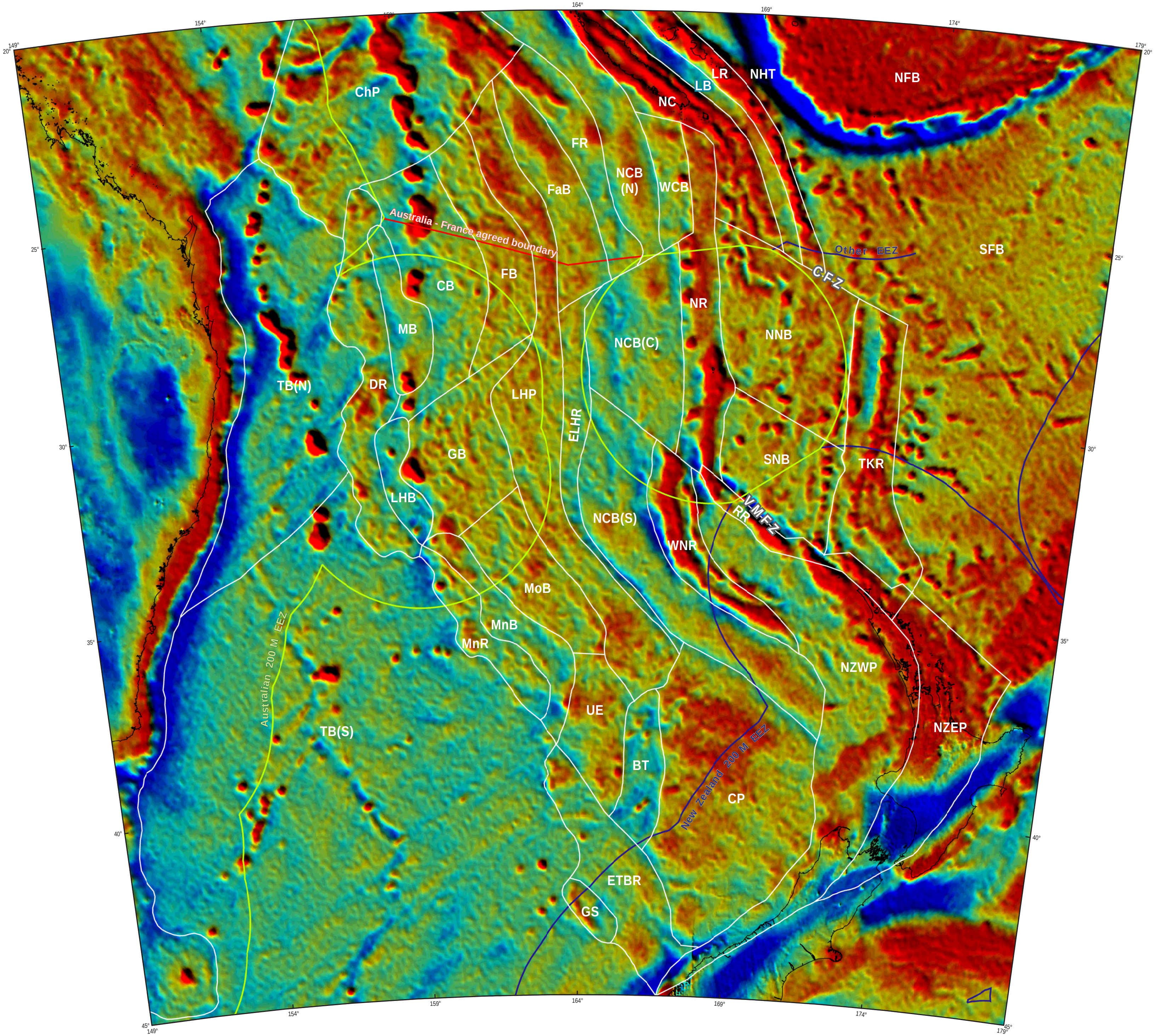
Plate 1

Bathymetry perspective

Based on gridded bathymetric data set of Petkovic & Buchanan (2002).

Stagg, H. M. J. et al., 2002 - Geological framework of the southern Lord Howe Rise and adjacent areas. Geoscience Australia Record 2002/25

23/OA/1421



High resolution plot files of Plates 1-9 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .JPEG on this CD

Structural/Tectonic Provinces

BT	Bellona Trough
CB	Capel Basin
CFZ	Cook Fracture Zone
ChP	Chesterfield Plateau
CP	Challenger Plateau
DR	Dampier Ridge
ELHR	east Lord Howe rift
ETBR	east Tasman Basin rift
FaB	Fairway Basin
FB	Faust Basin
FR	Fairway Ridge
GB	Gower Basin
GS	Gilbert Seamount
LB	Loyalty Basin
LHB	Lord Howe Basin
LHP	Lord Howe Platform
LR	Loyalty Ridge
MB	Middleton Basin
MnB	Monowai Basin
MnR	Monowai Ridge
MoB	Moore Basin
NC	New Caledonia
NCB(C)	New Caledonia Basin (central)
NCB(N)	New Caledonia Basin (north)
NCB(S)	New Caledonia Basin (south)
NFB	North Fiji Basin
NHT	New Hebrides Trough
NNB	North Norfolk Basin
NR	Norfolk Ridge
NZEP	'New Zealand eastern province'
NZWP	'New Zealand western province'
RR	Reinga Ridge system
SFB	South Fiji Basin
SNB	South Norfolk Basin
TB(N)	Tasman Basin (north)
TB(S)	Tasman Basin (south)
TKR	Three Kings Ridge complex
WCB	West Caledonian Basin
WNR	West Norfolk Ridge system
VMFZ	Vening Meinesz Fracture Zone

0 400 km

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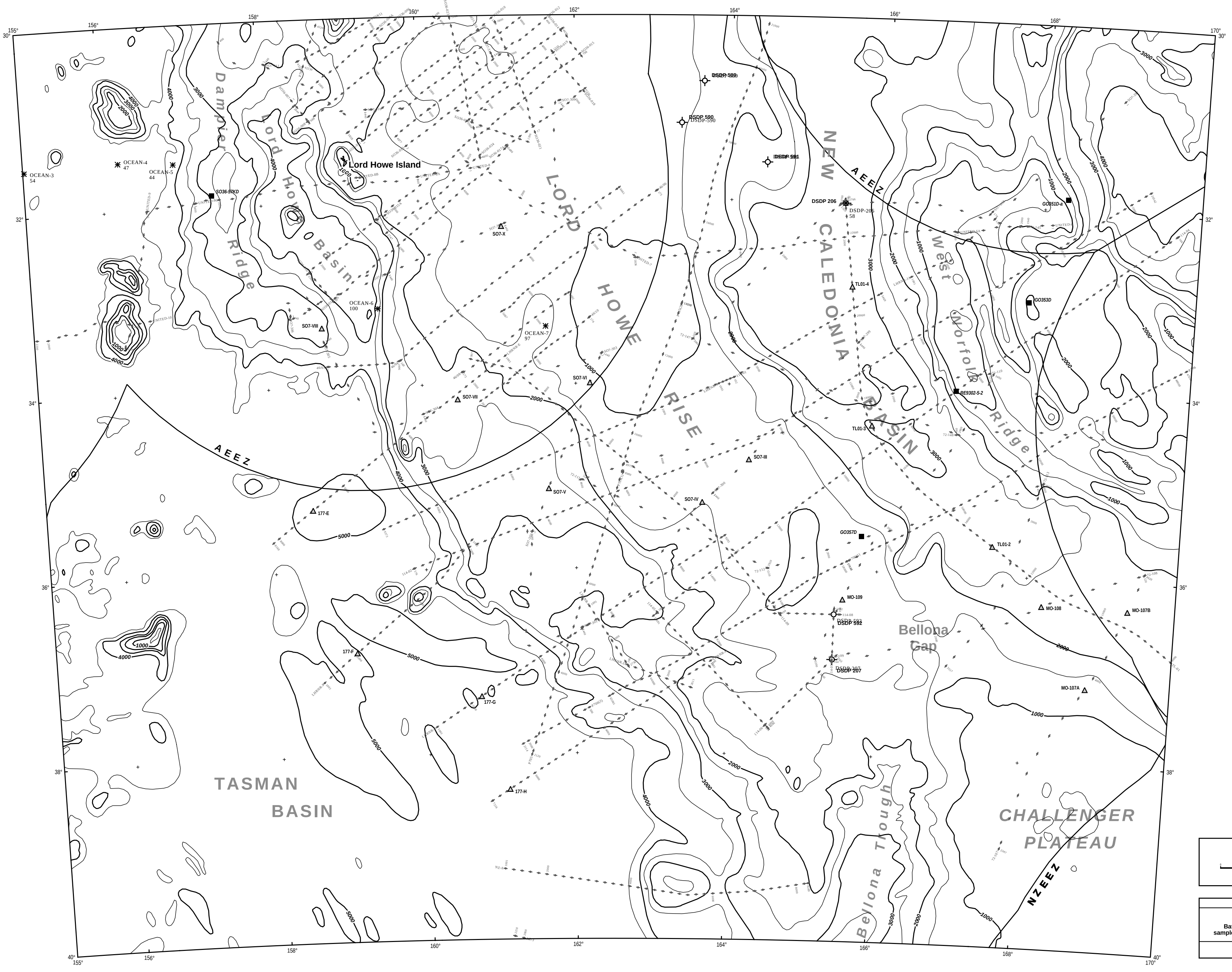
Plate 2

Gravity image with structural/tectonic province outlines

Stagg, H. M. J. et al., 2002 - Geological framework of the southern Lord Howe Rise and adjacent areas. Geoscience Australia Record 2002/25

23/OA/1422

SOUTHERN LORD HOWE RISE



High resolution plot files of Plates 1-9 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .JPEG on this CD

Legend

- Deep Sea Drilling Project site
- GO357D — Dredge station
- 177-H — Sonobuoy refraction station
- 54 — Heatflow station with value (mW.m^{-2})

1:1500000

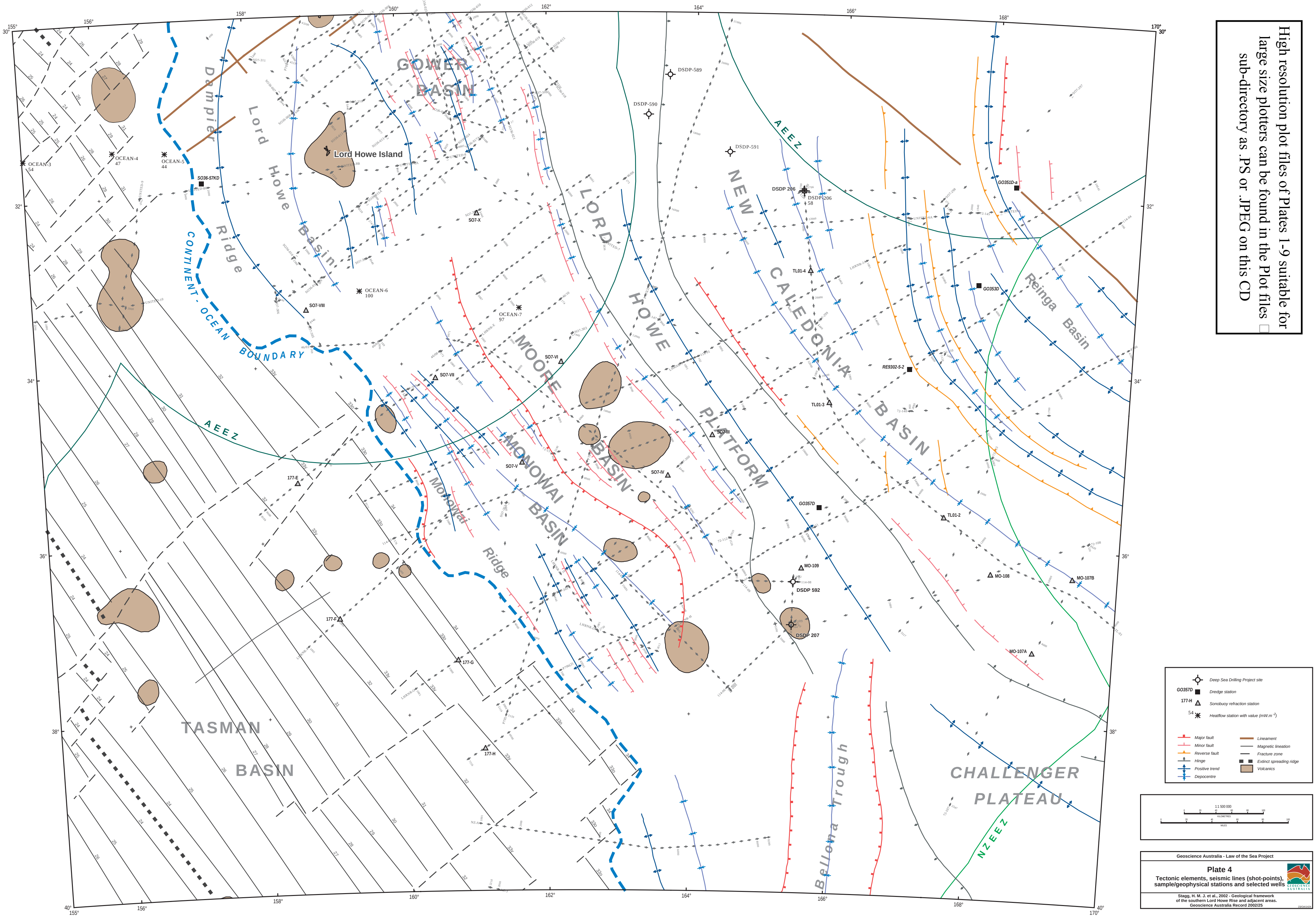
Geoscience Australia - Law of the Sea Project

Plate 3

Bathymetry, seismic lines (shot-points), sample/geophysical stations and selected wells

Stagg, H. M. J. et al., 2002 - Geological framework of the southern Lord Howe Rise and adjacent areas. Geoscience Australia Record 2002/25

SOUTHERN LORD HOWE RISE



High resolution plot files of Plates 1-9 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .JPEG on this CD

Geoscience Australia - Law of the Sea Project

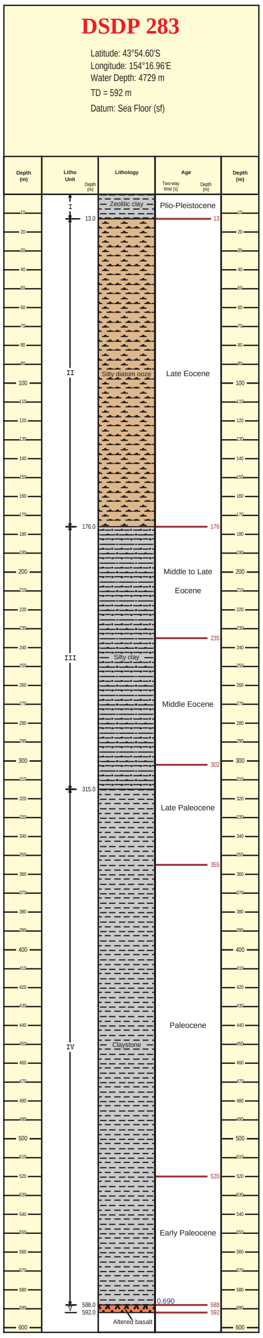
Plate 4

Tectonic elements, seismic lines (shot-points), sample/geophysical stations and selected wells

Stagg, H. M. J. et al., 2002 - Geological framework of the southern Lord Howe Rise and adjacent areas. Geoscience Australia Record 2002/25

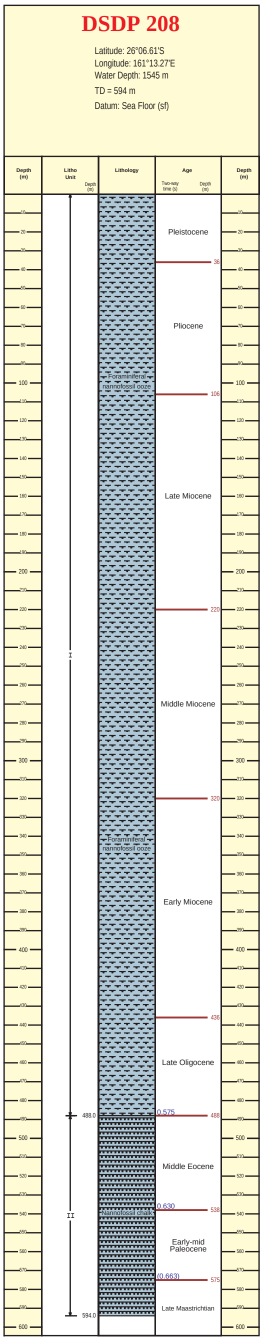
23/OA/1424

Lithostratigraphic columns for DSDP holes 283, 208, 207, 206 and Wainui-1 on the southern Lord Howe Rise



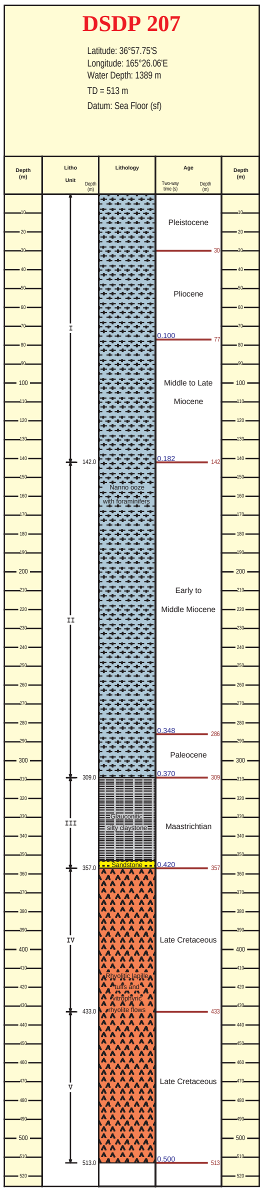
Data Sources

Derived from Kennett, J.P., Houtz, R.E. et al., 1974.
Initial Reports of the Deep Sea Drilling Project, Volume 29.



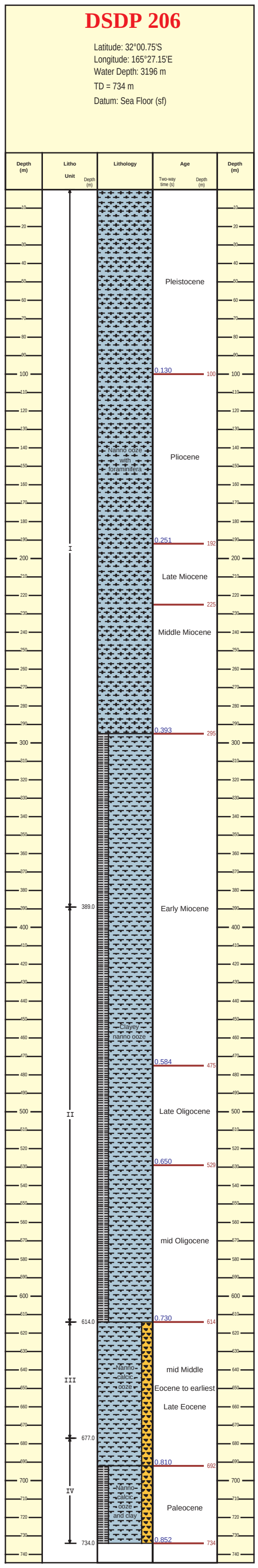
Data Sources

Latitude, longitude, water depth, total depth, lithology unit,
seismic two-way time and age, derived from Burns, R., Anderson, J. et al, 1973.
Initial Reports of the Deep Sea Drilling Project, Volume 21.



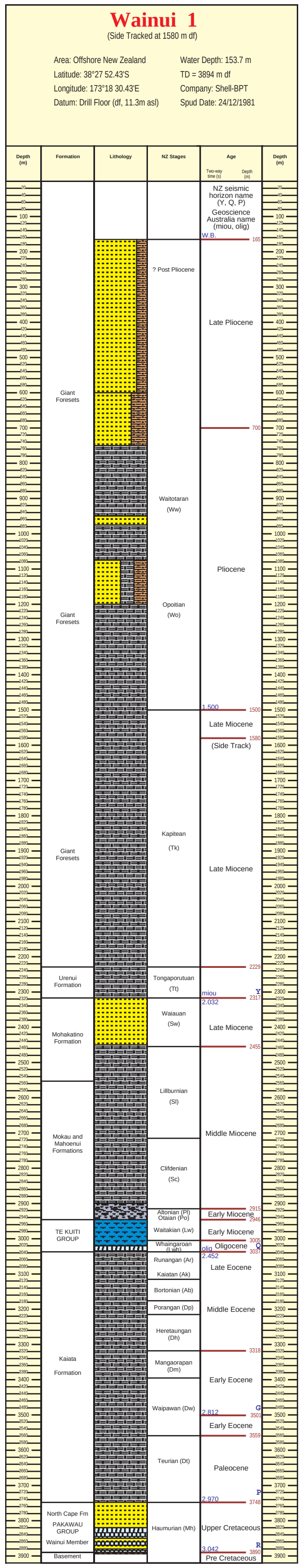
Data Sources

Latitude, longitude, water depth, total depth, lithology unit,
seismic two-way time and age, derived from Burns, R., Anderson, J. et al, 1973.
Initial Reports of the Deep Sea Drilling Project, Volume 21.



Data Sources

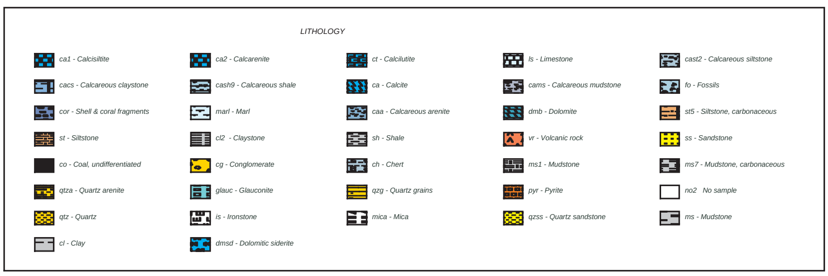
Latitude, longitude, water depth, total depth, lithology unit,
seismic two-way time and age, derived from Veevers, J.J., Hertz, J.R. et al., 1974.
Initial Reports of the Deep Sea Drilling Project, Volume 90.



Data Sources

Latitude, longitude, water depth, total depth, lithology unit,
seismic two-way time and age, derived from Shell BPT well summary sheet, 1982.
Lithology, seismic two-way time approximate - measured from diagram.

High resolution plot files of Plates 1-9 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .JPEG on this CD



Geoscience Australia - Law of the Sea Project

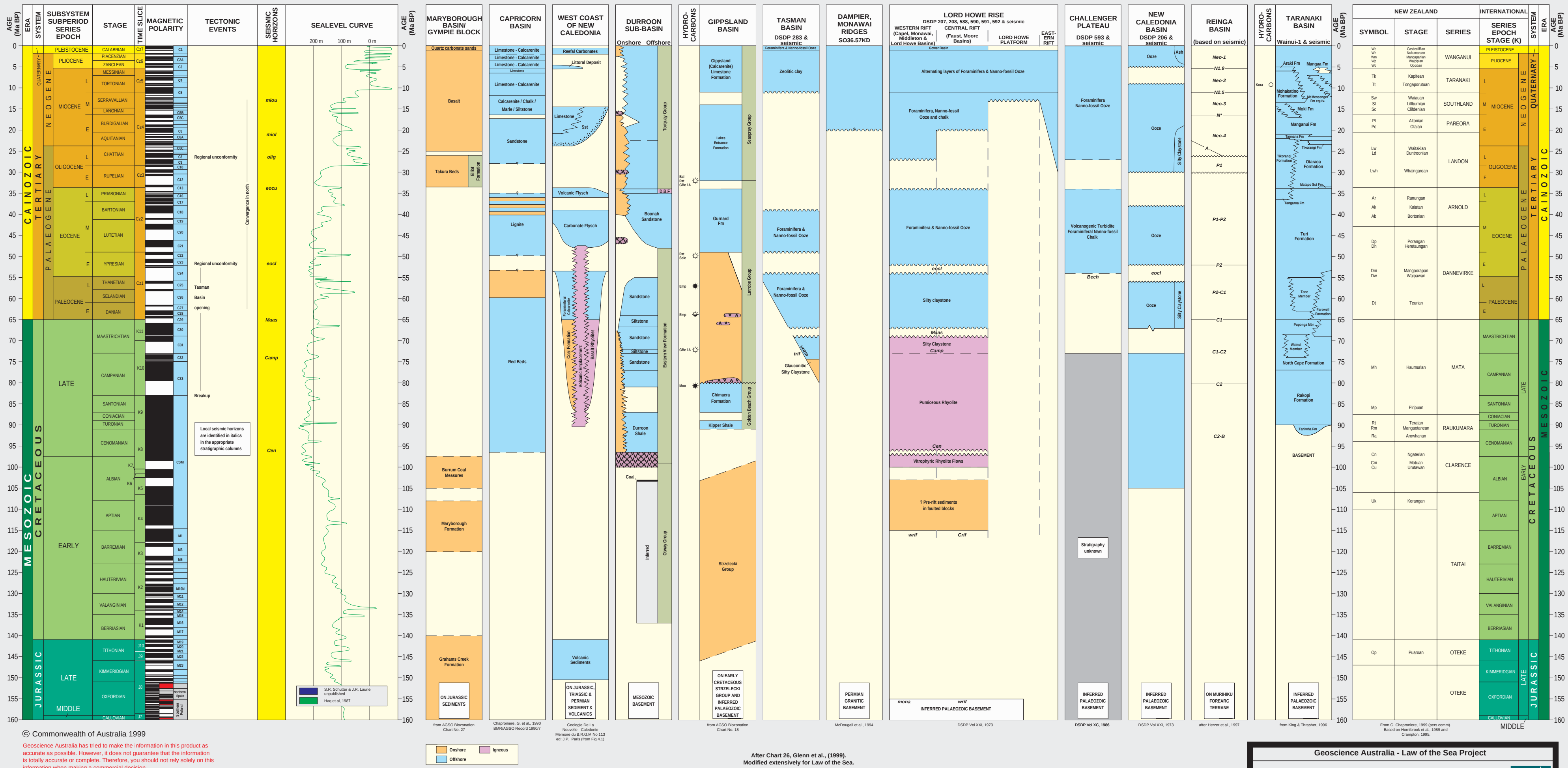
Plate 5

Lithostratigraphic columns for DSDP holes 283, 208, 207, 206 and Wainui-1

Stagg, H. M. J. et al., 2002 - Geological framework of the southern Lord Howe Rise and adjacent areas.
Geoscience Australia Record 2002/25
23/OA/1425

LORD HOWE RISE REGION

STRATIGRAPHY, SEALEVEL, TECTONIC EVENTS AND SEISMIC HORIZONS



After Chart 26, Glenn et al., (1999).
Modified extensively for Law of the Sea.

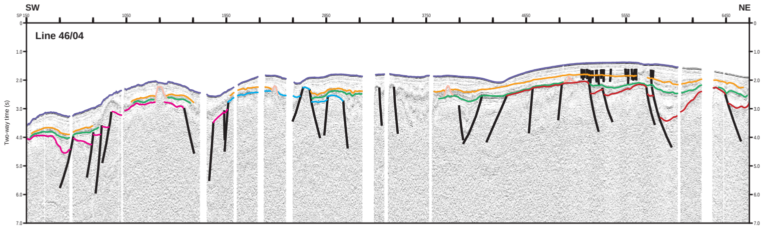
Geoscience Australia - Law of the Sea Project

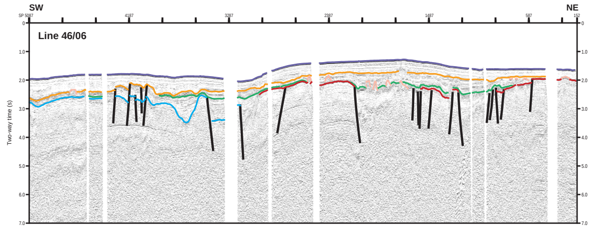
Plate 6

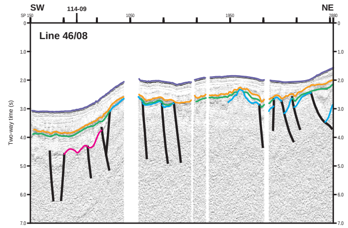
Lord Howe Rise region - stratigraphy, sealevel, tectonic events and seismic horizons

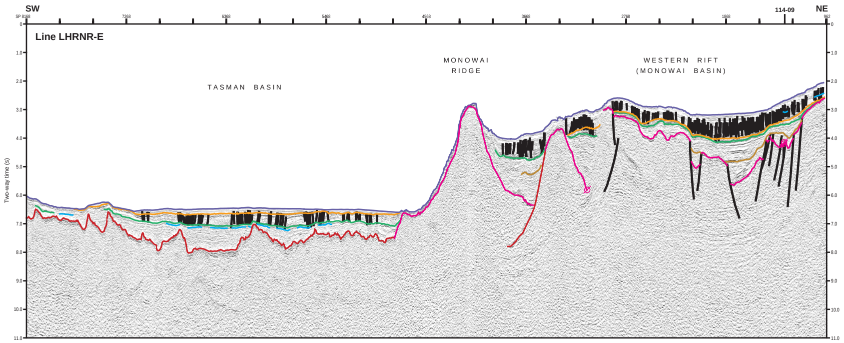
Stagg, H. M. J. et al., 2002 - Geological framework of the southern Lord Howe Rise and adjacent areas. Geoscience Australia Record 2002/25

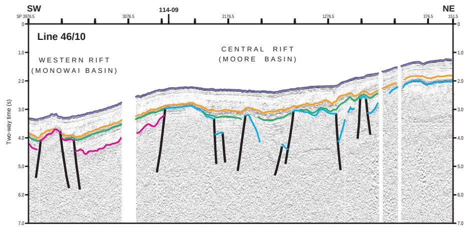
High resolution plot files of Plates 1-9 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .JPEG on this CD

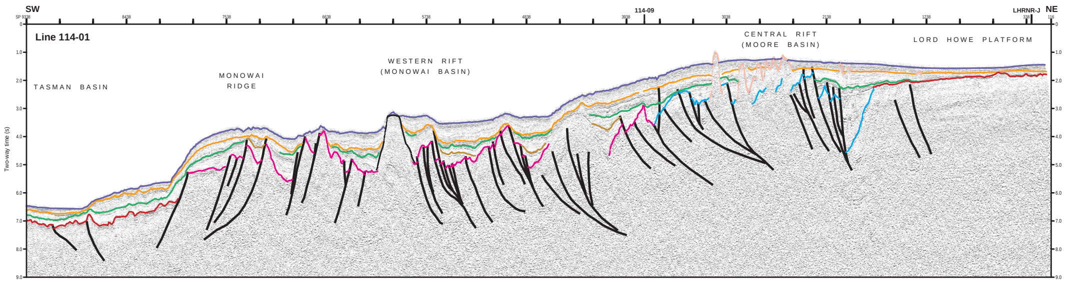


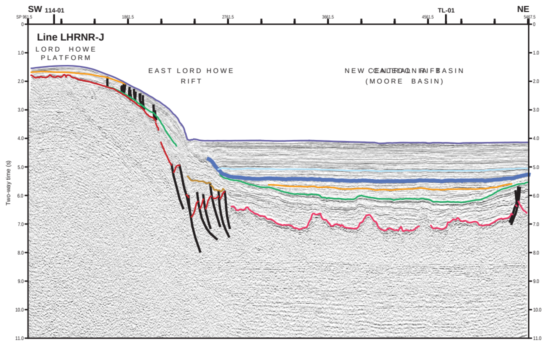












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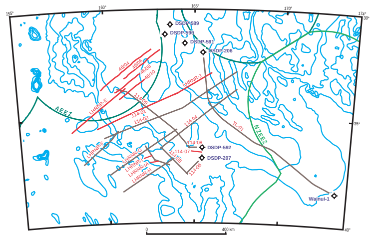

Seismic horizon	Description
wb	water bottom
bsr	bottom-simulating reflector
miou	Upper Miocene
miom	Middle Miocene
miol	Lower Miocene
olig	Oligocene
eocu	Upper Eocene
eocl	Lower Eocene
maas	Maastrichtian
camp	Campanian
cen	Cenomanian
plan	planated basement - Lord Howe Platform
erif	rifted basement - eastern margin Lord Howe Rise
bech	rifted basement - Bellona-Challenger province
crif	rifted basement - central rift province
wrif	rifted basement - western rift province
trif	rifted basement - Tasman Basin
ncb	basement - New Caledonia Basin
tara	Taranaki Basin basement
vmio	Miocene volcanics
vcam	Campanian (breakup) volcanics
tsdr	top Seaward Dipping Reflector Sequence (SDRS)
lay2	top oceanic crust layer 2 (volcanic basement)
moho	Moho

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Plate 7

Interpreted seismic sections: Sheet 1

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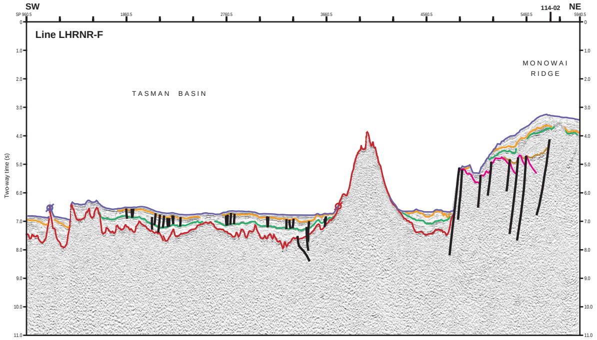

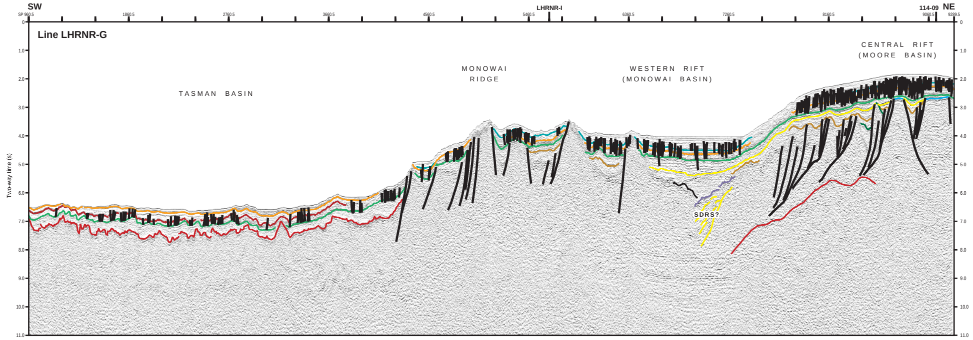

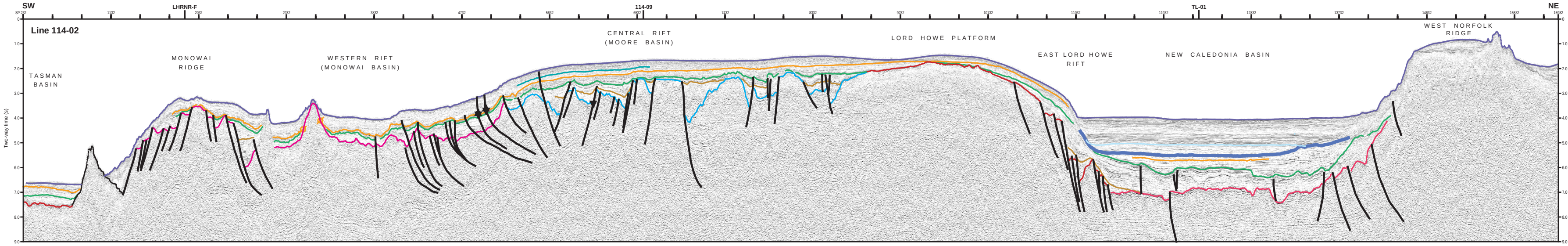

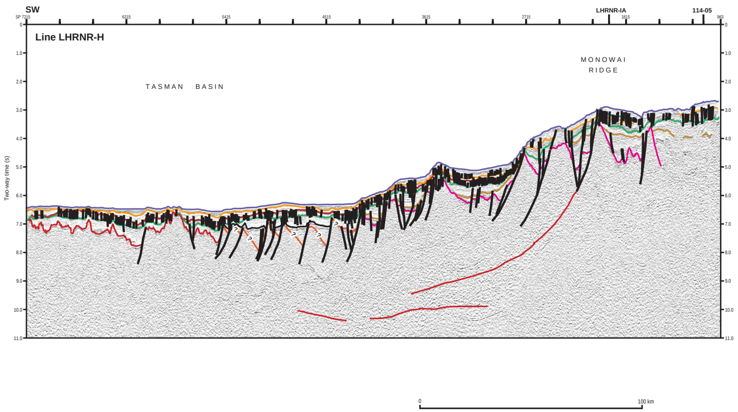

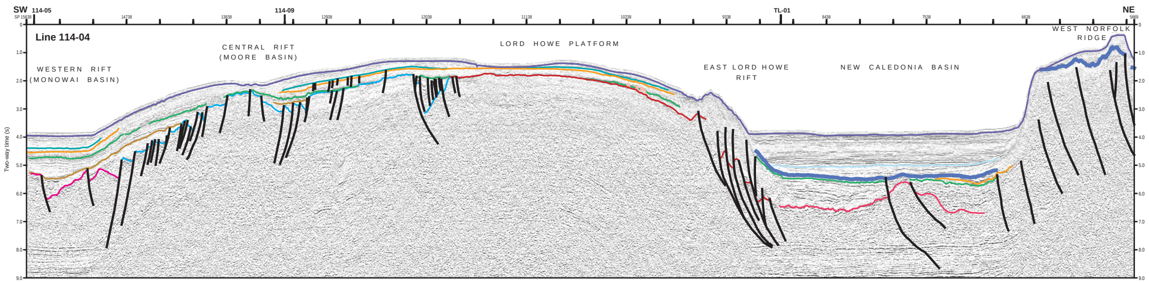

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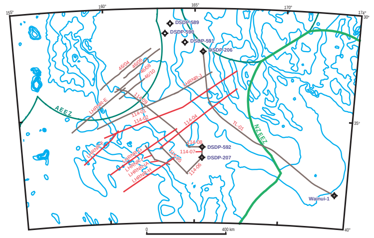

Seismic horizon	Description
wb	water bottom
bsr	bottom-simulating reflector
miou	Upper Miocene
miom	Middle Miocene
miol	Lower Miocene
olig	Oligocene
eocu	Upper Eocene
eocl	Lower Eocene
maas	Maastrichtian
camp	Campanian
cen	Cenomanian
plan	planated basement - Lord Howe Platform
erif	rifted basement - eastern margin Lord Howe Rise
bech	rifted basement - Bellona-Challenger province
crif	rifted basement - central rift province
wrif	rifted basement - western rift province
trif	rifted basement - Tasman Basin
ncb	basement - New Caledonia Basin
tara	Taranaki Basin basement
vmio	Miocene volcanics
vcam	Campanian (breakup) volcanics
tsdr	top Seaward Dipping Reflector Sequence (SDRS)
lay2	top oceanic crust layer 2 (volcanic basement)
moho	Moho

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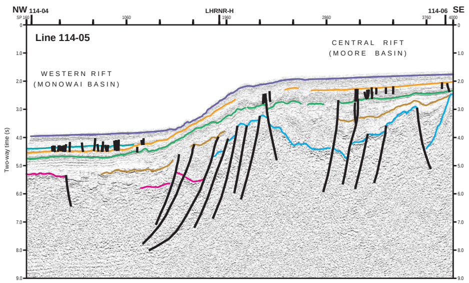
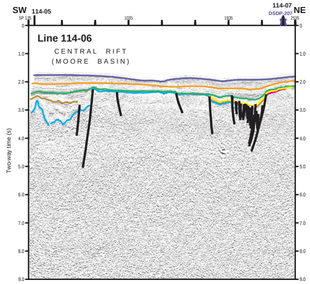
Plate 8

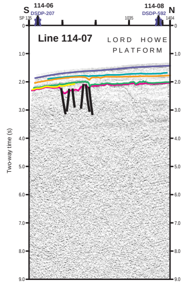
Interpreted seismic sections: Sheet 2

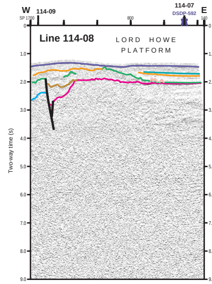
Stagg, H. M. J. et al., 2002 - Geological framework of the southern Lord Howe Rise and adjacent areas. Geoscience Australia Record 2002/25

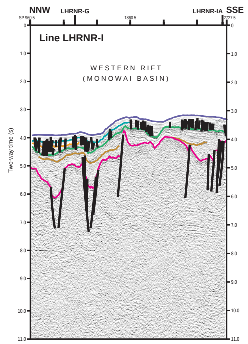
23/OA/1428

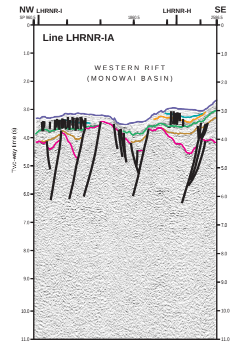


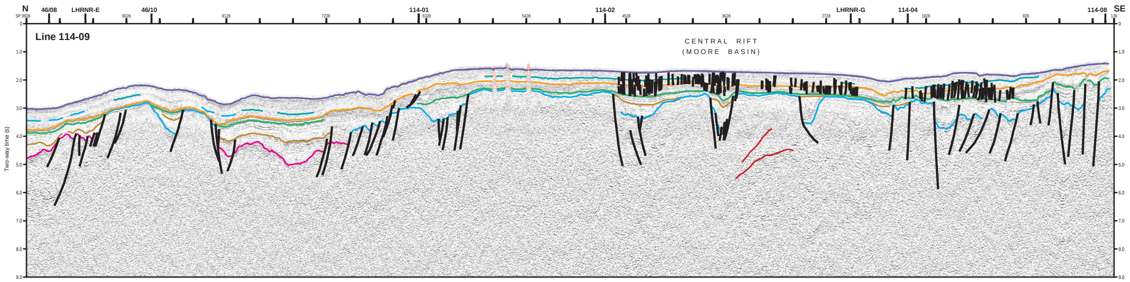


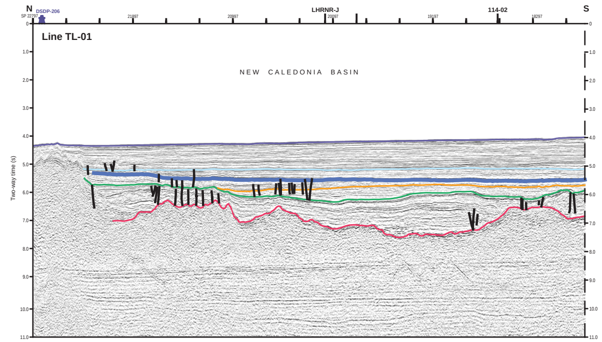


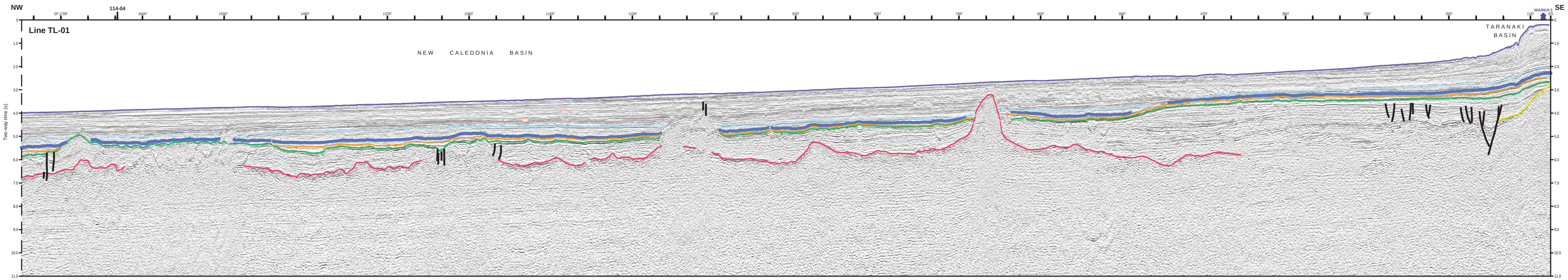












0 100 km

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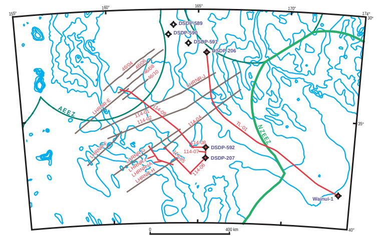

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Plate 9

Interpreted seismic sections: Sheet 3

Stagg, H. M. J. et al., 2002 - Geological framework of the southern Lord Howe Rise and adjacent areas. Geoscience Australia Record 2002/25

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Instructions for the CD-ROM

Geological framework of the southern Lord Howe Rise and adjacent areas

This CD-ROM contains the above-titled document as GeoscienceAustraliaRecord2002_25.pdf

To view this document on PC, install the Adobe Acrobat Reader v4.0 located in the Acrobat\Win_NT sub-directory on this CD, double click on the file Acrd4enu.exe and follow the installation prompts.

Once the reader is installed, go to the Record directory, double click on the GeoscienceAustraliaRecord2002_25.pdf to launch the document.

Please note:
Additional readers for Macintosh and Unix are also supplied on this CD
For Macintosh use, Acrobat\Macintosh\ar405eng.bin
For Unix use, Acrobat\Unix\sunsparc-rs-405.tar.gz

Directories on this CD

Acrobat directory:
Sub-directories of Adobe Acrobat Reader installation files for Win_NT, Macintosh, Unix and Help, which includes © Acrobat copyright, Adobe Acrobat Reader Guide and information on Adobe.

Plot files directory:
With sub-directories containing PostScript (.PS) and Joint Photographic Experts Group (.JPG) plot files of the A0 plates used in this Record. These are all suitable for plotting to large format plotters.

Record directory:
GeoscienceAustraliaRecord2002_25.pdf

If you have problems printing the pdf file, it may be that your Acrobat Driver is not the latest version. It may be necessary to install the updated Acrobat Driver from the Adobe Web site

Here is the link for the ADOBE Universal Postscript Windows Driver Installer 1.0.6 - English
<http://www.adobe.com/support/downloads/detail.jsp?ftpID=1500>

And for the Mac users ... the link for the Adobe PostScript printer driver 8.8 for Macintosh - English

<http://www.adobe.com/support/downloads/detail.jsp?ftpID=1494>