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GEOLOGICAL CROSS-SECTION ACROSS THE OFFSHORE NORTHERN CARNARVON BASIN

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TABLE OF CONTENTS

SUMMARY

The Offshore Northern Carnarvon Basin in total contains over 17 km of Early Palaeozoic to recent sediment, which comprises maximum thicknesses of over 10 km of Permo-Carboniferous to recent sediment (Westralian Superbasin) and 7 km of Pre-Visean sediment. It is the second most prolific hydrocarbon province in Australia, containing one giant oil field (Barrow Island) and numerous large accumulations of liquid and gaseous hydrocarbons. The major hydrocarbon accumulations and shows are mainly reservoired in either Late Triassic or Early Cretaceous sediments, that have porosity and permeability ranging from excellent to poor. Good reservoirs also exist in Permian sequences. Source potential of the overall sequence is very good, but widely variable from Permian units with intervals of high organic carbon contents to very thick and productive units such as the Jurassic with consistently fair to good organic carbon contents. The maturation history of the region is complex, being dependant on the nature of local hydrocarbon sources and the timing of regional heating events associated with Jurassic breakup and later Cainozoic structural events. Along the inshore part of the cross-section there is a "window" into the Pre-Permian tectonic history of the Northwest Shelf, that suggest initial basin development in the Early Ordovician with compressive tectonics and erosion in the Visean. Relaxation in the post-Visean period initiated the Westralian Superbasin. In the Mesozoic at least two, and possibly three periods of strike slip tectonics have affected this area, combining transtensional, simple strike slip and transpressional structural domains. A speculative link is suggested between these structural terrains and the timing of regional sea floor spreading and reactivation of pre-existing local fault trends.

INTRODUCTION

DATA SET

CANDACE 1 (OCCIDENTAL, 1982)
HERMITE 1 (WAPET, 1977)
MERMAID 1 (WAPET, 1978)
EMMA 1 (OCCIDENTAL, 1983)
CAMPBELL 2 (BOND, 1986)
TRYAL ROCKS 1 (WAPET, 1970)
GORGON 1 (WAPET, 1981)
ZEEPAARD 1 (ESSO, 1980)
ZEEWULF 1 (ESSO, 1979)
VINCK 1 (ESSO, 1980)
ODP 766 (OCEAN DRILLING PROGRAM, 1989)

O82 MARINE SEISMIC SURVEY (OCCIDENTAL, 1982 - 82)
NORMA MARINE SEISMIC SURVEY (WESMINCO, 1985 - 85N)
DEBORAH MARINE SEISMIC SURVEY (MESA, 1981 - 81)
X78A MARINE SEISMIC SURVEY (ESSO, 1978 - X78)
SCIENTIFIC INVESTIGATION 10SL (GSI, 1976 - WAS76)
EXMOUTH PLATEAU SURVEY 1986, SURVEY 55 (BMR, 1986 - 55)

SCALE

The cross-section has been drawn at 1:100,000 scale with a vertical to horizontal exaggeration of 1. The total length of the line is 712 km and has a maximum depth of approximately 10 km.

HORIZONS DRAWN

A total of 14 horizons were carried on the seismic and drawn on the cross-sections (Plate 1);

1) Cainozoic - Late Miocene - top Cz4
2) Cretaceous - Top Cretaceous - top K11
3) Cretaceous - Top Cenomanian - top K8
4) Cretaceous - Base Aptian - base K4
5) Cretaceous - Valanginian/Hauterivian - intra K2
6) Jurassic - Top Jurassic - top J10
7) Jurassic - Callovian - top J6
8) Triassic - Top Triassic
9) Triassic - Base Carnian - base T5
10) Permian - Top Permian - top P7
11) Carboniferous - Visean Unconformity
12) Carboniferous ?/Devonian ?
13) Early Palaeozoic ?
14) Basement - Top igneous basement

TIME DEPTH PLOTS

Time/depth plots have been drawn for eleven wells (Plate 2). These plots are not burial history curves, but simply represent the palaeontological dating performed in each well, and show the precise nature of the biostratigraphic control which exists for the cross-section. The boxes drawn on the time/depth curves are the actual depth range of the palaeontological zones assigned in the well completion report.

The age dating is reliable for all wells. The dating in the older wells has been supplemented with updates by Morgan and Ingram (1988) where required. The plot made for ODP 766 is only general in nature as the age control was derived from the initial reports of the drilling, which had no specific sample depth locations and zonations, but just a diagram of a generalised stratigraphic column and stages with depth.

SEISMIC QUALITY

The majority of the seismic data was of good quality especially in the deeper water areas. The western end of line 82-38 is of very poor quality; from our investigations this may be a result of poor initial stacking velocities which differ significantly from the subsequent well velocity data. Seismic line BMR 55-2 was recorded in twenty-four hour time along the horizontal axis rather than distance, and as such the location along the cross-section is at best only approximate. The distance travelled by the survey vessel per unit time was fairly constant along this line, and thus an approximation was made to relate the time travelled as equal to a constant ratio of the distance travelled, thus allowing digitisation of the events and conversion to depth on computer. To accurately locate events on the cross-section on this line it will be necessary to refer to the time of day (number above the cross-section) and replot onto the base map showing the line length and time of day intervals (Plate 1 - Location Map). However, despite the above, for the purposes of the cross-section and at the scale drawn, the locations are considered to be accurate.

RESULTS

DATING OF HORIZONS

Basement

Mermaid 1 encountered a granitic wash overlying what was described as a granitic gneiss containing "micro-gneiss". No age date was mentioned within the well completion report, although a Proterozoic age was assigned due to correlation with onshore outcrop.

Devonian ? and Carboniferous ?

No wells intersect sediments dated as Carboniferous or Devonian, but the dated sequence in Candace 1 penetrates to near the base of the Permian, and on seismic is underlain by over two seconds of sediment which contains at least one significant unconformity and may include Early Palaeozoic sediments (Plate 1 - Section J-K). The base of Candace 1 contains an undated sequence of pyroclastic breccia which may be of Pre-Permian age. An extrapolation was made onto the cross-section of the sequence penetrated in Kybra 1 which included Early Carboniferous sediments (Bentley, 1988).

Permian

Late Permian sediments (time slice P 6 to P7 - Kazanian to Tatarian) were penetrated in Mermaid 1 as a thin sequence overlying igneous basement, and Candace 1 encountered almost the entire Permian sequence. None of the other wells along the cross-section penetrate into the Permian.

Triassic

Candace 1 intersected Early Triassic sediments (time slices T1 to T3 - Scythian to Ladinian); Hermite 1, Mermaid 1 and Gorgon 1 intersected Early to Late Triassic sequences (comprising time slices T1 to T6 - Scythian to Norian); Zeepaard 1 and Zeewulf 1 intersected the Late Triassic (time slices T5 to T6 - Carnian to Rhaetian); Vinck 1 intersected a very thick (2 km) latest Triassic sequence (time slice T6 - Norian to Rhaetian). The resolution of the age control in Zeepaard 1, Zeewulf 1 and Vinck 1 is not sufficient to be assured of the exact biostratigraphic correlation between them. However on the interpretation presented here (Plate 2) it appears from facies and age correlation that almost 2 km of Late Triassic sediment could have been eroded from the other wells on the Exmouth Plateau relative to Vinck 1.

Jurassic

Gorgon 1, Zeepaard 1, Zeewulf 1 and Vinck 1 intersected a thin sequence of Late Jurassic sediments (time slices J8 to J10 - Oxfordian to Tithonian). A thicker Middle and Late Jurassic sequence was penetrated in Emma 1, Campbell 2 and Tryal Rocks 1 (time slices J6 to J10 - Bathonian to Tithonian). In Hermite 1 a thick Early to Late Jurassic sequence was intersected (time slices J1 to J8 - Hettangian to Oxfordian).

Cretaceous

An almost complete Cretaceous sequence is present in all wells, except for the absence of; time slice K1 (Berriasian) in Candace 1, Emma 1, Mermaid 1 and ODP 766; time slice K11 (Late Maastrichtian) in Zeepaard 1 and Zeewulf 1; and K4 (Aptian) in Zeewulf 1. There is no age control for the Cretaceous in Hermite 1, or for the Late Cretaceous in Candace 1, Mermaid 1, Campbell 2 and Gorgon 1. There is poor resolution of the age control in time slices K4 and K3 (Aptian to Barremian) in Tryal Rocks 1.

Cainozoic

Tryal Rocks 1, Zeewulf 1 and ODP 766 are the only wells to have consistent age control throughout the Cainozoic, with segments of time slices ranging from Cz1 to 5 (Paleocene to Miocene) being absent. Vinck 1, Gorgon 1, Campbell 2, Emma 1, Mermaid 1, Candace 1 and Hermite 1 have no age control at all.

TIME AND FACIES DIAGRAMS

Time and facies correlation diagrams were drawn by extrapolating the time/depth plots for each well to produce time space, time slice correlation and time slice - facies diagrams (Plate 2). All three diagrams essentially portray similar data, except that the time space diagram is plotted against time and the time slice correlation and time slice facies diagrams are plotted against depths using the base of the Cretaceous as a datum. The reliability of the extrapolations can be directly assessed by examining the data points on the time depth plots of each well.

Time Space

This diagram shows the significant breaks in deposition (unconformities and unrecognised condensed intervals) evident from the well data along the cross-section. They include;

- Late Triassic (time slice T6 - Rhaetian)
- Late Triassic to Late Jurassic (time slice T6 to time slice J8 - Rhaetian to Oxfordian/Kimmeridgian)
- Late Jurassic (time slice J8 - Oxfordian to Kimmeridgian)
- Early Cretaceous (time slices K1 to K2 - Berriasian to Valanginian)
- Late Cretaceous - Early Cainozoic (time slices K11 to Cz1 - Maastrichtian to Paleocene)
- Late Cainozoic (time slices Cz3 to Cz4 - Oligocene to Late Miocene)

Time Slice Correlation

Although only a thin Late Permian sequence is penetrated in Mermaid 1, on seismic this sequence appears to thicken rapidly to the west on the downthrown side of the major fault systems, before dipping off the bottom of the seismic records on line 82-38 (Section H-I - Plates 1, 5 & 6). Candace 1 has an almost complete Permian sequence, which on adjacent seismic shows considerable evidence of thickening into the faults which were very active prior to and during the Permian, resulting in the deposition of a number of syn-depositional fan systems (Plates 7 & 8). By comparison with the region of the western Timor Sea on the Ashmore Platform, and the Onshore Carnarvon Basin sequence, Permian and older Palaeozoic sediments were expected to underlie the Offshore Carnarvon Basin. Evidence of pre-Permian sediments occurs on seismic lines inshore from Barrow Island (82-144 - Section J-K - Plates 1, 7 & 8).

Within the Triassic there is very little thickness change between time slices T1 and T4 (Scythian - Ladinian) when Mermaid 1 and Gorgon 1 are compared. In the Late Triassic the tops and bases of time slices T5 and T6 are usually absent as they were not penetrated or have been truncated, thus not allowing comparison. (See discussion below on Vinck 1 time slice T6 - Time Slice Facies Correlation). On seismic, no evidence of thickening is evident except at the top of time slice T6 where a marine unit onlaps from east to west in the vicinity of Vinck 1 (Plate 1 Section A-B). Identifying regional thickening trends on seismic is complicated by the recurrence of small rotated fault blocks.

Thick Jurassic sediments are evident on seismic within the Kangaroo Trough, but only a relatively thin (≈600 m) incomplete sequence has been penetrated along the cross-section in Emma 1, with a thicker more complete sequence in Hermite 1 (≈ 1300 m). On the Exmouth Plateau only a thin veneer of time slices J10 to J8 (Oxfordian to Tithonian) is evident in the wells, but down dip between the rotated Triassic fault blocks a thicker sequence exists which could extend into the Early Jurassic (Section C-D - Plate 1).

Cretaceous sediments are present in all wells, ranging from time slices K1 to K11 (Berriasian to Maastrichtian). The sequence thickens offshore to around Zeepaard 1, whereupon it thins offshore to ODP 766. Local build-ups of Cretaceous sediments occur along the cross-section within time slice K1 (Berriasian) and in time slice K8 (Cenomanian)(Section C-D - Plates 1, 3 & 4), as well as being evident in the well correlations.

Although there is poor age control in the Cainozoic and a number of depositional breaks, the overall sequence thickens offshore to around Gorgon 1, whereupon it thins offshore to ODP 766.

Time Slice Facies

The Early Permian comprises paralic and fluvial sequences. It is overlain by Late Permian paralic sediments which thin as they onlap igneous basement. These units probably pass offshore into marine units. On seismic the Permian includes fan sequences adjacent to the major fault systems and high blocks.

The Early Triassic penetrated in the inshore wells contains a thick marine sequence which is overlain in the Late Triassic by an alternating sequence of paralic and fluvial sediments. In Gorgon 1 the Early Triassic (time slices T3 to T1) sequence contains no marine influence. This may be an artefact of the resolution of the age control in this well which could conceivably only contain time slice T3 and none of the earlier Triassic. The Late Triassic sediments in the wells in the offshore areas are dominated by fluvial environments with some paralic settings. Thus comparison of the Late Triassic environments shows that whilst the inshore wells contain a predominance of paralic settings, the offshore wells are more dominated by fluvial sequences. The exception is Vinck 1 which has a paralic dominance, and onlap of a marine transgression in the latest Triassic. Whilst the resolution of the age control may contribute to the apparent anomaly of coeval continental environments offshore from coastal sequences, other solutions could include; land masses adjacent to the Exmouth Plateau shedding sediments eastward, and/or the arching and geomorphological development of parts of the Exmouth Plateau as a structural high in Triassic times resulting in a fluvial plain offshore but still connected to the main continental land mass.

Jurassic sedimentation is dominated by marine environments, with paralic sediments occurring in most wells in the latest Jurassic.

In the Cretaceous, paralic and fluvial sediments are dominant in the Early Cretaceous where it is present, and grade up into paralic sequences of the Barrow Formation deltas, especially in the thick sequences in the offshore wells. Closer inshore these paralic units are either thin or absent and the environments appear to be dominated by marine sequences, suggesting a marine embayment north of Barrow Island, relative to the Exmouth Plateau. In the later Cretaceous and the entire Cainozoic, marine environments are universally distributed.

HYDROCARBON PROSPECTIVITY

Reservoir

Permian reservoirs in Candace 1 and Mermaid 1 average from 15-23 % porosity. For the inshore wells the Early Triassic sediments have porosities ranging from 10-40 % and in the Late Triassic they range from 14-37 %. In the wells further offshore, the Triassic sediments have ranges of 10-25 % porosity (average 15 %) and 10-500 md permeability. In Vinck 1, from the top of the Triassic to total depth, the porosities range from 16-25 % to 0-10 % due to increased burial, quartz overgrowth and authigenic minerals.

Upper Jurassic sediments have poor reservoir characteristics overall, but where developed range from 14-28 % porosity (average 20 %) and have 0-58 md permeability. Cretaceous reservoirs are restricted to the Early Cretaceous and are highly variable in porosity and permeability. They range from 7-40 % porosity and very low to 1000 md permeability in the inshore, to 8-30 % porosity with very low to good permeability in the wells further offshore. No reservoir information is available for the Cainozoic except for the occurrence of some sands developed in time slice Cz 4 (mid Miocene) in Tryal Rocks 1. As they occur beneath an unconformity and are not recorded in nearby wells, they may be of only local significance. However, as for the Western Timor Sea region (Bradshaw, 1991) it is normal practice to drill blind throughout this section, and thus the potential of this interval as a reservoir could be underestimated. The main problem in such a scenario would be the capacity of the sequence to provide effective seals.

Seal

Along the Candace Terrace, the Early Carboniferous Moogooree Limestone forms a regional seal for Middle to Late Devonian clastic sediments (Bentley, 1988; Hocking, 1988), and the Early Triassic Locker Shale (timeslices T1 & T2) forms a regional seal for Late Permian sandstones. Many plays in this area rely on lateral seals, in the form of fault seals (Flinders Fault System) and also incised channels infilled with Early Triassic shale (Bentley, 1988). In Vinck 1, a Late Triassic transgressive marl forms a local seal and several intra-Triassic seals occur within the Late Triassic. Barber (1988) questions the integrity of lateral fault seals within the Triassic on the Exmouth Plateau, noting that usually only where thin sands are juxtaposed against thick argillaceous sediments are there any gas sands developed. Effective vertical seals can be demonstrated in the offshore wells where the major play involves Triassic sandstones overlain by latest Jurassic and earliest Cretaceous siltstones and shales (timeslices J9, J10 & K1). Early Cretaceous shales also occur as seals overlying the sands of the Early Cretaceous Barrow Group (timeslices K1 & K2).

Source Rock

Although recognising that any statement as to the source quality of the Pre-Permian section is largely conjectural, Bentley (1988) interprets the absence of hydrocarbons at Candace 1, Kybra 1 and Arabella 1 as suggesting that the Pre-Permian section has little or no source potential. However, the interpreted marine environments for parts of the Carboniferous and Devonian sediments (Hocking, 1988), the numerous intervals with total organic carbon contents (TOC) of 0.5 to 1 % that occur within the Moogooree Limestone in Kybra 1, and the thick section yet to be drilled (Plates 1, 7 & 8 - Section J-K) suggests that potential source rocks may exist.

Within the Permian there is excellent source potential. Onshore the Early Permian (timeslice P3) has TOC's of up to 7.3 % and averages 4 % (Percival & Cooney, 1985). Offshore in the Late Permian (timeslice P4) there are TOC's of 3 to 5 % and up to 8 % with mixed marine and terrestrial character to the organic matter and excellent oil and gas generating potential (Bentley, 1988).

The lower Triassic Locker Shale has good source potential, particularly in the lower parts (timeslices T1 & T2). Inshore it has up to 2 % TOC with organic matter that has a mixed marine and terrestrial character that would yield oil and gas (Bentley, 1988). The Late Triassic (timeslices T5 & T6) Mungaroo Formation is considered to be an excellent source rock in the Barrow and Dampier Sub-basin and also on the Exmouth Plateau (Woodside, 1988; Barber, 1988; Cook & others, 1985), with TOC's ranging from 0.7 to 6.3 % with an average of 3 % in Vinck 1 over the entire 2 km thick Mungaroo section.

The major Jurassic interval for source rock is the Dingo Claystone, which occupies almost all the Jurassic timeslices. In Hermite 1 and Emma 1 the TOC contents range from 0.5 to 3.5 % with an average of 1.5 % from 77 samples over a gross sample interval thickness of 1500 m occupying timeslices J1 to J8. The Dingo Claystone has been correlated with oils in Cretaceous and Jurassic reservoirs from wells such as Harriet, Bambra and Barrow Island (Bentley, 1988), and from wells along the Rankin and Legendre Trend to the north (Woodside, 1988).

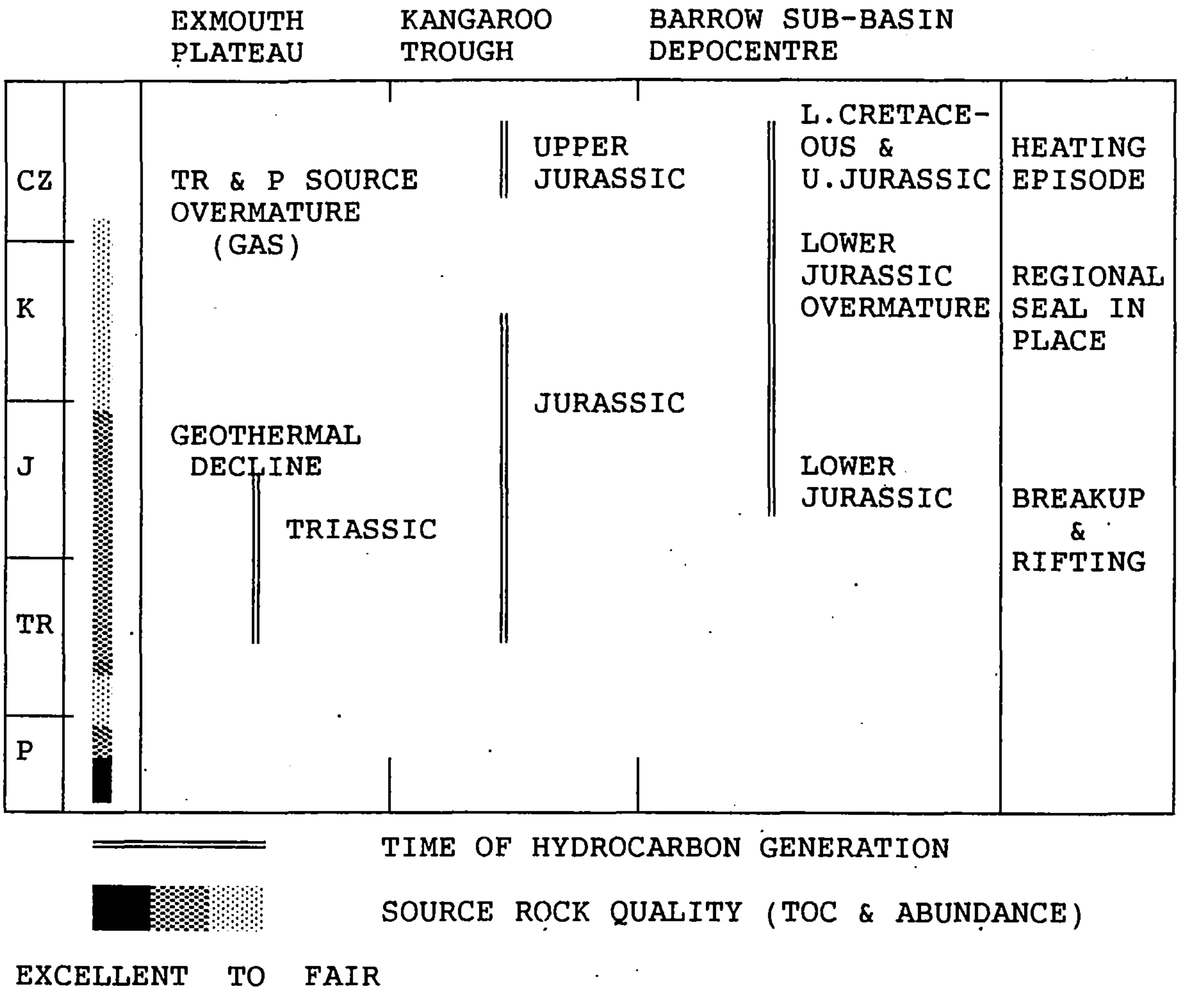
Potential Cretaceous source rocks occur on the Exmouth Plateau where in Vinck 1, Zeepaard 1 and Zeewulf 1 the TOC contents range from 0.99 to 1.71 % with an average of 1.3 % from 39 measurements.

Maturation

The maturation levels of the numerous potential source rocks from Pre-Permian to Cretaceous vary markedly along the line of the cross-section due to the different ages and tectonic terranes encountered. Inshore on the Candace Terrace, only the Pre-Permian sequence can be considered as being within the oil mature window, such that only the base of the section in Candace 1 is mature. Bentley (1988) believes that the Palaeozoic sequence had low geothermal gradients and would not have reached maturity for oil generation until the Tertiary. West of the Flinders Fault System in wells such as Hermite 1 and Emma 1, the drilled section is essentially immature down to the Triassic and Jurassic respectively, verging on marginal maturity only near the base of the wells. Within the depocentre of the Barrow Sub-basin the thick Jurassic has only just reached the early phases of oil generation (Kopsen & McGann, 1985), and it is suggested that there was a strong temperature gradient increase in the Middle Miocene, which was responsible for the generation of oil at that time. Further offshore on the Exmouth Plateau, the Triassic Mungaroo Formation is believed to have been generating oil since late in the Triassic or early in the Jurassic, through until the Tertiary (Cook and others, 1985).

Barber (1988) using burial history modelling produced three scenarios for the different regions on and adjacent to the Exmouth Plateau (Table 1).

Table 1 - Summary of burial history models and hydrocarbon generation from Barber (1988).



Over Jupiter 1, a high block on the Exmouth Plateau, it was suggested that the middle and lower Triassic reached peak maturity by the Late Triassic, and continued to expel hydrocarbons until the middle Jurassic. Following the increased heating associated with middle Jurassic rifting and breakup and subsequent erosion and uplift, there was a decline in regional geothermal gradients, which resulted in cessation of hydrocarbon generation. This scenario suggests that the entire sequence post the Middle Jurassic on the Exmouth Plateau is immature. In the southern Kangaroo Trough, Barber (1988) believes there were two periods of expulsion. The first stage began with the Triassic generating hydrocarbons in the Late Triassic to Early Jurassic, and with continual burial the Lower Jurassic proceeded to enter the Early stages of maturity by the end of the Early Cretaceous. The second stage consisted of the Upper Jurassic entering the early phase of generation following a

Late Tertiary heating episode. In the thick Upper Jurassic and Lower Cretaceous depocentre of the Barrow Sub-basin, the Lower Jurassic began generating hydrocarbons in the Late Jurassic to Early Cretaceous, and with continual burial up until the Early Tertiary became overmature for oil generation. The Upper Jurassic and Lower Cretaceous began generating hydrocarbons with the Late Tertiary heating episode.

As can be seen from Table 1, periods of hydrocarbon generation occurred when both no traps were in place (pre-rifting) and when no regional seal had been deposited. The early generation of hydrocarbons on the Exmouth Plateau lead Barber (1988) to believe that the dry gas discovered so far is largely due to an overmature source in the lower Triassic and Permian. This scenario varies significantly from that of Cook and others (1985) as they suggest that generation continued from the Triassic or Early Jurassic, through until the Tertiary, although at a diminishing rate as the sequence became increasingly passive after rifting. The slightly different scenario of Cook and others (1985) together with their analysis of the oil generative potential of the Triassic Mungaroo Formation, led them to suggest that significant accumulations of oil should occur on the Exmouth Plateau, rather than it being solely a gas province. The simple observations of the lack of wet gas or oil on the Exmouth Plateau would seem to suggest that Barber (1988) may be correct. Comparing the broad convex up shape to the burial history curve of the Exmouth Plateau with the overall concave down nature of the Kangaroo Trough and Barrow Sub-basin (Barber, 1988 - Fig 9) leads to the conclusion that although generation may have occurred early on the Exmouth Plateau it would have lost most of its entropy when uplifted, whereas the other areas have been in relatively constant subsidence and thus maintained their state of generation by not being uplifted substantially and cooling off.

Shows

The Carnarvon Basin is second only to the Gippsland Basin, as the most prolific hydrocarbon province in Australia. Not only does it contain the large Barrow Island oil field but there have been significant oil discoveries over the last few years at Wanaea 1 and Cossack 1 (Bint, 1991), Yammaderry 1, Cowle 1 and Roller 1 (McLerie and others, 1991), Ramillies 1 and Griffin 1. Along the cross-section there are hydrocarbon occurrences of gas and condensate in the Triassic, and oil, gas and condensate in the earliest Cretaceous, with the most significant hydrocarbon occurrences in Campbell 2, Gorgon 1 and Vinck 1 (Plate 1).

Campbell 2 was drilled updip of Campbell 1 and encountered a gross hydrocarbon column of 24 m (20.6 m net gas / 1.5 m net oil) in time slice K1. Gorgon 1 tested condensate and gas in both timeslice K1 and over a gross pay of 189 m in timeslices T5 and T3 to T1, and has probable reserves of 2,020 BCF (McClure & others, 1988). Vinck 1 tested numerous thin gas and gas and condensate sands with logs showing a net thickness of 142 m from timeslice T6.

STRUCTURE AND TECTONICS

Pre-Visean

Very little has been written regarding Palaeozoic tectonics in the offshore, due to the poor seismic imaging of this interval, and its perceived lack of prospectivity. Most recent references suggest that the final phase of rifting on the Northwest Shelf had its precursor movements in the Permian or earlier, and usually refer to the onshore geology to describe the Silurian to Permian tectonic history. The onshore geology from the southern Carnarvon Basin has been interpreted to indicate that the Carnarvon Basin was an intracratonic basin that opened northwards with an initial period of rifting beginning in the Late Ordovician or Early Silurian (Hocking, 1988) and continued through until the Permian. Veevers (1984) describes the inception of the Carnarvon Basin in the late Early Ordovician as due to the radiation of failed rift arms from the extension of the Tethyan Ocean during breakup. New palaeomagnetic age determinations from the basal sequence in the Carnarvon Basin, the Tumblagooda Sandstone, suggests it could be as old as Early Ordovician (Schmidt & Hamilton, 1990) and thus extend this initial rifting back even further.

Section J-K (Plates 1, 7 & 8) shows a very thick pre-Visean section developed on the down side of a major fault. Thickening is evident into the fault (from west to east) at all levels from the Early Palaeozoic up to the Visean unconformity and beyond into the Permian. Numerous levels of what appears to be fanglomerates can be seen on the seismic (Plates 7 & 8) on the down side of the fault. Up to 7 km of pre-Visean sediment is preserved by this fault ranging well down into the Palaeozoic and perhaps into the Ordovician; this approximates the cumulative onshore thicknesses of 6.1 km for the pre-Visean given by Hocking (1988). This fault is a segment of the Sholl Island Fault which forms the eastern bounding edge of the Candace Terrace and Peedamullah Shelf. Seismic data shows (Plates 7 & 8) that it was involved in controlling deposition and structuring from the earliest phases of the basin development. Although the arcuate northerly alignment of the Sholl Island Fault matches the supposed northward opening of the basin described above, its extensional listric nature in a westerly direction suggests that the northern Carnarvon Basin at this location was not an intracratonic interior sag or interior fracture as described by Hocking (1988) from studies of the Palaeozoic sequence of the southern Carnarvon Basin. Instead, the northern Carnarvon Basin appears to be an area of overall west or southwest extension, probably associated with the postulated failed rift described by Veevers (1984). The central rift zone must have lain much further to the west, undoubtedly being reactivated during the later Mesozoic breakup and either rifted off or buried at depth.

Recognising the long history of the Sholl Island Fault trend implies that similar fault trends such as the Deepdale Fault and perhaps segments of the Flinders Fault will be of similar age, as are the northerly trending faults in the southern Carnarvon Basin including the Darling Fault (Hocking and others, 1987). The northerly trends of the faults within the Barrow Sub-basin are abruptly changed in the Dampier Sub-basin, implying either a change in the tectonic province, age of faulting and/or a branching in the main controlling deep seated fault system. If the northeasterly trends could be shown to have been initiated in the Early Palaeozoic, similar in age to the northerly trends, then a regional view could be that the northeast trend of the Flinders Fault System and the Legendre-Enderby Trends would represent the major strike slip direction in the Early Palaeozoic, with the Sholl Island and Deepdale Faults representing synthetic faults to the throughgoing sinistral strike slip direction. The current "dog leg" shape to the Sholl Island Fault with its extension to the north into the region of the Legendre Trend could, with simple northeast aligned sinistral transtensional movement throughout its history, produce the thickening trends shown along the fault. The Candace Terrace and Peedamullah Terrace would thus be a zone of release along the fault bend. The listric nature of the fault shown on this seismic line does not match the classical steeply dipping strike slip fault profile, suggesting that either this line is at a tangent to the true dip direction and/or that the direction of tensional release was not perpendicular to the original fault direction, thus perhaps causing the fault to splay out in a listric fashion.

Stratigraphic and tectonic correlation of the older pre-Visean Unconformity sequence along the Northwest Shelf is daunting because of the lack of both seismic control and well intersections. However, if the Tumblagooda Sandstone is assumed to be older than previously described and is assumed to have a syntectonic origin as shown by growth over the Sholl Island Fault and its proximal and palaeogeographical relationship to the Darling Fault (Walley et al, 1990), then an early phase of rifting and initiation of basin architecture can be described. Fission track ages of Silurian and Ordovician in the Yilgarn are also relevant to the development of this history (Bradshaw and Vizy, 1991). Possible further developments of this concept could be correlation of the early phase of rifting with the Ordovician to Early Silurian salt in the Canning Basin (Foster & Williams, 1991) & Petrel Sub-basin and the undated pre-Permian salt now documented in the Timor Sea (Smith & Sutherland, 1991). Many vagaries exist as to the timing and dating of these early events and sequences on the Northwest Shelf, but analysis of the newly acquired deep crustal seismic by the BMR RV Rig Seismic (Stagg, Brassil and others, 1991) may begin to answer some of these questions.

Visean Unconformity

Although none of the wells used along the cross-section intersect the pre-Permian, Kybra 1 is located just off Section J-K

(Plates 1, 7 & 8) and penetrated to the Early Carboniferous (Visean) (Bentley, 1988). A major unconformity is evident within the well and on seismic data, occurring between the Visean and the latest Carboniferous and earliest Permian. The unconformity can be traced from the Sholl Island Fault to the Flinders Fault System, before it is lost off the bottom of the section. There is significant angularity on the underlying Visean units, which appears to be partly due to rotation on the listric Sholl Island Fault. This break equates with the change from the Uluru to the Innamincka regime of Veevers (1984), and the initiation of the Westralian Superbasin of Yeates and others (1987). The original definition of the Westralian Superbasin included the Permian to Cretaceous sequence along the Northwest Shelf, however the clear break and change in depositional style on Section J-K (Plates 1, 7 & 8) is at the Visean unconformity. The sediments above the unconformity comprise the Lyons Group which extends from the Early Permian down into the Late Carboniferous and which as a group is within the terminology of the Westralian Superbasin (Bradshaw and others, 1988). Thus the definition is amended here to include the glacial sequence and its components above the Visean Unconformity. The underlying sequence is believed to be similar in age to that described for the Bedout High and Londonderry High (Bradshaw, 1990; 1991), although there the pre-Permian sediment has not been intersected by drilling.

The significance of the Visean Unconformity is that it is synchronous with the later movements of the Alice Springs Orogeny (Mt Eclipse Movement) as described by Bradshaw & Evans (1988) in central Australia and equivalent with the Alice Springs Orogeny as described in the Canning Basin by Goldstein (1989), and is the tectonic period that initiates the development of the Westralian Superbasin. The significance of this period of deformation has previously been recognised by Veevers (1984) for eastern and central Australia and has been correlated across Gondwana as the epeirogenic movements and mountain building that triggered the Permo-Carboniferous glaciation (Powell & Veevers, 1986). Veevers and others (1991 - Fig. 15) show this period (320 Ma - Namurian) as an episode of penetration from the northwest of the Tethyan divergent ridge. Braun and others (1991) have proposed a north-south crustal scale shear zone to account for the anomalous coincidence of major crustal shortening in central Australia and extension in Western Australia in the Canning and Bonaparte Basins, suggesting that it operated from the Middle Devonian to the Early Carboniferous.

Williamson and others (1990) proposed Permo-Carboniferous rifting on the Exmouth Plateau based on deep crustal seismic data and interpretation of two landward dipping detachment horizons. A similar sub-horizontal major discontinuity is evident along Line 55-02 (Plate 1 - Section A-B) which has been tentatively labelled as a detachment. However, along the irregularities on this horizon there is no corresponding adjustment in the thick Triassic sediments overlying the horizon. This horizon may instead represent a major erosional surface, possibly the Visean Unconformity.

Permo-Carboniferous

The only relatively complete Permo-Carboniferous sequence imaged along the cross-section is on Section J-K (Plates 1, 7 & 8), which shows substantial syn-tectonic deposition of the Permo-Carboniferous sequence adjacent to the Sholl Island Fault. On section H-I the Permian rapidly thickens off the high block of igneous basement on the shelf into the basin. Only minimal extension (< 5%) is apparent at the top Permian and Triassic for the Vulcan Graben (Bradshaw, 1991) and similarly low values occur along this cross-section, although without being able to image the Permian sequence at depth as can be done in the Timor Sea. The major period of basin forming deformation along this cross-section was associated with the Visean Unconformity, and it is the relaxation following this period of Gondwana wide plate re-adjustment that initiated the extension to form the Westralian Superbasin. Recently this extension has been suggested to be ?Early Permian (Etheridge and others, 1991), but from the data on Section J-K (Plates 1, 7 & 8) it would most likely be Late Carboniferous in age, immediately following the Visean Unconformity.

Triassic to Cainozoic

Numerous accounts have been written about the Mesozoic and Cainozoic tectonic and structural development of the Offshore Carnarvon region, especially concerning the rifting episodes associated with the breakup and final separation of Australia and Greater India (including, Falvey & Mutter, 1981; von Rad & Exon, 1983; Veevers, 1984 & 1988; Yeates and others, 1987; Parry & Smith 1988; Fullerton and others, 1989; Boote & Kirk, 1989; Stagg & Willcox, 1991; Veevers and others, 1991; Veevers & Li, 1991.). As such, only a brief review of this period of tectonics is contained herein, with reference to the specific applications to this cross-section.

Preliminary structural movements to later Jurassic sea floor spreading were active from at least the Late Triassic (Rhaetian). Inshore at Hermite 1 a possible break in the Rhaetian is suggested from the age control, palynomorph reworking and log data. Earlier movement is suggested along the Enderby Trend where growth fault development started from at least the Permian, was very active in the Early Triassic, and continued through until the Early Jurassic (Veenstra, 1985). Unconformities at the top of the Late Triassic sequence occur in many of the Exmouth Plateau wells, although the precise timing of the event is poorly constrained as the Triassic units are overlain by Late Jurassic sediments.

Analysis of the facies and age control between Vinck 1, Zeewulf 1 and Zeepaard 1 suggests that up to 2 km of Rhaetian sediment could have been eroded from the eastern edge of the Exmouth Plateau (Plate 2). Alternative interpretations are possible as the age control in these wells is not specific, although seismic data does show a series of down to the west fault blocks that could easily accommodate the erosion postulated (Plate 1 - Section B-C). Barber (1988 - Fig. 8) shows a major break in reflectance values across this unconformity in Zeepaard 1, which substantiates the possible extent of erosion, although Barber (1988) postulates that the break is due to localised intrusions, and no similar break is evident from the reflectance data in Zeewulf 1.

The early phases of rifting have been described as flexure and subsidence (rather than faulting), leading to the development of the Barrow Sub-basin as an elongate downwarp in the Late Triassic (Parry & Smith, 1988; Barber 1988). In the Early Jurassic during the Pliensbachian the "pre-rift" or "rift onset" unconformity produced isostatic adjustment, uplift and erosion over the western Exmouth Plateau (Barber, 1988). The "Callovian", "Breakup" or "Main" Unconformity which occurred during the middle Jurassic was widespread, affecting deposition and tectonics along the entire length of the Northwest Shelf. It equates with the initiation of sea floor in the Argo Abyssal Plain as indicated from DSDP 261 and ODP 765 (Bradshaw, 1991: Veevers & Li, 1991; Veevers and others 1991). The development of the Rankin Trend horst blocks is believed to have resulted from this phase of structuring (Woodside, 1988), and produced onlap of the Upper Jurassic and Lower Cretaceous onto the fault blocks, as can be seen at Gorgon 1 (Section D-E - Plate 1).

Wrenching

Woodside (1988) noted the en echelon arrangement of the normal faults along the Rankin Trend and suggested that the Rankin to Madeleine Trend is a deep seated wrench zone. Parry & Smith (1988) believe that the "triangular horsts" of the Rankin Platform actually formed by intersection of two en echelon systems, one being the pre-rift north-south fault trends and the later being the rift bounding faults which trend southwest to northeast. Williams and Poynton (1985) documented the evidence for a right lateral wrench component for the fields on trend with the Barrow Island Anticline. These ideas can be easily assessed on a regional perspective from strain ellipse comparison on a modern day structure map such as presented by Woodside (1988 - Fig. 1). This includes the north to northeast trending anticlines of the Barrow Island Trend, the east-west offsets and bounding faults to these anticlines which are synthetics, and the major throughgoing wrench being orientated northeast parallel to, if not represented by, the Flinders and Rosemary Fault System. This type of analysis suggests that the en echelon Rankin Trend faults did not form at the same time as the Barrow Island Trend as they are in the wrong orientation to fit the same strain ellipse.

Assuming that the major Mesozoic structural control has been the Flinders and Rosemary Fault Trends, then an earlier left lateral trend can be described for the Rankin Trend. Whilst the

Barrow Island Trend fits well just with a simple right lateral system, a component of transtension must be considered for the left lateral Rankin Trend. As the Rankin Trend is mapped in Triassic units and the Barrow Trend in Cretaceous, it is assumed that the left lateral transtensional Rankin phase preceded the right lateral Barrow Island phase. Woodside (1988) believe that the growth on the Barrow Island Anticline commenced in the Middle Jurassic with major growth periods in the Late Cretaceous and Tertiary. This suggests that the left lateral phase may be pre-breakup in age, and perhaps related to the Rhaetian erosion seen inshore and also on the Exmouth Plateau. The preferred alternative is that the left lateral phase was active during breakup (and probably earlier), and the right lateral phase is restricted to the Late Cretaceous and Tertiary.

Horizontal transmission of stress through the upper lithosphere for thousands of kilometres across plates has been described as a mechanism for structuring basins (Etheridge and others, 1991). Consequently, comparison was made with the spreading patterns of sea floor presented by Veevers and others (1991) as an attempt to give some insight into the relative timing of these tectonic events and their likely origins.

The Barrow Island phase can be resolved if it is assumed that it relates to the latest phases of sea floor spreading depicted by Veevers and others (1991 - Figs 7-14). During this phase the Indian and Southern Ocean initiate as rifts in the Cenomanian and are active spreading zones during the period Santonian to recent. The spreading directions rotate from south-southeast to south with the switch to a purely south extension occurring in the middle Eocene. These predominantly south spreading directions and plate movement correlate well with the principal north to north-northeast anticlinal axes of the Barrow Island trend, and the timing of the spreading equates exactly with the major growth observed on these anticlines by Woodside (1988). The change in the regional stress regime and subsequent tectonic instability produced by the plate motion associated with the sea floor spreading is believed to have been accommodated along the Flinders and Rosemary Fault Systems as northeast trending strike slip movement. This movement produced anticlines elongated in a generally northerly direction, perpendicular to the synchronous sea floor spreading. As noted above the bounding east-northeast to east-west faults of the numerous fields along the Barrow Island Trend are synthetics to this strike slip direction. Similarly, Etheridge and others (1991) note that the regional stress field in North America has a compressional axis roughly perpendicular to the mid-Atlantic spreading ridge.

Analysis of the Rankin Trend is more difficult, probably due to the overprinting of several structural styles and directions. The orientation of the horst blocks suggest a left lateral relationship, but to produce a strain ellipse correlation with the

Flinders and Rosemary Fault Trends as the major strike slip orientation, a considerable degree of transtensional motion must be envisaged. Thus northeast directed sinistral strike slip motion must have occurred but with a substantial overprint of northwest extension. This can be resolved utilising the sea floor spreading directions which originate in a northwest direction from at least the Oxfordian until the Valanginian, then switch to west-northwest until the Cenomanian (Veevers and others, 1991 - Figs 3-6). The resultant spreading direction over this period is thus northwest. Precursor tensional motion to the breakup would have contributed to the initiation of this regime during rifting, thus suggesting that the Rankin Trend probably pre-dates the Middle Jurassic. On Section D-E (Plate 1) numerous movement and thickening trends can be seen across the Gorgon structure. Lower Jurassic units appear to thin onto the structure and there are thickness changes throughout the section up until the Cenomanian. The major fault movement terminates prior to the Aptian. This suggests that the precursor breakup tectonics did affect the Rankin Trend structures and movement continued long past their major growth associated with Jurassic breakup.

The regional analysis of these trends suggests that despite the contrasts between the fault blocks in the Triassic units and the folds in the Cretaceous strata, both can be related to the sea floor spreading history. As postulated above the Rankin Trend developed from spreading that was very local (Argo, Gascoyne and Cuvier Abyssal Plain) and resulted in a major component of extension associated with the strike slip motion. It thus contains extensional features (fault blocks) rather than wrench features (anticlines). In the Barrow Trend the spreading was distant (along the southern margin) and its affect locally was to reactivate major fault zones into wrench motions. It thus produced anticlines and associated synthetic fault patterns.

Although this type of regional overview obviously requires further detailed scrutiny by checking against fault history along the trends postulated, it can be utilised as a working hypothesis worthy of further investigation.

Cainozoic Compression and Dextral Rotation

Previous interpretation of the northern Carnarvon Basin suggested that the Cape Range Anticline formed by east-west compression during Miocene collision with Timor (Malcolm and others, 1991). However, the zone of subduction with the Asian plate would have resulted in a generally southward directed compression, which is parallel to the extension direction of the Cape Range and Barrow Island Trends. There was some degree of north-south compression late in the tectonic history of this area that can be related to collision with the Asian Plate, as the Late Cretaceous and Tertiary are repeated in South Pepper 4 across the east-west South Pepper Fault where reverse movement was accommodated

(Williams and Poynton, 1985). Evans (1982) drew attention to the widespread nature of strike slip styles of en echelon deformation around the Australian plate in the Tertiary in the Gippsland, Eromanga/Cooper, Eromanga/Pedirka and Carnarvon Basins, all with different orientations. Veevers (1984) noted this and related it to dextral motion of Australia relative to the rest of the enclosing plate, caused by sinistral shear of the Pacific and Indo-Australian Plates in New Guinea. If these events can be related then the supposition for the origin of the Barrow Island Trend described earlier would have to be invalid. However, as noted by Evans (1982) local pre-existing structures such as basement blocks and deep seated faults will through reactivation have placed constraints on the final orientations of the anticlinal trends. This may have produced differing orientations across the plate from the same original principal vector of motion. The synchroneity of these events may also be in doubt as more recent work such as Woodside (1988) suggests that anticlinal growth in the Carnarvon Basin was active in the Late Cretaceous to the Tertiary, and that this style of structuring was punctuated by Miocene southward directed compression as noted above.

Other Structural Events

A number of events have occurred in this region that are poorly constrained due to poor age control, the long structural history and the complex evolution from part of Gondwana to the Australian Plate. The area is further complicated by the possible interaction with additional continents such as India that may have been adjacent to the Northwest Shelf. Some of these events identified along and adjacent to the cross-section include;

- Strike slip motion along the Sholl Island Fault at Candace 1 where Lower Triassic units are folded and overlain by relatively undeformed Late Cretaceous. The orientation of the folds along the fault fit with a left lateral strike slip motion, thus indicating correlation with the formation of the Rankin Trend in the Late Triassic and Jurassic.
- The deformation that formed the northeast trending anticlines of the Madeleine and Legendre Trend. As they have the same orientation as the Candace Anticline they could relate to the same period of left lateral movement in the Late Triassic and into the Jurassic. This would equate them with the timing and sense of movement associated with development of the adjacent Rankin Trend, but they would have had to been under a more convergent phase than has been used to explain the fault block terrain of the Rankin Trend. If they are of strike slip origin, they fit well with a throughgoing wrench direction predominantly north-south, which could be a deep seated northern extension of the Sholl Island and Deepdale Fault Systems.
- Rhaetian erosion inshore at Hermite 1 that could equate with precursor events to breakup and to erosion on

the Exmouth Plateau (see text for Vinck 1, Zeepaard 1 and Zeewulf 1), and perhaps to the strike slip events described at Candace 1.

The interaction of pre-existing structures and reactivation of them will be the controlling factor in resolving many of these events, and some may be resolved into the existing framework when better timing control and structural analysis from deep crustal seismic becomes available.

PLAYS

There is a large variety of plays along the length of the cross-section, ranging in age from Palaeozoic to Cainozoic, and most have been adequately discussed by numerous authors. Bentley (1988) details the diversity and complexity of plays along the inshore regions, many of which have a large dependence on stratigraphic factors. As such, no single test should be considered as verifying the validity of a play in this area, especially as the area is adjacent to major accumulations and updip from a thick source rock. Recent success at Wandoo 1 on the shelf region of the Dampier Sub-Basin should give renewed encouragement for exploration along the Peedamullah and Candace Terraces. Plays in the Barrow and Dampier Sub-basins can be sub-divided into pre-breakup and post-breakup as detailed by Vincent and Tilbury (1988) and recently summarised by Stagg and Willcox (1991). Reservoirs occur in Cretaceous, Jurassic and Triassic units with trap types varying from down side rollover anticlines with wrench components to tilted fault blocks and horst blocks. Some stratigraphic components have been introduced to these plays including features such as low stand fan complexes. Further offshore the plays are restricted to Mesozoic tests principally in the Triassic. If the analysis of Cook and others (1985) is correct then there still remains the potential for liquid hydrocarbons in these deeper water regions. As numerous large accumulations are known from the existing play types in this area, they will continue to be pursued, but as shown from Wandoo 1 the focus may change depending on the most recent successes.

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