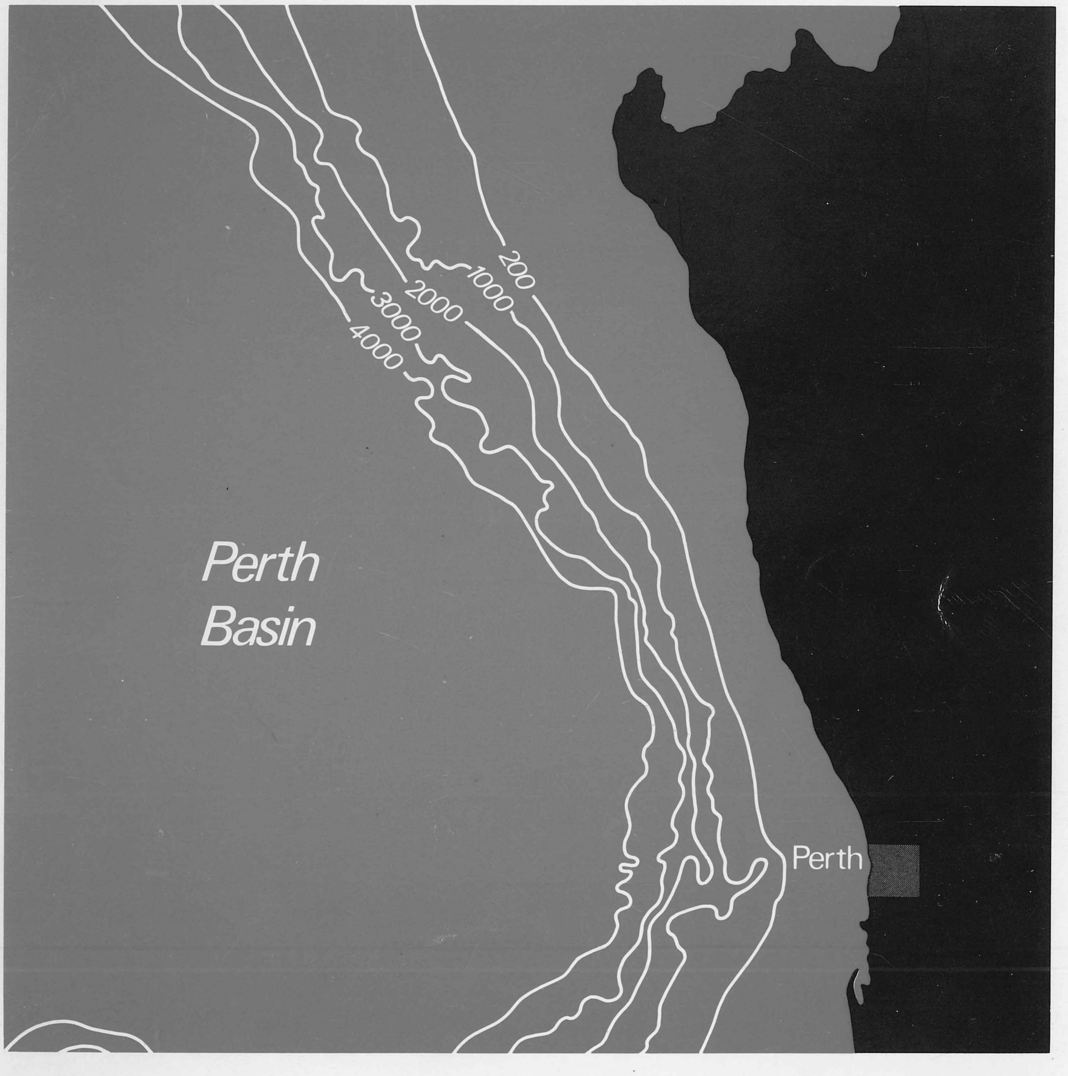
Bureau of Mineral Resources
Geology and Geophysics

North Perth Basin Workshop



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Division of Marine Geosciences & Petroleum Geology

NORTH PERTH BASIN

WORKSHOP

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SUMMARY

Results from a regional seismic reflection survey by BMR, coupled with seismic and well data from industry, have delineated the major tectonic and stratigraphic elements of the offshore North Perth Basin. Three sub-basins have been defined in the offshore region, each of which is the product of a particular rifting episode during the history of the basin. These sub-basins, the Edel, Abrolhos, and Houtman Sub-basins range in age from Early Permian to Early Cretaceous.

The Edel Sub-basin underwent a period of rifting and extension during the Early Permian which produced a series of rotated fault blocks and had relatively shallow décollement of their extensional faults. A post-rift aggradational phase is considered to have laid down Late Permian to Middle Triassic fluvial and alluvial sediments. The sub-basin, while containing in the order of 8000 m of sediments, has undergone relatively little subsidence compared to the other sub-basins. This is attributed to the absence of large sub-detachment thinning during the rifting phase. This sub-basin is relatively unexplored and its petroleum potential is difficult to assess. However, the Permian and Early Triassic horizons that have produced hydrocarbons onshore are believed to extend into this sub-basin.

Rifting is considered to have commenced somewhat later in the Abrolhos Sub-basin, during the Late Permian, and has produced a series of rotated fault blocks that have subsided progressively

to the west. The synrift sequence within the sub-basin is relatively thin. However, a thick sequence of mainly continental sediments was deposited during a prolonged post-rift sag phase which extend from the Early Triassic to the Neocomian. Reactivation of the fault blocks during the Neocomian produced numerous structures that are potential hydrocarbon traps. This, and the deposition of significant source rocks, makes this sub-basin highly prospective.

The Houtman Sub-basin is considered to have undergone rifting at the time of breakup in the Neocomian. The sub-basin contains a thick sequence of mainly Jurassic rocks, which have experienced extension in the east and wrench faulting to the west. Recent works in the onshore Perth Basin indicated the oil production from the Jurassic sediments. This may open up an new exploration play in the Houtman Sub-basin.

The boundaries between the sub-basins, other than along basement highs, are believed to be strike-slip faults. This proposal is supported by the drastic changes in stratigraphy and basin geometry across these boundaries. The entire offshore North Perth Basin is considered to have been formed by the process of transtension, probably from the earliest phase of rifting. This has culminated in separation and seafloor spreading by oblique extension along the Zenith-Wallaby Fracture Zone to form a transform passive margin.

INTRODUCTION

In July 1986, R.V. Rig Seismic surveyed the transform passive continental margin that forms the offshore extension of the North Perth Basin (Fig. 1). The data consists of 2445 km of continuous 48-channel seismic reflection profiles, acquired simultaneously with bathymetry, gravity and magnetics; four sonobuoy refraction profiles; 11 heatflow stations; 29 gravity core stations; 16 grab sites; 10 dredge stations; five box core sites; 325 km of side scan sonar traverses; and one underwater camera station. Navigation was provided by a combination of satellite navigation (Transit Doppler System and Global Positioning System) and Syledis.

The pricipal objectives of the survey were:

1. To elucidate the stratigraphic and structural history of the offshore North Perth Basin, particularly with respect to its hydrocarbon prospectivity.
2. To determine the tectonic structure of the continent /ocean boundary, and the relationship between transform continental margins and basin structure.
3. To investigate the sedimentology and geochemistry of the Quaternary slope carbonates in order to develop models of sedimentation on starved margins.

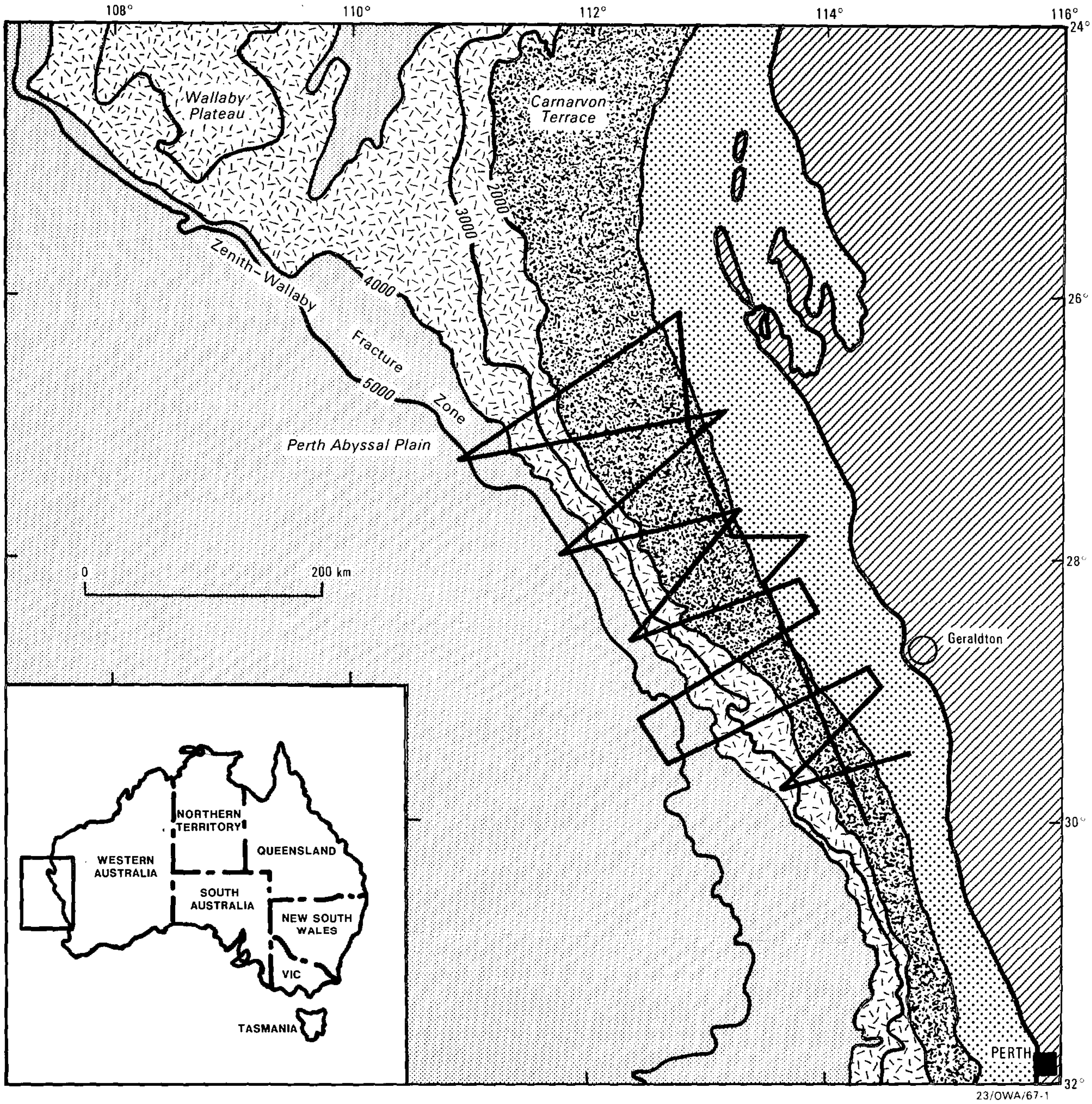


Fig. 1. Bathymetry of the North Perth Basin region showing the Zenith-Wallaby Fracture Zone extending along the continental margin. Ship tracks are BMR seismic lines carried out in 1986.

Regional Setting

The Perth Basin is a north-south trending linear trough that extends about 1000 km beneath the coastal region and continental margin of southwest Australia (Fig. 2). The basin covers an area of 45,000 km^2 offshore (Playford et al. 1976). The eastern margin of the basin is bounded by the Darling Fault, which separates the basin from the Archaean Yilgarn Block. The Darling Fault has been downthrown to the west by about 15 km since the Early Palaeozoic (Jones 1976). The basin has a history of rifting and rift-fill since at least the Ordovician, which culminated in the complete separation of India from Australia during the Neocomian (Markl 1974a,b, 1978a,b; Larson et al. 1979; Veevers et al. 1985). Seafloor spreading is thought to have occurred about a northeast trending ridge and along transform faults, such as the Zenith-Wallaby Fracture Zone (Falvey and Veevers 1974; Markl 1974b).

Regional Bathymetry

The continental margin of the offshore Perth Basin (Fig. 1) consists of a 50 to 100 km wide continental shelf, a relatively steep continental slope and a fairly wide continental rise. The continental shelf, which in this region is known as the Rottnest Shelf (Carrigy and Fairbridge 1954), consists of a relatively wide inner shelf plain and a more narrow outer shelf slope. Ridge and trough topography on parts of the shelf indicate possible karst processes have been active during periods of low sea level. Near the outer edge of the shelf between 28^{o} and $29^{o}S$ lie the islands and coral reefs of the Houtman-Abrolhos Group, which exhibit many significant karst features. The depth of the shelf

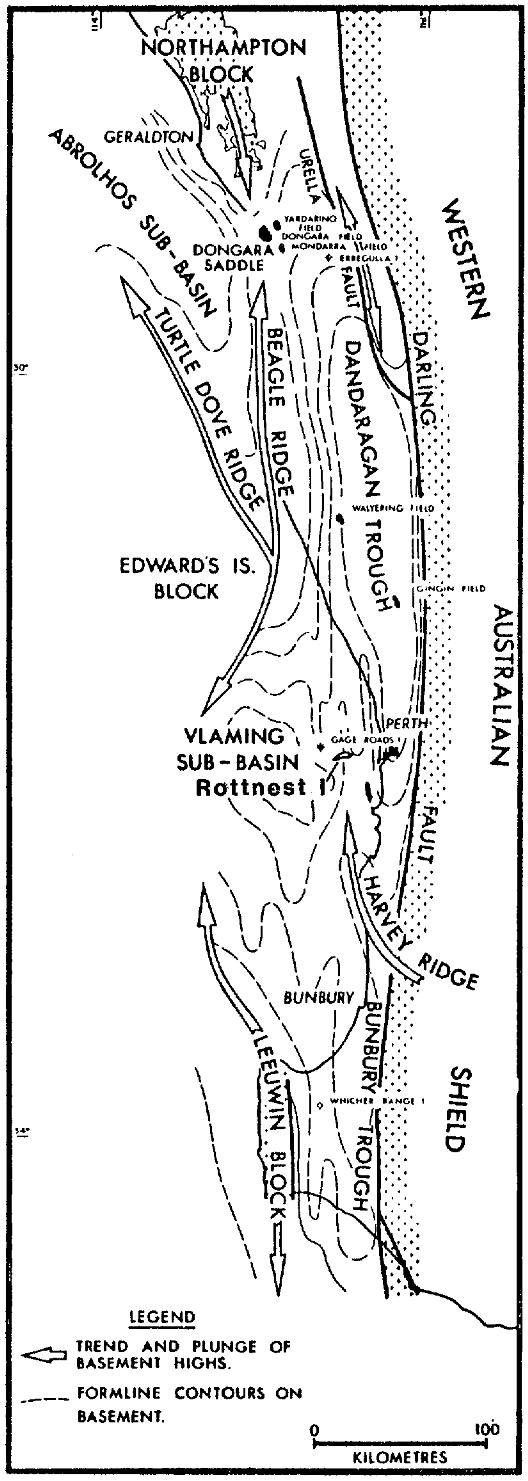


Fig. 2. Tectonic elements of the Perth Basin (after Jones 1976).

break varies between 150-200 m, and is characterized by a marked change in slope.

The continental slope extends from the shelf break to about 4000 m. Falvey and Veevers (1974) divided the slope into a smooth and relatively gentle upper slope (200-2000m) and a relatively steep (3-5^{o}) lower slope. In the northern part of the area, the Carnarvon Terrace occupies the upper slope between 400 and 1600 m and slopes gently seawards at angles of 0.5 to 1^{o} (Symonds and Cameron 1977). On the lower slope, submarine canyons have dissected the seafloor in many places. A steep, linear escarpment, the Wallaby-Perth Scarp, extends in a southwesterly direction from the southern flank of the Wallaby Plateau to the lower slope adjacent to Perth (Fig. 1). The scarp has a relief of up to 1500 m (Symonds and Cameron 1977), with gradients of 10 to 30^{o} along the southern edge of the Wallaby Plateau (von Stackelberg et al. 1980). The scarp is the physical expression of the Zenith-Wallaby Fracture Zone that forms the continent/ocean boundary along the transform margin.

Along the Wallaby-Perth Scarp, the continental rise is very narrow, but south of 28^{o}S it increases its width dramatically and occupies the area between the 4500 and 5500 m isobaths (Fig. 1). At the base of the rise, the Perth Abyssal Plain occurs at a depth of about 5600 m. Along the steep wall of the Wallaby-Perth Scarp and the continental slope to the south, numerous submarine canyons (e.g. the Fremantle Canyon) have incised the seafloor, and have acted as conduits for sediment supply to the deep basin (Falvey and Veevers 1974; Quilty et al. in press).

Previous Data

Modern offshore geophysical observations in the Perth Basin were first made in 1935 by Vening Meinesz (1948) with the recording of over 200 gravity meter readings from a submarine (Jones 1976). The next phase of investigation was conducted between 1960-1964 by the University of New South Wales and the Lamont-Doherty Geological Observatory, whose joint surveys provided seismic refraction, magnetics and gravity data over the southwestern part of the basin (Hawkins et al. 1965). During 1971-1972, two extensive reconnaissance surveys, one by BMR and the other by Shell Development Pty Ltd, were conducted over the continental margin of southwestern Australia. Results from these surveys (Shell 1973; Branson 1974; Petkovic 1975; Symonds and Cameron 1977) have been helpful in understanding the structural setting of this region. Additional cruises by the Lamont-Doherty Geological Observatory and the Royal Australian Navy (HMAS Cook) have revealed the pattern of seafloor magnetic anomalies in the Perth Abyssal Plain and the tectonic style of the continent/ocean boundary (Markl 1974a,b; 1978a,b; Larson et al. 1979; Veevers et al. 1985).

Geological samples have been obtained throughout the region by drilling and dredging. During DSDP Leg 27 (Veevers and Heirtzler et al. 1974), Neocomian basaltic basement was penetrated at site 259, located on the Perth Abyssal Plain (Fig. 3). Volcanoclastics have also been dredged along the northern section of the Wallaby-Perth Scarp (von Stackelberg et al. 1980).

Offshore petroleum exploration in the Perth Basin started in 1965. A total of 21 wells have been drilled offshore, eight of

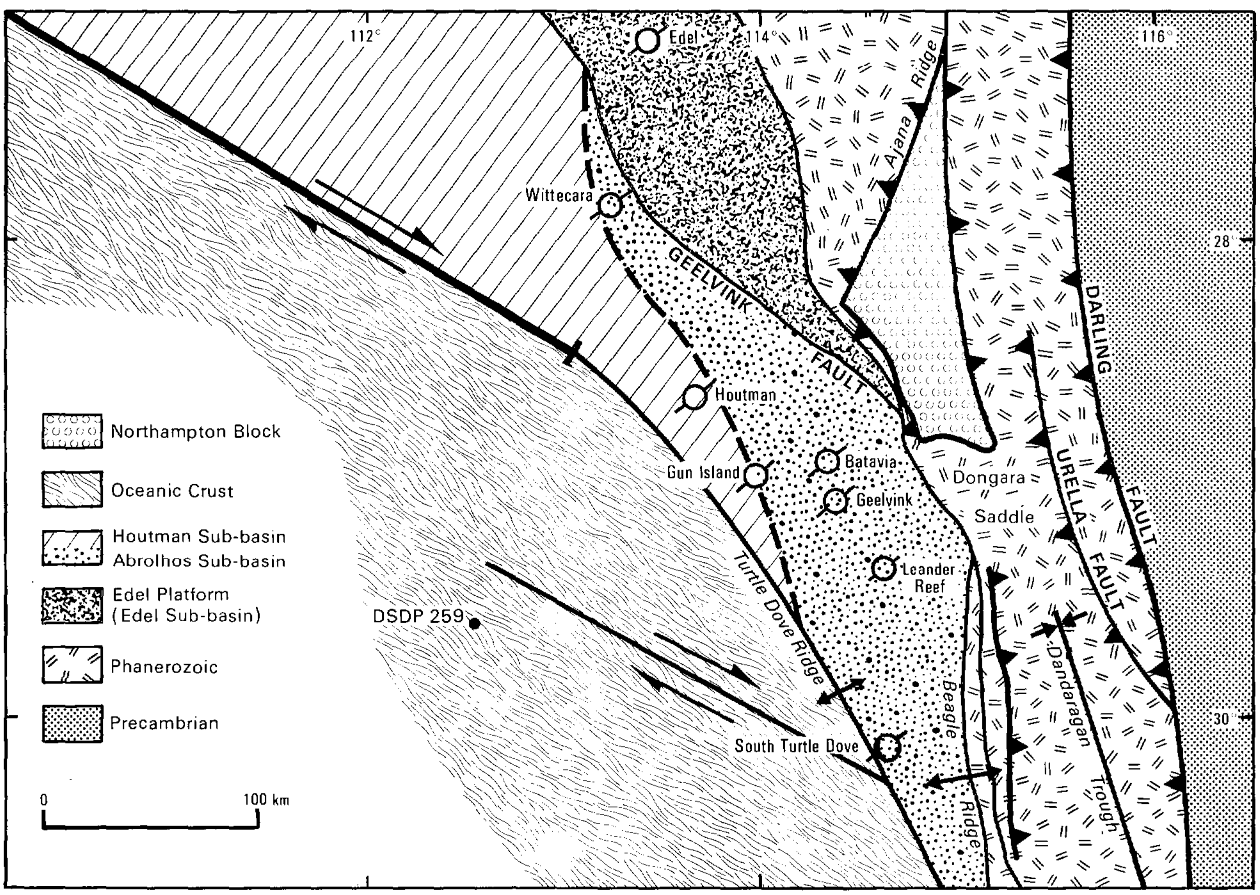


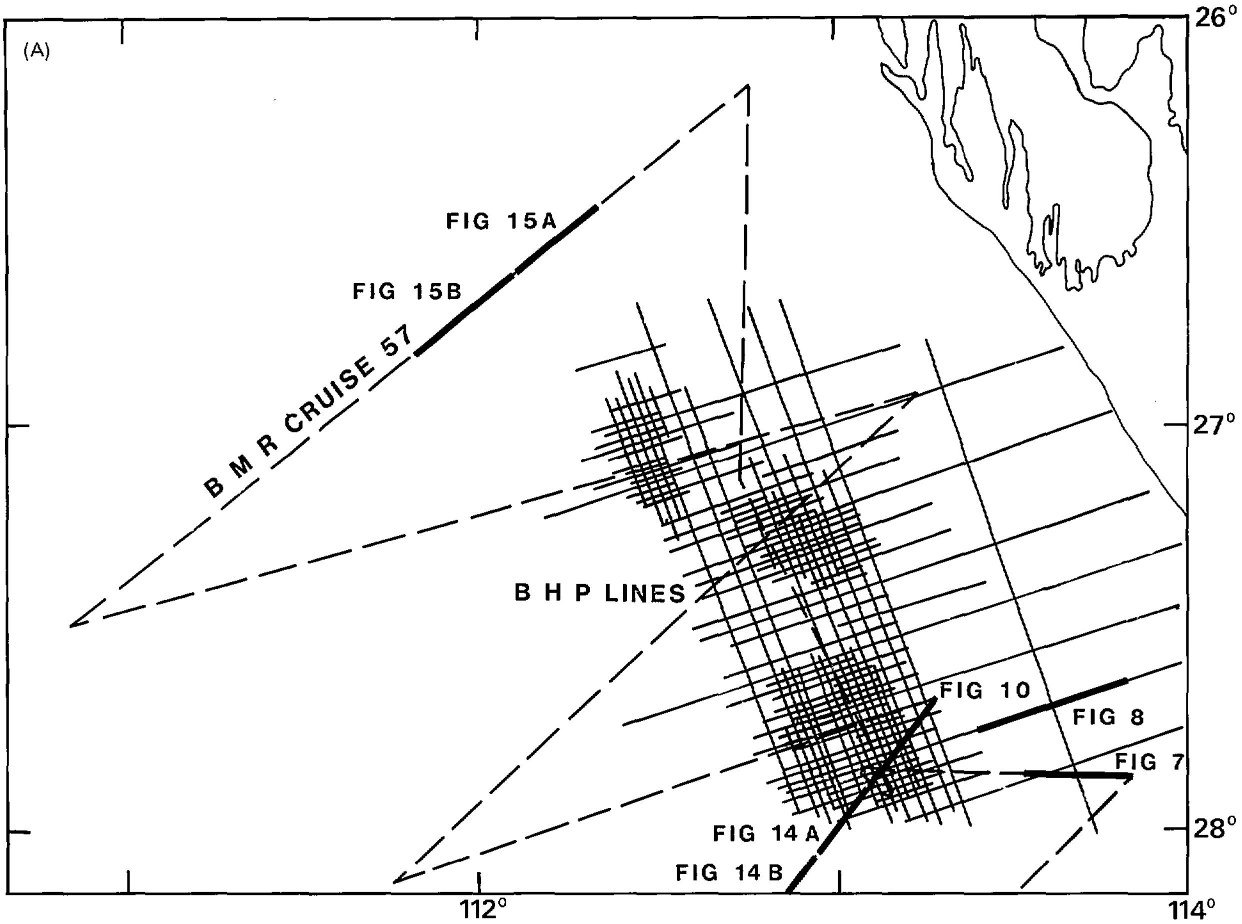
Fig. 3. Tectonic structure maps of the offshore North Perth Basin showing well locations.

which are located in the northern part of the basin (Fig. 3). Gun Island-1 (Hawkins 1969) was drilled in 1968 on an island of the same name in the Houtman-Abrolhos Group. The well was drilled to a depth of 3728 m and proved the existence of a thick Jurassic sequence offshore in this area. The next well, Edel-1 (Ocean Ventures Pty Ltd 1972) was drilled on the shallower part of the shelf to the north, the Edel Platform (Fig. 3). It encountered some 300 m of Tertiary carbonates before penetrating a thick sequence of volcanics, volcanoclastics and unfossiliferous red beds; the latter were considered to be equivalent to the Early Silurian Tumblagooda Sandstone, and this, together with the presence of volcanics, seriously downgraded the prospectivity of the Edel Shelf.

In the southern part of the Abrolhos Sub-basin, two wells, South Turtle Dove-1B (1830 m) and Geelvink-1A (3053 m), were drilled by Wapet in 1975 and 1978 respectively (Meath and Wright 1979). Geelvink-1A encountered a complete Mesozoic section and bottomed in Permian sediments, whereas in South Turtle Dove-1B the Jurassic section is missing. Two other wells, Batavia-1 (2941 m) and Houtman-1 (3860 m), were drilled in 1978 by Esso Australia Ltd on either side of the Houtman-Abrolhos Group (Galloway 1978 a & b). Batavia-1 reached the Permian, whereas Houtman-1, located on the outer shelf, did not penetrate beyond the Jurassic. Leander Reef-1 was drilled on the inner shelf off Dongara in 1983, and bottomed in Permian at a total depth of 2837 m. In 1985 BHP Petroleum Pty Ltd drilled Wittecarra-1 in the northern part of the Abrolhos Sub-basin and this reached Permian at a depth of 2890 m (Smith and Cowley 1987).

In addition to the eight exploration wells, some 8000 km of seismic reflection profiles have been acquired in the offshore region of the North Perth Basin (Fig. 4).

A number of studies, including geohistory analysis, source rock geochemistry and maturation patterns, have been published on the offshore Perth Basin using released oil company data (Kantsler and Cook 1979; Thomas 1979, 1984; Falvey and Deighton 1982). In addition, a number of review studies of all or part of the Perth Basin detailing the structure, tectonics, and stratigraphy of the area, have been published (e.g. Jones and Pearson 1972; Jones 1976; Playford et al. 1976; Megallaa 1980; Smith and Cowley 1987; Bergmark and Evans 1987; Warris 1988).



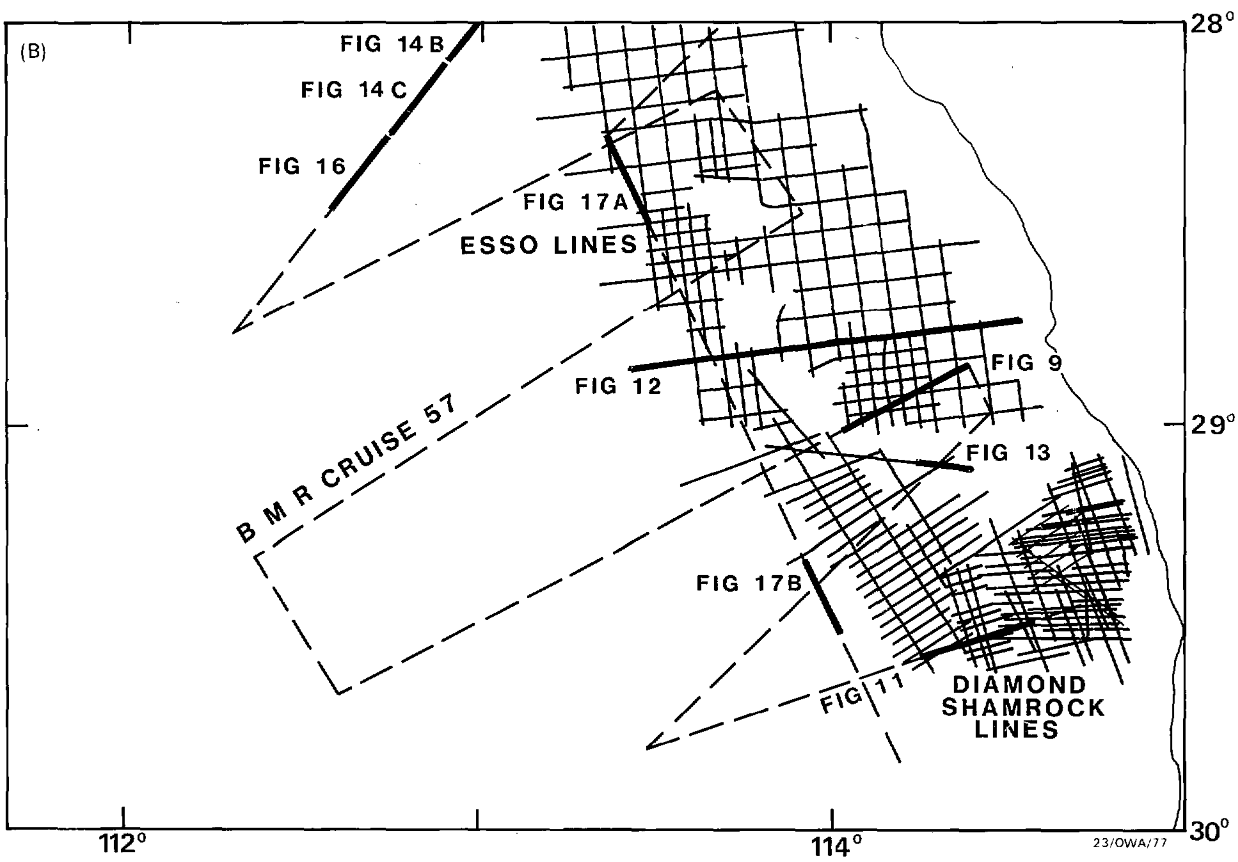


Fig. 4. Ship track maps of BMR cruise 57 and oil company seismic lines. Oil company lines included BHP, Petrofina, Esso and Diamond Shamrock data. Ship tracks are shown in A and B parts.

REGIONAL GEOLOGY

The Perth Basin existed as a series of grabens or half grabens throughout most of the Late Palaeozoic and Early Mesozoic. Basin development is proposed to be a direct result of movement on the Darling Fault (Jones 1976; Playford et al. 1976). The combination of faulting and rifting has resulted in a basin that is essentially a series of en echelon troughs separated by block-faulted structural highs (Veevers 1984). Movement on the Darling Fault, and subsidence of the troughs, has led to shedding from the adjacent Precambrian highs of an enormous amount of sediment that has filled the troughs and sub-basins.

The major tectonic elements are shown in Figure 2. The Dandaragan Trough is bounded on the east by the Darling Fault and to the west by a basement high known as the Beagle Ridge. To the north it shallows onto the Precambrian basement of the Northampton Block. The trough was a significant depocentre from Early Permian to Cretaceous times, and contains more than 15 km of sediments (Playford et al. 1976), which are mainly clastic wedges deposited during periods of large displacement on the Darling-Urella Fault system. To the south, another graben or rift basin, the Bunbury Trough, is also bounded on the east by the Darling Fault (Fig. 2). This trough is partly separated from the Dandaragan Trough by the Harvey Ridge. More than 6 km of Phanerozoic sediments were deposited within the deepest part of the Bunbury Trough adjacent to the Darling Fault.

There are two major troughs beneath the continental shelf of the offshore Perth Basin, the Vlaming Sub-basin in the south and the Abrolhos Sub-basin to the north (Fig. 2). These offshore basins are essentially en echelon to the structural lows of the onshore Dandaragan and Bunbury Troughs. The Vlaming Sub-basin, whose limits are relatively undefined, is believed to have developed as a result of the Late Jurassic to Early Cretaceous tectonism. Maximum deposition was to the west of Rottnest Island, where some 15 km of sediment are believed to have been deposited (Playford et al. 1976).

The major structural feature of the offshore North Perth Basin is the Abrolhos Sub-basin (Fig. 3). To the southeast the sub-basin is bounded by the Beagle Ridge, a shallow basement high that separates it from the Dandaragan Trough, whereas to the east it is bounded by the Precambrian Northampton Block. Between these basement highs lies the Dongara Saddle, the major hydrocarbon producing area in the Perth Basin. To the northeast the Edel Platform lies adjacent to the Abrolhos Sub-basin (Fig. 3). The two sub-basins are divided by a major hinge line, called the Geelvink Fault (Megallaa 1980). To the northwest it is bounded by another sub-basin, the Houtman Sub-basin (Symonds and Cameron 1977), whereas to the southwest it is bounded by a basement high, the Turtle Dove Ridge (Fig. 3). This ridge parallels the Wallaby-Perth Scarp to some extent, and is separated from it by a narrow trough (Symonds and Cameron 1977).

Tectonic History

The Perth Basin has a history of rifting that extends from the Early Permian up until the final separation of Greater India and

Australia during the Neocomian (Larson et al. 1979; Veevers et al. 1985). In the North Perth Basin the initial phase of rifting in the Early Permian was followed by a prolonged period of subsidence and normal faulting (Smith and Cowley 1987). Breakup is considered to have produced oblique-slip extension in the northern part of the basin that overprinted previous structures to varying degrees (Marshall and Lee 1987).

During the Early Palaeozoic, most of the Perth Basin appears to have been non-depositional, even though subsidence and adjacent uplift of the Precambrian basement to the north possibly began as early as the Silurian. Early tectonic movement was restricted to the Darling Fault and possibly along the edges of the Northampton Block. The earliest phase of rifting offshore occurred in the north during the Late Carboniferous or Early Permian (Smith and Cowley 1987). Initially, rifting is believed to have commenced beneath the Edel Platform, and subsequently propagated to the Abrolhos Sub-basin by the Late Permian (Marshall and Lee 1987). In both areas rifting resulted in a series of half grabens, produced by displacement on low-angle, east-dipping extensional faults. This pre-rift phase, resulted in a marine transgression during the Early Permian (Sakmarian); glaciers on the uplifted hinterland to the east of the Darling Fault deposited tillites into these half grabens. Further uplift along the Darling Fault, and concomitant sedimentation in the adjacent downwarps, produced shallow marine and coal measure deposits. A relative rise in sea level in the Early Triassic produced a widespread transgressive sea (Yeates et al. 1986) which extended from the north into the Perth Basin. According to Megallaa (1980), the sea gained access to the Abrolhos Sub-basin via the rift that developed to the west of the Geelvink Fault.

By the Early Triassic, the extensional regime that had started in the Late Carboniferous to Early Permian had produced a series of en echelon rifts and shallow basement highs. A prolonged post-rift sag phase resulted in large volumes of poorly sorted fluvial and alluvial sediments being deposited in the basin during the Late Triassic. During the Jurassic, and extending into the early part of the Neocomian, a thick sequence of fluvial and paralic sediments were deposited in the Perth Basin.

A second phase of rifting occurred prior to breakup and the onset of seafloor spreading during the Neocomian. The Late Jurassic sequence beneath the continental slope was displaced by a series of low-angle, west-dipping extensional faults, many of which show relatively shallow décollement (Marshall and Lee 1987). Rifting is believed to have been followed by a period of widespread uplift and erosion which produced the intra-Neocomian breakup unconformity (Falvey 1974; Falvey and Mutter 1981).

The age of breakup has been dated at 120-135 Ma B.P. from magnetic lineation studies in the Perth Abyssal Plain (Markl 1974a; Larson 1977; Veevers et al. 1985; see Fig. 2). Veevers et al.(1985) recognise the continent/ocean boundary at about magnetic anomaly M10, which places the age of breakup around 121-125 Ma B.P. The oldest fossils recovered from DSDP site 259, which lies close to the continent/ocean boundary, are about 115 Ma B.P. (Veevers et al. 1985).

The onset of seafloor spreading saw Greater India move away from Australia/Antarctica along the axis of a northeast-trending ridge and along transform faults, such as the Zenith-Wallaby Fracture

Zone (Markl 1974a; Falvey and Veevers 1974; Veevers et al. 1985). Oceanic crust to the south of this fracture zone has been offset by numerous transform faults (Veevers et al. 1985). These fracture zones and their narrowing spacing are considered to have formed as a result of oblique extension of the upper crust.

Within the margin, the oblique extension of the crust resulted in reactivation of the faults forming the older half-graben features in the Abrolhos Sub-basin. Because of the significant strike-slip component, as a result of oblique extension, many of the producing structures appear to be wrench faults, with antithetic faults forming flower structures that are in places quite complex (e.g. Fig. 3 in Marshall and Lee 1987).

By the end of the Neocomian, the present form of the Dandaragan and Bunbury Troughs was established. Continued subsidence of the Abrolhos and Vlaming Sub-basins occurred in response to cooling of oceanic crust adjacent to the newly developed continental margin. A widespread marine transgression resulted in the deposition of shallow marine clastic deposits along the subsiding margin. As India cleared the Wallaby Plateau, open sea conditions were established and an increasingly greater amount of carbonate sediment was deposited on the margin. Continued marine deposition has occurred up to the present time; the only breaks being related to regression during eustatic sea level falls, six of which have been identified in the Late Cretaceous and Cainozoic sequence (Apthorpe 1979; Quilty 1980). Normal passive margin development was interrupted in the Late Tertiary by a compressional event in the Carnarvon and North Perth Basin. In the Carnarvon Basin this produced a number of anticlines (e.g.

the Cape Range Anticline), while in the southern Carnarvon Basin and the Abrolhos Sub-basin, there was reversal of movement on faults (Smith and Cowley 1987).

STRATIGRAPHY

Offshore Stratigraphy

The series of troughs and basement highs that form the present Perth Basin is bounded on the east by the 1000 km long Darling Fault and extends to the west beneath the continental shelf and slope. Because of poor exposure throughout much of the basin, a great deal of what is know about the stratigraphy of the basin is based on drillhole data. Earlier work on the stratigraphy of the basin was by McWhae et al. (1958), with contributions by Johnstone and Willmot (1966), Jones and Pearson (1972), Jones (1976), and culminating in a comprehensive stratigraphic synthesis by Playford et al.(1976).

Sediments within the basin range from Silurian to Holocene. The basin was, however, probably inactive throughout the most of the Palaeozoic. In the north, Precambrian crystalline basement is overlain by the Tumblagooda Sandstone, an Early Silurian fluviatile red-bed sequence. This unit is considered to have been laid down during an active period of faulting along the Darling Fault (Playford et al. 1976).

Relatively, continuous deposition did not begin in the North Perth Basin until the Early Permian (Fig. 5). At the base of the Permian, the glacigene Nangetty Formation, consisting of tillites, sandstones and conglomerates, was laid down in a marginal marine environment. In the Carnarvon Basin the equivalent Lyons Group is up to 3 km thick (Lavering 1985). Smith

PERIOD	EPOCH	FORMATION	LITHOLOGY	ENVIRONMENT
QUATERNARY	Pleistocene	Coastal Limestone		Marine
TERTIARY	Miocene	Trealla Limestone		Marine
	Oligocene-Eocene	Giralia Calcarenite		Marine
	Paleocene	Cardabia Calcarenite		Marine
CRETACEOUS	Late	Toolonga Calcilutite		Marine
	Early	Winning Group		Marine to Continental
JURASSIC	Late	Yarragadee Formation		Continental
	Middle	Cadda Formation		Marine
	Early	Cockleshell Gully Fm (Cattamarra, Eneabba)		Marginal Marine to Continental
TRIASSIC	Late	Lesueur Sandstone		
	Middle	Woodada Formation		Marine
	Early	Kockatea Shale		Marine
PERMIAN	Late	Wagina Sandstone		Marine
	Early	Caryngynia Formation		Mainly Marine
		Irwin Coal Measures		
		Holmwood Shale		Marine to Continental
		Nangetty Formation		
SILURIAN		Tumblagooda Sandstone		Continental
PRECAMBRIAN		"Basement"		

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Fig. 5. Stratigraphy of North Perth Basin.

and Cowley (1987) consider this thick sequence to be the result of extremely rapid subsidence associated with initial rifting, and that the Nangetty Formation is the basal synrift unit beneath the Edel Platform.

Marine shales of the Holmwood Shale and Carynginia Formation underlie and overlie respectively the regressive Irwin River Coal Measures (Fig. 5). Alternations in the depositional environment during this phase suggest variations in the rate of sea level change and/or subsidence. The Carynginia Formation, which is a distal facies of the time-equivalent Sue Coal Measures, was possibly deposited during a rise in sea level as glacial conditions abated (Smith and Cowley 1987).

Late Permian tectonic activity resulted in tilting and erosion of the previous units and the Late Permian continental to paralic Wagina Sandstone was deposited on the erosional unconformity. The thickness of this unit is highly variable, varying from 0-298 m in the sub-surface onshore (Bergmark and Evans 1987). Wells in the Abrolhos Sub-basin suggest that the Wagina Sandstone is not present offshore. The Wagina Sandstone has been interpreted as an alluvial fan delta which spread westward from the Darling Fault into a shallow sea (Bergmark and Evans 1987).

Gentle subsidence continued into the Triassic and the return to a marine environment saw the widespread deposition in the North Perth Basin of the Early Triassic Kockatea Shale. This predominantly shaley formation is generally greenish-grey to black. The basal marine section, containing fossiliferous limestone and calcareous shales, is time transgressive, as it onlaps the Northampton Block (Playford et al. 1976). The middle and upper sections are more silty and represent a regressive phase (Jones 1976). Sandstones at the base of the Kockatea Shale occur throughout most of the North Perth Basin, although they are absent in most of the offshore wells (Smith and Cowley 1987). These basal Triassic sandstones are believed to have been deposited in a number of environments, ranging from fluvial to marine (Bergmark and Evans 1987). The Kockatea Shale is thickest in the Dandaragan Trough where it thickens gradually south from the Northampton Block and east from the Beagle Ridge.

The Middle Triassic Woodada Formation, which conformably overlies the Kockatea Shale, is present only in the sub-surface. Plant microfossils suggest that it is paralic, and that it represents part of the regressive phase between the Kockatea Shale and the continental Lesueur Sandstone (Playford et al. 1976). In the Mount Horner region the environment of deposition is considered to be deltaic in part (Warris 1988).

The Lesueur Sandstone (Late Triassic) is a fine to very coarse, cross-bedded, quartz sandstone unit. It overlies the Woodada Formation with either conformity or slight disconformity. The environment of deposition is fluvial, the entire Triassic having been marked by a sharp transgression followed by a gradual regression from shallow marine, in some areas possibly prodelta (Warris 1988), through to fluvial. Local variation in thickness across growth faults is a characteristic of the Lesueur Sandstone in the North Perth Basin (Jones 1976).

Deposition in the Jurassic consisted of a thick continental Lower Jurassic unit (Cockleshell Gully Formation), a thin Middle Jurassic marine to paralic sequence (Cadda Formation), and another thick continental unit in the Upper Jurassic that continued into the Lower Cretaceous (Yarragadee Formation).

The earliest sediments of the Cockleshell Gully Formation are interbedded multicoloured claystones and coarse-grained sandstones of the Eneabba Member. This phase of alluvial flood plain sedimentation was succeeded by the fluvial-coal swamp-lacustrine sediments of the Cattamarra Coal Measures (Thomas 1984). In the Mount Horner area this member has been divided into a lower fluvial unit, which consists of interbedded sandstones, siltstones and coal, and an upper transitional unit which is possibly estuarine (Warris 1988).

In the North Perth Basin a marine transgression from the northwest in the Middle Jurassic initiated deposition of the Cadda Formation, a light to dark grey shale, siltstone and sandstone with lenticular calcareous beds grading into limestone. The Newmarracarra Limestone of the time equivalent Champion Bay Group contains a profuse fauna of brachiopods, mollusks, ammonoids, bryozoans and foraminifera, indicating that it was deposited in a warm epicontinental sea that, while shallow, maintained open circulation. The period of deposition of the limestone represents the peak of the marine transgression into the North Perth Basin (Warris 1988).

The Darling and Urella Faults were very active during the Jurassic, and the uplifted Precambrian blocks east of the faults produced alluvial plain and fluvial deposits that culminated in the Late Jurassic Yarragadee Formation, consisting of up to 4500 m of poorly sorted, interbedded sandstone and siltstone. This style of sedimentation continued into the Early Cretaceous.

During the Neocomian, deposition was interrupted by uplift and erosion, associated with the onset of drifting during the breakup of Greater India away from the western margin of Australia. As a result of thermal cooling of the newly-formed continental margin, gradual subsidence of the shelf since the Cretaceous has produced a seaward-thickening wedge of marine carbonates beneath the slope of the North Perth Basin. This carbonate sequence is analogous to Late Cretaceous to Quaternary sequences in the adjacent Carnarvon Basin (Smith and Cowley 1987).

Offshore Stratigraphy

The offshore part of the North Perth Basin, in particular the Abrolhos Sub-basin, contains a thick sequence of Late Palaeozoic, Mesozoic and Tertiary sediments that are considered to exceed 8 km in thickness (Playford et al. 1976; Megallaa 1980). Results from the eight petroleum exploration wells drilled in the offshore region indicate that sediments thicken significantly west of the Northampton Block - Beagle Ridge basement high (Fig. 3). and that their stratigraphy is equivalent to the onshore North Perth Basin.

Both the Gun Island-1 and Houtman-1 wells encountered a relatively thick (up to about 2000 m) Late Jurassic Yarragadee Formation (Fig. 6) and neither well extended beyond the Cockleshell Gully Formation. These outer shelf wells penetrated a relatively thick (240-330 m) sequence of Middle Jurassic marine shales (Cadda Formation).

Closer to shore, the Batavia-1, Geelvink-1A, and Leander Reef-1

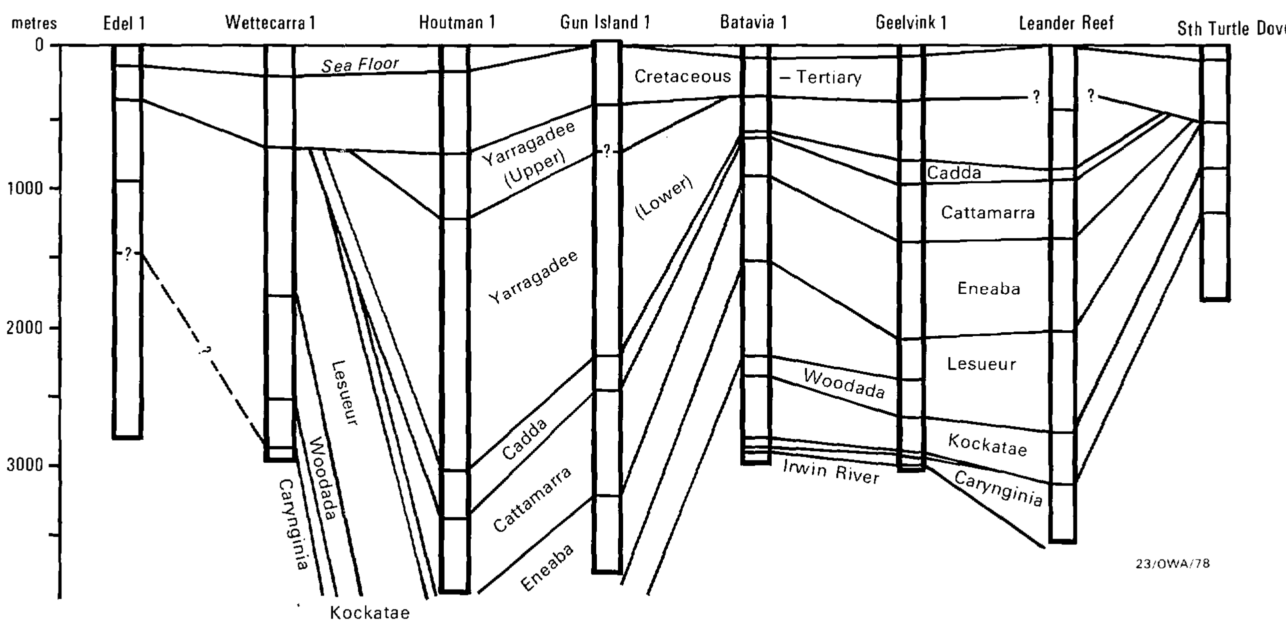


Fig. 6. Cross section of wells in the offshore North Perth Basin area.

wells (Fig. 6) encountered a thinner, but fairly complete Mesozoic sequence, unconformably overlying what appears to be a condensed Early Permian sequence. A basal Triassic sandstone sequence was encountered in Batavia-1 and Geelvink-1A, but it is absent in both Leander Reef-1 and Wittecarra-1. This unit is 20 m thick in Geelvink-1A and 56 m in Batavia-1. The sandstone consists of clean, rounded and well-sorted medium quartz, but porosity in this unit offshore has been significantly reduced by secondary quartz overgrowth. Its absence in the other wells has been attributed by Smith and Crowley (1987) to continuous reworking of these presumed strandline deposits, eventually restricting them to the tops of palaeo-highs on the tilted Permian fault-blocks.

The Jurassic sequence is absent in Wittecarra-1 to the north and South Turtle Dove-1B on the southwest flank of the Abrolhos Sub-basin. At Wittecarra-1 a thick sequence (950 m) of non-marine sandstones of the Late Triassic Lesueur Sandstone dominates the stratigraphy (Fig. 6). At South Turtle Dove-1B an extremely thin Cretaceous unit (18 m) unconformably overlies a relatively thin (662 m) Triassic sequence (Fig. 6).

DATA ACQUISITION AND PROCESSING

Cable Configuration

The seismic cable was 2400 m long, consisting of 48 channels each of 50 m length. Cable depth was monitored by depth detectors and controlled by SYNTRON individually-addressable birds. Target cable depth was 10 metres, and this was normally maintained within a range of ±2 m. The offset from the energy source to the centre of the first channel was 320 m.

Energy Source

Two BOLT 500 cu. in. (total of 16.4 L) airguns fired at 2000 psi provided the energy source. The guns were towed on either side of the streamer cable and nominal gun depth was 8 m.

Recording Parameters

Record length - 7.5 seconds
Sampling rate - 2 msec.
Shot spacing - 50 m (giving 24-fold CDP coverage)
High-cut filter - 128 Hz
Low-cut filter - 6 Hz
Data recorded in BMR modified SEG-Y format (demultiplexed)
Nominal ship speed - 5.5 knots

Seismic Processing

The seismic data were processed according to the following scheme:

1. geometry definition
2. digital resampling of the data to 4 msec.
3. display of neartrace and selected shots
4. FK filtering to remove refracted and direct arrivals; display of neartrace and selected shots (applied to all the shallow water data, usually down to 1-2 seconds water depth).
5. gain correction
6. velocity analysis (data resampled to 8 msec. for this process only)
7. selection of stacking velocities
8. muting
9. deconvolution (gapped)
10. NMO correction
11. non-gathered stacking (24-fold)
12. multiple suppression in the FK domain, followed by stacking (applied to all the data from the upper slope, i.e. from the shelf break down to 2-3 seconds water depth; not applied to data on the continental shelf)
13. post-stack deconvolution (spiking) and band-pass filtering
14. AGC and water bottom mute, giving final stack display
15. migration, AGC and water bottom mute, giving final migrated display

INTERPRETATION OF SEISMIC RESULTS

Structural and Stratigraphic Analysis

The following interpretation has been derived from the analysis of 2445 km of BMR seismic reflection data which was integrated with industry data. This section has been subdivided into those elements that pertain to the three sub-basins within the offshore North Perth Basin. These sub-basins are:

1. Edel Sub-basin,
2. Abrolhos Sub-basin, and
3. Houtman Sub-basin.

Edel Sub-basin

This is a new name to replace what has previously been referred to as the Edel Shelf or Edel Platform (Smith and Cowley 1987). The term "sub-basin" is applied because a relatively thick (at least 2.5 seconds TWT) pre-rift and rift fill sedimentary sequence is present in this region beneath a post-rift, aggradational sequence that has a reasonably uniform thickness of about 1.5 seconds (TWT). The rifted sequence is not clearly defined on those few BMR lines that extend into the sub-basin, except for line 16 (Fig. 7) where there are indications of tilted fault blocks below 1.5 seconds (TWT). However, the rifted sequence is clearly visible on industry lines that cross the sub-basin (e.g. Fig. 7E in Smith and Cowley 1987). Both these and line 16 show a series of shallow-dipping extensional faults that

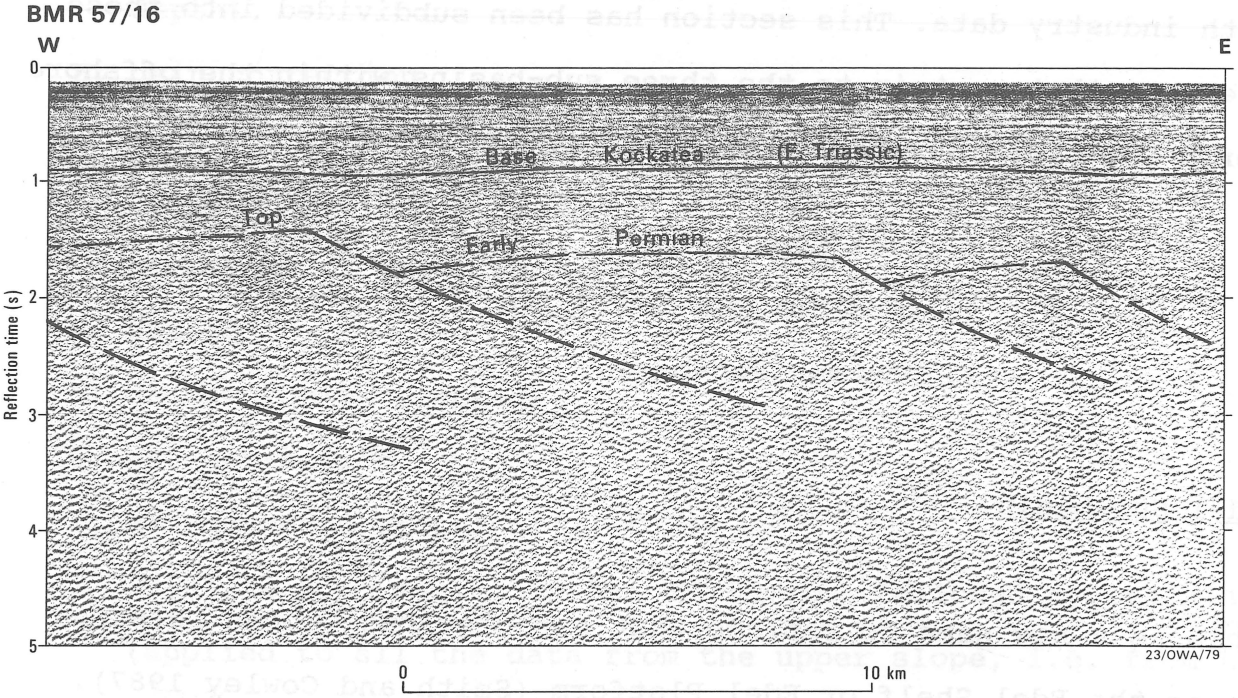


Fig. 7. Seismic interpretation of portion of BMR line 57/16 in the Edel Sub-basin. Location is shown in Fig. 4-A.

dip landwards (Figs. 7 & 8). Décollement of the faults is relatively shallow and at different levels. On the westernmost faults there are only small dip-slip displacements relative to the easterly faults, where extension is of the order of 20 %. We interpret the western faults have the oblique-slip motion, and implies that the boundary between the Edel and Abrolhos Sub-basins is a strike-slip zone.

Initially, the aggradational upper post-rift sequence was interpreted as Silurian Tumblagooda Sandstone, whereas Smith and Cowley (1987) interpreted the underlying tilted fault blocks to be composed of Tumblagooda Sandstone or possibly Precambrian rocks. From ties to wells in the south, we consider that rifting in the Edel Sub-basin took place in the Early Permian (Marshall and Lee 1987), and that the tilted fault blocks consist of lowermost Early Permian and older sediments. The stratigraphic succession in the Perth Basin, in particular the paucity of Devonian and Carboniferous rocks, would suggest that the rotated fault blocks do, in part, consist of Tumblagooda Sandstone.

Seismic sections show wedges of synrift sediments onlapping the tops of the rotated fault blocks and filling the half grabens. The synrift fill is considered to be Early Permian, probably consisting of the Irwin River Coal Measures, Holmwood Shale and Carynginia Formation. The marine units within this succession possibly represent restricted facies because of the size and isolated nature of each half graben. The top of the synrift sequence is truncated by an erosional unconformity that appears to be regional throughout the sub-basin and which forms the base of the aggradational post-rift succession (Figs. 7 & 8). Ties

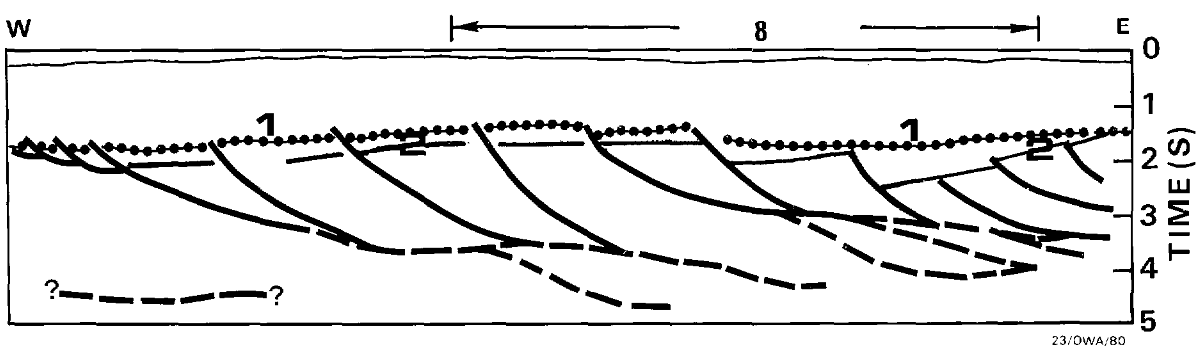


Fig. 8. Line-drawing interpretation of portion of BHP line 124B in the Edel Sub-basin. Reflector 1 - Early Triassic; 2 - Early Permian. Location is shown in Fig. 4-A.

with wells to the south indicate that the unconformity is the same age as the tops of the tilted fault blocks in the Abrolhos Sub-basin (i.e. late Early Permian Artinskian?).

Above the unconformity the post-rift sequence is relatively planar and horizontal, with only minor displacement on near-vertical, sag-phase faults that have generally developed above the extensional faults. Smith and Cowley (1987) indicate that the majority of the post-rift sediments are of Late Permian age; however, as a result of ties to wells and seismic lines to the south we suggest that a thick Triassic section is also present. Seismic data indicates that the base of the Kockatea Shale occurs at about 1.0 seconds (TWT). This would imply that a thick Late Permian sequence, which would be either the Wagina Sandstone or its equivalent, is present within the Edel Sub-basin, in addition to the Triassic sediments. At this stage we do not consider that any of the sediments below the Neocomian unconformity are Jurassic in age. This is largely based on the absence of Jurassic sediments in both Wittecarra-1 and Edel-1.

Within the Edel Sub-basin neither the pre-rift nor post-rift successions show any indication of differential subsidence that might have been expected as a result of cooling of the lithosphere in the post-rift phase. This suggests that there was minimal sub-detachment thinning beneath the sub-basin and that the sub-basin is the result of simple shear of the upper crust. This in turn suggests that the locus of extension in the sub-basin shifted to the west at a relatively early stage.

The only well drilled in the sub-basin, Edel-1, encountered Permian volcanics, sandstones and shales below what is considered to be Triassic sediments. Age control in this well is extremely poor; the only age data, which is from plant microfossils at around 1400 m, is Middle to Late Triassic (Ocean Ventures 1972). The Edel-1 stratigraphy, though poor, would tend to support an Early Triassic sequence, equivalent to the Kockatea Shale, below 1400 m, which in turn supports the interpretation of the base of the Kockatea Shale being at about 1.0 seconds (TWT) on the seismic records. The Edel-1 structure is considered by Smith and Cowley (1987) to be a result of igneous intrusion at depth. The presence of Early Permian volcanics in the well support this contention. The composition of the volcanics, nosean phonolites, lamprophyres and trachytes (Le Maitre 1972) probably indicates volcanism occurred during rifting. Domal structures, similar to the Edel-1 structure occur at the eastern ends of BMR lines 11 and 12. The ends of these lines are the closest BMR lines to Edel-1, and the domes possibly represent other areas of Early Permian igneous intrusion.

Abrolhos Sub-basin

The boundaries of the Abrolhos Sub-basin have been delineated in a previous section, but the nature of some of these boundaries has not been discussed. While the northeastern boundary with the Edel Sub-basin is considered to be strike-slip, further south the boundary appears as a simple monoclinal flexure with the Edel Sub-basin sitting relatively high and the Abrolhos Sub-basin sediments thickening westwards on top of inclined fault blocks (Figs. 9 and 10). Although the underlying structure cannot be resolved in the south, the differences in structure style on either side of the Edel - Abrolhos boundary imply a continuation

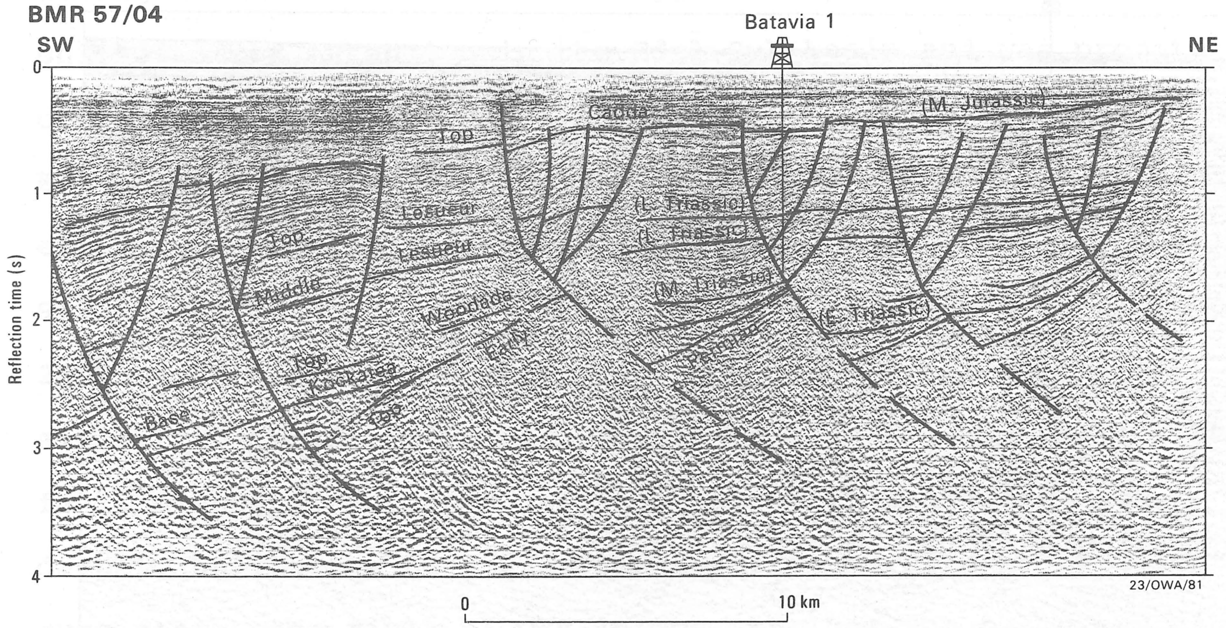


Fig. 9. Seismic interpretation of portion of BMR line 57/04 in the Abrolhos Sub-basin. Location is shown in Fig. 4-B.

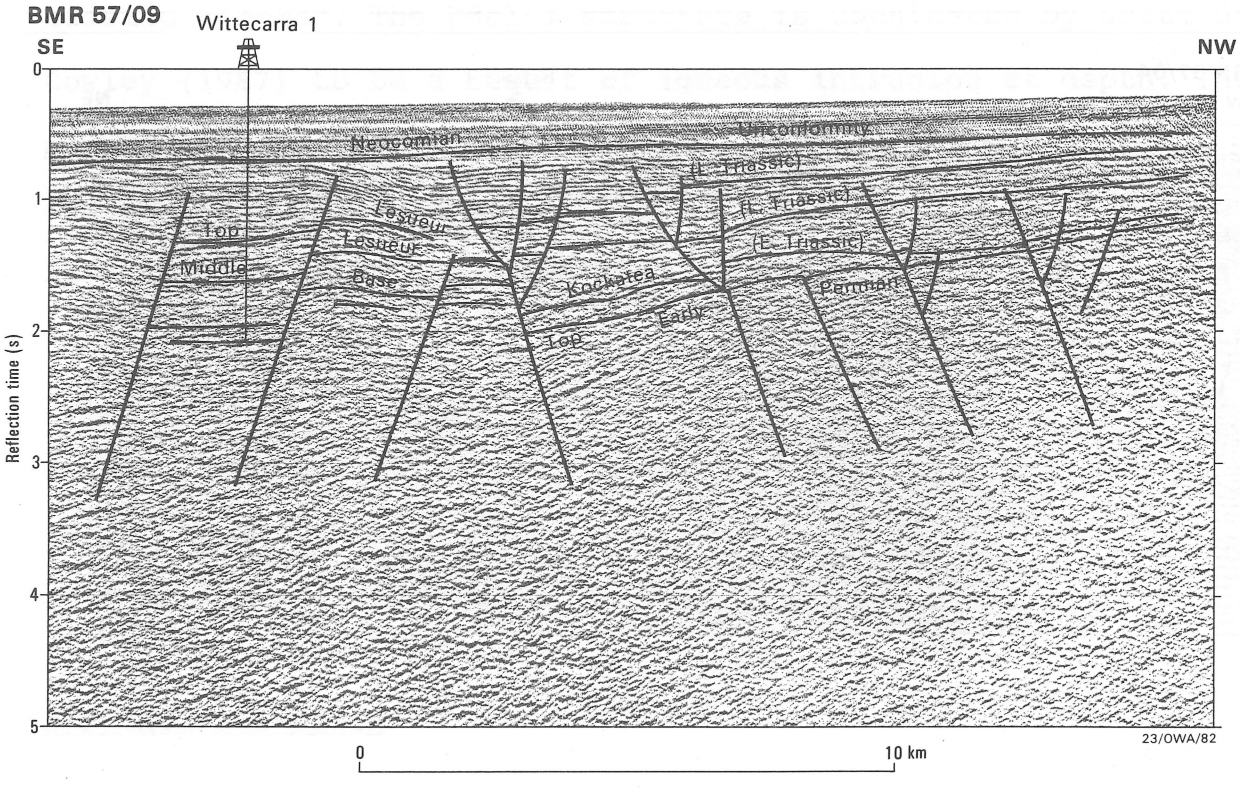


Fig. 10. Seismic interpretation of portion of BMR line 57/09 in the Abrolhos Sub-basin. Location is shown in Fig. 4-A.

of the strike-slip fault. The boundary with the Turtle Dove Ridge is also faulted, but there also appears to have been uplift of the basement ridge at some stage (Fig. 11).

Whereas rifting in the Edel Sub-basin is considered to have occurred during the early part of the Early Permian, in the Abrolhos Sub-basin rifting commenced somewhat later, probably during the Late Permian. This suggests that the locus of rifting shifted after extension in the Edel Sub-basin and was prematurely curtailed for an unknown reason. In the Abrolhos Sub-basin the Early Permian sequence is displaced by low-angle, east-dipping extensional faults forming a series of tilted fault blocks (Fig. 9). Extension within the larger fault blocks is of the order of 20-25 %. While the orientation of the extensional faults is similar to the Early Permian faults in the Edel Sub-basin, their fault planes are steeper and décollement is therefore much deeper. Unlike the Edel Sub-basin, where there is no differential subsidence, the fault blocks in the Abrolhos Sub-basin are high in the east ($\simeq$1.0 sec. TWT) and have subsided to at least 3 seconds near the western margin of the sub-basin (Fig. 12). This probably indicates that sub-detachment thinning did take place during this phase of rifting, and that the post-rift sag phase was controlled by decay of the thermal anomaly produced by the crustal thinning to create an asymmetric basinal profile.

Synrift sediments onlap the tops of the rotated fault blocks, but they form a relatively thin sequence, probably no more than a few hundred metres thick (Figs. 9 and 10). From mapping the base of the Kockatea Shale on seismic sections, it is apparent that while the top edges of the tilt blocks are sometimes planated and the

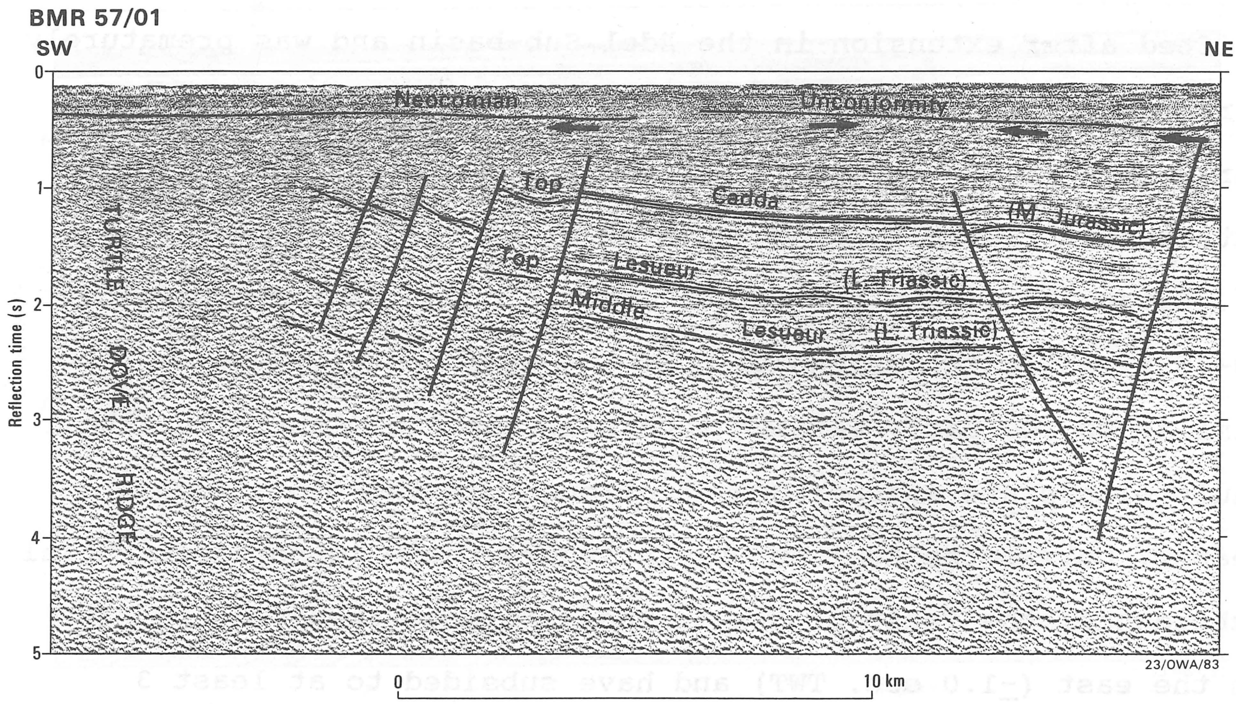
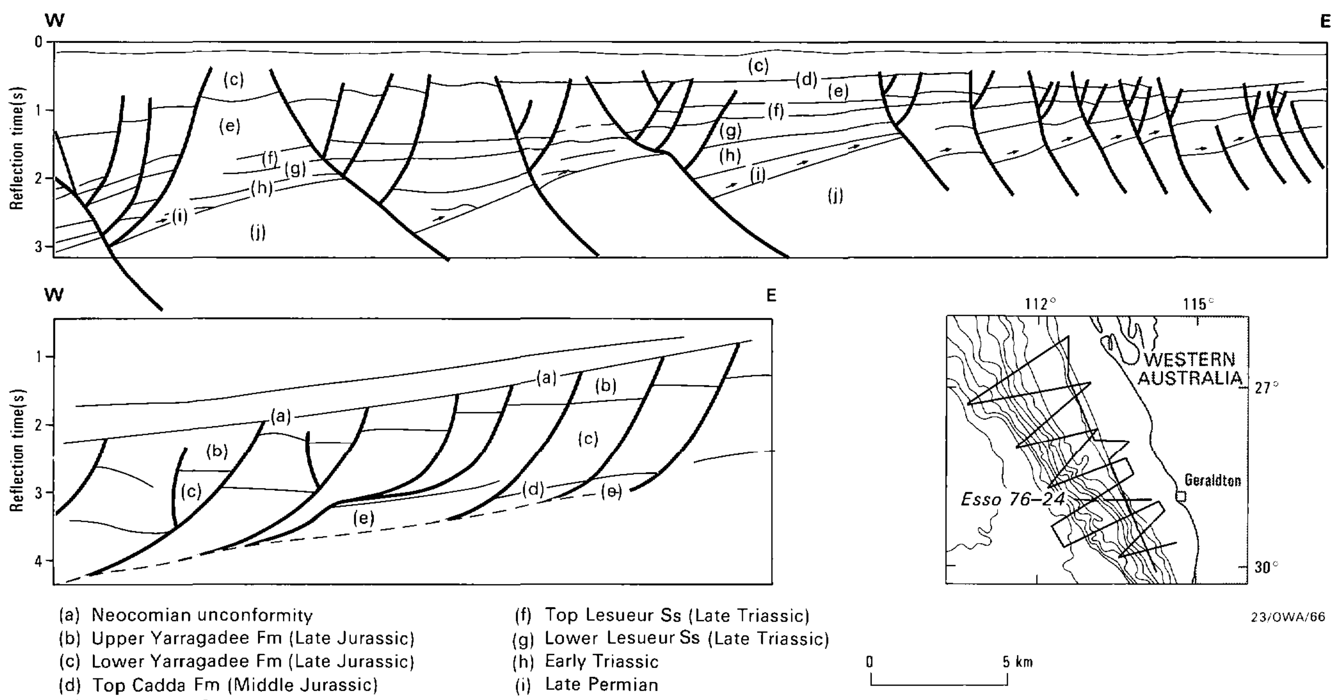


Fig. 11. Seismic interpretation of portion of BMR line 57/01 showing the Turtle Dove Ridge. Location is shown in Fig. 4-B.



(a) Neocomian unconformity
(b) Upper Yarragadee Fm (Late Jurassic)
(c) Lower Yarragadee Fm (Late Jurassic)
(d) Top Cadda Fm (Middle Jurassic)
(e) Cockleshell Gully Fm (Early Jurassic)
(f) Top Lesueur Ss (Late Triassic)
(g) Lower Lesueur Ss (Late Triassic)
(h) Early Triassic
(i) Late Permian
(j) Early Permian

Fig. 12. Line-drawing interpretation of Esso line 76/24. Location is also shown in Fig. 4-B.

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Kockatea Shale directly overlies them, the majority of synrift sediments are probably Late Permian equivalents of the Wagina Sandstone. These sediments are likely to be restricted marine rather than the fan delta depositional environment proposed by Bergmark and Evans (1987) for the Wagina Sandstone onshore.

The post-rift phase is marked by subsidence and deposition of a thick sequence of Triassic and Jurassic sediments (Figs. 9 & 12). Sag-phase deposition conforms to the general subsidence pattern of the sub-basin with a relatively thin sedimentary cover to the east ($\simeq$2500 m) becoming progressively thicker to the west, as can be seen in both seismic sections and exploration wells (Figs. 6, 9, & 10). Seismic sections indicate that the sag phase was essentially aggradational. On the western side of the basin, where sediments are thickest, the sag phase was accompanied by relatively high-angle normal faulting. These faults show little vertical displacement (<0.1 sec. TWT).

In the central and southeastern parts of the basin ties to wells, such as Batavia-1, Geelvink-1B, and Leander Reef-1, indicate more or less continuous deposition between the Early Triassic Kockatea Shale and the Late Jurassic Yarragadee Formation. However, along the eastern, southern and northern margins of the sub-basin Jurassic sediments are either totally or partly missing. This may be a result of erosion arround the breakup time. The Jurassic section is missing in the north (as shown by Wittecarra-1) and in the south, where the Jurassic progressively sub-crops over the Turtle Dove Ridge. It is also absent further south in South Turtle Dove-1B. In the east the Jurassic progressively sub-crops towards the boundary of the Edel Sub-basin (Fig. 12).

Reactivation of the older extensional faults in the Late Jurassic/Early Cretaceous is considered to have been brought about by oblique extension throughout the basin around the time of breakup (Marshall and Lee 1987). This reactivation manifests itself in propagation of the original fault through the post-rift sequence, coupled with the development of single, or more commonly, multiple antithetic faults (Figs. 9 & 12). In places, such as on the Geelvink structure, the interplay of faults is quite complex (Fig. 13). The geometry of the faults bears some resemblance to the flower structures associated with wrench faults. Although, there has probably been some lateral movement on these faults, but the amount of movement is considered to have been relatively minor. We suggest that this style of faulting occurred to accommodate the strain produced by oblique extension. Compressional structures have quite commonly developed within these fault blocks as a result of this style of movement, and vertical displacement is only of the order of 0.2 seconds (TWT). It is interesting that this type of reactivation is not apparent in the Edel Sub-basin, suggesting that there is decoupling between the two sub-basins, presumably along the proposed strike-slip boundary.

Houtman Sub-basin

The Houtman Sub-basin, as defined by Symonds and Cameron (1977), is a north-northwest trending, fault-bounded Mesozoic trough. They consider that the sub-basin is bounded to the east by a major fault downthrown to the west, and by a basement high along the western margin. To the southeast, they imply that the sub-basin is split into two limbs on either side of the Turtle Dove

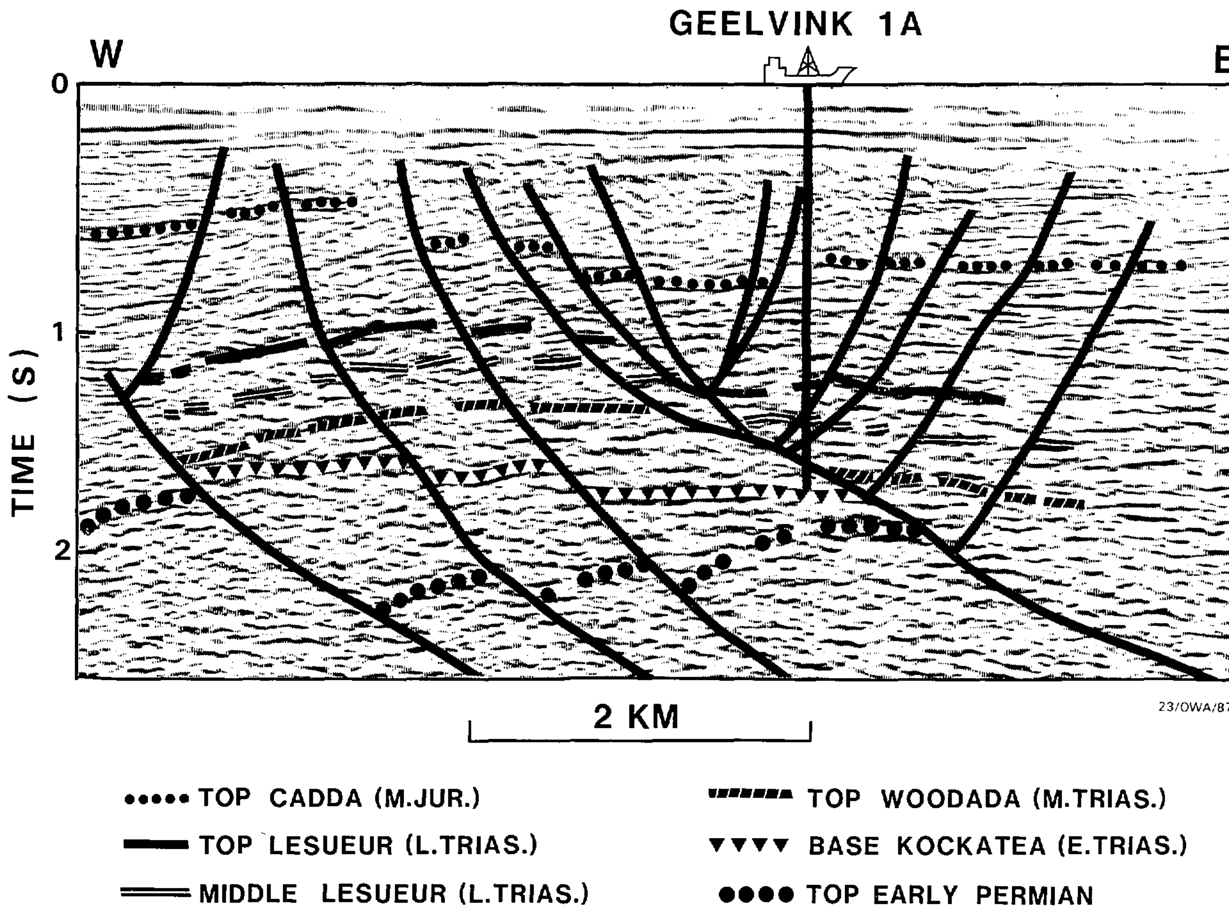

Fig. 13. Interpretation of Geelvink structure on portion of Diamond Shamrock line 85/04. Location is shown in 4-B.

Ridge. Sediments within the basin are considered by Symonds and Cameron (1977) to range in age from Permian to Triassic and Late Jurassic to Early Cretaceous. These sediments dip to the east and are cut by antithetic and vertical normal faults.

The recent BMR lines confirm the existence of a major sub-basin to the west of the Abrolhos Sub-basin, which we interpret to be the Houtman Sub-basin. In the southeast the Houtman Sub-basin is bounded and possibly faulted against the Turtle Dove Ridge. There is no clear evidence to suggest that the Houtman Sub-basin exists on the eastern side of the Turtle Dove Ridge as proposed by Symonds and Cameron (1977); the Abrolhos Sub-basin occupies this region.

The major eastern boundary between the Houtman and Abrolhos Sub-basins to the north of the Turtle Dove Ridge consists of a fault zone, which on the seismic sections appears as a segment where no coherent reflections are visible. This zone is of the order of 5-10 km in width, and it is usually present to the immediate east of the shelf break (Fig. 14-A). We interpret this wide fault zone is a major zone of strike-slip motion, mainly on the basis of differences in structure and sediment thickness on either side of the fault zone. For example, to the east (i.e. Abrolhos Sub-basin) there is a relatively thin Late Jurassic sequence with high angle faults cutting sag-phase (Triassic and Jurassic) sediments, whereas to the west in the Houtman Sub-basin the Late Jurassic sequence is considerably thicker and the low-angle extensional faults, with dipping in both way, are the major structures.

To the north the boundary between the Abrolhos and Houtman Sub-

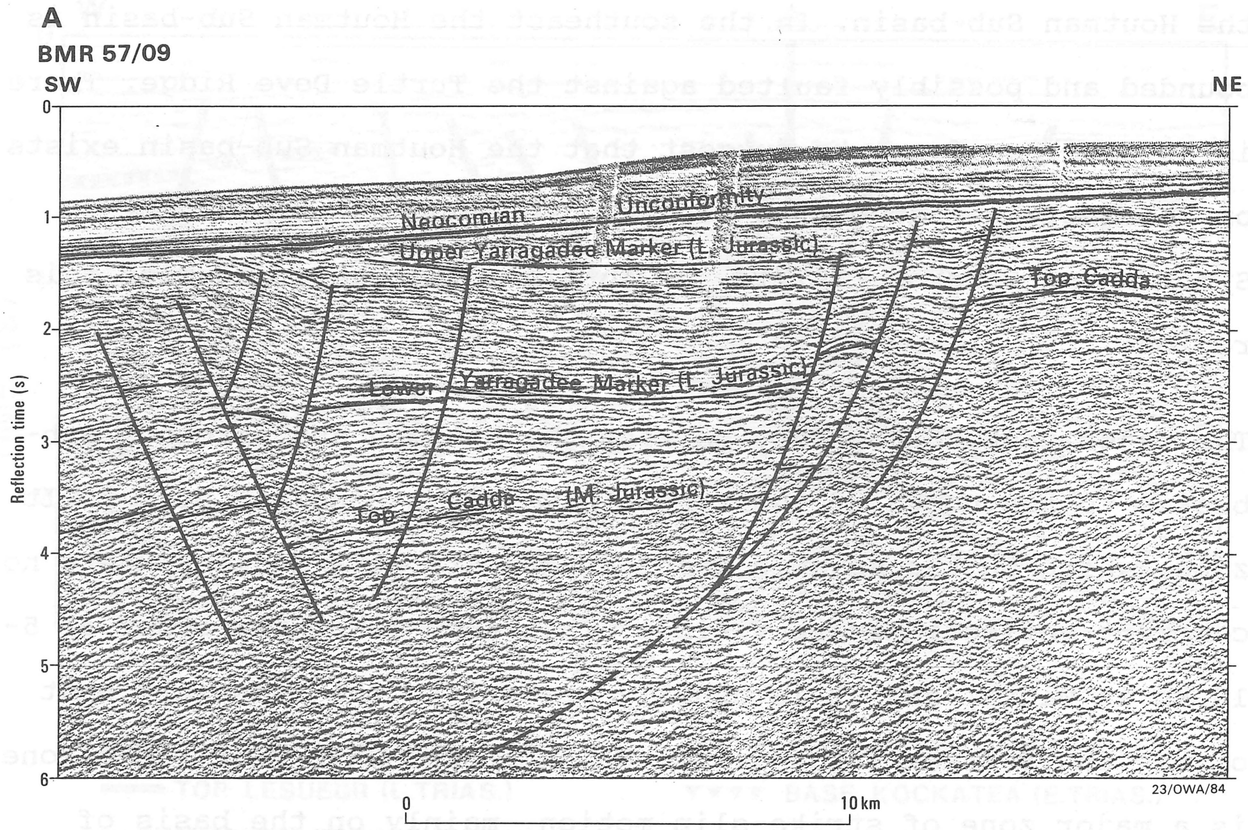

Fig. 14. (14.A) Seismic interpretations of portion of BMR line 57/09 in the Houtman Sub-basin. Interpretations include A, B and C sections. Locations are shown in Fig. 4-A&B..

B
BMR 57/09

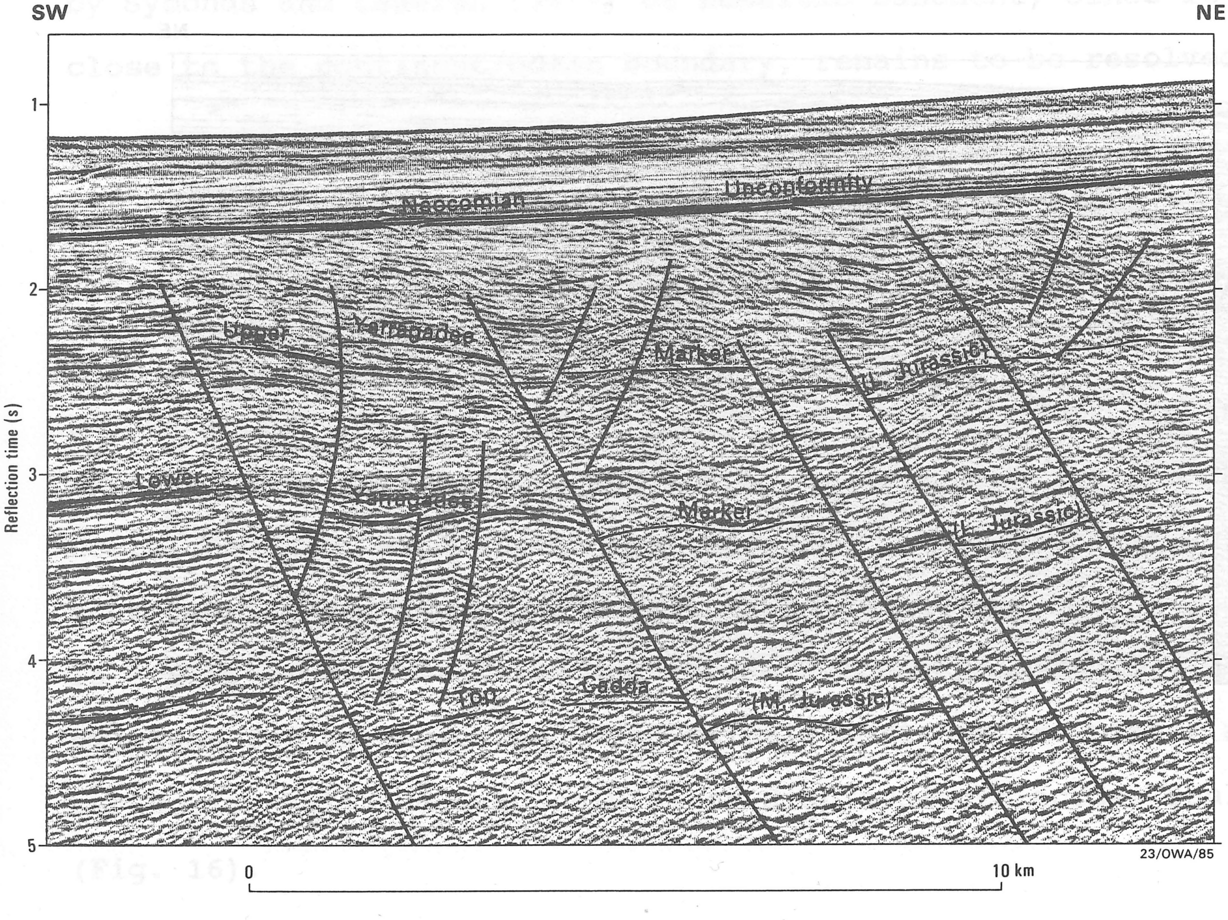

Fig. 14. Seismic interpretations of portion of BMR line 57/09 in
(14.B) the Houtman Sub-basin. Interpretations include A, B and C sections. Locations are shown in Fig. 4-A&B..

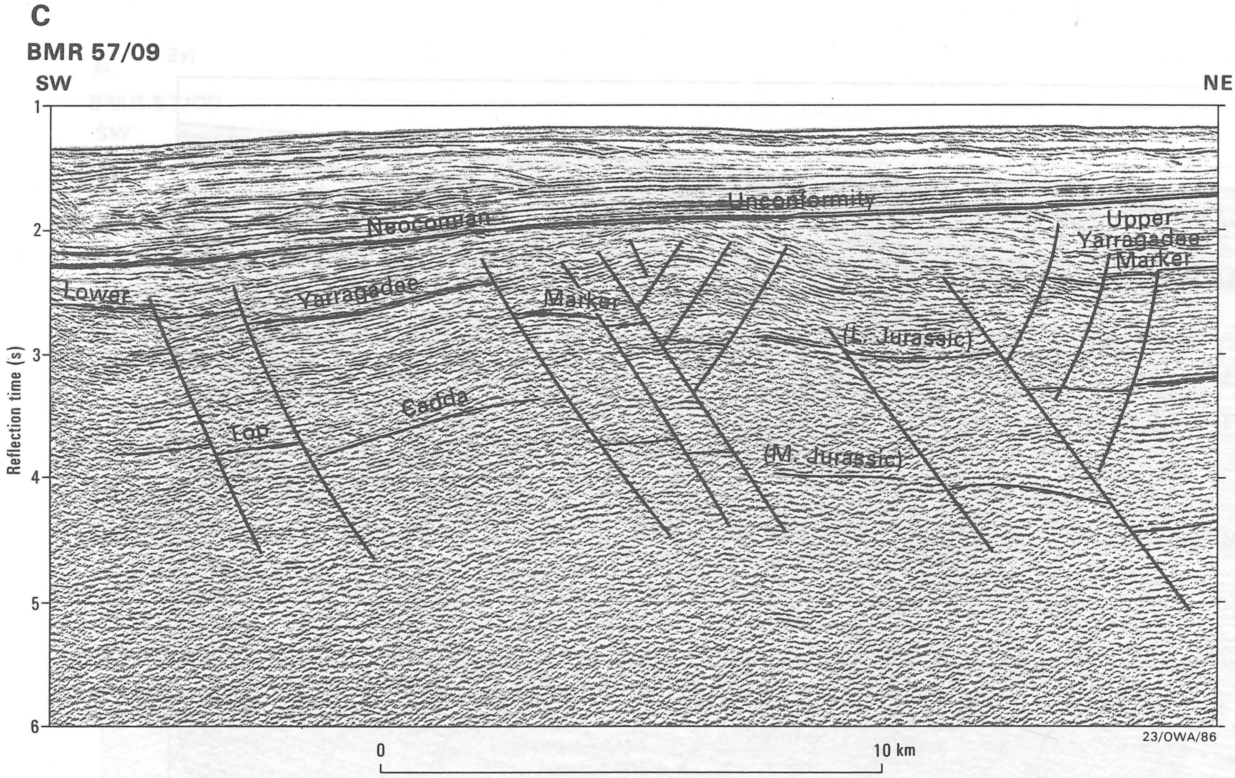

Fig. 14. Seismic interpretations of portion of BMR line 57/09 in
(14.C) the Houtman Sub-basin. Interpretations include A, B and C sections. Locations are shown in Fig. 4-A&B.

basin is poorly defined. However, the seismic lines indicate that north of 28^{o} the Abrolhos Sub-basin begins to narrow, and it appears that north of Wittecarra-1 the Houtman Sub-basin is directly adjacent to the Edel Sub-basin (Fig. 15-A). The western margin of the Houtman Sub-basin does appear to be bounded by basement, but whether this is "crystalline" basement as suggested by Symonds and Cameron (1977) or basaltic basement, since it is close to the continent/ocean boundary, remains to be resolved.

Faulting within the sub-basin is predominantly of two types; extensional faulting on the eastern margin of the sub-basin (Figs. 14 A, B & C). and wrench faulting on the western margin (Fig. 16). Extension is of the order of 15-20 % with major fault planes dipping to the west, as opposed to the easterly dipping extensional faults in the Edel and Abrolhos Sub-basins. In the north, however, extensional faults dip both east and west, with east-dipping faults on the eastern side of the sub-basin (Fig. 15 A & B). Wrench faulting occurs where there is virtually no evidence for extension and most seismic horizons are planar and sub-horizontal, and with only minor displacements across faults (Fig. 16).

Sediments within the sub-basin are considered to be predominantly Jurassic. This is based on ties to the Houtman-1 well, the only exploration well drilled so far in this sub-basin. It is possible to trace a prominent reflection, which is interpreted to be the top of the Cadda Shale (Middle Jurassic) from ties to the Houtman-1 well, along the eastern side of the sub-basin. (Fig. 14-A). However, in the central part of the sub-basin, the Cadda horizon is successively downfaulted to the west. In the western

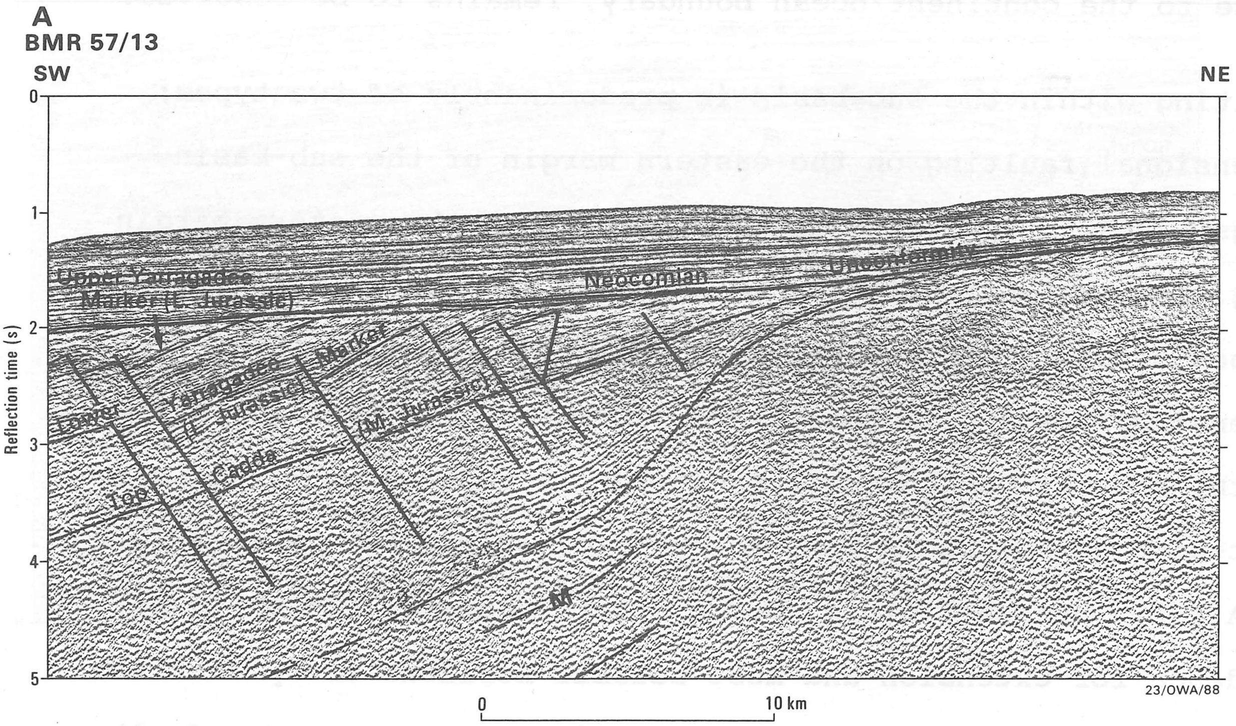

Fig. 15. Seismic interpretations of portion of BMR line 57/13 in (15.A) the Houtman Sub-basin. Interpretations consist of A and B parts. Locations are shown in Fig. 4-A.

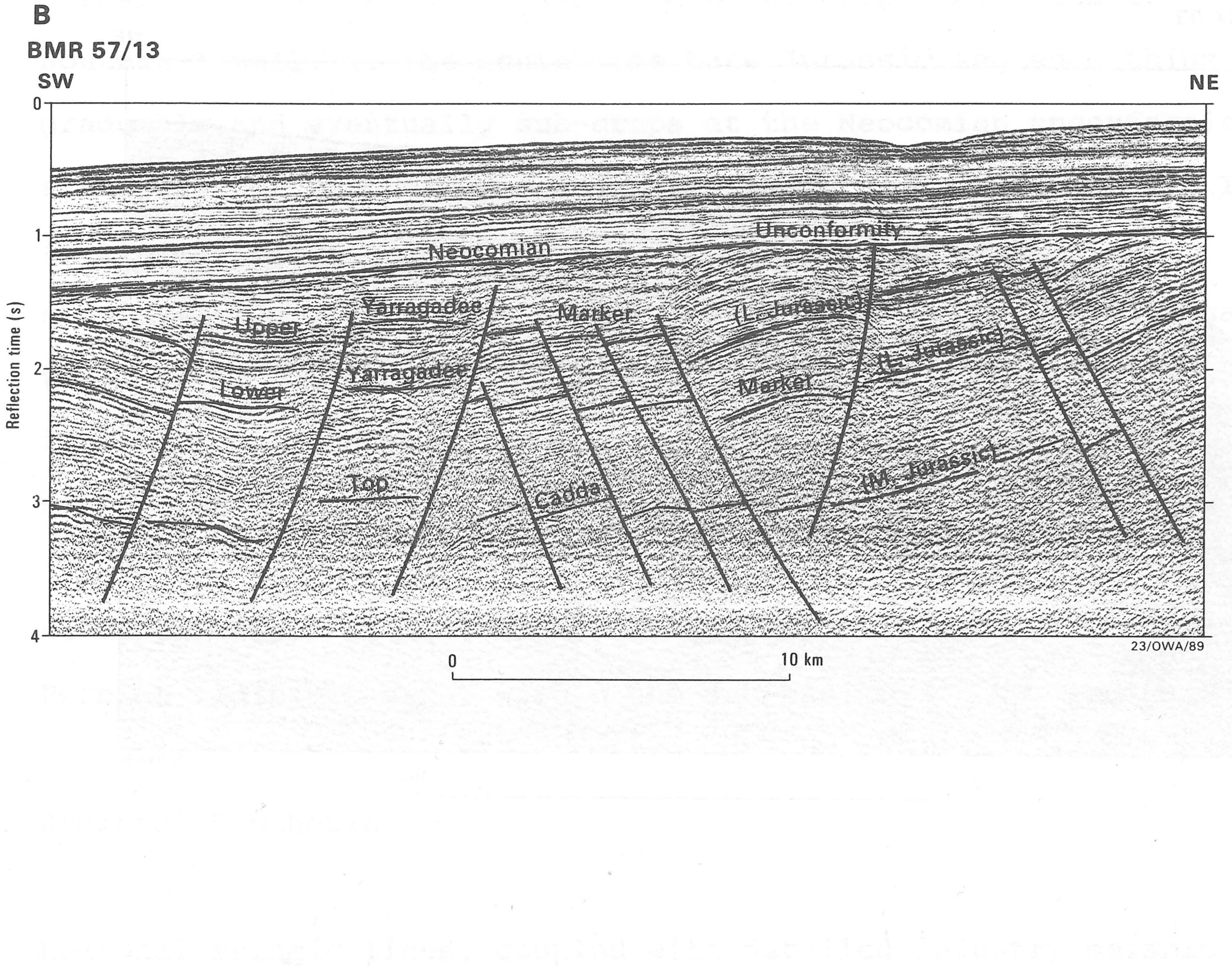

Fig. 15. Seismic interpretations of portion of BMR line 57/13 in
(15.B) the Houtman Sub-basin. Interpretations consist of A and B parts. Locations are shown in Fig. 4-A.

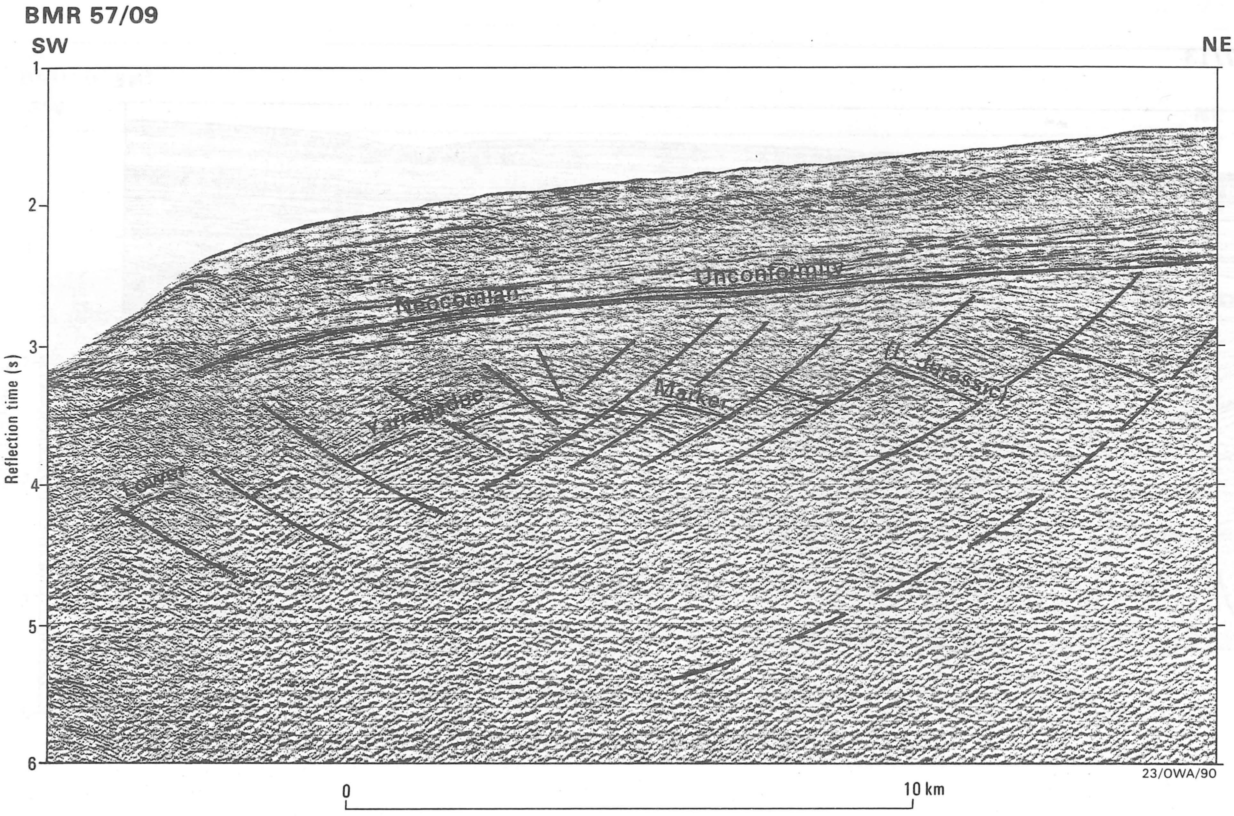

Fig. 16. Seismic interpretation of portion of BMR line 57/09 showing wrench faulting in the eastern Houtman Sub-basin. Location is shown in Fig. 4-B.

part of the sub-basin, where wrench faulting is dominant, a prominent reflection is interpreted as the lower Yarragadee Marker (Fig. 16). A thick sequence, which is equivalent to the Late Jurassic Yarragadee Formation, occurs throughout most of the sub-basin, but it does tend to thin or is absent in the north, and to the south in the vicinity of the Turtle Dove Ridge. This thinning of the Jurassic sediments can be seen in BMR line 18, a strike line on the outer shelf and upper slope that ties to the Houtman-1 well. To the south, the Late Jurassic sequence thins gradually and eventually sub-crops at the Neocomian unconformity along the northern edge of the Turtle Dove Ridge (Fig. 17-B). It is also apparent that the Early Jurassic sequences thin and eventually sub-crop along this basement high. It would seem that the lack of Jurassic sediments in the South Turtle Dove-1B well is a common feature over the entire ridge. Similarly, to the north, the Late Jurassic sediments thin substantially, but they do not sub-crop on line 18 (Fig. 17-A). Although they may exist at depth, there is no evidence to suggest that either Triassic or Permian sediments exist within the sub-basin.

Regional Synthesis

Regional seismic lines, coupled with detailed industry seismic and well data, have delineated three sub-basins within the offshore North Perth Basin. These sub-basins represent the products of rifting and extension that commenced in the Early Permian and culminated during the Neocomian with the separation of Australia from Greater India. Three phases of rifting are apparent, each phase resulting in the formation of a new sub-basin. While the timing between the formation of the Edel Sub-

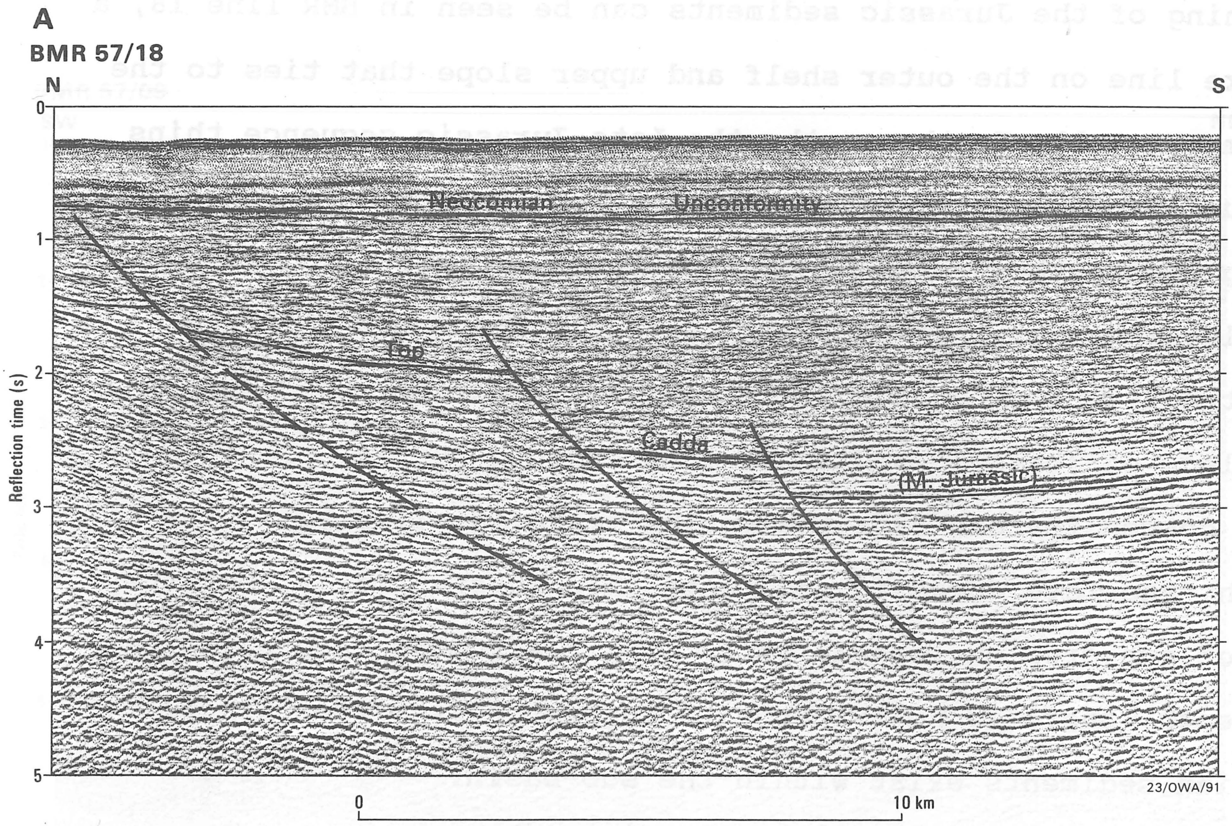

Fig. 17. (17.A) **Seismic interpretations of portion of BMR line 57/18 showing the N-S structures of the Houtman Sub-basin. There are A and B sections. Locations are shown in Fig. 4-B.**

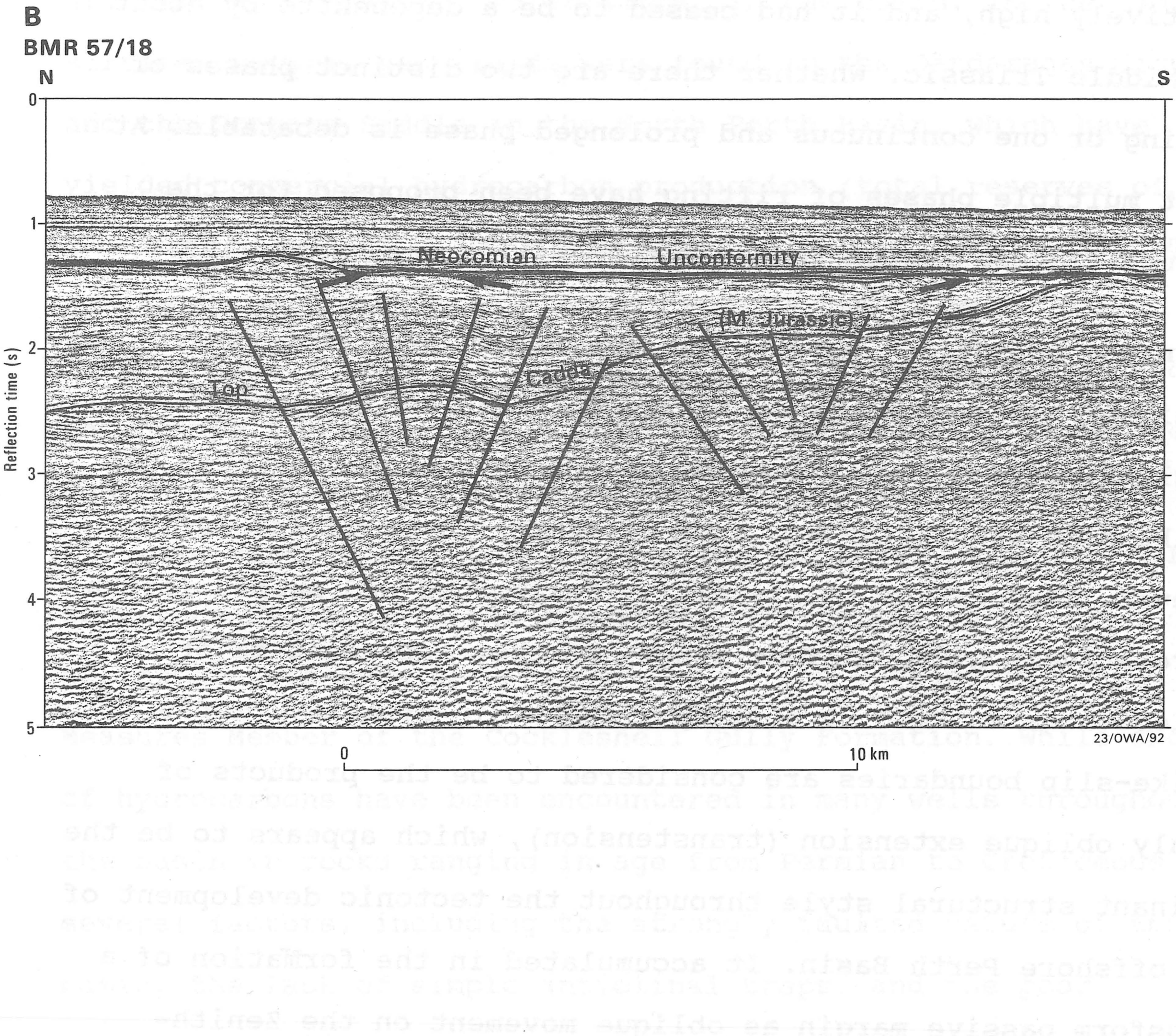

Fig. 17. Seismic interpretations of portion of BMR line 57/18 showing the N-S structures of the Houtman Sub-basin.
(17.B) There are A and B sections. Locations are shown in Fig. 4-B.

basin and the Abrolhos Sub-basin is relatively close, there is a gap of some 100 Ma between the timing of rifting in the Abrolhos and Houtman Sub-basins. During this interval there was large-scale subsidence of the Abrolhos Sub-basin, with large quantities of predominantly alluvial and fluvial sediments being deposited into the sub-basin; meanwhile, the Edel Sub-basin had remained relatively high, and it had ceased to be a depocentre by about the Middle Triassic. Whether there are two distinct phases of rifting or one continuous and prolonged phase is debatable. At least multiple phases of rifting have been proposed for the Exmouth Plateau region to the north (Williamson et al. 1988).

The major boundaries between the sub-basins have been postulated as either basement highs or strike-slip faults. Whereas the Beagle Ridge and Turtle Dove Ridge are obvious boundaries, the strike-slip boundaries are more difficult to prove and define. However, they can be fairly easily delineated and mapped (often as relatively wide, diffuse zones) as they represent major dislocations in both stratigraphy and basin geometry. These strike-slip boundaries are considered to be the products of highly oblique extension (transtension), which appears to be the dominant structural style throughout the tectonic development of the offshore Perth Basin. It accumulated in the formation of a transform passive margin as oblique movement on the Zenith-Wallaby Fracture Zone. The interpretation of the North Perth Basin as a transtensional basin has implications for petroleum exploration as discussed in the next section.

PETROLEUM POTENTIAL

Petroleum exploration in the Perth Basin commenced in 1954 (Playford et al. 1976), but it was not until 1959 that the first deep well was drilled (BMR-10A). Over 100 wells have been drilled, both onshore and offshore, in the basin. In the mid sixties, several gas fields were found in the Dandaragan Trough and the Dongara Saddle in the North Perth Basin, which have yielded commercial hydrocarbon production (total reserves of 0.59 x 10^6 m^3 oil; 0.05 x 10^6 m^3 condensate; 3.01 x 10^9 m^3 gas). The producing sections in the Dongara Saddle are of Permian and Triassic age. These include the Irwin River Coal Measures and Carynginia Formation (Early Permian), the Yardarino Sandstone Member of the Wagina Sandstone (Late Permian), and the basal Triassic sandstone at the base of the Kockatea Shale (Dongara Sandstone Member). In the Dandaragan Trough, oil and gas/condensate have been produced from the Cattamarra Coal Measures Member of the Cockleshell Gully Formation. While shows of hydrocarbons have been encountered in many wells throughout the basin in rocks ranging in age from Permian to Cretaceous, several factors, including the strongly faulted nature of the basin, the lack of simple anticlinal traps, and the poor reservoir quality of many of the rocks, have attributed to the lack of significant commercial finds.

While the overall structural trapping and reservoir qualities of the basin can be considered to be poor, there is general agreement that the basin contains many potential source rocks of Permian to Jurassic age (Kantsler and Cook 1979; Thomas 1984).

These include the Holmwood Shale, Irwin Coal Measures, and Carynginia Formation (Permian); the Kockatea Shale (Triassic); and the Jurassic Cattamarra Coal Measures Member, Cadda Formation and Yarragadee Formation (Thomas 1984). Most of these units contain significant amounts of organic material, but it is mainly related to coal or dispersed, terrestrial organic matter. Oils and condensates throughout the basin are extremely waxy and mostly paraffinic in nature (Powell and McKirdy 1976), indicating a terrestrial source. Source rocks in the North Perth Basin contain Type III kerogen and are mainly gas-prone. An exception is the marine Kockatea Shale, which is a Type II source rock and is oil-prone (Thomas 1984). The gas produced at Dongara, Mondarra, and Yardarino is believed to be generated from the Lower Triassic and Permian source rocks, predominantly the latter, whereas the source of oil is considered to be the Kockatea Shale (Thomas 1984; Warris 1988). The Early Jurassic Cattamarra Coal Measures Member provides both source and reservoir for gas/condensate in the central Dandaragan Trough (Gingin and Walyering fields).

According to Kantsler and Cook (1979) the Perth Basin has a geothermal gradient range of between 20^{o} C/km and 40^{o} C/km, with higher than average gradients (>30^{o} C/km) associated with shallow basement. In the North Perth Basin, Thomas (1984) shows present-day gradients of the order of 19^{o} to 50^{o} C/km, with higher gradients associated with the Beagle Ridge and Northampton Block and low gradients in the Dandaragan Trough (Fig. 18). Vitrinite reflectance data from the North Perth Basin show that maturation levels and rank gradients vary throughout this part of the basin (Kantsler and Cook 1979; Thomas 1984). The thermal anomaly in the

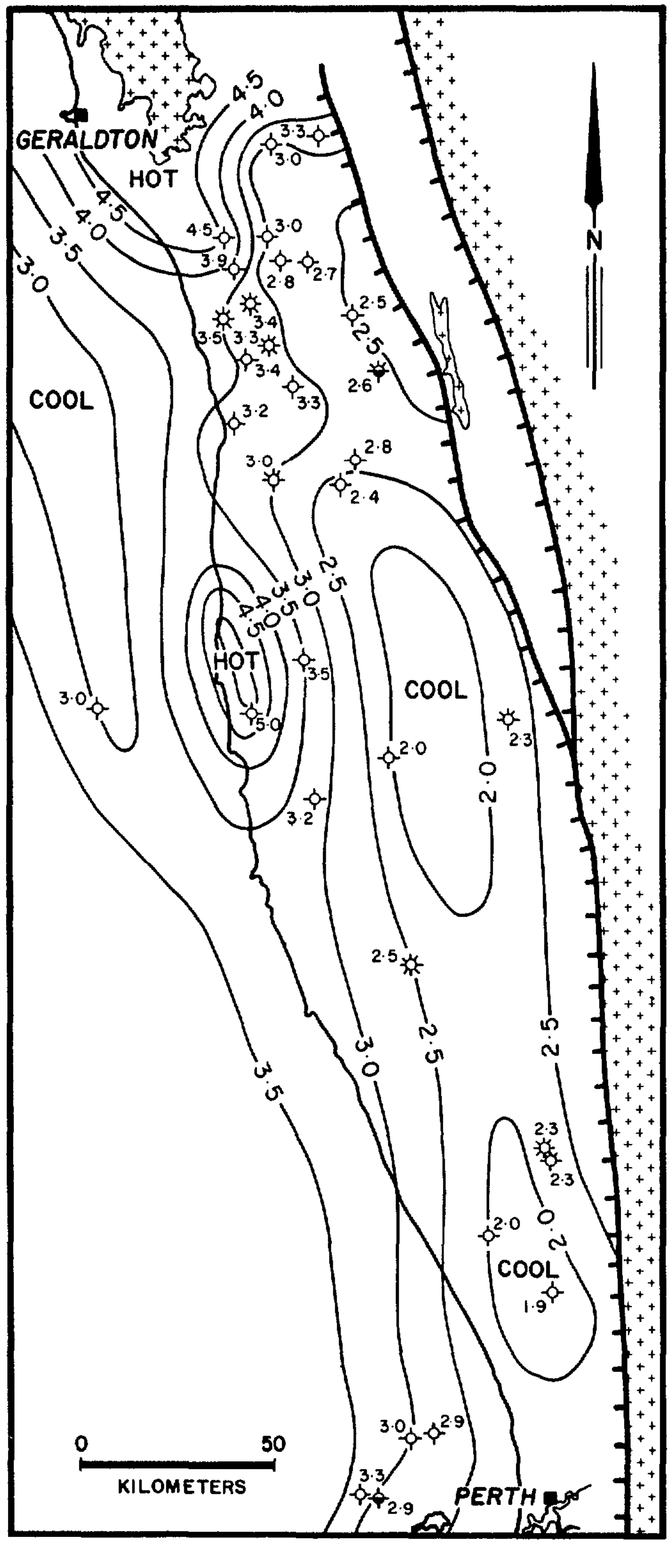

Fig. 18. Geothermal gradient map of Perth Basin (after Thomas 1986).

vicinity of the Beagle Ridge has previously been attributed to high heatflow between the Permian and Jurassic, associated with initial rifting in the basin (Kantsler and Cook 1979), whereas Thomas (1979, 1984) associates it with igneous intrusion during the Neocomian. However, it is also probably due to a thermal effect associated with a basement high.

Offshore Exploration

Offshore petroleum exploration has mainly been confined to the Vlaming Sub-basin in the south and the Abrolhos Sub-basin in the north. Geohistory analysis of some of the offshore wells in the Perth Basin (Falvey and Deighton 1982; Smith and Cowley 1987) indicate initial high basement subsidence rates that decay exponentially to almost zero. All six wells analysed show fairly similar subsidence patterns, except for greater apparent subsidence in the North Perth Basin since breakup.

In the North Perth Basin it is considered that the Early Mesozoic section in the Abrolhos Sub-basin is currently within the zone of oil generation, and probably commenced oil generation during the Cretaceous (Kantsler and Cook 1979). Minor gas shows were encountered in Houtman-1 when drilling in the Jurassic section of the well (Galloway 1978a) and minor signs of oil were encountered in the Early Jurassic Cockleshell Gully Formation in Leander Reef-1 (Lindner 1985).

Source Rocks

Within the Permian marine sequences the organic material is both sparse and oxidised (Smith and Cowley 1987), whereas the Irwin River Coal Measures contains up to 14 percent organic carbon. In the Abrolhos Sub-basin it is likely that these units are either overmature or gas prone. Within the Edel Sub-basin it has been suggested that liquid hydrocarbons may have been produced from Permian sediments earlier in its burial history and that these have subsequently migrated to higher levels or been converted to gas (Smith and Cowley 1987).

The best source potential, both onshore and offshore, is in the Kockatea Shale. The basal part of the Kockatea Shale tends to have a higher organic carbon content, is rich in acritarchs and dinoflagellates, and is oil prone. In Batavia-1 the main zone of oil generation (R_V 0.5-1.0%) lies within the Kockatea Shale (Cook 1978); however, TOC is relatively low, averaging 0.54% (Burns 1978). At Wittecarra-1 TOC values within the Kockatea Shale are also low (0.1-0.5%), which led Smith and Cowley (1987) to suggest that in the northern Abrolhos Sub-basin marine conditions were more open than in the south. The highest TOC values in Wittecarra-1 were in the overlying Woodada Formation, but whereas the Kockatea Shale is in the main phase of oil generation, the Woodada Formation is less mature and would only recently have generated significant hydrocarbons (Smith and Cowley 1987). A similar situation exists within this formation in the Batavia-1 well.

Higher in the sequence, potential source rocks include the Cattamarra Coal Measures Member, Cadda Shale and Yarragadee Formation. The Cattamarra Coal Measures Member is relatively high in organic carbon, and carbonaceous shales within this unit can be considered as fair to good oil-prone source rocks (Warris 1988). Similarly, marine shales within the Cadda Formation have relatively high TOC concentrations and are considered to be the best potential source rock within the Jurassic sequence (Warris 1988; Smith and Cowley 1987). In the Abrolhos Sub-basin all three units are considered to be immature, most having vitrinite reflectance of $\leq$0.5 percent. However, it is possible that these units are more mature in the Houtman Sub-basin where they are more deeply buried. The presence of gas in Houtman-1 supports this and implies that sediments in the Houtman Sub-basin contain at least gas-prone sources. The increased thickness of the marine Cadda Formation offshore, as seen in Gun Island-1 and Houtman-1 (Fig. 6) is a possible indication that good oil-prone source beds are also present in the Houtman Sub-basin.

Reservoirs and Seals

Lower Permian units appear to be uniformly poor with respect to reservoir quality. Most sandstones are tight, mainly because of the presence of carbonate cements and clay matrix. The indication that an equivalent of the Late Permian Wagina Sandstone could be present as synrift fill within the half grabens of the Abrolhos Sub-basin presents the possibility that a Wagina Sandstone play, contrary to opinions expressed by Bergmark and Evans (1987), does exist offshore. A Wagina Sandstone reservoir in the half grabens would be sourced from the underlying and adjacent Early Permian sediments within the rotated fault blocks, whereas updip the Kockatea Shale could be both source and seal.

The basal Triassic sandstone has, in the past, been the major target for petroleum exploration in the North Perth Basin. This has arisen because it is the most productive reservoir onshore (e.g. Dongara, Mondarra, Yardarino). The Dongara Sandstone Member is a medium to very coarse grained well-sorted quartzose sandstone with an abundant clay matrix (Bergmark and Evans 1987). While Hosemann (1971) considered that the basal Triassic sandstone was deposited as beach bar and strandline accumulations, Bergmark and Evans (1987) cite the presence of dickite within the clay matrix as evidence for a non-marine origin, and propose a fluvial environment of deposition. The patchy distribution of the basal Triassic sandstone in wells offshore (and onshore) indicates that this unit has either been removed by erosion, or that it has a fairly restricted depositional environment. Smith and Cowley (1987) suggest that the sandstone is restricted to the flanks of Permian tilt blocks or onlapping basement blocks.

The basal Triassic sandstone has been encountered in Batavia-1 and Geelvink-1A, but it is absent in other wells that reached the base of the Triassic (e.g. Wittecarra-1, Leander Reef-1, South Turtle Dove-1B). In Batavia-1 a 56 m thick section of clean quartz sandstone, with minor siltstone, shale and coal, is present at the base of the Kockatea Shale, whereas in Geelvink-1A it is 20 m thick. Both wells indicate that the sandstone is impermeable, with secondary quartz overgrowths, clay matrix and silica cement reducing porosity to less than 10 percent. The thickness of the basal Triassic sandstone in Batavia-1 is as thick as the greatest thickness onshore (average thickness onshore is of the order of 20-40 m). The paucity of this unit offshore in relation to the thick sequence in Batavia-1 could indicate that this sandstone offshore is an equivalent of the Late Permian Wagina Sandstone that is proposed to exist as a synrift fill within the half grabens formed by the Early Permian tilt blocks.

Higher in the sequence, potential reservoirs exist in the Lesueur Sandstone, Cockleshell Gully Formation, Cadda Shale and Yarragadee Formation. Porosities are likely to be variable within most of these units. Oil shows in Leander Reef-1 indicate migration of hydrocarbons, presumably from the Kockatea Shale, to units higher in the sequence where sands are likely to be less tight. Potential seals in the basin include the Kockatea Shale, Cockleshell Gully Formation and the Cadda Shale. The Neocomian unconformity is unlikely to be a good seal in the Edel and Abrolhos Sub-basins because of its proximity to the seafloor. However, the unconformity could be a prospective seal in the Houtman Sub-basin where it is overlain by a thick marine sedimentary sequence.

Basin Prospectivity

The three sub-basins within the offshore North Perth Basin, while having similar sedimentary histories and equivalent formations, present widely different play concepts.

<u>Edel Sub-basin</u>

Sediment thickness in this relatively unexplored sub-basin appears to be of the order of 8000 m. The only well in the sub-basin (Edel-1) penetrated volcanics and poorly fossiliferous sediments of presumed Triassic and Permian age. However, seismic data in the region indicates that large portions of the sub-basin are likely to be unaffected by volcanism, and our assignment of ages to various reflections suggest that the sub-basin contains prospective Early Triassic and Permian sediments. Extension of the lower sequence has produced rotated fault blocks which could have formed potential structural traps, although there appears to be a general lack of roll-over associated with these structures. The potential for an unconformity trap exists at the top of the Early Permian where there is reasonable relief developed. Such a trap would have the ability to accumulate hydrocarbons produced from Early Permian synrift sediments and earlier pre-rift sediments. While the latter are probably overmature, the synrift sediments are likely to have good source potential and could be mature. If the post-rift sediments of the Edel Sub-basin were not substantially eroded and deposition did cease by the Middle Triassic, as postulated, then the synrift sediments could be mature. It has not been substantiated whether the Kockatea Shale is present in the Edel Sub-basin. What has been interpreted as the base of the Kockatea Shale has been tied to wells in the south, but whether it is the same organic-rich sequence as occurs onshore and in the Abrolhos Sub-basin is not known. However, the thin cover of younger sediments in the Edel Sub-basin could mean that any equivalent of the Kockatea Shale is not sufficiently mature to have generated significant quantities of hydrocarbons. Obviously, the Edel Sub-basin requires more drilling and seismic data before its petroleum potential can be adequately evaluated.

Abrolhos Sub-basin

This sub-basin has received the most attention from exploration companies in the past, and because of its structural and stratigraphic elements, and shallow water depth, it will probably attract most exploration effort in the offshore Perth Basin in the future. While the six wells drilled in the sub-basin have not found any significant hydrocarbon discoveries there have been shows in one well (Leander Reef-1). Many of the early wells were drilled on complex structures that are related to reactivation of the older extensional faults. In Geelvink-1A, the wrench-style faulting produced keystone structures, but most structures would have been breached by the extensive reactivation faulting. Most other wells have been drilled over similar, if less complex, features. Compressional structures produced by reactivation in the Late Jurassic/Early Cretaceous still represent the best structural trap within the sub-basin, but it is possible that hydrocarbons produced within the Early Triassic and Early Permian section have migrated up the faults to these higher levels. It is significant that the only shows within the sub-basin were in the Cockleshell Gully Formation (Early Jurassic) associated with the compressional structures.

All wells drilled to date appear to have penetrated strata that can be considered to contain mature source rocks. The presence of these source rocks, which are equivalent to those onshore in the Dongara Saddle and Dandaragan Trough, and the existence of numerous, fault-bounded structural traps, indicate that the Abrolhos Sub-basin has the potential to be a significant hydrocarbon province.

Houtman Sub-basin

The position of this sub-basin beneath the continental margin places most of it in water depths that are considered to be too deep for exploration at the present time. However, there appear to be some parts of the sub-basin that do occur in relatively shallow water, particularly in the north. The only well in the sub-basin, Houtman-1, was drilled on its eastern flank. The presence of a thick Jurassic section in the well makes it attractive from the viewpoint of the possibility of a mature sequence that is of a different age to that elsewhere within the offshore region of the North Perth Basin.

Potential structural traps within the Houtman Sub-basin are structures produced by extensional faults on its eastern margin, and compressional structures produced by wrench faulting towards its centre. The latter structures are in relatively deep water (>1000 m) and are thus unattractive at the present time. The extensional faults have produced only minor roll-over structures, and these tend to be quite small because of the closely-spaced nature of the faulting. However, some potential structures do exist at what has been mapped as the top of the Cadda Shale, which is also a potentially good seal from indications elsewhere within the Perth Basin.

The possibility of unconformity traps is quite good, because of the relative relief and amount of burial of the Neocomian unconformity within the sub-basin. This is the best potential trap in the sub-basin as it has the ability to accumulate hydrocarbons that have migrated along faults and/or porous strata that sub-crop at the Neocomian unconformity (Fig. 13). Again, the water depth over these prospects is the major constraint.

REFERENCES

Apthorpe, M.C. (1979). Depositional history of the upper Cretaceous of the Northwest Shelf, based upon Foraminifera. APEA Journal, 19, 74-89.

Bergmark, S.L. and Evans, P.R. (1987). Geology controls on reservoir quality of the North Perth Basin. APEA Journal, 318-330.

Branson, J.C. (1974). Structure of the western margin of the Australian continent. Oil and Gas, 20-9, 24-35.

Burns, B.J. (1978). Geohistory, Batavia-1, Abrolhos Basin. In: Galloway, M.C. (ed.), Batavia well completion report. Esso Australia Ltd. (unpubl.).

Carrigy, M.A. and Fairbridge, R.W. (1954). Recent sedimentation, physiography and structure of the continental shelves of Western Australia. Roy. Soc. West. Australia J., 38, 65-95.

Cook, A.C. (1978). Organic petrology of a suite of samples from Batavia-1. In: Galloway, M.C. (ed.), Batavia well completion report. Esso Australia Ltd. (unpubl.).

Falvey, D.A. (1974). The development of continental margins in plate tectonic theory. APEA Journal, 14, 95-106.

Falvey, D.A. and Deighton, I. (1982). Recent advances in burial and thermal geohistory analysis. APEA Journal, 22, 65-81.

Falvey, D.A. and Mutter, J.C. (1981). Regional plate tectonics and the evolution of Australia's passive continental margins. BMR J. Aust. Geol. Geophys., 6, 1-29.

Falvey, D.A. and Veevers, J.J. (1974). Physiography of the Exmouth and Scott Plateaus, Western Australia, and adjacent Wharton Basin. Mar. Geol., 17, 21-59.

Galloway, M.C. (1978a). Houtman-1 well completion report. Esso Australia Ltd. (unpubl.).

Galloway, M.C. (1978b). Batavia-1 well completion report. Esso Australia Ltd. (unpubl.).

Hawkins, L.V., Hennion, J.F., Nafe, J.E. and Thyer, R.F. (1965). Geophysical investigations in the area of the Perth Basin, Western Australia. Geophysics, 30, 1026-1052.

Hawkins, R.D. (1969). Gun Island No. 1 well completion report. BP Petroleum Development Australia Pty Ltd. (unpubl.).

Hosemann, P. (1971). The stratigraphy of basal Triassic sandstone, North Perth Basin, western Australia. APEA Journal, 11, 59-63.

Johnstone, M.H. and Willmott, S.P. (1966). Stratigraphy of the Permian of the northern Perth Basin. APEA Journal, 6, 100-104.

Jones, D.K. (1976). Perth Basin, In: Economic Geology of Australia and Papua New Guinea, Petroleum. Leslie, R.B., Evans, H.J., and Knight, C.L., (eds.), Australian Inst. Mining Metall. Mon., 7, 108-126.

Jones, D.K. and Pearson, G.R. (1972). Tectonic elements of the Perth Basin, APEA Journal, 12, 17-22.

Kantsler, A.J. and Cook, A.C. (1973). Maturation patterns in the Perth Basin. APEA Journal, 19, 94-107.

Larson, R.L. (1977). Early Cretaceous breakup of Gondwanaland off Western Australia. Geology, 5, 57-60.

Larson, R.L., Mutter, J.C., Diebold, J.B., Carpenter, G.B. and Symonds. P. (1979). Cuvier Basin: a product of ocean crust formation by Early Cretaceous rifting off Western Australia. Earth Planet. Sci. Lett., 45, 105-114.

Lavering, I.H. (1985). Permian environments and palaeogeography of the onshore Carnarvon Basin and implications for petroleum prospectivity. PESA Journal 7, 40-46.

Le Maitre, R.W. (1972). Report on volcanic rocks from the Edel No. 1 well. In: Edel No. 1 well completion report, Ocean Ventures Pty Ltd. (unpubl.).

Lindner, A.W. (1985). Oil and gas development in Australia in 1984. Amer. Assoc. Petrol. Geologists Bull., 60, 1856-1870.

Markl, R.G. (1974a). Evidence for the breakup of eastern Gondwanaland by the early Cretaceous. Nature, 251, 196-200.

Markl, R.G. (1974b). Bathymetric map of the eastern Indian Ocean. Initial Rep. Deep Sea Drilling Project, 26, 967-968.

Markl, R.G. (1978a). Further evidence for the Early Cretaceous breakup of Gondwanaland off southwestern Australia, Mar. Geol., 26, 41-48.

Markl, R.G. (1978b). Basement morphology and rift geometry near the former junction of India, Australia and Antarctica. Earth

Planet. Sci. Lett., 39, 211-225.

Marshall, J.F. and Lee, C.S. (1987). Tectonic framework of the North Perth Basin, western Australia. BMR Research Symposium 1987, Applied Extension Tectonics, 173-177.

McWhae, J.R.H., Playford, P.E., Lindner, A.W., Glenister, B.F., and Balme, B.E. (1958). The stratigraphy of Western Australia. Geol. Soc. Australia Jour., 4, 1-161.

Meath, J.R. and Wright, J.C. (1979). Geelvink No. 1 and No. 1A well completion report, Perth Basin WA-13-P. West Australian Petroleum Pty Ltd. (unpubl.).

Megallaa, M.N. (1980). A geophysical study of the central-southern Carnarvon Basin. Geol. Surv. West. Australia Rec., 1979/10, 112 pp.

Ocean Ventures Pty Ltd. (1972). Edel No. 1 well completion report (unpubl.).

Petkovic, P. (1975). Geophysical results from southwest margin. Bur. Miner. Resour. Aust. Rec., 1975/180.

Playford, P.E., Cockbain, A.E. and Low, G.H. (1976). Geology of Perth Basin. Geol. Surv. West. Australia Bull., 124, 311 pp.

Powell, T.G. and McKirdy, D.M. (1976). Geochemical character of crude oils from Australia and Papua New Guinea. In: Leslie, R.B., Evans, H.J. and Knight, C.L. (eds.), The Economic Geology of Australia and Papua New Guinea, part 3, Petroleum. Aust. Inst. of Mining and Metall., pp. 107-184.

Quilty, P.G. (1980). Sedimentation cycles in the Cretaceous and

Cenozoic of Western Australia. Tectonophysics, 63, 349-366.

Quilty, P.G. Lowry, D.C., Moore, A.M.G. and Thomas, B.M. (in press). The Fremantle Canyon, Western Australia - development and geological history. Mar. Geol.

Shell Development (Australia) Pty Ltd. (1973). Interpretation report on scientific investigation, conducted with M.V. Petrel (unpubl.).

Smith, G.C. and Cowley, R.G. (1987). The tectono-stratigraphy and petroleum potential of the north Abrolhos Sub-basin, western Australia. APEA Journal, 112-136.

Symonds, P.A. and Cameron, P.J. (1977). The structure and stratigraphy of the Carnarvon Terrace and Wallaby Plateau. APEA Journal, 17, 30-41.

Thomas, B.M. (1979). Geochemical analysis of hydrocarbon occurrences in the north Perth Basin, Australia. Amer. Assoc. Petrol. Geologists Bull., 63, 1092-1107.

Thomas, B.M. (1984). Hydrocarbons, source rocks and maturity trends in the Northern Perth Basin, Australia. In: Demaison, G. and Murris, R.J. (eds), Petroleum Geochemistry and Basin Evaluation. Amer. Assoc. Petrol. Geologists Memoir, 35, 391-403.

Veevers, J.J. (1984). Phanerozoic earth history of Australia. Oxford Geological Sciences series No. 2, Oxford University Press, New York, 418 pp.

Veevers, J.J. and Heirtzler, J.R. et al. (1974). Initial report of Deep Sea Drilling Project, leg 27. U.S. Govt. Printing

Office, Washington, D.C..

Veevers, J.J., Tayton, J.W., Johnson, B.D. and Hansen, L. (1985). Magnetic expression of the continent-ocean boundary between the western margin of Australia and the eastern Indian Ocean. J. Geophysics, 56, 106-120.

Vening Meinesz, F.A. (1948). Gravity expeditions at sea. In: Mulder, A.J. (ed.) Delft, Drukkerij Waltman, 4, 1923-1939.

von Stackelberg, U., Exon, N.F., von Rad, U., Quilty, P., Shafik, S., Beiersdorf, H., Seibertz, E., Veevers, J.J. (1980). Geology of the Exmouth and Wallaby Plateaus off northwest Australia: Sampling of seismic sequences. BMR J. Aust. Geol. Geophys., 5, 113-140.

Williamson, P.E., Kravis, S., Falvey, D.A. and N.W. Australia Study Group (1988). Crustal structure of the Exmouth Plateau region. International Workshop & Symposium, Seismic Probing of Continents and their Margin. 159.

Warris, B.J. (1988). The geology of the Mount Horner oilfield, perth Basin, western Australia. APEA Journal, 88-99.

Yeates, A.N., Bradshaw, M.T., Dickins, J.M., Brakel, A.T., Exon, N.F., Langford, R.P., Mulholland, S.M., Totterdell, J.M. and Yeung, M. (1986). The Westralian Superbasin: an Australian link with Tethys. In: McKenzie, K.G. (ed.), Proceeding of the International Symposium on Shallow Tethys 2, 199-213.