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with consideration of its petroleum potential

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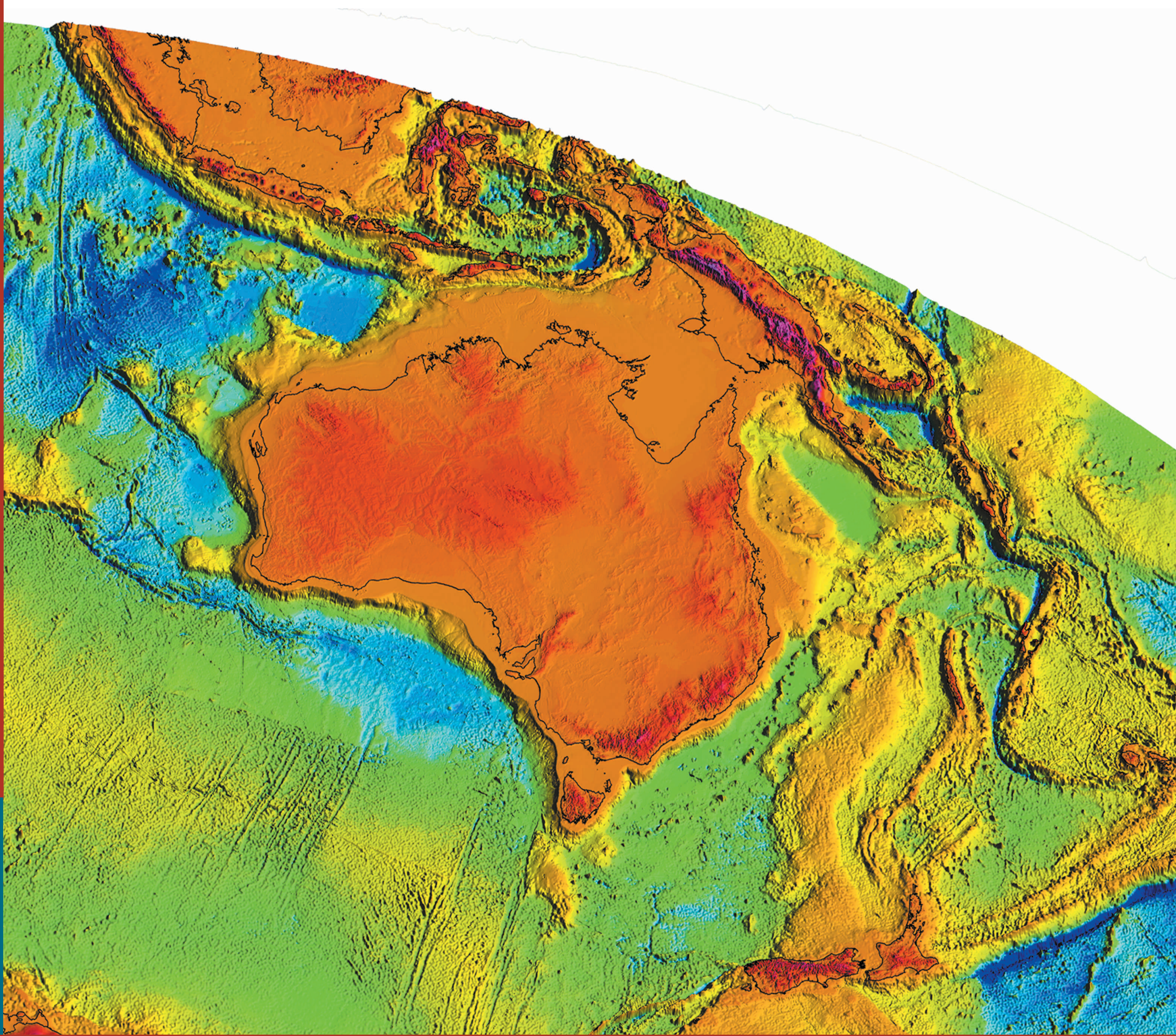

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GEOLOGICAL FRAMEWORK OF THE CENTRAL LORD HOWE RISE (GOWER BASIN) REGION with consideration of its petroleum potential

by

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TABLE OF CONTENTS

TABLES

FIGURES

PLATES

SUMMARY

The *Gower Basin* forms part of the 'Central Rift Zone' of the Lord Howe Rise (LHR) in the Tasman Sea. It lies about 100 km to the east of Lord Howe Island, approximately between latitudes 29°and 34°S. It appears to lie entirely within Australia's (200 n. mile) Exclusive Economic Zone (EEZ) generated by Lord Howe Island and Middleton Reef.

The Lord Howe Rise is a 'ribbon' of crust about 1600 km long and 250-600 km wide that has separated from continental Australia by oblique extension, approximately on a northeasterly azimuth. Its crestal water depths range from 750-1200 m below sea level and it is most clearly outlined by the 2000 m isobath. It is part of a vast extensional terrane spread through the Tasman Sea, stemming from the rifting and dispersal of Gondwanaland. The rifting process probably took place from the Late Jurassic, following a protracted period of plate convergence during the Palaeozoic and Early Mesozoic. The events and basin development were allied to those along Australia's Southern Margin. Breakup and dispersal commenced in the late Santonian and seafloor spreading led to formation of the small Middleton and Lord Howe Basins, the Dampier Ridge, and the Tasman Sea Basin. That process continued until the Early Eocene, after which the region again became subject to convergent tectonism along the eastern margin of the Australian Plate.

The structure of the LHR is asymmetric in relation to its conjugate on the eastern margin of Australia, in that extensional basins formed during the rifting stage are now largely confined to the western half of LHR ('Western and Central Rift Zones'), with only minor rifts being preserved along the eastern seaboard of the continent. The 'basement' underlying these features is assumed to be composed of a wide range of Palaeozoic and Early Mesozoic terranes, probably an equivalent of the New England Fold Belt and overlying depocentres, together with volcanics.

The limits of the Gower Basin are currently ill-defined, though it appears to have a width of approximately 250 km and may be more than 500 km in north-south extent. In reconstructions of the LHR against eastern Australia, the southern part of the Gower Basin lies along the northern edge of the Gippsland Basin, and it would appear that the two basins share a common history until the Santonian breakup. The Gower Basin was first identified as a region of relatively thick sedimentation during seismic operations conducted with the BGR *Sonne* (Survey 36a) in 1985. This survey was followed up by operations with AGSO's (now Geoscience Australia) *Rig Seismic* (Surveys 46 & 206) in 1985 and 1998. The Gower Basin is the only region of the LHR that is covered by a relatively systematic seismic grid, though the line spacing of 20-40 km is still very regional in nature.

The Gower Basin is an oblique extensional feature that comprises several north-northwest-trending horsts and graben offset by at least three northeast-trending accommodation zones. The main graben system lies adjacent, and to the west, of a region of planated basement (the Lord Howe Platform) that makes up the eastern half of LHR. The sediment fill within the graben averages 1.5-3.0 km but reaches a maximum of 4+ km in places. The nature of the sedimentary section is known only from two Deep Sea Drilling Project (DSDP) sites, drilled adjacent to the Gower Basin

that penetrated the younger section. The rocks recovered comprised Maastrichtian sandy siltstones of shallow marine origin, overlain by mainly foraminiferal oozes and clays deposited in a rapidly deepening environment.

This study of seismic data indicates that the Gower Basin contains a substantial older section. Two phases of syn-rift sedimentation have been recognised that bear close analogy to those in the Durroon Sub-basin of Bass Strait, and also similarity to the Gippsland and Otway Basins. The oldest sequences are interpreted to be equivalents of the latest Jurassic Casterton Beds and Early Cretaceous Otway/Strzelecki Groups. During the mid Cretaceous (Cenomanian) these underwent substantial uplift, ?inversion, and erosion. A further syn-rift phase then ensued: probably of Cenomanian-Campanian age, it is considered to be an equivalent of the Golden Beach Group in the Gippsland Basin, but may have been more marine in character. Breakup and seafloor spreading commenced in the latest Santonian to early Campanian (Chron 33).

Following separation from continental Australia, the Gower Basin region is interpreted to have entered a period of non-marine (?fluvial-lacustrine) to shallow marine deposition. Subsidence of the graben, and differential compaction of their infill, led to the deposition of 1500-1800 m of sediment in some areas, possibly within a restricted marine environment. This may have included potential petroleum source beds. As thermal subsidence proceeded the region gradually deepened: by the middle Oligocene it had reached an 'oceanic phase' and was receiving largely pelagic sediments. From about the Miocene onwards the strata have been broadly folded in response to compression along the plate boundary to the northeast.

There is good seismic evidence for the presence of diapiric-like features within the Gower Basin. Diapirs that seem to emanate from the syn-rift section, near the axis of the main graben system, could well be shale or possibly even salt. Those that occur in the upper part of the section are, however, more likely to be volcanic intrusions, three phases of volcanism having been identified on Lord Howe Island.

Structurally, the Gower Basin could be described as a 'poly-history basin', in that it has developed through an extended period, encompassing the ?Late Jurassic – Recent, via oblique extension, inversion, subsidence and compressional folding. This has given rise to a plethora of potential petroleum traps, including rift-margin structures, syn-rift folds and inversion structures, pinchouts, and possible diapiric features and ?carbonate buildups. As in the Bass Strait basins, the early syn-rift fill is likely to comprise sediments with a high volcanogenic component, and is thus unlikely to provide either a good source or reservoir. However, from the Cenomanian onwards the region appears to have come under increasing marine influence and the prospects for finding source beds deposited in restricted marine environments seem reasonable. Reservoir beds are expected within the varied non-marine to shallow marine sequences laid down after breakup. Seals could be provided both within these sequences and within the younger pelagic oozes.

In terms of petroleum prospectivity, the greatest uncertainty is the thermal maturity of potential source beds that have been subject to a limited overburden in some areas. However, there is positive evidence for the active generation and migration of hydrocarbons in other parts of the LHR, by way of ‘bottom simulating reflectors’ and ‘flat spots’, in the Fairway, Middleton and Monawai Basins.

INTRODUCTION

This is one of a series of three reports dealing with the geological framework of the Lord Howe Rise (LHR) region of the Tasman Sea. These Geoscience Australia[1] (GA) reports cover the Northern LHR (Van de Beuque *et al.*, in press), Central LHR Gower Basin (Willcox & Sayers, this report), and the Southern LHR (Stagg *et al.*, in press). They provide part of Geoscience Australia's commitment to examine possible legal boundaries, geology and resource potential, of regions to which Australia may lay claim under the 1982 United Nations Convention on the Law of the Sea (UNCLOS). A further report that will deal with the petroleum prospectivity of the Gower Basin and LHR in general is also being prepared (Bradshaw *et al.*, in prep).

The Gower Basin is the most significant area of thick sediment that has so far been identified on LHR. It was first outlined in 1985, during seismic operations conducted by BMR (a GA predecessor) and the Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR, the then West German Geological Survey) aboard R/V *Sonne* (Survey 36a; Roeser & Shipboard Party, 1985; Figure 1). Further assessments of the area were made using AGSO's (now Geoscience Australia) R/V *Rig Seismic* (Surveys 46 & 206; Whitworth & Willcox 1985; Lafoy *et al*. 1998; Bernardel *et al*. 1999). The Gower Basin is the only part of the LHR that is covered by a relatively systematic seismic grid, though the line spacing of 20-40 km is still very regional in nature.

In addition to a greater than average sediment thickness for LHR, interest in the Gower Basin area also stems from its position in reconstructions with continental Australia. These indicate that the southern flank of the basin may once have lain approximately along the projected northern edge of the Gippsland Basin, which is productive for liquid hydrocarbons, and that the two basins may have shared a similar pre-breakup history (Figure 2). This has led to speculation that the Gower Basin may have reasonable prospectivity for petroleum (Willcox 1981; Symonds & Willcox 1989). Further, seismic monitor sections recorded aboard the R/V *Sonne* showed features that appear to be diapirs of shale or salt and could thus provide significant traps for any hydrocarbons.

The area under consideration in this report extends from about 158 to 163°E and from 29 to 34°S. The interpretation is based on reprocessed seismic profiles (Surveys 36A and 46) that now provide a fair-good quality data set through the Gower Basin area.

Under UNCLOS, Australia has jurisdiction over a significant portion the Lord Howe Rise (LHR) region that stems from the presence of Lord Howe Island, Norfolk Island, Elizabeth and Middleton Reefs, and the Exclusive Economic Zones (EEZs) that they

[1] Geoscience Australia (GA) 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.

[2] 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.

generate (Table 1). However, the limit of the total Legal Continental Shelf (LCS)[2] in the LHR/Norfolk region to which Australia can lay claim will be derived from a combination of the islands' EEZs, together with the application of several UNCLOS formulae, and seabed boundaries negotiated with France (New Caledonia) and New Zealand (Symonds & Willcox, 1989, Figure 2, Table 1).

Table 1: Approximate areas of the EEZs and LCS in the LHR/Norfolk region

EEZ generated by Lord Howe Island etc.	430 000 km^2
EEZ generated by Norfolk Island	390 000 km^2
LCS extension using UNCLOS formulae	580 000 km^2
Total LCS for LHR/Norfolk region	1400 000 km^2

The LCS in the LHR/Norfolk region incorporates several regional geological provinces and sedimentary basins that may have potential for petroleum. Under any management regime associated with Australia's claim over this region, a knowledge of the resource potential of these basins is required. This framework study of the central Lord Howe Rise (Gower Basin) lies within Australia's EEZ. It can be used as a guide to the type of geological features that may be present on the Lord Howe Rise as a whole, particularly in areas where the distribution of seismic data are sparse.

BACKGROUND

The Lord Howe Rise is the major physiographic feature in the Tasman Sea, extending north-northwest from the South Island of New Zealand to Lord Howe Island, then northwards to the Chesterfield Islands Group at about 20°S (Figures 1 & 2, Plate 1). It is a ribbon-like plateau feature that is most clearly outlined by the 2000 m isobath. Its crest lies generally at about 750 to 1200 m below sealevel and is surmounted by the small volcanic island edifices. The Lord Howe Rise has a length of approximately 2500 km and a width of 450-650 km. To the west of Lord Howe Island, between 26 and 34°S, it is separated from the Dampier Ridge by the small Middleton and Lord Howe Basins. Beyond this, the 4500 m deep Tasman Basin extends to the narrow continental margin of eastern Australia. To the east, it is separated from the Norfolk Ridge by the New Caledonia Basin, which has a depth of 3000-3500 m.

The rises, ridges and basins of the Lord Howe Rise region are interpreted to comprise mainly continental fragments that detached from the eastern margin of continental Australia during the latest Jurassic and Cretaceous. The rifting and breakup process that gave rise to these features led to the formation of the Tasman Sea and New Caledonia Basins. The continental fragments were themselves composed of terranes that accreted to the eastern flank of the Australian craton during the Palaeozoic and early Mesozoic eras. The region has passed through the full gamut of continental margin development, ranging from compression and accretion, through passive margin extension, breakup and seafloor spreading, to present-day convergence within a subduction/obduction setting. While both compression and extension have taken place in a broadly east-west sense, the azimuth of relative motion between lithospheric plates has varied widely through time. The resulting geology is thus complex.

This study concentrates on an area of the Lord Howe Rise (LHR) that lies adjacent to Lord Howe Island and to its east and northeast (Figure 2). It extends from 158 to 163°E and from 29 to 34°S (approximately 550 x 650 km). Water depths within the area range from about 1000 to 3000 m, except for localised shallows associated with the Lord Howe Island seamount. It is of particular interest, in that it is the only area on the LHR that has been systematically covered by seismic reflection techniques. A loose grid, comprising approximately 5000 km of seismic profiles, is available from surveys conducted mainly by the German BGR's vessel R/V *Sonne* (Roeser & Shipboard party, 1985) and AGSO's (now GA) R/V *Rig Seismic* (Whitworth & Willcox, 1985; Plate 2). During a preliminary interpretation aboard ship, the area was identified as one that included substantial sedimentary depocentres that were referred to collectively as the *Gower Basin*.

DATA

Bathymetry

The main sources of grided bathymetric data in the central Lord Howe Rise area are a 30 arc-sec grided bathymetric model (Buchanan, 1998) and the predicted bathymetry (Smith & Sandwell, 1994).

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. 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.

Plate 1 shows the 30 arc-sec data merged with the predicted bathymetry without degrading the original data.

Contour bathymetric data, derived from the General Bathymetric Chart of the Oceans (GEBCO) and from the AGSO Offshore Resource Map Series (ORMS), have been used as a backdrop for displaying survey lines and interpretation results (Plate 1).

Seismic Reflection

The Lord Howe Rise is a 'frontier area' as regards commercial hydrocarbon exploration. Most seismic reflection surveys have been very regional in nature and comprise a number of broadly-spaced and unsystematic traverses. This study has been made use of the only two gridded profile sets on the Lord Howe Rise (Plate 2); namely -

BGR *Sonne* 36 (1985): BGR (Bundesanstalt für Geowissenschaften und Rohstoffe, of the then Federal Republic of Germany) in cooperation with BMR (now GA) 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 good quality, with excellent resolution of basement topography and internal sedimentary character. They comprise the main data set in the northern part of the study area.

AGSO *Rig Seismic* Survey 46: This survey was the inaugural operation with the R/V *Rig Seismic* and comprises four lines on the western flank of the Lord Howe Rise to the south of Lord Howe Island. The data are of average/poor quality and do not have the resolution of *Sonne* 36 (Whitworth & Willcox, 1985).

Also,
AGSO *Rig Seismic* Survey 206 (1998) "FAUST1": Survey 206 (FAUST1) was a joint Australian-French deep-seismic survey acquired by AGSO in 1998 (Lafoy *et al*., 1998 ; Bernardel *et al*., 1999). 4564 km of high-quality data were recorded over the northern Lord Howe Rise, New Caledonia Basin and Norfolk Ridge system along four lines, of which three are oriented ENE-WSW, while the fourth is oriented N-S along the axis of Lord Howe Rise. Although these data lie largely to the north of the Gower Basin study area, the profiles are useful in discerning the geological evolution, since the data are of particularly high resolution.

Seismic Velocities

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.

Potential Field

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

Sandwell & Smith (1997) 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) (Plate 3).

Deep Sea Drilling Program

Three legs of the Deep Sea Drilling Project (DSDP) have drill-sites in the LHR region. Leg 21 (Burns, Andrews *et al*., 1973) drilled Sites 203 to 210, of which Site 206 is in the New Caledonia Basin, and Sites 207 and 208 are on the Lord Howe Rise. Leg 29 (Kennett, Houtz *et al*., 1974) drilled Sites 275 to 284; Site 283 in the southwest Tasman Basin and Site 284 on the Challenger Plateau. Leg 90 (Kennett, von der Borch *et al*., 1986) drilled Sites 587 to 594 on the Lord Howe Rise, Challenger Plateau and Chatham Rise. However, these sites were drilled primarily for palaeoceanographic purposes and are of limited value to this study because they only penetrated the younger section.

Dredging and Coring

While a large number of seabed samples have been recovered since the late 1960s, most of them consisted only of surficial sediments.

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

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

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

Heat-flow

Heat-flow data are sparse in the study area, with the only data available coming from seven stations in the Tasman Basin and on the western Lord Howe Rise (Grim, 1969) and from Deep Sea Drilling Project (DSDP) Sites 206 and 587 in the New Caledonia Basin and northern Lord Howe Rise, respectively.

PREVIOUS STUDIES

Seafloor Spreading

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 data and satellite gravity data. This interpretation of the breakup of the Tasman Basin is considerably more complex than previous authors have interpreted. They showed that Tasman Sea spreading cannot be modelled as a simple two-plate spreading system and they identified 13 microplates (Gaina *et al.,* fig. 6) that were active during breakup and spreading. This complex microplate history was accompanied by several changes in spreading azimuth, and involved several failed rifts, and is described in some detail below.

Seafloor spreading was initiated in the southern Tasman Sea (84 Ma) as a result of rifting between the Challenger Plateau and the middle Lord Howe Rise. A brief left-lateral transtension phase led to the formation of the Bellona Trough, which contains Cretaceous sediments (Wood, 1993), before the onset of spreading in the Tasman Basin. Following this event the Challenger Plateau attached to the middle Lord Howe Rise and the combined structures separated from Australia. Magnetic lineations identified between the Challenger Plateau and the Gilbert Seamount Complex (84–77 Ma) correspond to the next episode of spreading resulting in about 250 km of oceanic crust being emplaced between these structures. At about 77 Ma the spreading stopped and Gilbert Seamount, which was previously attached to the South Tasman Rise, transferred to the Challenger Plateau. As will be noted later in our interpretation, it is possible that the crust between the Gilbert Seamount and Challenger Plateau is either highly extended continental crust, or an amalgam of continental and oceanic crust.

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

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

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

Tasman Basin spreading ceased between 56 and 52 Ma following a slowing of the spreading rate. This event reflects a major change in plate driving forces of the Australian plate, which predates the beginning of India-Eurasia collision.

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

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 (for example, Lister *et al*., 1991) 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 was 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. 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*., 1991).

Bradley (1993) adapted this detachment model to the development of the offshore Sydney Basin. The depiction of LHR in this interpretation 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 and Lord Howe/Middleton Basins is interpreted to be highly attenuated continental crust, with no evidence of the emplacement of oceanic crust in either basin; and/or

- 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.

Geology of Bass Strait Region

The pre-drift configuration of the Lord Howe Rise with respect to continental Australia indicates that the central part of the rise once lay adjacent to the Bass Strait basins (that is, to the proto-Gippsland and Bass Basins), probably at an incipient triple junction. Thus seismic megasequences within the Gippsland and Bass Basins that have been interpreted as pre-breakup units should have equivalents on the Lord Howe Rise. Willcox *et al*. (1992; Figures 2 & 4) identified such megasequences and interpreted them in terms of major tectonic events associated with rifting and breakup/seafloor spreading for the Southern Ocean and Tasman Basin. These megasequences, considered to range in age from Jurassic to Oligocene, have been incorporated into both extensional and wrench related/compressional structures.

Willcox *et al*. (1992) envisaged these structures to have formed by relative movements between the Australia, Lord Howe and Antarctic Plates, together with two microplates (King Island- Tasmania and Bassian microplates; Figure 4).

During Cenomanian to Campanian times (~95-80 Ma) the ?Bassian microplate (occupying southern Bass Strait) and the Lord Howe Plate appear to have remained coupled, despite rifting between them that had probably been taking place since the Late Jurassic. The Lord Howe Plate was moving in a highly oblique left-lateral sense with respect to the Australia Plate. In so doing, it dragged the Bassian Plate with it and gave rise to slight anti-clockwise rotation of that plate, creating compression and overthrusting in the Gippsland Basin, within the synrift sediments of the Early Cretaceous Strzelecki Group. Along the trailing edge of the Bassian Plate commensurate extension was taking place. This is observed as rifting and tilt-block formation within the Durroon Sub-basin of the Bass Basin (previously known as the Boobyalla Sub-basin; Figure 5). In that sub-basin, Early Cretaceous 'synrift' sediments of the Otway Group (the Strzelecki Group equivalent) are themselves showing a pre-rift geometry with respect to the younger Late Cretaceous and Palaeogene Eastern View Coal Measures. The Eastern View Coal Measures are divided by a well-defined Campanian unconformity into a classic (fan-shaped) synrift section and a younger Campanian - ?Oligocene sag-phase section.

This model predicts that the general geometry and relationship of seismic megasequences within the Durroon Sub-basin should be closely allied to the situation on the central part of the Lord Howe Rise. In fact, it appears that the Durroon profiles provide an almost perfect analogy with those in the Gower Basin (compare Figures 5 & 6, see also Figure 7).

Heat-Flow

Heat-flow data are sparse in the Lord Howe Rise region. Some have been derived from surficial sediment thermal gradient measurements published by Grim (1969) and others from DSDP Sites 206 (Burns, Andrews *et al*., 1973) and 587 (Kennett, von der Borch *et al*., 1986). Both these methods of measuring heat-flow are subject to multiple sources of error and caution must be used in over-interpreting the results, particularly where there is only a few measurements in a large area.

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

Hydrocarbon Assessment

Willcox *et al*. (1980) undertook a regional assessment of the hydrocarbon prospectivity of the Lord Howe Rise. This assessment, which is still largely relevant, has been taken further by Symonds & Willcox (1989) who assessed the hydrocarbon prospectivity of areas beyond the EEZ. As no petroleum exploration has taken place in the Lord Howe Rise region, these assessments of the hydrocarbon potential were based largely on the results of the Deep Sea Drilling Program, analysis of seismic profiles to estimate sediment volume and depositional environments, and analogy with tectonically similar basins (other rift basins and most notably the Bass Strait basins). Using these principles of volumetric analysis and statistical recovery from major basins worldwide, Symonds & Willcox (1989) provided a 'best estimate' for the western flank of the Lord Howe Rise beyond the 200 nm EEZ of 0.56 billion cubic metres, that is 3.5 billion barrels. Since the volume of sediments on western LHR, within the EEZ appears to be of similar magnitude, and the type and distribution of basins is much the same, we can anticipate a similar potential recovery of around 3.5 billion barrels. The central part of the Lord Howe Rise (Gower Basin) would account for perhaps 30-50% of this potential recovery.

Non-conventional Hydrocarbon Resources

Exon *et al*. (1998) have reported a 'bottom-simulating reflector' (BSR) that extends over an area of at least 25 000 km^2 of the eastern flank of the northern Lord Howe Rise and adjacent New Caledonia Basin at water depths of 1500-3600 m. BSRs generally indicate an interface between overlying sediment containing methane hydrate (a frozen crystalline mixture of methane and water) and underlying sediment containing bubbles of free methane gas. BSRs have also been identified on the western flank of the northern Lord Howe Rise, where it descends into the Middleton Basin, and in the northern part of the Monawai Basin (Van der Beuque *et al*., 2001). These BSRs could essentially indicate a 'cap' that provides an effective seal for gas (both biogenic and/or thermogenic) migrating from the underlying section.

These observations constituted 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.

Minerals

At present, very little is known about the non-petroleum mineral resource potential of the Lord Howe Rise region.

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

SEISMIC INTERPRETATION

Seismic Sequences and Bounding Unconformities: interpreted ages and depositional environments

In most basins, the largest-scale sequences (first-order megasequences of Hubbard *et al*. 1985; Haq *et al*. 1988) are formed by basin-wide tectonic events (eg. extension, cooling, flexural loading etc). Eleven major seismic sequences have been identified within the Gower Basin. They have been labelled from seabed downwards as GB1, GB2…..etc, and are overlain by unconformities or correlative conformities, U1 = water bottom, U2, U3 etc ……. U11 = pre-rift sediments/volcanics (Table 2). A further subdivision of the pre-rift section (GB11) may be possible within parts of the area, if older basins can be identified. The seismic sequences GB6-GB11 are seismic megasequences in the strict sense, whereas seismic sequences GB1-GB5 are significant sequences, but probably of lesser order.. The eleven seismic sequences are shown on a typical seismic profile in Figure 6 and Plate 7, and an interpretation of the major profiles in the Gower Basin region is displayed in three montages (Plates 4-6). For convenience, GB1-GB11 have all been referred to as '*megasequences*'.

Table 2: Seismic megasequence/sequence and horizon nomenclature
(NB. colours approximate those on profiles and seismic sections)

Megasequences	Bounding unconformity
Water layer	
	U1 (Water bottom)
GB1	
	U2/yellow
GB2	
	U3/black
GB3	
	U4/light green
GB4	
	U5/blue green
GB5	
	U6/light blue
GB6	
	U7/dark green
GB7	
	U8/blue
GB8	
	U9/black
GB9	
	U10/purple
GB10	
	U11/red (Pre-Gower Basin rift)
	U11/violet (Volcanic/Oceanic)
GB11	
	IB/pink (Intra-basement)

In addition, penetrative features (such as intrusions and ?diapirs) and sedimentary anomalies, are outlined as follows:

Rift & sag phase intrusions/diapirs	orange
Late stage intrusions/seamounts	brown
Sedimentary disruption features	Pale yellow

The geometrical characteristics of each seismic sequence, its structural and depositional setting, and an estimate of its age, are given in Table 3. This leans heavily on analogy to the Durroon Sub-basin of the Bass Basin for the pre-breakup section, which has a markedly similar stratigraphic and structural style. (compare Figures 5 & 6; also see Figure 7).

Table 3: Seismic Sequence Analysis (NB. colours approximate those on profiles and seismic sections)

Megasequence or Sequence	Bounding U/c	Reflection Character			External Shape	Thickness estimate (m)	Interpretation (from seismic characteristics, DSDP Sites & character correlation to Bass Strait basins)
		Upper Boundary	Lower Boundary	Internal			
	U1=wb						
GB1		Concordant/Erosional	Concordant/subtle onlap	Parallel/low amplitude	Sheet	200-500	Bathyl, pelagic ooze.
	U2						?Mid Miocene: overlies fractured competent beds possibly comprising siliceous layers.
GB2		Erosional truncation	Subtle onlap	Parallel-chaotic/low amplitude-medium at top	Sheet	300-350	Open marine pelagic ooze with siliceous layers.
	U3						Limited extent, ?Late Oligocene.
GB3		Largely concordant	Subtle onlap	Parallel/low amplitude	Sheet		
	U4						? mid Oligocene; seems to mark change in sediment provenance; start of open oceanic circulation.
GB4		Concordant/subtle truncation	Concordant/ subtle bottomlap	Parallel with some mounding/high amplitude	Sheet with some drape & thinning over highs	200-300	Has characteristics of a marine transgressive unit. Probably largely marine terrigenous but absent at DSDP 207 & 208 (E.Eocene – E. Miocene hiatus).?Erosion of platforms and horsts. .
	U5						Early or Mid Eocene (52 or 42 Ma)
GB5		Erosional truncation	Onlap	Largely parallel-divergent/medium amplitude, discontinuous	Wedge infill with some compaction drape & thinning over highs	100-750	Largely Palaeocene marine sag-phase. DSDP nanno chalk & radiolarite, foram ooze/clay (Unit 2). GB4/5/6 approx *age equivalent* to Latrobe Group.
	U6						Poorly-defined unconformity of probable Maastrichtian age at DSDP sites.
GB6		Subtle truncation	Onlap	Largely parallel-divergent/ medium amplitude, discontinuous	Infill with some compaction drape & thinning over highs	100-750	Probable sag-phase unit with erratic/slow subsidence: shallow marine non-oceanic circulation to S atDSDP 207, but bathyal siliceous chalks at DSDP 208 further north on LHR
	U7						Campanian (~84 Ma)
GB7		Erosional truncation	Well-defined onlap	Parallel-divergent/ relatively high amplitude, continuous	Infill of underlying structure, growth against faults	0-600	Probably represents the second and final stage of rifting/rift-fill; coastal plain to restricted marine
	U8						Cenomanian

(continued over)

Table 3 *(continued)*: Seismic Sequence Analysis

Megasequence or Sequence	Bounding U/c	Reflection Character			External Shape	Thickness estimate (m)	Interpretation (from seismic characteristics, DSP Sites & character correlation to Bass Strait basins)
		Upper Boundary	Lower Boundary	Internal			
	U8						Cenomanian
GB8		Concordant to erosional trucation	Well-defined onlap	Highly variable: divergent – chaotic/ medium amplitude, changing continuity	Thick sediment wedges with inversion relationships in places	0-2100+	Appears to be the major synrift sediment package that has been strongly inverted at U8 time. Appears to correlate with Otway/Strzelecki Groups.
	U9						Not recognised in all areas
GB9							Similar to GB8 where present
	U10						earliest Cretaceous
GB10		Concordant/erosioanl	Baselap	Variable but often very high amplitude, continuous over short distances	Wedges, mounds, fault-blocks	Absent in some areas; 0-2500	Characteristics of early rift volcanics. ?Late Jurassic
	U11						Metasedimentary/sedimentary type
	U11						Volcanic/oceanic-type
GB11		Strongly erosional		Varied: none to stratified		11 000+	Seismic basement in most areas: probably comprises varied lithologies and infrabasins of the Tasman Fold Belt, probably with some older Mesozoic basins under the LHR rift zone. Continuous with volcanic basement types and possible oceanic crust, largely to the west
	IB/pink			Sub-parallel			Events within Pre-rift section

Pre-rift Complex

<u>Megasequence GB11</u>(underlying U11):

Palaeozoic-early Mesozoic cratonised 'basement'and ?older basins

This megasequence, considered to be the acoustic basement on many of the seismic reflection profiles, comprises a thick zone with varied reflection quality and characteristics, ranging from sub-parallel/continuous, to chaotic. Its upper surface (U11) generally lies at approximately 2.2 seconds twt (two-way time) in the east, and at about 4-5 s twt where discernible under the Gower Basin, a depth range of approximately 1800 m to 6000 m. Its thickness to a possible detachment surface at about 6 s twt is probably more than 11 000 m.

Megasequence GB11 forms the basement to the east of the Gower Basin, on what has been termed the 'Lord Howe Platform' (Figure 8a). This platform is characteristic of the entire eastern side of the LHR, and separates a western 'rift province' from the New Caledonia Basin to its east. On the platform, the basement is markedly planated, though remnants of overlying half-grabens that contain pockets of syn-rift sediments, have occasionally been preserved. In places, there is evidence of internal stratification within the basement, displaying folds and fault-blocks, within what appear to be old basins. There are also indications of sub-horizontal planes deep within the basement that could be interpreted as detachment surfaces.

The internal reflection characteristics, coupled with measurements of the P-wave velocities of 6.0 km/s (Shor *et al*., 1971) and crustal thicknesses of approximately 26 km implied from the gravity values, indicate that the basement is made up of submerged continental crust. Basement rocks have not been recovered from the LHR or its immediate area; however, metamorphosed granite and ?microdiorite or andesite of mid Permian age (250-270 Ma) have been dredged from the Dampier Ridge (McDougall *et al*., 1994). It is considered likely that the pre-rift 'basement' on LHR is composed of a wide range of the Palaeozoic and Early Mesozoic terranes, probably an equivalent of the New England Fold Belt and any overlying basins.

The 'basement' of GB11 is down-faulted to the west of the Lord Howe Platform and floors the rift province (Gower Basin). Although elevated basement horst-blocks are present throughout the rift (for example, Figure 8b), there is a tendency for the basement surface and its underlying structure to be masked by high reflectivity and seismic absorption within the overlying sequences. This is most clearly the case where there is a thick syn-rift fill equated to Megasequence GB10. This first stage of syn-rift deposition is interpreted as volcanics and appears to include thick flows and sills (Figure 8c). It has been suggested (S. van der Beuque, personal communication) that the pre-rift rocks that directly underlie the rift province maybe younger than those on the platform (possibly Early Cretaceous) and, if that were the case, the Gower Basin may be formed over a pre-existing late Mesozoic depocentre. However, there is no clear-cut evidence for such a conclusion.

More elevated 'basement' ridges occur through the western part of the Gower Basin. In these areas the surface appears to be somewhat more rugged than under the basin, and GB11 has little discernible internal structure. This 'basement' is interpreted to comprise a greater proportion of volcanic rocks. In the far-west, where the 'basement' drops away across the flank of the LHR, it is indistinguishable from the basement of the adjacent Lord Howe Basin, which could be 'oceanic'.

Synrift Sequences

Megasequence GB10 (U10-U11): latest Jurassic

This megasequence is widespread, but largely confined to the half-grabens of the Gower Basin where it typically has a wedge-type geometry. In a few places it extends onto the intervening highs. Towards the eastern edge of the basin, where later inversion is considered to have occurred, GB10 staddles inverted blocks of the pre-rift section.

GB10 is variable in both its reflection amplitude and geometry, but in many of the graben it exhibits very high amplitude/continuous reflections over short distances. The nature of these events, together with their abrupt termination, suggest that they are an expression of major outpourings of volcanic lava and sills during the first stages of syn-rift deposition (Figure 9). Volcanogenic sediments and alluvial fans are probably also present within the unit. Assuming that seismic velocities of 4000-5000 m/s are typical for such deposits, Megasequence GB10 would have a thickness of 0-2500 m.

The proposed volcanic lithostratigraphy of Megasequence GB10 and its location at the bottom of the graben indicate that it may be approximately equivalent to the latest Jurassic Casterton Beds of the Otway Basin, though no direct correlation can be made.

Megasequences GB9/GB8 (U8-U10): Early Cretaceous

These two megasequences appear to be present through most of the graben that make up the Gower Basin, and can also be recognised within remnant half-grabens under the planated Lord Howe Platform. Their relative thicknesses are unknown in most places, since the unconformity that separates them (that is, U9) cannot always be identified. GB9/GB8 represents the bulk of the graben fill and ranges in thickness from zero over graben flanks and horsts to approximately 1.5s twt (that is, about 2100+m) within the deepest features. In some half-grabens these megasequences exhibit a 'fan-like/wedge-like' geometry that is typically syn-rift, and shows that the bounding fault has been active during their deposition.

The seismic signature of GB9/GB10 is very variable, with reflections ranging from chaotic to relatively continuous, but often of moderate amplitude. Following their deposition, there is clear evidence of basin inversion, accompanied by folding and faulting. That event effectively terminates the first syn-rift phase. Where GB9/GB10 are uplifted and inverted, these syn-rift deposits generally exhibit the more chaotic internal reflection pattern. This suggests that the stratal continuity has been disrupted possibly due to fracturing or more probably due to slumping. However, the possibility remains that these more elevated parts of the megasequences are the product of volcanism. Elsewhere, 'fuzzy zones' indicate that some volcanics are probably present within parts of these megasequences that are almost certainly sedimentary.

The seismic characteristics of these megasequences suggest that they are probably equivalents of the Crayfish and Otway Groups in the Bass Basin and the Lower and

Upper Strzelecki Groups in the Gippsland Basin. U9 may represent the unconformity separating the Lower and Upper Strzelecki Groups, that is the 'Intra Strzelecki' unconformity defined seismically by Willcox *et al.* (1992, figures 3 & 4). On that basis, GB10 would be syn-rift, whereas GB9 may represent a later stage of rift infill. The Lower Strzelecki Group of the Gippsland Basin (recently dated as Berriasian to Barremian) has been identified as syn-rift, while the overlying Upper Strzelecki Group (Barremian to latest Albian) is identified as post-rift (Norvick & Smith, 2001).

Late Rift Sequences

Unconformity U8 : Mid Cretaceous/ ?Cenomanian

On many profiles, but particularly in the north, the U8 unconformity represents a high amplitude topographic surface (for example, see Plate 7) with adjacent 'highs' and 'lows' exhibiting reflection time differences of up to 1.5 seconds, perhaps almost 2 km. This surface shows only minimal erosion, and the topography appears to have been rapidly infilled by the overlying sediments of Megasequence GB7. On the basis of its seismic characteristics the U8 unconformity is correlated with that at the top of the Otway Group in the Durroon Sub-basin. Although correlation is imprecise, in the Durroon area this tectonic event appears to be expressed as extension and block-faulting of the Otway Group, whereas on the LHR it seems to have given rise to uplift and inversion of GB8/GB9 in many of the pre-existing graben-like structures. This inversion may reflect continued activity along a subduction zone to the east, at the boundary of the Australian Plate. The lack of erosion at the U8 unconformity in the Gower Basin could be attributable to the inversion having taken place below wavebase, or more likely rapid inundation of the rugged surface by coastal and marine deposits. The well-layered nature of the overlying deposits of GB7 in many areas, would be consistent with its being a marine sequence.

On the basis of the available information it would seem that U8 defines a Mid Cretaceous event, probably in the Cenomanian. This was a period of extension and unroofing along the Southern Margin of Australia that preceded breakup and seafloor spreading in the latest Santonian to Campanian (A33 time) (Sayers *et al*., in press).

Megasequence GB7 (U7-U8): ?Cenomanian or Turonian to late Santonian

Megasequence GB7 largely infills the topography created by the Mid Cretaceous tectonism. It shows marked onlap onto the U8 surface and in some areas growth of GB7 against faults is observed. In many places it has relatively high amplitude and continuous reflection characteristics It is very variable in thickness but is typically 0-600 m.

This megasequence can probably be regarded as a second phase of syn-rift fill on the LHR. Its seismic character suggests that it could represent a marine deposit restricted largely to the grabens, or alternatively a coaly/coastal deposit within small basins flanked by a rugged topography. Character correlation indicates that GB7 is probably equivalent to the lowermost part of the Eastern View Coal Measures in the Durroon Sub-basin (Figure 7). Its correlative in the Gippsland Basin would seem to the Late Cretaceous Golden Beach Group of Lowry & Longly (1991), that is the Turonian to late Santonian Emperor and Golden Beach Sub-groups of Norvick *et. al* (2001).

Unconformity U7 : Late Cretaceous /Campanian

The U7 unconformity is a well-defined erosional surface through the LHR region, and is interpreted to mark the end of the rift phases of basin development. In older terminology, it would have been regarded as a 'breakup unconformity'. This fits well with current ideas re the onset of seafloor spreading and a thermal subsidence phase at approximately A33 time for both the Southern Margin and the Tasman Sea.

Thermal Subsidence Phase Sequences

Megasequences GB5/GB6 (U5-U7): Campanian to Palaeocene

GB5 and GB6 are widespread megasequences, made up of sediment packages that are thickest over the underlying depocentres and thinnest over the structural (largely basement) highs. Onlap onto their basal unconformities and their general depositional geometry appears to have been a result of differential compaction of the earlier deposits. They are separated by a mild unconformity (U6). Their internal reflection characteristic is one of parallel-divergent reflections, of medium amplitude, varying from continuous to somewhat discontinuous. This contrasts with the high continuity of the overlying and underlying megasequences, GB4 and GB7. Typically, the thickness of each of these megasequences ranges from about 100-750 metres.

These units are considered to represent the main phase of thermal subsidence in the LHR region. However, subsidence of the region may have been slow or erratic, at least in the early stages. The internal reflection signature of GB5/GB6 tends to indicate that open marine conditions may not have been fully established for some time and that depositional environments may have switched between fluvial/coastal deposits through to possible marginal marine.

The most likely age of the U6 unconformity that separates GB5 and GB6 is within the Maastrichtian, and the megasequences would thus be equivalent in age only to the lower Latrobe Group of the Gippsland Basin. At DSDP Site 207 on the southern LHR, units of approximately this age comprise glauconitic sandy siltstones, which is indicative of marine influence. At DSDP Site 208 on the northern LHR and north of the Gower Basin, the lithological sequence consisted of Late Oligocene to Late Pleistocene calcareous ooze overlying Late Cretaceous to early Middle Eocene siliceous fossil-bearing chalk. The palaeontological results from that site suggest that bathyal conditions prevailed. The evidence would thus lead us to conclude that during Maastrichtian times the southern and central parts of the LHR were under marginal marine conditions, whereas the northern LHR was at bathyal depth. This conclusion is unexpected, since the magnetic anomalies show that seafloor spreading in the Tasman Basin, and presumably sag-phase subsidence, spread from the south to the north. It may be evidence for an earlier period of extension and/or spreading in areas such as the Lord Howe Basin, that lead to subsidence of the northern part of LHR to form a marginal plateau.

Unconformity U5: Early or Middle Eocene

The origin of the U5 unconformity is uncertain. It terminates the largely Paleocene Megasequence GB5, and thus approximates to a time when the Tasman Sea Basin ceased spreading in the Middle Eocene (~42 Ma). However, it seems more probable that it marks the period of major plate readjustment in the Early Eocene (~52 Ma) that was associated with formation of the 'Hawaiian-Emperor bend' in the Pacific Ocean and the onset of 'fast spreading' in the Southern Ocean.

Marine Transgressive Phase

<u>Megasequence GB4</u> (U4-U5): Late Eocene to Early Oligocene

Megasequence GB4 forms a sheet across all area to the west of the Lord Howe Platform, with minor compaction drape and mild onlap onto the more elevated blocks. Its average thickness is approximately 200-300 metres through the Gower Basin. It is characterised by basal onlap, high amplitude and very high reflection continuity.

GB4 appears to be the major transgressive marker that may have followed a relative lowering of sea level in the Early or Middle Eocene and preceeds the onset of open marine conditions. Its most probable age span is from Late Eocene to Early Oligocene. This sequence is largely absent at DSDP 206 and 207. The Late Oligocene unconformity overlying this megasequence represents a Middle Eocene/Late Oligocene hiatus associated with planation over the Lord Howe Platform and some of the more elevated horst blocks.

Oceanic Phase

<u>Megasequences GB1-GB3</u> (U1-U4): Oligocene to Recent

These megasequences blanket the region, including nearly all high standing blocks and platforms. The unconformity U3 that separates out GB3 from GB2, can be recognised in only a few locations. In general, these three megasequences are characterised by parallel, low amplitude but near continuous reflections. Each displays mild onlap onto the sequence below. Typical thicknesses of GB1, and GB2/GB3 combined, are of the order of 500 and 300-350 metres, respectively. The uppermost 100-150 metres of GB2 is characterised by a band of high amplitude, high continuity reflections that has been extensively effected by 'micro-faulting', creating numerous small offsets of the strata.

The section penetrated at DSDP Sites 206 and 207 shows that these megasequences are composed of deep sea oozes and clays, and that the fractured band probably resulted from later movements acting upon highly competent strata with a mainly siliceous content (?chert bands). Unconformity U2, at the top of this band, appears to be Middle Miocene. The clear change in seismic signature in going from GB4 to GB2/GB3 marks a relatively abrupt cut-off of the terrigenous sediment supply and a switch to deep-sea largely pelagic sedimentation. This was presumably caused by a major change in oceanic circulation that followed separation of the Antarctic and Australian Plates in the region of the South Tasman Rise.

There appears to have been a buckling of strata probably from about the Middle Miocene until fairly recent time, probably in response to compression created by a new plate boundary to the northeast. At about this time a compressional regime also effected the Gippsland Basin and created many of the productive anticlines. Megasequences GB1-GB3 were gently folded or up-arched as a result of these events and are in places truncated at the sea floor. A thin layer of post-deformational pelagic sediments may overlie the broad folds, but is not readily resolved in the seismic profiles.

Penetrative features: ?volcanism and/or diapirism

Volcanic intrusions and/or diapiric features are observed on the seismic data throughout the Gower Basin (their distribution being further discussed under 'Structure'). They are difficult to distinguish from each other, as they are usually relatively small and have little magnetic or gravity expression. Their outline is indicated by patches with chaotic or poorly-defined seismic reflection characteristics. Since they have a tendency to absorb or scatter the seismic energy, the structure underlying them is in most places poorly resolved, and this adds to the difficulty in determining their provenance. For example, Figure 11 shows a suite of these features protruding from the syn-rift fill of one of the larger graben. Several explanations for their origin are possible:

- their upward penetration indicates they may be volcanics intruded into the basin during the Early Eocene (~U5 time), or that
- they may be shale diapirs, or
- possibly salt diapirs emanating from syn-rift fill of the graben, mobilised by the thickness of the overburden and reactivation, again during say the Early Eocene.

Structures that may be 'rim synclines', usually created by the withdrawal of salt, can be envisaged adjacent to some of these penetration features. Regardless of their cause, the penetrative-type features appear to have been intruded/mobilised in at least two, and probably many more, phases (Early Eocene outlined in orange, and through the Neogene as outlined in brown, in Figure 11a/b).

Another prevalent feature on the profiles are large patches that are seismically chaotic or transparent. Where they are located along the flanks of major horst blocks they are considered to be of probable volcanic origin, having been sourced by conduits associated with the boundary faults. Some of the youngest of these structures extend to seaflloor as seamounts. In other areas, for example below the relatively steep flanks of the Lord Howe Basin, other incoherent patches could be either volcanic in origin or possibly slump zones.

Several small 'mound-like' features are observed through part of the sedimentary section that can be interpreted as shallow marine: these may be biohermal or once again small volcanic bodies (Figure 14).

STRUCTURE

The broad structure of the Gower Basin region is exemplified in the seismic reflection montages (Plates 4-6) and as a structural elements map (Plate 8) based on these data. The map shows the dominant faults and structural trends, outline of the depocentres and penetrative features such as seamounts and volcanic and/or diapiric bodies.

The structural elements map displays the pre-rift and basement types as determined from the interpretation. The extent of the depocentres (Plate 8, shaded areas) is based on the termination of the U7 unconformity by either erosion or onlap (Table 3). That unconformity is the Campanian erosional surface that marks the end of the syn-rift phase of basin development, and overlies megasequence GB7. The structural trends and sedimentary thickness estimates are also posted. Those estimates were derived from sonobuoy refraction velocities (Willcox *et al*., 1981, table 1): namely, 2.0 km/s for the post Miocene (megasequences GB1-GB3); 2.8 km/s for the largely sedimentary rift-fill (megasequences GB4-GB9); and 4.0 km/s for the syn-rift volcanics (megasequence GB10). The structural elements map also shows the extent of the Lord Howe Rise Seamount (the edifice surmounted by Lord Howe Island) based on a detailed bathymetry contour map made from multi-sweep data acquired during AGSO Survey 222 (Hill *et al*., 2000).

Structurally, the map confirms that the Gower Basin region comprises an eastern 'basement' platform (the 'Lord Howe Platform'), and a complex array of horst and graben structures that trend generally to the north-northwest (part of the 'Central Rift Zone' of LHR; Stagg *et al*., in press). Previous studies have suggested that the grabens are 10-20 km wide, several tens of kilometres in length, and contain up to 4000+ metres of sediment (Willcox *et al*., 1980, 1981). This new study shows that some of the grabens may be as wide as 40 km and that many are 80-100 km in length, a size that is perhaps about half that of well-explored and productive features in the Gippsland Basin such as the 'Central Deep'.

Pre-rift characteristics

The pre-rift 'basement' has been divided into three categories based on reflection seismic characteristics (Plates 4-6):

- planate, block-faulted surface found in the eastern and central parts of the Gower Basin region;
- poorly or non-defined areas of the pre-rift, confined largely to the central part; and
- rough and/or undulating 'basement' found in the west.

In general, the pre-rift 'basement' with the planate surface is bounded by well-defined high-angle faults with dips in the order of 85 degrees. It is very characteristic of the Lord Howe Platform, a feature that makes up most of the eastern half of LHR, and that bounds the eastern side of the Gower Basin. It also appears to underlie at least the eastern side of the Gower Basin, were it has been hinged or downthrown to the west along a major fault or fault-set that soles out at between 4 and 5 seconds twt (approximately 5-6 km). This boundary fault-set can be interpreted as a sub-branch of a westerly-dipping detachment system, in which the LHR forms part of the 'Lower Plate' and continental Australia is the 'Upper Plate' (Lister *et al*., 1986). Planate 'basement' also makes up the broad structural highs located directly east of Lord Howe Island, and highs that flank the north-northwest-trending graben system, where they lie between the two northeasterly-trending offset-structures interpreted as accommodation zones on the map (Plate 8).

On the Lord Howe Platform, the pre-rift section is incised by pockets of syn-rift that are the remnants of deeply eroded/planated half-grabens. In places, there is evidence of internal stratification within the pre-rift, displaying folds and fault-blocks, within what appear to be old basins. There are also indications of sub-horizontal planes deep within the pre-rift that could be interpreted as detachment planes. As discussed under 'Seismic sequences…..' it is considered likely that the planate region on LHR is composed primarily of a wide range of the Palaeozoic and Early Mesozoic sediments and metasediments, probably an equivalent of the New England Fold Belt and its overlying depocentres.

The second 'basement' category ('poorly-defined/non-defined') generally underlies the deeper depocentres in the central part of the basin. The poor definition may be due to greater depth of burial in these areas, a greater volcanic/igneous content, or more probably the presence of an extrusive unit within the early-stage rift fill that reflects most of the seismic energy (GB10, Table 4). This may indicate that areas of poor definition were a locus of volcanic activity during the syn-rift phase. An example can be seen on line SO-36A-17A (Plate 5) from the central-south part of the Gower Basin, where the poorly-defined character may be an expression of heavily intruded continental crust. In this example, such an interpretation is based on the change in 'basement' topography, relative lack of faults, an abundance of volcanic bodies mapped within the sedimentary sequence and crust that is shallower than that in the deep ocean areas to the west.

The third 'basement' category ('rough or undulating') includes seamounts bounding the western edge of the Gower Basin and underlying the Lord Howe Basin. The crust associated with this 'basement' type may form part of a continent-ocean transition (COT) or be truly oceanic, and reflects a more volcanic origin. This crustal type could thus be the product of considerable extension and intrusion of continental crust, with extrusives probably making-up the upper part of the basement. Such a relatively thick pile of volcanics and volcanoclastics within or above the 'basement' would reduce penetration of seismic energy and diminish reflections from greater depths.

Differences in 'basement' topography and crustal characteristics exist between the Gower and Lord Howe Basins. The top of 'basement' underlying the Lord Howe Basin is deeper (~5 s twt) than that on the western edge of the Gower Basin (~2.5 – 4.0 s twt), suggesting that the crust is significantly thinner. Also, beneath the Lord Howe Basin (for example, at the western end of lines 46-03 and SO-36A-15A, Plates 5-6) the 'basement' has oceanic characteristics though no clearly-defined seafloor spreading magnetic anomalies have as yet been identified. However, Weissel & Hayes (1977), in their reappraisal of the Tasman Sea spreading pattern, supported an earlier proposal by Ringis (1972) that the oldest anomalies, A32 and A33, should be found in the Middleton and Lord Howe Basins. The closest magnetic anomalies actually identified are located in the Tasman Basin, west of the Dampier Ridge, which itself bounds the western edge of the Lord Howe Basin (Figure 2). It is possible that the crust underlying the Lord Howe Basin and the Monawai Basins to its south (Figure 2) could form part of a failed ocean ridge initiated during the Cretaceous magnetic quiet period (83 – 120 Ma).

Tectonic provinces and structural trends

Areas of planate pre-rift/'basement' and areas of poorly-defined 'basement' form a regional NNW-SSE structural trend (Plate 8). This may prove more complex if line spacing were reduced from the present 30 km. The main structural elements are, from east to west: the planated province of the Lord Howe Platform; an elongated NNW-SSE trending horst-graben province, that is the prime component of the Gower Basin; and a broad NNW-SSE trending ridge in the west that separates the Gower Basin proper from the Lord Howe Basin.

The above features appear to be offset, perhaps by as much as 40 km, across at least three northeasterly trending zones, that we interpret as transfer faults or more probably as complex accommodation zones. The most prominent of these pass to the north and south of the Lord Howe Seamount (the pedestal for Lord Howe Island) and a third probably lies further south between the two seismic data sets.

Gower Basin horst and graben province ('Central Rift Zone'):

There are three NNW-SSE trending ridges/elongated horst structures paralleling each other between the two northern accomodation zones (Plate 8). These horst structures are of the order of 15-20 km in width and may be up to 100-150 km long. The sedimentary cover over these structures ranges in thickness from 0.3 – 1.8 km. Four NNW-SSE aligned grabens/troughs parallel the horst structures and these are of the order of 20-40 km in width and up to 100-150 km long. Our conservative estimates of the sedimentary fill within the grabens/troughs, based on an average of sonobuoy refraction velocities, (Willcox *et al*., 1981) generally ranges from 1.3-3.1 km, but with one estimate as large as 6.1 km. If megasequence GB10 were to consist of sediments rather than volcanics, the effective sediment thickness would be in excess of 4 km in several of the graben.

Both horst and graben have a different structure south of the central transfer (Plate 8), where they give way to two wider troughs (60-80 km) separated by a broad ridge (30-40 km). Conservative thickness estimates of sediment fill within these troughs range from 1.0-2.5 km but could be as thick as 4.1 km. Similar troughs (~ 50-90 km wide) and a broad ridge (~ 50-60 km wide) have been mapped south of the southern-most accommodation zone (Plate 8). In that area, thickness estimates range from 0.7-2.4 km and could extend up to 4.0 km. Localised thinning of the depocentres in the southern area is caused, at least in places, by the presence of volcanic bodies (Plate 6, Line 46-06).

Western Ridge complex:

This ridge complex is located directly west of the horst and graben province. It varies in width from 110 km in the north, through 80 km in the central area, to 210 km in the south. It is made up, in part, of a complex of narrower ridges that may comprise some horst-blocks, separated by shallow grabens. The western ridge complex is on average less faulted than structures in the eastern area, its basement is probably continental in the north, but heavily intruded by volcanics towards the south. There are indications that this ridge complex may merge with the horst-graben province in the southern part of the Gower Basin (see Plate 8, Line 46-10). Continuation of the ridge complex to the south, beyond the southernmost accommodation zone, is conjectural.

The thickness of sediment overlying the western ridge complex ranges from 0.1-2.2 km but is generally less than 1.5 km. A maximum thickness could be up to 3.3 km, but only at a single location.

Lord Howe Basin:

The Lord Howe Basin forms the westernmost structural province in the Gower Basin region, to the west of the Lord Howe Seamount. In that province, our sediment thickness estimates range from 0.9-2.8 km but may be greater.

Faults and fold structures:

The reliability of fault trends is limited by the large average 30-km grid spacing of seismic lines, but on a regional scale they appear to parallel the NNW-SSE trending ridges and troughs, except near the cross-cutting fault zones where NE-SW trending faults are predicted.

Basin-forming extensional faults:

The dominant fault type in the Gower Basin is normal-extensional, probably formed over what appears to be westerly-dipping detachment at about 6+ km depth. The westerly dipping fault/ramp that bounds the western flank of the Lord Howe Platform is interpreted as a sub-branch of this detachment system. The dip of this bounding fault varies from line to line, often having the appearance of alternate ramp and normal fault segments. It seems probable that the steepest segments may represent normal fault offsets created by the intersection with cross-cutting transfers faults. In many places, the primary normal faults are associated with one or more antithetics, and the sedimentary section between them appears to have been squeezed. This is considered to provide evidence that the extensional process was somewhat oblique and that these normal/antithetic faults sets are an expression of wrenching. Seismic interpretation indicates that the primary normal/antithetic fault system was largely active during the syn-rift phase of basin development, and that such faults are most likely of Early Cretaceous age.

Accommodation zones:

As discussed above, three NE-SW trending transfer faults, or more probably accommodation zones, have been inferred from the mapping. The presence of the northern and central accommodation zones (Plate 8) is based on offsets of the elongated horst and graben structures and from variations in character of the pre-rift. There is a tendency for elevation of the pre-rift surface to step across the zones and, in some cases, there is evidence for increased volcanism around them. The existence of the southern accommodation zone (Plate 8) is only surmise, as it is postulated to lie in the area between the two seismic data grids. An apparent offset of the western ridge complex and its adjacent troughs, together with an offset of the Lord Howe Platform, are indicators of its presence. As the accommodation zones are created to allow for differential extension within the compartments that they partition, they must have been initiated at the time of basin formation, and would probably have remained active through the syn-rift phase. This would date them as ?latest Jurassic or earliest Cretaceous.

Reversed faults and reactivation folds:

Our interpretation shows that the principal syn-rift section (Megasequences GB8/GB9) appears to have been uplifted, folded and to some extent inverted, in the mid Cretaceous (U7 time; probably ~Cenomanian; as shown for example on Plate 7). This process was associated with what seems to have been a reversal on several fault-planes that dip to the east or northeast. This event is most obvious towards the north and is probably more pronounced towards the master fault that bounds the Lord Howe Platform. While some of these reverse fault planes may have been initiated in the ?Cenomanian, many appear to have resulted from reactivation of the older extensional fault system. Associated with this event is the development of some 'flower structures' and possibly also some volcanism.

The trends of these reversed faults and syn-rift structures cannot be determined with the line spacing of the present seismic grid, and it can only be assumed that they broadly parallel those of the pre-rift 'basement', that is NNW-SSE.

Neogene faults/folds & brittle deformation:

The Late Cretaceous and Palaeogene was a period of late rift-fill and compaction drape, in which gentle synclines formed over the main graben, and arches over the old basement highs.

By the Neogene, probably from the Middle Miocene (U2 time) onwards, the region seems to have come under the influence of mild compressive event, probably related to plate convergence to the east. This is expressed as broad, low amplitude folds that appear to extend almost to seabed. Along the western side of the Gower Basin region a few large faults also influence the seabed topography. Neogene movements have had a distinct effect on one particular band of Middle Miocene strata: they have resulted in complex micro-faulting within a suite of competent beds that on the basis of the DSDP results have been shown to contain bands of siliceous material.

Distribution of penetrative features:

The penetrative features discussed above appear to be grouped into largely in two structural associations: many are clustered within the larger graben, particularly in the graben that lies adjacent to the main basin boundary fault along the Lord Howe Platform; while others may be 'strung out' along the horsts and more elevated areas, often above graben boundary faults. Although it is pure speculation, it may be that we are dealing with three categories of penetrative features that can possibly be separated on the basis of their structural association. Those clustered within the graben' syn-rift sediments could possibly be diapiric in origin; those over the structurally elevated areas are most likely to be volcanic features in which boundary faults have acted as conduits; while those within the younger part of the section which have no obvious association could be bioherms.

GEOLOGICAL EVOLUTION

Tables 4 & 5 provide a summary of the geological history of the Gower Basin, and the timing of volcanism/diapirism, as interpreted from this largely seismic study.

At this stage, the geological evolution of the Gower Basin region, and indeed that of the LHR as a whole, has to be largely inferred from our knowledge of southeast Australian geology, and in particular that of the previously ajoining Bass Strait basins prior to Tasman Basin spreading. Reconstructions of the LHR against eastern

Australia, place the 'dog-leg' bend in LHR (to the south of Lord Howe Island) along the northern edge of the Gippsland Basin. In the Jurassic and Early Cretaceous, developing rift basins along northern and southern arms of the proto Tasman Basin, and through the Bass Strait region, may have essentially formed a plate triple junction just east of Bass Strait. Our knowledge of this syn-rift phase of basin development is based on structural similarities and seismic character correlations with the Bass Basin (Durroon Sub-basin) and Gippsland Basin. The situation during the thermal subsidence phase is more directly known, at least from the Maastrichtian onwards, since that geological section has been penetrated at DSDP Sites 206-208.

The pre-rift 'basement' through the region has had a long and complex history. The gravity data and P-wave velocities, together with scattered dredge hauls, show that most of the LHR and Dampier Ridge to its west are composed of continental crust, though the nature of crust in the intervening Lord Howe and Middleton Basins is unclear. The pre-rift itself is presumed to relate to the New England Fold Belt, and to the docked terranes of eastern Australia (Megasequences GB11), but it could include some younger but unrecognised basins.

In the ?Jurassic or earliest Cretaceous, the 'basement' that underlies the Gower Basin is believed to have comprised an eroded surface, overlying a complex of sediments and metasediments with associated ?granitic intrusions and volcanics. This complex is at relatively shallow depths under the Lord Howe Platform and, apart from elevated horst blocks, is probably 4-6 km deeper beneath the basin. The seismic signature suggests that basement may have been more volcanic in the west. A possibility remains that the pre-rift rocks flooring the Gower Basin could include other potentially prospective basins.

Latest Jurassic –Early Cretaceous extensional phase

In the latest Jurassic, or possibly earlier, lithospheric extension (rifting) occurred within the Gondwana supercontinent and heralded a breakup process that eventually led to the separation of Antarctica and the Lord Howe Rise region from what is now continental Australia. This process, once considered to have evolved as an anticlockwise 'unzipping' of the continents, is now thought to have been a more synchronous event in the south and southeast, with the main episode of breakup having taken place in the latest Santonian to early Campanian (A33 time). While extension was relatively simple along the western part of Australia's Southern Margin, were it took place on a northwest-southeast azimuth (Willcox & Stagg, 1990), the situation may have been much more complicated in the southeast. For the Bass Strait/LHR region, Willcox *et al.* (1992) postulated movements between a number of small plates that included a 'Bassian Microplate' and a 'Lord Howe Plate' (Figure 4B).

Within the parlance of 'upper/lower plate extension' (Etheridge *et al.*, 1989), the interpretation of a westerly-dipping sub-branch of a detachment system under the Gower Basin, would appear to place the Gower Basin on a 'lower plate', with respect to continental Australia that was a conjugate 'upper plate'. However, somewhere to the south, possibly at the major Tasman Basin transform that aligns with the northern edge of the Gippsland Basin, the upper plate/lower plate polarity must have switched. In that area the lower plate has been interpreted on the northern (mainland) side of the

Gippsland Basin (Willcox *et al*., 1992).

First syn-rift phase

Most of the ?Late Jurassic/Early Cretaceous graben in the Gower Basin were first flooded by volcanics and then generally filled with huge volumes of syn-rift sediments (Megasequences GB10 and GB9/GB8). These units bear analogy to the latest Jurassic Casterton Beds of the Otway Basin, and the Early Cretaceous Otway and Strzelecki Groups of the Bass Basin (Durroon Sub-basin) and Gippsland Basin. In those areas the sediments are reported to have a high volcanogenic component derived from an eastern source. Palaeocurrent measurements within the Strzelecki Ranges of Victoria (Constantine, pers. comm.) indicate provenance of the volcanoclastic sediments from an eastern source - possibly a deep-water basement ridge that lies near the foot of the continental slope off Gippsland, or a volcanic province on southern LHR (Veevers *et al*., 1982; Willcox *et al*., 1980).

In the Gower Basin, the Early Cretaceous (?Strzelecki Group equivalent) sediments in some graben, comprise two sequences separated by an erosional unconformity (Unconformity U9 of this report). A similar situation has been recognised in the Gippsland Basin where Colwell & Willcox (1993) report an intra-Strzelecki horizon. It appears to separate a 'lower' sequence that exhibits structurally controlled 'synrift-type' geometries, and could comprise typical synrift paludal and/or lacustrine deposits, and an the ‘upper’ sequence may once have been far more extensive, since it shows analogy to the Otway Group of the Bass Basin, Otway Basin, and probably even to the Sorell Basin west of Tasmania. Depositional remnants of the ‘upper sequence’ are also present on the Mornington High, onshore Victoria. These sediments would thus seem to have been far more widespread, suggesting that in the ?Late Jurassic-Early Cretaceous they may once have formed an extensive blanket over the southeast Australian/LHR region. A subdivision of the Strzelecki Group is also recognised by Norvick & Smith (2002, figure 2) and they place the boundary of the ‘Lower’ and ‘Upper’ Strzelecki in the earliest Barremian.

Mid Cretaceous (Cenomanian) tectonism:

There is clear evidence from the Gower Basin seismic profiles for an episode of relatively rapid uplift and inversion of the syn-rift deposits at a time corresponding to Unconformity U8. This resulted in reversal on some of the basin-forming normal faults and the development of some wrench-related flower structures. The uplifted features also show possible evidence of slumping. This event followed the deposition of the section that is interpreted as an age equivalent to the Otway/Strzelecki Groups and is thus dated as Mid Cretaceous, most probably Cenomanian (Plate 7). It is of major importance on the Gower Basin part of LHR, in that it gives rise to some of the larger structures over which the younger sediments have been draped and differentially compacted. To the north of the Gower Basin there has been little erosion following this event, which might suggest that the area was either already below wavebase, or subsided rapidly below wavebase, at this time. Although the underlying megasequences, GB9/GB8, do not obviously have a marine seismic character; however, the overlying megasequence, GB7, shows high amplitude/high continuity reflections that could indicate marine deposits.

In the Bass Strait basins, a Cenomanian event that is probably equivalent to that (U8 unconformity event) in the Gower Basin has been noted by Davidson & Morrison (1986) and it was discussed in some detail by Willcox *et al*. (1992).

In the Gippsland Basin it is expressed structurally as:

- numerous near-vertical faults and 'flower fault structures' which generally detach on the 'northern basement ramp' and extend upwards to the top of the Strzelecki Group (Willcox *et al*., 1992, figure 6),

- block-faulting along the southern edge of the basin, giving rise to the Southern Strzelecki Terrace and Southern Platform, and accentuating the Central Deep,

- first development of wrench-related anticlines with attendant onlap of the overlying sequence,

- intense wrenching and faulting to create the Northern Strzelecki Terrace and folding which detaches on the basement ramp, and

- overthrusting of the Strzelecki Group and the ramp surface, towards the western headwalls.

In the Durroon Sub-basin (that is, Boobyalla Sub-basin in Figure 4) the seismic data indicates that, following deposition of the Otway Group, the basin underwent extension, and then entered a syn-rift phase. This syn-rift phase is analogous to that observed on the southwestern LHR conjugate margin and also within the Gower Basin (Second Syn-rift Phase; Figure 5).

Based on these Gippsland Basin/Durroon Sub-basins observations, Willcox *et al*. (1992) proposed that following deposition of the Early Cretaceous Otway/ Strzelecki Groups, the postulated Bass Strait microplates underwent complex relative movements (Figure 4C). They surmised that continued coupling of the 'Lord Howe Plate' with the 'Bassian Plate', imparted slight anticlockwise rotation to the Bassian Plate. This resulted in compression of the Gippsland Basin Strzelecki Group to its north, with concomitant rifting of the Durroon Sub-basin Otway Group to its southwest. This event was considered to have probably taken place in the ?Cenomanian.

It needs to be emphasised, however, that the dating of the Gippsland Basin compression and the Durroon Basin extension was not precise, and that there is some evidence to suggest that the two processes may not have been synchronous. In fact, for the Durroon Sub-basin, Baillie & Pickering (1991; Figures 5 & 7) describe a Tasman Rift event of Turonian to early Campanian age, in which sediments infill tilt-blocks composed of Otway Group sediments. This conclusion is supported by recent studies (J. Blevin, personal communication), in which the onset of strong syn-rift geometries around the Durroon-1 well, have been dated as Turonian to Late Santonian, based on the age of the oldest syn-rift sediments. Whether or not any Cenomanian syn-rift deposition occurred in the flanking half-graben is still unknown.

Considerable thicknesses of Strzelecki Group sediments were eroded from the margins and 'platform areas' of the Gippsland Basin during the mid-Cretaceous. In the Banks Strait area (south of Flinders Island) folding and uplift of the Early Cretaceous Otway Group was followed by erosion of perhaps 2000 metres of section.

The dating of this event is also consistent with observations from the Ceduna Tarrace region of the Great Australian Bight. In that region, the late Cenomanian, or more probably the Turonian, was a period of renewed uplift and faulting on the margin. Near the axis of the Ceduna Depocentre there is evidence for reversal and thrusting on earlier faults. At that stage, an 'outer basement high' was formed by a mechanism that may have involved the unroofing and flowage of upper mantle material (Sayers *et al*., in press). The same 'basement high' has also been recognised south of the Eyre Sub-basin by Stagg & Willcox (1992), where it was described as a 'basement hummock' possibly at the limit of continental crust. The Cenomanian also reported to be absent in the Otway Basin (A. Krassay, personal communication).

This prominent Cenomanian event, expressed largely as rifting along the Southern Margin, but as uplift, inversion and wrenching in parts of the Gippsland Basin and in the Gower Basin, is presumed to have marked an major episode of plate re-adjustment. Veevers (2000) correlates this event with a clockwise bend in the linear volcanic chains of the Pacific at 99 Ma (earliest Cenomanian), and interprets it as a change from 'head on' subduction of the Pacific Plate beneath eastern Gondwana, to sinistral oblique subduction and back-arc spreading in the western Pacific.

Second syn-rift phase

During the early part of the Late Cretaceous there was substantial topographic infill within the Gower Basin (Megasequence GB7) with perhaps 0-600 metres of sediment being deposited, during what can be regarded as a second phase of syn-rift fill. As mentioned above, this may well have taken place within a coastal to restricted marine environment, thus having the potential to have provided petroleum source rocks in the Gower Basin. Again, analogy with the Gippsland Basin and character correlation with the Durroon Sub-basin (Figure 7), leads us to conclude that this section is most likely of Cenomanian-Campanian age and is probably a correlative of the Golden Beach Group (*N. senectus* zone, Figure 3). Willcox *et al*. (1992) described a similar structural setting for the Golden Beach Group, and came to the conclusion that it was the main tectonostratigrphic unit associated with Tasman Basin rifting. Along the margins of the Gippsland Basin 'Central Deep' and in the deepwater Gippsland Basin the Golden Beach sediments are regarded as a viable exploration target.

Breakup and the thermal subsidence phase

Seafloor spreading (breakup) commenced in the latest Santonian to early Campanian (~84 Ma, Chron 33) and extended to about the Early Eocene, when spreading ceased (~52 Ma).

Some re-activation of the of the old Cenomanian structures appears to have taken place during the Campanian due to continued coupling of the Australian and Lord Howe Plates, then in the closing stages of their oblique left-lateral contact. The commencement of seafloor spreading was in the Campanian, the oldest identified magnetic anomaly being A33, as on the Southern Margin of Australia. A thermal pulse associated with breakup probably resulted in relative shallowing of the Gower Basin and possibly even a reversion to non-marine conditions for a brief period. However, although the first megasequence to be deposited during this phase is not obviously marine in seismic character (GB6), a tie to DSDP Site 207 on the southern LHR suggests that this unit comprises glauconitic (shallow marine) sandy siltstone, and a tie to DSDP 208 to the north of the Gower Basin gives indicators for mid-bathyal water depths at that location. The character of megasequence GB5 suggests that fully marine conditions were well established by the Maastrichtian.

The thermal subsidence phase of basin development (Megasequences GB4/GB5 & GB6) led to the deposition of approximately 1500-1800 metres of sediments within depocentres that developed over the underlying 'lows', but only a few hundred metres over the structural 'highs'. Sedimentation commenced as onlap onto the undulating 'breakup unconformity' (that is, unconformity U7) and eventually draped across the entire region. By the close of this phase, probably in the Early Eocene, the water had deepened considerably, and at DSDP Site 207 the section comprises foraminiferal ooze and clay with subordinate siliceous ooze, and at DSDP Site 208 nannofossil chalk and radiolarite. A mild unconformity that separates GB5 from GB6 would appear to correlate with a Maastrichtian unconformity at DSDP 207.

In terms of age, these megasequences are approximately equivalent to the Latrobe Group of the Gippsland Basin. In their lowermost part, they may provide similar organic source material to the productive Latrobe Group, but through time would steadily have become associated with more remote and deep-water facies. This may, or may not, have been favourable to the accumulation of a potential petroleum source.

The termination of Tasman spreading in the Early Eocene (52 Ma) is marked by only a mild unconformity. A more prominent unconformity (U5) is presumed to be related to global plate re-organisation (signified by the pronounced bend in the Hawaiian-Emperor Seamount Chain) and the commencement of 'fast spreading' on Australia's southern margin which occurred in the Late Eocene (~42 Ma, Chron 18). At about this time the New Caledonia Basin, and to a lesser extent the LHR, came under renewed east-west compression, probably in relation to a new plate boundary to the east. Obduction took place in New Caledonia. Also, flowage and diapir formation in the Gower Basin seems to have occurred during the Eocene.

The Gower Basin was blanketed by a distinctive unit, 200-300 metres thick, from the Late Eocene to the Early Oligocene (Megasequence GB3). It is considered to have been deposited during a period that approximates a time between the onset of 'fast spreading' in the Southern Ocean and clearance of the Australian and Antarctic Plates in the region of the South Tasman Rise (~35 Ma, Chron13). This would have marked an abrupt change in oceanic circulation, currents, and possibly sediment provenance. On the basis of its seismic characteristics of very high amplitude/high continuity, this unit looks like a major marine influx through the Gower Basin. Whether it represents a renewal of marine conditions following a relative lowering of sea-level at the end of GB4/GB5, or a change in lithology to, say, more terrigenous input or maybe siliceous cherty sediments, is unclear.

Oceanic Phase: Miocene folding

From the mid Oligocene the Gower Basin entered an 'oceanic phase'. The clear change in seismic signature in going from GB4 to GB2/GB3 probably represents a relatively abrupt cut-off of the terrigenous sediment supply and a switch to deep-sea largely pelagic sedimentation. This was presumably caused by a major change in oceanic circulation that followed separation of the Antarctic and Australian Plates. The equivalent section penetrated at DSDP Sites 206 and 207 shows that these megasequences are composed of deep sea oozes and clays, and that a distinctive fractured band within them probably results from later movements effecting highly competent strata with a mainly siliceous content (?chert bands). Unconformity U2, at the top of this band, appears to be Middle Miocene.

There appears to have been a buckling of strata probably from about the Middle Miocene until fairly recent time, probably in response to compression created by plate boundary interactions to the northeast. However, it is strange that at about this time a compressional regime also effected the Gippsland Basin and created many of the productive anticlines. Megasequences GB1-GB3 were gently folded or up-arched as a result of these events and are in places truncated at the sea floor. A thin layer of post-deformational pelagic sediments may overlie the broad folds, but is not readily resolved in the seismic profiles.

Table 4: Geological History

Age	Event	Environment	Correlation	Megasequence	Comment
Palaeozoic & Early Mesozoic	Pre-Lord Howe Rise; pre rift	Partially cratonised basement with folding, faulting & volcanism; includes some areas with residual stratification	Tasman Geosyncline & possibly some older Mesozoic basins such as Esk Trough equivalent	GB11	Eroded pre-rift complex of variable age. Areas of more volcanic basement appear to be prevalent towards the west, and becomes indistinguishable from what may be Cretaceous 'oceanic crust' along the western flank of the LHR.
?Latest Jurassic	Extension			Unconformity U11	Detachment sub-branch appears to dip W or SW from the LH Platform, under the western LH (Gower Basin) province.
?Latest Jurassic – earliest Cretaceous	Initial extension & commencement of syn-rift deposition	Unknown, but possibly a mix of alluvial fans with substantial volcanism in many grabens	Could be broadly equivalent to Casterton Beds in Otway Basin	GB10	In many places the synrift volcanics are difficult to distinguish from volcanic basement; also,some sills may have been injected later in the rift phase.
Earliest Cretaceous	?Further block faulting in some graben			Unconformity U10	The termination of sills is difficult to distinguish from the edges of fault-blocks in some areas.
Early Cretaceous	Major syn-rift sedimentary phase	Unknown, but possibly a mix of alluvial fan, fluvial & lacustrine; subordinate volcanics	Probably equivalent to the Otway Gp in Otway/ Bass Basins & Strzelecki Gp in Gippsland Basin	GB9/GB8	Reasonable character correlation with Otway/Strzelecki Groups (see Figure 7); may comprise volcanogenic sediments. Mid Strzelecki unconformity U9 also recognised in Gippsland Basin.
Mid Cretaceous (?Cenomanian)	Crustal shortening; major episode of basin inversion: (Probably the final episode of subduction to east of LHR)			Unconformity U8	Reverse faulting, wrenching, & some overthrusting; either due to W to E compression, particularly adjacent to LH Platform, and/or left-lateral oblique extension between LHR & mainland Australia. Minimal subsequent erosion. (Extension in Durroon Sub-basin, Bass Strait, at this time).
Late Cretaceous (?Cenomanian-Santonian)	Substantial topographic infill with some growth against faults; onlaps Cenomanian folds	High reflection continuity indicates that this megasequence may include marine units	Probably equivalent to the older part of the Golden Beach Formation in Gippsland Basin	GB7	The Golden Beach Formation is usually considered to extend from Cenomanian to Campanian; however, the effect of Tasman Sea breakup in the Santonian may have been delayed in more elevated areas such as Gippsland.
Campanian	End of syn-rift & infill phases; onset of 'Southern Margin' & Tasman Basin seafloor spreading (A33)			Unconformity U7	
?Approx. Campanian - Maastrichtian	?Thermal subsidence (sag) phase; some infill & compaction drape	Unknown; but seismic characteristics & DSDP results suggest fluvial-lacustrine, coastal and marginal marine conditions	None	GB6	Age equivalent to early Latrobe Group of Gippsland; however, no direct correlation between Gippsland & LHR following breakup. At DSDP 207 (southern LHR) this unit comprises glauconitic sandy siltstone indicating marginal marine; at 208 (northern LHR) indicators are for mid-bathyal water depths.

(continued over)

Table 4 *(continued)*: Geological History

Age	Event	Environment	Correlation	Megasequence	Comment
?Maastrichtian				Unconformity U6	Poorly-defined unconformity at DSDP sites
largely Palaeocene	?Latter part of thermal subsidence (sag) phase; some infill & compaction drape	Unknown; although seismic characteristics suggest fluvial-lacustrine & marginal marine as for GB6, the DSDP results indicate that bathyal conditions more likely	DSDP208 (Unit 2) – nanno chalk & radiolarite DSDP 207 (Unit 2) – foram ooze/clay	GB5	
Early or Middle Eocene	?Plate readustments 52 Ma; or end spreading 42 Ma.			Unconformity U5	42 Ma end of Tasman spreading, but more likely 52 Ma plate readjustment (Hawaiian-Emperor bend)
L. Eocene – E.Oligocene	?Lowstand Broad folding Start Southern Ocean fast spreading. New convergent plate boundary to east.	Marine, possibly high terrigenous input	Hiatus at DSDP 207 & 208	GB4	?Erosion of platform/horsts during lowstand.
Mid Oligocene	Australian & Antarctic Plates clear south of Tasmania			Unconformity U4	Unconformity encompasses entire Middle Eocene-Late Oligocene in some areas, particularly over the platforms & horsts.
	Oceanic phase	Bathyal marine	DSDP (Unit 1) – foram/nanno ooze from this period onwards	GB3/GB2	Deep sea oozes & clays, with chalk & siliceous content. ?Late Oligocene Unconformity U3 not recognised in all areas.
Middle Miocene	Compression & broad folding continue. Active convergence to east.		Overlies fractured siliceous competent beds (?cherts)	Unconformity U2	Unconformity characterised by numerous bedding fractures. Extended period of folding probably due to crustal shortening near plate margins.
		Bathyal marine	Deep sea ooze	GB1	
Recent					Formation fomation of gas hydrates on New Caledonia Basin flank of the LHR

Table 5: Volcanism and/or Diapirism

Age	Event	Megasequence	Comment
?Latest Jurassic – earliest Cretaceous	Widespread syn-rift volcanism with major sills	GB10	Often difficult to distinguish from the basement.
Early Cretaceous	Minor volcanism in late syn-rift phase	GB9/GB8	Zones of disruption or high reflectivity.
Late Cretaceous	?Major intrusions above graben flanking faults		
?Estimate Eocene or Oligocene	Formation of penetrative features in Eocene & older section, particularly in the deeper graben & over flanking faults	GB4-GB10	These features could be a mix of volcanic intrusions & ?shale diapirs of varied ages. Within some graben (see Figure 11) could be either volcanic or a result of shale/salt mobilisation of the early graben fill.
Neogene	Intrusion	GB3-GB1	Relatively young intrusions, including the formation of some seamounts.

PETROLEUM POTENTIAL

The western side of the Lord Howe Rise has been recognised as a potential hydrocarbon province since the mid-1970s (Willcox, 1981), although it has never been actively explored. None of the DSDP wells penetrated the syn-rift section in any of the rifts, and an assessment of the hydrocarbon prospectivity is still largely dependent on an understanding of the regional palaeogeography and on comparisons with the formerly adjacent Australian continental margin.

Sediment thicknesses within the Gower Basin are estimated to average between 1.5-3.0 km in thickness and reach a maximum of 4+ km. This potential upside thickness may, however, be significantly higher depending on the age and range of rock types within the seismic 'basement'.

The 'basement' on the conjugate portion of the Australian margin includes the New England Fold Belt, the postulated Currarong Orogen (Veevers, 1982; Alder *et al*., 1998) or the Lachlan Fold Belt, the Permian to Triassic Sydney Basin and features similar to the Esk Trough, and the Cretaceous to Cainozoic Gippsland Basin. If Sydney Basin equivalents are present beneath the western Lord Howe Rise, they probably form part of the seismic/economic basement and are unlikely to be clearly resolved in the seismic data. Features that are considered analogous to the early stages of the Gippsland and Bass Basins are better defined.

The critical events and characteristics of the Gower Basin which are pertinent to its petroleum potential are given in Table 6.

Source, reservoir and seal

This study shows that the Gower Basin contains many depocentres in which the probable Cretaceous section is quite thick – in places more than 2000 m – and may under ideal conditions have had the potential to produce hydrocarbons. However, we have no direct evidence of depositional environments that prevailed in these depocentres prior to the Maastrichtian, and hence our considerations of source potential remain conjectural.

Based on the observations made on Atlantic-type (rifted) margins in general, Symonds & Willcox (1989) suggested that the sediment fill could be predominantly fluvio-lacustrine, and therefore may contain a high proportion of terrestrial kerogen, which is generally gas-prone. The seismic data interpreted herein are somewhat more favourable, in that they indicate the presence of marine units more favourable for generation of liquid hydrocarbons within the Cenomanian-Santonian section that terminates the syn-rift phase. These units may be equivalent to the older part of the Golden Beach Formation of the Gippsland Basin. Furthermore, the sequences overlying them, of Campanian to Middle Eocene age, have seismic signatures that are also consistent with the presence of fluvial-lacustrine and marginal marine environments.

Symonds & Willcox (1989) concluded that wave-base erosion and planation of some horst blocks in the Late Cretaceous indicates that the western Lord Howe Rise was still at shallow water depths at that time, with deposition possibly confined to the intervening grabens. This would imply that depositional environments within the grabens may well have been restricted and anaerobic, a situation favourable for generation of hydrocarbons. At DSDP Site 207 (Burns, Andrews *et al*., 1973) to the south of the Gower Basin restricted shallow marine silts and clays of Maastrichtian age are known to veneer the horst blocks. These sediments may contain suitable organic material, but in that area are unlikely to have been buried deeply enough to have reached thermal maturity (for discussion of geohistory subsidence curves of the LHR region, see Bradshaw *et al*, in prep).

The reconstruction of the Gippsland Basin against the southwestern Lord Howe Rise (Monawai Basin) has been used to suggest that a potential hydrocarbon province may be present (Willcox, 1981; Symonds & Willcox, 1989). Willcox (1981) noted, however, that in the Gippsland Basin all but one of the major hydrocarbon discoveries are in reservoirs at the top of the Latrobe Group, below the Eocene-Oligocene unconformity. Whether or not an equivalent source and trapping mechanism could have developed on the LHR is unknown, since the two areas were conjugates by that time. Although an Eocene-Oligocene unconformity is present in the Gower Basin region, there is no direct equivalent of the Latrobe Group source, though the older part of the Golden Beach Group may be present.

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

Source rock maturity and heat-flow

In most places on Lord Howe Rise, the Late Cretaceous syn-rift section is overlain by less than 1000 m of younger sediments, which is probably insufficient to produce source rock maturity, unless the heat flow has been abnormally high. However, the deepest grabens within the Gower Basin, those that lie largely adjacent to the Lord Howe Platform (Plate 8), have subsided enough to allow for a greater overburden.

Bottom-simulating reflectors (BSRs) have been identified in the northern part of the Monawai Basin and within the New Caledonia Basin, while some flat spots have also been observed. If these BSRs are due to the presence of gas hydrates, and if those gas hydrates are of thermogenic rather than biogenic origin, then this would indicate that active hydrocarbon generation is taking place at least on some parts of the LHR.

If the limited high heat-flow values (60-70% higher than average) recorded at the southern end of Lord Howe Basin and at the northern end of the Monawai Basin are at all representative of the Gower Basin area, then Cretaceous source rocks in the grabens may have reached thermal maturity.

Recently acquired high-quality seismic data and satellite synthetic aperture radar (SAR) imagery indicate possible direct hydrocarbon indications beneath the eastern flank of Lord Howe Rise, in the north. Bottom simulating reflectors (BSRs) observed in seismic reflection data on the northeast (and southwest) flanks of the Lord Howe Rise may indicate the presence of gas hydrate. In the northeast, the general coincidence of the BSR with the western updip flank of the Fairway Basin may indicate a thermogenic component to the gas hydrates. Also, in this area, some evidence for low-level oil slicks and films on SAR imagery, combined with seismic evidence for fluid migration through the sedimentary section, may indicate that active hydrocarbon generation is taking place. Should suitable source rocks also be present in the southern sector of the New Caledonia Basin, then it is reasonable to assume that generation may be taking place on the LHR.

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

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

Petroleum plays and traps

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

This study shows that the Gower Basin comprises a major north-northwest trending system of graben, up to 100 km in width and containing up to 4000+ m of Cretaceous and younger sediments, situated to the west of the Lord Howe Platform. The graben system is segmented by at least three northeasterly trending transfer/accommodation zones. The region has apparently undergone two distinct ‘syn-rift’ phases in the Cretaceous, separated by a basin inversion event of probable Cenomanian age. Mild regional folding associated with compressional tectonism is evident from the Middle Miocene but may have commenced in the Middle Eocene. Low amplitude folds and occasional faults extend to seabed. Penetrative features occur within the section: these are difficult to interpret, but may comprise diapirs within the syn-rift section and several phases of volcanism. A few small features, that may represent biogenic upgrowths, are present in the early part of the Palaeogene.

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

This scenario of a 'polyphase basin' has led to the development of numerous potential petroleum traps associated with the graben and their flanks, as well as wrench-related ramps and anticlines related to the accommodation zone. As indicated in Table 6, most traps and seals appear to have been in place before any generation from the Late Cretaceous. However, generation from the Golden Beach equivalent section may have preceded formation of the broad mid Miocene folds, and the development of a substantial regional seal.

More specifically, such traps/plays would include:

Rift margins (Figure 15a):

Entrapment against the bounding faults of the larger graben and against major faults within the graben. To be viable, plays of this type would depend on migration from a suitable source within the Early to Mid Cretaceous syn-rift section, with migration having taken place in the latest Cretaceous or Cainozoic, from areas with sufficient overburden. The bounding faults would need to provide an adequate seal or, if not, would need to provide a conduit to overlying traps within the Tertiary

Reactivation folds, rollovers and inversion structures (Figure 15b):

Numerous structures occur within the syn-rift section within the graben. These are envisaged to comprise two categories based on the phases of basin development: firstly, anticlinal and ?wrench-related structures within the Early to mid Cretaceous syn-rift section that are considered to have developed in the ?Cenomanian largely as a result of a 'basin inversion' event; and secondly, more subtle compaction, drape and pinchout features that developed during the Cenomanian and Santonian during a second phase of syn-rift infill.

Basin margin pinchouts (Figure 15c):

Major pinchouts occur along the flanks of the graben and particularly against the Lord Howe Platform to the east of the main graben depocentres. They are present in both the syn-rift section and in the post-rift section, probably up to the Oligocene. Potential traps of this type are expected to be elongate and widespread. Compaction/drape over areas of rugged basement may also offer significant plays.

Diapiric-type structures (Figure 15d):

The nature of the diapiric-like structures through the Gower Basin region remains conjectural, in that they could be a product of either shale/?salt mobilisation or phases of volcanism. However, those that lie within the major graben depocentres and appear to originate from within the syn-rift fill, may represent classic diapirs. In places they exhibit evidence of associated 'rim synclines', uplift of adjacent sediments at their flanks, and uparching of the overlying section. Mapping of the 'diapir fields' is not possible from the existing seismic grid, however the data indicate that most seem to occur near the axis of the main depocentre west of the Lord Howe Platform. A detailed study of these features is warranted as they could provide plentiful petroleum targets.

The recent discovery of similar diapirs within the Fairway Basin, to the northeast, is encouraging (Exon *et al*., 1998). Some 100 of these have been interpreted, each 5-15 km across. They appear to be sourced from a homogeneous layer about 2-2.5 s below seafloor and have risen vertically through the sediment, often to within 0.5 s of the seafloor. In some areas they seem to have coalesced into elongated ridges up to 50 km in length.

Possible carbonate buildups (Figure 15e):

Numerous 'buildup-type features' occur within the Cainozoic. Many of these appear to have been intruded into the section from the Middle Eocene onwards, and the uparching of the younger strata suggests that they are volcanic intrusions (probably equivalent to some of the three phases of volcanism recognised on Lord Howe Island). However, a few of these features are seismically transparent and appear to be onlapped by the overlying beds, a situation reminiscent of carbonate buildups. Their presence on or about the Middle Eocene unconformity lends support to such an origin, since from that time on the region moved from marginal marine conditions into a more bathyal regime.

Wrench-related accommodation structures:

Although the regional mapping carried out in this study provides only a tentative indication of structural offsets at probable transfer faults within accommodation zones, it is likely that significant wrench-related anticlines may be present within these zones. Furthermore, ramp structures that usually occur between the fault offsets at accommodation zones may provide effective pathways for the migration of any hydrocarbons into such structures.

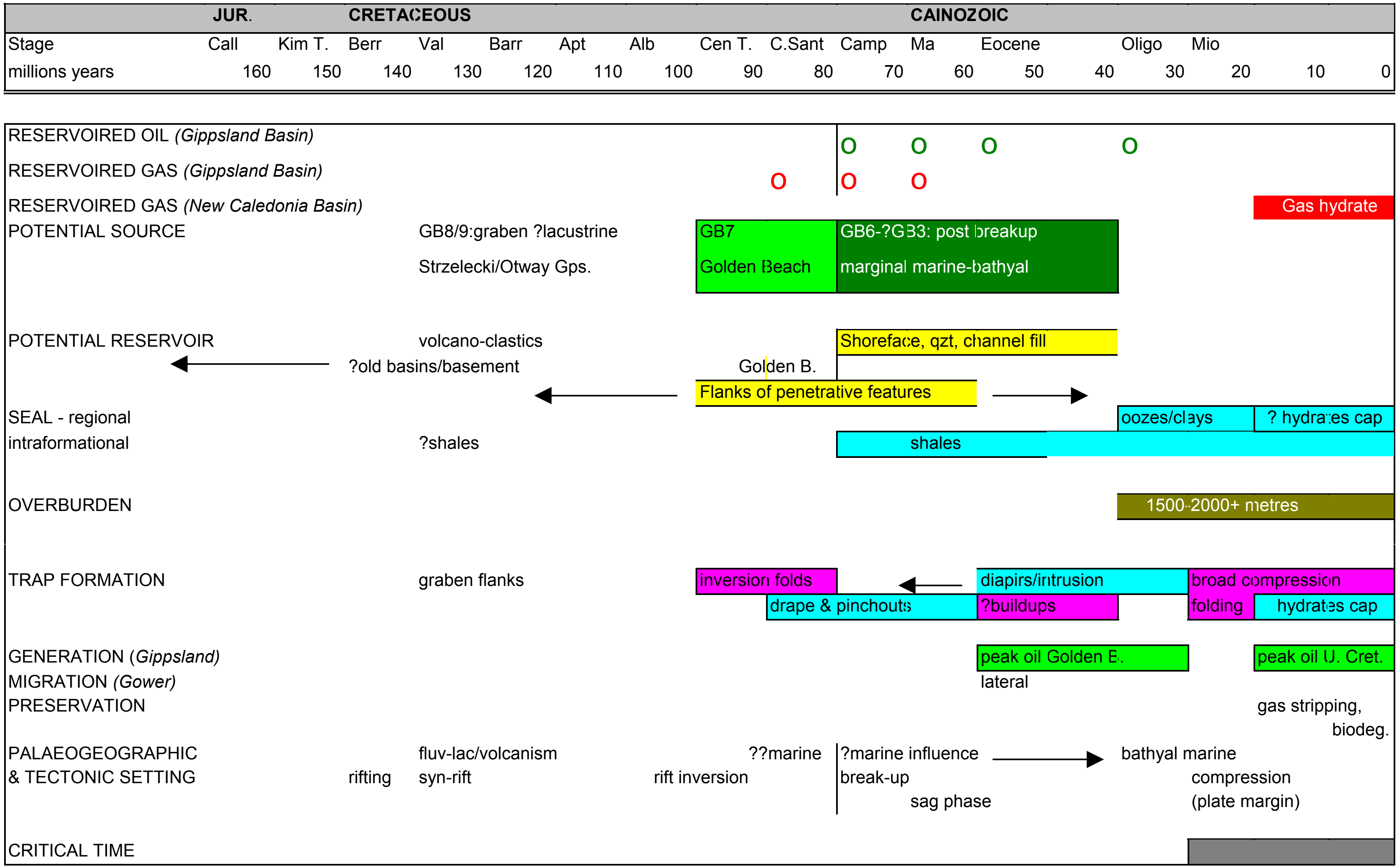
Discussion

Structurally, the Gower Basin could be described as a 'poly-history basin', in that it has developed through an extended period, encompassing the ?Late Jurassic – Recent, via oblique extension, inversion, subsidence and compressional folding. This has given rise a plethora of potential petroleum traps, including rift-margin structures, syn-rift folds and inversion structures, pinchouts, and possible diapiric features and ?carbonate buildups. As in the Bass Strait basins, the early syn-rift fill is likely to comprise sediments with a high volcanogenic component, and is thus unlikely to provide either a good source or reservoir. However, from the Cenomanian onwards the region appears to have come under increasing marine influence and the prospects for finding source beds deposited in restricted marine environments seems reasonable. Reservoir beds are expected within the varied non-marine to shallow marine sequences layed down after breakup. Seals could be provided both within these sequences and within the younger pelagic oozes.

A summary of the critical events that would be significant for the generation, migration and entrapment of any petroleum generated within the Gower Basin is shown in Table 6. It is considered that the most critical phase of the basin's development was probably from about the Miocene onwards. By that time, all potential source rocks would be blanketed and probably sealed by younger sequences. Also, most potential traps associated with the graben-fill, their flanks, and mobilisation of 'diapiric features' would be in place. The broad compression folds would have been actively forming at that time, but in most places there appears to have been little associated faulting that might have allowed any migrating hydrocarbons to seep away at seabed.

In terms of petroleum prospectivity, the greatest uncertainty is the thermal maturity of potential source beds that have been subject to only a limited overburden in some areas. If source material is present deep in the grabens (though probably terrestial in nature) the situation would be more favourable. There is some positive evidence for the active generation and migration of hydrocarbons in the region: Symonds *et al*. (1999) having reported on the presence of 'bottom simulating reflectors' (BSRs) and 'flat spots', on seismic data from the eastern margin of the Middleton Basin, and in the Fairway, Monawai and New Caledonia Basins. For the Fairway Basin, they have concluded that considerable quantities of free gas may be trapped less than 600 m below the seabed. Such gas could be generated from rift-related organic-rich sediments in the basins, and has the potential to have migrated updip onto LHR, perhaps beneath a seal of early forming gas hydrates (Exon *et al*., 1998). Satellite synthetic aperture radar (SAR) imagery has also shown some evidence of 'low level' oil slicks and films in the Fairway and Middleton Basins roughly coincident with the BSRs.

Table 6: Gower Basin Events Chart



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Wood, R.A., 1993. The Challenger Plateau. In: Balance, P.F., *South Pacific Sedimentary Basins*, Elsevier, 351-364.

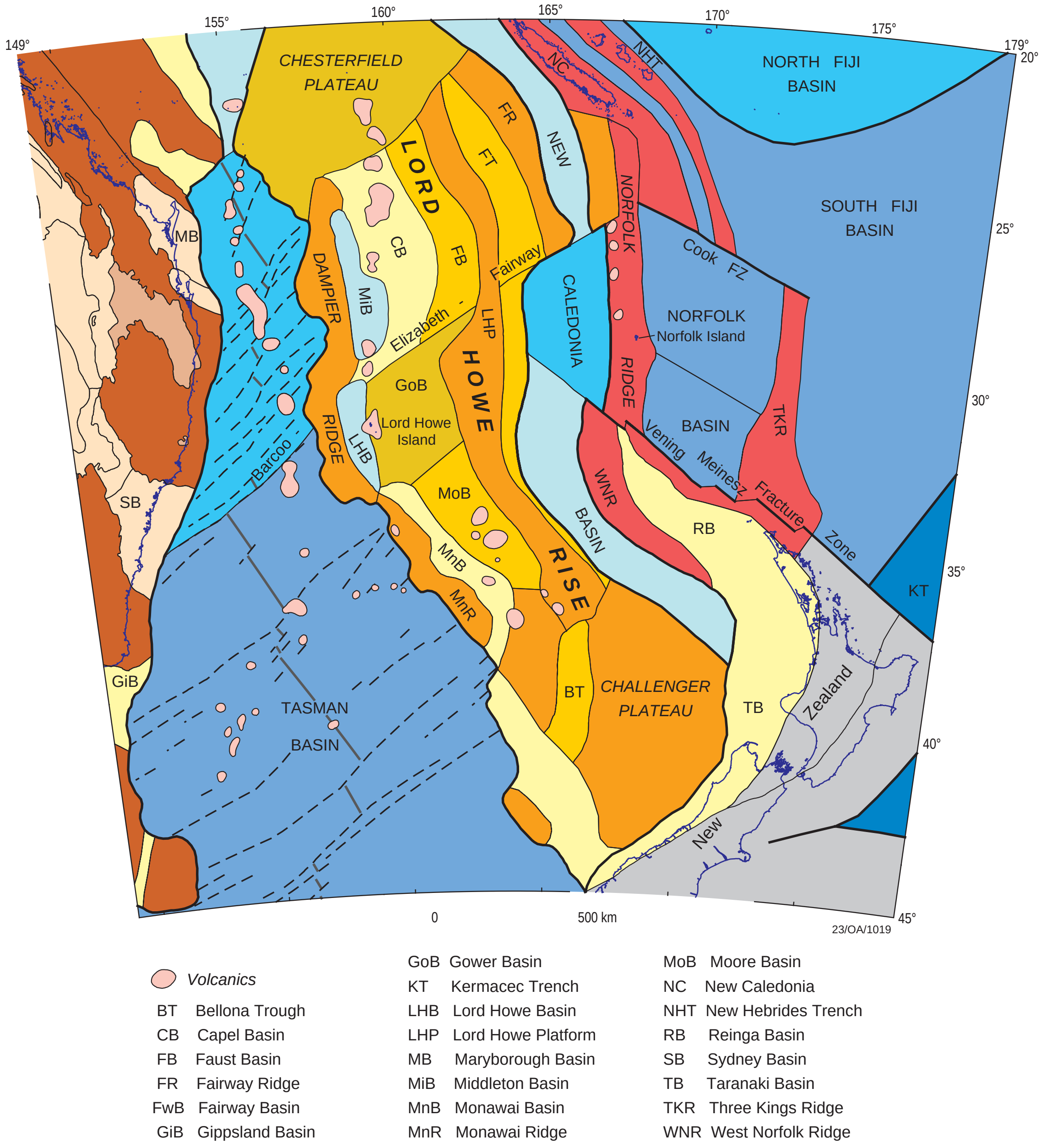


Figure 1. **Tectonic provinces of the Lord Howe Rise region.**
(after Stagg *et al.*, 2000)

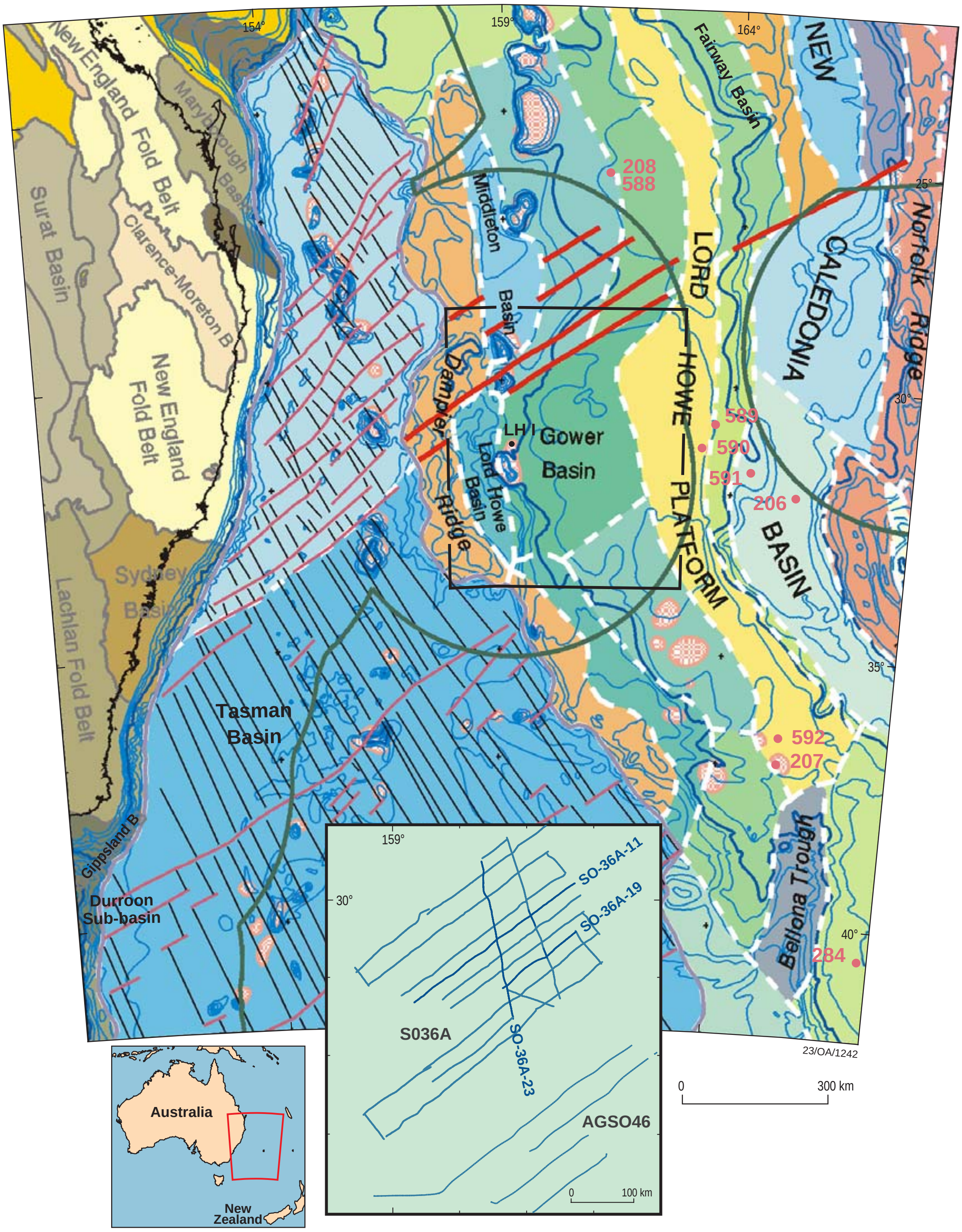


Figure 2 **An AEEZ and legal continental shelf in the LHR/Norfolk region, Tasman Sea, superimposed on structural elements & bathymetry.** Shows isobaths (2000 m heavy), sedimentary basins, Miocene volcanic centres (pink), seafloor spreading anomalies (black), transform faults (pink), major lineaments/transfer zones (red), numbered DSDP sites, Australian Exclusive Economic Zone (olive green), & Gower Basin study area. LHI=Lord Howe Island. (Modified from Van de Beuque *et al.*, in press).
Inset maps: show region, and tracks within Gower Basin study area for *Sonne* SO36A & *Rig Seismic* AGSO46 surveys.

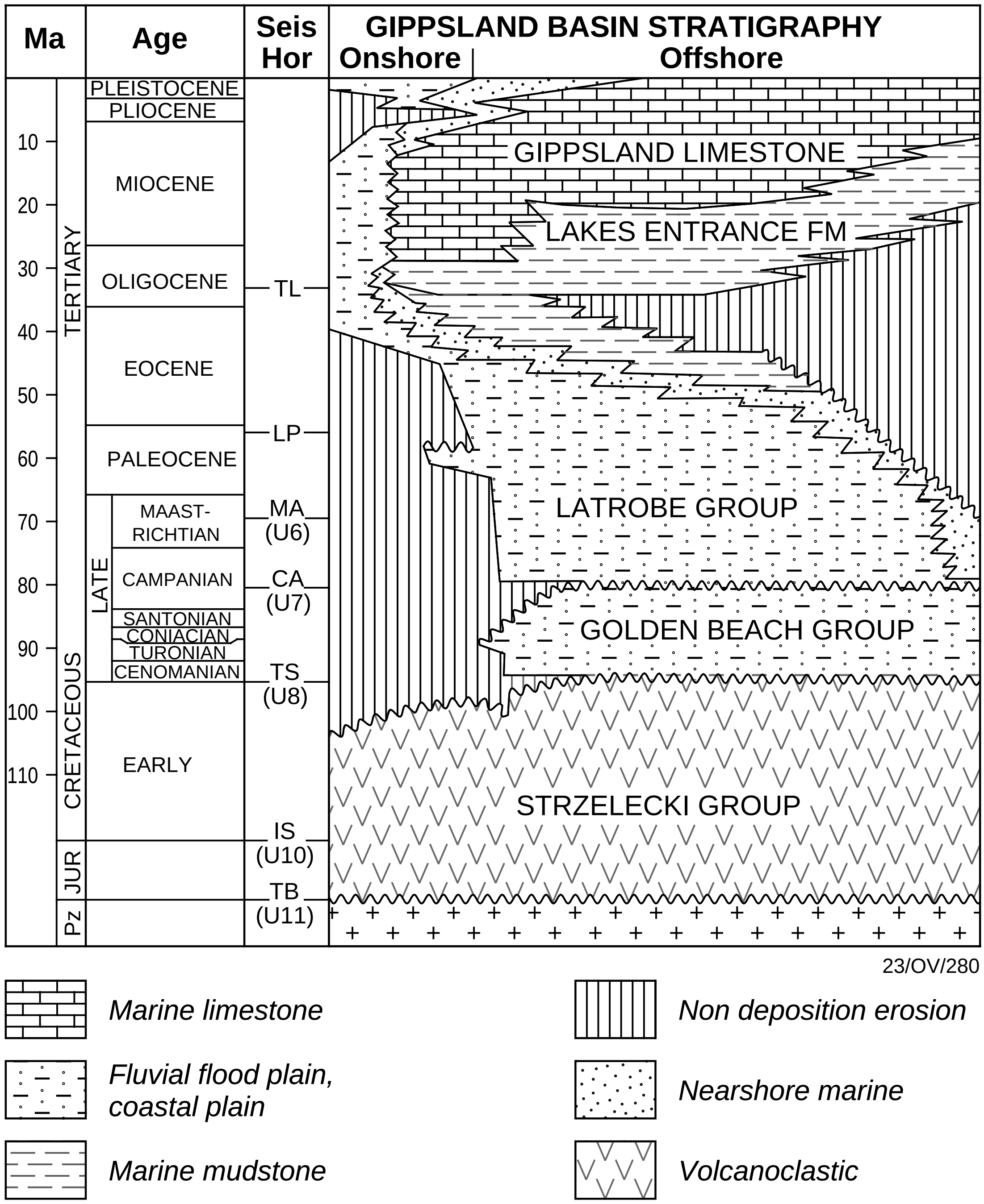


Figure 3. **Gippsland Basin stratigraphy.**
(After Esso, 1988; Rahmanian *et al*., 1990; with seismic horizon identification after Willcox *et al*., 1992).
Note: The Intra-Strzelecki Group unconformity (that is, IS or U10) probably correlates with the Barremian unconformity of Norvick & Smith (2001, figure 2). Also, the Golden Beach Group as shown in this figure has now been sub-divided by Norvick & Smith (2001) into Emperor Group (below) and Golden Beach Group (above), spanning the Turonian to Campanian.

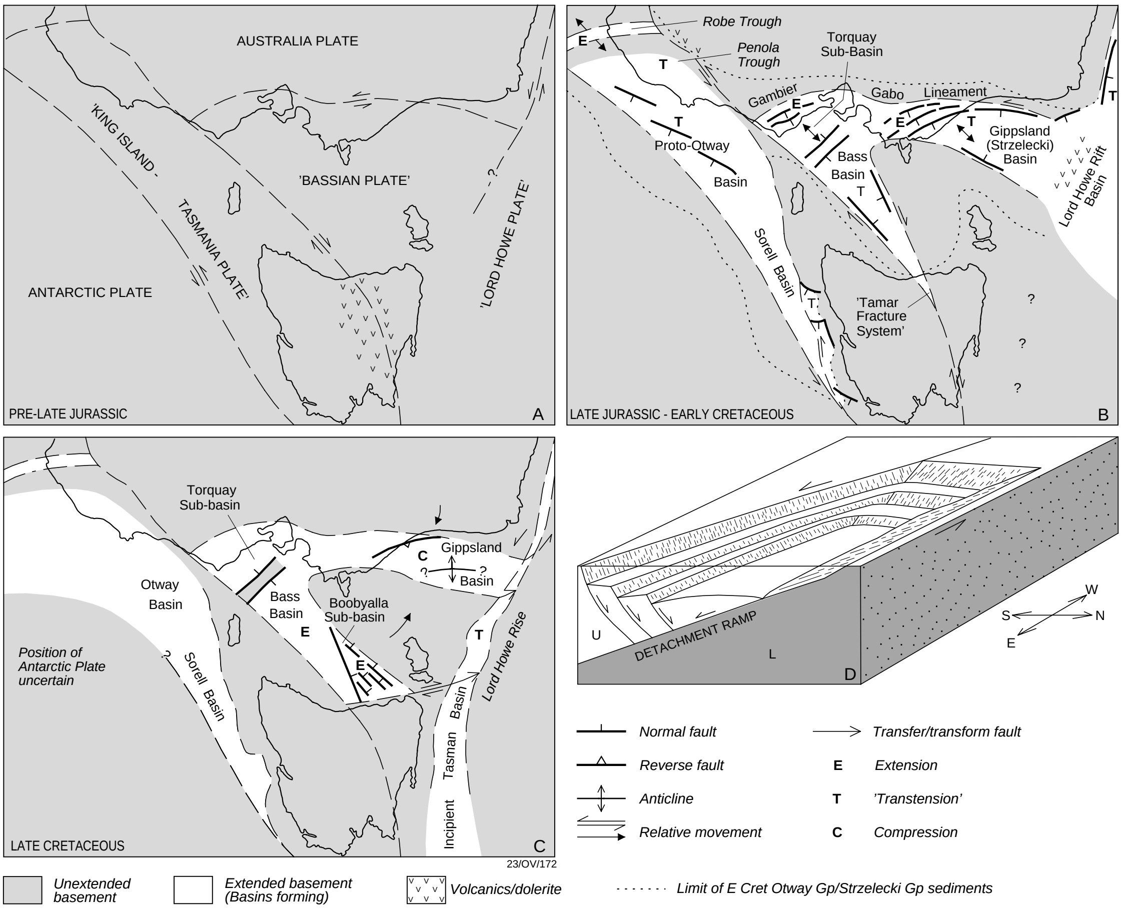


Figure 4. Conceptual model for formation of the Bass Strait basins.
(After Colwell & Willcox, 1993, fig 12).

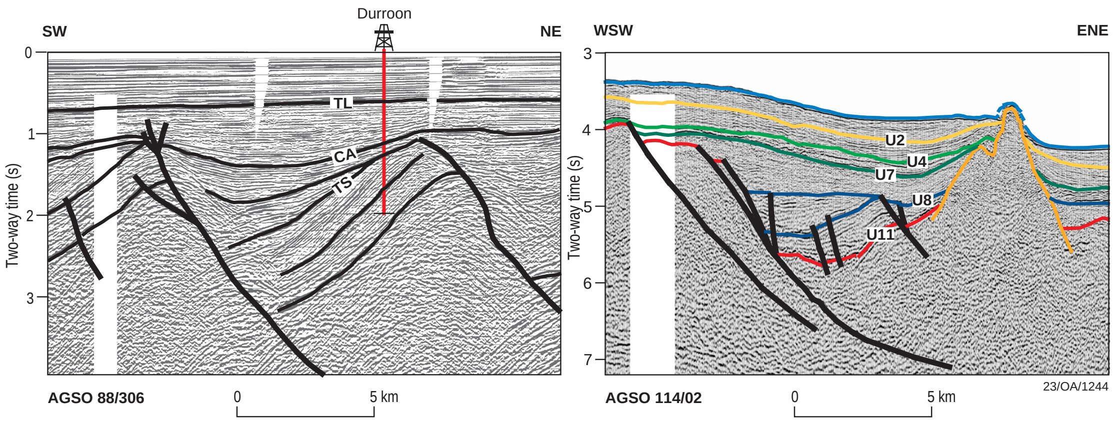
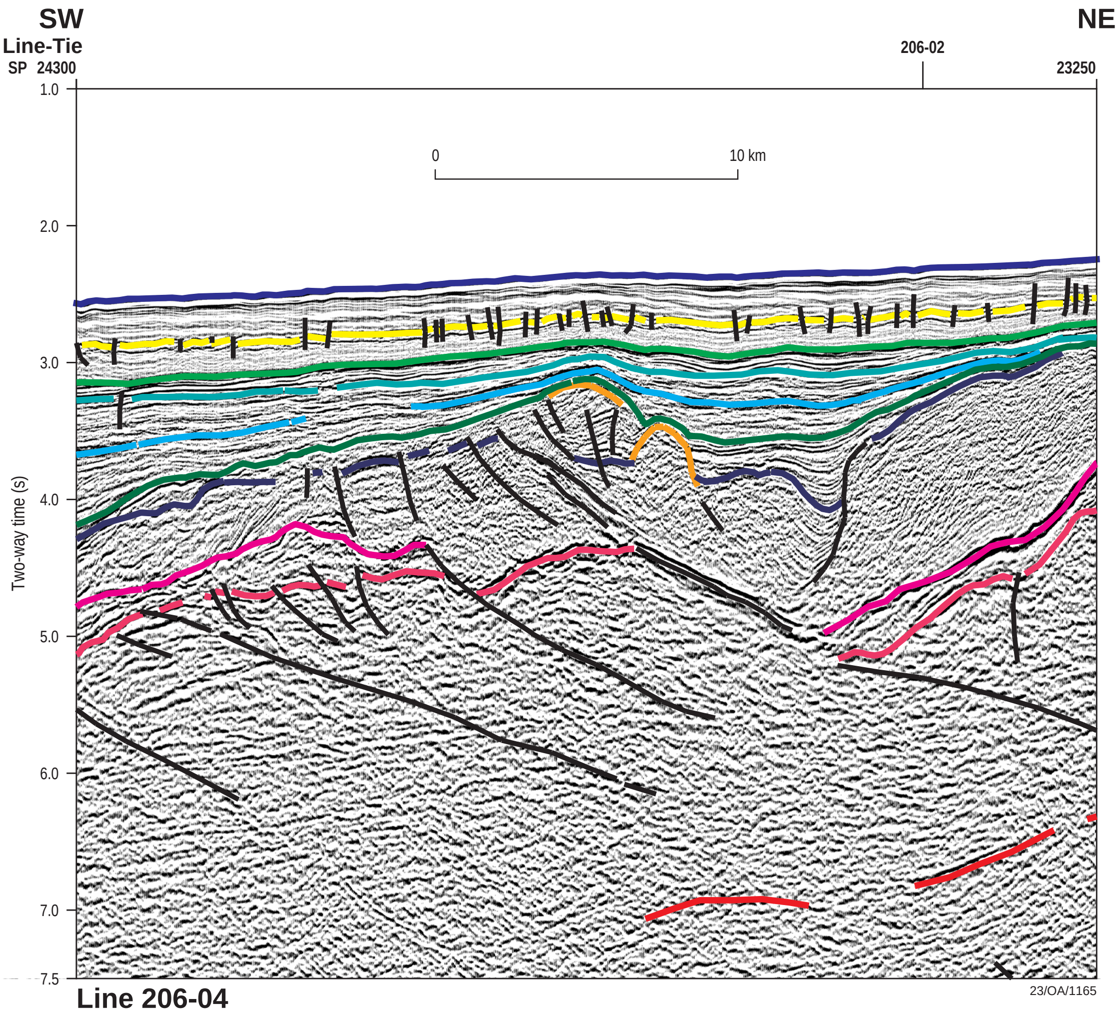


Figure 5. **Comparison of seismic data from Durroon (Boobyalla) Sub-basin of Bass Basin (left) and southwestern LHR (right).**
(TS=top Aptian-Albian Otway/Strzelecki Group; CA=Campanian breakup unconformity; TL=top Campanian-Eocene Eastern View Coal Measures;V=volcanics. After Symonds *et al*., 1996)



Megasequences	Unconformity	Age
Water layer		
	U1 (wb)	
GB1		
	U2	Middle Miocene
GB2		
	U3	
GB3		
	U4	?Mid Oligocene
GB4		
	U5	E. or M. Eocene
GB5		
	U6	?Maastrichtian
GB6		
	U7	Campanian
GB7		
	U8	Cenomanian
GB8		
	U9	
GB9		E. Cretaceous
	U10	
GB10		
	U11	?L. Jurassic
	Volcanic/Oceanic	Pre-rift
GB11		
	Intra-basement	

Figure 6. **Seismic profile showing representative sequences in the Gower Basin (part of Line 206-04).**

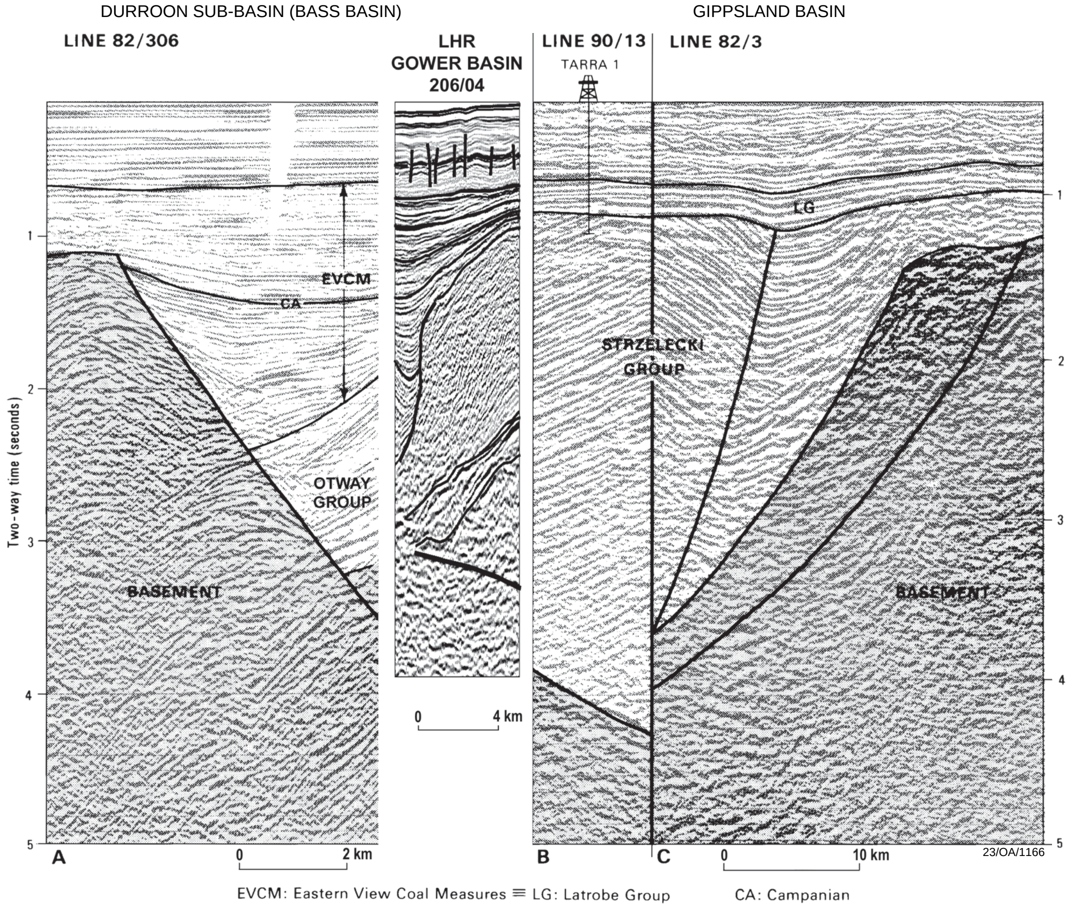


Figure 7. **Comparative seismic: Durroon Sub-basin (Bass Basin) – Gippsland Basin – Gower Basin (LHR).**
(based on Willcox *et al*., 1992).

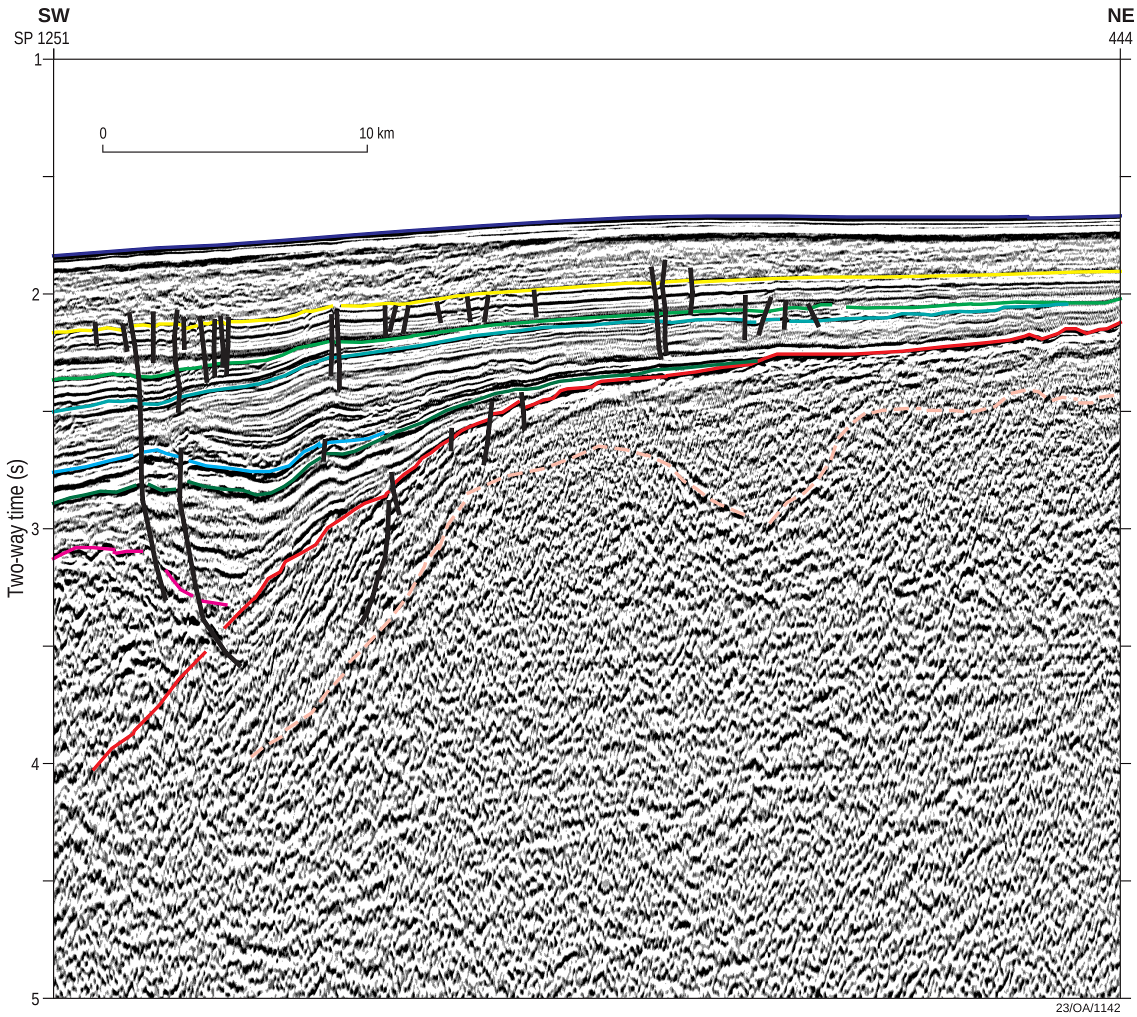


Figure 8a. Seismic sections showing 'Basement' characteristics.
Basement of the 'Lord Howe Platform' (Line SO36-15). This is a region of planated basement, which flanks the eastern side of the Gower Basin and underlies at least part of it. The Lord Howe Platform is probably composed largely of rocks that are equivalent to those of the New England Fold Belt. For legend, see Table 2.

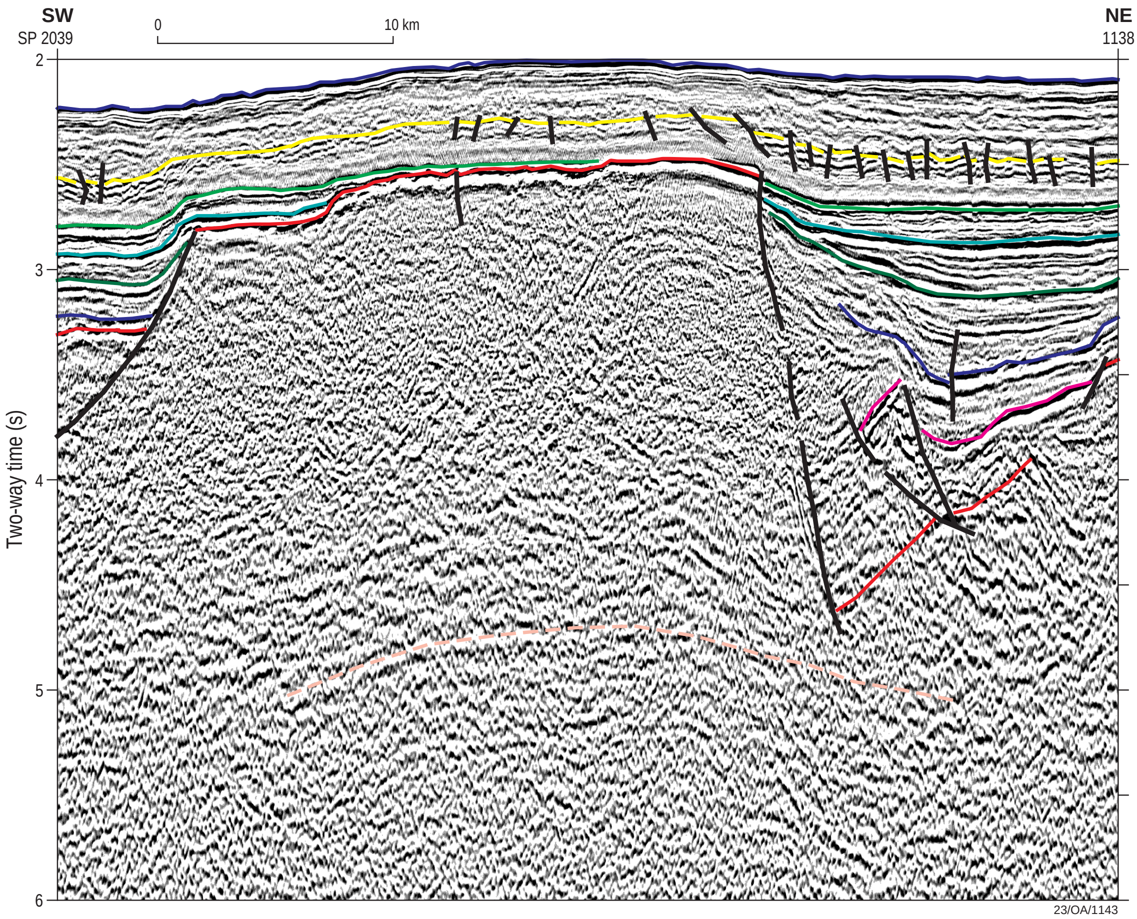


Figure 8b. **Seismic sections showing 'Basement' characteristics.**
Rifted basement block in the Gower Basin (Line SO36-21). This block shows little internal stratification possibly due to the masking effect of overlying basement volcanics. The poorly-defined reflectors at approximately 5s twt may represent intra-basement structure or possibly a detachment surface. For legend, see Table 2.

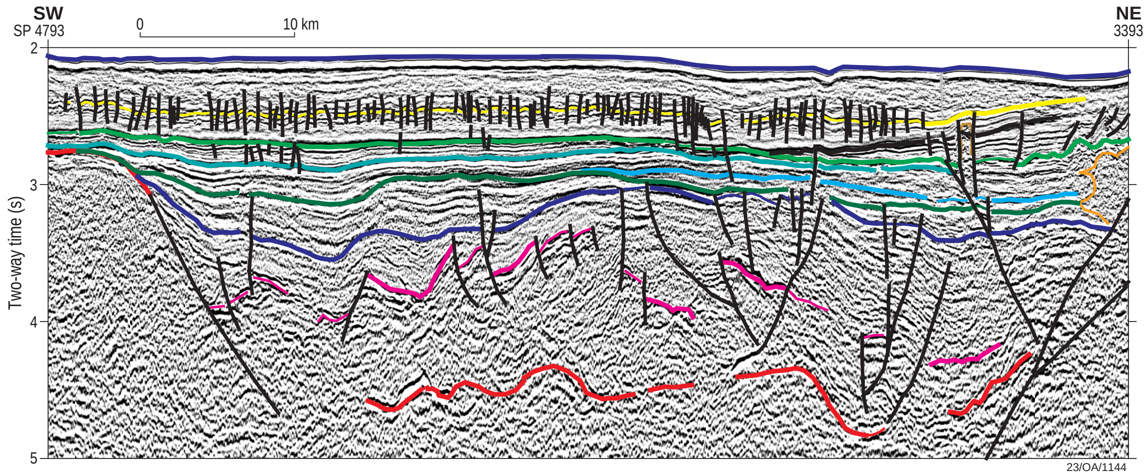


Figure 8c. Seismic sections showing 'Basement' characteristics.
Volcanic and/or oceanic basement. Volcanic-type basement appears to underlie some graben within the Gower Basin (Line SO36-06a) and shows a rugged surface and little or no internal stratification. The interpretation tends to be somewhat subjective, since the overlying synrift volcanics may mask the basement characteristics. Towards the western side of the Gower Basin, the volcanic-type basement may abut 'oceanic crust'; however, this is conjectural and cannot be proven from the seismic data. For legend, see Table 2.

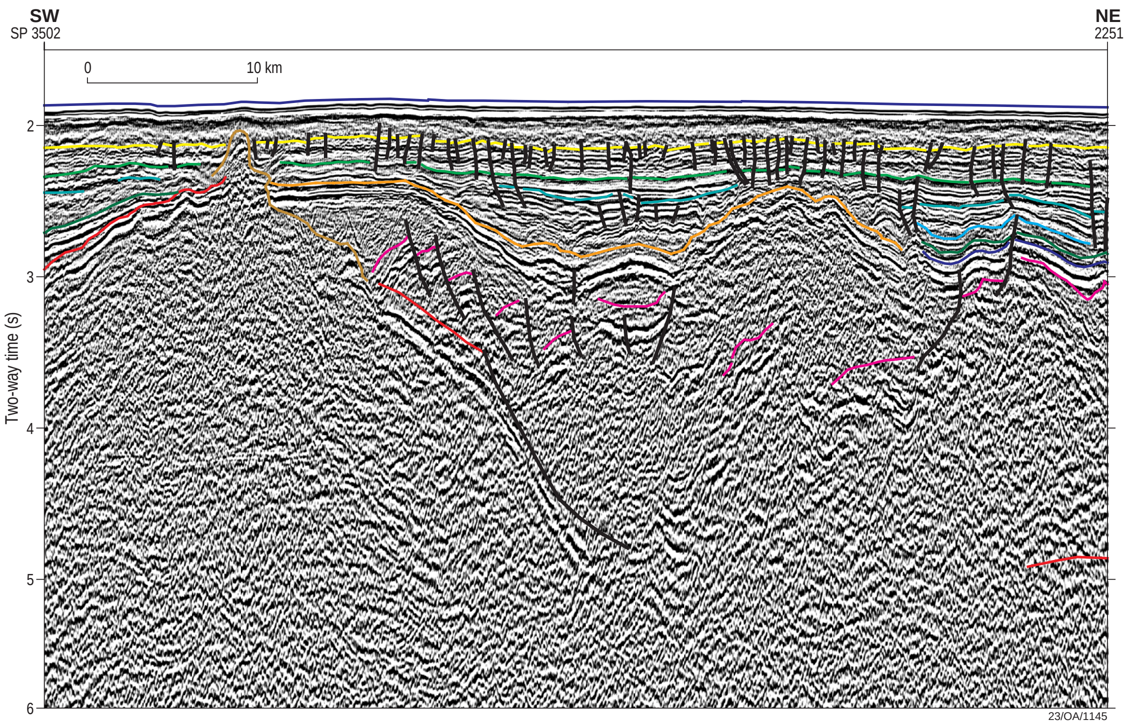


Figure 9. **Seismic section showing rift-phase volcanics (Line SO36-15).**
The rift-phase volcanics are high-amplitude events that represent sills, and have probably been disrupted by later faulting (see purple horizon). Two phases of post-rift volcanics also appear to be present in this area and are represented by the orange and brown horizons. For legend, see Table 2
.

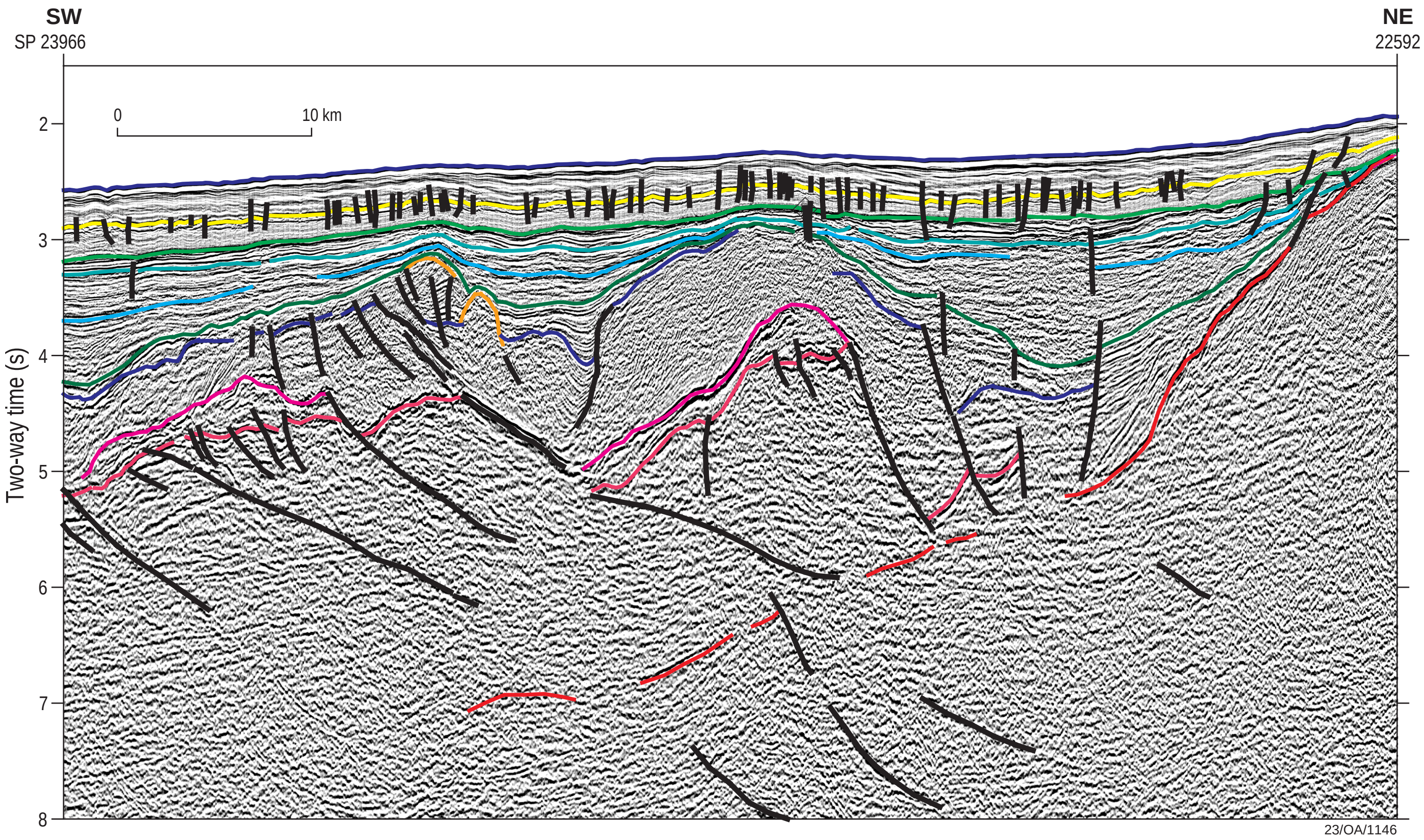


Figure 10. Seismic section showing basin inversion (Line 206-04).
A major phase of shortening and basin inversion is interpreted to have taken place probably in the Santonian ('blue time'). Note the onlap of the younger rift-fill sediments. The faults associated with the inversion appear to dip to the east or northeast. For legend, see Table 2.

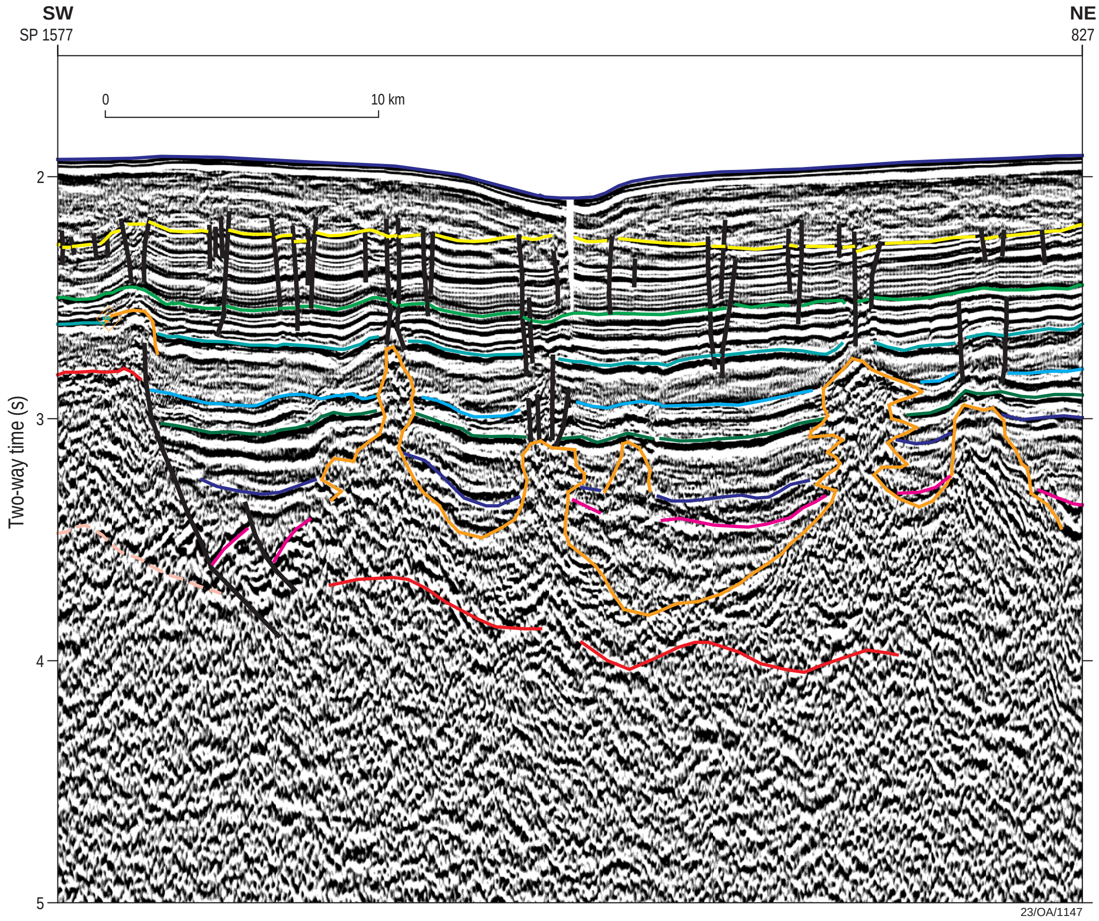


Figure 11a. Seismic sections showing volcanic intrusions and/or diapiric features.

Penetrative-type structures within the rift-fill and sag-phase sediments of a large graben (below orange horizon) (Line SO36-19). These are either diapirs activated during compaction of the syn-rift sediments, or volcanic intrusions of ?Early Eocene age. The magnetic data are inconclusive. For legend, see Table 2.

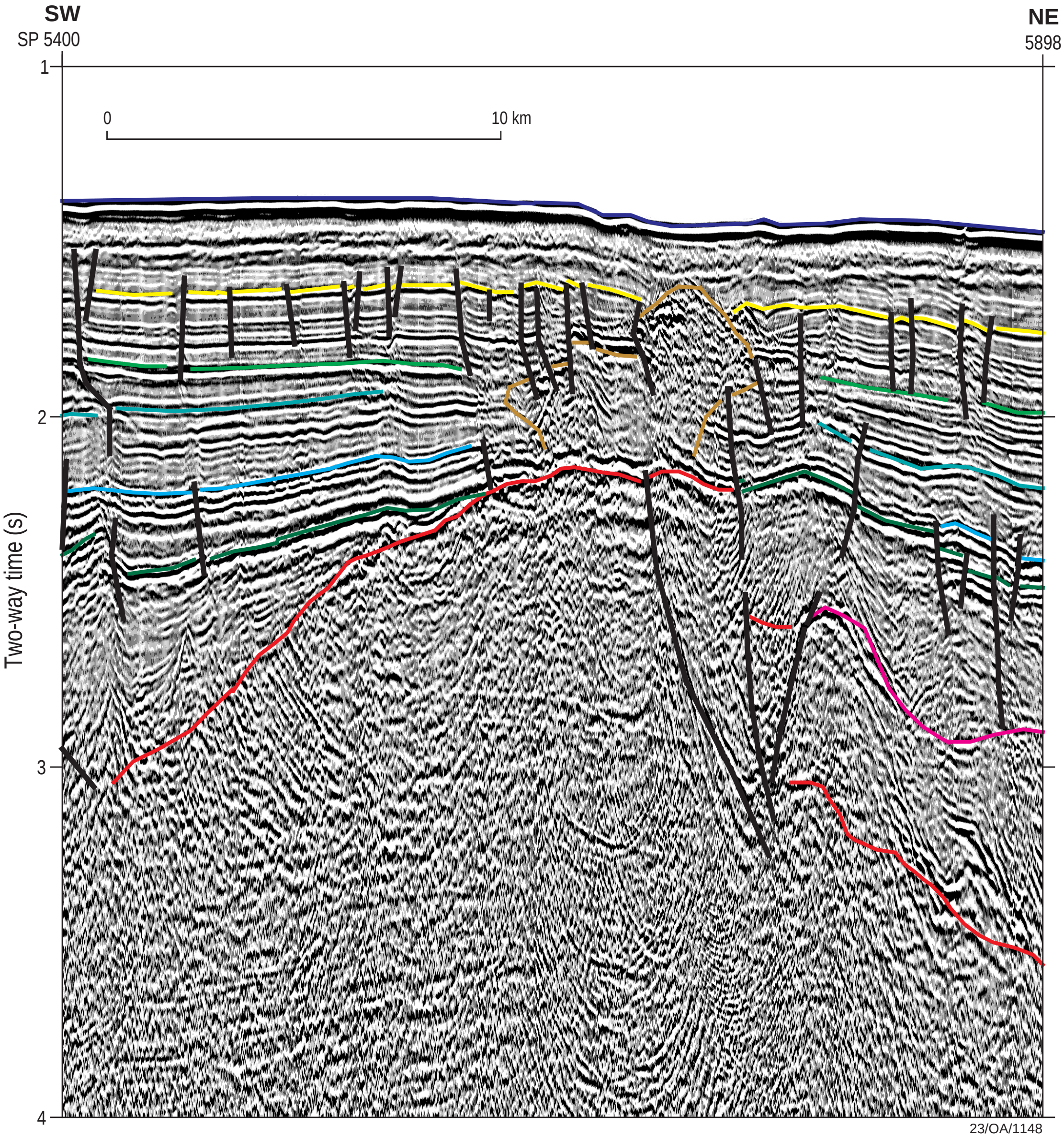


Figure 11b. Seismic sections showing volcanic intrusions and/or diapiric features.

Penetrative-type structures within the younger sediments (brown horizon) (Line 46-04). Many of these features lie over faults near the edge of tilt-blocks and have relatively high amplitudes reminiscent of volcanic intrusions; however, there is a possibility that in some instances these could be diapirs or biogenic buildups. For legend, see Table 2.

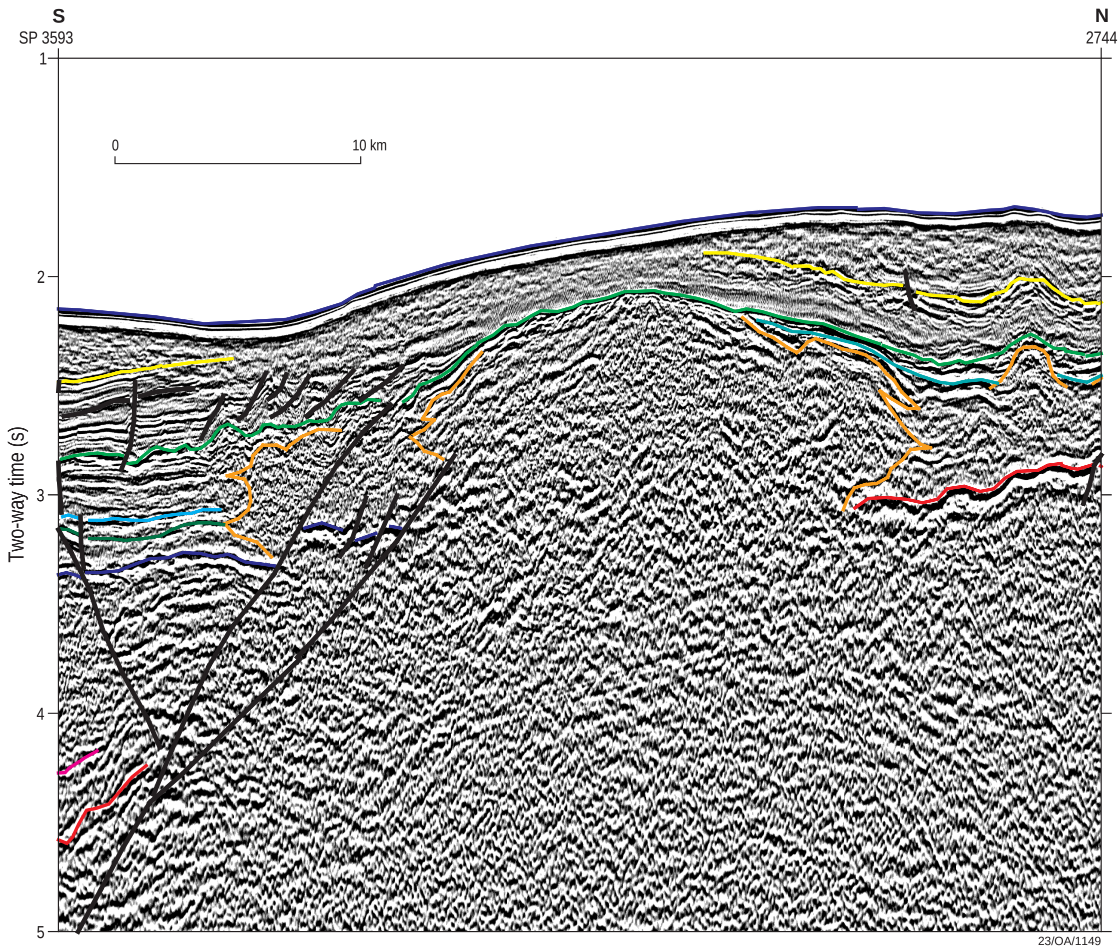


Figure 12a. Seismic sections showing large volcanic bodies.
Large volcanic-like feature developed over graben bounding fault (Line S035-21). Although it is located near the edge of a major uplifted block, a position favourable for reefal growth, its size makes a biogenic origin less likely.

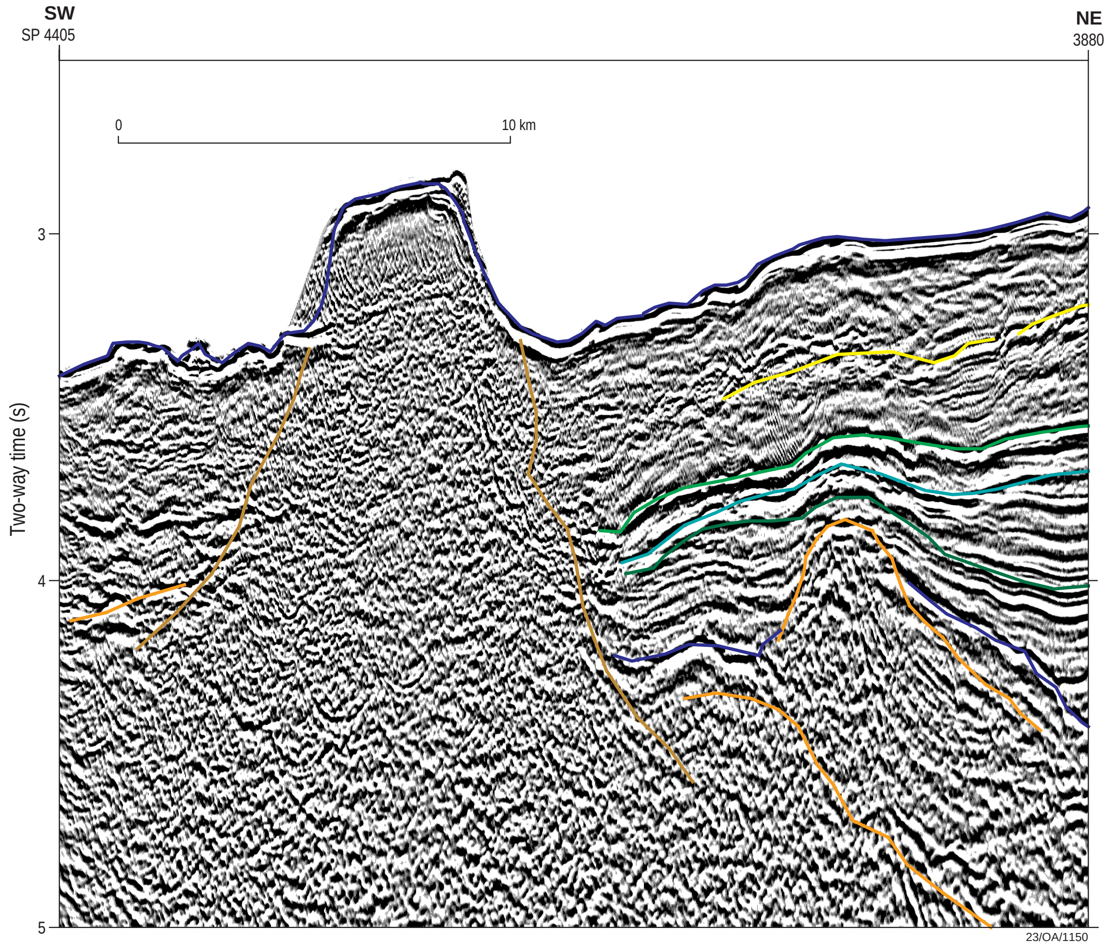


Figure 12b. Seismic sections showing large volcanic bodies.
A large volcanic intrusion on the seafloor, essentially a small seamount of approximately 300 metres elevation (Line SO36-06). For legend, see Table 2.

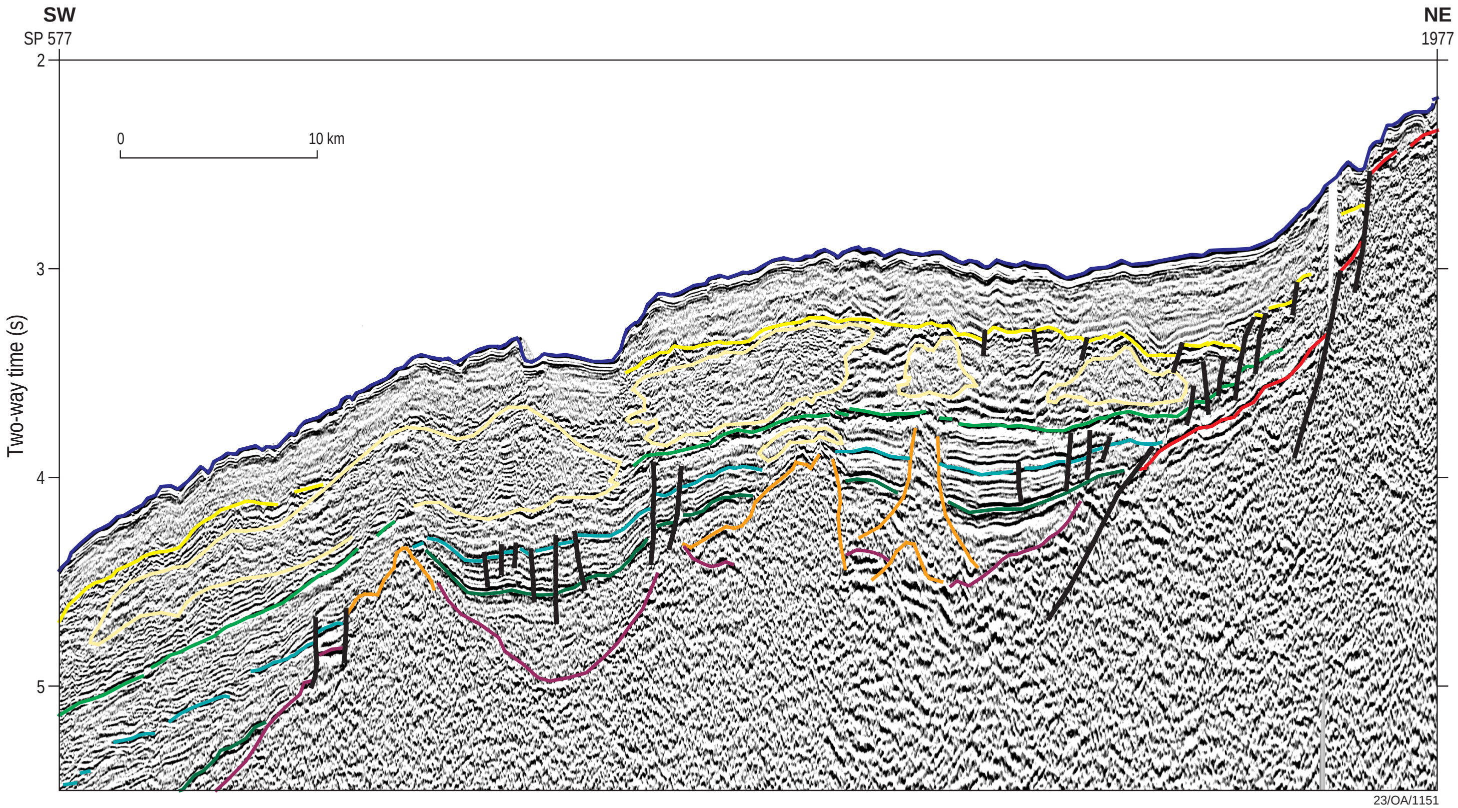


Figure 13. Seismic section showing sedimentary structures (Line SO36-08).
Sedimentary disturbances (?slump-like features) occur below the continental slope to the west of the Lord Howe Rise in the Gower Basin region. Some of these features lie above volcanic intrusions, which may also have contributed to their seismic characteristics. For legend, see Table 2.

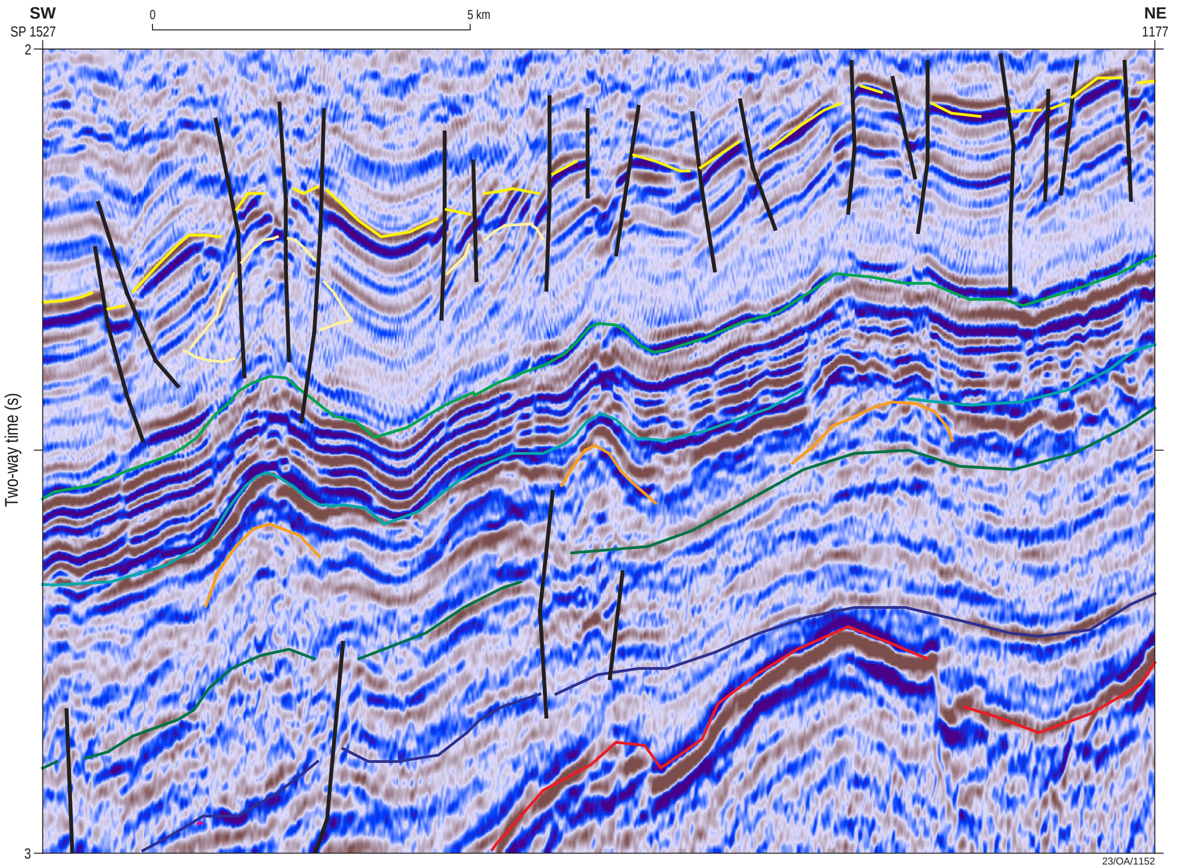


Figure 14. Seismic section showing possible biohermal features (Line SO36-12).
For legend, see Table 2.

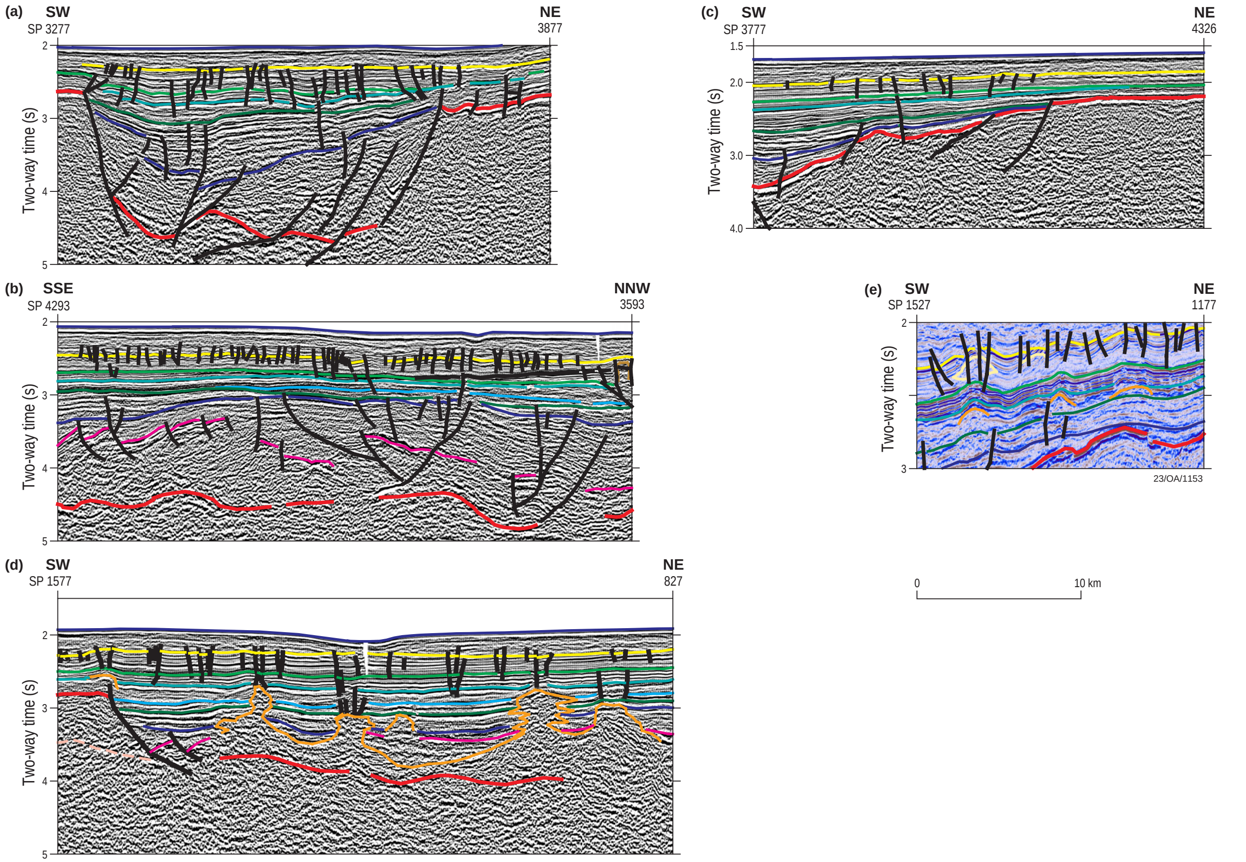
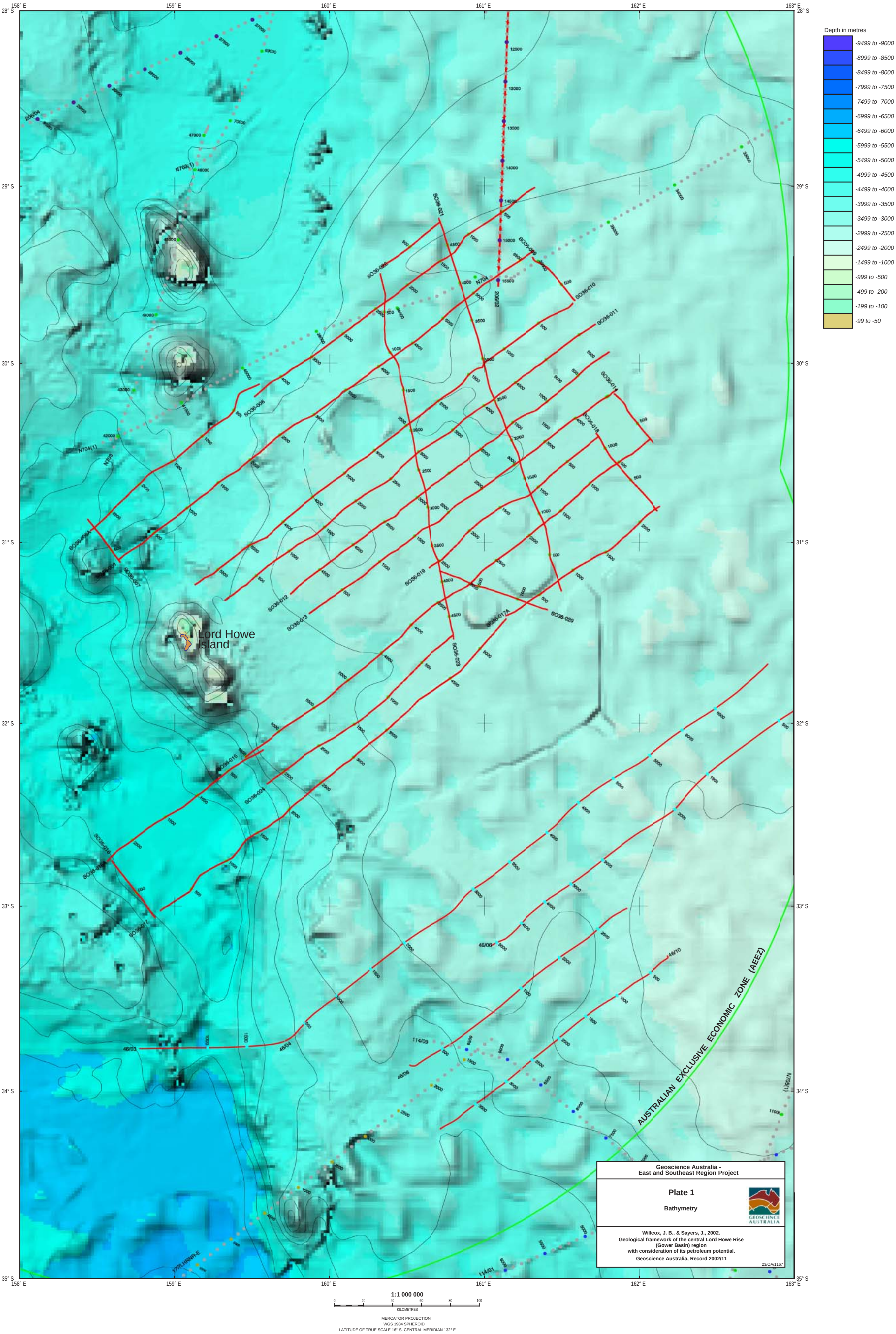
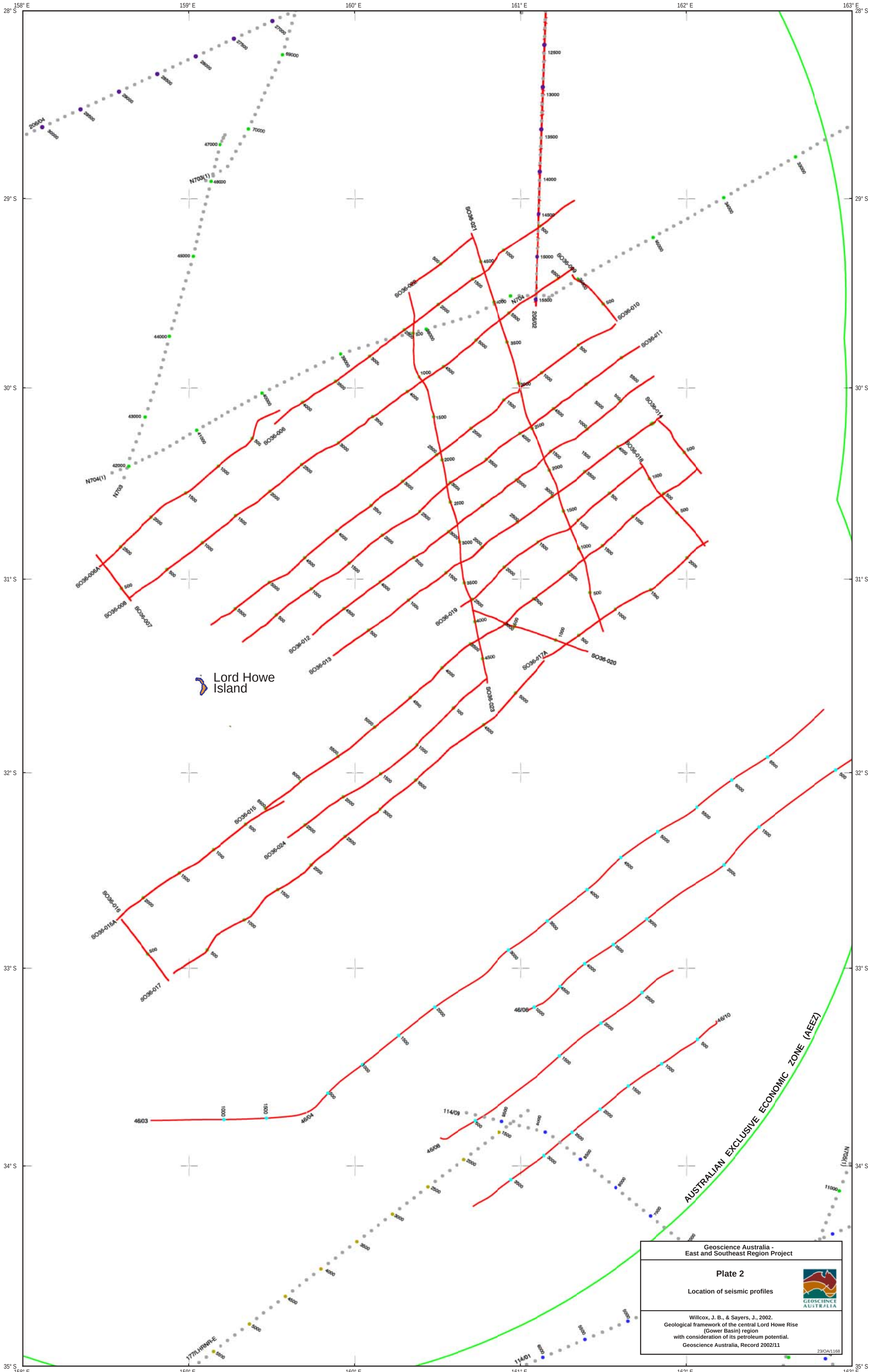


Figure 15. Examples of potential petroleum trap types.
(a) rift margins, (b) syn-rift folds/rollovers/inversion, (c) pinchouts, (d) ?diapiric features, and (e) ?carbonate build-ups.

Lord Howe Rise - Gower Basin



Lord Howe Rise - Gower Basin



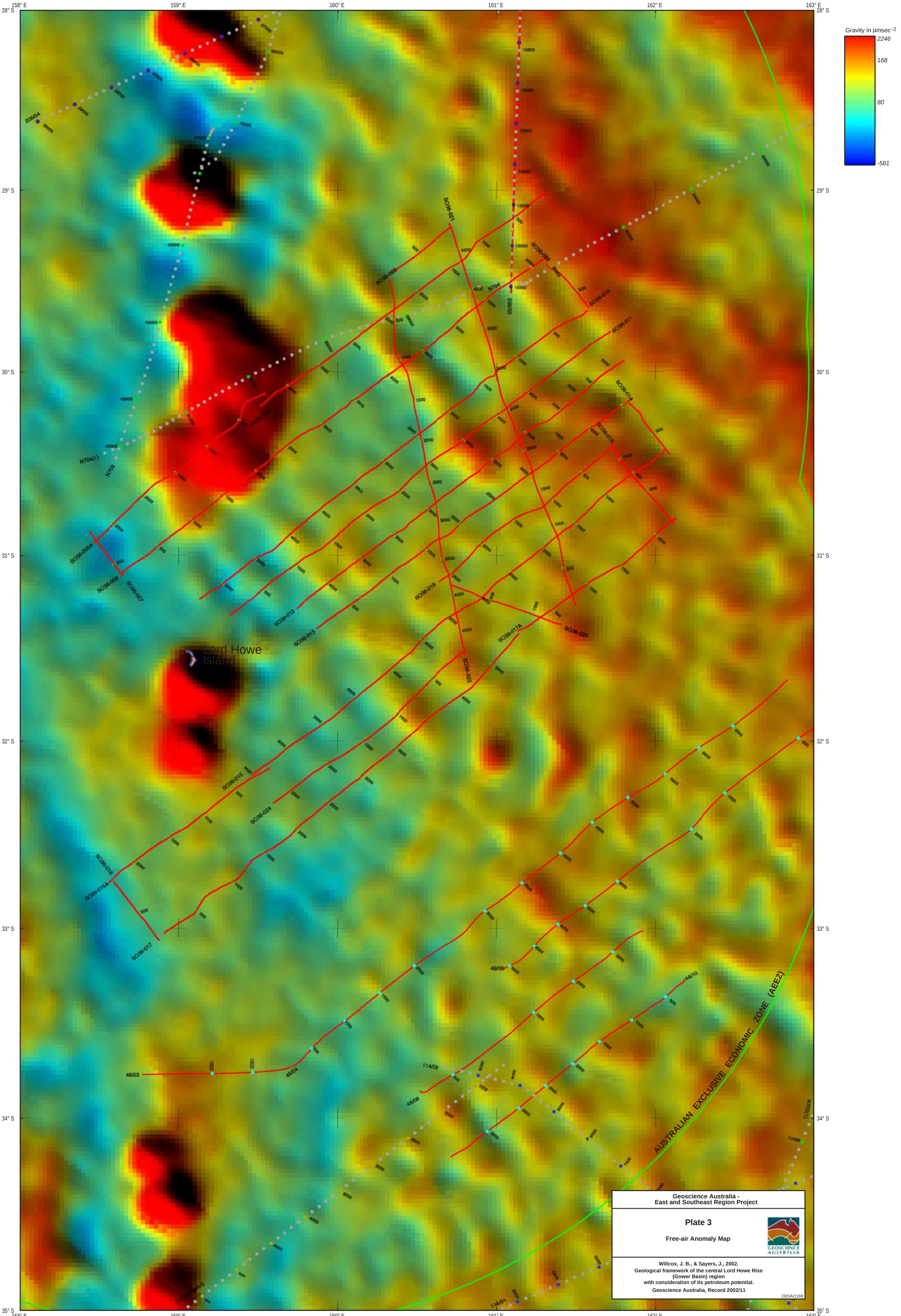
1:1 000 000

0 20 40 60 80 100

KILOMETRES

MERCATOR PROJECTION
WGS 1984 SPHEROID
LATITUDE OF TRUE SCALE 16° S. CENTRAL MERIDIAN 132° E

Lord Howe Rise - Gower Basin

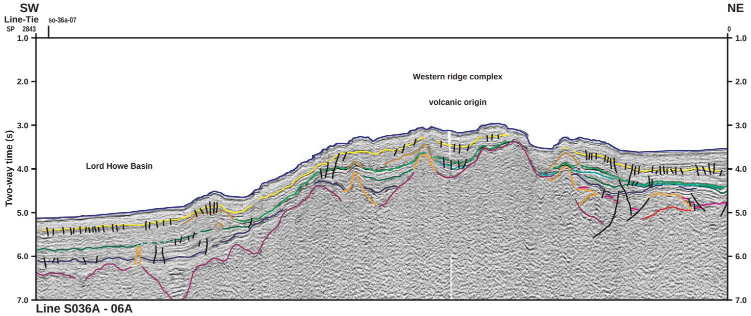


1:1 000 000

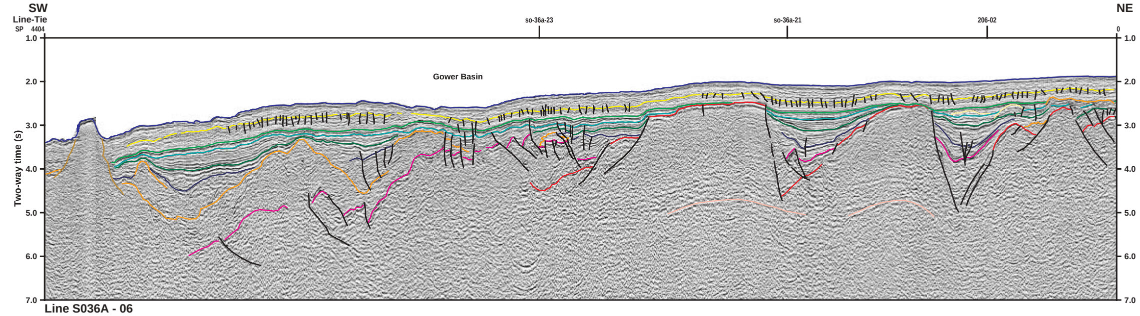
0 20 40 60 80 100

KILOMETRES

MERCATOR PROJECTION
WGS 1984 SPHEROID
LATITUDE OF TRUE SCALE 16° S, CENTRAL MERIDIAN 132° E



Line S036A - 06A



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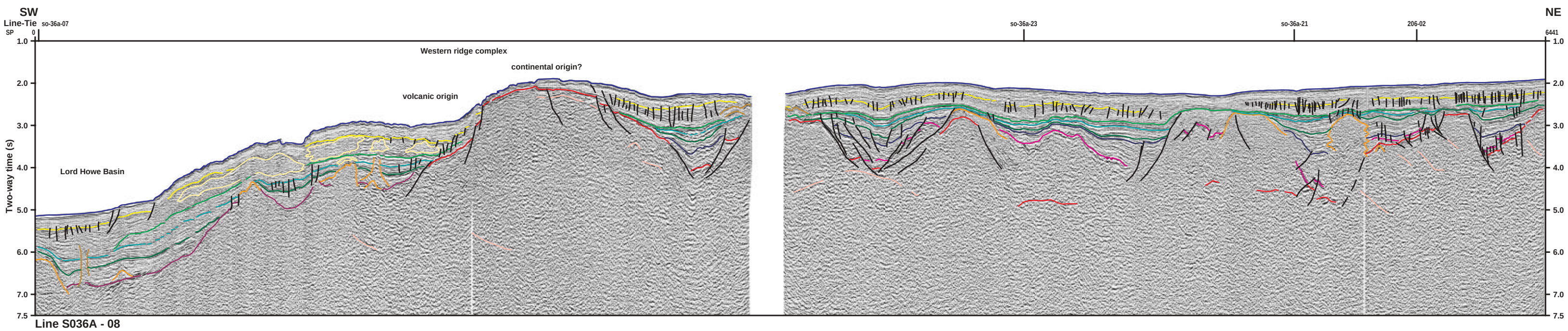
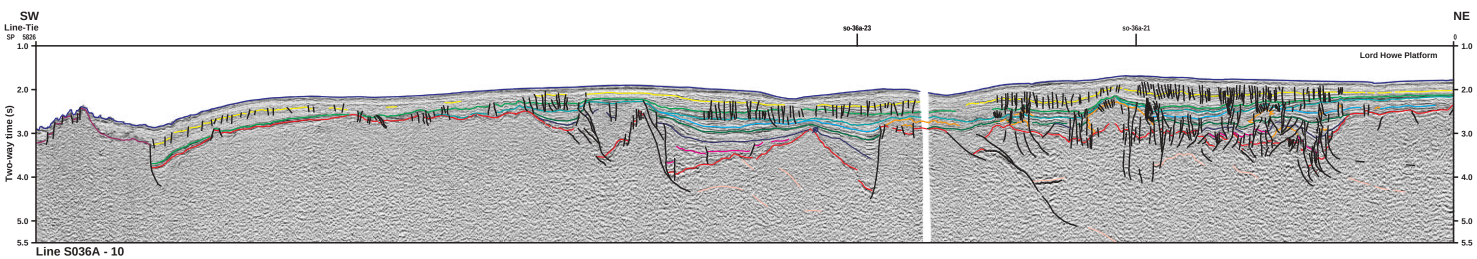


Line S036A - 08



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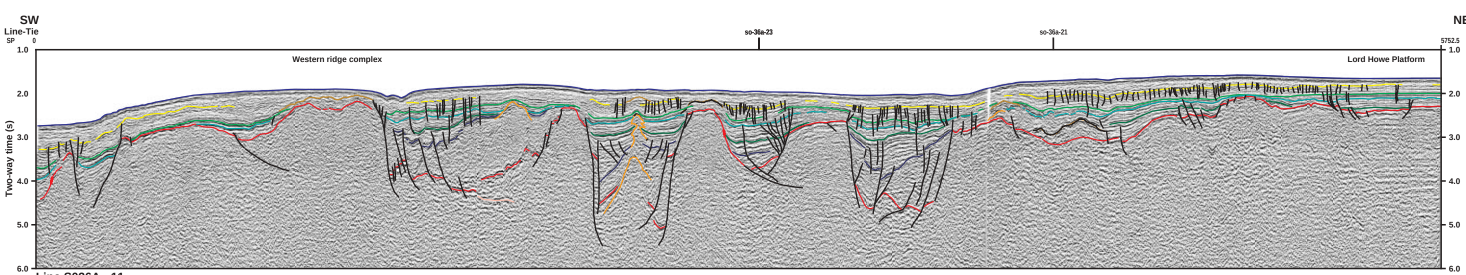

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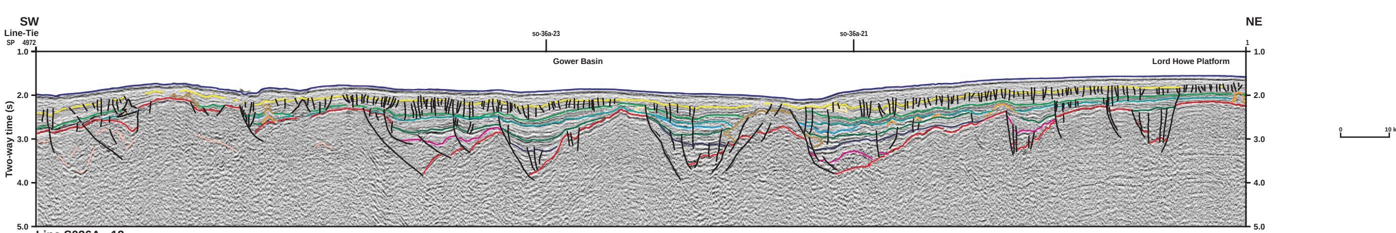
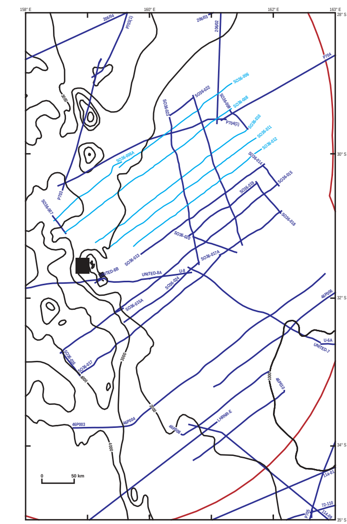


Line S036A - 12



Megasequences	Unconformity	Age
Water layer		
	U1 (wb)	
GB1		
	U2	Middle Miocene
GB2		
	U3	
GB3		
	U4	?Middle Oligocene
GB4		
	U5	E. or M. Eocene
GB5		
	U6	?Maastrichtian
GB6		
	U7	Campanian
GB7		
	U8	Cenomanian
GB8		
	U9	
GB9		E. Cretaceous
	U10	
GB10		?L. Jurassic
	U11	
	Volcanic/Oceanic	
GB11		Pre-rift
	Intra-basement	

Rift and sag phase intrusions/diapirs

Late stage intrusions/seamounts

Sedimentary disruption features

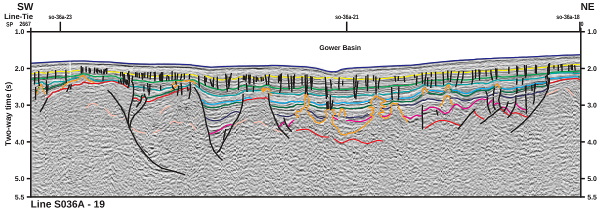
Geoscience Australia -
East and Southeast Region Project

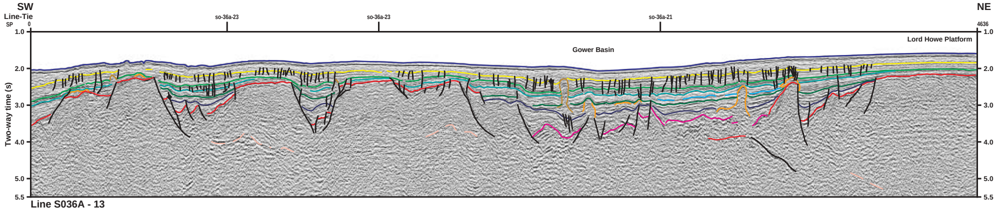
Plate 4

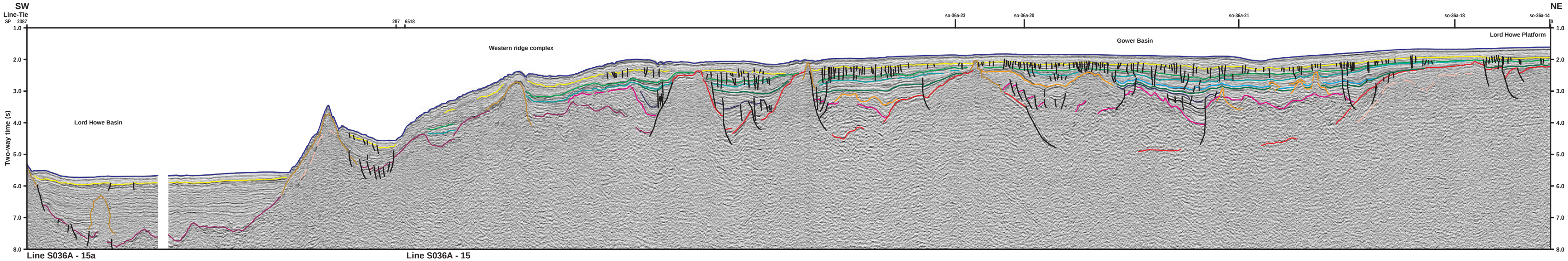
Montage: BGR Sonne Survey SO-36 profiles in northern Gower Basin Region

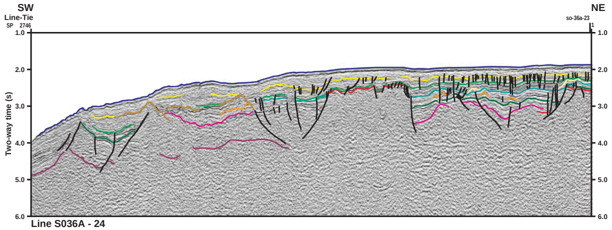
Willcox, J. B., & Sayers, J., 2002.
Geological framework of the central Lord Howe Rise (Gower Basin) region with consideration of its petroleum potential.
Geoscience Australia, Record 2002/11

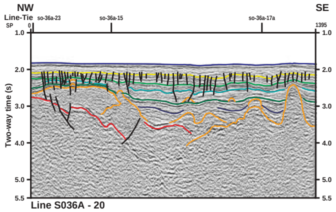
23/OA/1161

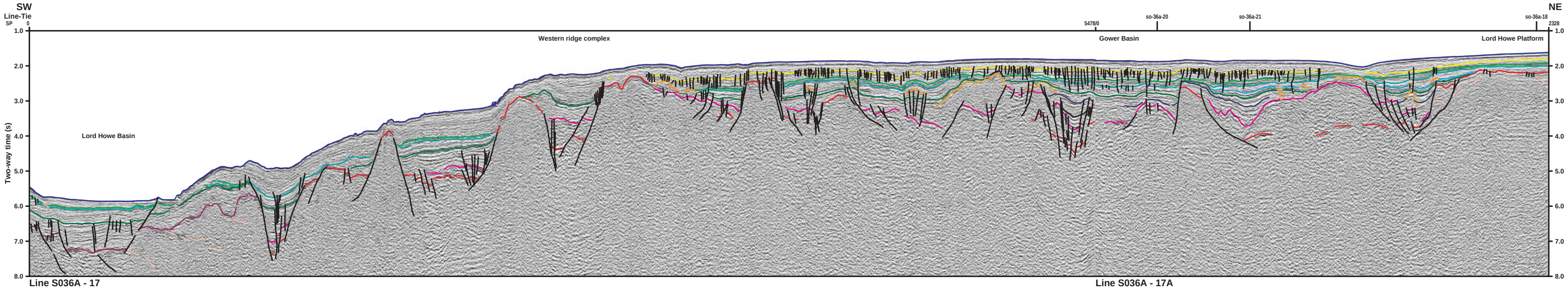




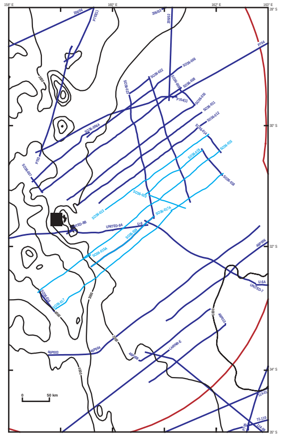








0 10 km



Megasequences	Unconformity	Age
Water layer		
	U1 (wb)	
GB1		
	U2	Middle Miocene
GB2		
	U3	
GB3		
	U4	?Middle Oligocene
GB4		
	U5	E. or M. Eocene
GB5		
	U6	?Maastrichtian
GB6		
	U7	Campanian
GB7		
	U8	Cenomanian
GB8		
	U9	
GB9		E. Cretaceous
	U10	
GB10		?L. Jurassic
	U11	
	Volcanic/Oceanic	
GB11		Pre-rift
	Intra-basement	

Rift and sag phase intrusions/diapirs

Late stage intrusions/seamounts

Sedimentary disruption features

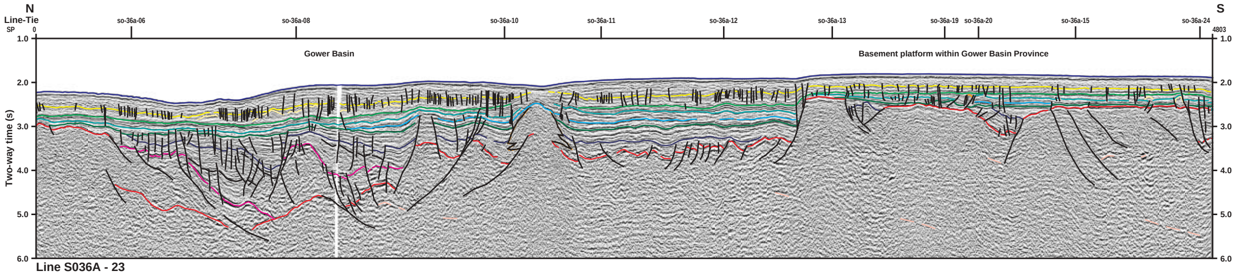
Geoscience Australia -
East and Southeast Region Project

Plate 5

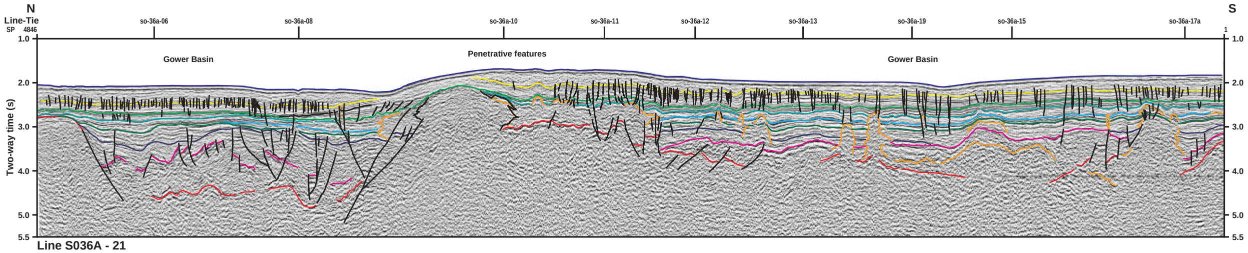
Montage: BGR Sonne Survey SO-36 profiles in central Gower Basin Region

Willcox, J. B., & Sayers, J., 2002.
Geological framework of the central Lord Howe Rise (Gower Basin) region with consideration of its petroleum potential.
Geoscience Australia, Record 2002/11

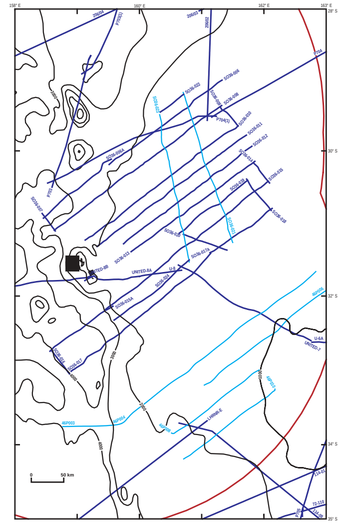
23/OA/1162

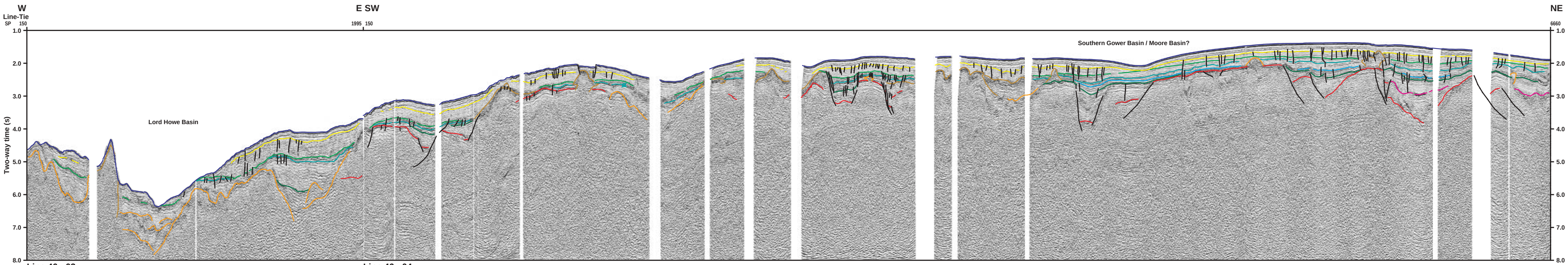


Line S036A - 23



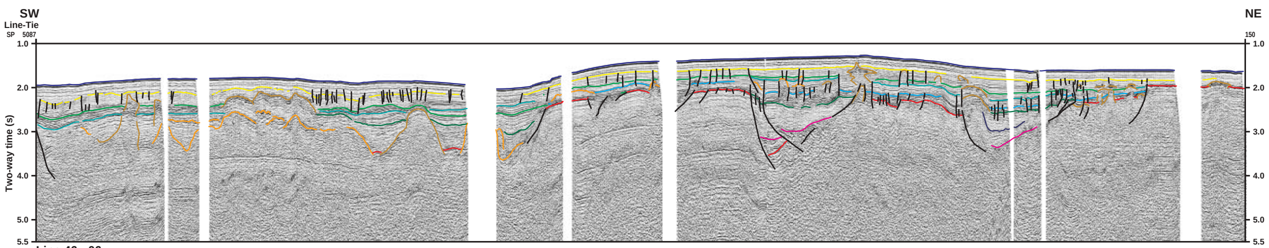
Line S036A - 21





Line 46 - 03

Line 46 - 04

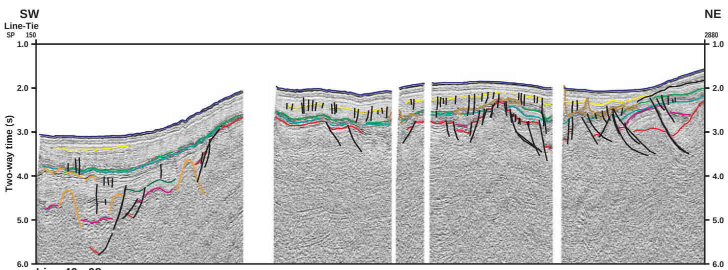


Line 46 - 06

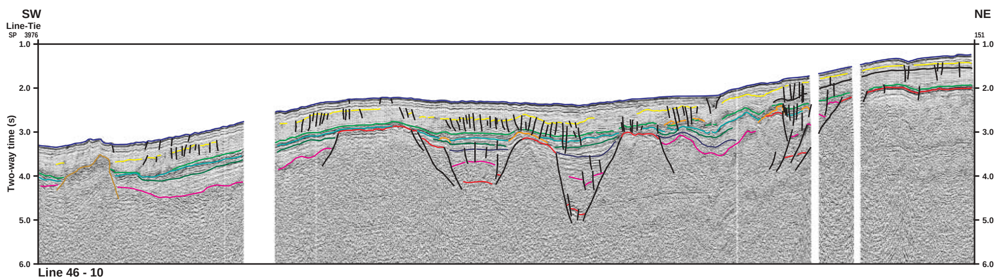
0 10 km

Megasequences	Unconformity	Age
Water layer		
	U1 (wb)	
GB1		
	U2	Middle Miocene
GB2		
	U3	
GB3		
	U4	?Middle Oligocene
GB4		
	U5	E. or M. Eocene
GB5		
	U6	?Maastrichtian
GB6		
	U7	Campanian
GB7		
	U8	Cenomanian
GB8		
	U9	
GB9		E. Cretaceous
	U10	
GB10		?L. Jurassic
	U11	
	Volcanic/Oceanic	
GB11		Pre-rift
	Intra-basement	

- Rift and sag phase intrusions/diapirs
- Late stage intrusions/seamounts
- Sedimentary disruption features



Line 46 - 08



Line 46 - 10

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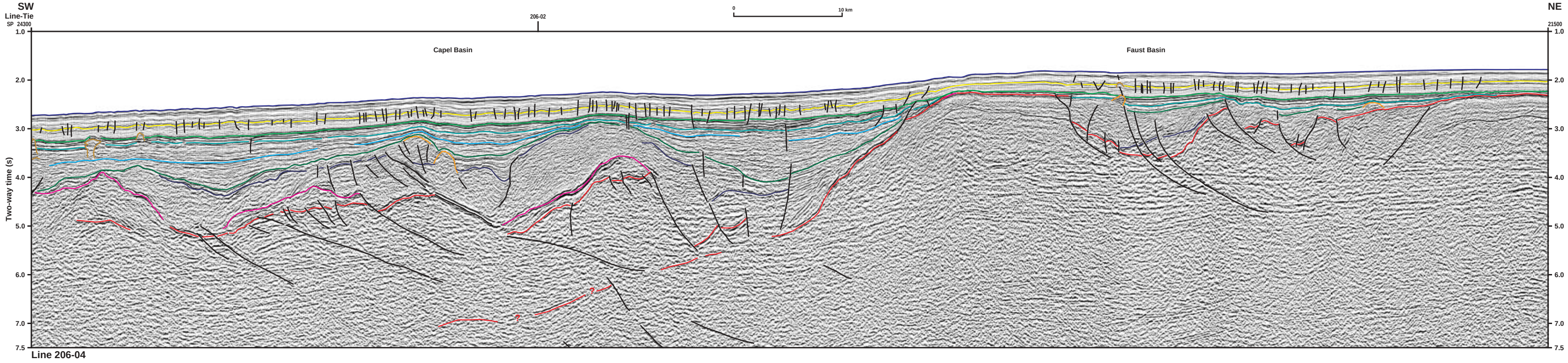
Plate 6

Montage: AGSO Rig Seismic Survey 46 profiles in southern Gower Basin Region

Willcox, J. B., & Sayers, J., 2002.
Geological framework of the central Lord Howe Rise (Gower Basin) region
with consideration of its petroleum potential.
Geoscience Australia, Record 2002/11

23/OA/1163



Megasequences	Unconformity	Age
Water layer		
	U1 (wb)	
GB1		
	U2	Middle Miocene
GB2		
	U3	
GB3		
	U4	?Middle Oligocene
GB4		
	U5	E. or M. Eocene
GB5		
	U6	?Maastrichtian
GB6		
	U7	Campanian
GB7		
	U8	Cenomanian
GB8		
	U9	
GB9		E. Cretaceous
	U10	
GB10		?L. Jurassic
	U11	
	Volcanic/Oceanic	
GB11		Pre-rift
	Intra-basement	

Rift and sag phase intrusions/diapirs
Late stage intrusions/seamounts
Sedimentary disruption features

Geoscience Australia -
East and Southeast Region Project

Plate 7

AGSO Rig Seismic Survey 206/04 profile illustrating basin evolution

Willcox, J. B., & Sayers, J., 2002.
Geological framework of the central Lord Howe Rise (Gower Basin) region with consideration of its petroleum potential.
Geoscience Australia, Record 2002/11

23/OA/1164

Lord Howe Rise - Gower Basin