BMR Journal of Australian Geology & Geophysics, 11, 11–36

Australia's petroleum potential in areas beyond an Exclusive Economic Zone

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The United Nations Convention on the Law of the Sea gives Australia the option of proclaiming a Legal Continental Shelf around both the continent and its island territories, over which it would control exploration and exploitation of the natural resources of the seabed and subsoil. A Legal Continental Shelf is considered to extend throughout the natural prolongation of the land territory to the outer edge of the continental margin, which, where it extends beyond the 200 nautical mile limit (Exclusive Economic Zone — EEZ), is defined by a two-part formula based on measurements from 'foot of continental slope' reference points. To fully use this formula, both bathymetric and sediment thickness information are required.

The area of a Legal Continental Shelf around Australia and its territories would be approximately 12 million km² (about 1.5 times the area of the continent itself), which would be one of the largest Legal Continental Shelves in the world. Eight regions of this shelf, totalling more than 3 million km², would extend beyond an EEZ. Sediment thicknesses greater than 2000 m — sufficient to have generated hydrocarbons from any potential source rocks — occur in six of these regions: Lord Howe Rise/Norfolk Ridge, South Tasman Rise, Great Australian Bight, Naturaliste Plateau, Exmouth/Wallaby Plateaus and Kerguelen Plateau. Most of the remote parts of the Australian margin with possible resource potential would lie within a Legal Continental Shelf.

Our relative rating of petroleum potential of regions beyond an EEZ is based on both a qualitative and quantitative assessment. The potential petroleum recovery estimates are greatest for western Lord Howe Rise and the southern Kerguelen Plateau, but relatively high values were also obtained for the South Tasman Rise and the eastern flank of Lord Howe Rise. Of the deepwater ocean basin areas, the New Caledonia Basin has the greatest potential recovery, although the estimates are clearly unrealistically large. Small but potentially high-yielding basins, such as the Taranui Sea Valley on the Norfolk Ridge, are also of interest.

Over all, the assessment indicates that the western flank of Lord Howe Rise has the greatest petroleum potential, even though the relatively small size of some of its individual basins tends to downgrade the chance of finding 'giant' and thus economically viable fields. However, this part of Lord Howe Rise appears more promising when the equivalent area and potential within an EEZ around Lord Howe Island are considered. The southern Kerguelen Plateau produced the largest potential petroleum recovery estimates of any of the moderate water depth regions; however, its real potential will remain unknown until its origin (continental or oceanic) and volcanic history are better understood.

Although the regions discussed are in relatively deep water (generally over 1000 m), they are not consistently any deeper than areas of plateaus and slopes within an EEZ, such as the Exmouth Plateau, which has been explored and drilled. Since areas with petroleum potential beyond an EEZ are remote, and in some cases in hostile environments, their exploration is unlikely to be economically viable in the near future; however, they may well provide Australia with a strategic resource into the next century. In the light of Australia's dwindling petroleum resources, these regions should not be overlooked in long-term planning by government and industry.

Introduction

The mineral resources of the oceans, especially oil and gas, have assumed increasing importance in the last 20 years. At present, about 20 per cent of the world's petroleum supply comes from submerged areas, generally from shelfward extensions of known structures and from producing fields onshore. Gradual depletion of these areas and any accompanying escalation in oil prices will undoubtedly entice explorers into the more remote and deepwater regions. Such a situation is particularly relevant to Australia, with its vast area of continental shelf and marginal plateaus (Fig. 1), particularly if the declining resources of the Gippsland Basin fields are not rapidly offset by new discoveries in the onshore and nearshore basins. The importance of establishing a legal regime which would allow Australia to explore and exploit its deepwater mineral resources has been emphasised by Prescott (1979, 1985).

The 200 nautical mile (n.m.) line, which defines Australia's Fisheries Zone and lies beyond areas covered by most oil exploration surveys, is frequently taken to be the limit of national interest. However, significant areas of continental margin, and related legal continental shelf, lie beyond an EEZ, and may have mineral potential which could be exploited into the next century. Although those areas are remote, their water depth in many places is no greater than that of the marginal plateaus and slopes within the 200 n.m. limit.

This study has three components: the delimitation of seabed boundaries around Australia to identify regions of the continental margin which extend beyond an EEZ; a review of regional setting, basin development, and aspects of petroleum geology; and a brief discussion of methodology leading to estimates of petroleum potential, which serve as a guide to the relative importance of these regions.

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Seabed boundaries

An Australian Exclusive Economic Zone

In 1982, international agreement was reached on jurisdiction of over 100 million square kilometres of ocean. The Convention on the Law of the Sea was adopted at the eleventh session of the Third United Nations Conference on the Law of the Sea, after deliberation in a series of Law of the Sea Conferences, initiated in 1973, but stemming from the Truman Proclamation of 1945 (Ross, 1979). Australia has since signed but not ratified the Convention.

In accord with the Law of the Sea Convention (Articles 55–57) (United Nations, 1983), Australia could proclaim an 'Exclusive Economic Zone' (EEZ) over which it has the right to explore and exploit living and non-living resources of the seabed, subsoil and superjacent waters. An EEZ extends for 200 nautical miles from the baseline from which the breadth of the territorial sea is measured (Fig. 2). The Australian EEZ delimitation is essentially formed by a suite of arcs of 200 n.m. radius around Australia and its island territories. The total area enclosed would be about 8.6 million km² (Table 1). Where the EEZs (and Legal Continental Shelves) of adjacent states overlap, the seabed boundary is subject to negotiation[2].

[2]A negotiated seabed boundary separates Australia (and/or territories) from Indonesia (except for East Timor, the Ashmore Reef area and Christmas Island), Papua New Guinea, and the French territories of the New Caledonia region and Kerguelen Island. Negotiations are under way with New Zealand and Indonesia.

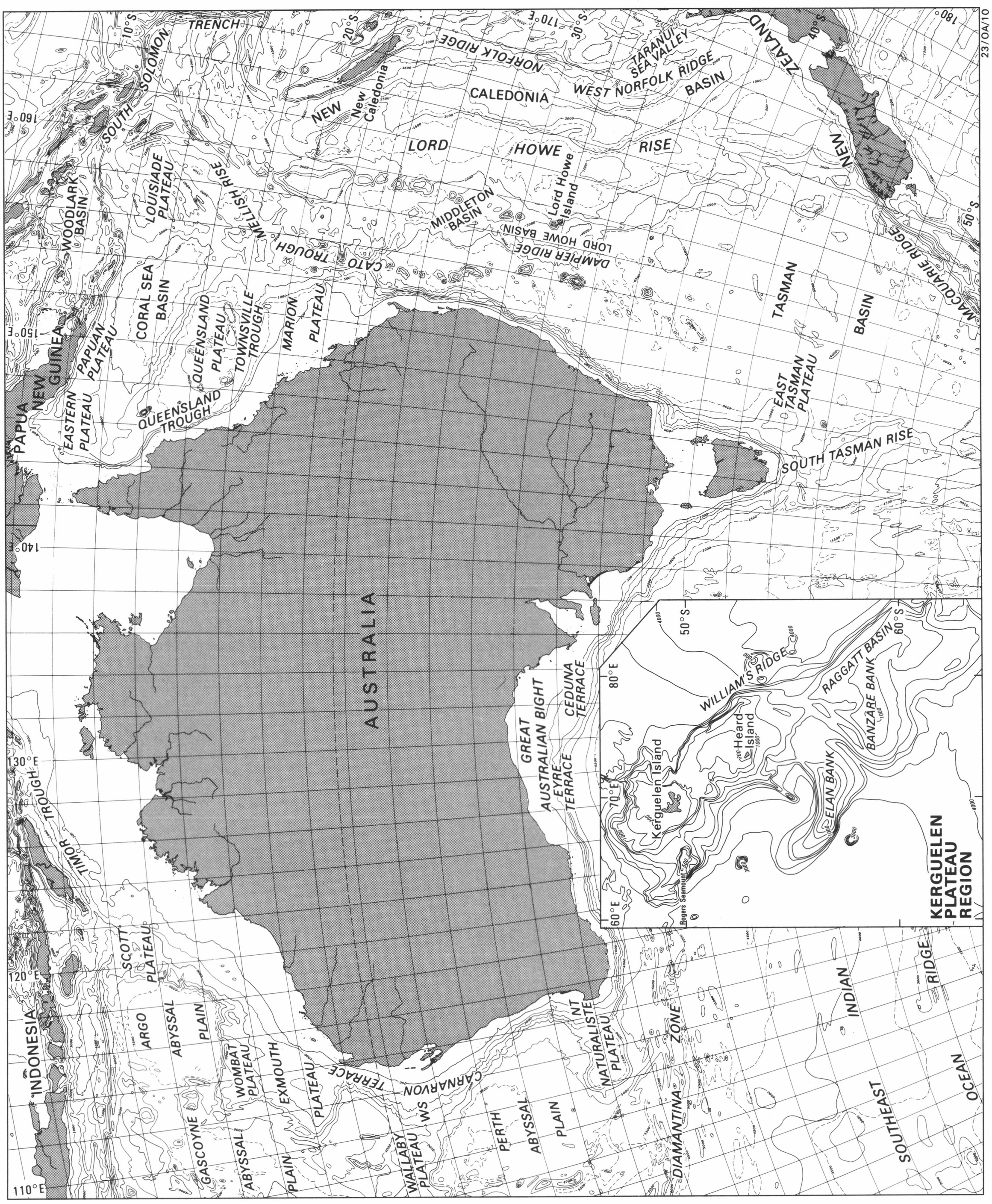


Figure 1. Bathymetry of the Australian region and Kerguelen Plateau region (inset) showing the main physiographic features. Isobaths around Australia are 200 m, then 1000 m intervals (solid line), and in places the intermediate 500 m levels (dashed line). Isobaths on the Kerguelen Plateau are 200 m, then 500 m, intervals. Based on Plate Tectonic Map of the Circum-Pacific Region, Southwest Quadrant, Base Map (AAPG, 1978); Houtz & others (1977); Ramsay & others (1986b). NT = Naturaliste Trough, WS = Wallaby Saddle.

Australia has not declared a full EEZ, but in 1979 it established a 200 n.m. Australian Fishing Zone.

An Australian Legal Continental Shelf

An important aspect of the Law of the Sea Convention is the definition of a 'Legal Continental Shelf' (Article 76 of the Convention), which is quite distinct from the morphological continental shelf. A coastal state has sovereign rights over its 'legal' shelf for the purposes of exploring and exploiting the natural resources of its seabed and subsoil. The main points of Article 76 are that

1. The legal continental shelf of a coastal State comprises the sea and subsoil ..... throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles
2. Where the continental margin extends beyond the 200 nautical mile limit (EEZ) its outer edge is defined by the so-called Irish Formula, which is in two parts:

   (i) A line delineated by the outermost fixed points at which the thickness of sedimentary rocks is at least 1 per cent of the shortest distance from the foot of the continental slope (sediment thickness formula, Fig. 3a), and

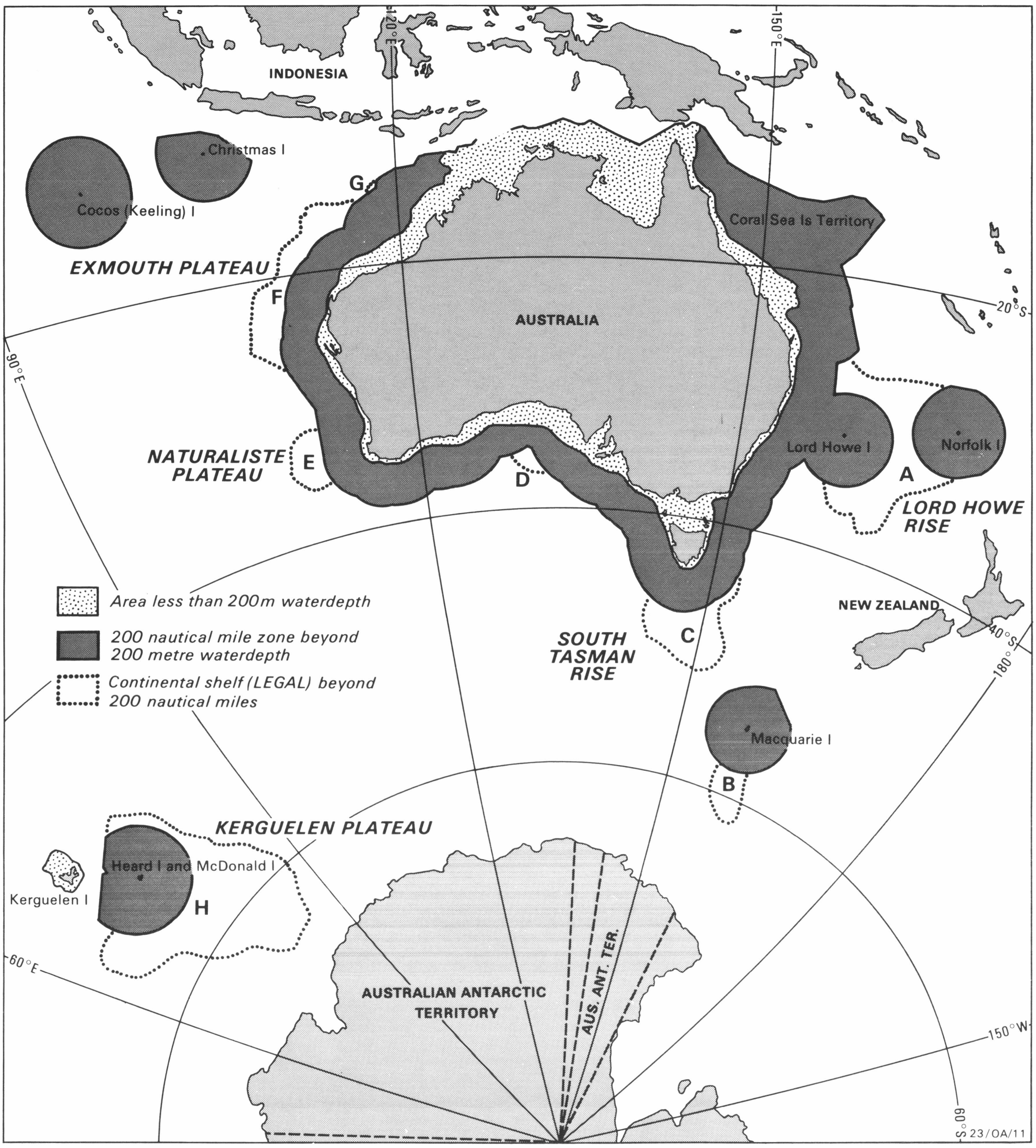


Figure 2. Approximate limits of a 200 nautical mile Exclusive Economic Zone (EEZ) and Legal Continental Shelf around Australia and its island territories.
The geomorphic shelf (<200 m water depth) is stippled; the area of an EEZ beyond the geomorphic shelf is screened; the limit of a Legal Continental Shelf beyond an EEZ is indicated by dotted line. Also shown are regions of the Legal Continental Shelf beyond an EEZ (A to H) discussed in the text.

(ii) A line not more than 60 nautical miles from the foot of the continental slope (Hedberg Line, Fig. 3b).

The legally defined outer edge of the continental margin is cut back by a formula, which is also in two parts, to give the outer limits of the Legal Continental Shelf beyond the EEZ. It consists of:

(i) A line not exceeding 350 nautical miles from the territorial sea baselines (Fig. 3c), and

(ii) a line not exceeding 100 nautical miles from the 2500 m isobath.

The limits of a Legal Continental Shelf are positioned by a combination of the various criteria contained in Article 76. The criteria that would be currently used to define a legal shelf over the parts of the Australian margin extending beyond an EEZ are indicated in Figures 4, 7 and 12 by E — 200 n.m. line, EEZ; H — Hedberg line; X — 350 n.m. cutoff; and Y — 2500 m isobath + 100 n.m. cutoff. N and M indicate where the legal shelf is, or may be defined by negotiated or median line boundaries with adjacent coastal states.

Because there is sporadic coverage and poor quality of seismic data beyond the foot of the slope, it is only possible to construct a sediment thickness line around approximately 15 per cent of the Australian margin. The application of the Irish Formula to define the outer edge of the continental margin around Australia is thus at present dependent mainly on the Hedberg Line.

Table 1. Approximate area statistics ($10^6 km^2$)

Australian landmass		7.8
Continental shelf (geomorphological)		2.0
EEZ	Australia + Lord Howe overlap	6.7
	Australia + island territories[1]	8.6
	Australia + island territories + AAT[2]	11.1
Legal Continental Shelf beyond EEZ	South to AAT	3.3
	South to EEZ around AAT	3.7
Total Legal Continental Shelf	Australia + territories, south to AAT	11.9
	Australia + territories, south to EEZ around AAT	12.3
	Australia + territories + EEZ around AAT	14.8

[1]Norfolk, Macquarie, Christmas, Cocos and Heard Islands
[2]Australian Antarctic Territory

Symonds & Willcox (1988) present basic data maps around Australia and over the Kerguelen Plateau, which show the detailed application of parts of Article 76, and include the positions of the 'foot of continental slope' reference points, the 'edge of continental rise' and the 'edge of the continental margin' as defined by the Hedberg line and sediment thickness formula.

The area of a Legal Continental Shelf around Australia and its territories (Fig. 2) would be approximately 11.9 million km^2 (about 1.5 times the area of the continent itself, and one of the largest in the world), or approximately 14.8 million km^2 if the Australian Antarctic Territory is included (Table 1).

Regions beyond an EEZ

Eight regions of a Legal Continental Shelf of Australia and its territories would lie beyond an EEZ (Figs 1 & 2), and cover a total area of more than 3 million km^2 (Table 1). These regions and their approximate areas are as follows:

A — Lord Howe Rise/Norfolk Ridge	0.87 million km^2
B — Macquarie Ridge	0.11
C — South Tasman Rise	0.54
D — Great Australian Bight	0.09
E — Naturaliste Plateau	0.19
F — Exmouth/Wallaby Plateaus	0.60
G — Argo Abyssal Plain	0.02
H — Kerguelen Plateau	0.91 (to AAT) 1.24 (to EEZ around AAT)

Although seismic data over most of these regions are sparse and of varied quality, it is apparent that areas of relatively thick sediment, which have at least some petroleum potential, occur in all regions except Macquarie Ridge and the Argo Abyssal Plain. Macquarie Ridge and the Argo Abyssal Plain are oceanic crust and have only a thin sediment cover, from which petroleum is unlikely to have been generated; these two regions do not warrant further consideration here.

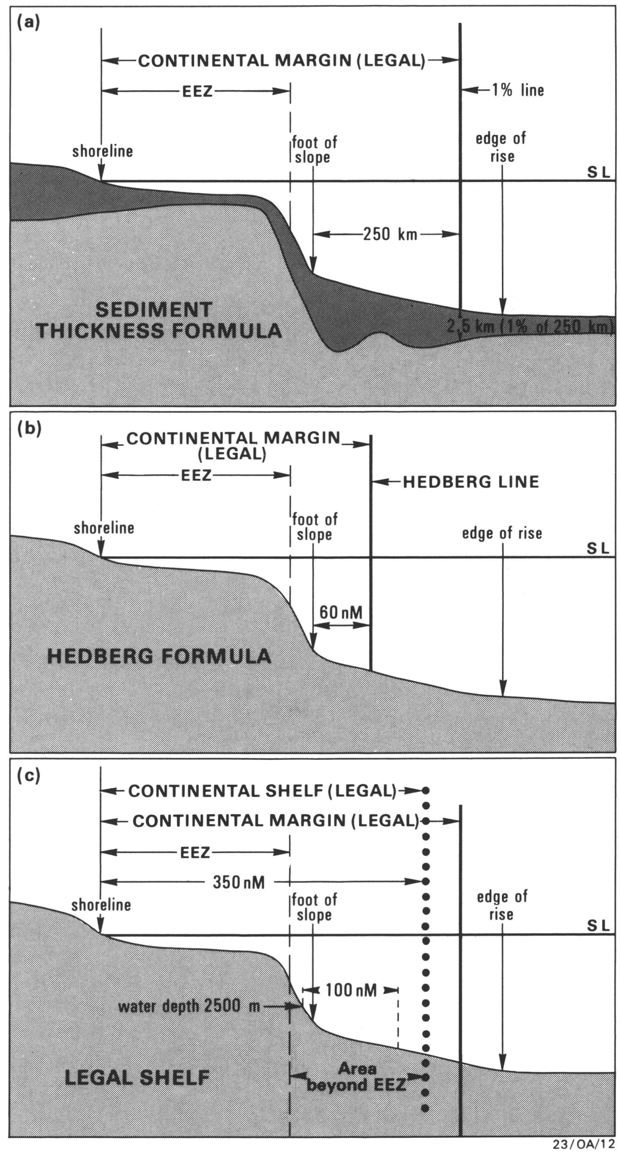


Figure 3. United Nations Convention on the Law of the Sea (Article 76) — procedures to determine seabed boundaries.
Definition of a Continental *Margin*, **(a)** using Sediment Thickness Formula (ie. thickness equal to 1 per cent of distance from foot of slope), and **(b)** Hedberg Line (60 nautical miles beyond foot of slope). **(c)** Definition of a Legal Continental *Shelf* using cutoff formula (a maximum of 350 nautical miles from the shoreline (actually baselines) or 100 nautical miles beyond the 2500 m isobath, whichever is the greater). Also shown is the area of a Legal Continental Shelf beyond an EEZ under consideration in this paper.

Owing to a lack of deep drilling in all eight regions, our understanding of the lithologies and depositional environments has to be inferred from seismic stratigraphy, and by analogy either with better known areas of similar geological style, or, in places, with contiguous areas within an EEZ.

The prospective areas within each region beyond an EEZ are labelled A1, A2, A3, etc., in Figures 4, 7 and 12.

Geology of regions beyond an EEZ

Lord Howe Rise (Region A)

Australia's seabed claim in this region stems from the presence of Lord Howe and Norfolk Islands, which are Australian territory and would both generate EEZs.

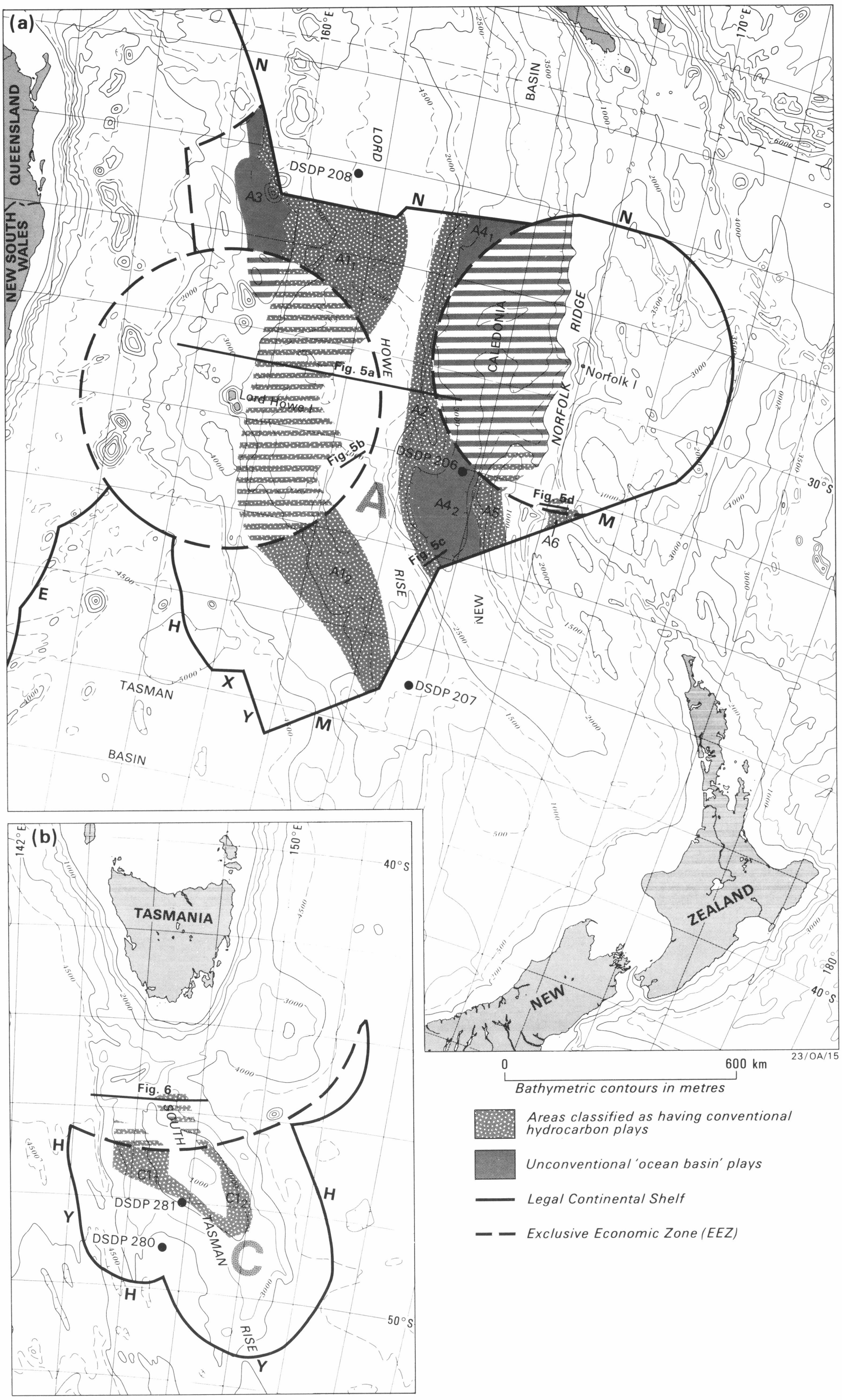


Figure 4. An EEZ and Legal Continental Shelf in (a) Lord Howe Rise/Norfolk Ridge Region (A), and (b) South Tasman Rise Region (C).

The criteria used to define a Legal Continental Shelf are: E = EEZ, H = Hedberg Line, X = 350 nautical mile cutoff, Y = 100 nautical mile beyond 2500 m isobath cutoff; N = negotiated boundary, M = median line with the adjacent coastal state. Isobaths are in metres. Shading shows areas of 'conventional' and 'unconventional' petroleum plays (see text), with $A1_1$, A_2, etc., being the areas referred to in Tables 3, 4 & 5. DSDP 206, 207, 208, 280 & 281 are Deep Sea Drilling Project drill sites. Heavy lines show location of seismic profiles and cross-sections presented in Figs 5 & 6.

Petroleum potential ratings: western LHR ($A1_1$ & $A1_2$)– fair; eastern LHR (A2)– fair/poor; Middleton Basin (A3)– unknown; New Caledonia Basin ($A4_1$ & $A4_2$)– unknown; West Norfolk Ridge (A5)– fair/poor; Taranui Sea Valley (A6)– fair; South Tasman Rise ($C1_1$ & $C1_2$)– fair/poor.

Regional physiography The major submarine feature in the region, the Lord Howe Rise (Figs 1 & 4a), extends north—northwest from the south island of New Zealand to Lord Howe Island and then north to the Chesterfield Island group at about 20° S. Lord Howe Rise is a plateau-like feature, which is most clearly defined by the 2000 m isobath — the crest of the rise is generally 750 to 1200 m below sea level. Lord Howe Rise is separated from the Norfolk Ridge by the New Caledonia Basin, which is an ocean basin with a relatively flat floor 3000–3500 m deep.

The Norfolk Ridge system is a steep-sided feature about 75 km wide, which extends from New Zealand to New Caledonia. The southern part of the ridge is offset to the west and forms a double-ridge system. The western part of the ridge is generally referred to as the West Norfolk Ridge; and the eastern part, as the Norfolk Ridge or, sometimes, the Wanganella Ridge (Eade, 1984). The crestal relief of the Norfolk/West Norfolk Ridge is more rugged than that of the Lord Howe Rise, and the depth ranges generally from about 500 to 1000 m. The two parts of the double-ridge system are separated by a narrow bathymetric trough, the Wanganella Trough. A significant bathymetric trough — the Taranui Sea Valley — lies on the eastern flank of the double-ridge system, near its point of offset.

Between 26° S and 34°, the small Middleton and Lord Howe Basins separate Lord Howe Rise from the Dampier Ridge to the west. Beyond this, the 4500 m deep Tasman Basin extends to the narrow continental margin of eastern Australia.

Regional geology The crustal structure of the Tasman Sea Basin, as interpreted from seismic refraction and gravity anomaly measurements (Officer, 1955; Dooley, 1963; Shor & others, 1971; Woodward & Hunt, 1971), and confirmed by identifiable seafloor spreading magnetic anomalies (Ringis, 1972; Weissel & Hayes, 1977), indicates that it is a normal oceanic basin. The crust beneath the New Caledonia, Middleton and Lord Howe Basins is commonly considered to be oceanic, though it is slightly thicker than typical oceanic crust.

Seismic refraction surveys and gravity modelling over Lord Howe Rise (Shor & others, 1971) indicate a crust 26 km thick and of continental origin. The rise is largely composed of crust with a P-wave velocity of 6.0 km/s, which is similar to values found for the Australian continent (Shor & others, 1971). Thus the Lord Howe Rise is a fragment of continental crust, seismically indistinguishable from the Australian continent. The complex nature of basement rocks beneath Lord Howe Rise, as shown by their seismic character and magnetic response, indicates that these rocks may once have formed part of the similarly complex Tasman Fold Belt of eastern Australia.

The Dampier Ridge is thought to be a continental fragment altered by rifting and igneous intrusions, and this theory seems to be confirmed by samples dredged by R/V *Sonne*, which has recovered granite, microdiorite and feldspathic sandstone (Roeser & others, 1985). The Lord Howe Rise and Dampier Ridge were detached from Australia during seafloor spreading, which commenced some 80 Ma ago and formed the Tasman, Middleton and Lord Howe Basins.

There is general agreement that at least part of the Norfolk Ridge system was rifted and separated from Gondwanaland, probably during the Late Cretaceous (Willcox & others, 1980; Kroenke, 1984), but several hypotheses have been advanced to explain the Tertiary development of New Caledonia and the Norfolk Ridge, and the adjacent New Caledonia Basin. These include the evolution of a complex arc system (Dubois & others, 1974; Kroenke, 1984), arc migration and marginal basin development (Karig, 1971; Packham & Falvey, 1971). The pre-Permian metamorphic and sedimentary rocks forming the core of New Caledonia were once part of the ancient Australian (Gondwanaland) continent, so it is most probable that the core of the Norfolk Ridge is also continental.

The plate tectonic model for the evolution of this part of the southwest Pacific appears to have been one of progressive rifting of the eastern margin of the Australia–Antarctic supercontinent (Gondwanaland), followed by continental break-up and seafloor spreading, island arc development and the creation of new ocean basins by further seafloor spreading. The fragments of continental crust that were rifted, thinned and left stranded between the Tasman Basin and the New Caledonia Basin during this process subsided to form a complex zone of troughs and plateaus, extending from New Zealand in the south, through Lord Howe Rise, to the Queensland Plateau in the north.

Recently, the region has been interpreted in terms of a detachment model (Lister & others, in press; Etheridge & others, in press) in which southeastern Australia is an underplated upper plate margin, with the Lord Howe Rise/Norfolk Ridge region being its complementary lower plate margin. This implies that a detachment system underlies the whole region, and that the Lord Howe Rise and Norfolk Ridge are composed of extended upper continental crust, whereas the small intervening ocean basins (except for the Tasman Basin) may be floored by highly thinned lower continental crust.

Western Lord Howe Rise (Areas $A1_1$ & $A1_2$, Fig. 4a; Fig. 5a,b) The general absence of Cretaceous extensional (rift) basins on the eastern seaboard of Australia has led to speculation that the basins may have become detached, and are now located beneath the western flank of Lord Howe Rise (Jongsma & Mutter, 1978). A zone of horst and graben structures, probably of this age and some 200 km wide, has been described (Fig. 5a; Willcox & others, 1980). The grabens are up to 50 km wide, several tens of kilometres long, and trend north–northwesterly. They terminate abruptly at transfer-like faults (Gibbs, 1984); the oblique angle that these faults make with the normal extensional faults suggests that the grabens formed within a 'transtensional zone'. These grabens are best developed on the western half of Lord Howe Rise north of Lord Howe Island, where their sediment fill is up to 4500 m thick in places (Roeser & others, 1985). Extensional basins south of Lord Howe Island appear to be less complex. Recent work (Whitworth & Willcox, 1985) has indicated that some fault blocks in the southern area may contain dipping sedimentary strata of Mesozoic age, rather than solely Tasman Fold Belt rocks, as previously believed (Fig. 5b). These sediments may be age equivalent to the older (Strzelecki) sequences in the Gippsland Basin.

The nature of the sediment fill within the Lord Howe Rise basins is a matter for conjecture. It is generally assumed to be of Late Mesozoic age, but correlation with older eastern Australian basins — such as the Permo-Triassic Sydney Basin and Esk Trough, and the Triassic–Jurassic Clarence Morton Basin — cannot be completely dismissed. There are, for example, strong similarities between some seismic profiles on Lord Howe Rise and profiles in the Esk Trough region (BMR *Geotraverse* 16, Korsch & others, 1989), which warrant closer scrutiny.

If, however, the Lord Howe Rise basins formed according to classical models for development of Atlantic-type passive

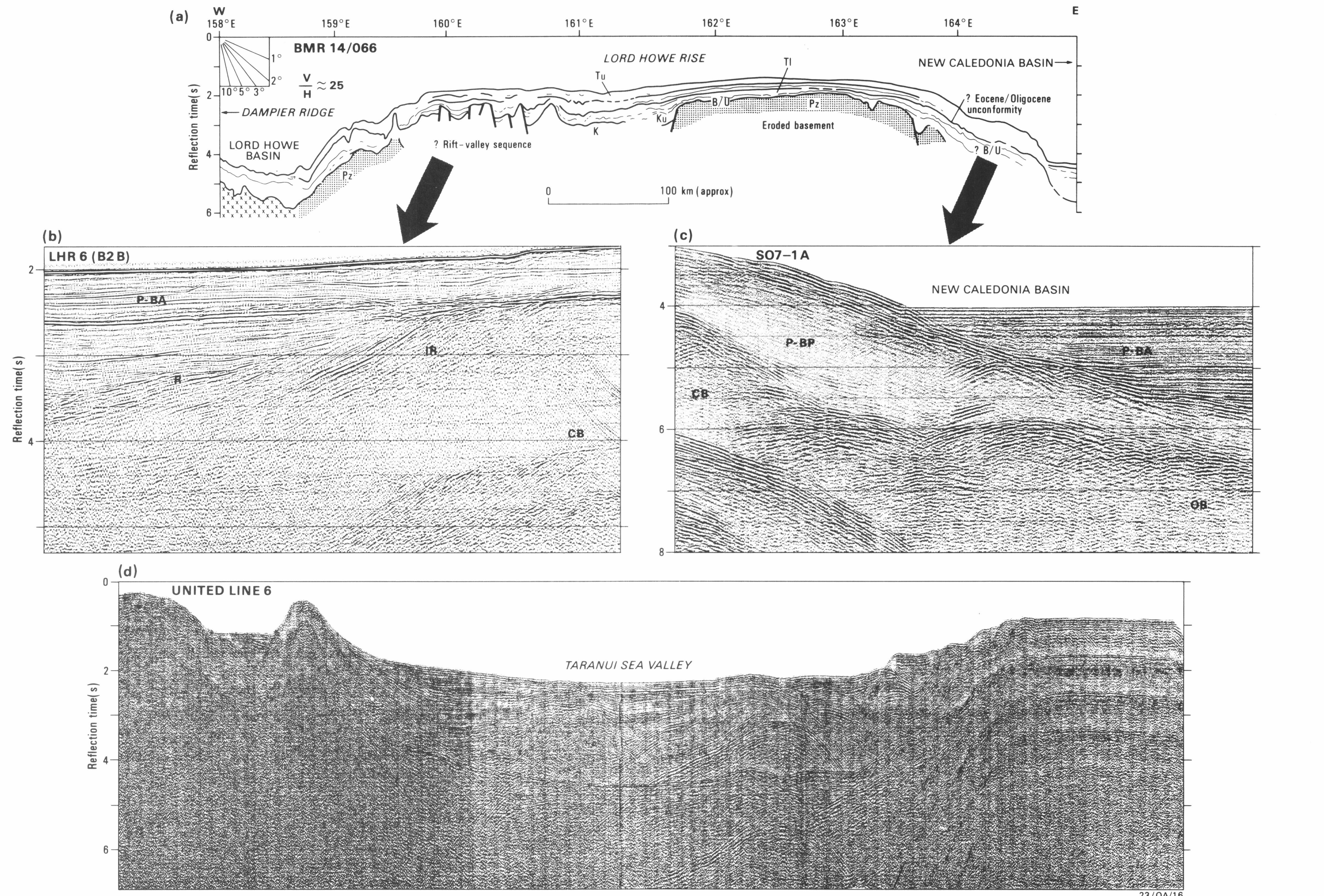


Figure 5. Cross-section and sesmic profiles from Lord Howe Rise (lHR) Region (A) (locations given in Fig. 4).

(a) Cross-sections of **LHR** based on **BMR** Line 14/066 (after Willcox, 1981). Tu = Miocene—Recent, T1 = Paleocene—Oligocene, **K** = Late Cretaceous, Pz = Palaeozoic, **B/U** = breakup unconformity, crosses = basement of unknown origin (possibly oceanic). Arrows show approximate structural location of seismic details below. **(b)** Seismic details from **BMR** *Rig Seismic* Line **LHR6** (width ~ 11 km) showing a sediment-filled graben on the Western flank of **LHR.** **(c)** Seismic detials from **BGR** *Sonne* Line S07-1A (width ~ 25 km), showing a wedge of pre-Maastrichtian sediment on the anicent on the ancient continental margin, now the eastern edge of **LHR. CB** =continental basement, **OB =? oceanic basement, IR** = infrarift (pre-rift) section, **R** = rift-fill sediments, **P—BA** = post-breakup (aggradation), **P-BP** = post-breakup (progradtion). **(d)** Seismic profile, United Line 6 (width ~ 65 km), from West Norfolk Ridge (left) to Norfolk Ridge (right), showing thick folded and faulted sediments in the intervening taraning Sea Valley, continental margins, much of the earliest sediment fill would have been of fluvial-lacustrine origin, which could contain a high proportion of humic source material. During recent surveys, diapiric structures were identified which suggest the movement of shale, or possibly salt, within the basins (Roeser & others, 1985). In the overlying section, there is evidence that wave-base erosion has planated several of the horst blocks, and it can be inferred that a shallow (?anaerobic) sea, which would be expected to favour the deposition of oil-prone source rocks, may have occupied the intervening grabens during the Late Cretaceous. Results from the Deep Sea Drilling Project (DSDP) Site 207 (Burns & others, 1973) confirm that restricted shallow marine silts and clays of Maastrichtian age overlie the horst blocks of the southern Lord Howe Rise. Rocks of similar age and depositional environment were recently dredged from the deep continental slope off southern New South Wales (Packham, University of Sydney, personal communication, 1985). Hence, up to 3000 m of sediment containing potential petroleum source rocks may occur in the basins of the western Lord Howe Rise. Interbedded sandstone in the fluviatile and shallow marine sequences is the most likely potential reservoir rock, and pelagic ooze could provide a regional seal. Lord Howe Rise has been subjected to several periods of volcanism, but it is not known whether this had any adverse affect on the reservoir potential of rocks within the basins.

In most places on Lord Howe Rise, the Maastrichtian shallow marine sequence is overlain by less than 1000 m of overburden, which is probably an insufficient thermal blanket for petroleum generation, unless heat flow was abnormally high. Thus, in these areas, petroleum generation may only have taken place at depth within the grabens. On the eastern flank of the Lord Howe and Middleton Basins (Figs 1, 4a), however, the sedimentary overburden may be thick enough (up to 2000 m) for any source material within the Maastrichtian sediments to have matured.

The rift basins of the Lord Howe Rise might be expected to have had high geothermal gradients at the inception of seafloor spreading, and source rocks might well have matured with less overburden than would normally be required. There are some indications that heat flow is anomalously high. The only heat-flow measurement on the Lord Howe Rise, recorded on its western margin, gave a value of 100 mW/m^2 (Grim, 1969), which is about twice normal. It has also been suggested that the Tertiary volcanism in the region is related to northward drift over a mantle hot-spot (Vogt & Conolly, 1971), implying that a zone of high heat flow associated with the Lord Howe seamount chain might be present on the western Lord Howe Rise.

Reconstruction of the Australian region in the Cretaceous brings the central area of the Lord Howe Rise (just south of the Dampier Ridge) against the Gippsland Basin (Jongsma & Mutter, 1978; Shaw, 1978). It has been suggested that the Gippsland Basin formed within the failed-arm of a three-branched rift system (Burke & Dewey, 1973), and this implies that dissected remnants of the other arms should occur beneath Lord Howe Rise. According to Threlfall & others (1976), the non-marine shales and coals of the uppermost Cretaceous and Palaeocene Latrobe Group are the source of the oil and gas in the Gippsland Basin. The petroleum is most commonly trapped at the Eocene/Oligocene unconformity, which lies at the top of the Latrobe Group. The development of successive shorelines and palaeoslopes in the eastern part of the Gippsland Basin, and the dredging of shallow marine ?Latrobe Group from deep on the continental slope (Packham, University of Sydney, personal communication, 1985) strongly suggest that parts of the Latrobe Group have had a laterally equivalent marine section to the east, that is, now on Lord Howe Rise. In addition, the transition from predominantly continental to predominantly marine deposition is thought to have occurred earlier in the east. Thus rocks of similar type to those producing hydrocarbons in the Gippsland Basin, but of somewhat greater age, may have been deposited deep within the grabens on Lord Howe Rise.

Eastern flank of Lord Howe Rise (Area A2, Fig.4a; Fig. 5a,c) The eastern flank of Lord Howe Rise might have formed an ancient seaboard of the Australian–Antarctic supercontinent (Willcox & others, 1980). A considerable thickness (about 2000 m) of clastic sediment was deposited across this margin during or before the Late Cretaceous (Fig. 5c). Most of this sediment was probably derived from the now planated basement blocks to the west. The sedimentary (?pelagic) overburden ranges from about 1000 m on the eastern edge of the Lord Howe Rise to more than 2000 m in the New Caledonia Basin.

Depositional environments favourable for both the production and preservation of oil-generating matter of aquatic origin may have occurred on this continental slope, as is thought to be the case on many other continental slopes around the world (Dow, 1979).

Faulting, and folding of the? Late Cretaceous sediment wedge, could provide structural traps for petroleum. The progradation observed on some profiles may give rise to stratigraphic traps (Fig. 5c). Petroleum migrating up dip could be trapped against the basement surface and at unconformities, and sealed by the overlying pelagic oozes.

Middleton Basin (Area A3, Fig. 4a) Considerable thicknesses of Late Cretaceous sediments, including potential source rocks, might occur in area A3 on the flanks of the Middleton Basin, in a similar manner to that previously described for the rift basins beneath the western Lord Howe Rise. During rifting and the earliest phase of seafloor spreading in the late Cretaceous, Lord Howe Rise was probably a trough-bounded marginal plateau with the trough centred on the Lord Howe and Middleton Basins (Willcox & others, 1980). This implies a stronger marine influence within the Middleton Basin than within the rift basins beneath the Lord Howe Rise. The latest Cretaceous rocks are probably carbonate and terrigenous sediments deposited in a restricted marine environment.

New Caledonia Basin (Areas A4$_1$, A4$_2$, Fig. 4a; Fig. 5c) The New Caledonia Basin may contain at least 4000 m of sediment (3 s of reflection time) in places and, near its margins, the basal 2000 m of this section probably consists of Cretaceous marginal and shallow marine terrigenous sediments. This sequence was gently folded throughout the basin during the Late Cretaceous and early Tertiary, perhaps in response to convergent tectonics to the east. The basal sequence is overlain by deep-sea biogenic ooze.

The prospectivity of the New Caledonia Basin is difficult to assess, as both its origin and the depositional environment of the deeper sediment are uncertain. In theory, small enclosed ocean basins are among the most promising areas for petroleum accumulation (Hedberg & others, 1979). Proximity to land and large rivers ensures deposition of thick sedimentary sections, where both terrestrial and marine organic matter accumulate, even in the centre of the basins. The restricted nature of the basins limits circulation and favours the preservation of organic matter, either under bottom-reducing conditions or as a result of relatively rapid burial by sediments. Favourable reservoirs are to be expected in deltaic and submarine fan sediments within these basins. Small ocean basins, such as the New Caledonia Basin, are often situated in tectonically mobile environments, where fold and fault structures and repeated unconformities provide numerous play types.

West Norfolk Ridge (Area A5, Fig. 4a) In area A5, the offset southern extension of the Norfolk Ridge is actually a double-ridge system consisting of the broad West Norfolk Ridge in the west and the narrow Norfolk Ridge in the east; the two ridges are separated by the Wanganella Trough. A significant bathymetric trough called the Taranui Sea Valley occurs on the eastern flank of the double-ridge system near the point of offset of the ridge (Fig. 1).

The western part of the West Norfolk Ridge is underlain by relatively planar basement, which has been downfaulted to form flanking grabens which, in places, contain up to 3000 m of sediment. The sediments in the grabens are probably very similar to those already described within the rift basins beneath the Lord Howe Rise; however, on the West Norfolk Ridge, the rift-fill sediments have been folded, resulting in a larger variety of structural petroleum plays than on the Lord Howe Rise. The northern end of the Wanganella Trough (between areas A5 and A6) is underlain by at least 1500 m of sediment containing mounded and progradative facies. This might be a deltaic sequence deposited along the trough during subaerial erosion and planation of the northern West Norfolk ridge. This sediment undoubtedly thickens to the south beyond Australia's putative Legal Continental Shelf.

Taranui Sea Valley (Area A6, Figs 4a, 5d) Up to 4000 m of faulted and folded sedimentary rocks occur in a graben-like feature beneath the head of the Taranui Sea Valley, in less than 2000 m of water (Fig. 5d). Several prominent angular unconformities occur throughout the sedimentary section, but both the nature and depositional environment of the sediments and the nature of the underlying basement are unknown.

The structural style of the basin suggests wrench tectonics, and could indicate that the sediments were deposited in a dextral strike-slip zone which was responsible for the offset of the Norfolk Ridge.

South Tasman Rise (Region C: Areas $C1_1$ & $C1_2$, Fig. 4b)

The South Tasman Rise lies in water about 1000–3000 m deep, and is separated from the Tasmanian continental slope by a bathymetric and structural saddle (Figs 1 & 4b). The area of the Rise is about 150 000 km^2, and 70 per cent of the feature lies beyond an EEZ. Its margins appear to be shear zones related to the dispersal of Australia and Antarctica during the Late Cretaceous to Eocene (Willcox, 1986).

The generalised structure of the South Tasman Rise was interpreted by Willcox (1981) from two BMR seismic profiles across its northern part (Fig. 6). More recent seismic and geological sampling cruises (R/V *Sonne*; Hinz & others, 1985) have provided sufficient information for a regional analysis of its structure and seismic stratigraphy. Deep Sea Drilling Project Sites (DSDP) 280 and 281 (Fig. 4b) are located on the deep ocean floor to the south and near the structural culmination of the rise, respectively.

A continental origin for the South Tasman Rise is deduced from its location in continental reconstructions, the drilling results at DSDP Site 281, and its relatively quiet gravity and magnetic signature. At drill site DSDP 281, basement is composed of mica-schist overlain by a basal angular agglomerate. This agglomerate is overlain by late Eocene detrital sediments deposited in a shallow marine, deepening to a marine, environment. The drillhole penetrated Miocene to Holocene ooze above the late Eocene to Oligocene unconformity, which is widespread in the Tasman and Coral Seas.

The seismic interpretation suggests that the South Tasman Rise consists of a central, probably Palaeozoic, core flanked by two northwesterly trending rift basin systems (Areas $C1_1$ & $C1_2$), which contain up to 4000 m of sediment. The sedimentary sequences have been correlated with the Cretaceous and Tertiary of the Otway Basin (Willcox, 1981; Hinz & others, 1985). The basins are structurally complex, and potential reservoir porosity has probably been downgraded by the inclusion of volcanics. Whiticar & others (1985) reported small yields of thermogenically derived hydrocarbons from geological samples dredged from the northern extremity of the plateau.

Great Australian Bight (Region D: Areas D1 & D2, Fig. 7a)

In the Great Australian Bight, approximately 25 000 km^2 of continental rise to the southwest of the Ceduna Terrace lies beyond the EEZ (Figs 1 & 7a). Tertiary and Cretaceous sediments, 4000–5000 m thick, overlie deeply subsided continental (Area D1) and oceanic basement (Area D2) (Fig. 8; Willcox, 1978; Fraser & Tilbury, 1979). Early Cretaceous sediments, probably deposited in continental to shallow marine environments, might have hydrocarbon potential. In the past, most authors have suggested that the Early Cretaceous deposits are of dominantly continental origin; however, this view needs some revision in the light of Potoroo-1 and Jerboa-1 wells, which intersected Aptian and Albian sediments of restricted and near-shore marine origin, respectively (Stagg & Willcox, 1988). Marine sedimentation was presumably a consequence of an incursion from the west along the subsiding rift system. If restricted marine deposition occurred on the northern margin of the rift valley, then it seems reasonable to suppose that deeper, and possibly more protracted, marine conditions prevailed

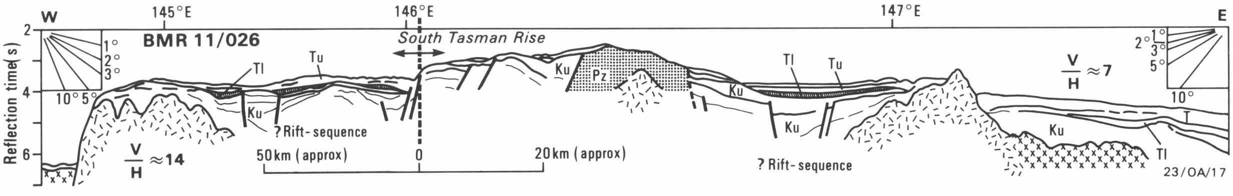
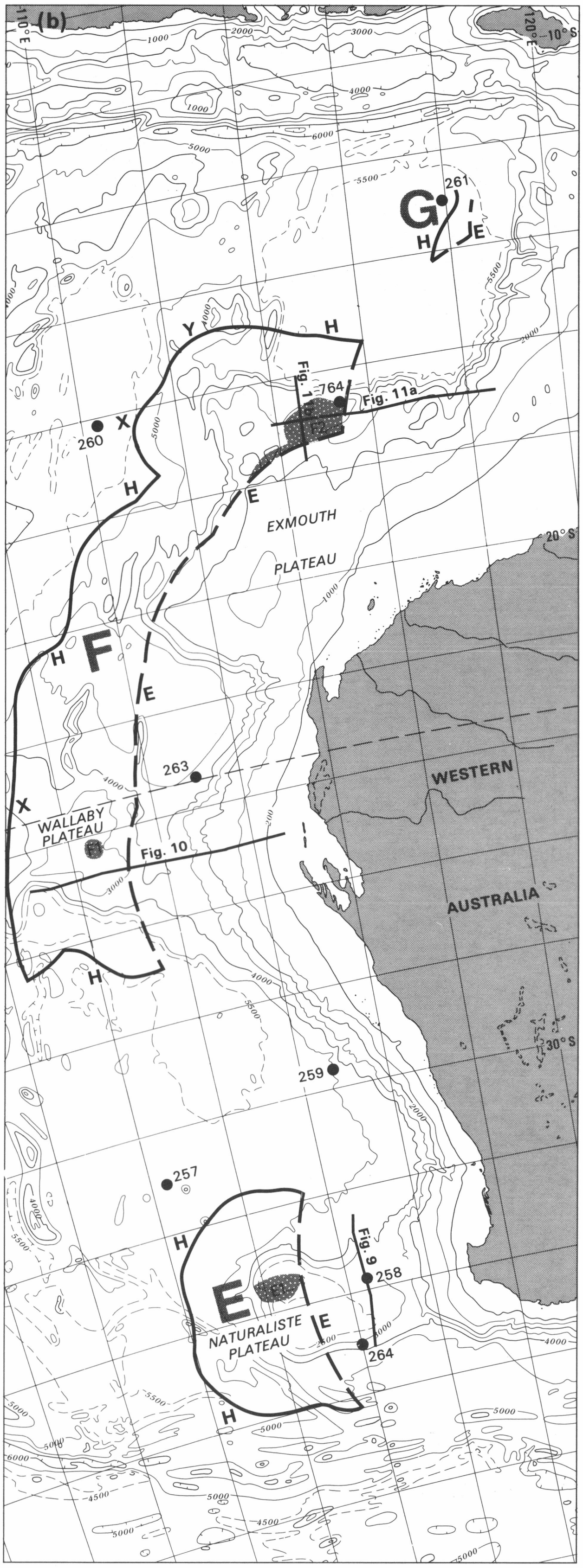


Figure 6. Cross-section of South Tasman Rise Region (C)
Based on BMR Line 11/026, showing rift basins developed on the flanks of the Rise (after Willcox, 1981). Note change in horizontal scale at about 146° E. Location given in Fig. 4.



over the depressed valley floor in the Bight region to the south. The presence of marine source rocks beneath the deepwater part of the Great Australian Bight Basin would considerably enhance its prospectivity.

In this region the basin-forming faults within basement indicate northwest–southeast extension (Lister & others, in press; Willcox & others, in press). Also prominent are Cenomanian northwest–southeast-trending normal faults, which are synsedimentary and have produced some drape and rollover in the overlying section. In the deeper water part of the basin, close to the northern boundary of region D, faulted anticlines have resulted from relative movement and dip reversal in closely spaced fault blocks (Fig. 8a).

In the past, the main problems perceived for oil exploration within the Great Australian Bight Basin were considered to be an apparent dearth of marine source rocks and a lack of reservoir sands, together with the uneconomic size of the structural traps in relation to the considerable water depths. A greater volume of marine source rocks can be expected in the deeper part of the basin in region D, but the great water depths (3000–5500 m) will certainly discourage exploration.

Naturaliste Plateau (Region E: Area E1, Fig. 7b)

About 50 per cent of the Naturaliste Plateau lies beyond an EEZ, in water 2200–5000 m deep (Figs 1, 7b). The origin

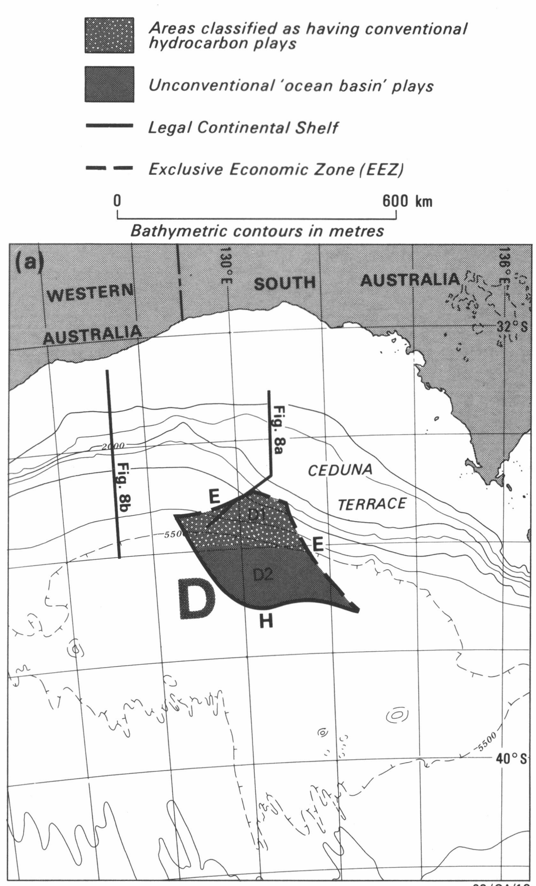


Figure 7. An EEZ and Legal Continental Shelf in (a) the Great Australian Bight Region (D), and (b) the Naturaliste Plateau Region (E), Wallaby/Exmouth Plateau Region (F) and Argo Abyssal Plain Region (G).
Criteria used to define a Legal Continental Shelf are: E = EEZ, H = Hedberg Line, X = 350 nautical mile cutoff, Y = 100 nautical mile beyond 2500 m isobath cutoff. Isobaths in metres. Shading shows areas of 'conventional' and 'unconventional' petroleum plays (see text), with D1, D2, etc., being the areas referred to in Tables 3, 4 & 5. 257, 258, 259, 260, 261, 263 and 264 are Deep Sea Drilling Project (DSDP) drill sites, and 764 is an Ocean Drilling Program (ODP) site. Heavy lines show the location of cross-sections presented in Figs 8, 9, 10 & 11.
Petroleum potential ratings: Great Australian Bight Region mid-slope (D1)– poor; lower slope and basin floor (D2)– unknown; Naturaliste Plateau (E)– poor; Wallaby Plateau (F1)– poor/nil; northwest Exmouth Plateau (F2)– fair/poor.

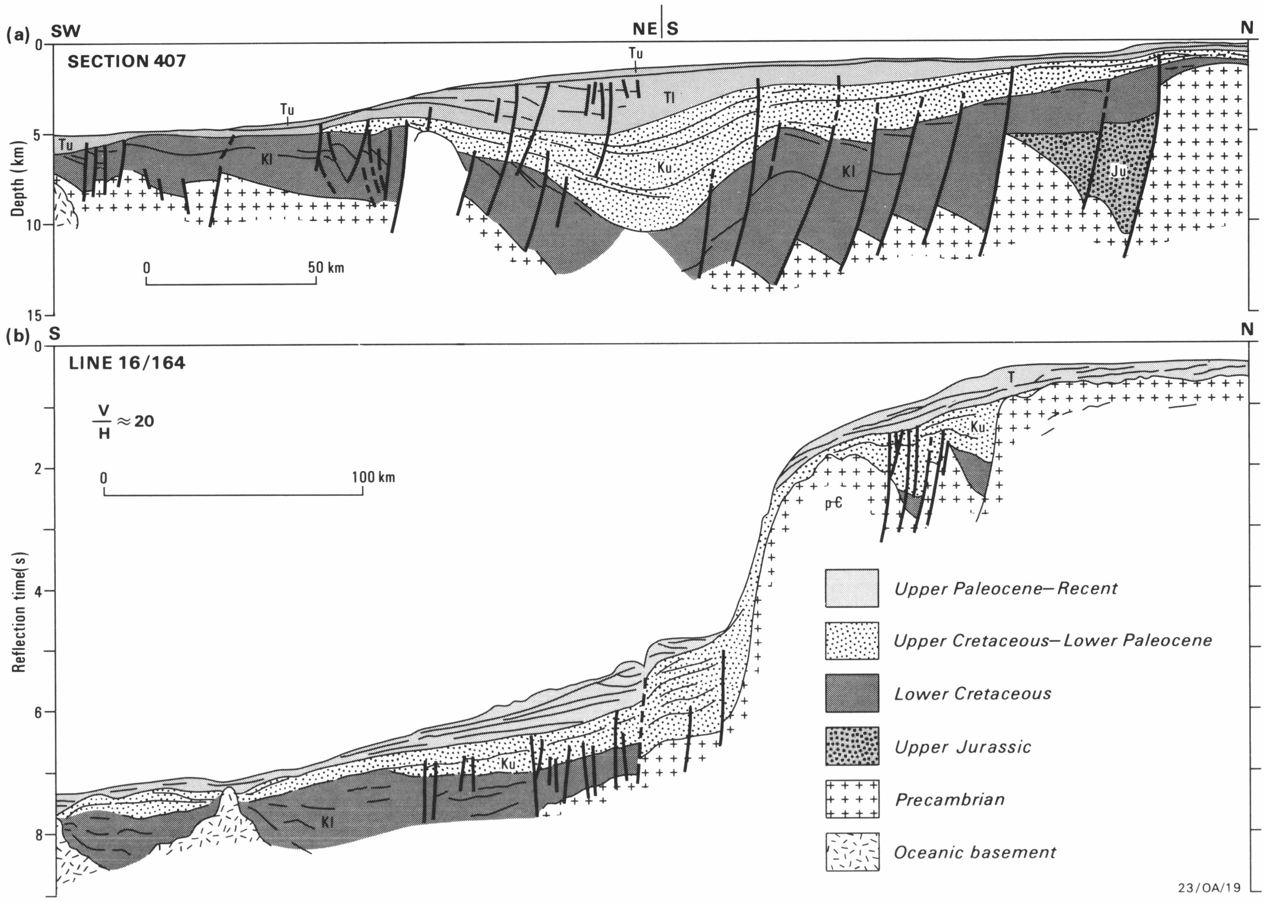


Figure 8. Cross-sections of the Great Australian Bight Region (D). Locations in Fig.7.
(a) Shell Line 407, across Ceduna Terrace area, showing the very thick (12+ km) sedimentary section in the Great Australian Bight Basin, extending under the continental rise beyond an EEZ (after Boeuf & Doust, 1975). **(b)** BMR Line 16/164, across the Eyre Terrace (Eyre Sub-basin) and continental rise, showing the thick sedimentary section in 3000+ m deep water (after Willcox, 1978). A similar section lies beyond an EEZ in the central Bight; opinion is divided as to whether the basement is oceanic (suggesting 'unconventional' play-types may be present) or of extended continental origin.

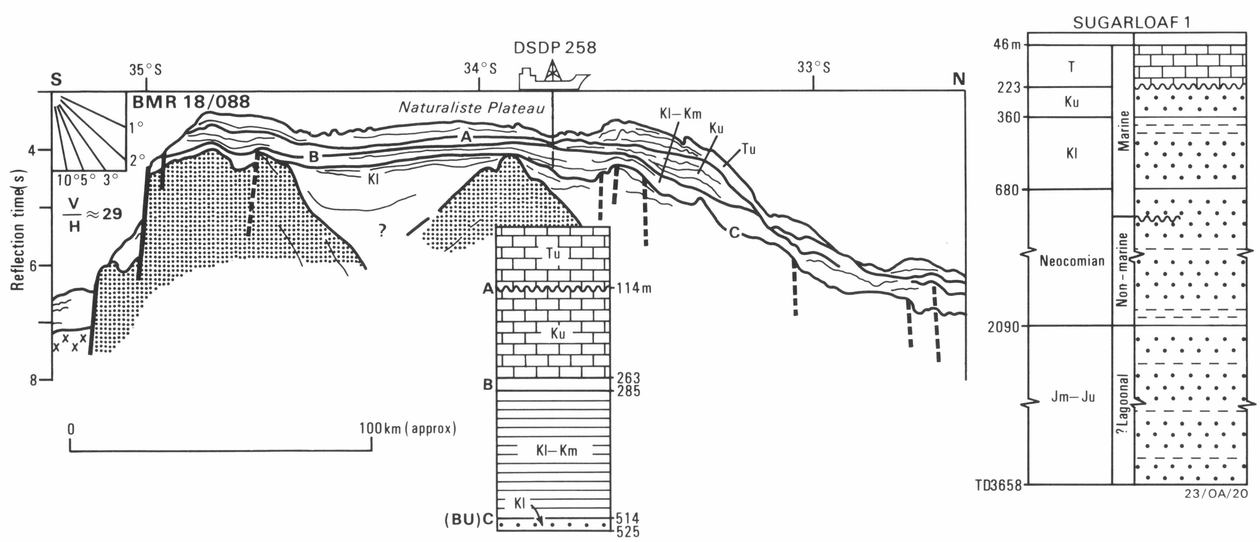


Figure 9. Cross-section of the Naturaliste Plateau Region (E), based on BMR Line 18/088 (after Willcox, 1981). Also shows stratigraphy for DSDP Site 258 and WAPET Sugarloaf No. 1 exploration well in the Perth Basin. Location in Fig. 7.

of the Naturaliste Plateau is uncertain, like that of the Wallaby Plateau (see later), but the weight of evidence tends to favour it being a continental feature (Jongsma & Petkovic, 1977).

The western part of the Naturaliste Plateau is similar to the Wallaby Plateau and contains few areas with thick sediment (Fig. 9). However, beneath the eastern part of the Plateau, within the EEZ, pre-breakup strata up to 2000 m thick lie between major crystalline basement blocks. Sonobuoy data show that these pre-breakup strata incorporate a refractor with a velocity of only 2.8 km/s, not uncommon for 'normal' rift-fill sediments. However, this velocity does not preclude volcanogenic sediments either. The post-breakup sediments are about 500 m thick over most of the area, but up to 2000 m thick in the Naturaliste Trough, which lies between the Plateau and the continental shelf.

The Naturaliste Plateau section can be dated by tying to an on-site sonobuoy profile recorded at DSDP Site 258, close to BMR Line 18/088 (Fig. 9). The tie indicates that the Horizon C unconformity is pre-middle Albian, the B reflector marks a contact of Albian detrital clay and Cenomanian chalk, and the A reflector lies within Miocene to Holocene foraminiferal ooze. The C unconformity can be dated more closely by making a tentative tie to Sugarloaf-1 well on the adjacent continental shelf (Willcox, 1981). It appears to correlate with the top of a Neocomian sandstone, and hence probably marks the onset of marine conditions and seafloor spreading in what is now the Perth Abyssal Plain. The sediments below this unconformity might have been deposited in marginal marine and continental environments and could have some petroleum prospectivity.

Two heat-flow measurements on the Naturaliste Plateau provide little information on source rock maturity. An extremely high value of about 220 mW/m^2 was obtained in the northwestern part of the Plateau (von Herzen & Langseth, 1965), but it is of doubtful accuracy. The other measurement, near DSDP Site 264, gave a near-average value of about 60 mW/m^2 (Jongsma & Petkovic, 1977).

The prospectivity of the Naturaliste Plateau beyond the EEZ is rated as poor.

Wallaby and Exmouth Plateaus (Region F)

Wallaby Plateau (Area F1; Fig. 7b) Nearly all the Wallaby Plateau lies in water 2200–4500 m deep beyond the EEZ (Figs 1, 7b). The Plateau appears to be formed by a thin sequence of post-breakup sediments draped over a folded and faulted, layered sequence, which in places resembles the pre-Jurassic sequence on the Exmouth Plateau (Fig. 10; Symonds & Cameron, 1977; von Stackelberg & others, 1980).

Until the late 1970s, the Wallaby Plateau was regarded as a thinned continental fragment (Symonds & Cameron, 1977). Veevers & Cotterill (1978) suggested that it is an accumulation of oceanic volcanics (an 'epilith') formed during the time of spreading in the Cuvier Abyssal Plain. A variety of volcanic and volcaniclastic rocks of unknown ages, obtained during dredging on the margins of the Plateau, led von Stackelberg & others (1980) to conclude that on the eastern and southern Wallaby Plateau 'the layered sequence beneath the main Neocomian unconformity consists of interbedded and weathered tholeiitic and differentiated alkali basalts, tuffs, basalt breccias and thick volcaniclastic sandstones and conglomerates'. A minimum mid-Cretaceous K/Ar age of 89 Ma was determined from an altered basalt from the southern Wallaby Plateau. Because the sequence sampled can be traced on seismic profiles from the margins to the centre of the Plateau, von Stackelberg & others (1980) suggested that intense volcanism and associated deposition of volcaniclastic debris flows formed the Plateau, during or after the Neocomian breakup of this region. They mentioned the alternative interpretation that a marginal intrusion or extrusive sequence had been sampled, and stated that 'whether continental crust lies below the layered volcanic material could be tested only by deep drilling in the centre of the plateau'. A seismic profile which passes through the middle of their sampled area indicates that there could well be a marginal intrusive body at this location, and thus the sequences sampled might not be representative of the rocks beneath the centre of the Plateau.

The origin of the Wallaby Plateau remains in doubt. If continental, the layered sequence beneath the intra-

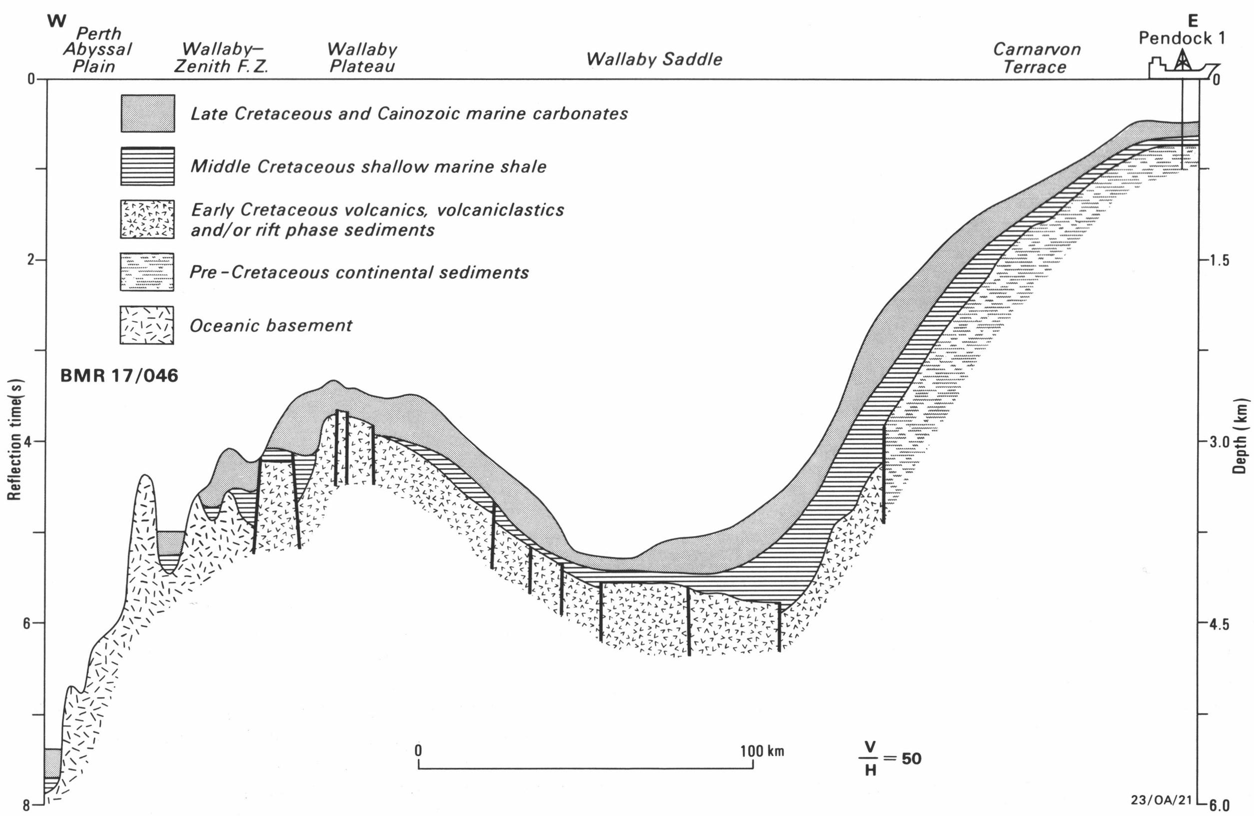


Figure 10. Cross-section of the Wallaby Plateau Region (F), based on BMR Line 17/046 (after Symonds & Cameron, 1977, and von Rad & Exon, 1983). Location in Fig. 7. Opinion is divided as to whether the Plateau, most of which lies beyond an EEZ, is floored by continental or oceanic basement.

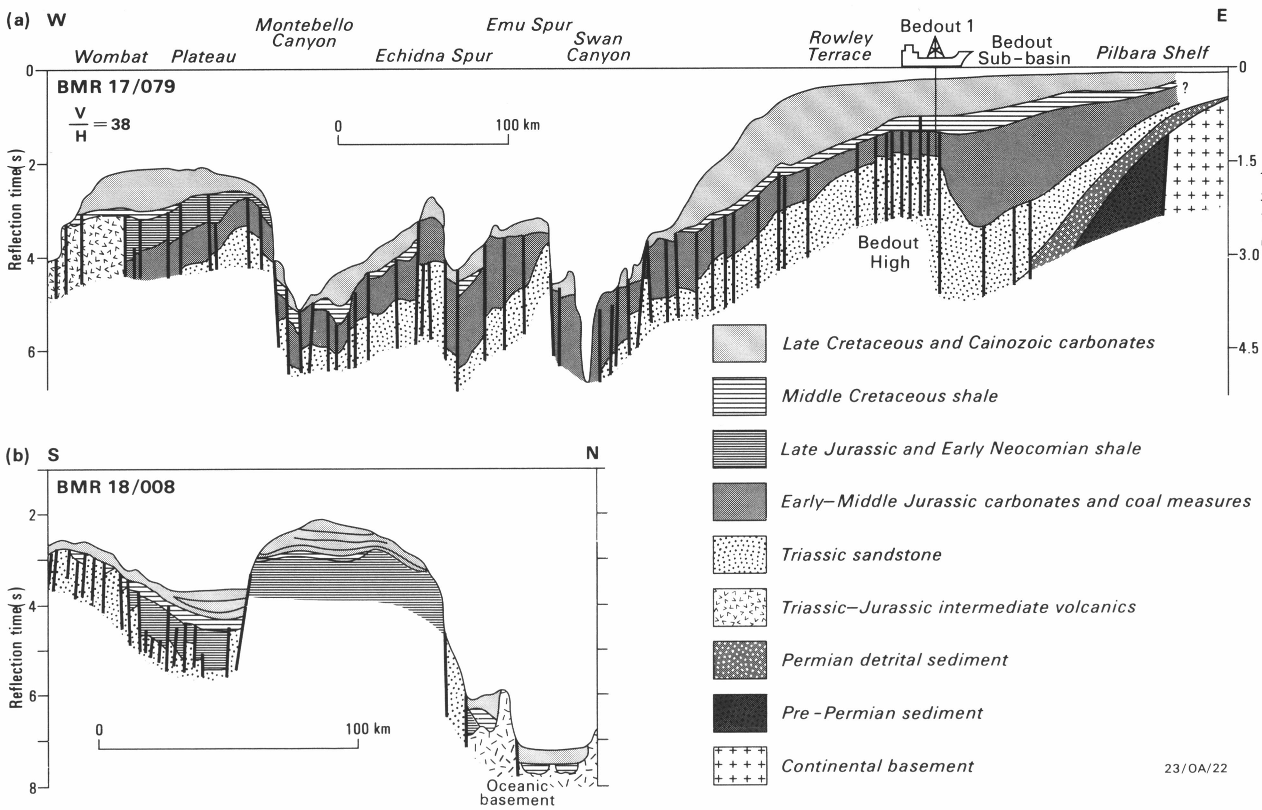


Figure 11. Cross-sections of the northern margin of the Exmouth Plateau Region (F), based on **(a)** BMR Line 17/079 from Wombat Plateau to Pilbara Shelf showing thick sediments on the numerous plateaus and spurs (after von Rad & Exon, 1983), and **(b)** BMR Line 18/008 showing prospective fault-block structures on the Wombat Plateau (after Exon & Willcox, 1980). Only the Wombat Plateau area lies beyond an EEZ. Locations given in Fig. 9.

Neocomian unconformity might consist of rift-phase sediments with some petroleum potential; however, if the sequence consists of volcaniclastics and lava flows, the Plateau would have no potential, owing to the absence of source and reservoir rocks.

Northwest Exmouth Plateau (Area F2, Fig. 7b) About 15 per cent of the area of prospective sediment on the Exmouth Plateau lies beyond the EEZ in water 1800–3000 m deep (Figs 1 & 7b). This includes the small Wombat Plateau (3000 km^2), from which samples of a Triassic to Middle Jurassic coal measure sequence have been dredged (von Rad & Exon, 1983). The northwest Exmouth Plateau is underlain by numerous fault blocks of probable Triassic age (Exon & Willcox, 1980) (Fig. 11). Although the Jurassic and younger strata are thinner in the northwest than elsewhere on the Plateau, this does not significantly affect the prospectivity of the Triassic blocks themselves, which still have ample overburden in places. Palaeogeographic considerations suggest that Triassic depositional environments might have been more marine in the north and northwest than elsewhere on the Plateau, thus favouring deposition of oil-prone aquatic kerogens (Willcox, 1981). Higher heat flow associated with intrusions, and proximity to ocean/continent boundary, might also be favourable factors. Recent drilling on the Wombat Plateau, as part of the Ocean Drilling Program (ODP), discovered a possible Triassic reef which could prove to be a significant new petroleum play in the region (Williamson & others, 1989).

Kerguelen Plateau (Region H: Areas H1 & H2, Fig. 12)

The Kerguelen Plateau is a major topographic high in the southern Indian Ocean adjacent to, but apparently structurally separate from, Antarctica (Fig. 1). The Plateau rises about 3700 m above the deep ocean floor and extends northwest for 2000 km. Australia's claim to the southern part of the Plateau stems from the presence of Heard and McDonald Islands which are Australian territory. About 70 per cent of the area to which Australia could lay claim lies beyond an EEZ, but this is complicated by the fact that about 40 per cent of this area overlaps with the Australian Antarctic Territory (AAT) beyond 60°S (Fig. 12). In this study, the areas of prospective sediment as far south as the saddle (Challenger Passage) between the Kerguelen Plateau and the margin of Antarctica are considered.

Heard, Kerguelen, and McDonald Islands consist of a series of Cainozoic volcanics overlying mid-Eocene–mid-Oligocene pelagic limestone (Nougier, 1969; Dosso & others, 1979; Clarke & others, 1983). The geology of the submerged part of the Plateau is poorly known. Geophysical surveys (Schlich & others, 1971; Houtz & others, 1977; Ramsay & others, 1986a,b) indicate that there are marked differences in the structure of the northern and southern parts of the Plateau. The northern sector includes the Plateau's islands and consists mainly of a series of igneous intrusions or basement horsts separated by basins. A major sedimentary basin lies immediately southeast of the Kerguelen Islands. By contrast, the southern sector shows evidence of intense block faulting (Ramsay & others, 1986b). The presence of a significant depocentre beneath the southeastern side of the Plateau was originally indicated by the study of Houtz & others (1977). A more recent BMR Rig Seismic survey in this area (Ramsay & others, 1986a) defined a large sedimentary basin (the Raggatt Basin), which occupies an area of about 50 000 km^2.

Any assessment of the petroleum potential of the Kerguelen Plateau is to some extent dependent on whether it has an

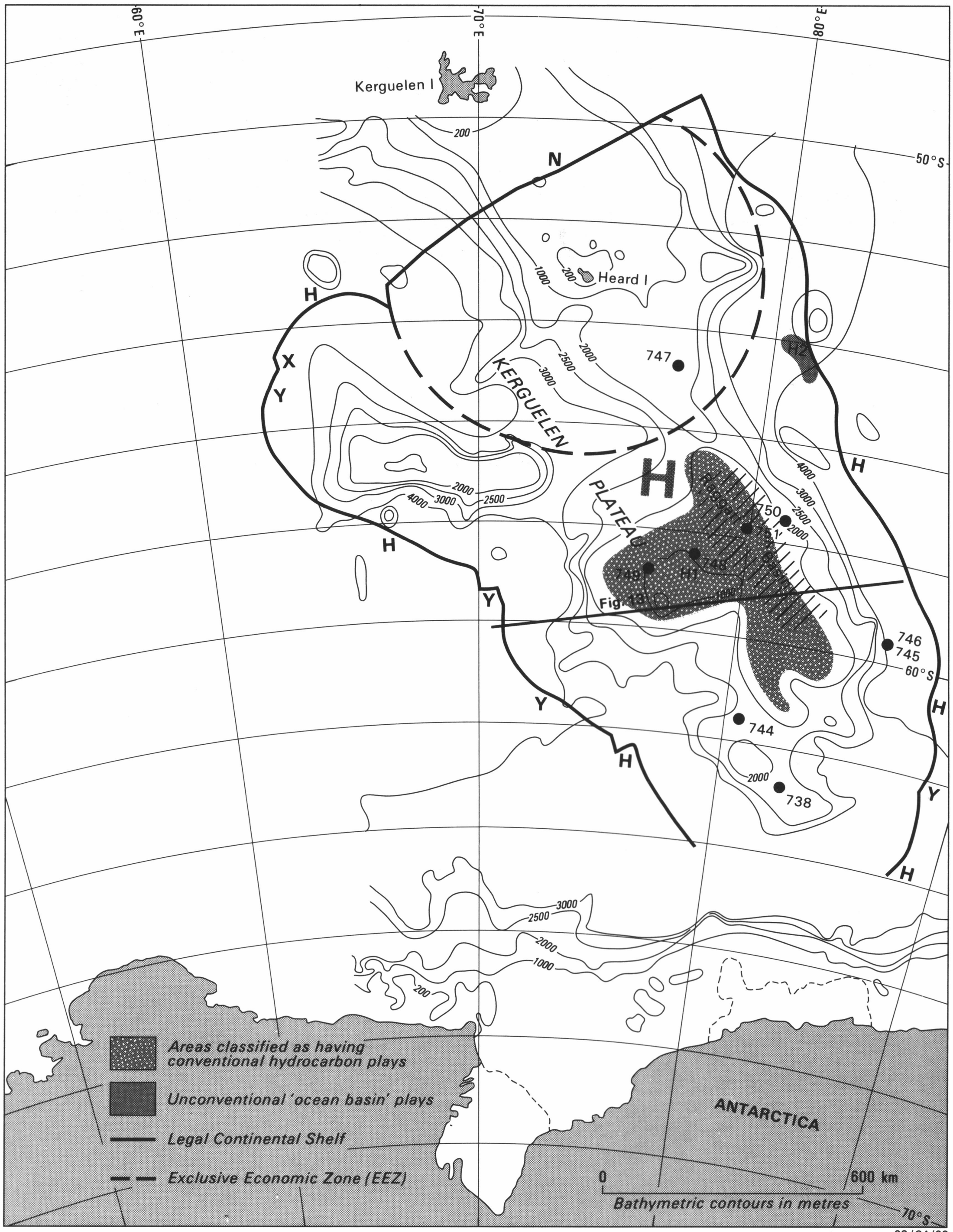


Figure 12. An EEZ and Legal Continental Shelf in the Kerguelen Plateau Region (H).
Criteria used to define a Legal Continental Shelf are: E = EEZ, H = Hedberg line, X = 350 n.m. cutoff, Y = 100 n.m. beyond 2500 m isobath cutoff; N = negotiated boundary with France. Isobaths are in metres. Shading shows areas of 'conventional' and 'unconventional' petroleum plays (see text), with H1 & H2 being the areas referred to in Tables 3, 4 & 5. Hatching shows approximate location of the recently discovered Raggatt Basin (Ramsay & others, 1986b). 738, 744, 745 and 746 are Ocean Drilling Project (ODP) drill sites. Heavy line shows the location of cross-section and seismic profiles in Fig. 13.
Petroleum potential ratings: southern Kerguelen Plateau (H1)– fair/poor (unknown basement type); eastern slope (H2)– poor/unknown.

oceanic or continental origin, and various approaches have been used in attempts to determine this. Houtz & others (1977) suggested that the Plateau (or at least a portion of it) is an uplifted part of a Mesozoic ocean basin; however, their Moho depth of 20–23 km, inferred from gravity modelling, is diagnostic of neither thickened oceanic nor thinned continental crust. Following a revision of the reconstruction of the Australian and Antarctic continents, Mutter & Cande (1983) concluded that they could not demonstrate an oceanic nature for any part of the Kerguelen Plateau. Their study showed that earlier continental reconstructions which resulted in overlap of the Kerguelen Plateau and Broken Ridge, and which were used to support an oceanic or constructional origin for the features, are no longer valid in the light of a recently proposed older breakup age for Australia and Antarctica of at least 90 Ma. On the

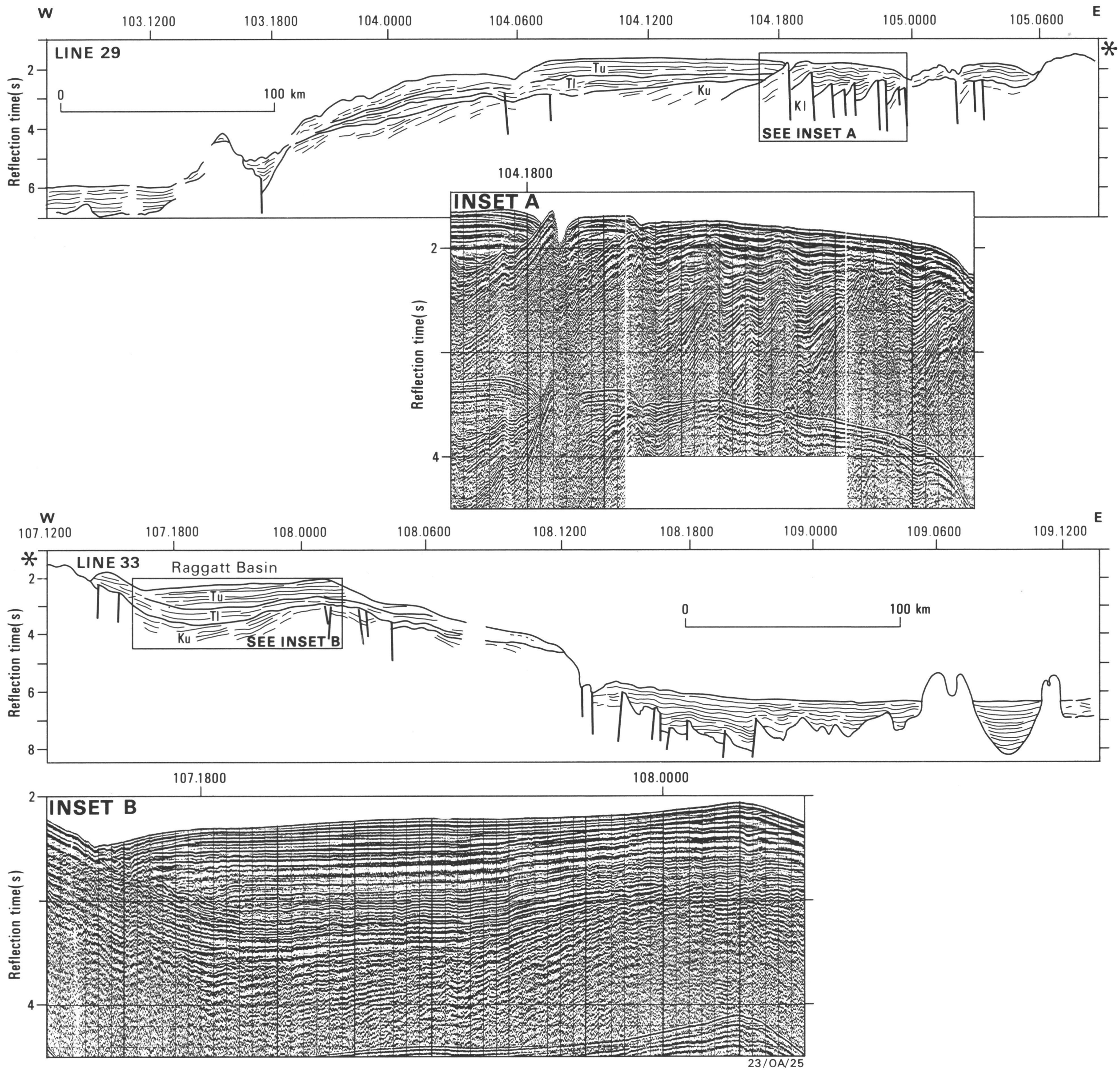


Figure 13. Cross-section of the Kerguelen Plateau (H), based on BMR Lines KP29 & 33 which adjoin at asterisk (Ramsay & others, 1986a). Interpretation by Symonds & Willcox before ODP drilling. Location given in Fig. 12.
Seismic details: (Inset A) Note tilt-blocks indicating extension beneath the central part of the Plateau, and (Inset B) showing relatively thick Tertiary and Cretaceous section in the Raggatt Basin.

basis of the geology of the Kerguelen Islands (Watkins & others, 1974) and isotope studies (Dosso & others, 1979; Dosso & Murthy, 1980), it was concluded that the northern part of the Plateau was oceanic. Although the petrology of basalts obtained from recent ODP drilling on the southern part of the Plateau (ODP Leg 120 Scientific Party, 1988a, 1988b) has also been used to infer oceanic affinity, trace element studies of dredged basalts appear to provide a contrary result by tentatively indicating continental contamination (Davies & others, in press).

Over all, opinion on the origin of the Kerguelen Plateau appears to have swung in favour of oceanic volcanic, possibly related to hotspot activity (Luyendyk & Rennick, 1977; Goslin & Patriat, 1984; Munschy & Schlich, 1987). However, at this stage, we feel that the balance of evidence favours the suggestion of Coffin & others (1986) that the northern and southern parts of the Plateau may have evolved by different processes. In the absence of evidence to the contrary, we have assumed that the southern Kerguelen Plateau was initially continental in origin, although it has undoubtedly experienced episodes of intense basaltic volcanism. Such an origin would be the most favourable for the generation of petroleum in this part of an Australian Legal Continental Shelf.

The present understanding of basin development beneath the southern Kerguelen Plateau comes mainly from limited sampling, and seismic stratigraphic studies (Colwell & others, 1988; Schlich & others, 1988; Coffin & others, 1988, 1989), which revealed the presence of significant sediment accumulations interpreted as Cretaceous–early Tertiary. Recently, nine sites were drilled on the Kerguelen Plateau, six in the south, as part of the Ocean Drilling Program (ODP) (ODP Leg 119 Scientific Party, 1988a,b; ODP Leg 120 Scientific Party, 1988a,b), and these provide the most definitive information on sediment type, palaeogeography and palaeoceanography of the Plateau. The Raggatt Basin is the largest depocentre within this region and lies almost entirely north of the AAT. Ramsay & others (1986a,b) estimated that up to 4000 m of sediment occurs within the Basin; however, from the available seismic data we calculate that in its thickest part there is probably no more than 3000 m of sedimentary section (Fig. 13). ODP drilling penetrated a Late Cretaceous–Tertiary section, which in places was overlying basaltic 'basement' of subaerial origin (ODP Leg 120 Scientific Party, 1988b; Coffin & others, 1988). On the western flank of the Raggatt Basin at ODP Site 748, the Late Cretaceous (Turonian) section contained restricted marine siltstone with a 0.5 per cent organic content, which could have source potential. At the base of this drill hole, undated pre-Turonian terrestrial sediment was recovered, and seismic data indicate that this may lie at least 200 m above acoustic basement. The section thickens substantially basinwards and indicates that the oldest sediment overlying 'basement' is terrigenous. At Site 748 the Campanian and Maastrichtian section consists of about 300 m of 'shelfal' carbonates, overlain by about 400 m of Tertiary foraminiferal ooze. In many places the 'basement complex' beneath the Raggatt Basin contains a thick section of dipping reflectors (Colwell & others, 1988), and drilling shows that the top of this section is subaerially erupted basalt. Whether or not this entire sequence consists of basalt and volcanogenic rocks, or includes rift-related/pre-rift sediments, is unknown at present. This has important implications for the petroleum potential of the region.

Our review of the geology of the Kerguelen Plateau indicates that the most prospective parts of an Australian Legal Continental Shelf in this region are the Raggatt Basin and the smaller basins and half grabens adjacent to the crest of the Plateau (Fig. 12, area H1). We have assumed that these features have a continental rift-related origin and for the purposes of this assessment can be categorised as Klemme Type 3 — Cratonic Rifts. Also included in the assessment is a small deepwater area of relatively thick sedimentary section on the eastern flank of the Plateau (Area H2). This area might overlie oceanic basement.

Petroleum potential

Klemme (1980 p. 187) noted that 'worldwide, more than 600 basins (Huff, 1980) and sub-basins are known to occur – of these, about a quarter by number (Fitzgerald, 1980) and about 50% by area and volume (Klemme, 1980, fig. 23) have production in some portion to almost all of the basin... About 50% of the world's basins by area and volume and three-quarters by number are non-productive'. We thus have every reason to expect that the offshore basins, or at least those which have well-explored analogues both onshore and beneath the shelf, will have similar potential. Krueger (1978) estimated that '65% of the reserves in the offshore will be found out to water depths of 200 m, and 30% from 200 m to 2500 m. In other words, 95% of the offshore hydrocarbon reserves will probably be found in waters shallower than 2500 m. The other 5% is divided 4% for the continental rise segment and 1% for the deep-ocean seabeds.' His estimate is, of course, entirely related to water depth and takes little account of the architecture and tectonic development of individual basins. It also reflects the fact that most thick and potentially productive sedimentary sections are found in shelf, plateau-like, and upper slope situations. Although 'more than half the total volume of marine sediments of the earth lies beneath the surface of deep marginal basins, continental rises, and abyssal plains' (Emery, 1975), such sequences are usually relatively thin and unlikely to contribute significantly to conventional petroleum reserves.

Assessment approach

Estimating resources of crude oil and natural gas in poorly explored regions is fraught with difficulty. There is, however, a need to provide some form of quantitative estimate for the more prospective areas beyond an EEZ, so that their importance relative to each other and to known basins can be assessed. Such calculations will be little more than a rough guide, and should not be used to give an impression of accuracy beyond the meagre knowledge available. As pointed out by Hedberg (1975), 'until at least one well has been drilled and tested in a new area, no one can be entirely certain that the area will produce any petroleum in spite of the rosiest outlook; conversely, in spite of dim advance prospects, no one can be entirely certain that the area will not be a bonanza'.

When evaluating any basinal area, seven multiplying factors need to be considered. These are (1) source beds, (2) migration paths, (3) reservoirs, (4) traps, (5) seals, (6) protection of traps and seals, and (7) timing. Within some remote frontier basins, it might be possible to estimate the presence and/or effectiveness of each of these factors by interpretation of regional seismic data and, in places, geological sampling and deep-sea drilling. However, in many frontier basins these factors are unknown, and only an estimate of sediment volume and structural style can be made.

Numerous basin classifications have been proposed (e.g. Weeks, 1952; Uspenskaya, 1967; Dewey & Bird, 1970; Halbouty & others, 1970a,b; Klemme, 1971a,b, 1975; Perrodon, 1971; McCrossan & Porter, 1973; Bally, 1975; Huff, 1978; Bally & Snelson, 1980; Bois & others, 1982; Kingston & others, 1983), and some of these have attempted to assess the petroleum potential of their various basin categories. Kingston & others (1983) provide a most useful classification in terms of basin-forming tectonics, depositional sequences, and basin-modifying tectonics, but only mention the potential of basins in a qualitative way. Classifications which would be of most use in estimating the quantitative petroleum potential of an area should combine a calculation of total sediment volume with the known petroleum yield of an analogous basin. The only classification of this type known to us is that of Klemme (1975), and we have used this for the basis of our quantitative estimates.

There are different opinions on the effectiveness of methods which use areal and volumetric yields in conjunction with geological analogues to determine the resource potential of poorly explored areas (Bultman, 1986; Miller, 1986; Ulmishek,1986; Resnick, 1986). For example, Bultman's (1986) study of highly explored North American basins led him to deduce that 'neither the richness or oil field density of a region is correlated to its tectonic setting'. He seriously questioned the use of geological analogy as a resource tool. However, his study did not include any Klemme-type 'cratonic rift' or 'pull-apart' basins of the type which predominate on Australia's continental margin (see Table 4), and which have gross similarities in tectonic and depositional history both within the Australian region and around the world. Despite Bultman's (1986) reservations, the global analogue approach might be appropriate for these basin types. Others (Miller, 1986), have suggested that the geological analogue method can be useful on a broad regional scale or in reconnaissance-type estimates of resource potential, particularly of poorly explored areas; however, the accuracy will depend on the validity of the analogue chosen (Miller, 1986). The more sophisticated assessment approaches, which use quantitative geochemical and geological modelling or projections of historical data (Forman & Hinde, 1986), cannot be applied to unexplored, non-producing areas unless at least some of the parameters are derived from areas with analogous geology (Miller, 1986).

Our assessment of petroleum potential in areas beyond an EEZ relies on:
(1) a *quantitative* evaluation, based on the global statistical analysis of Klemme (1975), with the added refinement of our concept of 'effective sediment volume', which eliminates the inclusion of spuriously large estimates of sediment volume derived from extensive areas of thin section with minimal potential, and
(2) a *qualitative evaluation*, in which the petroleum potential of tectono-stratigraphic units within unexplored basins is compared with analogous units in better known basins around the Australian margin.

The results are expressed numerically as potential petroleum recovery and qualitatively as a basin rating: both are speculative.

Quantitative evaluation

The original Klemme classification was based on those basins with giant fields (over 500 million barrels of oil) which account for a large proportion of present-day oil production; however,

Table 2. 'Yardstick' for evaluation of poorly explored basins (modified from Klemme, 1975)

	Basin type	*Recovery/km^3 of sediments*[1]		*Chance of*		*Field size*
		Kilolitres (m^3)	*Barrels*	*Commercial Production*	*Presence of 'Giant' fields*	*Largest field v total*
	1. Cratonic interior	1 400 High 700 Average 100 Low	9 000 4 500 1 000	30%	20%	—
Cratonic basins	2. Cratonic multicycle (large)	9 900 4 800 1 000	62 500 30 000 6 000	70%	65%	10–50%
Cratonic basins	(Small)	3 000 1 600 300	19 000 10 000 2 000	50%	30%	30%
Cratonic basins	3. Cratonic rift	17 900 5 600 800	112 500 35 000 5 000	50%	50%	30%
Intermediate basins	4. Intermediate extra-continental (4A. Closed)	23 800[2] 6 000 400	150 000[2] 37 500 2 500	50%	50%	14%
Intermediate basins	(4B. Foredeep)	2 400 1 000 —	15 000 6 000 300	40%	10%	14%
Intermediate basins	(4C. Open)	11 900 6 300 —	75 000 40 000 800	50%	65%	30%
	5. Pull-apart	Average approx. 1 600	10 000	30%	20%	?
	6/7. Inter-montane	158 700 7 100 200	1 000 000 45 000 1 300	20%	50%	35%
	8. Delta	8 700	55 000	50%	Few giants	6%
	Average for all basins	2 000 – 4 000	12 500 – 25 000	50%	50%	25%

[1]These figures represent volumes of oil or equivalent gas. On an approximate basis, 1 kilolitre (or cubic metre) of oil has the energy equivalence of 1000 cubic metres of gas.
1 kilolitre (or cubic metre) is equal to 6.2829 barrels.
1 cubic kilometre of sediment is approximately equal to 0.25 cubic miles, as per Klemme's original table.
[2]These exceptionally high values include Middle East fields.

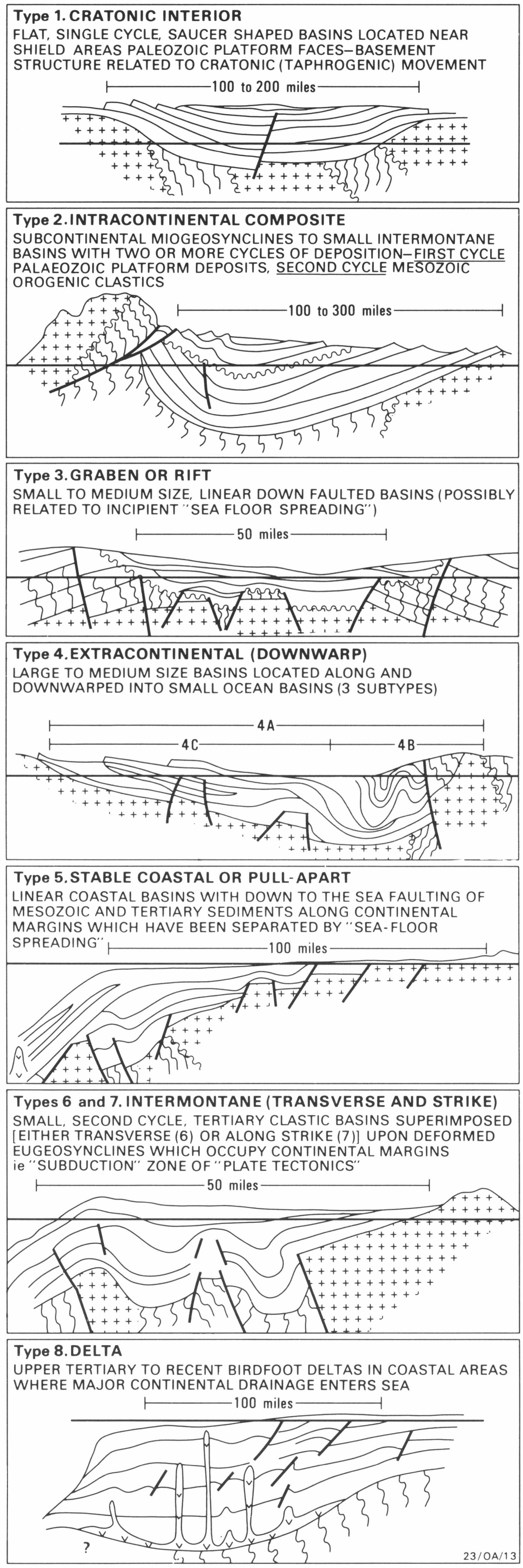


Figure 14. Basin types according to Klemme (1975), based on the classification of Halbouty & others (1970a,b).

it is also applicable to basins without giant fields, including poorly explored basins. Klemme (1975) recognised eight basin types based on the classification system of Halbouty & others (1970 a,b) (Fig. 14) : (1) cratonic interior, (2) intracontinental composite, (3) graben or rift, (4) extracontinental (downwarp), (5) stable coastal or pull-apart, (6) intermontane (transverse), (7) intermontane (strike), and (8) delta; and he assembled statistics on petroleum recovery per cubic mile of sediment, which we have converted to cubic kilometre, and exploration risk (Table 2). For example, we show in Table 2 that Type 5 — pull-apart basins — have a 30 per cent chance of commercial production (i.e. the geological risk is 0.3), that there is a 20 per cent chance of finding giant fields, and that in a producing basin the average oil recovery is about 10 000 barrels per km^3, or about 1600 kL/km^3. In a later version of this classification (Klemme, 1983), the basin categories were refined and related to field-size distribution, but revised petroleum recovery figures were not provided.

Using regional seismic data, we have categorised basins beyond the EEZ in terms of Klemme's Types 1 to 8. The effective sediment volume concept used in our calculations of petroleum recovery takes into account only that part of the section which is at least 2000 m thick — that is, the so-called 'kitchen area' — thus eliminating large areas of thin section which are unlikely to contain mature petroleum source rocks. This is in accord with Krueger (1978) who recognised that although 'the thickness of sediments is not a complete measure of the potential for hydrocarbon occurrences, it is certainly the most important attribute being an integral portion of all seven evaluation parameters' listed above. In regions where a prospective province exists, containing numerous poorly defined sub-basins of similar dimensions and having similar structural and depositional styles, the effective sediment volume of the whole province was calculated as follows (Fig. 15):

- determine total area of basin province (e.g. western flank Lord Howe Rise)
- estimate the proportion occupied by sub-basins with ≥2000 m of sediment, using any available seismic sections or other relevant information
- estimate the average thickness of sediment in the known sub-basins
- compute minimum, best and maximum estimates of area and volume (Table 3) to use in the calculations of potential petroleum recovery.

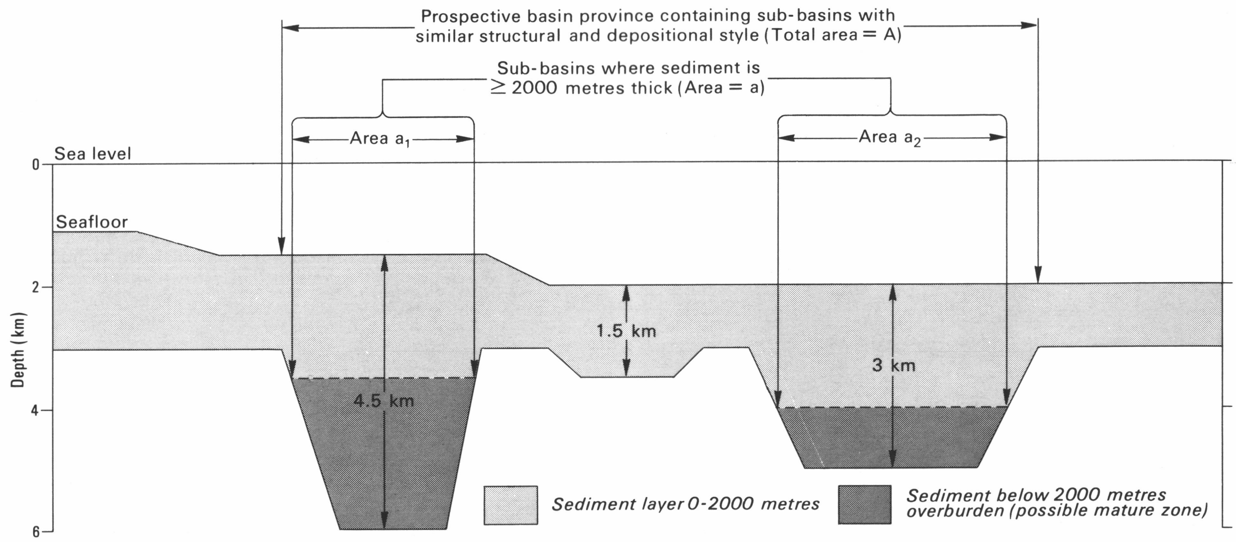
Using our estimates of effective sediment volume (Table 3) and Klemme's petroleum recovery figures (Table 2), we have calculated the minimum, best, and maximum estimates of potential petroleum recovery for each area (Table 5) as follows:

minimum estimate	=	low recovery x minimum volume estimate
best estimate	=	average recovery x best volume estimate
maximum estimate	=	high recovery x maximum volume estimate.

Qualitative evaluation

The statistical data associated with Klemme's classification have enabled us to provide a quantitative evaluation of the relative potential of basins beyond an EEZ. The method is, however, limited by Klemme's use of 'global'— largely North American and Middle Eastern — production statistics, which might in some cases be less appropriate for basins in the Australian region, even when they are tectonic counterparts of Klemme's basin types. The most significant problems are likely to arise from:

- peculiarities in sedimentation within Gondwanaland and on the Australia-India Plate, related to their particular latitude and climate



Estimation of effective sediment volume, assuming sub-basins have similar dimensions:

- Total area of basin province = A
- Total area of all sub-basins (≥ 2000 metres sediment) = a
  Area a = $a_1 + a_2$ = 54% A (in this example only)
- Average sediment thickness in sub-basins = 3.750 km
- Approximate sediment volume (≥ 2000 metres) = 3.750a km^3

Note: This volume calculation has only been applied where sub-basins are approximately equidimensional (e.g. Western Lord Howe Rise). The estimate is then within about 20% of the true volume ($4.500a_1 + 3.000a_2$) if all individual sub-basins could have been mapped. In a real situation ratio a/A is estimated from available data.

23/OA/30

Figure 15. Calculation of effective sediment volume. Used in areas with groups of structurally related basins, particularly western Lord Howe Rise. Also illustrates the concept of 'kitchen areas' (ie. the zone of potentially mature sediment), discussed in the text and used in the derivation of Tables 3 & 5.

Table 3: Areas and volumes of thick sediment (≥2000 m) for regions beyond an EEZ

Region	*Area name*[1]	*Estimated Areas ($10^3.km^2$)*			*Estimated Volumes ($10^3.km^3$)*		
		Minimum	*Best*	*Maximum*	*Minimum*	*Best*	*Maximum*
A	Western Lord Howe Rise ($A1_1$ + $A1_2$)	28	40	49	56	100	157
	Eastern Lord Howe Rise (A2)	37	40	43	75	100	128
	Middleton Basin (A3)	25	25	25	42	62	69
	New Caledonia Basin ($A4_1$ +$A4_2$)	43	43	43	108	129	151
	West Norfolk Ridge (A5)	1.6	1.9	2.3	3	5	7
	Taranui Sea Valley (A6)	1.6	1.6	1.6	4	5	5.7
C	South Tasman Rise ($C1_1$ + $C1_2$)	18	19	32	55	57	95
D	Great Australian Bight — mid-slope (D1)	21	21	21	63	73	94
	— lower slope and basin floor (D2)	29	29	29	88	102	131
E	Naturaliste Plateau (E1)	4.9	4.9	4.9	7	10	12
F	Wallaby Plateau (F1)	2	2	2	4	4.9	5.9
	Northwest Exmouth Plateau (F2)	12.8	12.8	12.8	32	38	45
H	Southern Kerguelen Plateau (H1)	52	66	85	104	165	255
	eastern slope (H2)	3.3	3.5	3.7	8.3	9.8	11.8

[1]Refer to Figs 4, 7 and 12 for Areas $A1_1$, $A1_2$, etc.

- tectonic events of local or regional extent, which might, for example, have given rise to features such as silled basins containing anoxic environments favourable to the preservation of kerogen
- the depositional environment of the source beds, the nature of the primary source material (that is, algal, bacterial or higher plant), and its degree of reworking. The oil-prone nature of the terrestrial source material in many Australian basins, for example, is quite different to typical terrestrial source rocks in northern hemisphere basins.

It is also important to distinguish the potential petroleum productivity of the particular tectono-stratigraphic units which make up Australian basins. For example, in the Gippsland Basin, it is the *post-breakup stage* which harbours the large oil and gas fields, owing largely to the occurrence

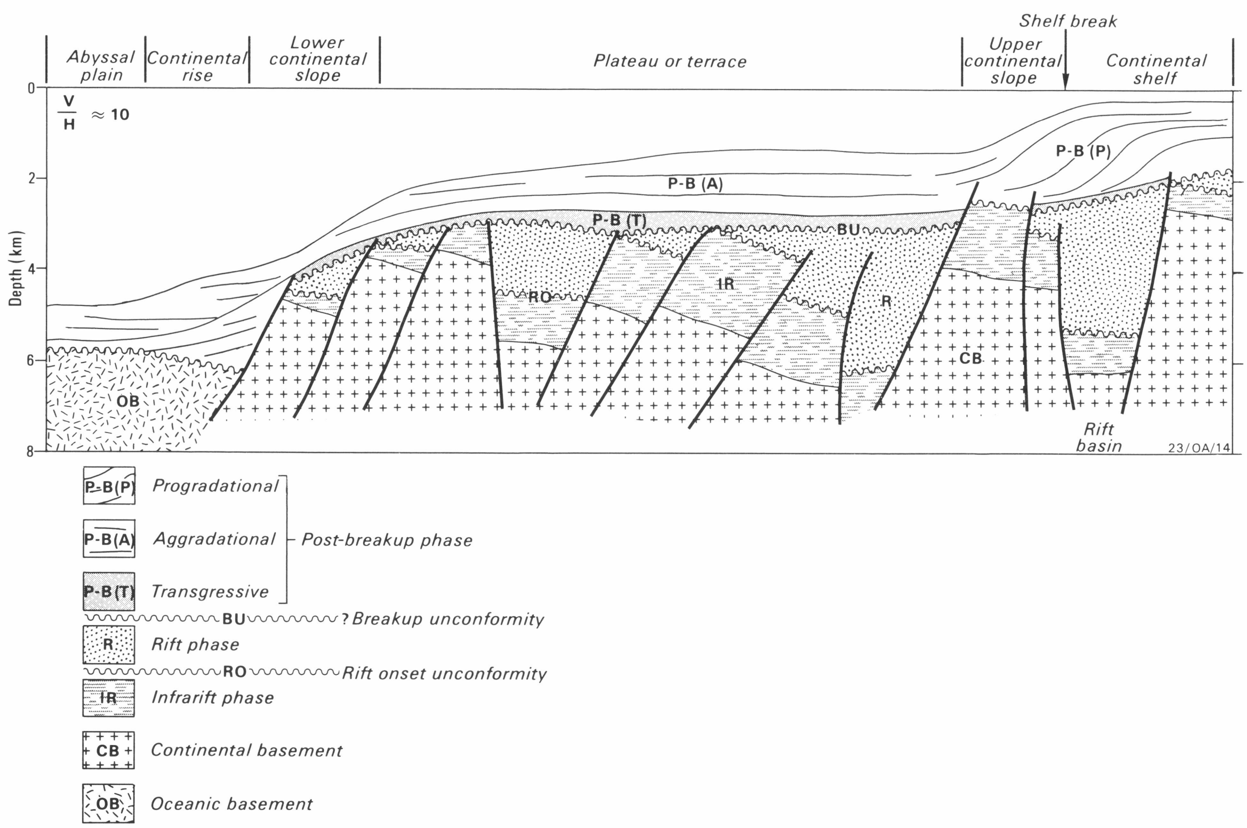


Figure 16. Tectono-stratigraphic units on a typical passive continental margin.
Shows the main phases of structuring and sedimentation — infrarift (prerift), rift and post-breakup — based on the nomenclature of Falvey & Mutter (1981).

Table 4: Geological classification for areas of thick sediment (≥2000 m) for regions beyond an EEZ

Region	*Area name*	*Basin Type Klemme (1975; Fig. 14)*	*Prospective tectono-stratigraphic units with significant plays (Fig. 16)*	*Play-types envisaged*	*Comment*
A	Western Lord Howe Rise ($A1_1$ + $A1_2$) basins	Type 3 — cratonic rift	IR/R	Tilt blocks, composed of infrarift (prerift) sediments in south; structural/stratigraphic traps within rift fill; breakup unconformity traps; possible diapiric structures in north	Gippsland Basin (Strzelecki Group) equivalents could occur within tilt-blocks in some areas
	Eastern Lord Howe Rise (A2)	Type 5 — pull-apart	R/P-B[P]	Mainly stratigraphic traps	Straddle ocean/continent boundary
	Middleton Basin (A3)	Type 4C & 5 — extra-continental (open) or pull-apart	R/P-B[A]	Mainly stratigraphic traps	Straddle ocean/continent boundary
	New Caledonia Basin ($A4_1$ & $A4_2$)	Type 4A? — extra-continental (closed)	P-B[A/oceanic]	'Unconventional' deep-ocean restricted basin	On oceanic crust. Prospectivity of basins of this type is unknown
	West Norfolk Ridge (A5)	Type 5 & 3? — pull-apart & cratonic rift	R		
	Taranui Sea Valley (A6)	Type 6 & 7 — intermontane	Uncertain association	Wrench related anticlines, drapes & unconformity traps	Basin-forming tectonics not understood; restricted basin
C	South Tasman Rise ($C1_1$ + $C1_2$)	Type 3 — cratonic rift	R	Typical half-graben tilt-block plays with reactivation to Oligocene	Some gas anomalies near NE basin boundary. Otway Basin stratigraphy may apply
D	Great Australian Bight — mid-slope (D1)	Type 5 — pull-apart	IR/R/?P-B	Fault-blocks and anti-clines created by rifting and wrenching	Analogous to Otway Basin but fewer Tertiary faults and greater chance of sealed traps
	— lower slope & basin floor (D2)	Type 4C? or 5 — extra continental (open) or pull-apart	R/P-B[A]	Fault-blocks and anti-clines created by rifting and wrenching	Very deep water, highly extended continental crust
E	Naturaliste Plateau (EI)	Type 3 — cratonic rift	?R		Volcanics/volcaniclastics in some places
F	Wallaby Plateau (F1)	Type 3 & 5 — cratonic rift & pull-apart	R		Origin of plateau in doubt — continental or oceanic?
	Northwest Exmouth Plateau (F2)	Type 3 & 5 — cratonic rift & pull-apart	IR/R	Largely fault blocks and associated structures	Analogous with Exmouth Plateau proper &? offshore Canning Basin
H	Southern Kerguelen Plateau (H1)	Type 3 — cratonic rift	?R	Unconf. traps in Raggatt Basin depocentre. ?Cretaceous tilt-block plays; downgraded in places where faults are shallow	Pre-breakup reconstruction against Naturaliste Plateau/Broken Ridge. Origin remains in doubt — dredging/drilling sampled basaltic basement and potential Ku source
	— eastern slope (H2)	Type 4C & 5 — extra-continental (open) & pull-apart	P-B[A/oceanic]	'Unconventional' deep ocean basin	Prospectivity of basins of this type is unknown

P-B = post-breakup; [A] = aggradational; [P] = progradational; [A/oceanic] = aggradation in ocean basin; R = rift; IR = infrarift of suitable source rocks and the presence of reactivation structures which provide the traps. Hence, categorising the Gippsland Basin simply as a *cratonic rift* (that is, a Klemme Type 3 basin) is only part of the story: although its overall rift-setting may be important, it is the peculiarities of the post-breakup sequence which led to the basin's high productivity. Klemme (1975) has recognised this limitation by categorising the Gippsland Basin as a Type 6/7 — Intermontane Basin— thus focussing on the reactivation of its Tertiary section rather than its primary rift phase development. In the case of the western Lord Howe Rise basins, the post-breakup tectono-stratigraphic unit is unlikely to be prospective, even though these basins first developed within the same rift sytem as the Gippsland Basin. This is because these two areas were separated by seafloor spreading from the Late Cretaceous, thus isolating the Lord Howe Rise basins from a high terrigenous sediment supply and the Tertiary reactivation.

We have attempted to overcome the limitation of our quantitative analysis by providing a qualitative, somewhat intuitive, assessment of each area. This involves identification of the tectono-stratigraphic units related to the infra-rift/prerift (IR), rift (R) and post-breakup (P-B) phases of basin development (Fig. 16; Falvey, 1974; Falvey & Mutter, 1981), with a further subdivision of the post-breakup sequence into its transgressive (P-B[T]), aggradational (P-B[A]), and progradative (P-B[P]) components. In the case of deepwater deposition on oceanic basement we also recognise a post-breakup aggradational unit (P-B[A/oceanic]). Comparison of these units with those of other basins in the region enabled us to estimate the most likely play-types present (Table 4) and to provide a speculative rating of petroleum potential (Table 5).

Areas of relatively thick sediment beyond an EEZ can be broadly grouped into two categories. First, there are the areas where sediments have been deposited in structurally controlled basins (rift phase sediments) — mainly grabens and half-grabens — which we categorise as basin Types 3 and 5 (Table 4). By analogy with better explored areas, we envisage the sediment fill in these basins as mostly overlain unconformably by a thin sequence of shallow to deep marine sediments (post-breakup phase). Basins in this category occur on continental lithosphere, and contain the commonly explored petroleum plays. We have designated these as areas of 'conventional' petroleum plays on Figures 4, 7 and 12.

Secondly, there are areas of turbidite and pelagic sediments deposited in or on the flanks of deep ocean basins. Such basins generally occur on oceanic lithosphere and are in an environment beyond current exploration experience. We have categorised them as Type 4 — Intermediate Extracontinental — (Table 4), and have designated them as areas of 'unconventional ocean basin' plays on Figures 4, 7 and 12.

Results and discussion

Our evaluation of the six areas beyond the EEZ with significant sediment accumulation (areas A, C, D, E, F & H), is summarised in Table 5, with a qualitative rating of petroleum potential and a quantitative minimum, best and maximum estimate of speculative petroleum recovery.

The speculative rating given in Table 5 is an estimate of petroleum potential based on our limited knowledge of the areas. On the basis of existing information, there are no areas beyond the EEZ that can be rated as better than 'fair'. The prospectivity of the deep-ocean basin areas is essentially unknown.

Previous quantitative assessments of Australia's undiscovered petroleum resources (BMR, 1989) refer only to conventional oil and gas accumulations in traps that are not presently known to contain petroleum, and that could be produced within the next 20 to 25 years. As such, they have not included the relatively remote and deepwater regions beyond an EEZ considered in this study. Table 5 illustrates the relative importance of the remote areas in terms of their potential to have produced petroleum. Most of these areas are in deep water, and it is unlikely that anything other than 'giant' fields (say 500 million barrels) would be worth exploiting. Even if such giant fields were to exist, the question arises as to whether they could be recognised with an economically feasible exploration program, particularly given the enormous size and remoteness of the areas involved.

Two areas of intermediate water depth, which are within range of current exploration drilling technology, stand out as having relatively large recovery figures (Table 5). These are the western Lord Howe Rise (most likely estimate of 0.56 x 10^9 kL or 3.5 billion barrels) and the southern Kerguelen Plateau (0.95 x 10^9 kL or 5.98 billion barrels). These areas are considered or assumed to be continental in origin, to have stratigraphy and structure related to passive continental margin evolution, and to contain petroleum plays of a kind that have been tested elsewhere in the world. The basins on western Lord Howe Rise and the southern Kerguelen Plateau are considered to be mainly Type 3 — cratonic rift — which on a world-wide basis have a 50 per cent chance of providing commercial production, and also a 50 per cent chance that giant fields are present.

We consider the western Lord Howe Rise basins, although promising in terms of total potential recovery, individually less attractive, because they are mainly small. The accumulation of any large and commercially viable fields could have been limited by relatively small quantities of source rock. For most of the area we might be faced with an 'all or nothing' situation; that is, modest-sized fields could be present in most grabens or, alternatively, these grabens could all be barren. The few larger grabens and basins might be more promising: both the diapiric structures in the basin northeast of Lord Howe Island (Roeser & others, 1985), and possible Mesozoic infrarift (prerift) sequences in fault blocks southeast of Lord Howe Island (Whitworth & Willcox, 1985) warrant further investigation. Taken as a whole, we regard the western Lord Howe Rise basins as having fair (F) potential (Table 5).

The southern Kerguelen Plateau presents a similar problem to Lord Howe Rise, in that there is a vast volume of sediment which could have reached maturity, but we have no knowledge of whether maturation, migration and trapping have actually occurred. The southern Kerguelen Plateau has two problems: the possibility of volcanogenic detritus in potential? Cretaceous reservoirs, which could destroy their permeability; and Tertiary faulting, which is common in some places and could have prevented the sealing of any traps. The greatest disincentive to exploration is, of course, its remote and hostile environment. We rate the petroleum potential of the southern Kerguelen Plateau as fair to poor (F/P), although there is a large unknown component, owing to the Plateau's uncertain origin.

Two other areas which yield significant recovery figures are the South Tasman Rise (most likely estimate of 0.32 x 10^9 kL or 2.0 billion barrels) and the eastern margin of Lord Howe Rise (0.16 x 10^9 kL or 1.0 billion barrels). Although small yields of thermogenically derived hydrocarbons have been recovered from the surface sediments of the South

Table 5: Potential petroleum recovery and their qualitative rating for areas beyond an EEZ

Region	Area name	*Estimated recovery*[1]			*Qualitative rating*[3]
		Minimum	*Best*	*Maximum*	
A	Western Lord Howe Rise ($A1_1 + A1_2$) basin	0.04(0.28)	0.56(3.50)	2.8(17.70)	F
	Eastern Lord Howe Rise (A2)	0.12(0.75)	0.16(1.00)	0.20(1.28)	F/P
	Middleton Basin (A3)	0.01(0.03)	0.25(1.55)	0.82(5.18)	U
	New Caledonia Basin ($A4_1 - A4_2$)	0.04(0.27)	0.77(4.84)	3.60(22.60)[2]	U
	West Norfolk Ridge (A5)	0.002(0.02)	0.02(0.11)	0.13(0.79)	F/P
	Taranui Sea Valley (A6)	0.001(0.01)	0.04(0.23)	0.91(5.70)	F
C	South Tasman Rise ($C1_1 + C1_2$)	0.04(0.28)	0.32(2.00)	1.70(10.60)	F/P
D	Great Australian Bight — mid-slope (D1)	0.10(0.63)	0.12(0.73)	0.15(0.94)	P
	— lower slope & basin floor (D2)	0.14(0.88)	0.16(1.02)	0.21(1.31)	U
E	Naturaliste Plateau (E1)	0.10(0.04)	0.06(0.35)	0.21(1.35)	P
F	Wallaby Plateau (F1)	0.003(0.02)	0.02(0.11)	0.11(0.66)	P/N
	Northwest Exmouth Plateau (F2)	0.03(0.16)	0.14(0.86)	0.80(5.06)	F/P
H	Southern Kerguelen Plateau (H1)	0.04(0.26)	0.95(5.98)	6.07(38.25)	F/P(U)
	— eastern slope (H2)	0.001(0.01)	0.04(0.25)	0.14(0.89)	P(U)

[1] Recovery in kilolitres x 10^9 and billions of barrels (bracketed)
6.3 barrels are equivalent to a kilolitre (or cubic metre)
Note: Figures are rounded to the second decimal place.

[2] These maximum values are based on Type 4A basins that include recovery statistics from the Middle East (Table 2) : they are therefore unrealistically high.

[3] Qualitative rating : F = fair, P = poor, N = nil, U = unknown

Tasman Rise (Whiticar & others, 1985), indicating active petroleum generation now or in the past, the seismic data show abundant volcanics in the rift basins, which could downgrade reservoir potential. Both the eastern Lord Howe Rise and the South Tasman Rise are considered to have fair to poor (F/P) potential.

Of the deepwater ocean basin areas, the New Caledonia Basin appears to be the most significant. However, it should be noted that the maximum potential recovery figure for the New Caledonia Basin may be unrealistically large, because it has been placed in the Type 4A category, which incorporates the highly productive Middle East fields. The other deepwater areas which yield significant recovery figures are the Middleton Basin and the lower slope and basin floor in the Great Australian Bight. The exploration potential of areas of this type, which lie in such deep water, perhaps partially on oceanic lithosphere, is totally unknown.

As discussed above, any assessment of the kind presented in this paper tends to emphasise regions which generally have large areas and volumes of sediment, and which thus lead to large recovery figures. However, in terms of exploration success, the relatively small, potentially high-yield, areas should not be dismissed. The most notable of these beyond an Australian EEZ is the Taranui Sea Valley on the Norfolk Ridge, which appears to be a Type 6/7 Intermontane Basin. The relatively thick (4000 m) sediment, apparent structural complexity of the Taranui Sea Valley section, and its moderate water depth (about 1600 m), lead us to conclude that this area has fair (F) potential.

In order to dispel uncertainties and cynicism attached to the volumetric/analogue approach of Klemme, we have carried out some 'rule-of-thumb' comparisons of Klemme-type calculations with more sophisticated estimates of resources as determined by Forman & others (BMR, 1989). In doing this we have treated well-explored basins in the Australian continental margin in a very simplistic way commensurate with the meagre knowledge of basinal areas beyond an EEZ. That is, how would the potential petroleum recovery of the explored basins rate if they were known only from a few moderate quality seismic lines, which provide limited information on basin area, sediment thickness and structural style? Consider, for example, our calculations for the Gippsland Basin and Northern & Western Margin Basins given in Table 6 (see footnote).

The volumetric/analogue approach produces potential petroleum recovery estimates of the same order as the resource estimates derived by more sophisticated methods (Table 6). In the case of the Gippsland Basin, the volumetric/analogue estimate is about 0.5 of that derived from the aggregate of the 'demonstrated' (that is, proven by drilling) and 'undiscovered' (statistically predicted) resources. The Gippsland Basin therefore has a recovery factor of approximately 73 000 barrels/km^3, somewhat richer than the average of 35 000 presented by Klemme (1975), but well below the maximum of 112 500 for a cratonic rift basin (Table 2). As discussed above, Klemme (1975) categorised the Gippsland Basin as a Type 6/7 — Intermontane Basin — with an average recovery of 45 000 barrels/km^3 (Table 2). It is interesting to note that this intermontane value is

Table 6. Comparison of potential petroleum recovery calculations based on a volumetric/analogue approach (Klemme method) with the resource estimates given in BMR (1989)

Volumetric/analogue (Klemme method)				*Resources[1] BMR, 1989)*			
Basin type (Table 2)	*Average recovery (Bbl/km^3)*	*Dimensions (km)*	*Potential recovery ($Bblx10^9$)*		*Demonstrated ($Bblx10^9$)*	*Average undiscovered ($Bblx10^9$)*	*Total*
Gippsland Basin[3]							
Cratonic rift	35 000	Length ~ 150	2.9	Oil	3.446	0.560	~ 6.2
(Type 3)		Width ~ 80		Condensate	0.254	0.070	
		Thickness ~ 7		Gas[2]	1.635	0.220	
Northern & Western Margin Basins: Bonaparte Basin							
Cratonic rift	35 000	Length ~ 550	~ 6.3				
(Type 3)		Width ~ 65					
		Thickness ~ 5					
Barrow/Dampier Sub-basin				Oil	0.406	1.540	~ 15.0
				Condensate	0.482	1.200	
Cratonic rift	35 000	Length ~ 350		Gas[2]	7.333	4.025	
(Type 3)		Width ~ 60					
		Thickness ~ 6					
Exmouth Sub-basin			~ 6.7				
Cratonic rift	35 000	Length ~ 160					
(Type 3)		Width ~ 100					
		Thickness ~ 4					

[1]Resources for the 'Southern Margin Coastal Basins' (BMR, 1989, table 4) are almost equivalent to those from the Gippsland Basin, which is the major contributor: resources for the 'Northern & Western Margin Basins' (BMR, 1989, table 6) are mainly from the Bonaparte Basin and the Barrow, Dampier and Exmouth Sub-basins (graben).
[2]Salesgas has been converted to energy equivalent oil (see footnote, Table 2).

closer to the calculated recovery of 73 000 barrels/km^3 than the 35 000 barrels/km^3 cratonic rift value used in our calculations. For the 'Northern and Western Margin Basins' the volumetric/analogue estimate is 0.6 times the BMR (1989) figure, implying that the recovery factor might be a little higher than average.

Continued studies of basins in the Australian region should improve both the quality of the analogues and recovery factor estimates, enabling better quantitative assessment of the petroleum potential of unexplored areas.

Conclusions

Under the United Nations Convention on the Law of the Sea, a coastal state has sovereign rights over its Legal Continental Shelf for the purposes of exploring and exploiting the natural resources of its seabed and subsoil. This Shelf is considered to extend throughout the natural prolongation of the land territory to the outer edge of the continental margin, which, where it extends beyond a 200 nautical mile Exclusive Economic Zone, is defined by formulae within Article 76 of the Convention.

The area of a Legal Continental Shelf around Australia and its territories would be approximately 12 million km^2. Eight regions of this Shelf, totalling more than 3 million km^2 in area, would extend beyond an Exclusive Economic Zone. Sediment thicknesses greater than 2000 m — sufficient to have generated petroleum from any potential source rocks — occur in six of these regions: Lord Howe Rise/Norfolk Ridge, South Tasman Rise, Great Australian Bight, Naturaliste Plateau, Exmouth Plateau/Wallaby Plateau and Kerguelen Plateau. These regions are all in relatively deep water (generally over 1000 m), and some are in hostile and remote environments. However, they are not consistently deeper than some better explored areas within an EEZ, such as the Exmouth Plateau, which was drilled during a period of active oil industry exploration that began in the late 1970s.

Our assessment of the petroleum potential of the areas beyond an EEZ is both qualitative and quantitative. We believe that the quantitative approach is a useful tool, which has enabled us to rank and compare the potential petroleum recovery of Australia's remote regions. It is clear that, in terms of the recovery figures, the western flank of Lord Howe Rise and the remote southern Kerguelen Plateau are the most important regions beyond an EEZ. Despite our reservations regarding basin size, the western Lord Howe Rise as a whole is ranked highest, because an equivalent-sized prospective area also lies within the EEZ around Lord Howe Island. The South Tasman Rise and eastern flank of Lord Howe Rise are also of interest, as are small, potentially high-yield features such as the Taranui Sea Valley on the southern limit of an EEZ around Norfolk Island.

Since the early 1960s, the worldwide rate of petroleum discovery has been in apparent decline, although this has been the period of greatest exploration activity (Fitzgerald, 1980). The decline is a result, not of finding fewer fields, but of finding fewer 'super-giants', which account for 50 per cent of all oil yet discovered. Although the petroleum resources of Australia are comparatively small by world standards, the exploration trends and discovery rates have still tended to follow those for the rest of the world. If further giant fields are to be discovered, we should give at least some attention to the deeper water regions. Although exploration of the remote regions beyond an Exclusive Economic Zone is not viable in the present economic environment, these regions may well hold strategic resources that could benefit Australia in the next century.

Acknowledgements

This paper has evolved from numerous studies undertaken over the last 10 years. We acknowledge the helpful comments and criticisms received from our colleagues in BMR's Division of Marine Geosciences and Petroleum Geology and Resource Assessment Division, in particular David Forman, Colin Robertson and Lee Ranford. We thank Victor Prescott (Professor of Geography, University of Melbourne) for reviewing an early version of this paper. Figures were drawn by J. Convine.

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