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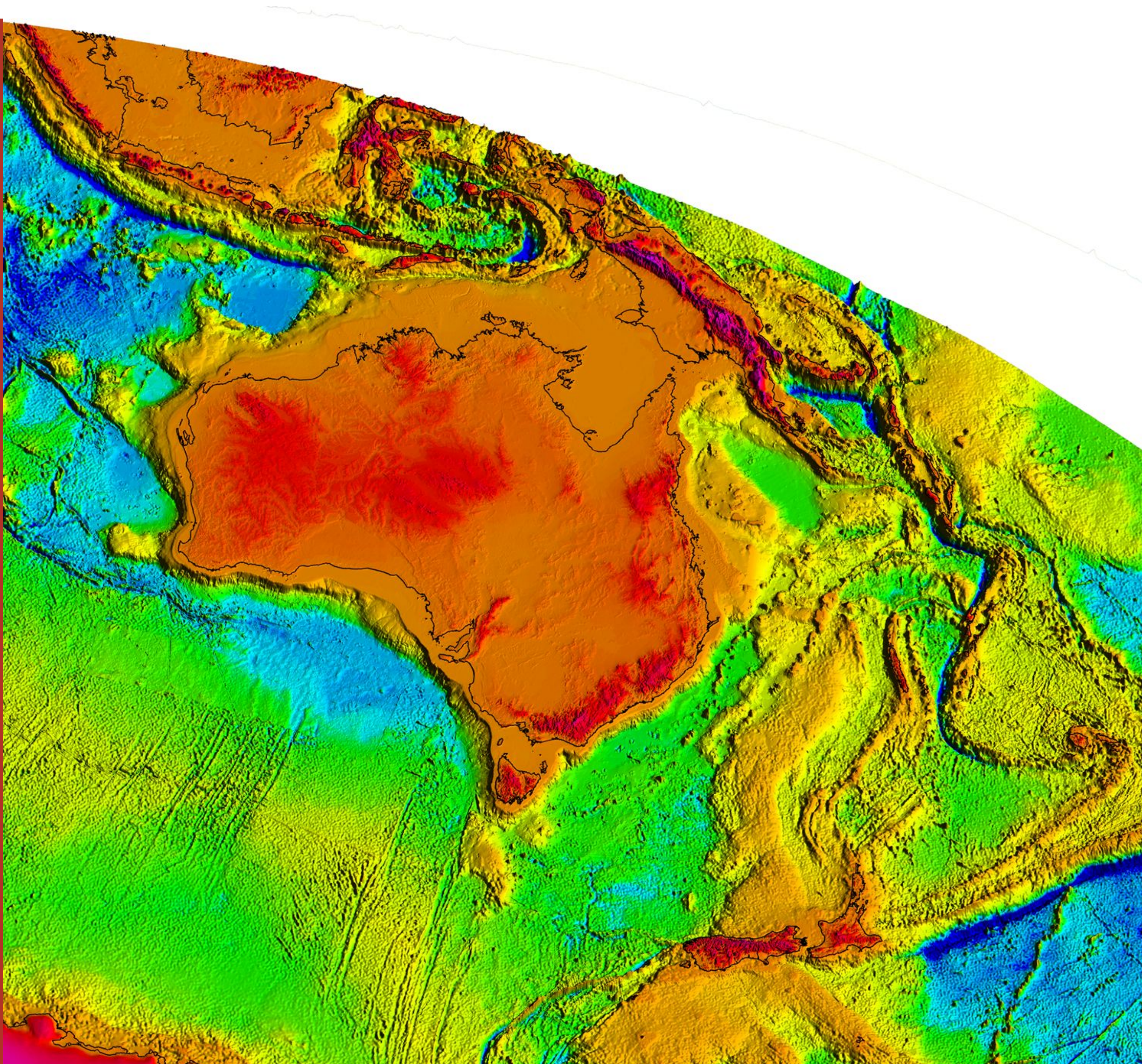

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Geoscience Australia Record **2003/01**

GEOLOGICAL FRAMEWORK OF THE NORTHERN LORD HOWE RISE AND ADJACENT AREAS

by

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FOREWORD

This is one of a series of three reports outlining the geological framework of the Lord Howe Rise (LHR) region of the Tasman Sea. These have been prepared as Geoscience Australia (GA) Records, and deal with juxtaposed areas that cover the Northern LHR (herein), Central LHR (Gower Basin; Willcox & Sayers, Record 2002/11), and the Southern LHR (Stagg et al., Record 2002/25). The three studies were set up as part of Geoscience Australia's Law of the Sea Project (1998-2004). They provide part of a commitment to examine potential marine jurisdictional boundaries in regions to which Australia may lay claim under the United Nations Convention on the Law of the Sea (UNCLOS).

The results of the northern LHR study, described herein, are based on the interpretation of Dr S. Van de Beuque, a graduate of the 'Universite de Bretagne Occidentale', who worked with AGSO (now Geoscience Australia) during 1998-1999. The work has also been presented as part of a post-doctoral thesis on the northern Lord Howe Rise and Three Kings Ridge, entitled 'Etudes Geologique des terminations nord de la Ride de Lord Howe et des Trois Rois' (Van de Beuque, 2000).

This Geoscience Australia Record was initially prepared by Dr Van der Bueque, but for completeness now includes some material derived from Stagg et al. (2002), and a revised nomenclature used to define the seismic stratigraphy, and bring it into line with that derived for the central LHR (Gower Basin) by Willcox & Sayers (2001, 2002).

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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 nm 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, off eastern Australia. The total area of the AEEZ around Lord Howe and Norfolk Islands and the extended Continental Shelf is about 1.4 million km^2. Information on the geological framework of the area includes conventional seismic and deep-penetration seismic, crustal refraction velocities, potential field, heat-flow, and geological samples from scientific drilling and from seabed dredging and coring.

The Lord Howe Rise extends, along strike, for more than 1600 km from the Challenger Plateau, west of New Zealand, to the Chesterfield Plateau, west of New Caledonia. Water depths range from 1000-5000 m. The rise is underlain by continental crust 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, recent interpretation of all the available regional data sets shows that potentially prospective sedimentary basins underlie it for much of its length.

The rise has a width of 400-500 km and comprises four sub-parallel provinces that extend for most of its length (Plate 1). 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 well-defined Cretaceous hinge;

- a central rift 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 Faust Basin in the north and the Moore Basin in the south;

- 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 Capel Basin in the north and the Monawai Basin in the south. 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; and

- a western 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 Monawai Ridge forms an intact outer margin to the Monawai 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 northern province, which includes the northern part of the Dampier Ridge, and the Middleton, Capel and Faust Basins; a central province, which includes the southern Dampier Ridge, Lord Howe and Gower Basins; and a southern province, which includes the the Monawai Ridge and Basin, the Moore Basin. The Bellona Trough, in turn, separates these southern features from the Challenger Plateau.

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 Monawai Basins), the eastern flank of Lord Howe Rise, adjacent to the New Caledonia Basin including the Fairway Basin, and possibly the New Caledonia Basin itself, where the sediment thickness reaches 3.5 s ‘two-way time’ (TWT; *c* 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 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.

Recently acquired high-quality seismic data and satellite Synthetic Aperture Radar (SAR) imagery provide 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 suggest 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, suggests indicate that active hydrocarbon generation is taking place. While non-conventional hydrocarbon resources cannot currently be exploited, their interpreted presence suggests that thermogenic hydrocarbons are currently being generated. This substantially 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 (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 (UNCLOS, 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 (Fig. 1). 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 optimise the Continental Shelf claims.

A preliminary analysis of the extent of Australia's Continental Shelf under UNCLOS (Symonds & Willcox, 1989) 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 extended Continental Shelf, totalling an area of about 3.7 million km^2, extend beyond the 200 nautical mile Australian Exclusive Economic Zone (AEEZ). Geoscience Australia[2] has the responsibility of 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 on profiles spaced about 30 nautical miles apart over areas of margin extending beyond the AEEZ. Internal GA assessments in the 1990s indicated that further data collection and analysis were needed in about six of the nine 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 claims (Fig. 1a).

This report presents the geological framework information relevant to the Australian claim on the northern Lord Howe Rise, north of Lord Howe Island. Equivalent reports for the southern Lord Howe Rise and Norfolk Ridge area have been prepared separately (Stagg et al., 2002).

[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.

[2] Geoscience Australia was previously called the Australian Geological Survey Organisation (AGSO) from 1993 to 2001, and prior to that, the Bureau of Mineral Resources (BMR) from its founding in 1946, to 1993.

Limits of the Study Area

The AEEZ and the extended Continental Shelf in the vicinity of Lord Howe and Norfolk Islands are complex (Lockwood et al., 1996) in their morphologic and geologic definition and large in area (Table 1; approximately 12% of Australia's Continental Shelf, excluding any claim around Antarctica). In addition to the boundary definition rules to be applied under UNCLOS Article 76, a boundary needs to be negotiated with New Zealand. Because of these boundary complexities, and because of the vast 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 northern area.

Table 1: Relevant areas of AEEZ and extended Continental Shelf.

Zone	*Approximate Area (km^2)*
AEEZ adjacent to Lord Howe Island	430 000
AEEZ adjacent to Norfolk Island	390 000
Extended Continental Shelf between Lord Howe and Norfolk Islands	580 000
Total relevant AEEZ & extended Continental Shelf	1 400 000

Limits of the northern sector

The northern sector is defined by the following longitudes – 155° to 170° E and latitudes – 21° to 30° S. These stretch from the Tasman Basin in the west, to the New Caledonia Basin in the east, and from the Chesterfield Plateau in the north to the northern Gower Basin in the south. Maps in this report extend to 32° S to ensure that they overlap with the southern Lord Howe Rise sector.

2 - BACKGROUND

While this study is directed at the geological framework of the northern sector of the Lord Howe Rise and adjacent basins and ridges, it is related to the regional geology of the wider area of the southwest Pacific and eastern Australia. This area ranges from New Zealand in the south to New Caledonia in the north, and from the basins and fold belts of eastern Australia in the west to the subduction setting of the Tonga-Kermadec Trench in the east. The geological history of the region ranges in age from the Palaeozoic to the Recent, but the most important phase was from the Cretaceous to the Cainozoic.

The present-day rises, ridges and basins of the Lord Howe Rise region are 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 are composed of terranes that were accreted to the eastern edge of the Australian craton 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

This region comprises several sub-parallel rises, ridges and basins (Figs 2 & 3), of which the Lord Howe Rise is the largest.

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 is 50% greater than the area of the North West Shelf, including the marginal plateaus, and is comparable in area with the state of Queensland.

The northern part of Lord Howe Rise is considered to be made up of of three segments separated by NW-trending lineaments and structural discontinuities (Fig 2). The northern segment merges with a region of complex topography, which includes features such as the Chesterfield / Kenn / and Mellish Plateaus. The central segment is NNW-trending and encompasses features such as the Middleton Basin, Faust Basin and the Fairway Ridge and Trough (Dubois et al., 1974). The Lansdowne Bank overlies the intersection between the northern segment of the Lord Howe Rise and the Fairway Ridge. A southern segment (not considered in this report) includes the Gower Basin area (Willcox & Sayers, 2002).

Excluding the isolated 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, along which 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.

Lord Howe Rise is separated from eastern Australia by the Tasman Sea. 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. The floor of the ocean basin 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^{o}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. This basin extends for about 2000 km from the "Noroits" seamounts west of New Caledonia to the continental margin of the North Island of New Zealand. As with the Lord Howe Rise-Fairway Ridge system, 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, but narrowing south of 23°S to 80 km, where the change of direction occurs from NW-SE to N-S. The floor of the basin is generally very flat-lying, at a depth of about 3400 m. Between 21° 20'S and 25° 10'S the eastern side of the New Caledonian Basin, (Plate 1), is a uplifted basin culminating at about 2200 m depth.

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.

2.2 DATA SETS USED IN THE STUDY

Bathymetry

The main sources of gridded Geoscience Australia 'in-house' bathymetric data used in the study are a 30 arc-sec gridded bathymetric model (*Pers. Comm.*, C. Buchanan) and the predicted bathymetry (Smith & Sandwell, 1995). The 30 arc-sec grided bathymetric model is based on all available ship track data, whereas the predicted bathymetry has been derived from the satellite gravity data (Fig. 6). The gravity field accurately reflects seafloor topography in the 15 to 160 km wavelength bands, except for areas with large sediment thicknesses. Large-scale bathymetric features are generally isostatically compensated and do not correlate with the gravity field. Smith & Sandwell (1994) developed an algorithm to predict depth from the satellite gravity, ground-truthing their model with the ship track data. Predicted bathymetry does not have sufficient accuracy and resolution to be used for navigational purposes, but it can be helpful in studies of remote areas, where other bathymetric data are sparse.

In the image presented in Figure 3, the 30 arc-sec data have been merged with the predicted bathymetry without degrading the original data; only areas with no data have been filled in with the predicted bathymetry values. A hillshading technique has been applied to highlight bathymetric features in the area.

Seismic Reflection

The Lord Howe Rise is a 'frontier area' with respect to hydrocarbon exploration, which is generally the principal stimulus to the acquisition of reflection seismic data. As such, the acquisition of seismic data in the region has been patchy and sporadic,at least until the 1990s. Principal data sets acquired since the early 1970s are tabulated in Appendix 2, and shown in Figure 4 and Plate 1. Recent seismic data from AGSO Survey 206 have been interpreted for the purpose of this report.

Roving reconnaissance 'Petrel' seismic (Shell International, 1971)

Five lines (Plate 1, 1001/701 to 705) from the Shell MV *Petrel* roving reconnaissance survey in the Australian region are located in the study area. The lines cover large distances (approximately 500-1000 km) and zig-zag from south to north crossing the Lord Howe Platform, New Caledonia, Middleton, Faust, and Fairway Basins, Fairway Ridge and Chesterfield Plateau. The data are of poor quality and are only slightly superior to a normal near-trace display. The original data are of poor quality and are only available on paper.

BMR Continental Margins Surveys 12, 13 & 15 (CGG, 1972)

Surveys 12 and 15 were recorded as a grid of E-W lines at 20 nm (~35 km) spacing. The surveys were acquired across the Tasman, Capel and Middleton Basins and Dampier Ridge. Survey 13 was recorded as an E-W grid in the southern Chesterfield Plateau and Faust Basin. 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 data.

Sonne 7A (BGR, 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, Middleton and Lord Howe Basins, Norfolk, West Norfolk and Dampier Ridges (Willcox et al., 1981). The survey was a cooperative venture between BGR and the then Bureau of Mineral Resources (BMR). Basic data processing was carried out, however, the resultant data are of poor quality by modern standards. Some of the data were migrated at a later date but are still of only fair quality. The data did not contribute significantly to this study.

Sonne 36A (BGR, 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 & 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 stratal geometry. These data were used in the interpretation of tectonic elements on the Lord Howe Rise (Fig. 2). A more detailed interpretation of these data is provided in Willcox & Sayers (2002) where the data were used to assess the geology of the Gower Basin.

AGSO Survey 177 (AGSO, 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. Line 177/LHRNR-BA is an east-west line and relevant to the northern LHR study.

AGSO Survey 206 (AGSO, 1998) "FAUST1"

Survey 206 (FAUST1) was a joint Australian-French deep-seismic survey acquired by AGSO on the *Rig Seismic* in 1998 (Lafoy et al. 1998; Bernardel et al., 1999). A total of 4564 km of high-quality data were recorded over the northern Lord Howe Rise, New Caledonia Basin and Norfolk Ridge system. 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. Survey 206 (FAUST1) was the primary seismic data set used in this study.

Velocity Data

Sedimentary and crustal refraction velocity data are available from a number of sources, summarised as follows:

- 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.

- 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.

The refraction velocity data is tabulated in Appendix 3 and the location of refraction stations are shown in Figs 4-5 and Plates 1-2.

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. 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).

Geological Data

The sources for well information and sample data include:

- The Deep-Sea Drilling Program (DSDP). Two DSDP legs have drilled wells that are relevant to this study. Leg 21 (Burns, Andrews et al., 1973) drilled Sites 206 and 208, on the Lord Howe Rise and in the New Caledonia Basin, respectively. Leg 90 (Kennett, von der Borch et al., 1986) drilled Site 587 on the Chesterfied Plateau, Site 588C in the Faust Basin and Sites 589-591 on the Lord Howe Platform (Fig. 2). However, these sites were drilled primarily for palaeoceanographic purposes and are of limited value to this study; and

- seabed samples from dredging and coring (Appendix 4).

Heat-flow Data

A few heat flow samples exist within the study area including one from Deep Sea Drilling Project (DSDP) Site 587 in the northern Lord Howe Rise. Results are contained in Appendix 5, and its significance is discussed later in this report.

2.3 PREVIOUS STUDIES

Despite the vast area encompassed by the Lord Howe Rise, Tasman and New Caledonia Basins 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 four broad categories:

- interpretations of local features and basins - Dampier Ridge (Symonds et al., 1988; McDougall et al., 1994); Chesterfield Plateau (Missegue & Collot, 1987); Lansdowne Bank (Mignot, 1984); Fairway Ridge (Ravenne et al., 1977; Lapouille, 1982); New Caledonia Basin (Wood & Uruski, 1989; Uruski & Wood, 1991); Lord Howe Rise (Launay et al., 1977);

- results of Deep Sea Drilling Project (DSDP) Legs 21 (Burns, Andrews et al., 1973) and 90 (Kennett, von der Borch et al., 1986);

- interpretations of the Tasman Basin spreading history – 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; and

- interpretations of the regional and plate tectonic setting – Powell (1996), Symonds et al. (1996), Van de Beuque (1999), Norvick et al. (2001), Norvick & Smith (2001).

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°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 and satellite gravity data. This interpretation of the breakup of the Tasman Basin is considerably more complex than previous authors have interpreted. Gaina et al. (1998) showed that Tasman Sea spreading cannot be modelled as a simple two-plate spreading system and they identified 13 microplates that were active during breakup and spreading. This complex microplate history was accompanied by several changes in spreading azimuth, and involved several failed rifts.

Seafloor spreading was initiated in the southern central Tasman Sea (84 Ma) as a result of rifting between the Challenger Plateau and the Lord Howe Rise. A brief left-lateral transtensional 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 central 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 the 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 the 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 of Gaina et al. (1998), 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 of the Australian plate, which predates the beginning of India-Eurasia collision.

An important aspect of the Gaina et al. (1998) interpretation is their estimates of the half-spreading rates. From 83 to 79 Ma (chron 33o), the half spreading rate is estimated at 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. (1998) do not suggest any reasons for the major increase in spreading rate.

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 is 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) may have formed the complementary lower plate margin (Fig. 9 in Etheridge et al. 1989). 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. In this adaptation, it is interesting that the depiction of the structure of the Lord Howe Rise has strong similarities with our interpretation of an eastern platform, and central and western rift provinces.

There are two important implications of the detachment model:

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

- 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

Direct knowledge of the stratigraphy of the northern Lord Howe Rise region is solely based on:

- Deep Sea Drilling Project Sites 208, 587, 588C, 589-591 (Lord Howe Rise) and Site 206 in the New Caledonia Basin; and
- dredged and cored seabed samples (eg Willcox et al., 1981; Roeser & Shipboard Party, 1985; Herzer et al., 1997).

As a consequence, the stratigraphy is poorly understood and a greater proportion of geological knowledge must be obtained from the seismic data (Chapter 4). The locations of the wells, key dredge and core samples are shown in Plate 2, and well logs shown in Plate 3.

3.1 STRATIGRAPHY DEDUCED FROM DSDP SITES AND SAMPLES

The summary is based largely on the DSDP reports for the sites in the area (Burns, Andrews et al., 1973; Kennett, Houtz, Andrews et al., 1975; Kennett, von der Borch et al., 1986). It is clear that in this oceanic environment, some regional unconformities are attributable to changes in oceanography, rather than to tectonic events.

Basement and near-basement rocks

Dredge station GO357D1 of ORSTOM Cruise 3 (Launay et al., 1976; Willcox et al., 1981) from the eastern flank of the southern Lord Howe Rise, recovered olivine basalt, gabbroic intrusions in the basalt, and hyaloclastic breccias. Seismic data indicate that these extrusive volcanic deposits lie on the basement, although basement rocks have not been recovered from the Lord Howe Rise or its immediate area. 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. This site is located further to the south, east of Tasmania, and has only indirect relevance to the northern Lord Howe Rise project area. Samples of a metamorphosed granite and ?microdiorite / andesite were found on the Dampier Ridge. These have been dated as 250-270 Ma (Late Permian) (McDougall et al., 1994).

Mesozoic

One DSDP site, and some samples dredged by ORSTOM, recovered sediments older than Cainozoic. DSDP Site 208, located in the central rift of the Lord Howe Rise, penetrated Upper Cretaceous sediments.

Cainozoic

DSDP Site 208 recovered a complete Lower Paleocene succession with siliceous microfossils (Fig. 7). Middle Eocene and upper Oligocene to Recent sections were also recovered (Kennet, von der Borsh et al. 1986).

Lower Eocene regional unconformity

A lower Eocene regional unconformity is represented by seismic horizon 'eocl', green colour on seismic sections (Fig. 7; Plates 4-5). The seismic representation of this unconformity at DSDP Site 208 is indicated by onlap of the Lower to mid-Eocene.

The unconformity spanning the Upper Paleocene to the lower Eocene is also present at DSDP Site 206 in the New Caledonia Basin.

Mid-Eocene unconformity

DSDP Site 208 shows a level of glauconite within the mid-Eocene succession that is indicative of a shallow water environment in the northern part of the Lord Howe Rise (Fig. 8). Chaproniere et al. (1990) inferred neritic to bathyal palaeo-environments in the Mid-Eocene that are overlain by Oligocene to Recent sediments deposited in a bathyal environment.

The Late Eocene to Oligocene regional unconformity

There is some variation in the extent, cause, and naming of this unconformity (Edwards (1973). It was documented by Bentz (1974) who referred to it as the Neogene / Paleogene unconformity. Kennett, Houtz et al. (1975) identified it as the 'intra-Oligocene' regional unconformity, while Nelson et al. (1986) refer to it as the Paleogene-Neogene regional unconformity. At Site 208, on the central rift of the Lord Howe Rise, the unconformity separates Middle Eocene from Upper Oligocene cabonate oozes.

Martini & Jenkins (1986), suggest that the Late Eocene to Oligocene hiatus is probably the result of seabed currents, rather than tectonic influences. However, Bentz (1974) associated it with a change in structural regimes, from an earlier era of block faulting to a subsequent period of subsidence. Eade (1988), in discussing the Norfolk Ridge system, refers to this hiatus as the 'Regional Unconformity', separating a succession of slumped deposits above from a folded and faulted Paleogene succession below. He asserts that it was formed by an Eocene tectonic event resulting from global plate tectonics, and not by current action. S. Van de Beuque considers that the widespread occurrence of the unconformity, and the associated peneplanation visible on seismic regional profiles, indicates subaerial erosion and a tectonic origin. It may be that the tectonic unconformity is extended upward in time, by non-deposition due to current action, in some localities, (eg at DSDP Site 207, southern Lord Howe Rise area), and that older Neogene sediments are present elsewhere. We believe, therefore, that at any given site the causes of the unconformity are tectonic in origin, affected by current action to a variable degree. These resulted in non-deposition in most localities, and to a lesser degree, erosion in other areas.

Mid Oligocene to Pleistocene

A complete mid Oligocene to Pleistocene succession is present at DSDP Site 206 in the New Caledonia Basin, and constitutes one of the most complete sequences of Neogene planktonic foraminifera and calcareous nannofossils recovered in the SW Pacific region (Burns, R.E., Andrews, J.E., *et al*., 1973).

Volcanic Rocks

Lord Howe Island and 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-Cainozoic or earlier, and the younger series has been dated at around 7.7 Ma, 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 there is little evidence of volcanic activity except for siliceous detritus in DSDP Site 208. On the southern part of the rise, however, DSDP Site 207 had a prominent ash record, and the site terminated in pumiceous lapilli tuffs and rhyolite flows erupted above or very near sea level; at about 94 Ma (Cenomanian), approximately 10 My prior to the first formation of oceanic crust in the Tasman Sea.

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 (Gardner et al., 1986) to be altered volcanic ash layers from regional sources, mainly in New Zealand. The quantity of volcanic glass, and laminae interpreted as altered volcanic ash, increases greatly in the early and middle Miocene and in the Quaternary succession.

Volcanic and igneous rock samples recovered from the Dampier Ridge comprised metamorphosed granite and ?microdiorite or andesite dated at 250-270 Ma (mid Permian) (McDougall et al., 1994).

Samples from the eastern Lord Howe Rise (Dredge site GO357D1, ORSTROM Cruise 3, 1975), included olivine basalt extruded subaqueously, gabbroic intrusions in the basalt, and hyaloclastic breccias mixed with biomicrite of possible mid Miocene age (Launay et al., 1976; Willcox et al., 1981).

3.2 STRATIGRAPHIC CONTROL AND KNOWLEDGE OF THE MAJOR PROVINCES

Tasman Basin

USNS *Eltanin* traversed the region during the late 1960s and early 1970s, and recovered unconsolidated surficial sediments, mainly Quaternary oozes. DSDP Site 283, in the southern Tasman Basin, penetrated the sedimentary succession and at total depth altered pillow basalt at 588 m below the sea floor (Kennett, Houtz et al., 1974; Stagg et al., 2002). An age compatible with oceanic magnetic anomaly 32 (c. 73 Ma) was expected, but the overlying Early Paleocene claystone is 10-15 Ma younger (Kennett, Houtz, Andrews et al., 1975), suggesting a period of non-deposition followed by extrusion of the basalt.

The succession from the Late Eocene tothe Late Pliocene is also absent. The hiatus is attributed to non-deposition rather than erosion because the underlying sediments are unconsolidated. The Plio-Pleistocene succession above the 'Oligocene' hiatus is less than 15 m thick.

DSDP Site 283 indicated that oceanic depths exceeding the silica and calcium carbonate compensation depths, had been reached by the Early Palaeocene. Diatoms and calcareous nannofossils were recovered in the Late Eocene section suggesting some shoaling of the Tasman Sea.

Taken as a whole, the sedimentary succession in the Tasman Sea consists of oceanic basement, overlain largely by terrigenous silt and clay, and in turn by siliceous ooze and calcareous chalk and ooze (Kennett, Houtz, Andrews et al., 1975, Chapter 44).

Lord Howe Rise

Western Rift Zone (Capel Basin)

The closest drill site to the Capel Basin is DSDP Site 208 (Fig. 2), located at the boundary between the Faust and Capel Basins. DSDP Site 208 drilled through the Tertiary-Cretaceous boundary succession and bottomed in latest Maastrichtian fossiliferous nannofossil chalk of normal oceanic affinity. The absence of clastics at the site indicates the oceanic environment has been present on the central Lord Howe Rise since at least the Maastrichtian, although glauconite in the Eocene sediment suggests some shallowing has occurred.

Central Rift Zone (Faust Basin, Gower Basin)

DSDP Site 587 (Kennet, von der Borch et al., 1986) is located on the southern slope of the Lansdowne Bank and penetrated the upper Miocene sequence. The closest drill site to the Gower Basin, within the central rift province, is DSDP Site 208 (Fig. 2) that is located at the boundary between the Faust and Capel basins. DSDP Site 208 drilled through the Tertiary-Cretaceous boundary succession and bottomed in latest Maastrichtian fossiliferous nannofossil chalk of normal oceanic affinity.

Lord Howe Platform.

Seabed sample GO357D1 of ORSTOM Cruise 3 (Launay et al., 1976; Willcox et al., 1981) was dredged from the flank of a pinnacle in the southwestern area of the Platform. The seabed sampled was not an exposure of basement but a volcanic edifice. The 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 has an abnormally low silica content (34%). The coral debris indicates that the water depth in the area was shallower during the Miocene eruption of the volcanics than its present 700+ m. Miocene volcanics are also part of the suite that formed Lord Howe Island and Ball's Pyramid.

Fairway Trough and Fairway Ridge

DSDP Site 587 (Kennet, von der Borch et al., 1986) is located on the southern slope of the Lansdowne Bank, penetrated the upper Miocene sequence and showed evidence of current effects. DSDP Site 587 is not directly located within the Fairway Basin but provides some control just north of it (Fig. 2).

New Caledonia Basin

DSDP Sites 206 (Leg 21) and 591 (Leg 90) were drilled in the New Caledonia Basin. Site 206 terminated in calcareous oozes of probable Early Paleocene age, and Site 591 terminated in Miocene sediments. The biostratigraphic succession of nannofossil oozes at Site 206 above the Eocene / Oligocene regional unconformity is notably complete. The Paleogene succession is disturbed by slumping, and middle Paleocene deposits were found beneath Early Paleocene sediments near the bottom of the hole. The regional unconformity, between the Late Paleocene and the Early Eocene was also evident at this site. It seems to have been a deepwater site throughout the Cainozoic, with oceanic biogenic deposits dominating the succession (Kennett, Houtz, Andrews et al., 1975).

4 - SEISMIC STRATIGRAPHY

Seismic sequences on the Lord Howe Rise have previously been described by Willcox et al. (1981), by Van de Beuque (1999) for the northern Lord Howe Rise, and Willcox & Sayers (2001, 2002) for the Gower Basin.

During this study, S. Van der Bueque identified some 30 seismic horizons through the Northern Lord Howe Rise region as a whole; these lie within several structural provinces that include the LHR and the adjacent ocean basins and ridges. The horizons, which were interpreted using *Geoquest*, include 10 categories of seismic 'basement', 5 categories of volcanics, and 'Moho', and are fully tabulated in Appendix 6. However, in the body of this report, we have simplified the horizon nomenclature to conform to the 15 unconformities that bound the main megasequences/sequences as interpreted by Willcox & Sayers (2001, 2002) for the Gower Basin area of LHR. This nomenclature has also been adopted for the Southern LHR by Stagg et al. (2002), thus enabling the entire LHR region to be discussed in terms of similar seismic horizons and megasequences.

Table 2: Megasequences and unconformites of Willcox & Sayers (2001 & 2002) for the Gower Basin area of LHR, with their proposed ages.

Seismic Horizons This report (Van de Beuque)	Megasequences Gower Basin, LHR (Willcox & Sayers)	Unconformities Gower Basin, LHR (Willcox & Sayers)	Proposed Ages (Willcox & Sayers)
	Water layer		
wb		U1 (blue)	Water bottom
	GB1		
a		U2 (yellow)	?mid Miocene
	GB2		
		U3 (black)	L. Oligocene
	GB3		
b		U4 (light green)	?mid Oligocene
	GB4		
c		U5 (blue/green)	Early or Middle Eocene
	GB5		
d		U6 (light blue)	?Maastrichtian
	GB6		
e		U7 (green)	Campanian
	GB7		
f		U8 (violet)	Cenomanian
	GB8		
g		U9 (black)	
	GB9		
h		U10 (purple)	earliest Cretaceous
	GB10		
plan/crif/wrif/ncb etc		U11 (red)	Pre-Gower Basin rift ?New England Fold Belt etc.
		U11	Volcanic/Oceanic Basement
	GB11		
		(pink)	Intra-Basement

There are major changes in the character of seismic sequences across the Tasman, Fairway, New Caledonia and West Caledonia Basins; Lord Howe Rise; Fairway, Norfolk and Loylaty Ridges; consequently, the seismic sequence characteristics will be discussed separately for each area. Extrusive and intrusive igneous suites and volcanogenic sediments are widespread, and their seismic characteristics will be discussed in section 4.6.

4.1 LORD HOWE RISE

Willcox et al. (1981) defined two main seismic sequences on LHR ('I' and 'II'). Sequence I consists of an upper unit with parallel reflectors that downlap onto the basal mid-Miocene age 'II' unconformity (equivalent 'U2', Appendix 6) and a lower unit characterised by a more chaotic configuration of reflectors but with reflectors generally concordant with the widespread Eocene / Oligocene unconformity (equivalent 'U3', Appendix 6).

Seismic lines from Survey 206 were tied to DSDP Site 208 and show a good correlation between thickness of seismic sequences and the thickness of sequences as determined from well-data (Burns, Andrews et al., 1973; Fig 7). The oldest sequences probably correspond to the main pre-Tasman rift formations of Australia, New Caledonia and New Zealand pre-dating continental breakup in the Campanian. The thickness of the pre-Cretaceous to Cretaceous sediments, based on seismic data, is about 2000 m and confirms the thickness estimates given by Ravenne et al. (1977).

Seismic 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 Faust Basin), and the deeper Western Rift province (Capel and Middleton Basins and Dampier Ridge).

Pre-rift seismic sequences

Pre-Cenomanian basement (Horizons 'plan', 'crif', 'wrif', 'dam', 'midd')

Basement of pre-Cenomanian and older age is interpreted as pre-rift beneath the Lord Howe Rise. However, in recognition of the varying basement character throughout the region, basement has been subdivided according to those character changes which correspond to different tectonic elements. These basement types and related seismic horizons are designated as: 'plan' (planated basement of the Lord Howe Platform), 'crif' (rifted basement of the central rift province) and 'wrif' (rifted basement of the western rift province), which includes 'dam' (Dampier Ridge) and 'midd' (Middleton Basin) basement types.

Beneath the Lord Howe Platform, the seismic character of the pre-rift section varies considerably, from seismically transparent to well-layered, folded and faulted strata. Fine-scale layering and structuring can, in places, be identified for up to 1s TWT (*c.* 3 km) below top of basement (Plate 5, line 206/01). The basement section probably consists of Palaeozoic rocks of the New England Fold Belt or its equivalents. DSDP Site 207, further to the south, recovered rhyolites, tuffs and flows of Cenomanian age (94 Ma) from below seismically defined basement, which indicates 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 is represented by a series of distinct to poorly-defined fault blocks with no internal reflectivity. The nature of the basement rocks under the central rift is likely to be similar to those rocks beneath the Lord Howe Platform as the crust has not been significantly thinned. It is, however, probable that the composition of basement under the western rift province (ie Dampier Ridge, Middleton and Faust Basins) is different to that under the central rift province (Capel Basin) as the crust has been significantly thinned as deduced from seismic data (Plates 4–5). The basement under the Dampier Ridge and Middleton Basin could be heavily intruded continental crust or even oceanic in nature, at least in part.

Interpreted lithologies: Palaeozoic New England Fold Belt equivalents, Permo-Jurassic "Teremba unit" of New Caledonia, volcanics under the Central Rift Province and Capel Basin. Possibly oceanic in nature under the Middleton Basin and Dampier Ridge.

Syn-rift seismic sequences

Cenomanian – Campanian (Horizons 'U8' & 'U7')

Cenomanian–Campanian age strata are generally about 0.2 to ~0.5 s TWT thick, characterised by sub-parallel, low-amplitude reflections, and generally of low continuity. The lower part of the Cenomanian–Campanian age interval onlaps basement while Horizon 'U7' has been truncated by erosion (eg Plate 4, Line 206/04 SP 17000–18000).

As Cenomanian to Campanian age rocks have not been sampled on the Lord Howe Rise, these strata are dated by analogy with rocks from the Gippsland Basin and by reference to the Tasman Basin spreading history where an Early Campanian age for breakup has been proposed (Sayers, Bernardel et al., in press; Sayers et al., 2001). The Cenomanian-Campanian age interval comprises syn-rift fill in the grabens of the Western and Central rift provinces that onlaps underlying basement. The nature of the rift fill is inferred to be volcano-sedimentary in origin, in part overlying rhyolites (94 Ma) as identified in DSDP 207 (McDougall and van der Lingen, 1974). The syn-rift section completely covers the pre-rift section (eg Plates 4–5, Lines 206/02 SP 7000–13900 and 206/04 SP 22900–25500) in the southern part of the Western Rift Province. This is in contrast to the northern part of the western rift province (eg Plate 5, Line 206/01 SP 12800–14000) where the Cenomanian–Campanian age interval is mainly identified in the lows adjacent to basement blocks.

Interpreted lithologies: Eastern Australian seaboard Cretaceous-aged equivalents.

Post-rift seismic sequences

Campanian – Early Eocene (Horizons 'U7', 'U6' & 'U5')

The post-rift Campanian – Early Eocene age succession initially filled in the topographic lows during the Campanian but became more widespread by the Eocene, eventually onlapping the shallowest parts of the Lord Howe Platform. Within this sequence, a Maastrichtian unconformity ‘U6’ (Appendix 6), has been identified on some lines (eg Plate 5, Line 206/02 SP7000–10000). This Maastrichtian age correlates to the oldest age-date obtained from DSDP Site 208 (Plate 3). The seismic character of the oldest part of the Campanian–Maastrichtian age interval is more chaotic and downlaps the lower ‘U7’ boundary. The Campanian–Maastrichtian age interval shows an important variation of thickness forming the post-rift fill within the graben of the western part of the Lord Howe Rise (eg Plate 5, Line 204/02 SP7000–10000). This sequence is correlated to unit E of Willcox et al. (1981). Reflection continuity and amplitude increase in the Maastrichtian–Early Eocene age interval, which is correlated to sequence D of Willcox et al. (1980). Horizon ‘U5’ is a highly reflective erosional surface, often showing signs of compression, and it is the oldest most prominent and consistent unconformity throughout the region.

Interpreted lithologies: shallow marine silty claystone. The presence of Glauconite in the mid-Eocene sediment (DSDP Site 208) could indicate that the bathymetry is shallower than expected than in an otherwise presumed open marine environment (Fig. 8) and that the northern part of the Lord Howe Rise was uplifted.

Early Eocene–Oligocene (Horizons ‘U5’, b_1 *, ‘U4’)

The Early Eocene–Oligocene age succession is composed of subparallel, high-amplitude reflectors that are discordant with those of the underlying interval. This interval is disrupted by extensive small-scale faulting, which rarely penetrates the base of this interval. The interval is correlated with sequence C of Willcox et al. (1981). The Oligocene unconformity ‘U4’, at the top of this age succession, also marks a regional change in ocean circulation following the final stages of separation between Australia and Antarctica.

The planation of the Lord Howe Platform and of some of the western blocks has been confidently dated as upper Oligocene in age (DSDP Site 208). The Early Eocene Horizon ‘U5’ is a regional unconformity. It’s planated surface is due to a period of sub-aerial erosion, contemporaneous with deposition of the early part of the Early Eocene–Upper Oligocene age interval. Evidence of compression (eg Plate 4, Line 206/04 SP 16500–17500) are identified on the eastern flank of the Lord Howe Rise, where the Early Eocene–Oligocene age interval has been uplifted. We suggest that the effect of the compression exposed the Early Eocene–Oligocene age interval that was subsequently sub-aerially eroded.

Interpreted lithologies: foraminiferal-nannofossil ooze and chert.

Post-Oligocene (Horizons ‘U3’, ‘U2’, ‘U1’)

The lower part of the post-Oligocene interval is distinguished by parallel, high-amplitude reflections, while the amplitude decreases in the upper part of the interval. Faulting intensity also decreases in the younger part of the section. The post-

* b_1 is an additional horizon identified by S. Van de Beuque. It has been interpreted as Upper Eocene (see Appendix 6).

Oligocene interval ranges in thickness from 0.1–0.5 s TWT (*c.* 100–500 m), and usually thins on to the planated basement. Its thickness is more uniform then that of pre-Oligocene sequences reflecting a period of subsidence of the northern Lord Howe Rise. Uniformity in thickness also partly reflects increased uniformity of deposition of pelagic sediments in a deep-water environment. Within the lower part of this sequence, a persistent minor unconformity 'U2' of probable Mid-Miocene age has been interpreted on several lines.

Interpreted lithologies: foraminiferal-nannofossil ooze.

4.2 TASMAN BASIN

Seismic sequences in the Tasman Basin have been previously identified mainly from Survey 177 data. Seismic horizons have been tentatively tied (Stagg et al., 2002), via Lines 125/2 and 125/3 to DSDP Site 283 (Kennett, Houtz, Andrews et al., 1975) in the southwestern Tasman Sea. All post-breakup (ie post-Early Campanian) sequences equivalent to those on the Lord Howe Rise have been identified although their seismic characteristics in this area are different.

Oceanic basement (horizon 'trif')

Tasman Basin oceanic crust is very rugged, with up to 1.5 s TWT (*c.* 1500 m) of relief above base-level and is a highly reflective surface on reflection seismic data (Plate 4, Line 206/04 SP 31000–38000). 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 (Plate 4, Line 206/04 SP 31000–32000). These reflectors may be the product of very slow early seafloor spreading; alternatively, they may also be the expression of highly extended continental crust. The base of crust is generally not recorded although there are occasional hints of Moho reflections at about 10 s TWT (Plate 4, Line 206/04).

Interpreted lithologies: oceanic crust basalts.

Campanian – Late Eocene (horizons 'U7', 'U6', 'U5', 'b_1')

Most 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 or oldest oceanic crust, for example, adjacent to DSDP Site 283 (Stagg et al., 2002). Reflection seismic data shows low-amplitude, parallel reflectors of high continuity that have been folded and eroded in the Late Eocene (Plate 4, Line 206/04). The upper part of the sedimentary section contains numerous small-scale faults in places whilst evidence of folding and erosion is preserved only on the eastern edge of the Tasman Basin.

Interpreted lithologies: terrigenous silty clay.

Late Eocene – Oligocene (Horizons 'b_1', 'U4')

The late Eocene – Oligocene interval is characterised by sub-parallel low-amplitude reflections with significantly less faulting than in the underlying section. The

Oligocene unconformity ‘U4’ is onlapped by younger sediments in isolated depocentres. ‘U4’ is more concordant with the overlying sequence in other areas where both sequences drape over basement high blocks.

Interpreted lithologies: silty clay and diatom ooze.

Post-Oligocene (horizons ‘U3’, ‘U2’, ‘U1’)

The post-Oligocene interval is generally very thin, ranging from almost absent to about 0.6 s TWT and onlaps the basal Oligocene unconformity ‘U4’. The same interval is characterised seismically by transparent, low-amplitude reflectors and by highly continuous reflectors in the upper part of the sequence to more chaotic in the lower part of the sequence. The interval also shows evidence of deformation and /or uplift.

Interpreted lithologies: clay.

4.3 FAIRWAY BASIN

Basement (Horizon ‘fair’)

The basement is seismically diffuse with no strong single basement reflector present. The basement surface is rough with high blocks protruding up to 0.5 s TWT above base-level. The internal character is transparent. The minimum age for the basement, based on the age of the sedimentary cover, is interpreted to be pre-Lower Cretaceous or older.

Interpreted lithologies: The composition of the basement is unknown as no geological samples exist. The high positive gravity anomaly and the presence of a magnetic lineament within the basin as well as the flat topography of the basement observed on the seismic line could suggest that the basement is part oceanic in nature and / or heavily intruded and extended continental crust.

Pre-Cenomanian (Horizon ‘U9’)

The pre-Cenomanian sequence onlaps basement, is generally a very thin layer ranging up to about 0.4 s TWT in thickness and is presumed to be pre-Cenomanian in age. The interval shows little internal character whilst the upper boundary is truncated in places suggesting erosion.

Cenomanian – Campanian (Horizons ‘U8’, ‘U7’)

To the north, on the eastern part of the Fairway Basin, the depocentre for the Cenomanian–Campanian time interval is up to 0.7 s TWT thick (Plate 5, Line 206/01). The layer is characterised by sub-parallel, high-amplitude reflections. The lower horizon ‘U8’ is identified as an onlap surface while the upper horizon ‘U7’ is identified by a truncated surface indicating some degree of uplift. To the south, the seismic character is similar to that of the Cenomanian–Early Eocene time interval, preventing an unambiguous interpretation of the Cenomanian–Campanian time interval.

Campanian – Early Eocene (Horizons 'U7', 'U6', 'U5')

The depocenter for the Campanian–Early Eocene interval is located along the eastern margin of the Lord Howe Rise merging into the Fairway Basin. On seismic, the Maastrichtian horizon ('U6') shows evidence of uplift adjacent to the Lord Howe Rise and Fairway Ridge (Plate 5, line 206/01). Both the basal horizon ('U7') and upper horizon ('U5') are onlap surfaces although 'U5' is recognised regionally.

Early Eocene – Oligocene (Horizons 'U5', 'b_1', 'U4')

On seismic, the Early Eocene–Oligocene interval is characterised by sub-parallel, high-amplitude reflectors. However, in contrast to the Lord Howe Rise (Central & Western Rift Provinces), the Upper Eocene–Oligocene time interval, here, is contemporaneous with a period of erosion. The depocenters for the Early–Late Eocene and Late Eocene–Oligocene intervals shift, respectively, from west to east and also incorporate evidence of uplift. The thickness of the interval ranges up to 1.0 s TWT (*c.* 1000 and 1500 m).

Interpreted lithologies: nannofossil ooze, product of erosion of the northern part of Lord Howe Rise.

Oligocene – Middle Miocene (Horizons 'U4', 'a_1', 'U2')

The above interval ranges in thickness consistently from about 0.2 to 0.3 s TWT (*c.* 200–300 m). The interval is characterised seismically by sub-parallel reflectors.

Interpreted lithology: nannofossil ooze.

Middle Miocene – Recent (Horizons 'U2', 'a_1/yellow', 'U1')

The Mid-Miocene to Recent interval ranges in thickness from 0.2–0.3 s TWT (c. 200–250 m) and is characterised by fairly uniform, sub-parallel, medium-amplitude reflectors. The thickness of this unit is consistent and, for the most part pelagic in origin.

Interpreted lithologies: nannofossil ooze, chalk, volcanic ash.

4.4 FAIRWAY RIDGE

Basement (Horizon 'fair')

The basement protrudes up to 2 s TWT above the surrounding base-level and has little to no internal seismic character. The "Lansdowne Bank-Fairway Ridge" system is characterised by gravity and magnetic anomaly highs and confirm the oceanic nature of the ridge proposed by Ravenne et al. (1977) and Lapouille (1982).

Interpreted lithologies: unknown, possibly oceanic crust with some basic volcanics.

Pre-Oligocene (Horizons 'U9', 'U5')

The pre-Oligocene interval is greatly thinned over the Fairway Ridge compared to its thickness in the surrounding New Caledonia and Fairway Basins (Plates 4–5, Lines 206/01–04). Horizons are folded and have been deformed by volcanic intrusion (Plate 4, Line 206/04).

Oligocene-Recent (Horizons 'U4, 'U2', 'U1')

The thickness of the Oligocene-Recent interval is about 0.5 s TWT underlying the Fairway Ridge. This interval is characterised by a deformed Mid-Miocene reflector ('U2'). The regional unconformity of Oligocene age coalesces with the basement of the northern part of the Fairway Ridge. A period of subaerial exposure is inferred, due to the effect of compression on the Fairway Ridge.

4.5 NEW CALEDONIA BASIN

Basement (Horizon 'ncb')

The basement is relatively flat-lying, deepening to the north from 5 to 8 s TWT in places where the basement surface becomes more rugged. Apparent basement highs with relief of up to 1.0 s TWT are probably related to basement tectonics (Plates 4–5, Lines 206/01–04), possibly reactivated during a compressive phase (Lines 206/01, –/03, –/04). There is little to no internal seismic character within basement. The nature of the acoustic basement in the New Caledonia Basin, whether oceanic or continental in origin, cannot be differentiated.

Interpreted lithologies: unknown, possibly crystalline oceanic crust with some basic volcanics.

Pre-Early Eocene (Horizons 'U9', 'U7', 'U5')

The Late Cretaceous to Early Eocene interval onlaps basement and is characterised by complex internal structure with strong parallel reflectors concentrated in the upper part of the section. Reflections are weaker and more chaotic in the lower part of the section. There are distinct cut-and-fill structures in different parts of the section indicating erosion by deep currents and reworking of those sediments. The section ranges up to 2 s TWT in thickness. The entire time interval has been faulted and folded, mostly on the western side of the Caledonia Basin. The Early Eocene unconformity is the most prominent reflector in the basin and best represents evidence for a compressive phase (Appendix 6).

Interpreted lithologies: nannofossil ooze in Tertiary, unknown in pre-Tertiary sequences.

Early-Eocene – Oligocene (Horizons 'U5', 'b_1', 'U4')

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 ('U4') is not readily identifiable. The average thickness of the Early Eocene–Oligocene interval ranges from 0.5–1.0 s TWT (*c*. 500–1000 m) but can reach 2.0 s TWT (*c*. 2000m) in the northern New Caledonia Basin (Plate 5, Line 206/01).

Interpreted lithologies: radiolarian and nannofossil ooze.

Oligocene – Middle Miocene (Horizons 'U4', 'U2')

The mid-Miocene reflector 'U4' is discontinuous. The overlying Miocene and younger section onlaps onto Horizon 'b' on the western flank of the New Caledonia Basin but this section is significantly deformed and folded on the eastern flank. The Oligocene–Mid-Miocene interval is in the order of 0.5–1.0 s thick TWT.

Interpreted lithologies: nannofossil ooze.

Middle Miocene – Recent (Horizons 'a', 'wb')

The Mid-Miocene to recent interval ranges up to 0.4 s TWT in thickness (*c*. 400 m) and is characterised by higher frequency, higher continuity, sub-parallel reflectors.

Interpreted lithologies: nannofossil ooze, chalk, volcanic ash.

4.6 MAGMATIC FACIES

Volcanic units have been widely identified in the Lord Howe Rise region, both directly through sampling (Lord Howe Island, DSDP Site 207, dredging) and indirectly on seismic data. Volcanics were emplaced in a wide range of settings and range in age between the Late Jurassic/Early Cretaceous and the Pliocene.

Middle Jurassic – Mid Cretaceous (pre-rift and rift stages)

Volcanogenic sediments of mid-Jurassic age (~165 Ma) have been found on the mainland in the Surat and Maryborough Basins. Other volcanic rock units include: (1) the Whitsunday volcanics (120–100 Ma), (2) volcanogenic sediments of the Eumeralla Formation (Otway Basin), Otway Group (Bass Basin) and Strzelecki Group (Gippsland Basin) and (3) intrusives/extrusives in the Boobyalla (now Durroon) Sub-basin, northeast Tasmania and intrusions along the southeast coast. It is likely that equivalent age volcanics are present beneath the Lord Howe Rise. Evidence of volcanism include volcanogenic sediments, intrusives, extrusives, including the Cenomanian rhyolites intersected at DSDP Site 207. The presence of extrusives probably accounts for the frequently poor imaging of rift blocks in the central and western rifts of the Lord Howe Rise. Intrusives such as Triassic granodiorite and Jurassic calc-alkaline basalts have been sampled on the southern part of the Wanganella Ridge (lying parallel and to the east of the West Norfolk Ridge, Figure 2; Rigolot, 1989).

Interpreted lithologies: rhyolite and other acid to intermediate volcanics.

Cretaceous (continental breakup)

Breakup volcanics are widespread and include:

- interpreted basalt flows overlying highly extended continental crust beneath the eastern flank of the Tasman Basin (Plates 4–5);
- a possible seaward-dipping reflector sequence (SDRS) in the southern Lord Howe Rise area (Stagg et al., 2002); and
- extensive flows, intrusions and volcaniclastic sediments associated with the final stages of rifting and interpreted in the Central and Western Rifts (Willcox & Sayers, 2002).

Volcanism appears to have started in the Late Cretaceous prior to the formation of the Tasman Basin, and to have continued for some period after continental breakup, with volcanic sills being interpreted in post-breakup sedimentary layers that overlie oceanic crust in the southern Lord Howe Rise area (Stagg et al., 2002). It is reasonable to assume that similar volcanic facies are present in the northern Lord Howe area. Volcanics of different ages have been interpreted ('vcam' and 'vcen', Appendix 6) although the absence of well-control prevents substantiating their age.

Interpreted lithologies: basalt.

Eocene-Oligocene

DSDP Site 592, 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 buried 500 m-high volcanic shield (Nelson et al., 1986). These volcanicoclastics were emplaced rapidly at bathyal depths around the time of 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. Volcanic rocks of this age have not been confirmed as yet in the northern Lord Howe Rise area.

Interpreted lithologies: basalt.

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 (Fig. 2). These parallel, N–S-trending chains of seamounts extend from the northern end of the Lord Howe 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. A third, less well-developed chain appears to have been emplaced beneath the central rift of the 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), to small-scale pinnacles on the Lord Howe Rise, which may either be buried in the sedimentary section or protrude above the seabed. The volcanic events identified in the northern Lord Howe Rise area (Plate 5, line 206/01 sp 10000–11000) are associated with the post Oligocene subsidence of the area (Van de Beuque et al., 1998a).

The seismic horizon 'Vmio' has been used to identify volcanics of Miocene age in the Gower Basin (Willcox & Sayers, 2002) and volcanic features of a probable Tertiary age have been included in this category and interpreted for the northern LHR.

Interpreted lithologies: basalt.

Other Seismostratigraphic Units

A prominent bottom simulating reflector ('BSR') (Appendix 6) has been identified in the Fairway Basin (Plates 4–5). This BSR manifests as a moderate amplitude reflector that cuts across across sedimentary structures and sequences at an average depth of about 0.4 s TWT below the seafloor. The origins of BSR's and the implications for the resource potential of the Lord Howe Rise are discussed later in this report.

Other basement horizons such as 'lb', 'nht', 'nr' have been used and are included in Appendix 6. These horizons have not been described in this chapter as they lie east of the Lord Howe Rise. They are, however, represented in seismic sections (Plates 4–5).

5 - STRUCTURE AND SEDIMENT DISTRIBUTION

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 low-quality or sparse data (eg Jongsma & Mutter, 1978), or have concentrated on localised areas within the region where more detailed data sets were available (eg Bentz, 1974; Willcox et al., 1981; Zhu & Symonds, 1994; Herzer et al., 1997). The interpretation summarised in this report and in Stagg et al. (2002) represents the first analysis of the regional structure based on the more modern 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 (Fig. 2, Plate 1). These tectonic provinces have been compiled from interpretation of the seismic (eg. Fig. 9), bathymetric and satellite gravity data. They include the Lord Howe Rise, Challenger Plateau and Bellona Trough, Tasman Basin, New Caledonia Basin, Norfolk and West Norfolk Ridge and Reinga Basin (Fig. 2, Plate 4).

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

5.1 LORD HOWE RISE

Jongsma and Mutter (1978) divided the Lord Howe Rise into an eastern 'stable platform', and a western 'rift zone', and interpreted the Lord Howe Rise and Australia as having separated through 'non-axial breaching' of the Tasman Sea.

In this study, the Lord Howe Rise is 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 and 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 Lord Howe Rise is largely determined by the locations of the major fracture zones in the Tasman Sea.

From east to west, we divide the Lord Howe Rise 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 transitional and difficult to define. 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 constructed by Bradley (1993).

Lord Howe Platform

The Lord Howe Platform 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 20°S, in the north, a distance of at least 1900 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 the Gower Basin (Fig. 2).

The internal seismic character of the basement ranges from transparent to low-amplitude reflections showing extensive layering and structuring, suggesting that it comprises in part of Palaeozoic fold belt sediments and meta-sediments, correlating with either New England or Lachlan Fold Belt rocks of eastern Australia. DSDP Site 207, in the southern Lord Howe Rise area, 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 seismically 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 and 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 rifting.

The margins of the platform are structurally distinctive. The eastern flank is marked by a 40–50 km-wide zone of major faults that are downthrown into the New Caledonia Basin. Throws on the faults are up to 4 km and, while most of the faulting is extensional, there is evidence of strong reversal indicating localised compression (Plates 4–5). 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 steep basement hinge and a flanking half-graben, which is faulted on its western margin. 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 Cainozoic. This half-graben 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 (Stagg et al., 2002).

Central and Western Rift Provinces

The Central and Western Rift Provinces lie to the west of the Lord Howe Platform. The boundary between the two provinces is not always obvious so that the division is also based on the relative level in TWT of the basement. This division into two parallel rift provinces, which are also sub-parallel to the Lord Howe Platform can be mapped along much of the length of the Lord Howe Rise.

The Central Rift underlies the western half of the bathymetric culmination of the Lord Howe Rise and is approximately 150 km in width. It is separated from the Planated Basement Province 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 by about 2s TWT (*c*. 3 km) to the west.

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, which is about 1 s (1−1.5 km) deeper than beneath the planated basement to the east, indicating greater crustal thinning beneath the Central Rift. This is supported by the gravity modelling of Zhu and Symonds (1994), who show a crustal thickness of about 20 km in this zone, and refraction station N16 of Shor et al. (1971) that gave a crustal thickness of 18 km beneath the northern Lord Howe Rise (Appendix 3).

Within the Central Rift, the tops of the basement blocks are typically poorly-defined, even where the overlying sedimentary cover is relatively thin. We speculate 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 sedimentary section overlying basement at Site 208 comprises 106 m of siliceous fossil-bearing nannofossil chalk ranging from Late Cretaceous to Mid-Eocene, overlain by Late Oligocene to late Pleistocene foraminiferal-nannofossil ooze (chalk) extending to 488 m (Burns, Andrews et al., 1973). Some level of glauconite have been identified in the mid-Eocene section. The major hiatus in the Oligocene traced in wells and seismic data throughout the Lord Howe Rise region could then be explained in the northern Lord Howe Rise as an uplift of this section of the ridge starting during the mid-Eocene.

The sequences overlying the basement of the central rift are made of: (1) Cretaceous sequences corresponding to the break up period and the first post-breakup section, (2) the very thin Lower Eocene/Oligocene section (less than 0.05 s TWT) and (3) the post-Oligocene section which is ubiquitous across the Lord Howe Rise, and thickens westwards into the central rift province and eastwards into the New Caledonia Basin.

The Western Rift Province is principally identified beneath the Capel Basin. Strongly faulted and intruded basement lies at depths of 5s TWT (*c*. 5−6 km), approximately

3 km deeper than in the central Rift, suggesting even greater crustal thinning than beneath the Central Rift and Eastern Planated Basement. This is again supported by the gravity modelling of Zhu and Symonds (1994) where a crustal thickness of slightly less than 20 km on Line 114/4 is interpreted (southern Lord Howe Rise area).

The western flank of the Capel Basin is structurally high, forming the bathymetric Monawai Spur. Basement beneath the outer margin is typically 1−1.5 s TWT (*c.* 1−2 km) shallower than the basement beneath the basin. The Monawai Basin and its outer high, in the southern Lord Howe Rise area, may be a correlative of the Lord Howe and Middleton Basins and their outer high, the Dampier Ridge in the northern Lord Howe Rise area. In this interpretation, extension in the Lord Howe and Middleton Basins proceeded much further than it did in the Monawai Basin, with the posssible (though unlikely) emplacement of some oceanic crust in the northern basins. If this correlation is valid, then it follows that pre-breakup extension and perhaps the earliest Tasman Basin spreading were concentrated between the Dampier Ridge and Lord Howe Rise in the north and west of the 'Dampier Ridge' (ie the Monawai Spur) in the south. The location of this jump in the focus 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 Capel Basin are not very distinct on seismic; possibly due to the presence of extensive volcanics within the sedimentary fill and incorporated into the blocks prior to the onset of rifting. The emplacement of volcanic rocks appears to have been a major factor in the development of the margin.

5.2 TASMAN BASIN

A number of high-quality seismic lines available to this study provide the first good images of the crust and sedimentary fill of the Tasman Basin. These lines include line 206/04 in the northern Lord Howe area and a single high-speed seismic line recorded during a joint Australian-French swath-mapping survey by the *vessel L'Atalante*, located in the southern Lord Howe area. Line 206/04 ties from the North Island of New Zealand, across the New Caledonia Basin, northernmost Challenger Plateau, Bellona Trough and Tasman Basin, to DSDP Site 283 and the South Tasman Rise. While the data are only of fair quality, they provide a valuable trans-Tasman tie to the DSDP site.

DSDP Site 283, in the southwest Tasman Sea, was drilled west of the extinct spreading ridge on crust slightly younger than about anomaly 31 (*c.* 68 Ma) in the interpretation of Gaina et al. (1998). Note that, in the DSDP initial report (Kennett, Houtz, Andrews et al., 1975), the site was interpreted to be located at anomaly 32, corresponding to about 71 Ma. Basement was directly overlain by earliest Paleocene silty claystone that is several million years younger than the basement (Kennett, Houtz, Andrews et al., 1975). 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 misidentification of weak magnetic anomalies. However, the seismic data recorded by the vessel *L'Atalante* clearly image the top of oceanic basement, show that Site 283 was drilled on a terrace of shallow basement (Stagg et al., 2002). 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.

The sedimentary section at Site 283 comprises Paleocene silty clay and silty claystone, Middle Eocene silty clay, Late Eocene silty diatom ooze, and Miocene to Pleistocene zeolitic clays (Kennett, Houtz, Andrews et al., 1975). The regional Oligocene unconformity is very marked in Site 283; however, the very thin post-Oligocene unconformity sediments are difficult to identify in conventional seismic data.

Analysis of sonobuoy refraction records from the vicinity of DSDP Site 283 by Kenneth, Houtz, Andrews et al. (1975) reveals a somewhat unusual velocity structure for oceanic crust, with a 'typical' oceanic layer three 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 gave a low velocity of 6.2 $km.s^{-1}$. While there is no obvious reason for these anomalous crustal velocities, we do note that the stations were located between and adjacent to the major Cascade and Bellona Fracture Zones that offset oceanic crust laterally by 100 and 200 km, respectively. It is possible, therefore, 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 in Appendix 3; Plate 1). Again, a 'normal' oceanic layer 3 is absent; instead 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 (*c*. 5–7 km). The unusually rugged surface of the basement appears to have three causes: (1) the original oceanic crust emplacement process, (2) the presence of many rugged fracture zones, subsequent magmatic intrusions and extrusions, and (3) 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 (Stagg et al., 2002), 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., 1999). Previous interpretations of such structuring have generally ascribed them to structural deformation in a setting of low magma supply (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 Province of the Lord Howe Rise is frequently ill-defined, and is possibly a zone of mixed oceanic (or magmatic) and continental crust, in a similar style to the northwestern margin of the Exmouth Plateau.

The sedimentary fill of the eastern Tasman Basin is interpreted, as at DSDP Site 283 to comprise of thick sequences of Paleocene to Early Eocene and mid- 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 evolution of the Tasman Basin.

5.3 FAIRWAY BASIN AND FAIRWAY RIDGE

The Fairway Basin and Fairway Ridge link the northern Lord Howe Platform to the northern New Caledonia Basin.

Shor et al. (1971) estimate a 15 km thickness of the crust beneath the Fairway Basin, which indicates a semi-oceanic origin. The nature of the basement of the Fairway Basin and Ridge is supposed to be of volcanic and/or oceanic nature (Ravenne et al., 1977). The succession of positive and negative magnetic anomalies and of a positive gravity anomaly on both the basin and the ridge emphasizes a probable oceanic origin (Van de Beuque et al., 1998b; Van de Beuque, 1999).

The stratigraphic interpretation is based on the tie of Line 206/02 with DSDP Site 208 (Burns, Andrews et al., 1973; Fig. 7). The sedimentary fill of the Fairway Basin is interpreted to comprise a thick sedimentary cover from Lower Cretaceous to Recent. The deformation of the pre-Oligocene section and the lateral variation of the depocentre reinforces the strong effect of uplift by compression on both the Lord Howe Rise to the west, and the Fairway Ridge to the east. This uplift is correlated with a regional compression event that affected the northern part of the Southwest Pacific during Eocene–Oligocene time.

The sedimentary cover over the Fairway Ridge thickens from 0.2 s TWT (*c*. 500m) in the north, to 0.5 s TWT in the south. The main characteristic of the sedimentary cover is that the northern part the sedimentay cover is dominently post-Oligocene in age and directly overlies the basement under the Fairway Ridge. Southward, older Eocene sediments are interpreted to directly overlie basement.

5.4 NEW CALEDONIA BASIN

Aspects of the geology of the New Caledonia Basin have been interpreted to varying degrees 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 and 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 and three dip lines across the basin (206/01, 206/03 and 206/04; Plates 4–5).

Wainui-1, in the Taranaki Basin, 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 very southern New Caledonia Basin. DSDP Site 206 is located on the flank of an apparent major basement high some 1000 km northwest 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 probably due to massive slumping of Cretaceous/Cainozoic sediments, which have 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 (Figs. 2 & 6):

- the ***northern sector*** that 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 the island of New Caledonia (Fig. 2). The average width of the deepest part of the basin is about 130 km.

- the ***central sector*** that extends from the NW–SE-trending Vening-Gifford-Cato Lineament in the south to the NE–SW-trending Barcoo-Elizabeth-Fairway Lineament (also defined later in this section) in the north. The central sector trends north–south and has an average width of about 250 km (red colored lineament in Fig. 2); and

- a ***southern sector*** that extends from the northern margin of New Zealand to about 30–31°S, where it is terminated by the NW–SE-trending Vening-Gifford-Cato Lineament (Stagg et al., 2002). 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 Fig. 2);

This report covers the central and northern sectors.

5.5 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. These lineaments are aligned along two principal trends: (1) NE–SW-trending, related to Cretaceous-early Cainozoic Tasman Sea spreading; and (2) NW–SE-trending, related to the collision between the Australian and Pacific Plates in the late Cainozoic. The NE–SW-trending lineaments are the more important in the structural segmentation of the Lord Howe Rise, and will be described in some detail here.

The Tasman Sea, Lord Howe Rise and the northern New Caledonia Basin appear to be latitudinally segmented by a series of NE–SW-trending crustal-scale lineaments (Fig. 2). This was also confirmed at a local scale in the Gower Basin (Willcox & Sayers, 2002). From south to north we identify the following segments within the northern province:

- Middleton Segment – bounded by the Barcoo-Elizabeth-Fairway Lineament to the south and the Brittania Fracture Zone to the north (BEFL; Stagg et al., 1999).; and

- Nova Segment – bounded by the Brittania Fracture Zone to the south and the Cato Fracture Zone and Cato trough to the north.

The most important of these boundaries is between the central and northern provinces, the Barcoo-Elizabeth-Fairway Lineament. This major crustal lineament has significant gravity expression 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 eastern planated basement, 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, along which they interpret 260 km of left-lateral strike slip motion from the onset of extension until about 63 Ma, corresponds to our less prominent boundary between the Monawai and Gower Segments and the southwards termination of the Dampier Ridge (Fig. 2). In the current study, there is no seismic evidence of a major crustal boundary on the main part of the Lord Howe Rise that would separate the central and northern blocks as suggested by Gaina et al. (1998); and

- 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).

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) (Table 3). 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 3: 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*
?Jurassic – earliest Cretaceous	Initial crustal extension & commencement of syn-rift deposition.	Both syn-rift volcanics & sediments probable.
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 -	Collision along northern	Eocene-Oligocene

Oligocene (55-38 Ma)	Australian margin. New Caledonia basin - ophiolite obduction in Late Eocene.	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 PHASE

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, and southeast South Australia;
- 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-Gunnedah-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 has yet to be found. 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 the 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:

- 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 'seaward dipping reflector surfaces' (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 (Veevers, 2000; Sdrolias et al., 2001). 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 (Aitchison et al., 1995).

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 (now Durroon) 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 (see for example, Sdrolias et al., 2001). 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 (see for example Sdrolias et al., 2001).

7 - RESOURCE POTENTIAL

7.1 ANALOGUE BASINS

Willcox et al. (1980) undertook a regional assessment of the hydrocarbon prospectivity of the Lord Howe Rise. This assessment was revised and updated by Symonds and Willcox (1989) and Symonds and Willcox (1993) who assessed the hydrocarbon prospectivity of areas beyond the EEZ. As no petroleum exploration has taken place in the 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).

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 has 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. (1998) 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 sediments of the Latrobe Group contain the main hydrocarbon-bearing units within the basin (PESA, 2002). The main source is within the continental fine-grained sediments of the Late Cretaceous and the prime reservoir units occur within 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 a marl of Oligocene age. 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 Miocene.

7.2 REGIONAL HEAT-FLOW

Heat-flow data are sparse in the Lord Howe Rise region. The data (Appendix 5, Plate 2) are derived from surficial sediment thermal gradient measurements published by Grim (1969), 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 are only a few measurements in such a large area.

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. Four measurements in the northern sector of the Tasman Sea range from 44 to 54 $mW.m^{-2}$, slightly less than the world-wide average of about 60 $mW.m^{-2}$, but somewhat higher than 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 from 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 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 although, only one lies in the northern Lord Howe Rise area. 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 (southern project area) 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 some 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. The stations with high heat-flows lie south of Lord Howe Island, where volcanism has been dated at 6.4–6.9 Ma (McDougall & Duncan, 1988).

A geohistory analysis of selected areas in the LHR region has recently been undertaken for Geoscience Australia by Burytech Pty Ltd (Bradshaw et al., in prep.). The geohistory modelling indicates that it is possible to generate and expel hydrocarbons in the deeper parts of the Gower Basin and from the deeper units in the northern New Caledonia Basin. The shallower New Caledonia Basin site did not attain high enough temperatures to expel oil, though some generation may have taken place in the late Tertiary.

7.3 GOWER BASIN

A brief outline of the petroleum prospectivity of the Gower Basin is given by Willcox and Sayers (2002). Seismic plates are available in Willcox and Sayers (2002), which show the architecture of the basin and the variety of petroleum traps.

7.4 FAIRWAY BASIN

Petroleum potential on the eastern side of the Lord Howe Platform has been known since the early 1970s. The region including the northern extent of the Lord Howe Platform, Chesterfield Plateau, Fairway Basin and Ridge, have been surveyed extensively with reflection seismic data (Mobil Oil Coorporation, Austradec, WNC). The recent discovery of BSRs (Exon et al., 1998) and the existance of a mud / salt layer (Auzende et al., 2000a & 2000b) have renewed an interest in the region, both scientifically and for petroleum exploration. The eastern side of the Lord Howe Platform that includes the Fairway Basin corresponds to the ancient continental margin of Gondwana (Willcox et al., 1980, 1981; Auzende et al., 2000a & 2000b) and, thus, forms part of a passive margin setting. The following sub-sections on prospectivity are only generalised comments as more data will need to be acquired to more precisely to understand the petroleum systems in the area.

Source, reservoir and seal

A considerable thickness of clastic sediments of Cretaceous age (in excess of 2000 m) were deposited on the eastern side of the Lord Howe Platform and in the Fairway Basin. These same clastic sediments also include the recently discovered salt/mud deposits. The depositional setting suggests that it was conducive to preserving Cretaceous-aged sediments although further work will need to be done.

Source rock maturity

Clay-rich sediments of Maastrichtian age (DSDP Site 207; Burns, Andrews et al., 1973) cap the horst blocks on the eastern side of the Lord Howe Platform. These sediments are probably rich in organic content but the 1000 meters or so of overlying sediment are too thin to cause generation within the Maastrichtian sediments (Stagg et al., 2002). In contrast, the thickness of post-Cretaceous sediments in the Fairway Basin is enough to cause generation from Cretaceous-aged clastic sediments.

Recent satelite images using synthetic aperture radar (SAR) have indicated third order slicks at the sea surface on the eastern side of the Lord Howe Platform and in the southern Fairway Basin (Fig. 10). These third order slicks in combination with recently discovered gas hydrates (Exon et al., 1998; Auzende et al., 2000a & 2000b) represent indirect indicators of hydrocarbon potential. It is also interesting to note the coincidence of the distribution of ‘bottom simulating reflectors’ (BSRs) with the extent of the salt-mud layers (Figs 11–12).

Petroleum plays and traps

Generation of hydrocarbons and the presence of structural traps on the eastern side of the Lord Howe Platform have been greatly enhanced by the presence of extensional

Mesozoic faults and Cenozoic compressional faults (Eade, 1988; Lafoy et al., 1994; Van de Beuque et al., 1998a). Stratigraphic traps could be present where sediments onlap the main Lord Howe Platform basement. These reservoirs are probably overlain by Cenozoic-aged pelagic sediments, possibly acting as a seal.

7.5 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 (Plate 3) 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. The New Caledonia Basin 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 with potential reservoirs present. As noted 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 that may have provided a suitable regional seal.

Source rock maturity

Recently acquired high-quality seismic data and ‘satellite synthetic aperture radar’ (SAR) imagery indicate possible hydrocarbon generation in the Fairway and New Caledonia Basins in the north (Fig. 10). Bottom simulating reflectors (BSRs) observed in seismic reflection data under the Fairway and New Caledonia Basins (Fig. 12) 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 (Fig. 12). Also, in this area, some evidence for low-level third-order 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.

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, although in very deep water (*c*. 3000 m).

7.6 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 km² 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. Figure 11 shows a BSR at a depth of 520–600 m below the sea-bed, a depth consistent with the expected thermal gradient for the region. It overlies diapiric structures emanating from a mobile layer of probable Early Cretaceous age. The variable morphology and deformation of the adjacent sediments suggest a 'salt' origin. The BSR is, in places, deformed above the diapirs, which could indicate migration of salt and/or hot fluids. A further BSR has also been identified on the western flank of the northern Lord Howe Rise, where it descends into the Middleton Basin, and another in the northern part of the Monawai Basin (Plates 4–5).

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 the Discussion section of this report.

7.7 SUMMARY

The most prospective areas are the central rift province of Lord Howe Rise (Gower Basin), the eastern flank of Lord Howe Rise, (Fairway Basin), and possibly in the New Caledonia Basin itself, where the sediment thickness reaches 3.5 s TWT (*c.* 4+ km). Less prospective basins include those of the central rift province (Faust Basin) and western rift province (Capel & Middleton Basins) where sediment thickness is low.

Despite the lack of wells and other rock samples in the northern Lord Howe Rise area, 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-graben on the western Lord Howe Rise, and in the New Caledonia Basin. 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, interpreted in the form of methane hydrates at several locations, cannot currently be exploited, their interpreted presence suggests that thermogenic hydrocarbons are currently being generated. This substantially upgrades the hydrocarbon prospectivity of the region.

7.8 MINERALS

At present, very little is known about the non-petroleum mineral resource potential of the Lord Howe Rise region. Symonds and Colwell (1992) have reported sampling results from a survey by the BGR research vessel Sonne (Roeser & Shipboard Party, 1985). On this survey, dredging on a major NW–SE-trending structural lineament about 250 km northeast of Lord Howe Island recovered Mn/Fe nodules containing pebbles of sandstone, quartzite, coralline and possible algal limestone, phyllite and granite (Appendix 4). 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).

8 – OBSERVATIONS AND UNRESOLVED GEOLOGICAL ISSUES

8.1 GEOMETRY OF POST-BREAKUP CONTINENTAL FRAGMENTS

The continental fragments that separated from eastern Australia during Tasman Basin spreading exhibit a largely consistent structural style throughout their north-south extent. Lord Howe Rise/Dampier Ridge, New Caledonia Basin and the Norfolk Ridge system comprise sub-parallel elongate fragments of continental or possibly hybrid crust that are narrow and are consistent in 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? Maps of the present-day structural entities of eastern Australia (eg Scheibner & Basden, 1996, Fig. 3.1), show a general north-south orientation of the fold-belts and sedimentary basins, though these are not as clearly defined as in the Lord Howe Rise region. Thus, it seems likely that the post-breakup configuration of continental fragments is a function of the geometry of accretion in eastern Australia during the Palaeozoic and Mesozoic, probably enhanced by overprinting of the 'Tasman' rift geometries..

8.2 IMPORTANCE OF NE-SW AND NW-SE CRUSTAL-SCALE LINEAMENTS

Satellite gravity data, in conjunction with 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 (Fig. 2) 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 NW–SE-trending crustal lineaments are similarly prominent, particularly in the eastern part of the study area. The Vening Meinesz Fracture Zone (VMFZ) is a very strong lineament, which has produced much of the present-day physiography at the southern edge of the Norfolk Ridge system. While NW–SE-trending lineaments have had less effect on the structuring of the Lord Howe Rise, there are suggestions in the satellite gravity, predicted bathymetry and 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 and 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 THE NATURE OF THE CRUST BENEATH THE LORD HOWE, MIDDLETON AND NEW CALEDONIA BASINS

The New Caledonia Basin and possibly also the Lord Howe and Middleton Basins could be interpreted to have formed through the emplacement of 'normal' oceanic crust. While we have not presented a detailed 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 features.

However, interpretation of the crustal type in the New Caledonia Basin is still equivocal. As noted previously in this report, reflection and refraction seismic data as well as 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.

8.4 SPATIAL AND TEMPORAL DISTRIBUTION OF VOLCANIC ROCKS

As has been noted previously in this report, volcanism is both temporally and spatially wide-ranging and has been an important factor in the development of the Lord Howe Rise region. 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 hydrocarbon prospectivity. We outline below the most important volcanic phases.

Early to mid-Cretaceous (*c.* 120–95 Ma)

From the Barremian to Cenomanian, the Otway, Bass and Gippsland basins in southeast Australia were filled 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 (Johnson & Veevers, 1984). 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 the 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 within acoustic basement or at 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 deposition of prospective sequences.

Late Cretaceous (*c.* 85–80 Ma)

While volcanics associated with breakup have not been sampled, their presence is inferred to be widespread based on seismic data. These volcanics include an interpreted Seaward-Dipping Reflector Sequence in the Monawai Basin to the south; 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.

Eocene – Oligocene (37–36 Ma)

Basaltic volcanics were emplaced rapidly at bathyal depths sometime during the Eocene to Oligocene period. 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 the Lord Howe Rise and the Challenger Plateau. Their impact on heat-flow and the quality of potential hydrocarbon reservoirs is likely to be relatively minor. Very little is known about this phase of volcanism in the northern Lord Howe Rise area.

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 Chain, which extend in excess of 1000 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 the 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 pinacles at the sea floor.

The Miocene volcanics also form part of volcanic edifaces on the Lord Howe Island and in the Gower Basin (Willcox & Sayers, 2002). 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. It is likely that the major impact on the hydrocarbon potential was a late heat-flow pulse associated with their emplacement.

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:

- degradation of reservoirs;

- degradation of existing hydrocarbon accumulations;
- provision of a late heat-flow pulse, in the case of the Miocene volcanics, possibly enhancing maturation which would otherwise be marginal in view of the general thickness of the overburden;
- extrusions and shallow intrusions can provide a seal, such as in the Kipper Field in the Gippsland Basin.

8.5 GAS HYDRATES

Anomalous seismic reflectors that intersect bedding reflectors and mimic the seafloor topography may indicate the presence of natural gas hydrates in continental margin sediment. The position of the reflector coincides with the transition boundary at the base of the gas hydrate zone. Bottom simulating reflectors (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 that was observed on line 114/09, to the south (Stagg et al., 2002). 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. 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 in various parts of the world 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, 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 regimes 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: Structures I and 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 continental 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, 1986), possibly favouring a deeper source and 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 some evidence for hydrocarbon seepage in the form of third order anomalies. Also, SAR anomalies interpreted as natural oil films occur over the eastern Lord Howe Rise. In association, seismic evidence for fluid migration has also been detected and together these data provide some evidence for the presence of hydrocarbon leakage.

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 indicate 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.

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 exploitation of 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, although 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. Not withstanding 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.

INFORMAL TERMS RELATING TO ARTICLE 76

Application of Article 76 of UNCLOS raises several concepts and terms, which will be referred to frequently in interpretations of seismic / bathymetric survey lines for the purposes of LCS definition. Following are simplified definitions of the more important terms that we commonly use.

Firstly, a *Hedberg arc* may be drawn, with a radius of 60 n miles, from an interpreted FoS position. Where this arc intersects the seaward extension of the survey line is called the *Hedberg point.* With a series of FoS positions established around a continental margin, at a spacing of less than 120 n miles, a series of intersecting Hedberg arcs may then be constructed. Clearly, as the spacing between survey lines (and therefore, the FoS positions) decreases, the envelope of the intersecting Hedberg arcs approaches a 60 n mile buffered locus of the FoS, except in some cases where the latter contains embayments. This is part of the reason for Geoscience Australia's 'safe minimum' approach, where we aim to space survey lines ~30 n mile apart, where logistically possible. The final outcome, the true *Hedberg Line* (the informal name for the line that defines the outer edge of the 'legal' continental margin, as contained in Article 76, paragraph 4(a)(ii)), is constructed by joining selected points on the Hedberg arcs by straight lines, not more than 60 n mile long. This would normally be done in a manner such as to maximise the size of the enclosed 'legal' continental margin. This true Hedberg Line will normally only intersect the survey line at the Hedberg point where the locus of the FoS is a straight line, which is unusual in the context of LCS, since it is normally generated by irregularly shaped marginal plateaus.

Secondly, a *Sediment Thickness point* may be determined, by interpretation of a seismic survey line (or possibly by drilling), where the 1% sediment thickness criterion is satisfied. In contrast to the Hedberg arc, this is strictly a single point, which may be joined to adjacent Sediment Thickness points to form the *Sediment Thickness Line* (the informal name for the line that defines the outer edge of the 'legal' continental margin, as contained in Article 76, paragraph 4(a)(i)), or to selected points on Hedberg arcs, again by straight lines, not more than 60 n mile in length.

Finally, the fixed points (not more than 60 n mile apart) comprising the line which defines the outer limits of the LCS, may not lie beyond one or other of two cut-offs. The first cut-off is 350 n mile from the baseline (informally called the *350 n mile cut-off line*), and the second is 100 n mile beyond the 2500 m isobath (informally called the *isobath cut-off line*). The former is purely a geometrical construction from the Territorial Sea baselines, whereas the latter depends on definition of the 2500 m isobath.

APPENDIX 2: DETAILS OF SEISMIC SURVEYS

Survey	*12, 13, 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	Sonne 7A
Contractor	BGR / BMR
Vessel	*Sonne*
Year	1978
Streamer length (m)	2400
Seismic channels	24
Sample rate / rec. length (ms)	No information
Group length / interval (m)	No information
Shot interval (m)	No information
Recording fold	24
Cable depth (m)	No information
Source type / power or volume	No information
Nominal vessel speed (kn)	No information
Primary navigation	Transit Satnav + sonar doppler
Secondary navigation	No information
Tertiary navigation	No information
Primary echo-sounder	No information
Secondary echo-sounder	No information
Magnetic data	yes
Gravity data	yes

Survey	Sonne 36A
Contractor	BGR / BMR
Vessel	*Sonne*
Year	1985
Streamer length (m)	2400
Seismic channels	24
Sample rate / rec. length (ms)	No information
Group length / interval (m)	No information
Shot interval (m)	No information
Recording fold	24
Cable depth (m)	No information
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	No information
Primary echo-sounder	No information
Secondary echo-sounder	No information
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, called FAUST1 by French
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

PART 1: SONOBUOY LOCATIONS

Station	Latitude	Longitude	Water depth (m)	Reference
N1	-22.483333	168.250000	~ 2000	Shor et al. (1971)
N2	-21.650000	168.500000	~ 2000	Shor et al. (1971)
N7	-24.300000	167.433333	~ 1000	Shor et al. (1971)
N8	-23.150000	167.250000	~ 1000	Shor et al. (1971)
N9	-23.516667	165.633333	~ 3000	Shor et al. (1971)
N10	-23.000000	164.950000	~ 3000	Shor et al. (1971)
N11	-24.066667	161.883333	~ 1000	Shor et al. (1971)
N12	-27.100000	155.866667	> 4000	Shor et al. (1971)
N13	-27.783333	156.100000	> 4000	Shor et al. (1971)
N14	-27.666667	158.900000	~ 3000	Shor et al. (1971)
N15	-28.400000	159.250000	~ 3000	Shor et al. (1971)
N16	-28.250000	161.533333	~ 2000	Shor et al. (1971)
N17	-28.416667	163.183333	~ 2000	Shor et al. (1971)
N18	-27.883333	166.083333	> 3000	Shor et al. (1971)
N19	-26.933333	166.166667	~ 3000	Shor et al. (1971)
N20	-27.150000	167.333333	< 1000	Shor et al. (1971)
N21	-26.683333	167.616667	~ 1000	Shor et al. (1971)
N22	-26.966667	168.183333	~ 3000	Shor et al. (1971)
N23	-27.616667	169.000000	~ 3000	Shor et al. (1971)
SO7-XIII	-26.2463	161.3383	1690	Willcox et al. (1981)
SO7-XIV	-29.2616	160.4001	1630	Willcox et al. (1981)
PF108	-34.3910	150.3169	onshore	Collins (1988)
PF109	-32.8438	150.8146	onshore	Collins (1988)
PF110	-34.7598	149.4407	onshore	Collins (1988)
PD002	-30.3854	133.3317	onshore	Collins (1988)
PD004	traverse	traverse	onshore	Collins (1988)
PMU02	traverse	traverse	onshore	Collins (1988)
PPI01	-34.890	149.720	onshore	Collins (1988)
177-au9	-26.305497	167.175425	~ 1000	Ramsay et al. (1997)
177-au11	-26.385144	166.479756	~ 3000	Ramsay et al. (1997)
177-au12	-26.579013	164.788380	~ 3000	Ramsay et al. (1997)
177-au13	-26.875800	162.196128	~ 2000	Ramsay et al. (1997)

Note 1: Stations PF108 to 110, PD002, PD004, PMU02, PPI01 are onshore refraction stations.

PART 2: VELOCITY ANALYSES

SO7-XIII

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	1.69	2.25
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
2.27	3.17	3.53
2.49	3.17	3.53

PFI08

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.80	0	0
5.85	5.00	1.72
6.10	7.00	2.39
6.12	11.00	3.70
6.10	13.50	4.52
6.50	15.00	5.00
6.80	25.00	8.01
7.00	34.50	10.76
7.80	39.00	11.98
8.12	41.50	12.61
8.14	60.00	17.16

PFI09

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
4.70	0.00	0
4.90	2.00	0.83
5.75	3.20	1.28
5.90	6.50	2.41
6.35	8.00	2.90
6.37	11.00	3.84
6.36	17.00	5.73
7.00	20.00	6.63
7.02	22.00	7.2
6.70	23.00	7.49
6.72	27.00	8.68
7.18	32.00	10.12
7.70	41.00	12.54
8.04	43.50	13.18
8.05	60.00	17.28

PFI10

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.60	0.0	0
5.75	2.00	0.70
5.80	2.50	0.87
5.95	3.30	1.14
5.96	5.50	1.88
5.80	7.00	2.39
6.00	14.50	4.93
6.30	16.00	5.42
6.60	26.50	8.68
6.80	28.00	9.13
7.10	33.00	10.57
7.20	40.00	12.53
7.60	42.50	13.21
7.95	43.00	13.34
7.97	50.00	15.10
7.60	52.00	15.61
7.62	60.00	17.71
8.00	63.00	18.48
8.02	70.00	20.23

PD002

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
4.90	0.00	0
4.90	5.50	0.33
6.04	5.50	0.33
6.04	6.60	0.68
6.52	6.60	0.68
6.52	24.60	13.06
7.86	24.60	13.06
7.86	30.00	15.44

PD004

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

PMU02

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
6.15	0.00	0
6.15	20.00	6.5
6.75	20.00	6.5
6.75	35.00	10.94
7.98	35.00	10.94
7.98	100.00	27.23
8.36	100.00	27.23
8.36	120.00	32.01
8.23	120.00	32.01
8.23	190.00	49.02
8.72	190.00	49.02
8.72	225.00	57.05

PPI01

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
5.60	0.00	0
5.60	3.40	1.21
6.40	3.40	1.21
6.40	4.30	1.49
6.62	4.30	1.49
6.62	13.30	4.21
7.15	13.30	4.21
7.15	23.40	7.04
6.98	27.00	8.06
7.38	34.10	10.04
7.38	41.40	12.02
7.40	42.00	12.19

N1

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

N2

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	2.20	2.93
2.15	2.20	2.93
2.15	3.22	3,88
3.48	3.22	3.88
3.48	5.42	5.14
5.16	5.42	5.14
5.16	9.02	6.54
5.95	9.02	6.54
5.95	14.62	8.42
6.92	14.62	8.42
6.92	20.10	10.00
8.04	20.10	10.00

N7

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

N8

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

N9

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	3.60	4.8
2.15	3.60	4.8
2.15	4.72	5.84
3.20	4.72	5.84
3.20	6.22	6.78
4.95	6.22	6.78
4.95	7.82	7.43
6.02	7.82	7.43
6.02	9.12	7.86
6.83	9.12	7.86
6.83	12.82	8.94
8.11	12.82	8.94

N10

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	3.62	4.83
2.15	3.62	4.83
2.15	4.72	5.85
3.20	4.72	5.85
3.20	6.02	6.66
4.95	6.02	6.66
4.95	7.42	7.23
6.02	7.42	7.23
6.02	9.32	7.86
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
1.50	1.03	1.37
2.15	1.03	1.37
2.15	1.86	2.14
4.26	1.86	2.14
4.26	3.06	2.7
6.19	3.06	2.7
6.19	3.86	2.96
6.99	3.86	2.96

N12

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	4.77	6.36
2.42	4.77	6.36
2.42	6.47	7.76
5.58	6.47	7.76
5.58	11.17	9.44
7.85	11.17	9.44

N13

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	4.80	6.4
2.42	4.80	6.4
2.42	6.39	7.71
5.58	6.39	7.71
5.58	9.69	8.89
7.85	9.69	8.89

N14

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	3.43	4.57
2.15	3.43	4.57
2.15	4.49	5.56
3.62	4.49	5.56
3.62	6.89	6.89
5.29	6.89	6.89
5.29	7.99	7.31
6.86	7.99	7.31
6.86	17.49	10.08
7.80	17.49	10.08

N15

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	3.41	4.55
2.15	3.41	4.55
2.15	5.30	6.31
3.62	5.30	6.31
3.62	6.20	6.81
5.29	6.20	6.81
5.29	9.60	8.1
6.86	9.60	8.1
6.86	10.90	8.48
7.80	10.90	8.48

N16

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

N17

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	1.17	1.56
2.15	1.17	1.56
2.15	1.47	1.84
3.90	1.47	1.84
3.90	2.37	2.3
5.95	2.37	2.3
5.95	15.57	6.74
6.82	15.57	6.74
6.82	28.97	10.67
8.03	28.97	10.67

N18

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	3.56	4.75
2.15	3.56	4.75
2.15	4.53	5.71
3.74	4.53	5.71
3.74	6.33	6.67
5.07	6.33	6.67
5.07	7.83	7.26
6.36	7.83	7.26
6.36	9.53	7.79
6.92	9.53	7.79
6.92	16.93	9.93
7.98	16.93	9.93

N19

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	3.59	4.79
2.15	3.59	4.79
2.15	4.64	5.77
3.74	4.64	5.77
3.74	5.84	6.41
5.07	5.84	6.41
5.07	7.14	6.92
6.36	7.14	6.92
6.36	9.24	7.58
6.92	9.24	7.58
6.92	10.34	7.9
7.98	10.34	7.9

N20

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

N21

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	1.03	1.37
2.73	1.03	1.37
2.73	2.65	2.22
4.53	2.65	2.22
4.53	8.25	4.69
5.95	8.25	4.69
5.95	15.55	7.14
6.73	15.55	7.14

N22

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	3.25	4.33
2.15	3.25	4.33
2.15	3.99	5.02
3.97	3.99	5.02
3.97	5.89	5.98
6.05	5.89	5.98
6.05	7.99	6.67
7.04	7.99	6.67
7.04	11.49	7.66
8.17	11.49	7.66

N23

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.50	0.00	0
1.50	2.99	3.99
2.15	2.99	3.99
2.15	3.88	4.82
3.97	3.88	4.82
3.97	5.18	5.47
6.05	5.18	5.47
6.05	7.48	6.23
7.04	7.48	6.23
7.04	15.38	8.47
8.17	15.38	8.47

APPENDIX 4: GEOLOGICAL SAMPLE STATIONS

Note:

(1) Question marks have been used in the cruise / ship column where the cruise number is uncertain. The data in this table is preliminary only as no extensive quality controlling has been carried out.

Sources:

(1) National Geophysical Data Center (NGDC), Web home page http://www.ngdc.noaa.gov/ngdc.html.

(2) Institut de Recherche pour le Developpement (IRD), BP45 98848 Noumea Cedex, New Caledonia (unpubl).

(3) Deep Sea Driling Programs (DSDP).

Cruise / Ship	Identity	Source	Latitude (deg.)	Longitude (deg.)	Water depth (m)	device	age	Description (English translation)
71042604	PC042	1	-31.9780	165.5000	3185	core, piston	Quaternary	calcareous, nannofossils mud / ooze
71042604	FFC071	1	-28.8380	163.0080	1694	core, freefall	Quaternary	calcareous, biogenic mud / ooze
71042604	FFC072	1	-28.8370	163.0150	1713	Core, freefall	Quaternary	calcareous, biogenic mud / ooze
71042604	PC043	1	-26.2020	161.2570	1556	Core, piston	Quaternary	calcareous, nannofossils mud / ooze
71042604	FFC075	1	-25.5370	156.0680	4630	Core, freefall	Quaternary	calcareous, biogenic mud / ooze
71042604	FFC074	1	-25.5430	156.0700	4631	Core, freefall	Quaternary	calcareous, nannofossils mud / ooze
71042604	FFC076	1	-22.2420	156.0170	1606	Core, freefall	Quaternary	calcareous, biogenic mud / ooze
BATHUS2	CP736	2	-23.05	166.9667	452-464			slabs of sandstone, pockets of coarse sands
BATHUS2	CP737	2	-23.05	166.9833	350-400			slabs of sandstone, pockets of coarse sands
BATHUS2	DW730	2	-23.0333	166.9667	397-400			slabs of sandstone, pockets of coarse sands
BATHUS2	DW733	2	-22.9	166.8167	520			slabs of sandstone, pockets of coarse sands
BATHUS2	DW729	2	-22.8667	167.1833	400			slabs of sandstone, pockets of coarse sands
BATHUS2	DW720	2	-22.85	167.2667	530-541			slabs of sandstone, pockets of coarse sands
BATHUS2	DW723	2	-22.8333	167.4333	430-433			slabs of sandstone, pockets of coarse sands
BATHUS2	DW731	2	-22.8167	166.7333	300-370			slabs of sandstone, pockets of coarse sands
BATHUS2	DW732	2	-22.8167	166.75	236-264			slabs of sandstone, pockets of coarse sands
BATHUS2	DW727	2	-22.8	167.4833	299-260			slabs of sandstone, pockets of coarse sands
BATHUS2	DW719	2	-22.7833	167.2333	444-455			slabs of sandstone, pockets of coarse sands
BATHUS2	DW724	2	-22.7833	167.4167	344-358			slabs of sandstone, pockets of coarse sands
BATHUS2	DW726	2	-22.7833	167.4667	241-260			slabs of sandstone, pockets of coarse sands

BATHUS2	CP278	2	-22.7833	167.4667	241-245			slabs of sandstone, pockets of coarse sands
BATHUS2	DW718	2	-22.7667	167.2333	430-436			slabs of sandstone, pockets of coarse sands
BATHUS2	DW717	2	-22.7333	167.2667	350-393			slabs of sandstone, pockets of coarse sands
BATHUS2	DW716	2	-22.6667	167.2	290-227			slabs of sandstone, pockets of coarse sands
BATHUS2	DW715	2	-22.65	167.1667	202-227			slabs of sandstone, pockets of coarse sands
BATHUS2	DW739	2	-22.5833	166.4333	465-525			slabs of sandstone, pockets of coarse sands
BATHUS2	CP742	2	-22.55	166.4167	340-470			slabs of sandstone, pockets of coarse sands
BATHUS2	DW749	2	-22.55	166.4333	233-258			slabs of sandstone, pockets of coarse sands
BATHUS2	DW745	2	-22.5167	166.4167	400-440			slabs of sandstone, pockets of coarse sands
BATHUS2	DW746	2	-22.5167	166.4167	250			slabs of sandstone, pockets of coarse sands
BATHUS2	DW748	2	-22.4833	166.4	250			slabs of sandstone, pockets of coarse sands
BATHUS2	CP750	2	-22.4	166.2	1200-1400			slopes of ooze & sands
BATHUS2	CP751	2	-22.4	166.2	1300-1500			slopes of ooze & sands
BATHUS2	DW752	2	-22.3667	166.2333	330			slabs of sandstone, pockets of coarse sands
BATHUS2	DW753	2	-22.35	166.2333	144-155			slabs of sandstone, pockets of coarse sands
BATHUS2	CP755	2	-22.35	166.2167	495			slabs of sandstone, pockets of coarse sands
BATHUS2	DW757	2	-22.3167	166.2	330			slabs of sandstone, pockets of coarse sands
BATHUS2	DW758	2	-22.3	166.1667	377-386			slabs of sandstone, pockets of coarse sands
BATHUS2	CP759	2	-22.3	166.1667	370-420			slabs of sandstone, pockets of coarse sands
BATHUS2	CP760	2	-22.3	166.1667	455			slabs of sandstone, pockets of coarse sands
BATHUS2	CP761	2	-22.3	166.1667	490-500			slabs of sandstone, pockets of coarse sands
BATHUS2	CP767	2	-22.1667	165.9833	1060-1450			slopes of ooze & sands
BATHUS2	DW763	2	-22.15	166.05	483-530			slabs of sandstone, pockets of coarse sands
BATHUS2	CP764	2	-22.15	166.0333	560-570			slabs of sandstone, pockets of coarse sands
BATHUS2	CP770	2	-22.15	166.0667	400-402			slabs of sandstone, pockets of coarse sands
BATHUS2	CP769	2	-22.1333	166.0167	258-400			slabs of sandstone, pockets of coarse sands
BATHUS3	DW263	2	-25.355	159.774	225-150			Shelly sand
BATHUS3	DW265	2	-25.3517	159.7533	190-260			Shelly sand
BATHUS3	DW266	2	-25.3367	159.7617	240			Shelly sand
BATHUS3	DW270	2	-24.8142	159.5688	223			Shelly sand
BATHUS3	DW163	2	-24.7283	168.1317	260			Bioclastic coarse sand
BATHUS3	DW282	2	-24.1925	159.537	230			halimeda sand
BATHUS3	DW783	2	-23.9333	169.7667	614-617			Manganese coated blocks of sandstone
BATHUS3	DW784	2	-23.9333	169.7667	611-615			Manganese coated blocks of sandstone

BATHUS3	DW785	2	-23.9333	169.75	607-608			Manganese coated blocks of sandstone
BATHUS3	CP782	2	-23.9167	169.7667	615-621			Manganese coated blocks of sandstone
BATHUS3	DW786	2	-23.9	169.8167	699-715			Manganese coated blocks of sandstone
BATHUS3	DW781	2	-23.8833	169.7667	625-640			Manganese coated blocks of sandstone
BATHUS3	DW787	2	-23.8833	169.8	695-702			Manganese coated blocks of sandstone
BATHUS3	CP788	2	-23.8833	169.8167	652-750			Manganese coated blocks of sandstone
BATHUS3	DW789	2	-23.8333	169.8	671-674			Manganese coated blocks of sandstone
BATHUS3	DW790	2	-23.8	169.7833	685-715			Manganese coated blocks of sandstone
BATHUS3	DW791	2	-23.8	169.8	671-697			Manganese coated blocks of sandstone
BATHUS3	DW794	2	-23.8	169.8167	751-755			Manganese coated blocks of sandstone
BATHUS3	DW793	2	-23.7833	169.8	731-751			Manganese coated blocks of sandstone
BATHUS3	CP814	2	-23.7833	168.2833	444-530			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP815	2	-23.7833	168.2667	460-470			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW792	2	-23.7667	169.8	730-735			Manganese coated blocks of sandstone
BATHUS3	DW795	2	-23.7667	169.8167	735-755			Manganese coated blocks of sandstone
BATHUS3	DW796	2	-23.75	169.8167	728-730			Manganese coated blocks of sandstone
BATHUS3	CP813	2	-23.75	168.2667	410-415			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW819	2	-23.75	168.2667	487-486			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP812	2	-23.7167	168.25	391-440			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW818	2	-23.7167	168.2667	394-401			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP806	2	-23.7	168	308-312			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW817	2	-23.7	168.25	405-410			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP804	2	-23.6833	168	244-278			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP805	2	-23.6833	168.0167	278-310			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW808	2	-23.6833	167.9833	510-530			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP811	2	-23.6833	168.25	383-408			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW807	2	-23.6667	167.9833	420-438			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW810	2	-23.6667	167.9667	850-900			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW816	2	-23.6667	168.25	380-391			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP803	2	-23.65	167.9833	315-325			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW809	2	-23.65	167.9667	650-730			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW800	2	-23.5833	169.6	655			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW797	2	-23.5667	169.6167	657-660			Sedimentary blocks
BATHUS3	DW798	2	-23.5667	169.6	657-660			Sedimentary blocks

BATHUS3	DW799	2	-23.5167	169.6	697-744			Sedimentary blocks
BATHUS3	CP823	2	-23.3667	167.85	980-1000			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW826	2	-23.3667	168	498-558			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW827	2	-23.3667	168.0167	381-469			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW828	2	-23.3667	168.0167	318-360			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW825	2	-23.35	168	597-605			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW829	2	-23.35	168.0167	368-390			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP821	2	-23.3167	167.9667	864-880			Coarse sandstone debris, blocks of sandstone
BATHUS3	CP822	2	-23.3167	167.95	950-980			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW824	2	-23.3167	168	601-608			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW830	2	-23.3167	168.0167	361-365			Coarse sandstone debris, blocks of sandstone
BATHUS3	DW296	2	-23.2102	159.6045	178			blocks of sand
BATHUS3	DW295	2	-23.2095	159.5385	279			blocks of sand
BATHUS3	DW294	2	-23.183	159.5022	272			blocks of sand
BATHUS3	DW290	2	-23.1033	159.4383	300			blocks of sand
BATHUS3	CP843	2	-23.1	166.7667	886-925			slopes of ooze & sands
BATHUS3	CP844	2	-23.1	166.75	908			slopes of ooze & sands
BATHUS3	CP842	2	-23.0833	166.7833	830			slopes of ooze & sands
BATHUS3	CP831	2	-23.0667	166.9167	650-658			slopes of ooze & sands
BATHUS3	CP832	2	-23.05	166.8833	650-669			slopes of ooze & sands
BATHUS3	CP845	2	-23.05	166.9333	592-622			slopes of ooze & sands
BATHUS3	CP833	2	-23.0333	166.9667	441-444			slopes of ooze & sands
BATHUS3	CP834	2	-23.0333	166.9667	330-336			slopes of ooze & sands
BATHUS3	CP835	2	-23.0333	166.9667	350			slopes of ooze & sands
BATHUS3	DW836	2	-23.0333	166.9833	295-306			slopes of ooze & sands
BATHUS3	CP846	2	-23.0333	166.95	500-514			slopes of ooze & sands
BATHUS3	CP847	2	-23.0333	166.9667	405-411			slopes of ooze & sands
BATHUS3	DW837	2	-23.0167	166.9333	402-412			slopes of ooze & sands
BATHUS3	DW839	2	-23.0167	166.95	502-505			slopes of ooze & sands
BATHUS3	DW838	2	-23	166.9167	400-402			slopes of ooze & sands
BIOCAL	CP172	2	-24.9083	168.3717	527-480			Blocks of sand
BIOCAL	CP169	2	-24.7043	168.1587	230-590			pumices
BIOCAL	CP63	2	-24.4782	168.1287	2160			pumice without sediments
BIOCAL	CP68	2	-24.0062	168.1172	1430			consolidated blocks of chalky sediment, fortmt bioturbated

BIOCAL	CP58	2	-23.9422	166.6759	2660			pumice
BIOCAL	DS59	2	-23.9369	166.6852	2650			Yellow mud and pumice
BIOCAL	DW70	2	-23.4117	167.8942	965			Sand in small blocks, semi-consolidated
BIOCAL	DW53	2	-23.1633	167.7092	1005			Shelly sand
BIOCAL	CP30	2	-23.1408	166.6806				mud, pumice, indurated sediment
BIOCAL	CP29	2	-23.1253	166.6693	1100			yellow mud
BIOCAL	DW48	2	-23.0073	167.4793	775			shelly sand with ptéropodes
BIOCAL	DW38	2	-22.9957	167.2552	360			shelly sand with pentacrine
BIOCAL	DW39	2	-22.9178	167.3807	650			Massive sand, coralline
BIOCAL	DW44	2	-22.7883	167.2383	440			Sand with ophiures
BIOCAL	DW43	2	-22.7703	167.2418	400			Shelly sand
BIOCAL	DW41	2	-22.7522	167.1957	380			sand
BIOCAL	DW77	2	-22.2555	167.2568	440			Bioclastic sand
BIOCAL	KG73	2	-22.2159	167.4857	1285			Sand for meiofaune
BIOCAL	CP72	2	-22.1504	167.5531	2100			Yellow mud, pumce
BIOCAL	KG101	2	-21.4419	166.4073	1790			Yellow mud
BIOCAL	DS98	2	-21.4017	166.4961	2365			Oozy sediment
BIOCAL	KG89	2	-21.0382	166.9383	2070			Yellow mud very compacted
BIOGEOCAL	KG278	2	-22.8063	166.337	2250			coralline sand
BIOGEOCAL	KG222	2	-22.7437	166.4155	1675			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KG210	2	-22.7333	166.5162	1190			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KG221	2	-22.706	166.401	1915			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KK280	2	-22.7058	166.3985	2020			Blocks encrusted with Fe-Mn, sand and boulders
BIOGEOCAL	KG211	2	-22.6967	166.5422	975			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KK212	2	-22.6957	166.532	1150			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KG200	2	-22.6823	166.3888	650			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KK204	2	-22.6803	166.5308	603			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KG201	2	-22.6737	166.5453	595			Iron-manganese encrusted blocks, light coloured sand with

								pebbles
BIOGEOCAL	KK202	2	-22.6638	166.5383	599			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KG219	2	-22.6468	166.5615	570			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KK206	2	-22.643	166.4843	1100			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KG207	2	-22.6385	166.4893	1350			Iron-manganese encrusted blocks, light coloured sand with pebbles
BIOGEOCAL	KG227	2	-21.5473	166.3975	500			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KK231	2	-21.5422	166.4335	530			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG252ter	2	-21.5185	166.3553	330			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG228	2	-21.5173	166.4025	960			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KK230	2	-21.5167	166.3968	875			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG233	2	-21.5145	166.418	1040			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KK235	2	-21.4942	166.4218	1440			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KK237	2	-21.4915	166.4107	1410			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG234	2	-21.4888	166.424	1410			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KK244	2	-21.4887	166.4438	1470			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG240	2	-21.4858	166.4432	1520			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG241bis	2	-21.458	166.4382	1990			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KK284	2	-21.458	166.5277	2334			semi-compacted mud, encrusted with Fe-Mn, coralline sand
BIOGEOCAL	KK242	2	-21.4567	166.4377	1980			Semi-indurated ooze encrusted with iron-manganese, sand, coral

BIOGEOCAL	KK245	2	-21.455	166.4545	2210			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KK247	2	-21.4003	166.4812	2360			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG277	2	-21.2868	166.9383	2240			coralline sand
BIOGEOCAL	KG248	2	-21.2555	166.4782	2340			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG276	2	-21.22	167.0058	2200			coralline sand
BIOGEOCAL	KK251	2	-21.1013	166.4872	2320			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KG275	2	-21.0967	166.8857	1959			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KG268	2	-21.058	166.9557	1990			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KG263	2	-21.0395	167.0347	1330			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KG269	2	-21.039	166.9685	1810			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KG262	2	-21.0377	167.0338	1380			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KG267	2	-21.0367	166.9793	1935			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KG261	2	-21.034	167.0387	1508			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KK257	2	-21.022	167.0108	1680			Bioclastic sand, calcarenite,pumice debris
BIOGEOCAL	KG256	2	-21.016	167.02	1680			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KG255	2	-21.0158	166.9743	1770			bioclastic sand, calcarenite, debris of plant pumice
BIOGEOCAL	KK242bis	2	-21.452	166.4417	2010			Semi-indurated ooze encrusted with iron-manganese, sand, coral
BIOGEOCAL	KK236	2	-21.5238	166.4258	980			Semi-indurated ooze encrusted with iron-manganese, sand, coral
CHALCAL I	D42	2	-21.4783	166.35				Halimeda sand
CHALCAL I	D41	2	-21.47	166.37				Halimeda sand
CHALCAL I	D44	2	-21.4433	166.3833				Halimeda sand
CHALCAL I	D43	2	-21.4317	166.38				Halimeda sand
CHALCAL I	D61	2	-21.415	166.4017				Halimeda sand
CHALCAL II	DW72	2	-22.8833	167.3833				white sponges
CHALCAL II	DW70	2	-22.8783	167.3833				coral blocks
CHALCAL II	DW69	2	-22.7667	167.3333				coral blocks
CHALCAL II	DW71	2	-22.75	167.15				coral blocks
EVA100	DR117	2	-23.2667	169.425	1800			Grey detrital calcareous, encrusted ?, altered tuff
EVA100	DR120	2	-21.8503	169.0945	3600			Grey detrital calcareous, encrusted ?, altered tuff

EVA100	DR118	2	-21.7968	169.0108	2700			Grey detrital calcareous, encrusted ?, altered tuff
EVA100	DR119	2	-21.7633	168.975	2900			Grey detrital calcareous, encrusted ?, altered tuff
GEMINI	DW48	2	-21.2507	162.2568	48			vesicular lava, volcanic breccia
GEO III NORD	GO328D	2	-22.0383	167.3	1870			muds, volcanogenic sediments, ? encrusted
GEORSTOM III SUD	GO338D	2	-24.07	168.6483	1600			Altered ?, encrusted 3cm relique of Ol/P
GEORSTOM III SUD	GO340D	2	-23.925	169.85	1800			light beige grey mud encrusted,, qq pumices
GEORSTOM I	GEO I-20D	2	-24.0767	168.0083	1220			phthanite?, Detrital calcareous coral
GEORSTOM I	GEO I-22D	2	-23.9883	166.35	2675			pseudo-breccia,?, Encrusted with manganese
GEORSTOM I	GEO I-19D	2	-23.6867	168.2517	450			Encrusted & recrystallised calcareous coral
GEORSTOM I	GEO I-17D	2	-23.685	168.2283	1140			in-situ green clay, tuff, calcareous organic detritus
GEORSTOM I	GEO I-18D	2	-23.685	168.2383	585			calc + qq coraux calcareous & coralline ?
GEORSTOM I	GEO I-16D	2	-23.6167	168.8417	1240			Manganese encrusted boulders, hardened ?, silts
GEORSTOM I	GEO I-15D	2	-23.5383	168.8567	1325			Manganese encrusted boulders, hard vases, silts
GEORSTOM I	GEO I-14D	2	-23.5333	168.8333	1450			Manganese encrusted boulders
GEORSTOM I	GEO I-12D	2	-23.4833	168.0667	935			sandstone with organic content (?), loose sand, shells semi-
GEORSTOM I	GEO I-11D	2	-23.3317	168.2767	700			Encrusted & recrystallised calcareous
GEORSTOM I	GEO I-9D	2	-23.2633	168.2117	725			Calcareous blocks, debris, boulders
GEORSTOM I	GEO I-10D	2	-23.2417	168.2583	1220			in place, serpentine or phthanite sandstone
GEORSTOM I	GEO I-7D	2	-23.0983	168.405	1590			pumice , large calcareous blocks broken off
GEORSTOM I	GEO I-13D	2	-23.0017	168.5383	1340			organic sand, calcareous conglomerate encrusted with manganese ?, tuff
GEORSTOM I	GEO I-6D	2	-22.6667	169	1140			Red coloured altered tuff, detrital calcareous altered volcanics
GEORSTOM I	GEO I-2C	2	-22.5733	167.9467	1715			White calcareous mud
GEORSTOM I	GEO I-3D	2	-22.5333	167.9683	2100			Manganese encrusted conglomerate with calc. mud
GEORSTOM I	GEO I-4D	2	-22.12	168.4783	1375			Calcareous coral & mud, supplement manganese
GEORSTOM I	GEO I-5D	2	-22.0917	168.4833	1060			calcareous reef,organic sands, abundant nodules and encrustations
ILES DES PINS	TS 13	2	-23.0833	167.1				Sand with organic fragments
ILES DES PINS	TS 11	2	-23	167.3				Organogenic sand, minor ? chalk ?
ILES DES PINS	TS 3	2	-22.9083	167.4667				Ferruginous and phosphatic chalk
ILES DES PINS	TS 6	2	-22.8617	167.6				Organogenic chalk, debris of coral branches

ILES DES PINS	TS 5	2	-22.8583	167.5417				Organogenic chalk, debris of coral branches
ILES DES PINS	TS 14	2	-22.85	167.3583				Organogenic sand, minor ? chalk
ILES DES PINS	TS 16	2	-22.8	167.3583				Ferruginous and phosphatic chalk
ILES DES PINS	TS 17	2	-22.7417	167.1667				Organogenic sand, minor ? chalk
ILES DES PINS	CSE 4	2	-22.3917	167.2833				Ferruginous and phosphatic chalk
ILES DES PINS	TS 2	2	-21.7167	167.2583				Sand with organic fragments, chalk
LEG 021	208 30	3	-26.1100	161.2220	1545	drill, sediment	Palaeocene	
LEG 090	587 10	3	-21.1850	161.3330	1101	drill, sediment	Miocene	avg.den=1.71
LEG 090	588 25	3	-26.1120	161.2270	1533	drill, sediment	Miocene	
LEG 090	589 3	3	-30.7120	163.6400	1391	drill, sediment	Quaternary	
LEG 090	590A 26	3	-31.1670	163.3580	1299	drill, sediment	Miocene	
LEG 090	591 31	3	-31.5850	164.4480	2131	drill, sediment	Miocene	
NOVA-A	035G	1	-21.4500	164.1167	3566	core, gravity	unknown	Abyssal plain. Brown mud at top; calcareous ooze at bottom. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	036PG	1	-21.6833	167.3833	2148	corer, trigger wt.	unknown	Calcareous ooze. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	036P	1	-21.6833	167.3833	2148	core, piston	Pliocene	Abyssal plain. Questionable Pliocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	039G	1	-23.1500	167.2500	757	core, gravity	Pleistocene	Small hills. Small amount of benthic and planktonic Foraminifera, shell fragments and coral debris from core catcher. Pleistocene age on basis of a few planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	039GA	1	-23.1667	167.2500	757	core, gravity	Pleistocene	Small hills. Foraminifera, shell and coral debris. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	040PG	1	-23.0000	164.9667	3617	corer, trigger wt.	Pleistocene	Flat basin. Calcareous ooze. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core

								Log; revised position and water-depth data.)
NOVA-A	040P	1	-23.0000	164.9667	3617	core, piston	Pleistocene	Flat basin. Small amount of indurated calcareous ooze in core-catcher. Pleistocene age on basis of planktonic foraminifers; possibly some upper Pliocene forams, as well. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	048G	1	-28.2000	158.2167	2220	core, gravity	Pleistocene	West of foothills of Lord Howe Rise. Tan foraminiferal ooze. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	049G	1	-28.1667	158.2667	2189	core, gravity	Pleistocene	West of foothills of Lord Howe Rise. Tan foraminiferal ooze. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	050G	1	-28.1333	158.3167	2253	core, gravity	Pleistocene	West of foothills of Lord Howe Rise. Light tan foraminiferal ooze and clay. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	051G	1	-28.0833	158.3833	2335	core, gravity	Pleistocene	West of foothills of Lord Howe Rise. Light tan foraminiferal ooze and clay. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	053PG	1	-28.2667	161.5167	1607	corer, trigger wt.	Pleistocene	Small amount of light tan foraminiferal ooze with one pumice pebble in core catcher. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	053P	1	-28.2667	161.5167	1607	core, piston	unknown	White foraminiferal ooze. Some manganese coatings on foraminifera tests. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	056PG	1	-28.2833	162.6000	1408	corer, trigger wt.	Miocene	Small amount of sample combined with 56P contains foram ooze and consolidated foram ooze and rock fragments. Miocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	055P	1	-28.2833	162.6000	1393	core, piston	Quaternary	Very small amount of Recent and Pleistocene debris in core catcher. Age on basis of planktonic foraminifers.

								(Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	056P	1	-28.2833	162.6000	1408	core, piston	Miocene	Small amount of sample combined with 56PG contains foram ooze and consolidated foram ooze and rock fragments. Miocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	055PG	1	-28.2833	162.6000	1393	corer, trigger wt.	unknown	No core.
NOVA-A	062G	1	-27.1500	167.3167	744	core, gravity	unknown	No core.
NOVA-A	061G	1	-27.1667	167.3167	744	core, gravity	Pleistocene	Small core-catcher sample only. Foraminiferal ooze. Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
NOVA-A	064G	1	-27.6167	168.9833	3182	core, gravity	Pleistocene	Small hills. Light tan foraminiferal ooze. Questionable Pliocene/Pleistocene age on basis of planktonic foraminifers. (Core data from Shipboard Core Log; revised position and water-depth data.)
OC476	167-167	1	-31.5080	155.0170	4650	core, piston		terrigenous, mud or ooze
OC476	173-173	1	-31.4870	155.7470	4840	core, piston		terrigenous, mud or ooze
OC476	177-177	1	-31.5080	156.9050	4280	core, piston		terrigenous, mud or ooze
PROA	047G	1	-21.9500	167.9170	2010	core, gravity	Quaternary	
RC12	107	1	-26.0000	169.2000	3115	core, piston	Pleistocene	age=core bottom age is undifferentiated Pleistocene dominant lithology: laminated foraminiferal chalk ooze accessory lithology: structureless foraminiferal ooze accessory lithology: structureless volcanic ash accessory lithology: laminated chalk mottlin
RC12	108	1	-26.0330	165.8170	3354	core, piston	Pleistocene	age=core bottom age is undifferentiated Pleistocene dominant lithology: structureless foraminiferal chalk accessory lithology: structureless volcanic ash mottling: burrowing Paleontology: foraminifera echinoid spines mineralogy: dissem volc glass shards
RC12	109	1	-25.8830	157.8670	2930	core, piston	Pleistocene	age=core bottom age is undifferentiated Pleistocene dominant lithology: structureless foraminiferal chalk mottling: burrowing paleontology: foraminifera ostracods echinoid spines
RC12	112	1	-24.1330	159.0500	2566	core, piston	Pleistocene	age=core bottom age is undifferentiated Pleistocene

								dominant lithology: structureless foraminiferal chalk accessory lithology: structureless foraminiferal chalk ooze mottling: burrowing Paleontology: foraminifera pteropods bryozoa bivalves echinoid spin
RC12	113	1	-24.8830	163.5170	2454	core, piston	Pleistocene	age=core bottom age is undifferentiated Pleistocene accessory lithology: structureless foraminiferal chalk ooze dominant lithology: structureless foraminiferal chalk mottling: burrowing Paleontology: foraminifera mineralogy: mn oxide (dissem)
SUBPSO	PL09	2	-21.7933	169.1733	4790			volcanic breccia.
SUBPSO	PL08	2	-21.7375	169.1375	4650			polygenic breccia, coarse tuffs
SUBPSO	PL12	2	-21.61	169.1208	5230			volcanic tuffs, glassy clasts of palagonite
SUBPSO	PL11	2	-21.5683	169.1917	5500			calcareous mud
vegetaux	KK279	2	-22.8117	166.3265	2265			Blocks encrusted with Fe-Mn, sand and boulders
vegetaux	KK338	2	-21.4465	166.5225	2340			semi-compacted mud, encrusted with Fe-Mn, coralline sand
vegetaux	KK270	2	-21.055	166.9517	1990			Bioclastic sand, calcarenite,pumice debris
vegetaux	KK274	2	-21.027	166.9868	1890			Bioclastic sand, calcarenite,pumice debris
vegetaux	KK264	2	-21.0237	167.0285	1440			Bioclastic sand, calcarenite,pumice debris
vegetaux	KK271	2	-21.0067	166.9607	1800			Bioclastic sand, calcarenite,pumice debris
vegetaux	KK258	2	-21.0035	167.0042	1670			Bioclastic sand, calcarenite,pumice debris
?	DC168	2	-24.7667	168.15	232-720			blocks & shell fragments
bathus?	DW272	2	-24.6818	159.7167	500-540			Shelly sand
bathus?	DW159	2	-21.8108	159.4658	45			Coarse sand, blocks of sand
bathus?	DW160	2	-21.7067	159.4833	50			Sand with ptéropods
bathus/biocal?	CP158	2	-21.4917	159.2733	62-625			Sand with ptéropods
bathus?	DW151	2	-21.4317	158.9917	39			Fine sand
bathus?	DW322	2	-21.3167	158.0067	975			pumice
vegetaux?	KK319	2	-21.1003	166.8832	1985			Bioclastic sand, calcarenite,pumice debris
bathus?	DW150	2	-21.0733	158.6783	70			Coarse bioclastic sand

APPENDIX 5: HEAT FLOW DATA

Station	**Latitude (mW.m^{-2})**	**Longitude**	**Heat-flow**	**Reference**
DSDP 587	-21.197833	161.333167	56.9	Kennett, Houtz, Andrews et al. (1974)
Ocean-3	-31.508333	155.016666	54.0	Grim (1969)
Ocean-4	-31.471666	156.208333	47.0	Grim (1969)
Ocean-5	-31.508333	156.905000	44.0	Grim (1969)

APPENDIX 6: INTERPRETED SEISMIC HORIZONS

Seismic Horizon	Horizon type	Color & Geoquest no	Description
U1	Other	Dark blue, 5	water bottom
Bsr	Other	Light blue, 8	bottom-simulating reflector
A1/yellow	Sedimentary	Light yellow, 24	Upper Miocene
U2	Sedimentary	Yellow, 7	Middle Miocene
U3	Sedimentary	Black, 1	Lower Miocene
U4	Sedimentary	Light green, 4	Oligocene
b_1/green	Sedimentary	Blue/green, 11	Upper Eocene
U5	Sedimentary	Emerald green, 21	Lower Eocene
U6	Sedimentary	Light blue, 8	Maastrichtian
U7	Sedimentary	Dark green, 12	Campanian (Tasman Sea breakup)
U8	Sedimentary	Dark blue, 5	Cenomanian
U9	Sedimentary	Black, 1	Mid-Cretaceous
U10	Sedimentary	Purple, 6	Lower Cretaceous
Plan	Basement	Dark purple, 13	Planated basement – Lord Howe Platform
Crif	Basement	Dark pink, 22	Rifted basement – central Lord Howe Rise
Wrif	Basement	Dark purple, 13	Rifted basement – western Lord Howe Rise
Trif	Basement	Dark pink, 22	Rifted basement – Tasman Basin
Dam	Basement	Dark purple, 13	Rifted basement – Dampier Ridge
Ncb	Basement	Dark purple, 13	Basement – New Caledonia Basin
Lb	Basement	Dark purple, 13	Basement – Loyalty Basin and Ridge
Fair	Basement	Dark pink, 22	Basement - Fairway Basin and Ridge
Midd	Basement	Dark pink, 22	Basement - Middleton Basin
Nr	Basement	Dark pink, 22	.Basement - Norfolk Ridge
nht	Basement	Dark pink, 22	.Basement - New Hebrides Trench

Vmio	Volcanic	Brown, 10	Miocene volcanics
Vcam	Volcanic	Light blue, 8	Campanian (breakup) volcanics
vcen	Volcanic	Dark blue, 5	Cenomanian volcanics
tsdr	Volcanic	Yellow, 7, dashed line	top Seaward Dipping Reflector Sequence (SDRS)
bsdr	Volcanic	Emerald green, 21, dashed line	base SDRS
moho	Other	Red, 3	Moho

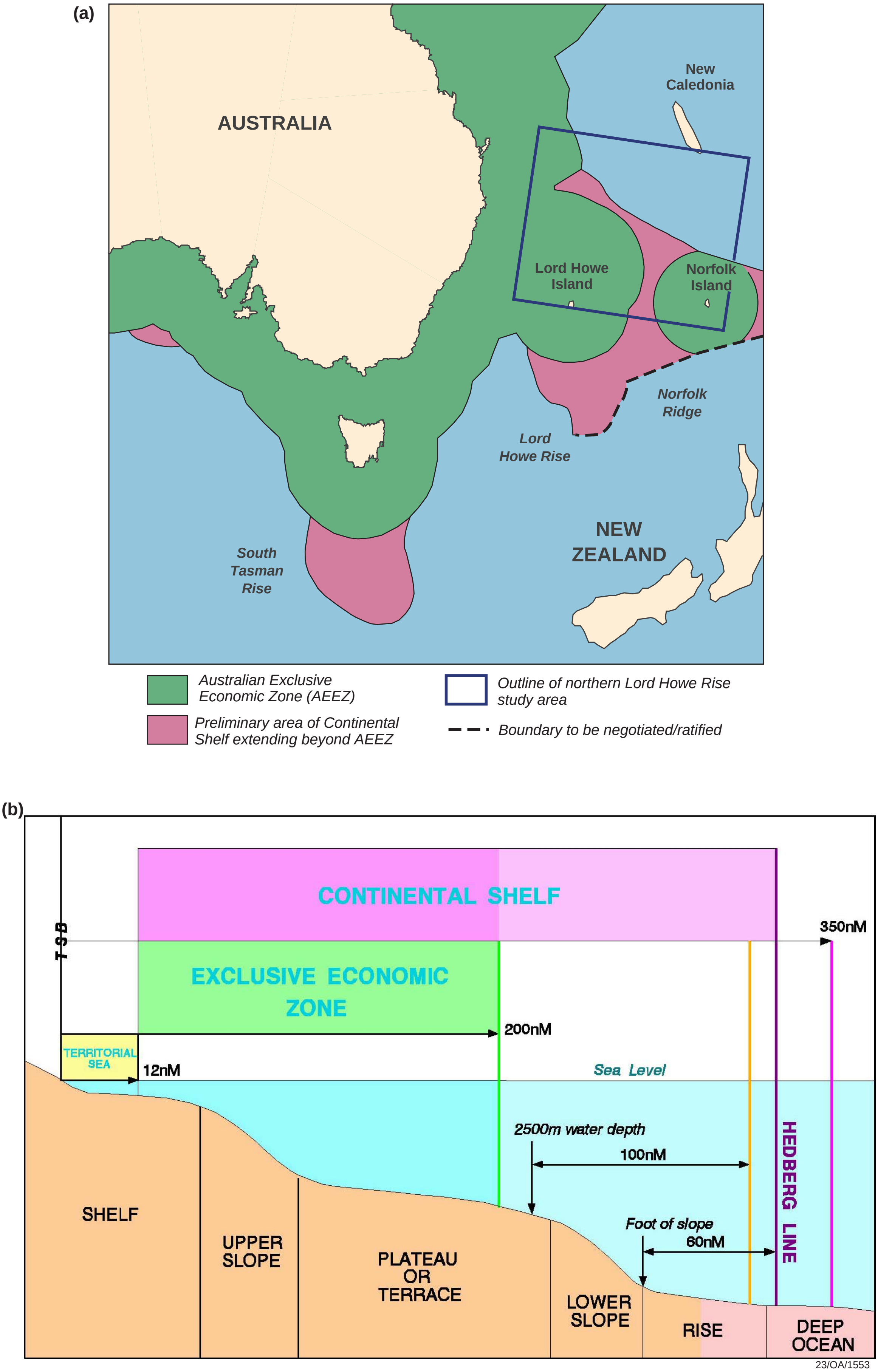


Figure 1: Marine jurisdictional zones off the eastern coast of Australia. (a) Location map. (b) Criteria used for defining boundaries, contained in the 1982 United Nations Convention on the Law of the Sea.

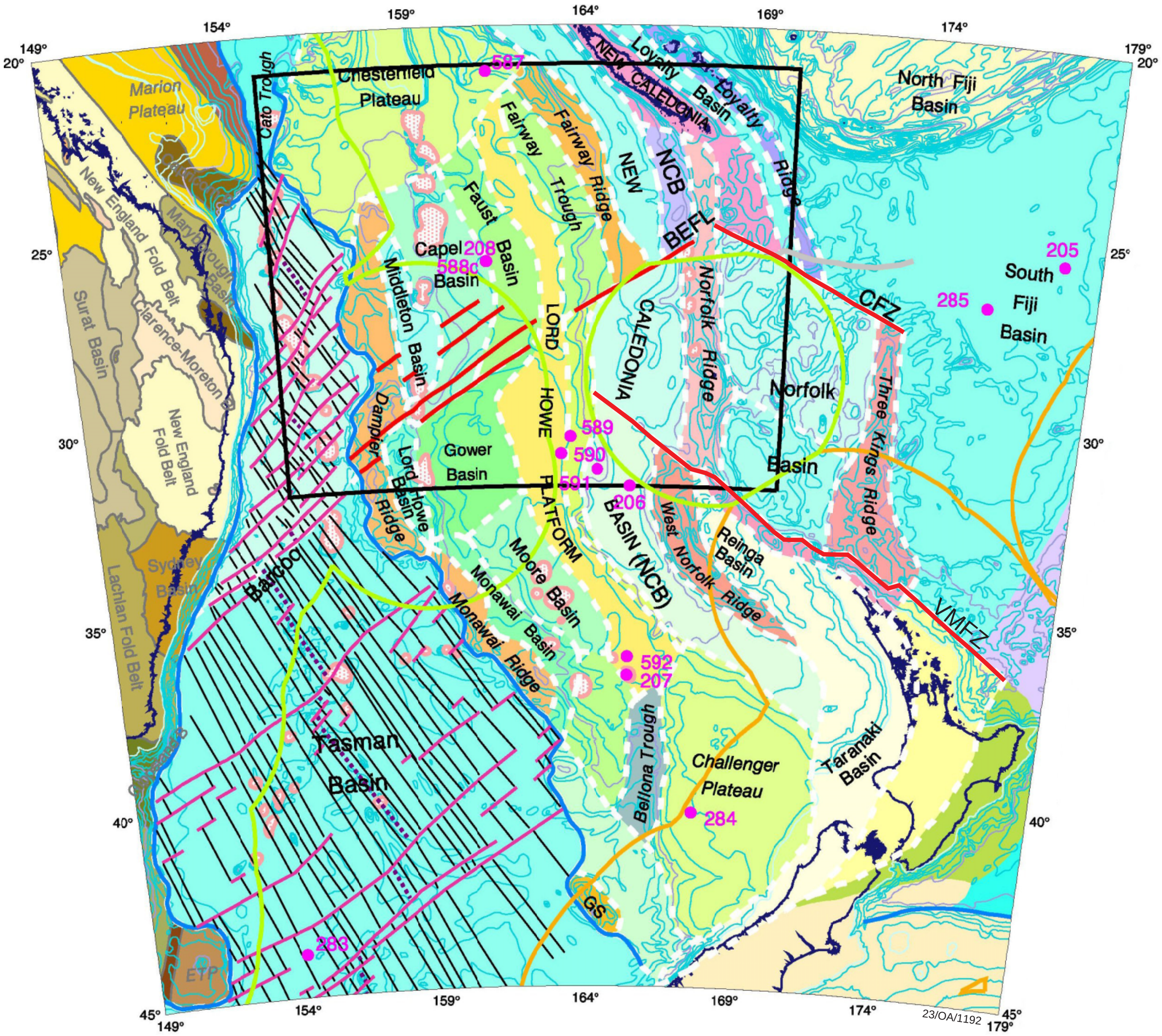


Figure 2. Structural provinces of the southwest Pacific - eastern seaboard of Australia (after Stagg et al., 1999). Legend: Solid black lines - seafloor spreading magnetic lineaments (after Gaina et al., 1998); mauve line - continent/ocean boundary (COB) in Tasman Basin; solid red lines - main transform faults; thick black line - northern Lord Howe Rise project area; solid green-yellow line - Australian Exclusive Economic Zone; solid orange line - Exclusive Economic Zone of New Zealand; blue contours are isobaths; pink circles are DSDP Sites; pink stipple - Miocene volcanics. Abbreviations: BEFL - Barcoo-Elizabeth Fairway Lineament; CFZ - Cook Fracture Zone; VMFZ - Vening Meinesz Fracture Zone; GS - Gilbert Seamount; ETP - East Tasman Plateau (Cascade Plateau).

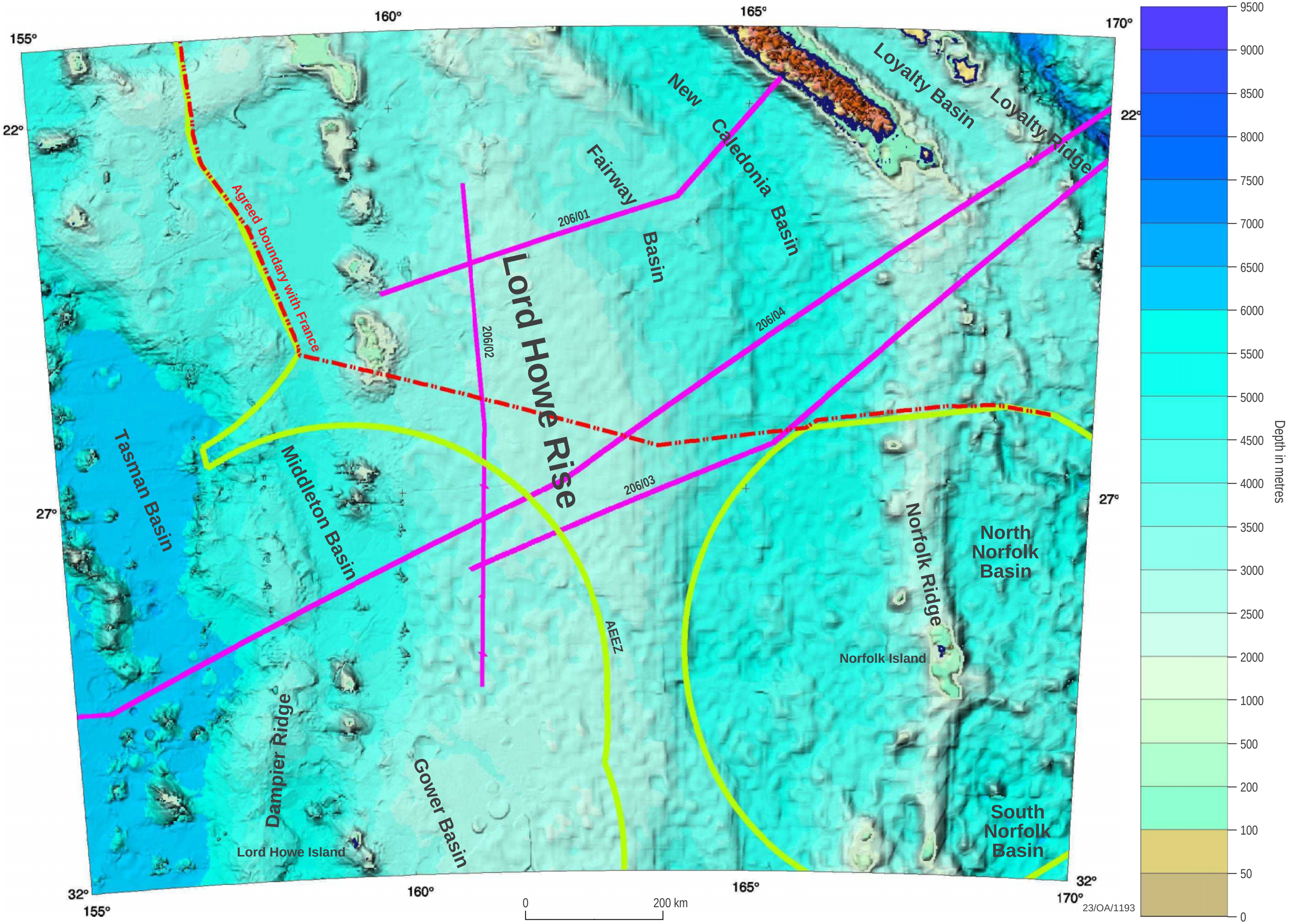


Figure 3. Bathymetry image of the northern Lord Howe Rise region. Compilation from predicted bathymetry (Smith, Sandwell & Small, 1997) and vessel acquired data. Legend: Magenta lines - Survey 206/FAUST 1 (Lafoy et al. 1998; Bernardel et al. 1999); AEEZ (lime green line) - Australian Exclusive Economic Zone.

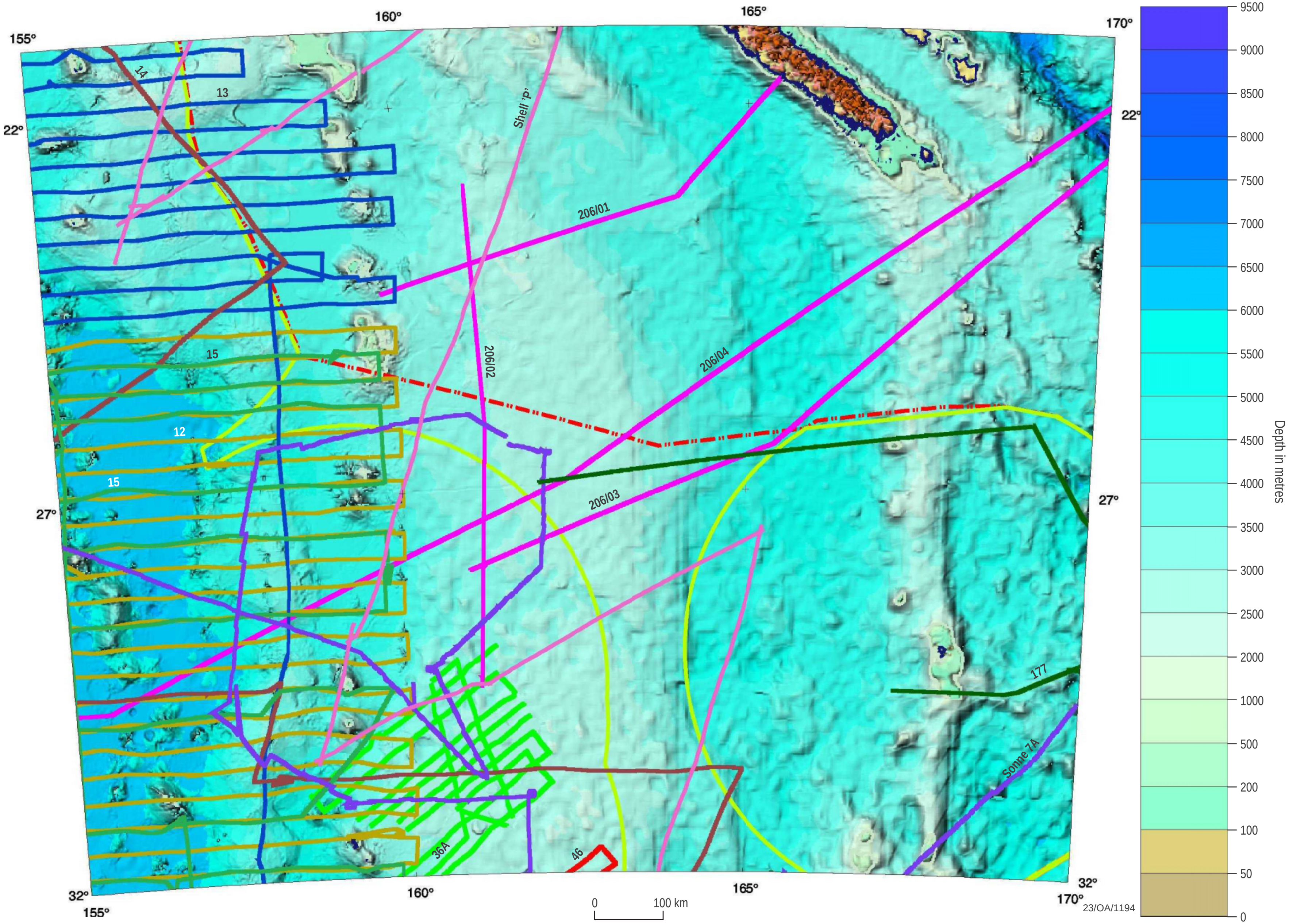


Figure 4. Location of seismic lines in the northern Lord Howe Rise region. Legend: Magenta lines - Survey 206 / FAUST1 (Lafoy et al. 1998; Bernardel et al. 1999); dark blue lines - Survey 13; green lines - Survey 15; light green lines - *Sonne* 36A; mustard yellow lines - Survey 14; pink lines - Shell Petrel; AEEZ (lime green line) - Australian Exclusive Economic Zone. Larger-sized map in Plate 1.

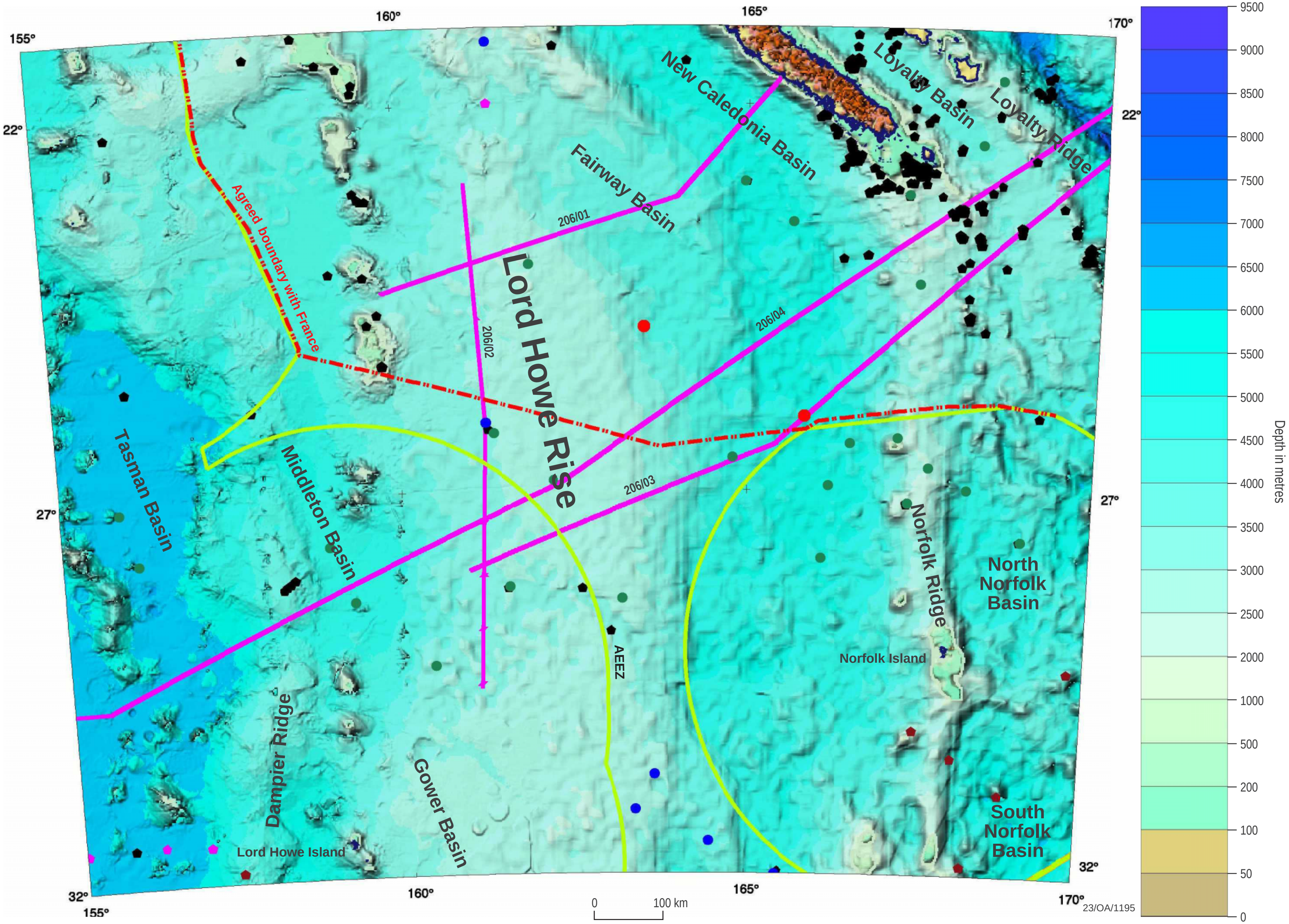


Figure 5. Location map of scientific wells (Deep Sea Drilling Project), sample-sites, heatflow and sonobuoy stations within the northern Lord Howe Rise red circle region. Legend: Magenta lines - Survey 206 / FAUST1; black pentagon symbol - NGDC dredge sites; brown pentagon symbol - IRD dredge sites; symbol - core grabs; pink circle symbol - DSDP sites; AEEZ (lime green line) - Australian Exclusive Economic Zone. Larger-sized map in Plate 2.

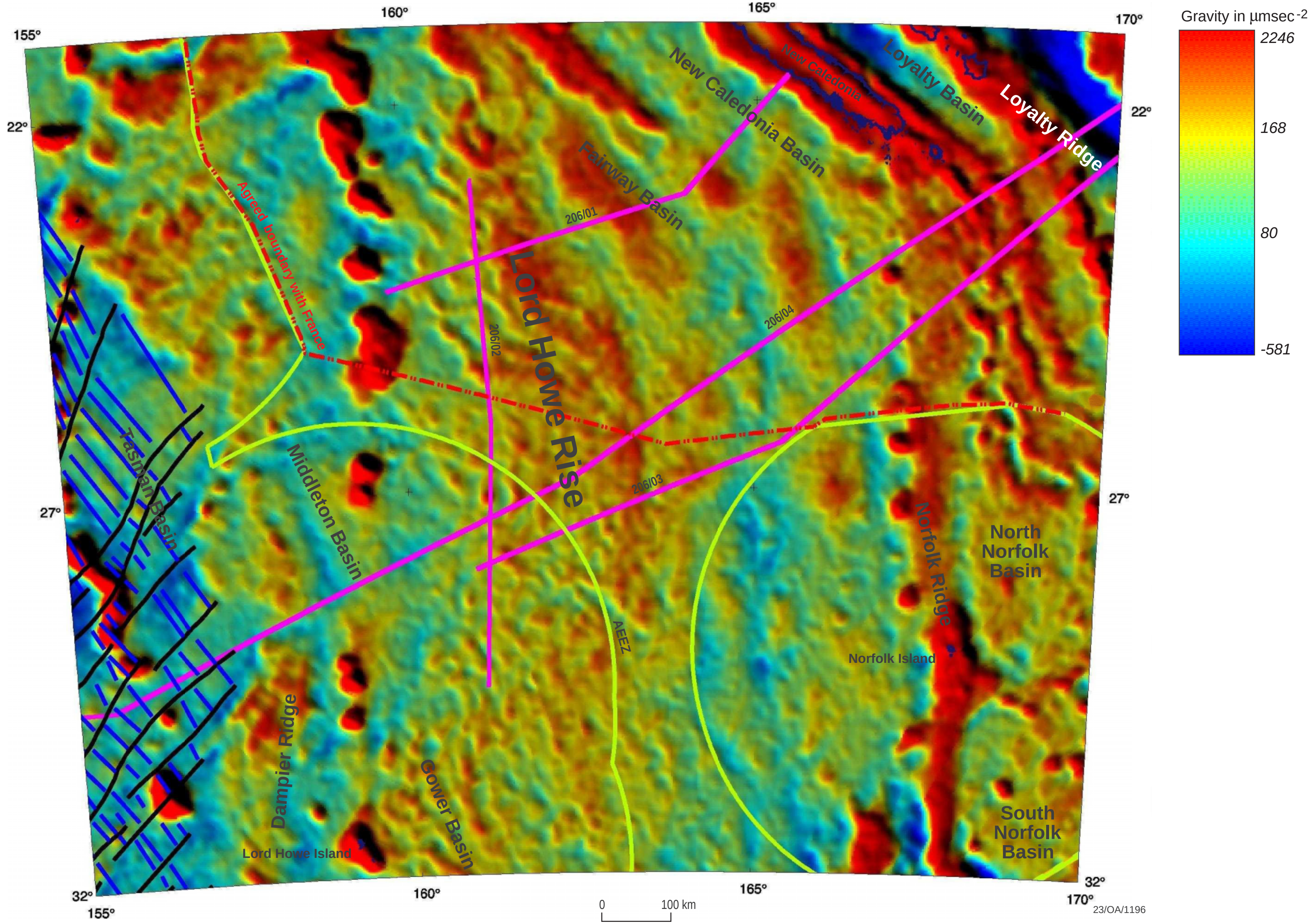


Figure 6. Satellite gravity image of the northern Lord Howe Rise region, with preliminary marine jurisdictional boundaries. Red coloring represents gravity highs and blue coloring represents gravity lows (after Sandwell & Smith, 1992). Legend: Magenta lines - Survey 206 / FAUST1 (Lafoy et al. 1998; Bernardel et al. 1999); AEEZ (lime green line) - Australian Exclusive Economic Zone.

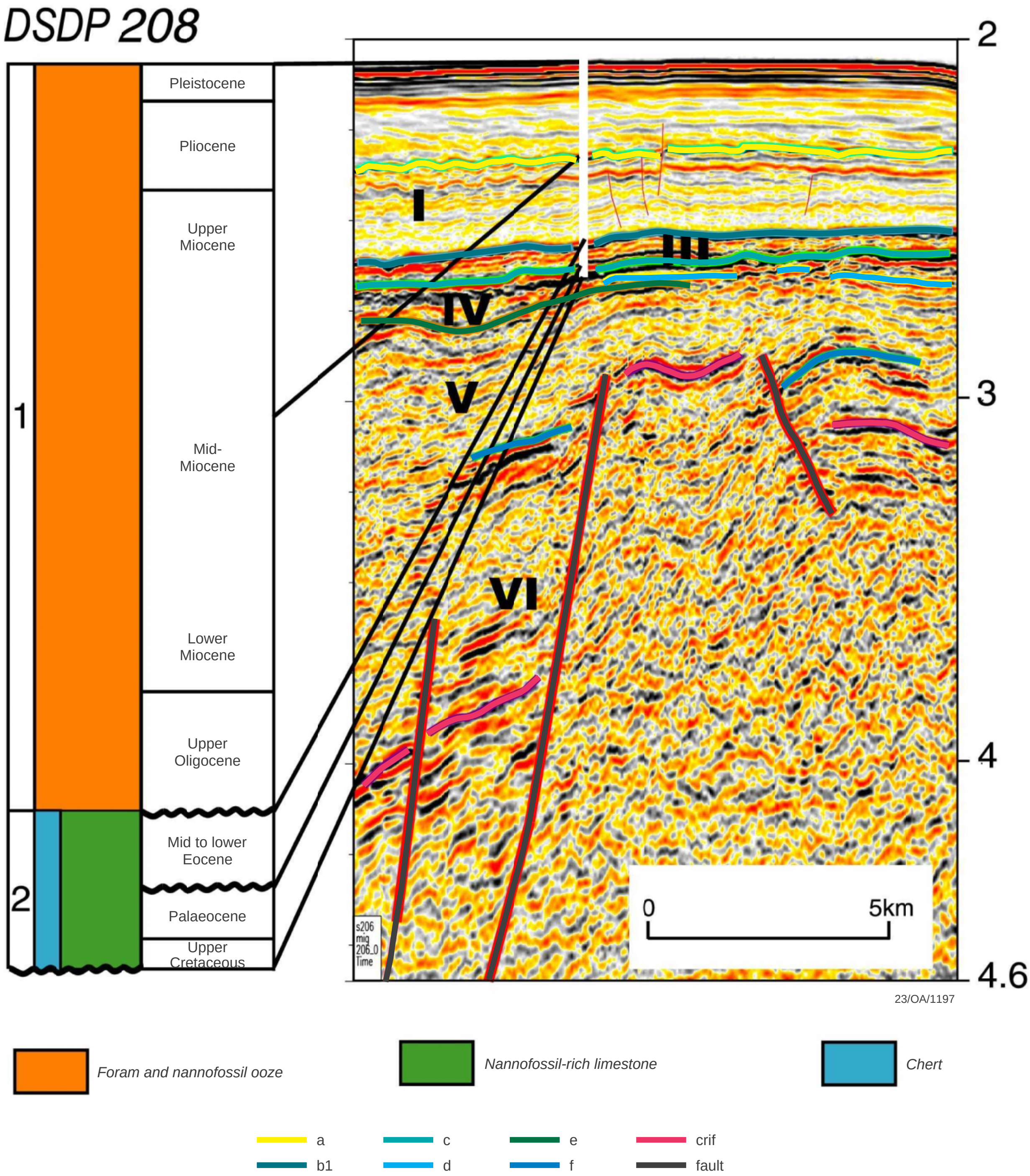


Figure 7. Stratigraphic column of DSDP 208 overlain on seismic reflection section 206-02. I to VI - assigned sequences (after Van de Beuque, 2000).

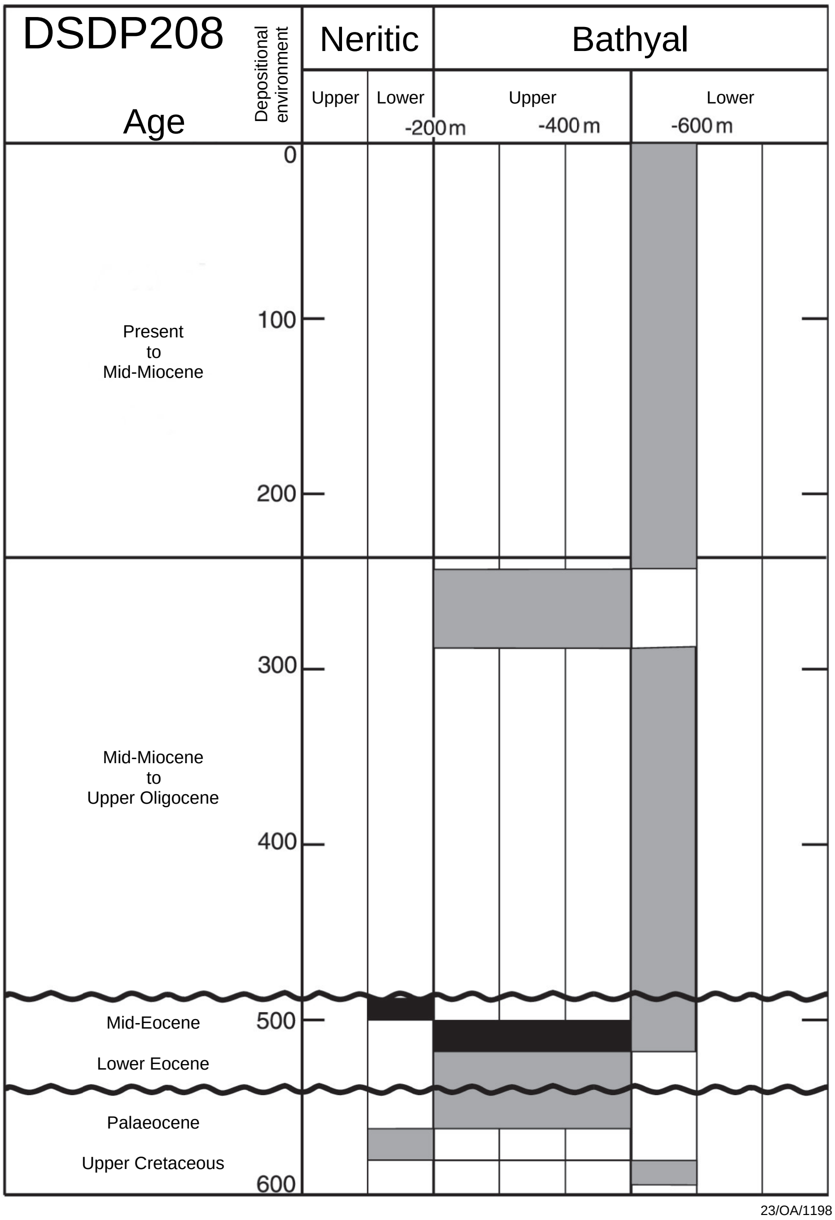


Figure 8. Palaeo-depths interpreted from DSDP Site 208. After Chaproniere et al. (1990). Shallow palaeo-depths are interpreted in the mid-Miocene from the abundance of glauconite in sediments.

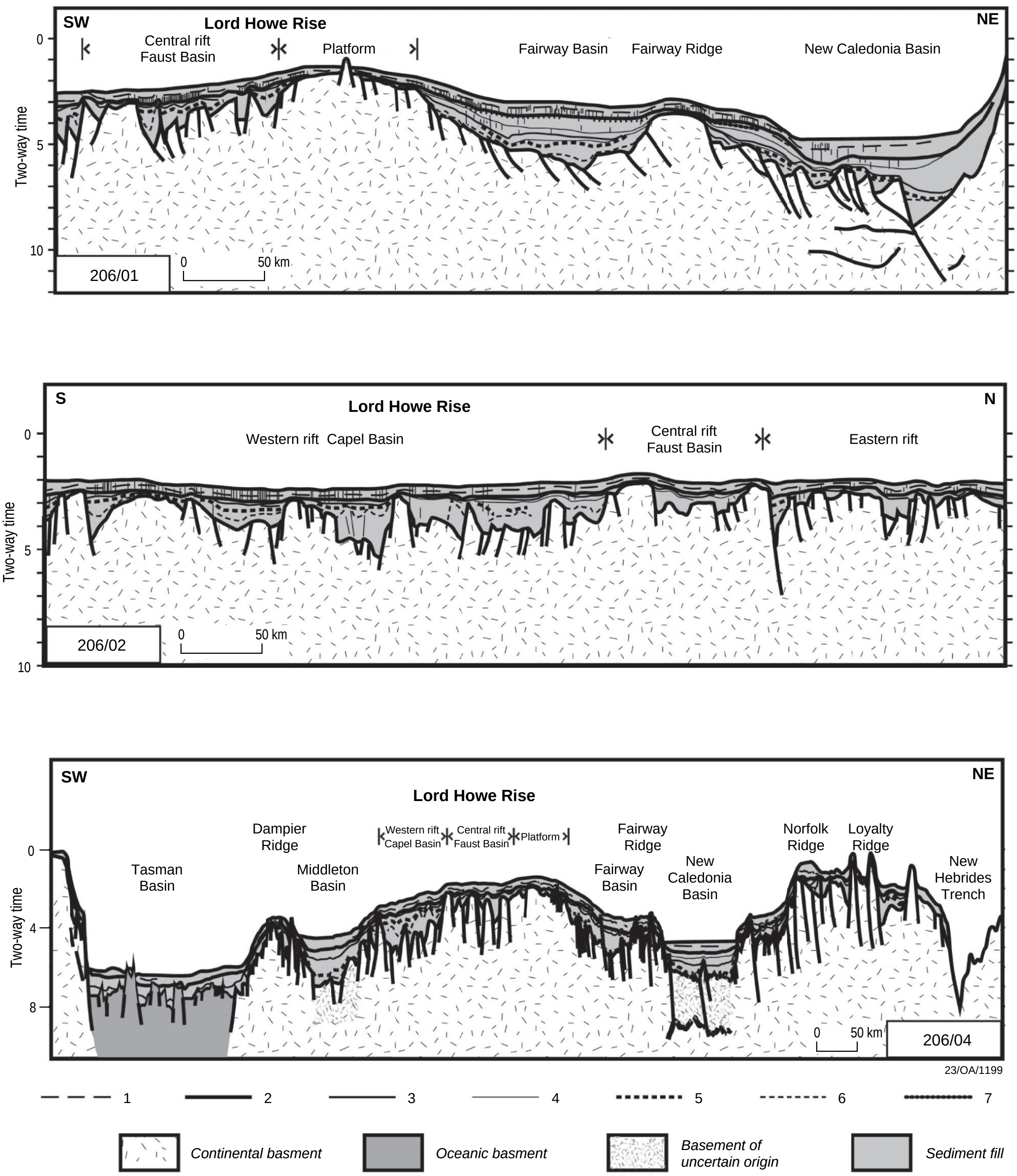


Figure 9. Simplified geological cross-sections based on an interpretation of Lines 206-1, 206-02 & 206-04. Modified from Van de Beuque (2000).

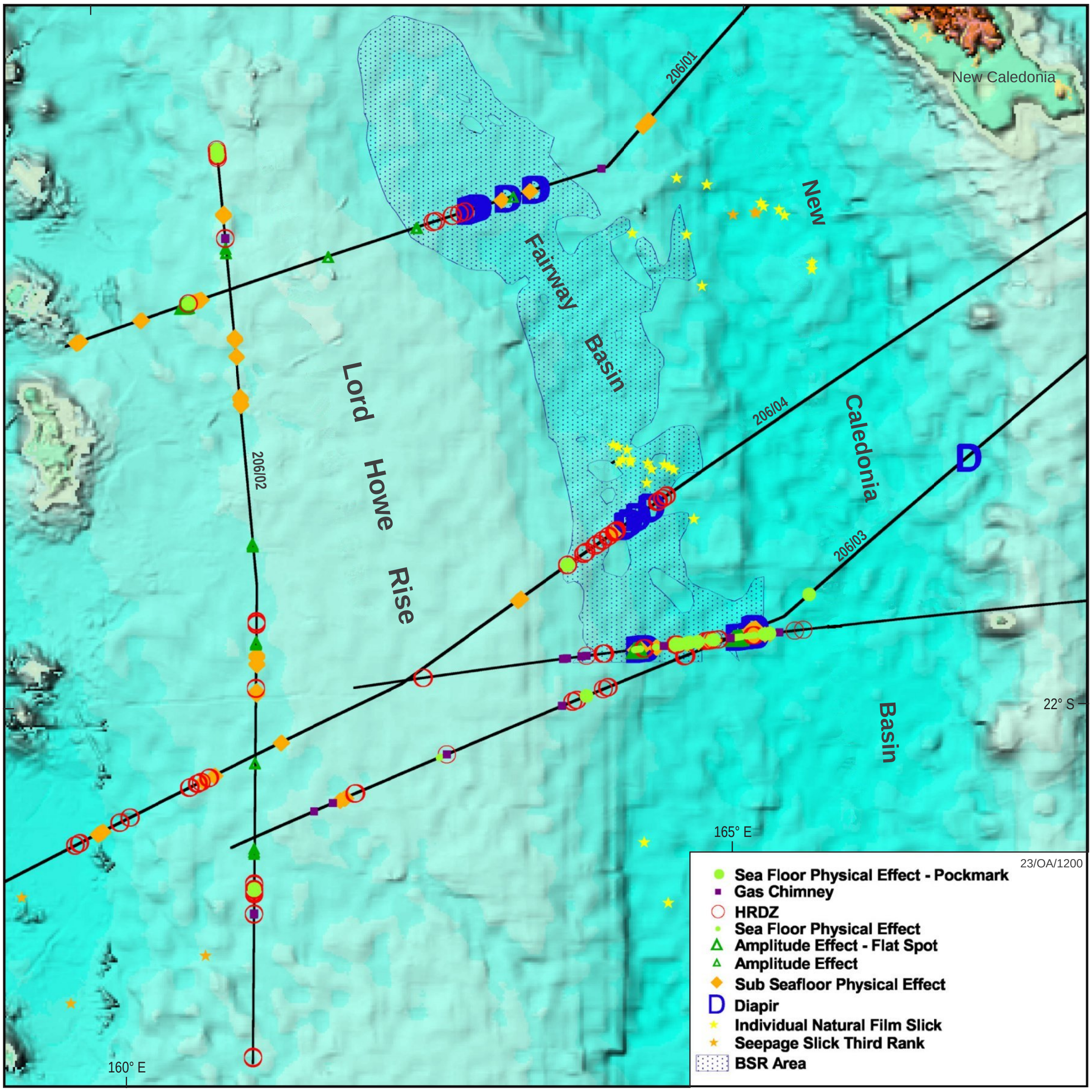


Figure 10. Map showing the distribution of direct hydrocarbon indicators across the northern Lord Howe Rise and Fairway Basin. Modified from Van de Beuque et al. (2000).

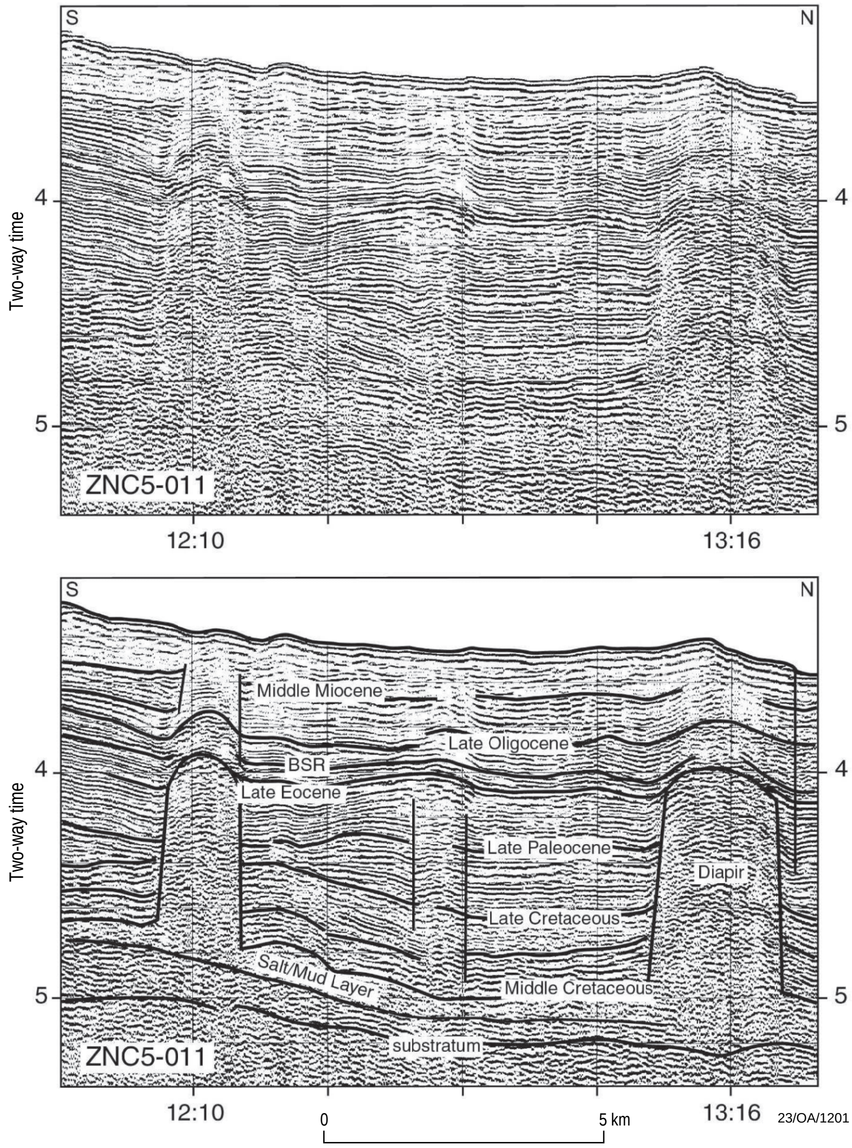


Figure 11. Seismic illustration, non-interpreted and interpreted, showing a 'bottom simulating reflector (BSR) overlying salt / mud structures in the Fairway Basin. Modified from Van de Beuque (2000).

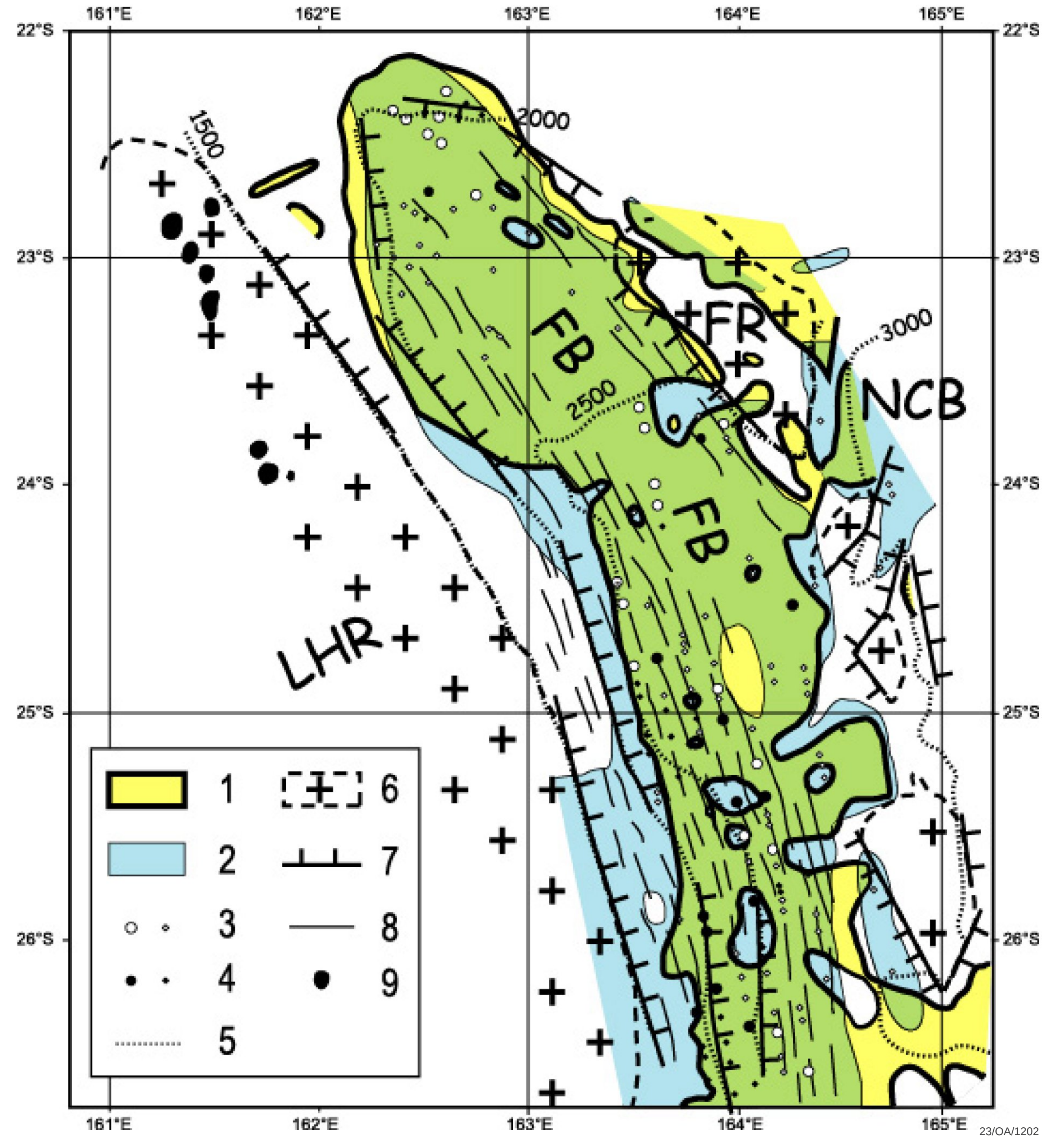
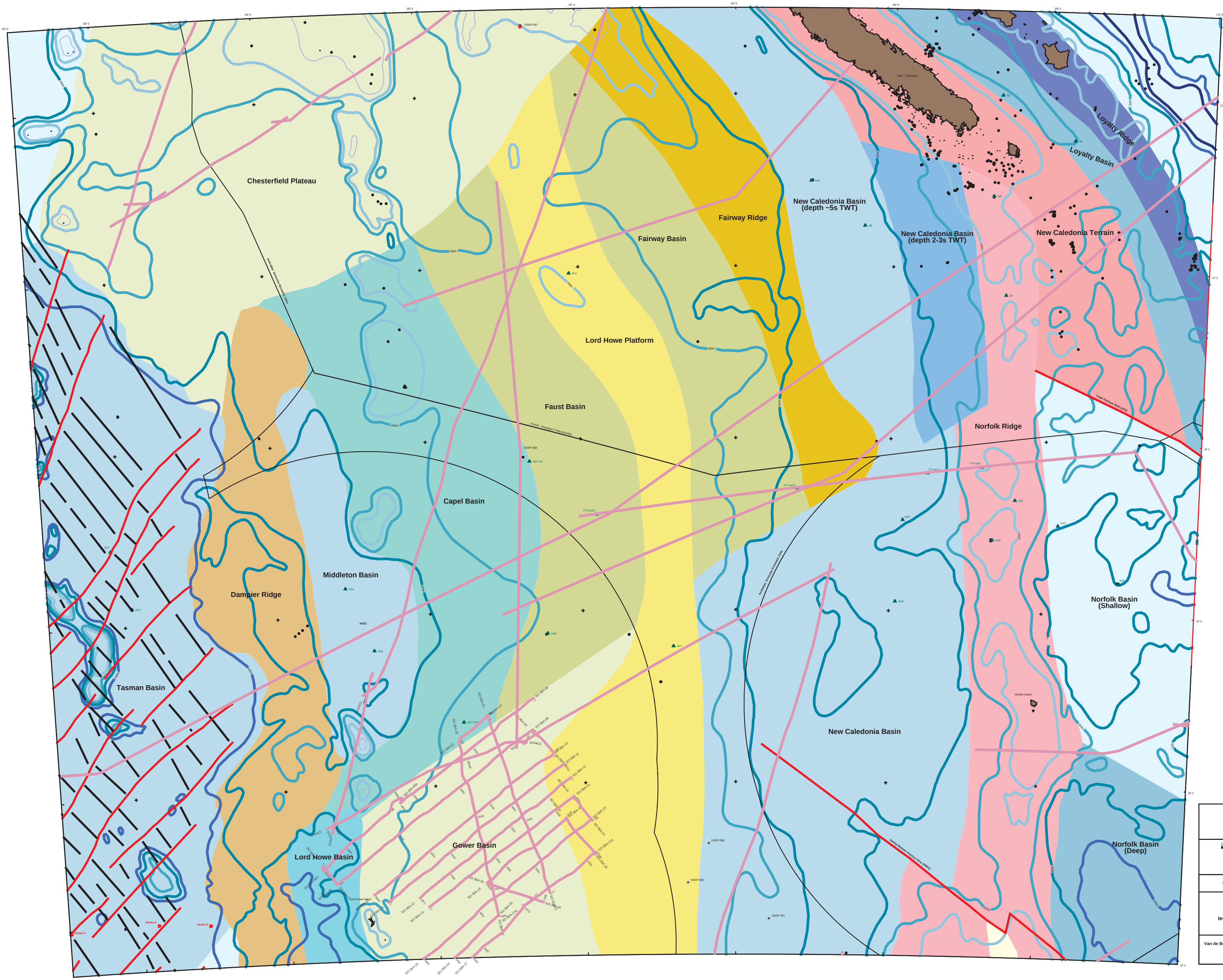


Figure 12. Map showing the distribution and superposition of gas hydrates with underlying salt-mud layers and diapirs. After Auzende et al. (2000b). Legend: 1 - extent of the BSR; 2 - extent of the salt layer and /or mud; 3 - deeply buried diapirs; 4 - diapirs at shallow depth; 5 - bathymetric contours (500 m interval); 6 - elevated basement; 7 - basement faults; 8 - sedimentary faults; 9 - volcanic edifices; LHR - Lord Howe Rise; FB - Fairway Basin; FR - Fairway Ridge; NCB - New Caledonia Basin.



Sonobuoy Locations
Samples Sites
Heat Flow Stations
Wells
ODP DSDP Wells

Bathymetry Contours
200m
1000m
2000m
3000m
4000m
5000m

0 30 60 90 120 150
KILOMETRES

LAMBERT CONFORMAL CONIC PROJECTION
WGS 1984 SPHEROID
PARALLELS 30° S AND 23° S, CENTRAL MERIDIAN 164° E
Mapsheet datum: "WGS 1984"

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Plate 1

Northern Lord Howe Rise
tectonic elements, with line and well locations

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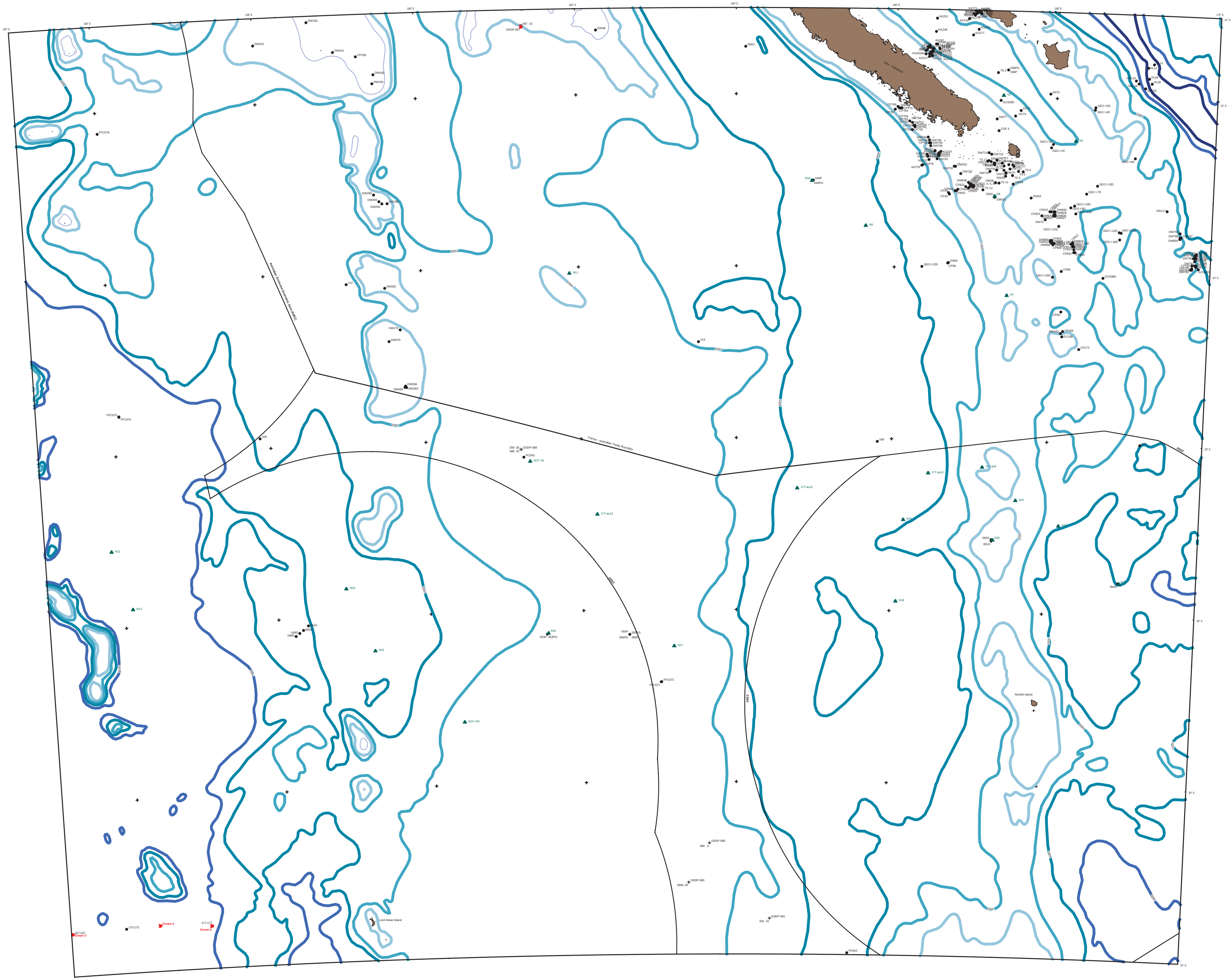
23/OA/1203



Sonobuoy Locations
Samples Sites
Heat Flow Stations
Wells
ODP DSDP Wells

Bathymetry Contours
200m
1000m
2000m
3000m
4000m
5000m

0 30 60 90 120 150
KILOMETRES

LAMBERT CONFORMAL CONIC PROJECTION
WGS 1984 SPHEROID
PARALLELS 30° S AND 23° S, CENTRAL MERIDIAN 164° E
Mapsheet datum: "WGS 1984"

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Plate 2

Northern Lord Howe Rise
Bathymetry, wells with sample stations

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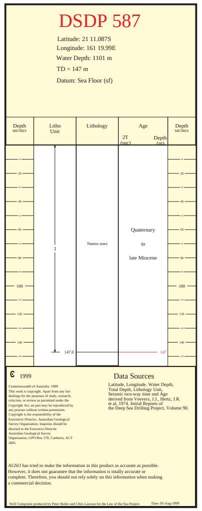

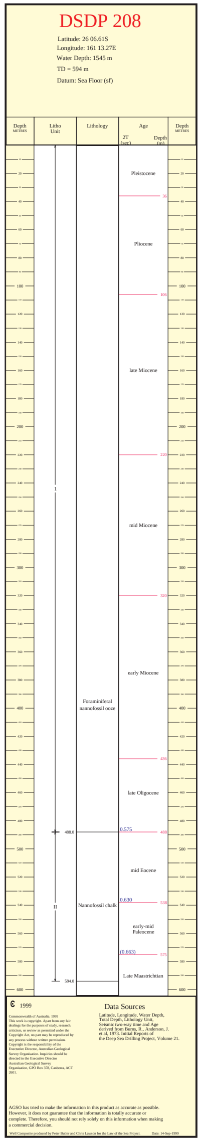

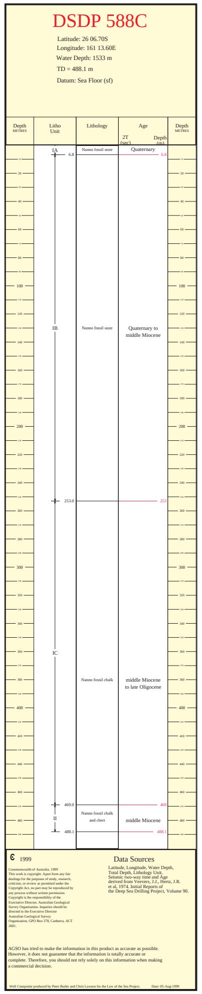

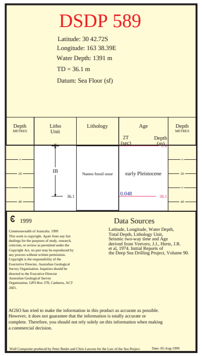

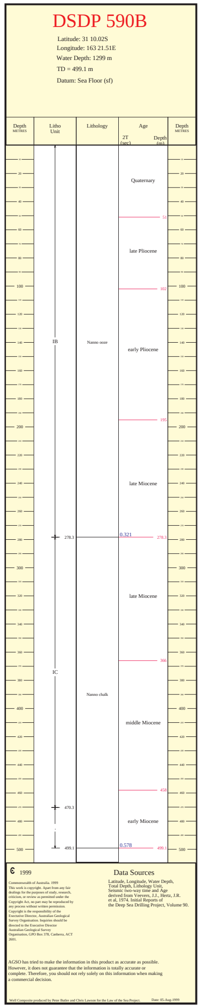

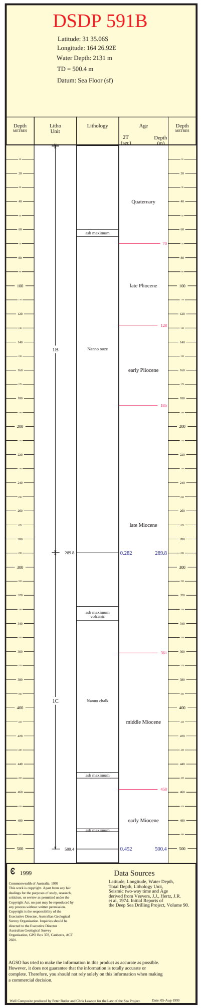

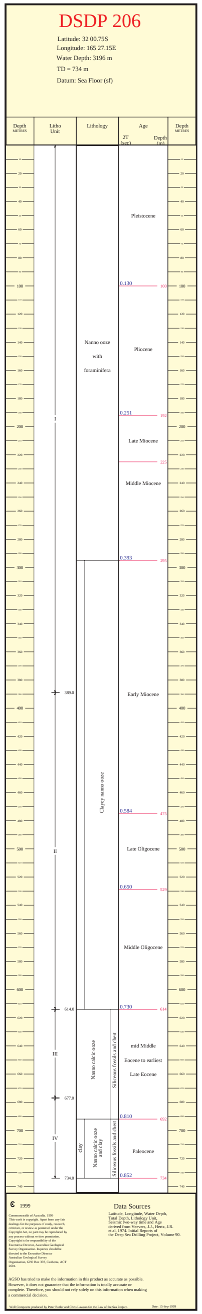

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Plate 3

Northern Lord Howe Rise
Well stratigraphy: DSDP Sites
206, 208, 587, 588C, 589, 590B, 591B

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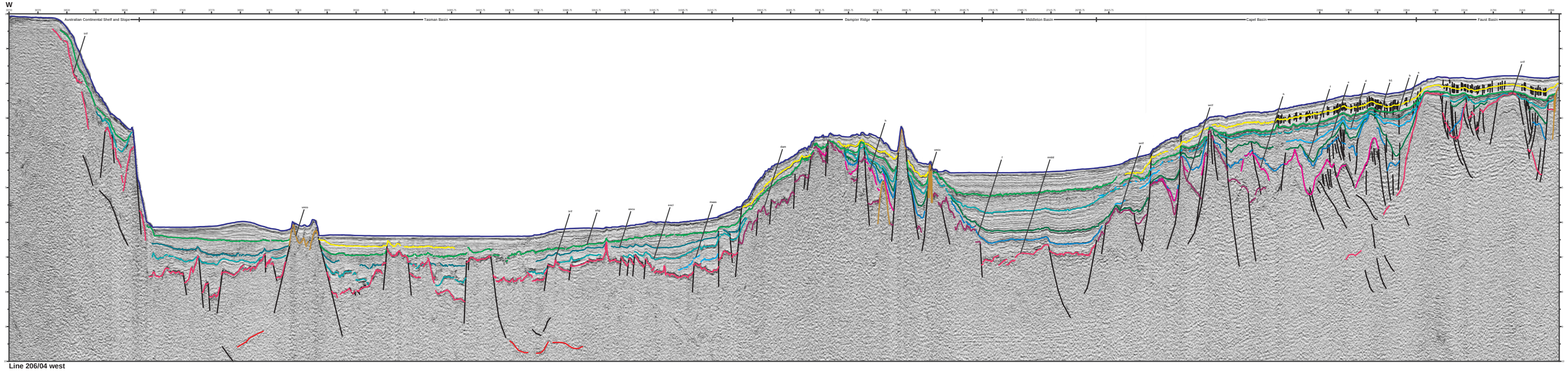

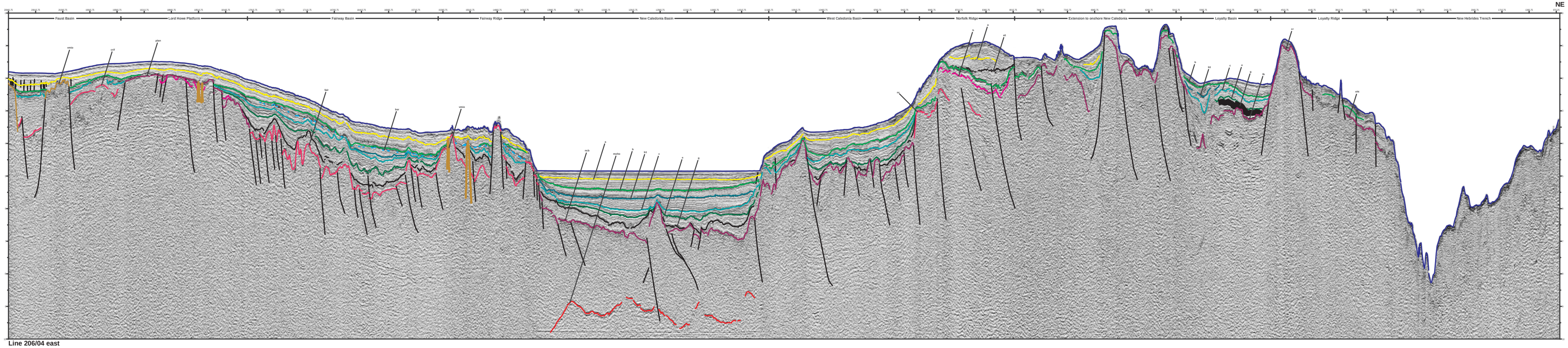

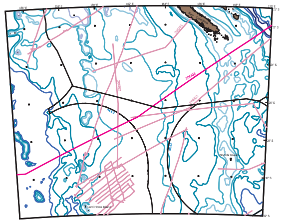

g	Sedimentary	Mid-Cretaceous
h	Sedimentary	Lower Cretaceous
plan	Basement	Planated basement - Lord Howe Platform
crif	Basement	Rifted basement - central Lord Howe Rise
wrif	Basement	Rifted basement - western Lord Howe Rise
trif	Basement	Rifted basement - Tasman Basin
dam	Basement	Rifted basement - Dampier Ridge
ncb	Basement	Basement - New Caledonia Basin
lb	Basement	Basement - Loyalty Basin and Ridge
fair	Basement	Basement, Fairway Basin and Ridge
midd	Basement	Basement, Middleton Basin
nr	Basement	Basement, Norfolk Ridge
nht	Basement	Basement, New Hebrides Trench
vmio	Volcanic	Miocene volcanics
moho	Other	Moho

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Plate 4

Northern Lord Howe Rise
Interpreted Seismic Sections (sheet 1)

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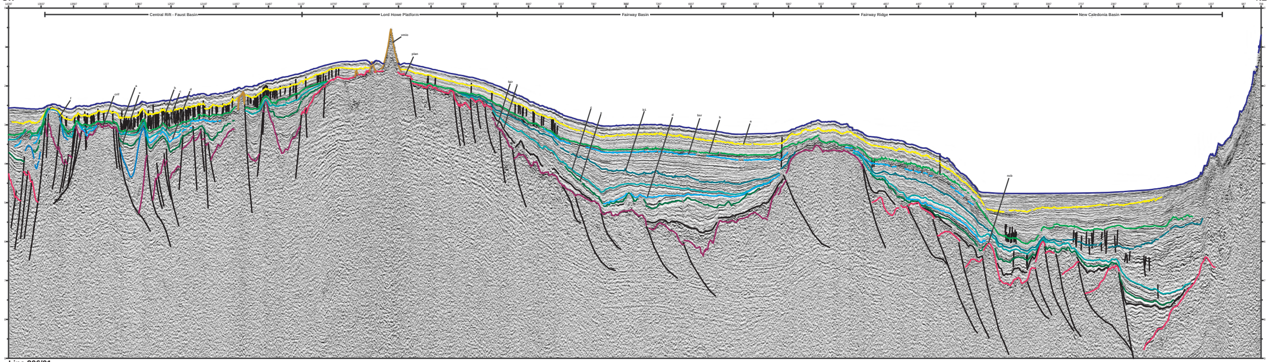
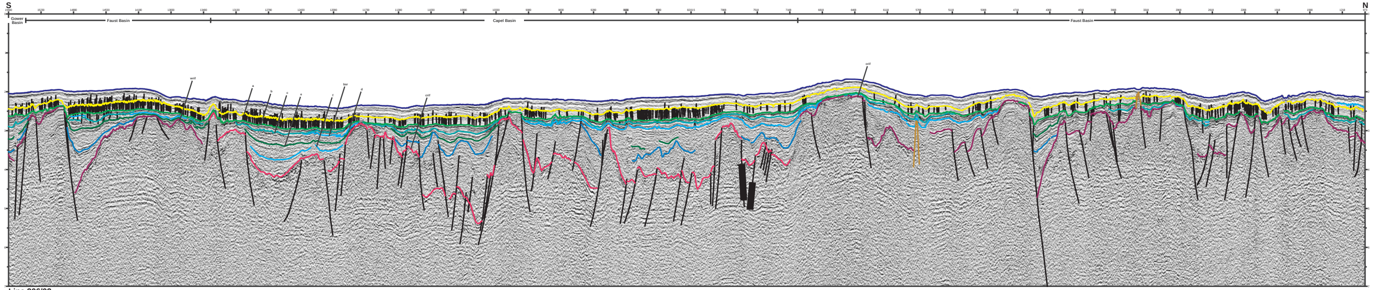


Line 206/01



Line 206/02

Seismic Horizon	Horizon type	Line	Description
wb	Other		water bottom
bsr	Other		bottom-simulating reflector
a	Sedimentary		Middle Miocene
b	Sedimentary		Oligocene
b1	Sedimentary		Upper Eocene
c	Sedimentary		Lower Eocene
d	Sedimentary		Maastrichtian
e	Sedimentary		Campanian (Tasman Sea breakup)
f	Sedimentary		Cenomanian
g	Sedimentary		Mid-Cretaceous
h	Sedimentary		Lower Cretaceous
plan	Basement		Planated basement - Lord Howe Platform
crif	Basement		Rifted basement - central Lord Howe Rise
wrif	Basement		Rifted basement - western Lord Howe Rise
ncb	Basement		Basement - New Caledonia Basin
lb	Basement		Basement - Loyalty Basin and Ridge
fair	Basement		Basement, Fairway Basin and Ridge
nht	Basement		Basement, New Hebrides Trench
vmio	Volcanic		Miocene volcanics

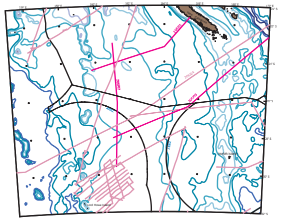


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Plate 5

Interpreted seismic sections (sheet 2)

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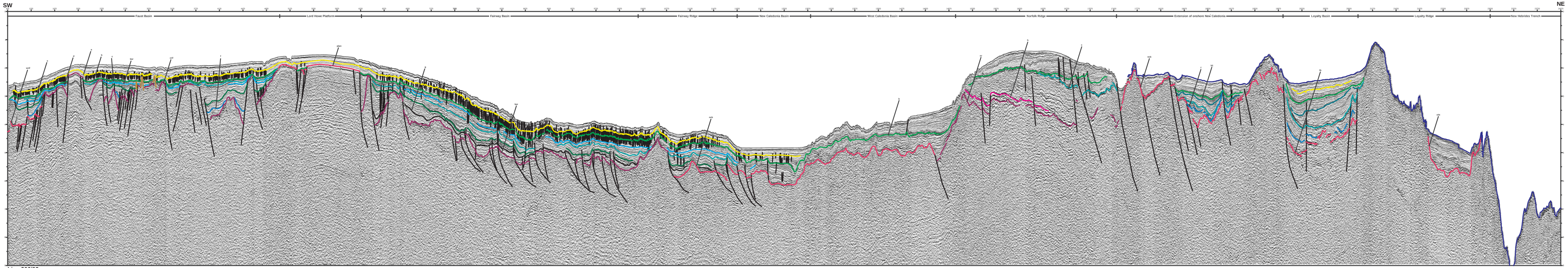

Line 206/03