AGSO Journal of Australian Geology & Geophysics, 17(5/6), 17–33

Architecture and evolution of the Australian continental margin

H.M.J. Stagg[1], J.B. Willcox[1], P.A. Symonds[1], G.W. O'Brien[1], J.B. Colwell[1], P.J. Hill[1], C-s. Lee[2], A.M.G. Moore[1] & H.I.M. Struckmeyer[1]

Interpretation of key seismic profiles around the Australian margin clearly show that the three principal rift-drift segments (northwestern/western, southern, and eastern) have distinct and different architecture.

The normally rifted northwestern and oblique-slip western margins have a polyphase rift/drift history that saw the progressive separation of continental blocks from the Permo-Carboniferous until the Neocomian. These multiple tectonic episodes produced a margin that is geologically complex and also shows a strong imprint of volcanism. The continental shelf and marginal plateaux of this margin are generally underlain by thick Phanerozoic sediments of the Westralian Superbasin, while areas of shallow crystalline basement are rare. The Phanerozoic section is generally thick and flat-lying, and extension of the upper crust is observed only adjacent to the inboard confined deep rifts and on the outermost margin. Even in these regions, the amount of upper crustal extension is rarely more than 20 per cent. Profiles through the basins, together with limited velocity information, suggest strongly that they formed largely as the result of lower crustal extension; i.e. the northwestern and western margins are probably 'upper plate' margins.

The southern margin, from the Naturaliste Plateau in the west to the South Tasman Rise in the southeast, formed during a single rift/drift episode that culminated in the separation of Australia and Antarctica in the Cretaceous. The age of onset of rifting is inferred to be in the Jurassic; however, the azimuth of extension is open to conjecture, with interpretations ranging from NW–SE to NNE–SSW. The preserved rift ranges in width from about 350 km in the normally extended crust in the west to no more than 100 km on the strike-slip margin west of Tasmania. In contrast to the northwest margin, the main basins of the southern margin lie beneath the continental slope and rise, while the shelf is largely underlain by shallow crystalline basement. Marginal plateau development is rare, with the major plateau (the Ceduna Plateau) interpreted to be largely sedimentary in origin, rather than structural. The primary basin-forming mechanism is interpreted to be extension of the upper crust. Also in contrast to the northwest margin, volcanism is apparently more restricted, except at the eastern and western ends of the rift.

The eastern margin has the least understood architecture on the Australian margin, largely owing to the dearth of seismic and drill information. The margin of the Tasman Basin is narrow and, with the exception of the deep and areally restricted Gippsland Basin, rift basin development is generally limited to the conjugate Lord Howe Rise. In contrast, the margins adjacent to the Coral Sea Basin are broad, particularly where the Queensland and Marion Plateaux have developed on the continental margin. These plateaux are distinct from those on the northwestern and southern margins in that they are structurally controlled, but consist largely of shallow, pre-rift basement.

Introduction

The Australian continental margin is about 1.5 times the area of the Australian landmass (Symonds & Willcox 1989, table 1) and varies in width from less than 100 km to more than 600 km. It is probably the third-largest margin in the world, after those of Canada and Russia. However, despite the economic importance of the margin, it is still poorly known and understood after more than 30 years of research and exploration by government, universities and the petroleum industry.

The range of papers dealing with the regional geology of the Australian continental margin is very limited. The most commonly referenced of these, Falvey & Mutter (1981), was largely based on seismic data, recorded in the late 1960s and 1970s, whose quality has now been greatly surpassed, particularly since the inception of deep seismic techniques. Other papers of similar vintage (e.g. Willcox 1981, BMR 1988, Symonds & Willcox 1989, Falvey et al. 1990) generally relied on those same data sets.

The architecture of the Australian continental margin provides valuable insight into the structure and evolution of continental margins globally, in that:

- the margin is largely a passive type, except in the north, where a Tertiary–Recent active margin is being created by collision of the Australian and Eurasian Plates in the Timor region and is reactivating and overprinting the older passive margin structures;
- the spreading history of the adjacent ocean basins is generally well understood;
- the margin contains a wide variety of morphology (from simple narrow margins, as off New South Wales, to broad margins containing marginal plateaus) and geological structures; and
- the margins have generally been starved of sediment since continental breakup, thus allowing the rift architecture to be resolved by seismic techniques.

In 1983, the Australian Government, through the Bureau of Mineral Resources (now the Australian Geological Survey, AGSO) began the Continental Margins Program (CMP), aimed at unravelling the history of the Australian continental margin, primarily to encourage and help industry explore for hydrocarbons . A by-product of this program, after 13 years of operation, is that many parts of the margin now have high-quality seismic reflection data available, extending from the continental shelf out to the adjacent ocean basins, which permit a much-improved understanding of the geology compared to what was previously available. However, the exploration orientation of the CMP means that there are still substantial parts of the margin which, because of their perceived low prospectivity, are still inadequately covered by modern data.

This paper presents representative transects across the margin and reviews our current understanding of its architecture (Fig. 1 & Transects Plate). These transects are displayed with the same colour-coded stratigraphy as used in the 1996 AGSO Phanerozoic Timescale (Foster et al. 1996).

Seafloor spreading in the Australian region

The Australian continent is bordered on its western, southern and eastern margins by normal oceanic crust, which began to form at about 155–160 Ma. Seafloor spreading ceased at about 55 Ma, except in the south between Australia and Antarctica, where it continues today. Breakup is perceived as proceeding in an anti-clockwise manner, as an 'unzipping' of a series of rift structures in the Gondwanan supercontinent, commencing off northern and northwestern Australia in the Late Jurassic, and ending in the Coral Sea Basin off northeastern Australia in the Early Eocene. The history of seafloor spreading around the whole of the Australian margin has been discussed by Falvey & Mutter (1981), and in some detail by Veevers (1984), Veevers et al. (1991) and Veevers & Li (1991). Although the age of breakup and pattern of seafloor spreading is often thought to be well understood, several inconsistencies remain, particularly in the relationship of the oceanic crust as dated by the magnetic seafloor spreading anomalies and the age of the overlying sedimentary section as dated by correlations with exploration wells.

[1] Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601
[2] Now at National Taiwan Ocean University, Taipei, Taiwan

Northwestern and western margins

From north to south, the northwestern and western margins are flanked by oceanic crust underlying the Argo, Gascoyne, Cuvier and Perth Abyssal Plains. This oceanic regime is also characterised by several large oceanic plateaux—the Wallaby Plateau and adjacent Zenith Seamount, and the Naturaliste Plateau.

The pattern of breakup in the Argo Abyssal Plain is important to the understanding of the development of the northern Exmouth Plateau, and the Browse and Roebuck (formerly 'offshore Canning') Basins. Larson (1975) first identified the magnetic anomaly series that gave the original 160 Ma (late Oxfordian)— ~145 Ma on the time scale of Burger (1990) and ~155 Ma, using the Young & Claoue-Long (1991) breakup age—but recent drilling of the southeastern Argo Abyssal Plain (Site 765) during Leg 123 of the Ocean Drilling Program (ODP) penetrated much younger sediments overlying oceanic basement. A late Berriasian to earliest Valanginian age was initially suggested (Baumgartner & Marcoux 1989, Gradstein et al. 1990). However, a K/Ar age on a basaltic hyaloclastite directly overlying basaltic basement and underlying the oldest sediments gave 155.3±3.4 Ma (Ludden & Dionne 1992); i.e. mid-Callovian, using Burger (1990), or latest Oxfordian, using Young & Claoue-Long (1991). Thus, Site 765 drilled on magnetic anomaly M26 gives a minimum radiometrically derived breakup age of 155 Ma, which is in agreement with the magnetically determined late Oxfordian stage, using the Young & Claoue-Long (1991) timescale.

Most interpretations of the seafloor spreading anomalies indicate that spreading took place on a northwest or north-northwest azimuth, oblique to the later spreading in the Gascoyne, Cuvier and Perth Abyssal Plains. This has led to the interpretation of two separate spreading regimes, with the Argo Abyssal Plain being created with the detachment of a hypothetical micro-plate ('Argo Land') in the Jurassic. However, a recent interpretation of gravity data, combined with a reinterpretation of magnetic anomalies (Mihut & Müller, 1998; Müller et al., 1998, implies that the azimuth of Jurassic opening in the Argo Abyssal Plain was identical to that of the Cretaceous seafloor spreading to the south in the Gascoyne, Cuvier and Perth Abyssal Plains. This indicates that breakup in the Argo Abyssal Plain was the first stage of a southwards-propagating rift, which separated Greater India from Australia in a stepwise fashion, and obviates the need to invoke the existence of an 'Argo Land' fragment of crust that detached from the Australian continent.

Given that there has been Tertiary convergence between the northern Australian margin and the Indonesian Arc, and ongoing collision at least as young as Pliocene adjacent to Timor, it is probably reasonable to assume that the Argo Abyssal Plain spreading pattern and Neocomian/Tithonian breakup extended to the northeast, seaward of the Bonaparte Basin, and as far as the western Arafura Basin.

The Early Cretaceous (~136–125 Ma) breakup of Greater India and Australia and the evolution of the Gascoyne, Cuvier and Perth Abyssal Plains controlled much of the development of the southern and western margins of the Exmouth Plateau, and the Perth and Carnarvon Basins. The breakup history has been interpreted by Larson (1977), Markl (1978), Veevers (1984), Veevers et al. (1985), Fullerton et al. (1989), Veevers & Li (1991) and, most recently, Müller et al. (1998). Müller et al. interpret breakup in the Gascoyne and Cuvier Abyssal Plains to have occurred before chron M14, while breakup in the Perth Abyssal Plain occurred before chron M10.

The northwestern and western margins are also characterised by widespread synrift and post-rift magmatism. The post-rift magmatism is most obviously marked by the development of the Wallaby and Naturaliste Plateaux and the Zenith Seamount. The evolution of these features is discussed in some detail in Mihut & Müller (1998).

Southern Ocean

Spreading south of Australia is generally perceived to be the best documented in the region and the most easily recognisable in terms of the classical 'Atlantic' model of rifting, and continent–continent breakup and separation. However, Etheridge et al. (1990), Willcox & Stagg (1990) and Stagg et al. (1990) have indicated that it is both geometrically and temporally complex.

Initially, breakup was believed to have begun at about 53 Ma (Weissel & Hayes 1972). However, Cande & Mutter (1982) and Veevers (1986) revised the initial breakup to between about 83 and 95 Ma, but with a very slow early spreading rate lasting until about 44 Ma (late Middle Eocene). The initial breakup direction now appears to have been north-northwest–south-southeast, although, this rapidly changed to the more commonly recognised north–south spreading pattern as separation proceeded. In the east, the spreading system is truncated by a series of major north–south transform faults, which step the ridge southwards by about 1100 km and give rise to the transform-dominated margin off the eastern Otway Basin, western Tasmania, and western South Tasman Rise.

Willcox & Stagg (1990) and Stagg et al. (1990) have suggested that 'western margin' Early Cretaceous breakup is represented on the southern margin by a major Neocomian unconformity in many of the sub-basins of the Great Australian Bight Basin. South of the Eyre Terrace, this unconformity is seen to extend across an igneous basement high at the magnetically defined continent–ocean boundary (COB) (Veevers 1986) and, in places, across rotated fault blocks to the south of the COB. If these blocks are highly extended continental crust it implies that the COB and adjacent oceanic crust have been incorrectly defined and lie somewhere further south. If they are composed of pre-Neocomian oceanic crust (Stagg et al. 1990), perhaps faulted during a reduction in magma supply and consequent reversion to extensional deformation (Lister et al. 1991), then the age of breakup appears to be in error. Resolution of the age and location of breakup has an important bearing on the thermal evolution and hydrocarbon potential of the region.

Eastern Australian ocean basins

The Coral Sea and Tasman Basins are the youngest oceanic basins adjacent to the Australian continent, and their seafloor spreading histories are important for understanding the development of the deepwater Gippsland Basin, its conjugate Lord Howe Rise margin, and the basins of the northeast Australian margin. The basins are connected by the Cato Trough, which is generally interpreted to be floored by oceanic crust of unknown age.

In the central Tasman Basin, breakup on an east-northeast azimuth has been interpreted to commence at about 80 Ma (Hayes & Ringis 1973, Weissel & Hayes 1977, Shaw 1978, 1979), although Veevers (1984) suggested that it may have occurred as early as 95 Ma. The Tasman Sea was typically modelled as being generated by a simple two-plate spreading system. More recently, the opening of the Tasman Sea has been modelled by Gaina et al. (1998) who propose a northwards-propagating rift and the existence of 13 separate continental blocks that acted as micro-plates between 90 Ma and 64 Ma. These blocks, which include fragments of the Lord Howe Rise and Dampier Ridge, gradually separated from the Australian continent, either by extension or strike-slip movement.

The areally restricted Coral Sea Basin is bordered by several submarine plateaux and is floored by oceanic crust dated by Deep Sea Drilling Project Site 287 as Early Eocene (Andrews et al. 1975). Interpretation of magnetic spreading anomalies indicates spreading took place on a northeast to north-northeast azimuth from 62 Ma to 52 Ma. Gaina et al. (in press) interpret finite rotations for the Coral Sea Basin that are different to those for the contemporaneous Tasman Basin to the south, and propose

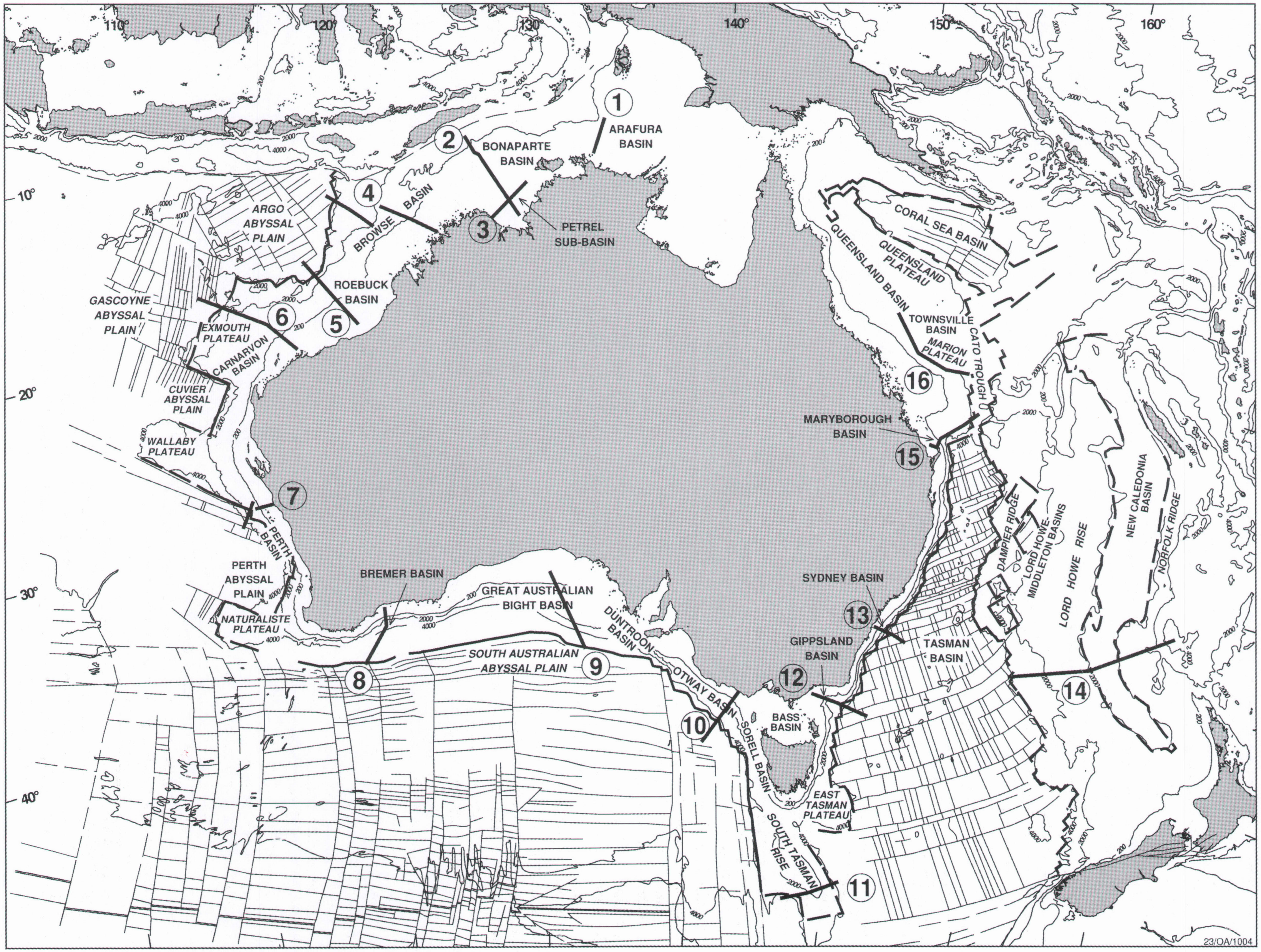
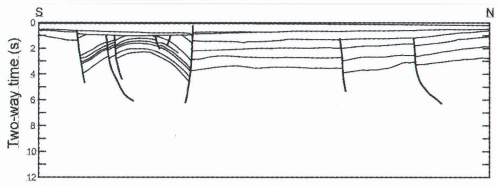


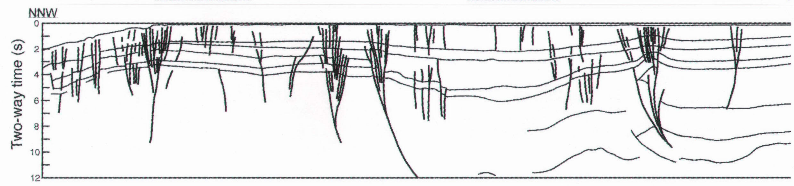
Figure 1. Generalised bathymetry and seafloor spreading anomalies of the Australian region, showing the locations of profiles contained in the Plate (indicated by circled numbers). Based on the AAPG Plate Tectonic Map of the Circum-Pacific Region, Southwest Quadrant.

TRANSECTS OF THE AUSTRAL

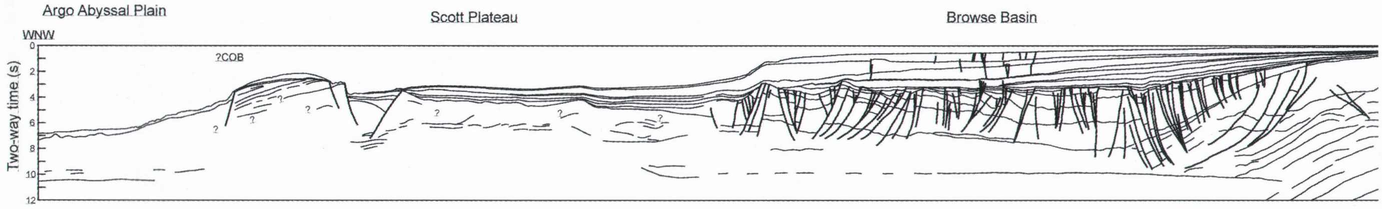
Petroleum and Marine Division, Australian



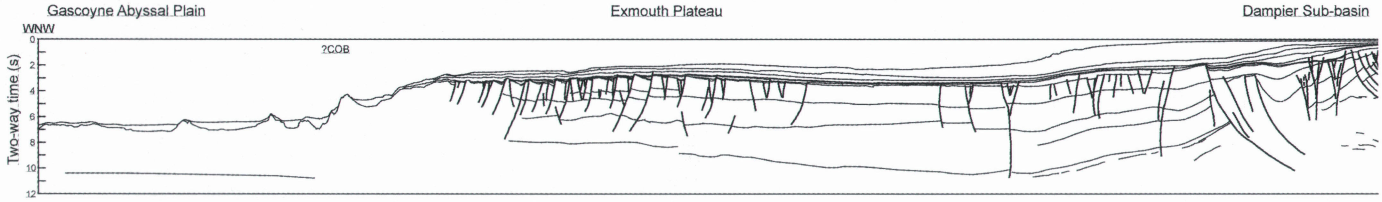
Profile 1: Arafura Basin, AGSO line 94-3



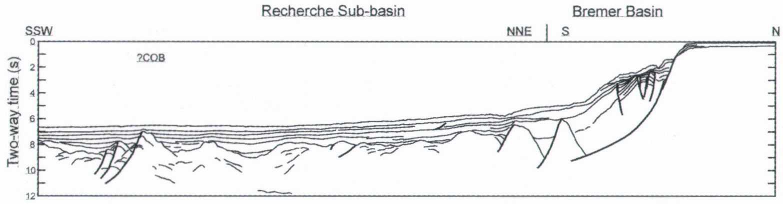
Profile 2: Bonaparte Basin, AGSO Lines 116-4 and



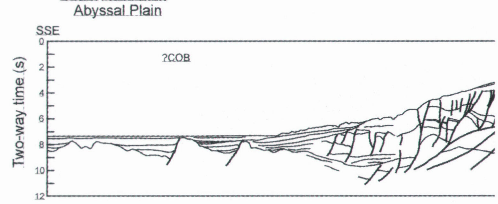
Profile 4: Argo Abyssal Plain - Scott Plateau - Browse Basin - Kimberley Basin, AGSO lines 119-4 and 128-1



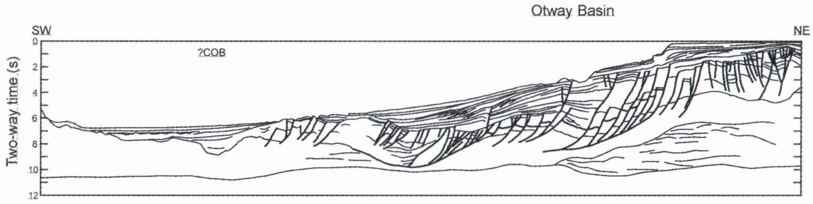
Profile 6: Gascoyne Abyssal Plain - Northern Carnarvon Basin, AGSO lines 101R-9 and 128-8



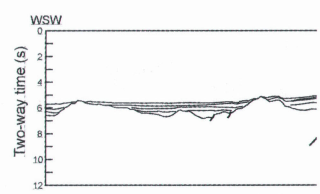
Profile 8: Recherche Sub-basin - Bremer Basin, ESSO line R74A-25 and Shell line N401



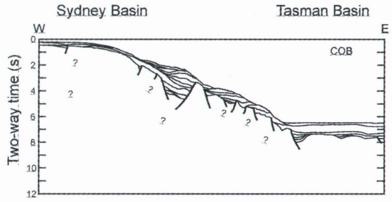
Profile 9: South Australian Abyssal



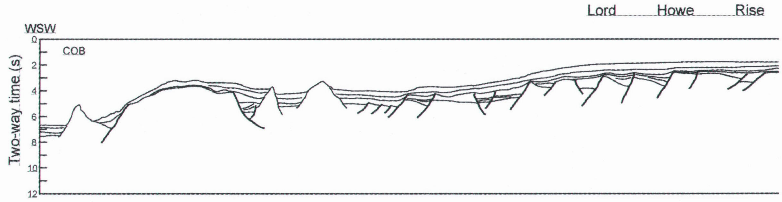
Profile 10: Otway Basin, AGSO line 137-9

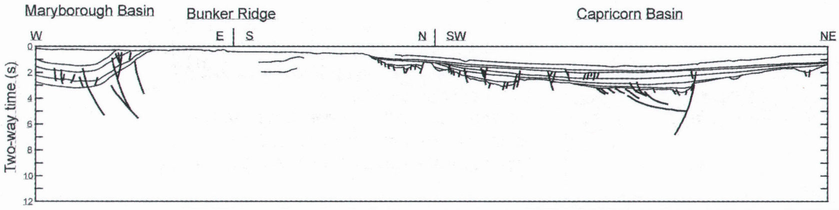


Profile 11: South

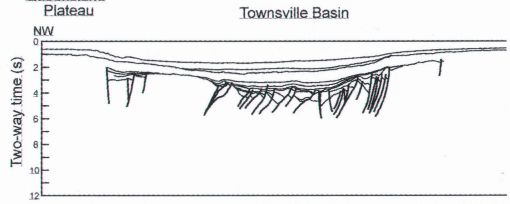


Profile 13: Sydney Basin - Tasman Basin, AGSO line 68-1





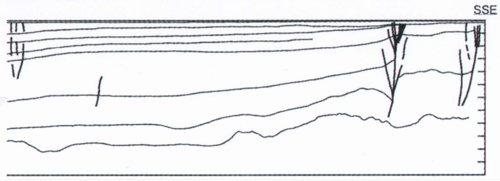
Profile 15: Maryborough Basin - Bunker Ridge - Capricorn Basin, AGSO lines 91-21, 15, 14, 26



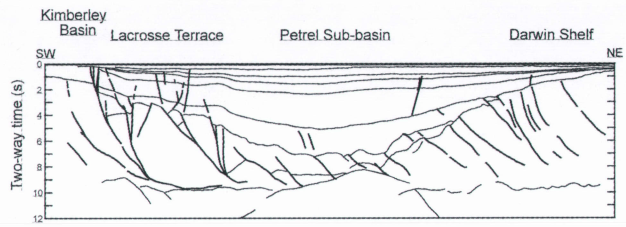
Profile 16: Queensland Plat

IAN CONTINENTAL MARGIN

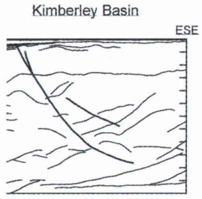
Geological Survey Organisation

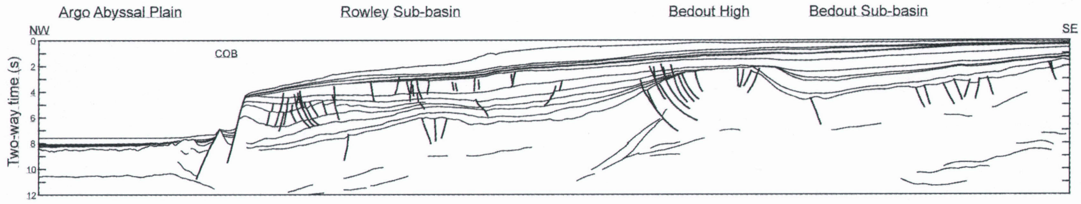


ı 100-5

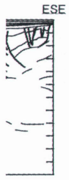


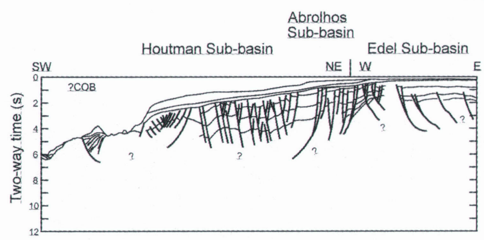
Profile 3: Petrel Sub-basin, AGSO line 100-2





Profile 5: Argo Abyssal Plain - Roebuck Basin, AGSO line 120-1



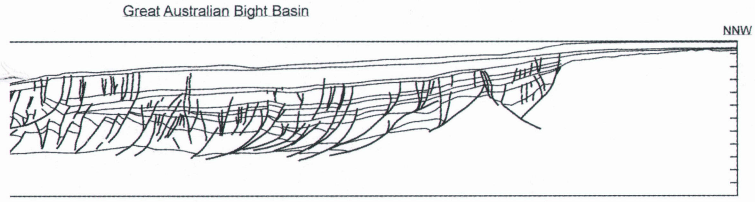


Profile 7: Perth Basin, AGSO line 57-9 and ESSO line A76-2

Compiled by: H. M. J. Stagg

Transect interpretation by: J. B. Colwell, H. M. J. Stagg, J. B. Willcox, P. A. Symonds, N. F. Exon, P. J. Hill, C-s. Lee, A. M. G. Moore, H.I.M. Struckmeyer & I. Borissova

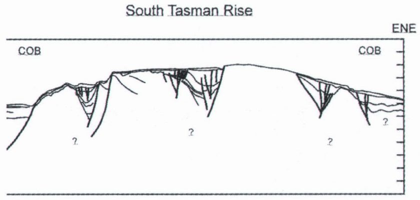
AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION



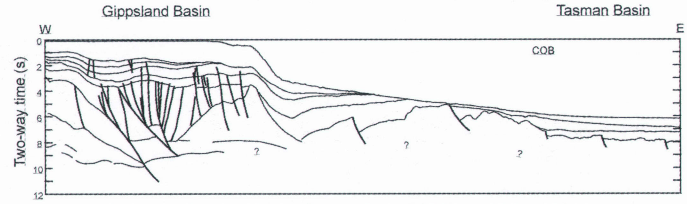
Plain - Great Australian Bight Basin, AGSO lines 199-8 and 119-11

- Cainozoic
- Cretaceous
- Jurassic
- Triassic
- ?Mid Carboniferous - Permian
- ? Carboniferous
- Late Devonian - Carboniferous
- Cambrian - Devonian
- Undifferentiated Palaeozoic
- Proterozoic
- Crystalline crust
- Oceanic crust
- Volcanics
- Mantle

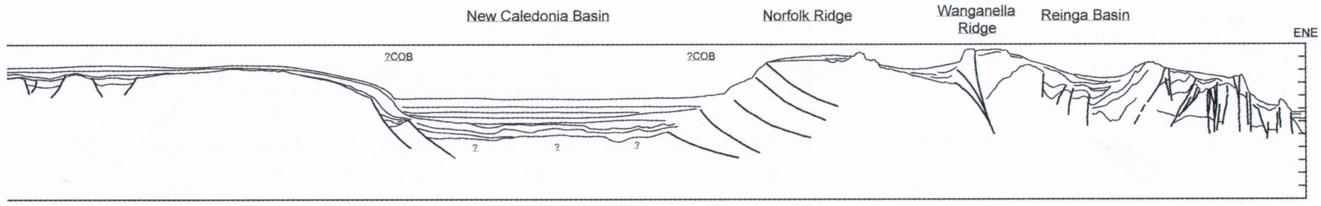
0 100 km



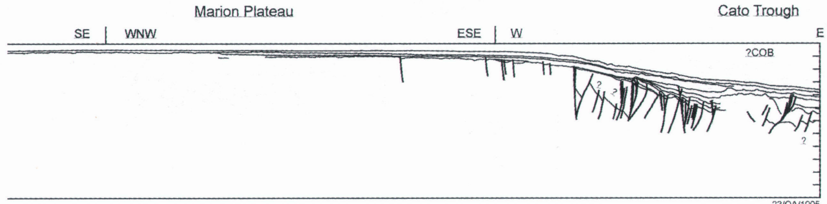
Tasman Rise, BGR line SO36-52



Profile 12: Gippsland Basin - Tasman Basin, AGSO lines 90-2 and 68-14



Profile 14: Lord Howe Rise, AGSO line 114-2



teau - Townsville Basin - Marion Plateau - Cato Trough, Shell line 73-1130

A large coloured version of this figure is included as a plate with this issue of the AGSO Journal. Further copies of the plate may be obtained from the Sales Centre, Australian Geological Survey Organisation, GPO Box 378, Canberra, A.C.T., 2601 http://www.agso.gov.au/information/bookshop.html that the differential motion was accommodated by the 'Louisiade triple junction'.

The Tasman Sea region has been interpreted both in terms of traditional rifting and breakup mechanisms (the asymmetric breaching model of Jongsma & Mutter 1978; for discussion see ***Southeast margin***) and, more recently, in terms of detachment concepts (Etheridge et al. 1990). In the latter interpretation, southeastern Australia is postulated as an underplated upper plate margin, with the Lord Howe Rise–Norfolk Ridge area comprising a complementary lower plate margin. This assumption implies that a detachment system underlies the whole region, and that the Lord Howe Rise and Norfolk Ridge are composed of variously extended upper continental crust, whereas small intervening basins such as the New Caledonia Basin, those separating Lord Howe Rise and the Dampier Ridge, and perhaps the Cato Trough, may be floored by highly thinned lower continental crust. This model tends to simplify the breakup history of the region by removing the need for small isolated areas of spreading and associated spreading ridge jumps.

Architecture and evolution

Northern margin

The northern margin of Australia beneath the Arafura Sea is little known and poorly understood. It extends from the Timor Sea to the Gulf of Carpentaria and contains the McArthur, Arafura and Money Shoal Basins of mainly Proterozoic, Palaeozoic, and Mesozoic age, respectively. These basins overlap to form a sedimentary pile that is at least 10 km thick. The structure of the Arafura Basin is illustrated by an AGSO profile extending from the southern margin of the basin, across the main depocentre of the Goulburn Graben, to the Australian-Indonesian border (Profile 1).

The shallow platform area of the Darwin Shelf and the mainly Mesozoic Money Shoal Basin north of it occupy the western Arafura Sea. The remainder of the Arafura Sea is underlain by the Arafura Basin, an intracratonic sag basin resembling the Williston or the Amadeus/Georgina Basins. The Mesoproterozoic McArthur Basin, which crops out onshore and contains known oil source rocks (Jackson et al. 1986), is interpreted to extend northward under the Arafura Basin; however, it is not penetrated by offshore drilling. The Arafura Basin dates from the Precambrian and subsequently evolved into a continental margin basin after Early Palaeozoic rifting on the northeastern rim of Gondwana. The Goulburn Graben, in the central Arafura Basin, is the only area where the sedimentary section has been penetrated, other than along the southern feather-edge of the basin, where Cambrian rocks outcrop in northern Arnhem Land and the Wessel Islands.

From the Middle Cambrian to the Permian, the Arafura Basin was a steadily subsiding sag basin in which a succession of marine and marginal marine clastics and carbonates was deposited. With the exception of the Goulburn Graben, the basin was subsequently subjected to only minor deformation. Profile 1 shows the flat-lying sag-style of the major part of the basin and the basin extending to the limit of Australian territory and beyond, into Indonesian waters.

While the Goulburn Graben was initiated in the Early Carboniferous (Bradshaw et al. 1990), the critical structuring event was a period of massive basin inversion in the Permo-Triassic (Etheridge & O'Brien 1994), during the time interval represented by the major angular unconformity between the lower Permian (Asselian) and Jurassic sections. The exact timing of the inversion is uncertain, owing both to the lack of well control in the key intervals and the location of the available wells on the crests of strongly eroded anticlines. It appears likely that the inversion took place during the Late Triassic (Etheridge & O'Brien 1994), coincident with the 'Fitzroy Movement' in the onshore Canning Basin to the south (Forman & Wales 1981, Horstman 1984). The Fitzroy Movement was probably driven by a major Gondwanan plate readjustment (Etheridge & O'Brien 1994).

The basin inversion resulted in the formation of a crustal-scale anticline, within the Goulburn Graben *per se*; with an attendant 4–4.5 km of uplift and erosion (Etheridge & O'Brien 1994, figure 5). The contemporaneous formation of negative flower structures in the Goulburn Graben and sinistral strike-slip movement along the graben bounding faults suggest that the event had a significant transpressional component in this area (Bradshaw et al. 1990, Lubatis et al. 1992). The erosion resulting from this inversional episode is evident on the flanks of the basin (Profile 1).

Along the northern North West Shelf, the sense of movement associated with the Fitzroy Movement is consistent with N to NNW-directed compression, perhaps with a total shortening of 2–5% (O'Brien et al 1993, Etheridge & O'Brien 1994, O'Brien et al. 1996).

Unconformably overlying the Arafura Basin are the Jurassic and Cretaceous clastics and Cainozoic carbonates of the Money Shoal Basin. On Profile 1, the easterly extremity of the Money Shoal Basin is represented by the slightly thicker Mesozoic section overlying the Goulburn Graben. The Money Shoal Basin is generally flat-lying and undeformed and thickens gradually to the west into the northern end of the Westralian Superbasin.

Northwest margin

Evolution of the Westralian Rift System. The northwest margin of the continent, generally referred to as the 'North West Shelf', extends for some 2500 km from the western end of the Arafura Sea to west of North West Cape and encompasses an area of some 800 000 km^2. The region is underlain by several major sedimentary basins, including, from north to south, the Bonaparte, Browse, Roebuck (or offshore Canning) and Northern Carnarvon Basins. Collectively, these basins comprise the northeast-trending Westralian Superbasin (Yeates et al. 1987), which was initiated in the Carboniferous and has since accumulated at least 15 km of sediment, principally in the Late Palaeozoic and Mesozoic. The Westralian Superbasin is underlain by several north- to northwest-trending intra-cratonic rift basins (the Petrel Sub-basin, Canning Basin, and Southern Carnarvon Basin), which accumulated most of their sedimentary fill during the Early Ordovician to Early Carboniferous. The northwest margin is subducting the Eurasian Plate in the north, while the central and southern North West Shelf abut the Jurassic Argo Abyssal Plain and the Cretaceous Gascoyne and Cuvier Abyssal Plains, respectively.

The evolution and architecture of the North West Shelf (previously described by AGSO's North West Shelf Study Group 1994, Elliott et al. 1996) is illustrated here with a set of deep-seismic dip profiles from the Bonaparte, Browse, Roebuck, and Northern Carnarvon Basins (Profiles 2, 4–6), and a dip profile from the Petrel Sub-basin (Profile 3) that characterises the pre-Westralian section on the margin, where it is well-developed. These profiles comprise the highest quality transect data available on the Australian margin, allowing a more confident and detailed interpretation than elsewhere.

As might be expected, these transects show that all the basins have been influenced by the same tectonic events, although the basin elements have responded differently to the various regional stress fields. While many events have margin-wide expression, only some are important in terms of primary basin formation.

In the Late Devonian to Early Carboniferous, extension on an approximately northeast azimuth between the Pilbara, Kimberley, and 'Darwin' blocks resulted in the formation of the intracratonic Fitzroy Trough in the Canning Basin, Petrel Sub-basin, and possibly the proto-Browse Basin (North West Shelf Study Group 1994). The Arafura Basin to the north may also have developed initially during this period.

In the Petrel Sub-basin, a series of limited (80–100 km wide) upper crustal rift segments of alternating polarity (O'Brien et al. 1993) developed over the highly structured, underpinning Proterozoic Kimberley Basin sequences, with the rift segmentation being closely controlled by this pre-existing basement grain (O'Brien et al. 1996). These upper crustal extensional segments were laterally offset by 50–100 km from the axis of maximum deep thinning of the lower crust/upper mantle (O'Brien et al. 1996). This partitioning of the upper crustal and lower crustal extension has produced a characteristic architecture in which perched upper crustal rift blocks are located principally along the flanks of the basin (effectively the large displacement margin), whereas the extremely thick (18–20 km) post-rift depocentre is located along the axis of the basin (O'Brien et al. 1996).

While some limited extension certainly took place in the upper crust (Profile 3, deep extensional fault blocks), deep thinning of the lower crust and mantle was the dominant lithospheric extensional process. Some workers (Lee & Gunn 1988) have even proposed that thinning of the lower crust may have led to injection of basaltic magmas along the basin axis, effectively incipient seafloor spreading.

This suite of Early–Middle Palaeozoic basins was bounded by regional strike-slip accommodation structures (AGSO North West Shelf Study Group 1994, figs 5–6), which, in the southeast, followed the Fitzmaurice and Halls Creek Mobile Zones (segments of the postulated Lasseter Shear Zone of Braun et al. 1991), which are known to have been reactivated at this time (Veevers & Roberts 1968). In the northwest, the basins were bounded by another complex accommodation feature, the North West Shelf Megashear (AGSO North West Shelf Study group 1994). The North West Shelf Megashear is considered to be of fundamental importance in the tectonic evolution of the North West Shelf, having had significant control in the formation of many large-scale structures which dominate the region.

In the mid-Carboniferous to Early Permian, a major episode of regional crustal thinning commenced, coinciding approximately with the North West Shelf Megashear, and giving rise to the Westralian Superbasin (Profiles 2, 4–6). A range of evidence indicates that this thinning occurred predominantly in the lower crust:

- There is a dearth of extensional faults in the Westralian Superbasin. For example, the entire Timor Sea province is characterised by a lack of upper crustal faulting, with thick (10–14 km) Permo-Triassic sag phase sediments being deposited. Minor upper crustal faulting has, however, been documented on the Yampi Shelf, on the inboard part of the Browse Basin (Profile 4), where the Rob Roy-1 well intersected an Early Permian syn-rift section. Similarly, while extensional faults have been recorded from the landward flank of the Northern Carnarvon Basin and the outer Exmouth Plateau (Profile 6), and the outer Browse Basin (Profile 4), the total extension on these faults is generally much less than 20% and the geometry of the Late Palaeozoic and Mesozoic section generally reflects deposition in a sag-style basin.
- In the Roebuck Basin (Profile 5), 10 km of Permian to Triassic sediments were deposited in a seawards-thickening wedge in the apparent total absence of extension in the upper crust (Colwell & Stagg 1994).
- Limited velocity information from the Northern Carnarvon Basin (Williamson et al. 1990, Stagg & Colwell 1994, fig. 12) and the Browse Basin (Symonds et al. 1994) indicate that much of the lower two-thirds of the crust has been removed.
- There is a Bouguer gravity high along much of the present-day continental shelf, despite the substantial thickness of Late Palaeozoic to Cainozoic sediment beneath most of it. Etheridge & O'Brien (1994) demonstrated that this gravity high is consistent with, and indeed requires, substantial crustal basement thinning beneath the shelf.

The observations outlined above demonstrate that the bulk of the Late Permian to Triassic sequence was deposited on moderately to highly extended continental crust along most of the north-western Australian margin, and that there has been relatively little crustal-scale extension since that time (O'Brien et al. 1993, Etheridge & O'Brien 1994). The combination of biostratigraphic, fission track and seismic evidence suggests that breakup of at least parts of the western Australian margin took place in the Late Carboniferous or Early Permian, when the 'Sibumasu Block' drifted away to the northwest (North West Shelf Study Group 1994). The majority of the Permo-Triassic section thus constitutes a sag phase deposited following breakup of the Late Palaeozoic Westralian rift.

While it is likely that lower crustal extension was the primary basin-forming driving force over much of the northern Australian margin during the extension, the role and extension history of the upper crust are more uncertain. It is difficult to envisage two- or three-fold thinning of the lower crust not being accompanied by commensurate extension of the upper crust. Several possible explanations are that:

- a large part of the upper crust was removed as large blocks above a major regional detachment;
- highly extended blocks beneath 10+ km of sedimentary section cannot be imaged by the seismic technique; or
- lithospheric extension was localised below the brittle–ductile transition, which effectively has acted to partition/decouple the upper and lower crusts and widely offset the zones of brittle and ductile deformation.

There is little systematic evidence on either the geometry of the Permo-Carboniferous extensional fault system or the precise direction of extension (O'Brien et al. 1992, 1993, Etheridge & O'Brien 1994). Limited evidence cited by Etheridge & O'Brien (1994) includes:

- Malcolm et al.'s (1991) study of the Exmouth region of the Northern Carnarvon Basin, which describes NE-trending, extensional half-graben of Late Carboniferous age;
- along the Candace Terrace in the Carnarvon Basin, Bentley (1988) described an extensional, basin-margin fault (the Sholl Island Fault) beyond which pyroclastic sediments of the Late Carboniferous Lyons Group were deposited;
- a detailed study of fault geometry and syn-rift horizon dip direction along the North West Shelf (Scott 1994) concluded that the Permian extension was approximately northwest-southeast.

Other indirect evidence includes the NE-trending, Early Permian extensional graben which was tested by the Rob Roy-1 well on the Yampi Shelf, inboard from the Browse Basin (O'Brien unpublished data).

This evidence, in total, suggests that the Early Permian Westralian extension took place on a northwest azimuth (AGSO North West Shelf Study Group 1994, Etheridge & O'Brien 1994), largely orthogonal to the overall structural grain (i.e. the normal fault orientation) of the basins. Examination of the major tectonic regimes of the North West Shelf has, however, suggested that the rift structures, thinning and subsidence patterns, and resulting basin distribution, may be offset and segmented by second-order features with a north to north-northwest trend (AGSO North West Shelf Study Group 1994). These features were probably largely inherited from old Precambrian to Proterozoic north-northwest–north-northeast trends (O'Brien 1993, O'Brien et al. 1993, Etheridge & O'Brien 1994), as seen in the adjacent Pilbara and Kimberley blocks (O'Brien et al. 1996). They may represent basement fractures or 'hard links' which pre-dated the mid-Carboniferous–Early Permian extensional processes, having acted to strongly segment the developing rifts by creating foci for fault relaying and polarity flips, as has been described in the Timor Sea by O'Brien et al. (1996).

Reactivation history. In the Late Permian or earliest Triassic, a major episode of uplift, faulting, and volcanism (the Bedout Movement) affected most of the North West Shelf, from the Carnarvon to the Browse Basin. This movement is particularly well-developed on the Bedout High in the Roebuck Basin (Profile 5) and on the landward flank of the Browse Basin (Profile 4). At present, there is no widely accepted explanation for this event on the North West Shelf, although it is documented in the basins of eastern Australia (Elliott 1993), and appears to be of plate-wide significance.

During the Triassic, sag-phase sedimentation continued right across the margin, although the greatest thickness was deposited in the south (Profile 6). Some minor extension on the flanks of the Northern Carnarvon Basin (Profile 6) and in the outer Browse Basin (Profile 4) may have occurred at this time, though the driving mechanism for this is unknown.

The key structural event to shape the architecture of the Western Australian margin was the Late Triassic Fitzroy Movement (Etheridge & O'Brien 1994). The event produced major structuring, which is pronounced in all the basins of the North West Shelf. Its effects are most obvious in the Arafura Basin, where a combination of crustal shortening and uplift induced significant (4–5 km) erosion (Profile 1). In the Petrel Sub-basin, the Fitzroy Movement resulted in the formation of numerous anticlines and monoclines over the upper crustal extensional blocks, with the flanks of the basin experiencing 1000–1500 m of uplift (O'Brien et al. 1993). In this and other areas regional uplift associated with the compressional stress was a factor in driving the sedimentary facies from fluvio-deltaics to continental red beds (O'Brien 1993, O'Brien et al. 1996). Its effects in the Northern Carnarvon Basin (where it was originally ascribed to 'rift onset') were also significant, and probably critical in the formation of petroleum traps. Etheridge & O'Brien (1994) proposed that the Lewis Trough, the key source-rock depocentre in the region, was actually a crustal-scale transpressional syncline which formed (over 'necked' or highly thinned crust) as a result of crustal shortening associated with the Fitzroy Movement. While this interpretation is still considered to be controversial, there is little evidence in the regional deep crustal seismic data to support an extensional origin for the Lewis Trough (axial Dampier Sub-basin, Profile 6).

The Late Triassic inversion was particularly important for the subsequent accumulation of hydrocarbons. Under inversion, rapidly subsiding downwarps developed over areas that had been highly thinned during the Westralian extensional event. These crustal-scale synclines became preferential depocentres for the organic-rich Jurassic source rocks that charged the majority of the oil accumulations on the North West Shelf. Examples of these crustal-scale downwarps include the Malita Graben (Profile 2), the central Browse Basin (Profile 4) and inboard part of the Northern Carnarvon Basin (Profile 6), and the development of Triassic–Jurassic structural traps in all basins except the Roebuck Basin.

Distribution of Early and Middle Jurassic sediments is far more variable than in the older section. On the outer platform areas (e.g. the Sahul Platform—Profile 3, outer Browse Basin—Profile 4, and Exmouth Plateau—Profile 6), the section ranges from thin to absent, whereas the inboard troughs (particularly in the Northern Carnarvon Basin) accumulated major thicknesses of sediment. During this time, the Roebuck Basin was a major anomaly on the North West Shelf, in that it continued to accumulate sediments in a simple sag-phase setting (Profile 5).

Continental breakup along the margin of the Argo Abyssal Plain at 155 Ma (Oxfordian) produced a major change on the central and northern North West Shelf. The Triassic–Jurassic section of the outer flank of the Roebuck Basin was uplifted and several hundred metres of section were removed by erosion (Profile 5). From the northern Browse Basin to the northernmost Carnarvon Basin, the Middle Jurassic section is terminated by a widespread erosional unconformity. However, the major consequence of the Argo breakup was the massive outpouring of basalt at the continent–ocean boundary (COB) that covers much of the Scott Plateau (Profile 4) and extends into the Browse Basin (Symonds et al. 1996). In contrast, the COB adjacent to the Roebuck Basin (Profile 5) is extremely abrupt and there is little evidence of volcanism, either from sampling or in the seismic data. A further product of Argo breakup are the isolated high-standing blocks that characterise both the Exmouth and Scott Plateau margins of the Argo Abyssal Plain (e.g. Profile 4, outboard end of profile). These blocks contain a thick, well-stratified section beneath a strong, sub-horizontal erosional unconformity with a thin veneer of overlying sediments. The largest of the blocks, the Wombat Plateau, on the northern margin of the Exmouth Plateau, is known to comprise Triassic sediments beneath the unconformity; however, seismic character and dredge hauls suggest that other blocks may have a large proportion of volcanics. At present, the origin of these high-standing blocks is unknown.

Since the Argo breakup, sedimentation in the Bonaparte, Browse, and Roebuck Basins has taken place in a thermal sag regime, with environments becoming more marine with time. Contemporaneously, in the Northern Carnarvon Basin, sedimentation was initially largely restricted to the inshore depocentres in the Late Jurassic. In the Early Cretaceous, a major delta (the Barrow Group delta) prograded northward across the Exmouth Plateau; Profile 6 is situated beyond the northern limit of this delta, and the Neocomian section here is thin or absent.

The final margin-breakup episode occurred in the Valanginian (131.5 Ma), with Greater India separating from Australia and creating the Gascoyne and Cuvier Abyssal Plains. As with the Jurassic breakup, this event was accompanied by widespread volcanism (Symonds et al. 1996), particularly along the northwest margin of the Exmouth Plateau (Profile 6), where the COB is overprinted with volcanics in a range of forms, including edifices, seaward-dipping wedges, and extensive lava flows.

After Valanginian breakup, sedimentation along the North West Shelf was generally slow through the remainder of the Cretaceous. In the Late Cretaceous, open marine carbonates became the dominant sediment type and, from the Palaeogene, these have produced prograding shelf-edge wedges, particularly in the northern basins.

The final event affecting the architecture of the North West Shelf was the collision of the northern margin of the Australian Plate with the Eurasian Plate, commencing in the Oligocene. This event produced extensive transtensional reactivation and, ultimately, breach of many charged hydrocarbon traps from about 5 Ma (Mio-Pliocene), contemporaneously with the development of the Timor Trough. Mio-Pliocene faulting is more strongly expressed in the Timor Sea and Browse Basins than it is in the Roebuck and Northern Carnarvon Basins.

Western margin

The western margin of the Australian continent is mainly underlain by the Perth Basin, a N–S-trending linear trough that extends for about 1000 km beneath the coastal region and continental margin. The eastern margin of the basin is bounded by the Darling Fault, which separates the basin from the Archaean Yilgarn Block. The Darling Fault is considered to have been down-thrown to the west by as much as 15 km since the early Palaeozoic. The basin is bounded offshore by the Neocomian oceanic crust of the Perth Abyssal Plain to the west, by the Naturaliste Plateau to the south, and by the North West Shelf and Wallaby Plateau to the north. Offshore, it includes the interfingering Edel, Abrolhos, and Houtman Sub-basins in the north, and the Vlamming Sub-basin in the south, while the onshore expression includes the Dandaragan and Bunbury Troughs (Marshall et al. 1989).

While the basin shows considerable structural variety, a composite profile in the northern half of the basin, comprising data from a 1976 Esso Australia survey and AGSO Survey 57 (Marshall et al. 1989), is considered to provide a typical cross-section of the basin (Profile 7). This line extends west across the continental shelf, then southwest to the edge of the Perth

Abyssal Plain, traversing the western flank of the Edel Sub-basin and the Houtman Sub-basin and an intervening unnamed structural ridge.

The Perth Basin is interpreted to have formed in a highly oblique extensional setting; i.e. it is a largely strike-slip to transtensional basin. This obliquity between Mesozoic extension and the pre-existing structural grain, together with a polyphase rifting history, has produced extremely complex structuring, which is evident in Profile 7. The structural complexity is poorly resolved, owing to high-velocity limestones in the near-surface layers.

Rifting and extension of the inboard Edel Sub-basin commenced in the Early Permian. The rift sequence is cut by a series of eastward-dipping extensional faults with décollement on the faults being relatively shallow and at a variety of levels. The faults on the western flank of the sub-basin (Profile 7, right end) show only minor displacement relative to the faulting further east (beyond the end of the profile), suggesting that this margin of the sub-basin was formed by strike-slip movement. Subsequent to the rifting, an aggradational phase is considered to have produced sequences of late Permian to Middle Triassic marine, fluvial and alluvial sediments. Total sediment accumulation in the Edel Sub-basin was some 6000 m, which is considerably less than in the adjacent sub-basins. Together with the 'perched' setting of the Edel Sub-basin, this is attributed to a relative lack of deep crustal thinning.

In the Late Permian, a second rifting phase initiated the Abrolhos Sub-basin, with the locus of rifting being relocated to the west, closer to the suture with Greater India. In the composite Profile 7, the Abrolhos Sub-basin can be seen beneath the eastern margin of the Houtman Sub-basin. This rifting produced a series of rotated fault blocks that subside increasingly to the west. The relatively thin basal syn-rift sequence within the sub-basin was succeeded by a prolonged rift phase, which produced a thick sequence of Early Triassic to Early Cretaceous alluvial, fluvial, and marine deposits.

In the third and final phase, rifting again stepped out to the west. This took place in the Late Jurassic and Early Cretaceous, immediately before continental separation in the Neocomian, and is clearly evident in the Houtman Sub-basin (Profile 7, central portion). The eastern boundary of the sub-basin, juxtaposed with the Abrolhos Sub-basin, consists of a major fault zone, 10–15 km wide, that has been interpreted as forming by strike-slip motion (Marshall & Lee 1988). The western boundary is formed by a basement high underlying the lower continental slope. Within the sub-basin, faulting of the thick Jurassic section is generally high angle and there is strong evidence for wrench motion (Profile 7, western flank of sub-basin). Rifting of the Perth Basin culminated in the Neocomian with a pulse of thermally induced uplift that produced a major erosional unconformity separating the rift and post-rift sections. This unconformity is of regional extent, being prominent in the southern part of the Northern Carnarvon Basin and also interpreted in the Bremer Basin on the southern margin (Profile 8).

After breakup, decay of the thermal anomaly underlying the margin produced differential subsidence and a thin seawards-thickening wedge of predominantly marine sediments beneath the outer shelf. These sediments are largely absent from the steeper parts of the transform margin continental slope, and the region has generally been sediment starved during the Late Cretaceous and Cainozoic.

Southern margin

The basins of the southern margin are largely the product of a protracted episode of Mesozoic extension in eastern Gondwanaland, which led to development of the 'Southern Rift System' (SRS; Willcox & Stagg 1990, Willcox 1990) and ultimately to breakup of the supercontinent into the Australian and Antarctic Plates. The SRS, containing the Bremer, Great Australian Bight, Duntroon, Otway, and Sorell Basins, extends for more than 4000 km, from Broken Ridge in the far west, to the South Tasman Rise (STR) in the southeast, with a major splay passing through the Bass Strait region. Compared to northwest Australia, the southern margin is very underexplored, and the amount of high-quality seismic transect data is very limited. The structure and evolution of the SRS is illustrated here with profiles across the Bremer Basin and adjacent continental rise, Great Australian Bight Basin, Otway Basin, and South Tasman Rise (Profiles 8–11).

Along the southern margin, Proterozoic and early Palaeozoic intracratonic basins underlie parts of the continental shelf and possibly extend into deeper water areas. The best known of these are the Denman Basin and Polda Trough in the eastern Great Australian Bight (GAB; Stagg et al. 1990, 1992). In addition, Palaeozoic features have been interpreted beneath the Bremer Basin off Western Australia (Stagg & Willcox 1991), Cambrian sediments occur in the St Vincent and Pirie–Torrens Basins off South Australia, and Cambro-Ordovician sediments of the Kanmantoo Trough extend offshore from Kangaroo Island. Further east, the SRS cuts across the Tasman Orogen. Some of these older basins are themselves aligned along zones of weakness in the Archaean Yilgarn Block, and the Proterozoic Fraser–Albany and Gawler Blocks. In places, these ancient features have influenced the geometry of the SRS, by way of changes in rift-trend and in influencing the location of accommodation zones (Stagg et al. 1990).

The age of rifting onset on the southern margin is ill-defined, owing to a lack of exploration wells that have sampled the pre-rift and early syn-rift sequences. Valuable evidence comes from the Eyre Sub-basin in the western GAB, where the Jerboa-1 exploration well penetrated a basal section, above Precambrian basement, consisting of Berriasian to earliest Valanginian fluvial/lacustrine sediments, in a syn-rift setting (Bein & Taylor 1981, Stagg et al. 1990, Blevin 1991). The age of the oldest syn-rift sediments in the adjacent grabens (Profiles 8 & 9) is unknown, but is surmised to be Late Jurassic or early Neocomian. Consequently, a Late Jurassic age is interpreted for the onset of rifting and extension in the SRS.

The extension history of the SRS is complex and poorly understood, with studies of different parts of the rift yielding contradictory evidence for the extensional transport direction (e.g. Willcox & Stagg 1990; Hill et al. 1995). The azimuth of the earliest phase of extension has been determined as NW–SE in the western GAB, based largely on the mapping of basement tilt-blocks within the Eyre Sub-basin (Willcox & Stagg 1990), and NNW–SSE along the western flank of the STR (Exon et al. 1995). If this stress regime operated throughout the SRS during rifting, then it might be predicted that the western SRS (as far east as the Ceduna Sub-basin) formed mainly under simple orthogonal extension, whereas the eastern SRS (Otway Basin to South Tasman Rise) was largely a left-lateral transtensional system. In an interpretation of deep-seismic data in the Gippsland Basin, Willcox et al. (1992) concluded that formation of the basin was compatible with this regional stress regime. In contrast, Hill et al. (1995), using a combination of techniques and data sets (dip analysis of the pre-rift section, balanced cross-sections, thermochronology, potential field data, deep-seismic data, and lithospheric modelling of basin subsidence), concluded that the NW–SE extensional phase was minor in the Otway Basin and that the basin was initiated in response to extension directed on a NNE–SSW azimuth, commencing at about 145 Ma, in the earliest Cretaceous. While a uniform lithospheric extension direction along the 4000 km length of the SRS is inappropriate (Hill et al. 1995), these major unresolved differences in the interpreted extension azimuth of the southern margin present a major impediment to a comprehensive understanding of the evolution of the SRS.

The degree of extension varies widely across the rift (Profile 8), from about 20% beneath the upper slope (Eyre Sub-basin and Bremer Basin) to 200–400% (Etheridge et al. 1990) beneath the broad continental rise in the western SRS. In this latter region, a thin lower crust lies directly beneath sag-phase sediments, while tilt-blocks of brittle upper crust have been almost entirely stripped-off along an interpreted detachment at the lower/upper crustal interface. That portion of the margin has been viewed by Etheridge et al. (1990) as a 'lower plate' margin, the conjugate 'upper plate' being preserved on the Antarctic margin. The 'perched' Eyre Sub-basin and the deeply subsided nature of the basement beneath the continental rise are either a direct consequence of the location of crustal detachments and consequent variations in crustal thinning or simply an offset between thinning in the upper and lower crust. The basins of the SRS, which apparently formed by upper crustal extension, are in marked contrast with the basins of the North West Shelf (Profiles 4–6) in which the thinning is confined largely to the lower crust, thereby producing major sag-style sedimentary basins.

The structural setting of the basins preserved on the Tasmanian margin and STR is less clear. Willcox & Stagg (1990) discussed the possibility of the STR lying adjacent to the Otway/Sorell Basins during the syn-rift phase in the Early Cretaceous, with rapid movement along the Tasmanian margin not occurring until commencement of the current episode of fast spreading in the Middle Eocene (A18, 42 Ma). The STR would thus have been an integral part of the Antarctic Plate at that time. This concept tends to be supported by similarity of the seismic sequences in the east Otway and STR Basins. More recently, Exon et al. (1996) proposed, from an analysis of seafloor spreading anomalies, that only the western portion of the STR has moved in this way, the eastern side remaining approximately in its present location, being essentially a part of the Tasmanian Palaeozoic block.

A marked change to sag-phase/post-breakup deposition appears to have taken place in the early Valanginian through much of the GAB. This is indicated by subsidence at a ?breakup-type unconformity that has been dated by a tentative tie to Jerboa-1. The unconformity is particularly pronounced in the Great Australian Bight and Duntroon Basins, where it has frequently acted as a décollement on which slippage of thick overlying shales has occurred. It also marks an important surface in the Bremer Basin that dates the formation of major faulted and eroded anticlines (Profile 8). The early Valanginian unconformity can be interpreted throughout the highly extended continental rise to a basement high that has been interpreted by Veevers (1986) as the continent–ocean boundary (COB), and which Stagg & Willcox (1992) postulated to be a core complex/serpentinite ridge. South of this ridge, interpreted Neocomian sediments overlie a zone of enigmatic crust, which is associated with magnetic lineations and has traditionally been regarded as seafloor of Cenomanian age (approximately A34, 95+ Ma; Cande & Mutter 1982, Veevers & Eittreim 1988). The section in this area is broken into rotated tilt-blocks, which could be due to rifting of old ?oceanic lithosphere (Profile 9). The structure and mode of emplacement of oceanic crust in such a highly extended rifted terrane, such as that south of Australia, are still poorly understood. Many of the features observed are common to rifted margins elsewhere in the world (for instance, the Scotia Basin of eastern Canada; Chian et al. 1995).

The relationship of the early Valanginian unconformity to the zone of enigmatic crust implies that Neocomian or older oceanic crust, or very highly extended continental crust, was formed beneath the western half of the SRS (southern ends of Profiles 8 & 9). Such a zone may have been an easterly projecting arm of the Perth Abyssal Plain (PAP), with its M-series seafloor spreading anomalies (Markl 1974). The latest Geosat images clearly define this province of 'Neocomian' oceanic crust with a fabric that indicates a NW–SE direction of spreading or extension, parallel to that in the PAP. The province narrows westwards between the Diamantina Zone and the continental margin and, apparently, merges into the highly volcanic terrane of the Broken Ridge/Naturaliste Plateau region. These observations suggest that, while Neocomian spreading was taking place in the GAB and PAP, volcanic outpourings were simultaneously taking place further west. Further segments of that 'Neocomian' seafloor also appear to lie to the east, off the Otway Basin margin and along the western margin of Tasmania. It would thus seem that a period of slow spreading, which was originally believed to have commenced in the Cenomanian (Cande & Mutter 1982), may have commenced much earlier, in the Neocomian or Late Jurassic, and was active along much of the southern margin.

Thermal subsidence of the margin eventually led to marine incursion in the Albian. However, this was short-lived, particularly in the central GAB region: in the Ceduna Sub-basin, where a major influx of terrigenous sediment in the Cenomanian led to regression and the outbuilding of a thick delta-complex in the Ceduna Sub-basin (Profile 9). Some marine influence occurs in the early Cenomanian in the Eyre Sub-basin and it seems probable that marine conditions would have prevailed nearer the axis of the rift.

In the Otway Basin/west Tasmanian region, transpressional reactivation along the plate boundaries led to the uplift of basin margin fault-blocks early in the mid-Cretaceous (Profile 10, outboard end). This was followed by the deposition of shoreline to restricted marine sequences of the Sherbrook Group (e.g. 1500 m of Belfast Mudstone), probably contemporaneously with deposition of the delta in the Ceduna Sub-basin. Similar sequences may also be present in the basins on the STR.

Towards the end of the Cretaceous, major tectonic movements took place on the outboard margin of the Australian Plate. In the Ceduna Sub-basin, the movement is dated as occurring after deposition of a Cenomanian–Maastrichtian delta, which was penetrated in Potoroo-1 on the basin's periphery. It is manifest as: uplift of an outer high by as much as 1500 m (Profile 9), followed by deep ?wavebase erosion; associated wrench faulting; possible overthrusting in a southerly direction at the outer margin high; and the buildup of structural mounds, which could be volcanic or possibly cool-water carbonates (Stagg et al. 1990). Widespread erosion of the outer Eyre Sub-basin and deep erosion of the wrench anticlines in the Bremer Basin (Profile 8) also appear to have occurred at this time. This tectonism was presumably the result of interaction between the Australian and Antarctic Plates, although the plates are generally assumed to have been well separated by this time, at least in the GAB. Continued plate interaction along the west Tasmanian margin might more reasonably be expected and has, indeed, been deduced from Late Cretaceous transpressional wrench-type structures in areas such as the Strahan Sub-basin of the Sorell Basin (Hinz et al. 1986). The presence of thinned continental or Neocomian oceanic lithosphere between the plates has apparently not impeded the transmission of the stresses created by interplate kinematics.

The Tertiary was a period of sediment starvation in the SRS, as seen in all the profiles except for the Otway Basin, where up to 2000 m of terrigenous shoreface–shallow marine sediment prograded southwestwards in the Palaeogene (Profile 10). The continued elevation of the margin is indicated by the presence of Middle Eocene shallow deltaic mudstones recovered from cores on the lower continental slope off Tasmania (N.Exon & E. Truswell pers. comm.) and Late Eocene to Oligocene shallow marine detrital sediments, penetrated at Deep Sea Drilling Project (DSDP) Site 281 (Kennett et al. 1975) on the STR. A major change occurred in the Late Oligocene, by which time continental crust of the Australian and Antarctic Plates was no longer in contact, circum-Antarctic circulation had developed, and the supply of terrigenous sediment was largely cut off. The Neogene was subsequently a period of temperate carbonate-dominated sedimentation.

The STR consists of a triangular core of Palaeozoic basement, flanked by basins containing up to 6 km of sediments. Although there is no direct evidence of their age, the seismic sequences in these basins are similar in character to those of the Otway Basin region and may once have been juxtaposed with it (Willcox et al. 1989). On the western half of the STR, many of the basins are V-shaped in section and separated by elevated 'slivers' of basement, and contain wrench faults, which extend upward through the section as far as the prominent mid-Oligocene unconformity (Profile 11). These structures suggest strike-slip reactivation in the basins until continental plate separation was complete.

Willcox deduced that 'although tectonic reconstructions show the STR in its present location ..... the available seismic data and extensional directions for the southern margin as a whole, suggest that the STR may have been part of the Antarctic Plate until the Eocene, and from then on became detached along its southern and western edges. .....(The STR may have moved) left-laterally during the ?Late Cretaceous, from a position conjugate to the Otway Basin.' (Willcox et al. 1989, p22).

An alternative, though less likely explanation for the origin of the STR basins, is that they are entirely the product of strike-slip plate interaction and were initiated only with the onset of fast seafloor spreading as late as the Middle Eocene. A similar mechanism was proposed as an origin for the west Tasmanian shelf basins, which Moore (in Moore et al. 1992) believed to become systematically younger from north to south. These, he proposed, were solely the result of continued plate contact along the Tasmanian transform margin.

Most recently, Exon et al. (1997) have postulated that the highly structured western block of the STR was the only part that lay between west Tasmania and Antarctica. Additional central and eastern blocks lay between southern Tasmania to the north, the East Tasman Plateau and the Lord Howe Rise to the east, and Antarctica to the south and west. In the Late Cretaceous, the northwest-orientated strike-slip faulting related to the early rifting of Australia and Antarctica, which may have started as early as the latest Jurassic, profoundly affected the west Tasmania margin (Hill et al. 1997), and the western block of the South Tasman Rise. The western block, still attached to Antarctica, moved about 450 km southeastward relative to Tasmania in this period. Faults also developed between Tasmania, the central and eastern blocks of the South Tasman Rise, and the East Tasman Plateau. In the latest Cretaceous, east–west extension and seafloor spreading between the South Tasman Rise and the East Tasman Plateau led to the formation of oceanic crust between them. However, the spreading between the South Tasman Rise and the East Tasman Plateau ceased at the end of the Cretaceous, when the Lord Howe Rise separated from the East Tasman Plateau.

Southeast margin

The southeast margin of the continent formed under the influence of rifting, breakup, and seafloor spreading that was directed NW–SE to N–S in the Southern Rift System and ENE–WSW in the Tasman Sea. The sedimentary basins that formed in this tectonic regime are geologically complex, particularly at the confluence of the two rift systems, in the vicinity of the Gippsland Basin. The architecture and evolution of the southeast margin is illustrated here by profiles from the Gippsland Basin, Sydney Basin, and Lord Howe Rise (Profiles 12–14).

The Gippsland Basin, which for 30 years was Australia's major oil-producing province, lies at the eastern end of Bass Strait (Profile 12). Sedimentation in the basin began in the Late Jurassic in a narrow rift related to incipient breakup along the southern margin, and continued through a Late Cretaceous period of rifting, associated with the opening of the Tasman Sea, and Tertiary post-breakup subsidence.

In general terms, the basin contains up to 8.5 s TWT (16 km) of sediments in an ESE-trending depocentre, bounded on its north and northwestern margins by a detachment ramp, and on its southern side by a relatively linear, listric fault system (Willcox et al. 1992, Colwell & Willcox 1993). The basin and the adjacent Bass and Otway Basins are thought to have formed part of a linked, largely strike-slip to transtensional system, which started to extend through Bass Strait, probably during the Late Jurassic as the rifting associated with southern margin breakup proceeded eastwards (Willcox et al. 1992). The deeper part of the basin probably continued to the east, on to what is now the Lord Howe Rise, but was split by the Late Cretaceous–Early Eocene opening of the Tasman Basin.

Traditionally, the sediments in the basin are divided into four major units: the non-marine, largely volcanogenic ?Late Jurassic–Early Cretaceous Strzelecki Group (generally regarded as economic basement), the Late Cretaceous Golden Beach Group, the Late Cretaceous–Eocene Latrobe Group (the main petroleum producer in the basin); and the overlying, marine, Oligocene and younger Seaspray Group. Only the Seaspray Group and the upper part of the Latrobe Group are well known from drilling in the basin.

The geometry of units and the relationship of the eastern part of the basin to the adjacent Tasman Basin are illustrated in Profile 12, which is a 'strike' section down the axis of the basin, extending in an ESE direction away from the Gippsland coast and reaching Tasman Basin oceanic crust at its far eastern end. The profile shows that the early (southern margin rifting) syn-rift sediments of the ?Late Jurassic–Early Cretaceous Strzelecki Group onlap a large, high-standing basement block under the outer shelf. Further east, below the continental slope and rise, the Strzelecki section appears to change seismic character, consistent with a large influx of volcanic flows. These flows onlap a broad basement ridge lying adjacent to the continent–ocean boundary.

Following initial rifting and basin fill, a major structuring and erosional event took place in the mid Cretaceous. This event is shown on the illustrated section by near-vertical faults and 'flower' structures extending to the top Strzelecki level, and by overthrusting of the Strzelecki Group and the underlying ramp surface towards the west. The event appears to correlate with the early stages of plate drifting in the central and eastern parts of the Great Australian Bight (Willcox & Stagg 1990) and with the onset of rifting in the southeastern part of the Bass Basin (Boobyalla Sub-basin), and, possibly, along the margins of the Tasman Basin.

The dating of magnetic anomalies in the Tasman Basin shows that seafloor spreading adjacent to the Gippsland Basin began at about Anomaly 33 time (Shaw 1978), i.e. during the Campanian, according to the latest AGSO Timescale. The Late Cretaceous section (Golden Beach and lower Latrobe Group) are essentially syn-rift deposits to the Tasman Basin rifting. Adjustments and reactivation from the mid Cretaceous of several postulated microplates in the Bass Strait region, largely in response to Tasman Basin rifting, may have given rise to the wrench-related and compressional structures that form the major petroleum traps (usually at top Latrobe level) in the Gippsland Basin.

In contrast to Australia's southern margin, (and the largely intracratonic Bass Strait basins in particular), much of the southeastern margin of Australia lacks major sediment accumulations above pre-rift basement. The margin is typically steep (up to 20° slope) and narrow (shelf generally less than 50 km wide).

The general form of the margin is shown in Profile 13, which extends in an ESE direction from the outer shelf offshore Wollongong to the floor of the Tasman Basin. The profile shows thin ?Cretaceous and younger sediments overlying basement (Sydney Basin Permo-Triassic sediments) on the shelf. A mid-slope graben is filled by a series of ?Cretaceous syn-rift deposits, which thicken into a major westerly (landward) dipping fault on the eastern side of the graben. Late Cretaceous and younger sediments, including slump deposits, blanket the graben and extend down the lower continental slope to the Tasman Basin (Colwell et al. 1993). Basement beneath the lower continental slope has been shown by dredging to consist of sedimentary and igneous rocks similar to those of the Palaeozoic Lachlan Fold Belt. The Tasman Basin fill probably ranges in age from Late Cretaceous to Recent.

The southeast Australian margin differs markedly from its Tasman Basin conjugate; that is, the western side of Lord Howe Rise and adjacent Dampier Ridge (DR on Fig. 1) (compare Profiles 13 & 14). Major rift basin development occurs thoughout the Lord Howe Rise /Norfolk Ridge (NR) region, but the syn-rift section has not been penetrated by drilling. However, dredging has sampled Campanian–Maastrichtian oil-bearing shale from the southeastern Norfolk Ridge (Herzer & Mascle 1996) and Cenomanian–Turonian coal measures from the West Norfolk Ridge (Zhu & Symonds 1995). The Tasman rift system appears to be best preserved beneath western Lord Howe Rise, where it consists of a zone, 200 km wide, of northwest-trending horst and graben structures, in water depths of 1000–2000 m (Willcox et al. 1980; Profile 14). Elsewhere, particularly beneath the eastern third of the Lord Howe Rise, relatively thin sediments overlie basement, which is commonly planated. On the western side of Lord Howe Rise, individual grabens within the rift zone are up to 50 km wide and several tens of kilometres long, and are best developed north of Lord Howe Island, where sediment fill is up to 4.5 km in places (Roeser & shipboard party 1985).

The structural differences between the southeast Australia and Lord Howe Rise margins can be accounted for either by an asymmetric rifting model, in which the main rift structures were preserved on the Lord Howe Rise flank of the rift (Jongsma & Mutter 1978) during the oblique Tasman Basin opening, or by a detachment model (Lister et al. 1986). In the detachment model, the southeast Australia margin is interpreted to be an 'upper plate', characterised largely by an absence of major rift structures and by uplift resulting in passive-margin mountains (Australia's Eastern Highlands). These are related to thermal buoyancy, caused by rise of the asthenosphere, as well as igneous underplating of mantle-derived melts (Etheridge et al. 1987, Lister & Etheridge 1989, Lister et al. 1991). The Lord Howe Rise forms a 'lower-plate' margin characterised by extensive rift development on its western flank.

Northeast margin

The continental margin off northeastern Australia extends over a distance of about 2000 km between Fraser Island in the south and the Gulf of Papua in the north, and covers more than of 900 000 km^2. The margin is underlain by modified continental crust formed as a result of Mesozoic fragmentation of a northeastern extension of the Tasman Fold Belt (Taylor & Falvey 1977, Mutter & Karner 1980, Symonds et al. 1984, Struckmeyer et. al. 1994). This fragmentation produced the present configuration of large marginal plateaus, such as the Queensland and Marion Plateaus, separated and straddled by late Mesozoic to Tertiary rift basins (e.g. Townsville, Queensland and Capricorn Basins) and, further landward, late Palaeozoic to early Mesozoic intracratonic downwarps (Laura, Styx and Maryborough Basins). The margin is bounded by oceanic crust of the Tasman Basin and Cato Trough to the south and southeast, respectively, and the Coral Sea Basin to the north and northeast.

The evolution and architecture of the northeast Australian margin are illustrated here with profiles from the Maryborough and Capricorn Basins (Profile 15) and the Cato Trough, Marion Plateau, Townsville Basin and Queensland Plateau (Profile 16).

During most of the Palaeozoic to early Mesozoic, the tectonic setting of the northeast margin of Australia was that of a convergent margin with periods of oblique subduction represented by northwest-trending deformation beds (e.g. Harrington & Korsch 1985, Murray et al. 1987). Basement underlying the present-day offshore northeastern margin is thus likely to comprise an amalgamation of Palaeozoic intrusions and lithified sediments. The Maryborough Basin developed in the earliest Triassic to Middle Jurassic as an epicratonic downwarp in a foreland setting (Hill 1994). Sediments associated with this depositional phase typically consist of basal fluviatile quartzose sandstones grading into finer sediments with thin coal seams near the top of the succession.

In the Jurassic to Early Cretaceous, the overall tectonic setting of the margin was still convergent, with the continent–ocean boundary lying east of the Lord Howe Rise (e.g. Veevers et al. 1991, Struckmeyer et al. 1991), which was later detached from the Australian continent in the Late Cretaceous to Paleocene through the opening of the Tasman Sea/Cato Trough by seafloor spreading. The northern Australian margin in New Guinea is thought to have been a passive margin during the Mesozoic with a major extensional episode occurring in the Late Triassic to Early Jurassic (Pigram & Davies 1987, Home et al. 1990, Struckmeyer et al. 1990, 1993). It is possible that these two opposing margin settings—i.e. convergent in the east and passive in the north—were connected via a strike-slip fault system along the northeastern margin of Australia (Symonds et al. 1984), which included possible subsidiary fault systems along the site of the present Queensland–Townsville–Capricorn Basin system.

It is not clear whether extension occurred simultaneously in all the basin elements; however, evidence from both the Townsville and Maryborough Basins (Struckmeyer et al. 1994, Hill 1994) shows that two distinct tectonic events occurred in the ?Late Jurassic to Early Cretaceous and the mid to Late Cretaceous. The Townsville Basin is likely to have formed in the ?Late Jurassic to Early Cretaceous by NW–SE-directed oblique extension, resulting in low to high-angle normal faulting and block rotation (Profile 16). Major NW/NNW-trending transverse structures, which segment the Townsville Basin into distinct structural elements, align with lineaments of the onshore Tasman Orogen, indicating that extension in the basin was accommodated by pre-existing, Palaeozoic structures. The transtensional tectonism was accompanied by volcanism and differential uplift. Neocomian volcanism and rifting in the Maryborough Basin was very likely linked to this tectonism and led to a second phase of deposition in the basin (Profile 16), producing up to 5 km of clastic shallow marine and deltaic sequences. In the Townsville Basin, up to 4 km of coarse to fine-grained clastics, derived from adjacent and intrabasin basement highs, and volcanics was deposited in a variety of environments, ranging from alluvial fans to fluvial and, possibly, lacustrine environments in the deeper parts of the basin. The Queensland Basin may also have been initiated during this time. Similar to the Townsville Basin, its formation was independent of the tectonism related to seafloor spreading in the Tasman and Coral Sea Basins (Scott 1993, Struckmeyer et al. 1994).

In the Maryborough Basin, inversion in the mid-Cretaceous resulted in folding along NW/NNW axes, normal and reverse faulting, and removal of up to several kilometres of section, while a mid to Late Cretaceous, NE–SW-directed extensional event, which later culminated in breakup and opening of the Coral and Tasman Sea Basins, was superimposed on the older rift system further outboard, resulting in reactivation and overprinting of the primary basin-forming structures, and uplift and differential erosion in the Townsville Basin. It is likely that the major basin-forming event in the Capricorn Basin occurred at this time, resulting in the deposition of up to 5.7 km of rift sediments during the late Cretaceous to Palaeogene.

During the Paleocene–Eocene episode of seafloor spreading in the Coral Sea Basin, and possibly in the Cato Trough, movement on reactivated faults continued and ?subaerial volcanism occurred in the eastern Townsville Basin. In the Capricorn Basin, a mid-Eocene transpressional event reactivated basement structures and produced minor faulting and folding (Profile 16). In post-Middle Eocene time, slow regional subsidence during the post-breakup sag-phase of continental margin development resulted in shallow marine conditions with carbonate deposition on the marginal plateaux. Minor reactivation events occurred in the mid-Oligocene to Late Miocene/Early Pliocene, probably as a result of collisional tectonism along the northern Australian margin. In post- Early Oligocene times, as the water depth over the plateaux increased, pelagic ooze, turbidites and slump deposits, in part derived from the flourishing carbonate platforms, became the major components of sedimentation in the adjacent basins.

Discussion

The profiles displayed show significant variations in basin architecture around the Australian continental margin. While seismic quality and penetration have steadily increased through time (data displayed are of early 1970s to early 1990s vintage), this alone would not account for the obvious structural variation from region to region. Salient features of the architecture of each margin segment are discussed here.

Interpretation of the ***northern margin***, particularly the Arafura Basin, is hindered by the sparse, relatively low-quality data available. The basin comprises an unknown thickness of Proterozoic and Palaeozoic section, deposited in an intra-cratonic setting which was probably several hundred kilometres wide. Except in the Goulburn Graben, structural reactivation is generally mild. The spreading history of any formerly adjacent seafloor is unknown, other than far to the west in the Argo Abyssal Plain region of the North West Shelf. The age of the basin and the commensurate quality of the seismic data make it difficult to say anything about the basin-forming mechanisms, except that the Goulburn Graben appears to have developed within a strongly transtensional environment and was inverted during the Late Triassic 'Fitzroy Movement'.

The ***northwestern margin*** is the most clearly imaged segment of the continental margin, by virtue of the large quantity of modern, high-quality seismic data that are available. The margin is 400–500 km wide and has a polyphase rifting history that saw the progressive separation of Sibumasu (?Late Carboniferous–Early Permian), 'Argo Land' (Jurassic), and Greater India (Neocomian) from the Australian continent. These rifting episodes have also left a strong volcanic imprint on the region. Volcanics have been penetrated by drilling in the Roebuck and Browse Basins and are widely interpreted in seismic data as sills, dykes and lava flows. The more substantial volcanic build-ups are shown on the outer continental margin, and beneath the Scott Plateau and Bedout High.

The continental margin is underlain by the major sedimentary basins of the Westralian Superbasin, both on the continental shelf and beneath the adjacent slope; areas of shallow crystalline basement beneath the shelf are rare. The location of the present-day shelf-slope break is largely controlled by the seaward limit of prograding Cainozoic sediments—i.e. the morphology of the shelf and slope is largely controlled by sedimentation patterns, as opposed to structural origins. While most of the Australian continental margin has been starved of sediment during the Cainozoic, parts of the North West Shelf accumulated up to 3000 m of sediment during this period.

The Phanerozoic sedimentary section typically has a layer-cake form, and extension in the upper crust is minimal other than on the inboard flanks of the basins, where confined rifts formed in the Northern Carnarvon, Browse, and Bonaparte Basins. This leads to the conclusion that, in general, the driving mechanism for basin subsidence on the North West Shelf was related to major thinning events in the lower crust; in the lexicon of models of passive margin formation, it can probably be considered to be an 'upper plate' margin.

The ***western margin*** is characterised by structures that reflect its formation in a transtensional environment. In particular, this is reflected by wrench-style structures and the interfingering geometry of the main intrabasin elements. While there is only one recognised episode of continental fragmentation—the separation of Greater India in the Neocomian—multiple phases of rifting, dating back to the Permian, are recognised in the interpretation of well and seismic data. As with the North West Shelf, volcanism is prominent, particularly at the northern (Wallaby Plateau and Zenith Seamount) and southern (Naturaliste Plateau) extremities of the basin.

The ***southern margin*** is the longest single segment of the margin and, as a consequence of the minor exploration levels west of the Otway Basin, is probably the most poorly understood. The age of onset of rifting is inferred to be in the Jurassic; however, the azimuth of extension is open to conjecture, with interpretations ranging from NW–SE (Willcox & Stagg 1990) to NNE–SSW (e.g. Hill et al. 1995). The width of the preserved rift ranges from about 350 km in the normally extended crust in the west, to no more than 100 km on the strike-slip margin west of Tasmania.

There are a number of important structural differences between the southern margin and the other major Australian extensional passive margin, the North West Shelf; these contrasts can be summarised as follows:

- The southern margin is interpreted to have formed largely through extension of the upper crust. The rotation of crustal fault blocks increases oceanwards, such that, beneath the continental rise, the blocks have been rotated through as much as 90° and may, in places, have been entirely stripped off the lower crust. In the terminology of passive margin formation, the southern margin can be considered to be a 'lower plate' margin.
- On the southern margin, the head of the primary detachment fault that is interpreted as underlying the highly extended deepwater part of the margin is located at or close to the shelf break; i.e. the shelf break is largely structurally controlled, whereas on the North West Shelf, the shelf break is largely the expression of sedimentation geometry.
- Most of the continental shelf on the southern margin is underlain by shallow crystalline basement, whereas on the North West Shelf it is generally underlain by thick sedimentary basins.
- While volcanic rocks are present on the southern margin, particularly at the eastern and western ends of the rift, they generally appear to be more limited in extent and volume than on the North West Shelf.
- The major marginal plateau on the southern margin (the Ceduna Plateau) is fundamentally the product of massive localised sedimentation during the Late Cretaceous. In contrast, the marginal plateaux of the North West Shelf are largely structural remnants of the rifting process.
- There is a general absence of unbreached rifts on the southern margin, with their attendant restricted environments of deposition, which may account (together with a very low density of exploration) for the relative lack of exploration success, compared to the North West Shelf.

These major contrasts between the northwestern and southern margins suggest that they represent two end-members of a family of models describing passive margin formation. Whether these are end-members of asymmetric detachment models is open to conjecture. However, it appears obvious that further comparative studies of the margin, particularly at the crustal scale, have considerable potential to refine our understanding of passive margin development.

Understanding of the architecture and evolution of the ***eastern margin*** of the Australian continent, from the east coast of Tasmania to the Gulf of Papua, is generally poor in comparison to the northwestern and southern margins. This is partly due to the perceived low hydrocarbon prospectivity of much of the margin, other than the Gippsland Basin, and also political constraints on activity that could be construed as exploration-oriented in northeastern waters, in the general region off the Barrier Reef Marine Park. Both these factors have resulted in a general dearth of high-quality seismic data (particularly at the crustal scale) and the near-absence of drilling information, other than in the Gippsland Basin. However, offsetting these problems are the potential positive factors of having formerly conjugate margins in relative proximity (the southeast margin and

Lord Howe Rise), and the fact that the eastern margin is the youngest of Australia's passive margins and, therefore, potentially, the least affected by post-breakup reactivation.

Variations in the architecture of the eastern margin along its length are pronounced. In the Tasman Basin, the Australian margin is generally very narrow, and much of the pre-breakup rift section is only preserved beneath Lord Howe Rise. However, even beneath Lord Howe Rise, basin development is quite limited and it appears that margin breakup was not preceded by extensive basin development, such as occurred on the northwestern and southern margins. While the Gippsland Basin is an obvious exception to this observation, it should be noted that this basin is very restricted in area and probably formed, at least in part, as the result of development of the southern margin.

In contrast, the margins adjacent to the Coral Sea Basin are broad and have seen the development of the major marginal Queensland and Marion Plateaux. These plateaux are distinct from those on the North West Shelf (structurally controlled, with a thick sedimentary section) and the southern margin (largely controlled by sediment distribution) in that they are structurally controlled, but consist largely of shallow pre-rift basement. This segment of the margin does contain restricted rifts, as for example in the Townsville Basin and Queensland Trough, but these contain sedimentary sections that are relatively thin when compared to those encountered on the North West Shelf.

References

AGSO North West Shelf Study Group, 1994. Deep reflections on the North West Shelf: changing perceptions of basin formation. In: Purcell, P.G. & Purcell, R.R. (editors), The sedimentary basins of Western Australia. Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1994, 63–76.

Andrews, J.E. et al., 1975. Initial Reports of the Deep Sea Drilling Project, vol. 30, US Government Printing Office, Washington, D.C.

Baumgartner, P.O. & Marcoux, J.P., 1989. Mesozoic facies evolution of northwest Australian margin (ODP Legs 122–123): does it document Indo-Australian breakup or Neotethys history? American Association of Petroleum Geologists Bulletin, 73, 332.

Bein, J. & Taylor, M.L., 1981. The Eyre Sub-basin: recent exploration results. APEA Journal, 21, 91–98.

Bentley, J., 1988. The Candace Terrace—a geological perspective. In: Purcell, P.G. & Purcell, R.R. (editors), The North West Shelf Australia. Proceedings of Petroleum Exploration Society Australia Symposium, Perth, 1988, 157–171.

Blevin, J.E., 1991. Geological cross-sections of the Eyre, Denman, and Ceduna Basins. Bureau of Mineral Resources, Australia, Record 1991/13.

Bradshaw, J., Nicoll, R.S. & Bradshaw, M., 1990. The Cambrian to Permo-Triassic Arafura Basin, northern Australia. APEA Journal, 30(1), 107–127.

Braun, J., McQueen, H. & Etheridge, M.A., 1991. A fresh look at the Late Palaeozoic tectonic history of western-central Australia. Exploration Geophysics, 22, 49–54.

BMR, 1988. Australia's petroleum potential. In: Petroleum in Australia—the first century. Australian Petroleum Exploration Association Limited, Sydney, 48–90.

Burger, D., 1990. Australian Phanerozoic Timescales: 8. Jurassic Biostratigraphic Charts and Explanatory Notes. Bureau of Mineral Resources, Australia, Record 1989/38.

Cande, S.C. & Mutter, J.C., 1982. A revised identification of the oldest seafloor spreading anomalies between Australia and Antarctica. Earth and Planetary Science Letters, 58, 151–60.

Chian, D., Keen, C., Reid, I. & Louden, K.E., 1995. Evolution of nonvolcanic rifted margins: new results from the conjugate margins of the Labrador Sea. Geology, 23(7), 589–592.

Colwell, J.B. & Stagg, H.M.J., 1994. Structure of the offshore Canning Basin: first impressions from a new regional deep-seismic data set. In: Purcell, P.G. & Purcell, R.R. (editors), The sedimentary basins of Western Australia. Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1994, 757–767.

Colwell, J.B. & Willcox, J.B., 1993. Regional structure of the Gippsland Basin: interpretation and mapping of a deep seismic data set. Australian Geological Survey Organisation, Record 1993/13.

Colwell, J.B., Coffin, M.F. & Spencer, R.A., 1993. Structure of the southern New South Wales continental margin, southeastern Australia. BMR Journal of Australian Geology & Geophysics, 13, 333–343.

Elliott, L.G., 1993. Post-Carboniferous tectonic evolution of eastern Australia. APEA Journal, 33(1), 215–236.

Elliott, C.I., Liu, S., Willcox, J.B. & Petkovic, P., 1996. North West Shelf Project: a lineament tectonic study of the architecture of northwestern Australia. Australian Geological Survey Organisation, Record 1996/50, 35 pp., 35 plates.

Etheridge, M.A., Branson, J.C. & Stuart-Smith, P.G., 1987. The Bass, Gippsland and Otway Basins, southeast Australia: a breached rift system formed by continental extension. In: Beaumont, C. & Tankard, A.J. (editors), Sedimentary basins and basin-forming mechanisms. Canadian Society of Petroleum Geologists, Memoir 12, 147–162.

Etheridge, M.A. & O'Brien, G.W., 1994. Structural and tectonic evolution of the Western Australian margin basin system. PESA Journal, 22, 45–63.

Etheridge, M.A., Symonds, P.A. & Lister, G.S., 1990. Application of detachment models to reconstruction of conjugate passive margins. In: Tankard, A.J. & Balkwill, H.R. (editors), Extensional tectonics and stratigraphy of the North Atlantic margins. American Association of Petroleum Geologists, Memoir 46, 23–40.

Exon, N.F., Hill, P.J. & Royer, J-Y., 1995. New maps of crust off Tasmania expand research possibilities. Eos, American Geophysical Union Transactions, 76(20), 201, 206–207.

Exon, N.F., Royer, J-Y. & Hill, P.J., 1996. *Tasmante* cruise: swath-mapping and underway geophysics south and west of Tasmania. Marine Geophysical Researches, 18, 275–287.

Exon N.F., Moore A.M.G. & Hill P.J. 1997. Geological framework of the South Tasman Rise, south of Tasmania, and its sedimentary basins. Australian Journal of Earth Sciences, 44(5).

Falvey, D.A. & Mutter, J.C., 1981. Regional plate tectonics and the evolution of Australia's passive continental margins. BMR Journal of Australian Geology and Geophysics, 6, 1–29.

Falvey, D.A., Symonds, P.A., Colwell, J.B., Willcox, J.B., Marshall, J.F., Williamson, P.E. & Stagg, H.M.J., 1990. Australia's deepwater frontier petroleum basins and play types. APEA Journal, 30(1), 239–262.

Forman, D.J. & Wales, D.W. (compilers), 1981. Geological evolution of the Canning Basin. Bureau of Mineral Resources, Australia, Bulletin 215 pp.

Foster, C.B., Bradshaw, J., Moss, G. & Wyatt, B., 1996. Australian Phanerozoic Biozones. Australian Geological Survey Organisation, Canberra.

Fullerton, L.G., Sager, W.W. & Handschumacher, D.W., 1989. Late Jurassic–Early Cretaceous evolution of the Eastern Indian Ocean adjacent to Northwest Australia. Journal of Geophysical Research, 94, 2937–53.

Gaina, C., Müller, R.D., Royer, J-Y., Stock, J., Hardebeck, J. & Symonds, P., 1996. The tectonic history of the Tasman Sea: a puzzle with thirteen pieces. Journal of Geophysical Research, 103, 12413-33.

Gaina, C., Müller, R.D., Royer, J-Y. & Symonds P., in press. The evolution of the Louisiade triple junction. Journal of Geophysical Research.

Gradstein, F.M. et al., 1990. Proceedings of the Ocean Drilling Program, Initial Reports, 123, College Station, Texas (Ocean Drilling Program).

Harrington, H.J. & Korsch, R.J., 1985. Tectonic model for the Devonian to middle Permian of the New England Orogen. Australian Journal of Earth Sciences, 32, 163–179.

Hayes, D.E. & Ringis, J., 1973. Seafloor spreading in the Tasman Sea. Nature, 243, 454–58.

Herzer, R.H. & Mascle, J., 1996. Anatomy of a continent-backarc transform—the Vening-Meinesz Fracture Zone northwest of New Zealand. Marine Geophysical Researches, 18, 401-27.

Hill, P.J., 1994. Geology and geophysics of the offshore Maryborough, Capricorn and northern Tasman Basins: results of AGSO Survey 91. Australian Geological Survey Organisation, Record 1994/1.

Hill, K.A., Finlayson, D.M., Hill, K.C. & Cooper, G.T., 1995. Mesozoic tectonics of the Otway Basin region: the legacy of Gondwana and the active Pacific margin—a review and ongoing research. APEA Journal, 35(1), 467–493.

Hill P.J., Meixner A., Moore A.M.G. & Exon N.F. 1997. Structure and development of the west Tasmanian offshore sedimentary basins: results of recent marine and aeromagnetic surveys. Australian Journal of Earth Sciences, 44, 579–596.

Hinz, K., Willcox, J.B., Whiticar, M., Kudrass, H.R., Exon, N.F. & Feary, D.A., 1986. The west Tasmanian margin: an underrated petroleum province?. In: Glenie, R.C. (editor), Second Southeastern Australia Oil Exploration Symposium, Petroleum Exploration Society of Australia, 395–410.

Home, P.C., Dalton, D.G. & Brannan, J., 1990. Geological evolution of the western Papuan Basin. In: Carman, G.J. & Carman, Z. (editors), Petroleum exploration in Papua New Guinea. Proceedings of First PNG Petroleum Convention, Port Moresby, 12–14th February 1990, 107–117.

Horstmann, E.L., 1984. Evidence for post-Permian epeirogenic uplift in the Canning Basin from vitrinite reflectance data. In: Purcell, P.G. (editor), The Canning Basin, W.A. Proceedings of Geological Society of Australia/Petroleum Exploration Society of Australia Canning Basin Symposium, Perth, 1984, 401–409.

Jackson, M.J., Powell, T.G., Summons, R.E. & Sweet, I.P., 1986. Hydrocarbon shows and petroleum source rocks in sediments as old as 1.7 x 10^9 years. Nature, 322, 727–729.

Jongsma, D. & Mutter, J.C., 1978. Non-axial breaching of a rift valley: evidence from the Lord Howe Rise and the Southeastern Australian margin. Earth and Planetary Science Letters, 39, 226–34.

Kennett, J.P. et al., 1975. Initital Reports of the Deep Sea Drilling Project, vol. 29. U.S. Government Printing Office, Washington, D.C.

Larson, R.L., 1975. Late Jurassic seafloor spreading in the Eastern Indian Ocean. Geology, 3, 69–71.

Larson, R.L., 1977. Early Cretaceous breakup of Gondwanaland off Western Australia. Geology, 5, 57–70.

Lee, R.J. & Gunn, P.J., 1988. The Bonaparte Basin. In: Petroleum in Australia—the first century. Australian Petroleum Exploration Association Limited, Sydney, 252–269.

Lister, G.S. & Etheridge, M.A., 1989. Detachment model for the uplift and volcanism of the Eastern Highlands. In: Johnson, R.W. (editor), Intraplate volcanism in eastern Australia and New Zealand. Cambridge University Press, New York, 297–312.

Lister, G.S., Etheridge, M.A. & Symonds, P.A., 1986. Detachment faulting and the evolution of passive continental margins. Geology, 14, 246–50.

Lister, G.S., Etheridge, M.A. & Symonds, P.A., 1991. Detachment models for the formation of passive continental margins. Tectonics, 10, 1038–1064.

Lubatis, V., Moore, A. & Bradshaw, J., 1992. Petroleum prospectivity evaluation—Arafura Basin. Australian Geological Survey Organisation, Record 1992/84.

Ludden, J.N. & Dionne, B., 1992. The geochemistry of oceanic crust at the onset of rifting in the Indian Ocean. In: Gradstein, F.M. et al., Proceedings of the Ocean Drilling Program, Scientific Results, 123: College Station, Texas (Ocean Drilling Program), 791–799.

Malcolm, R.J., Pott, M.C., & Delfos, E., 1991. A new tectono-stratigraphic synthesis of the north west Cape area. APEA Journal 31, 154–176.

Markl, R.G., 1974. Evidence for the breakup of eastern Gondwanaland by the Early Cretaceous. Nature, 251, 196–200.

Markl, R.G., 1978. Further evidence for the Early Cretaceous breakup of Gondwanaland off southwestern Australia. Marine Geology, 26, 41–48.

Marshall, J.F. & Lee, C.S., 1988. North Perth Basin Workshop. Bureau of Mineral Resources, Australia, Record 1988/35.

Marshall, J.F., Lee, C.S., Ramsay, D.C., O'Brien, G.W. & Moore, A.M.G., 1989. Offshore North Perth Basin. Bureau of Mineral Resources, Australia, Continental Margins Program Folio 3.

Mihut, D. & Müller, R.D., 1998. Revised seafloor spreading history of the Argo Abyssal Plain. In: P.G. & R.R. Purcell (editors) The sedimentary basins of Western Australia 2: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1998, 73-80.

Mihut, D. & Müller, R.D., in press. Volcanic margin formation and Mesozoic rift propagators in the Cuvier Abyssal Plain off Western Australia. Journal of Geophysical Research.

Moore, A.M.G., Willcox, J.B., Exon, N.F. & O'Brien, G.W., 1992. Continental shelf basins on the west Tasmanian margin. APEA Journal, 32(1), 231–250.

Müller, R.D., Mihut, D. & Baldwin, S., 1998. A new kinematic model for the formation and evolution of the west and northwest Australian margin. In: P.G. & R.R. Purcell (Eds) The sedimentary basins of Western Australia 2: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1998, 55-72.

Murray, C.G., Fergusson, C.L., Flood, P.G., Whitaker, W.G. & Korsch, R.J. 1987. Plate tectonic model for the Carboniferous evolution of the New England Fold Belt. Australian Journal of Earth Sciences, 34, 213–236.

Mutter, J.C. & Karner, G.D., 1980. The continental margin off northeast Australia. In: Henderson, R.A. & Stephenson, P.J. (editors), The geology and geophysics of northeast Australia. Geological Society of Australia, Queensland Division, Brisbane, 47–69.

O'Brien, G.W., 1993. Some ideas on the rifting history of the Timor Sea from the integration of deep crustal seismic and other data. PESA Journal, 21, 95–113.

O'Brien, G.W., Etheridge, M.A., Needham, D.J., Pridmore, D., Norman, C. & Cowan, D., 1992. Vulcan Sub-Basin, Timor Sea: An integrated structural study of image processed aeromagnetic and selected seismic data. Bureau of Mineral Resources, Australia, Continental Margins Program Folio 6, 134 pp.

O'Brien, G.W., Etheridge, M.A., Willcox, J.B., Morse, M., Symonds, P., Norman, C. & Needham, D.J., 1993. The structural architecture of the Timor Sea, north-western Australia: implications for basin development and hydrocarbon exploration. APEA Journal, 33(1), 258–278.

O'Brien, G.W., Higgins, R., Symonds, P., Quaife, P., Colwell, J. & Blevin, J., 1996. Basement control on the development of extensional systems in Australia's Timor Sea: an example of hybrid hard linked/soft linked faulting? APPEA Journal, 36(1), 161–200.

Pigram, C.J. & Davies, H.L. 1987. Terranes and the accretion history of the New Guinea Orogen. BMR Journal of Australian Geology & Geophysics, 10, 193–211.

Roeser, H. & shipboard party, 1985. Geophysical, geological and geochemical studies on Lord Howe Rise. Bundesanstalt fur Geowissenschaften und Rohstoffe Report, Cruise SO36 (1).

Scott, D.L. 1993. Architecture of the Queensland Trough: implications for the structure and tectonics of the northeastern Australian margin. AGSO Journal of Australian Geology & Geophysics, 14, 21–34.

Scott, D.L., 1994. Oblique lithospheric extension: a comparative analysis of the East African Rift System and some Australian margins. Ph.D. thesis, Australian National University, 186 pp.

Shaw, R.D., 1978. Sea floor spreading in the Tasman Sea: a Lord Howe Rise–eastern Australian reconstruction. Bulletin of the Australian Society of Exploration Geophysicists, 9(3), 75–81.

Shaw, R.D., 1979. On the evolution of the Tasman Sea and adjacent continental margins. Ph.D. thesis, University of Sydney.

Stagg, H.M.J. & Colwell, J.B., 1994. The structural foundations of the northern Carnarvon Basin. In: Purcell, P.G. & Purcell, R.R. (editors), The sedimentary basins of Western Australia. Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1994, 349–364.

Stagg, H.M.J. & Willcox, J.B., 1991. Structure and hydrocarbon potential of the Bremer Basin, southwest Australia. BMR Journal of Australian Geology & Geophysics, 12, 327–337.

Stagg, H.M.J. & Willcox, J.B., 1992. A case for Australia–Antarctica separation in the Neocomian (ca. 125 Ma). Tectonophysics, 210, 21–32.

Stagg, H.M.J., Cockshell, C.D., Willcox, J.B., Hill, A., Needham, D.J.L., Thomas, B., O'Brien, G.W. & Hough, P., 1990. Basins of the Great Australian Bight region: geology and petroleum potential. Bureau of Mineral Resources, Australia, Continental Margins Program Folio 5.

Stagg, H.M.J., Willcox, J.B. & Needham, D.J.L., 1992. The Polda Basin—a seismic interpretation of a Proterozoic–Meszoic rift in the Great Australian Bight. BMR Journal of Australian Geology & Geophysics, 13, 1–13.

Struckmeyer, H.I.M., Yeung, M. & Bradshaw, M.T., 1990. Mesozoic palaeogeography of the northern margin of the Australian plate and its implications for hydrocarbon exploration. In: Carman, G.J. & Carman, Z. (editors), Petroleum exploration in Papua New Guinea. First PNG Petroleum Convention, Port Moresby, 12–14th February 1990, Proceedings, 137–152.

Struckmeyer, H.I.M., Bradshaw, M., Walley, A.M. & Yeung, M., 1991. Mesozoic to Cainozoic evolution of the Australian plate margin—an overview. BMR-APIRA Phanerozoic history of Australia project notes (unpub.).

Struckmeyer, H.I.M., Yeung, M. & Pigram, C.J., 1993. Mesozoic to Cainozoic plate tectonic and palaeogeographic evolution of the New Guinea region. In: Carman, G.J. & Carman, Z. (editors), Petroleum exploration and development in Papua New Guinea. Second PNG Petroleum Convention, Port Moresby, 31st May–2nd June 1993, Proceedings, 261–290.

Struckmeyer, H.I.M., Symonds, P.A., Fellows, M.E. & Scott, D.L., 1994. Structural and stratigraphic evolution of the Townsville Basin, Townsville Trough, offshore northeastern Australia. Australian Geological Survey Organisation, Record 1994/50.

Symonds, P.A. & Willcox, J.B., 1989. Australia's petroleum potential in areas beyond an Exclusive Economic Zone. BMR Journal of Australian Geology & Geophysics, 11, 11–36.

Symonds, P.A., Fritsch, J. & Schluter, H.U. 1984. Continental margin around the western Coral Sea Basin: structural elements, seismic sequences, and petroleum geological aspects. In: Watson, S.T. (editor), 3rd Circum-Pacific Energy and Mineral Resources Conference, Hawaii, Transactions, American Association of Petroleum Geologists, Tulsa, 243–252.

Symonds. P.A., Collins, C.D.N. & Bradshaw, J., 1994. Deep structure of the Browse Basin: implications for basin development and petroleum exploration. In: Purcell, P.G. & Purcell, R.R. (editors), The sedimentary basins of Western Australia. Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1994, 315–331.

Symonds, P.A., Planke, S., Colwell, J.B. & Crawford, A.J., 1996. Volcanic evolution of the Western Australian continental margin. Geological Society of Australia, Abstracts, 41, 431.

Taylor, L.W.H. & Falvey, D.A., 1977. Queensland Plateau and Coral Sea Basin: stratigraphy, structure and tectonics. APEA Journal, 17, 13–29.

Veevers, J.J., 1984. Phanerozoic Earth history of Australia. Clarendon, Oxford, 418 pp.

Veevers, J.J., 1986. Breakup of Australia and Antarctica estimated as mid-Cretaceous (95 ± 5 Ma) from magnetic and seismic data at the continental margin. Earth and Planetary Science Letters, 77, 91–99.

Veevers, J.J. & Eittreim, S.L., 1988. Reconstruction of Australia and Antarctica at breakup (95 ± 5 Ma) from magnetic and seismic data at the continental margin. Australian Journal of Earth Sciences, 35, 355–362.

Veevers, J.J. & Li, Z.X., 1991. Review of seafloor spreading around Australia. II. Marine magnetic anomaly modelling. Australian Journal of Earth Sciences, 38, 391–408.

Veevers, J.J. & Roberts, J., 1968. Upper Palaeozoic rocks, Bonaparte Gulf Basin of northwestern Australia. Bureau Mineral Resources, Australia, Bulletin 97.

Veevers, J.J., Tayton, J.W., Johnson, B.D. & Hansen, L., 1985. Magnetic expression of the continent-ocean boundary between the western margin of Australia and the eastern Indian Ocean. Journal of Geophysics, 56, 106–20.

Veevers, J.J., Powell, C.McA. & Roots, S.R., 1991. Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading. Australian Journal of Earth Sciences, 38, 373–389.

Weissel, J.K. & Hayes, D.E., 1972. Magnetic anomalies in the southeast Indian Ocean, Antarctic Oceanology II, The Australian–New Zealand Sector. Antarctic Research Series, American Geophysical Union, 19, 165–96.

Weissel, J.K. & Hayes, D.E., 1977. Evolution of the Tasman Sea reappraised. Earth and Planetary Science Letters, 36, 77–84.

Willcox, J.B., 1981. Petroleum prospectivity of Australian marginal plateaus. In: Halbouty, M. (editor), Energy resources of the Pacific region. American Association of Petroleum Geologists Studies in Geology, 12, 245–72.

Willcox, J.B., 1990. Gravity trends as an expression of lithospheric extension on the southern margin of Australia. Australian Journal of Earth Sciences, 37, 85–91.

Willcox, J.B. & Stagg, H.M.J., 1990. Australia's southern margin: a product of oblique extension. Tectonophysics, 173, 269–281.

Willcox, J.B., Symonds, P.A., Hinz, K. & Bennett, D., 1980. Lord Howe Rise, Tasman Sea—preliminary geophysical results and petroleum prospects. BMR Journal of Australian Geology & Geophysics, 5, 225–36.

Willcox, J.B., Baillie, P., Exon, N., Lee, C.S. & Thomas, B., 1989. The geology of western Tasmania and its continental margin - with particular reference to petroleum potential. Bureau of Mineral Resources, Australia, Record 1989/13.

Willcox, J.B., Colwell, J.B. & Constantine, A.E., 1992. New ideas on Gippsland Basin regional tectonics. In: Energy, Economics and Environment Gippsland Basin Symposium, Joint PESA/AusIMM symposium, 22–23 June, 1992, Melbourne, Australasian Institute of Mining and Metallurgy, 93–110.

Williamson, P.E., Swift, M.G., Kravis, S.P., Falvey, D.A. & Brassil, F., 1990. Permo-Carboniferous rifting of the Exmouth Plateau region (Australia): an intermediate plate model. In: Pinet, B. & Bois, C. (editors), The potential of deep seismic profiling for hydrocarbon exploration. Editions Technip, Paris, 237–248.

Yeates, A.N., Bradshaw, M.T., Dickins, J.M., Brakel, A.T., Exon, N.F., Langford, R.P., Mulholland, S.M., Totterdell, J.M. & Yeung, M., 1987. The Westralian Superbasin: an Australian link with Tethys. In: McKenzie, K.G. (editor), Shallow Tethys 2: International Symposium on Shallow Tethys 2, Wagga Wagga, Proceedings, 199–213.

Young, G. & Claoue-Long, J., 1991. Age control on sedimentary sequences. BMR Research Newsletter, 15, 14–16.

Zhu, H. & Symonds, P.A., 1995. Seismic interpretation, gravity modeling and petroleum potential of the southern Lord Howe Rise region. In: 1994 New Zealand Petroleum Conference Proceedings, Ministry of Commerce, Wellington, 223–230.