REPORT
57

GOVERNMENT OF
WESTERN AUSTRALIA

GEOLOGY AND PETROLEUM EXPLORATION OF THE CENTRAL AND SOUTHERN PERTH BASIN WESTERN AUSTRALIA

by A. Crostella and J. Backhouse

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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Geology and petroleum exploration of the central and southern Perth Basin, Western Australia

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Abstract

Post-mortems of exploration wells and an overview of hydrocarbon potential are provided for the central and southern Perth Basin. This overview is based on a critical analysis of stratigraphic, engineering, seismic, geochemical, petrophysical, and palynological data. The stratigraphy is compared with the northern Perth Basin, and the pre-breakup lower Neocomian Parmelia Formation is further subdivided and redefined as the Parmelia Group. The main structural features have resulted from strike-slip movements related to the early Neocomian breakup tectonism, but vary considerably between the sub-basins. Hydrocarbons have been produced from the onshore northern Perth Basin since 1971. In contrast, in the onshore southern Perth Basin, no commercial fields have been discovered even though shows of gas and minor oil have been encountered in the wells drilled to date. Although the Permian to Cretaceous stratigraphic and structural evolution of the southern Perth Basin is similar to that of the northern Perth Basin, marine intervals that break the continuity of the prevailing coarse-grained terrigenous deposits in the northern region are not present in the south, where the environment of deposition was entirely continental up until the late Neocomian. Consequently, thick regional shales are absent and the area has poor sealing potential. On the other hand, potential reservoirs, source rocks for both gas and oil, and anticlinal traps are all well documented.

Exploration in the central Perth Basin has focused on the offshore Vlaming Sub-basin. In particular, it has concentrated on the Parmelia Group, which is over 3000 m thick, and on the overlying Gage Sandstone. Oil has been discovered in Gage Roads 1, but further drilling is required to evaluate the economic significance of this discovery. The lack of compressional features, such as anticlines, in most of the sub-basin, implies that hydrocarbons are likely to be reservoired in less conventional traps such as palaeotopographic highs, stratigraphic pinch-outs, or fault traps.

Within the onshore Beermullah Trough, in the northern part of the central Perth Basin, the presence of gas has been demonstrated in Jurassic rocks by five wells drilled on several large seismically defined anticlines. In this area, Jurassic rocks are over 4000 m thick, but only part of this interval has been tested to date. More testing is required to evaluate the hydrocarbon potential of the sub-basin.

In the onshore Mandurah Terrace, there are just five wells and limited seismic control, which is insufficient to assess the economic value of this area.

KEYWORDS: petroleum potential, Perth Basin, stratigraphy, geology, geological structures, anticlines, hydrocarbon shows, stratigraphic trap, petroleum reservoir, source beds, plays, sedimentary environment.

Introduction

The northerly trending Perth Basin extends along the southernmost 700 km of the western coast of Australia (Fig. 1), and contains a Permian to Holocene succession overlying Precambrian basement. Pre-Permian sedimentary rocks are present in the northernmost part of the basin (Mory and Iasky, 1996).

The area under review covers the central and southern portion of the Perth Basin south of latitude 31°S, between the Darling Fault to the east and longitude 116°E to the west, where the sedimentary sequence thins towards oceanic crust in deep water (Fig. 2).

The present review is based largely on a critical examination of unpublished results from reports on oil exploration wells. These reports are available from the

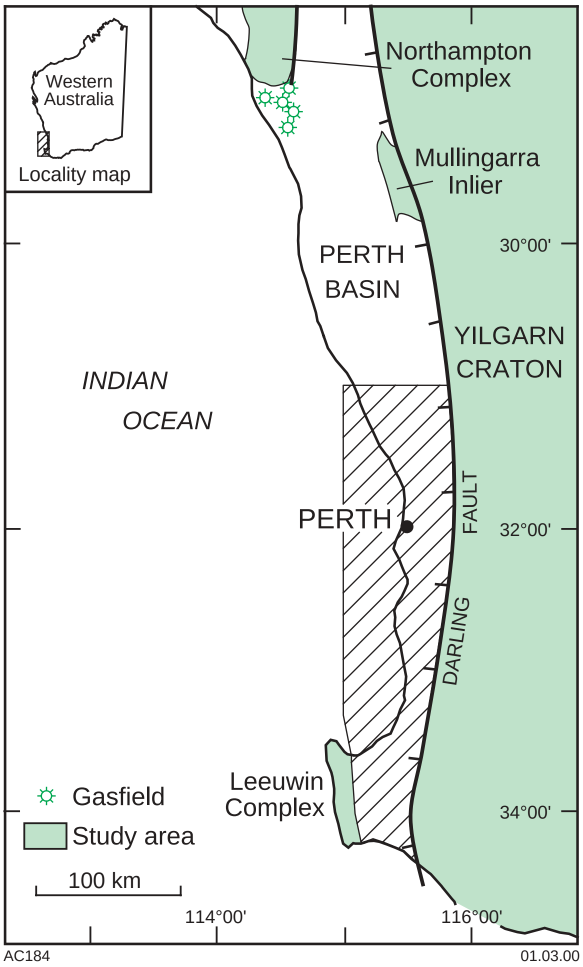

Figure 1. Location map of the study area

Department of Minerals and Energy (DME) in Perth, Western Australia. Key data on the wells are available in digital form (Geological Survey of Western Australia, 1996). Seismic data have also been examined to establish relevant structural relationships. Exhaustive reference lists of previous investigations can be found in Playford et al. (1976), Marshall et al. (1989, 1993), Iasky (1993), and Mory and Iasky (1996).

There are hydrocarbon indications in a number of stratigraphic horizons, but to date accumulations of economic significance have been discovered only in the northwestern onshore part of the basin (Fig. 1), mainly within Permian reservoirs. This Report, part of the Petroleum Exploration Initiatives Project currently in progress within the Geological Survey of Western Australia (GSWA), compares the northern part of the Perth Basin, as studied by Mory and Iasky (1996), with the central and southern parts of the basin.

Onshore, the stratigraphic succession is predominantly Permian to Jurassic in age, with only a veneer of Cretaceous to Holocene rocks (Fig. 3). The lower Neocomian section is more than 3000 m thick in the Vlaming Sub-basin because of extremely rapid subsidence at that time. Beneath the Cretaceous rocks in the Vlaming Sub-basin, only the Upper Jurassic rocks have been penetrated by drilling, and the presence of older sedimentary rocks can be inferred only from onshore data.

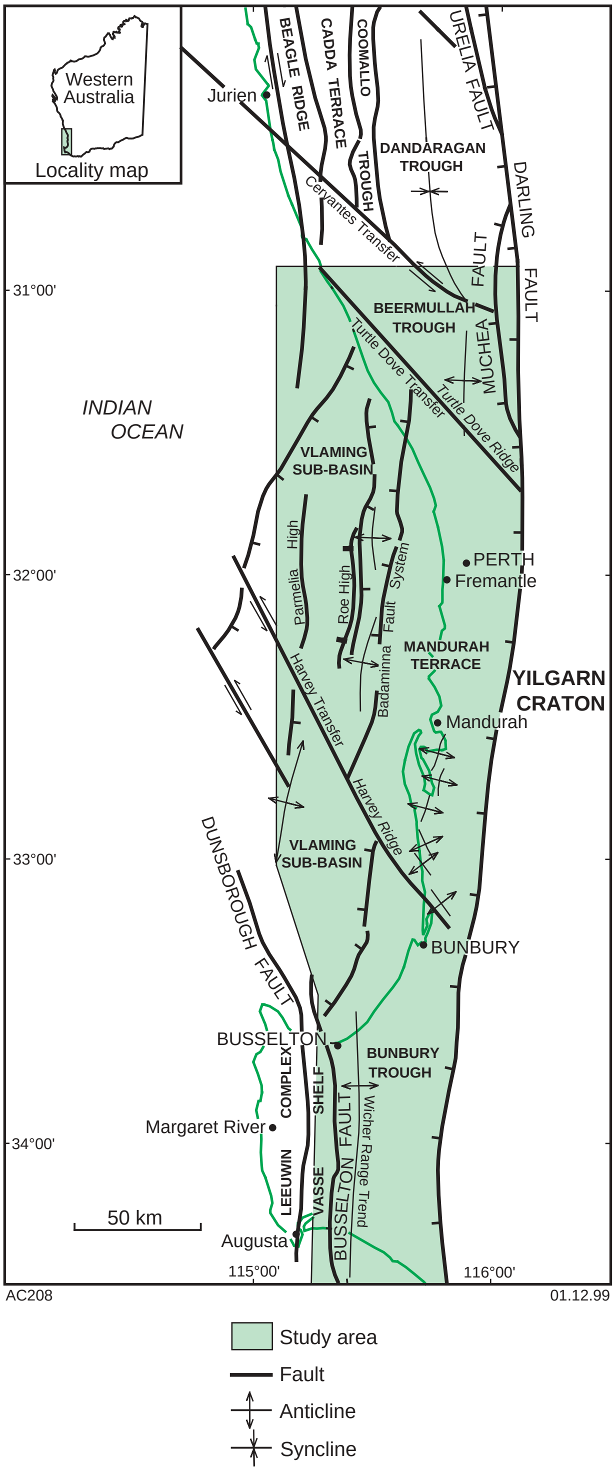

Figure 2. Basin subdivisions and tectonic lineaments of the central and southern Perth Basin

The Perth Basin originated as a rift basin, but locally the intensity of rifting varied considerably. The resultant rates of sedimentation and formation thicknesses varied as shown in Plates 1 and 2. The breakup of Gondwana-

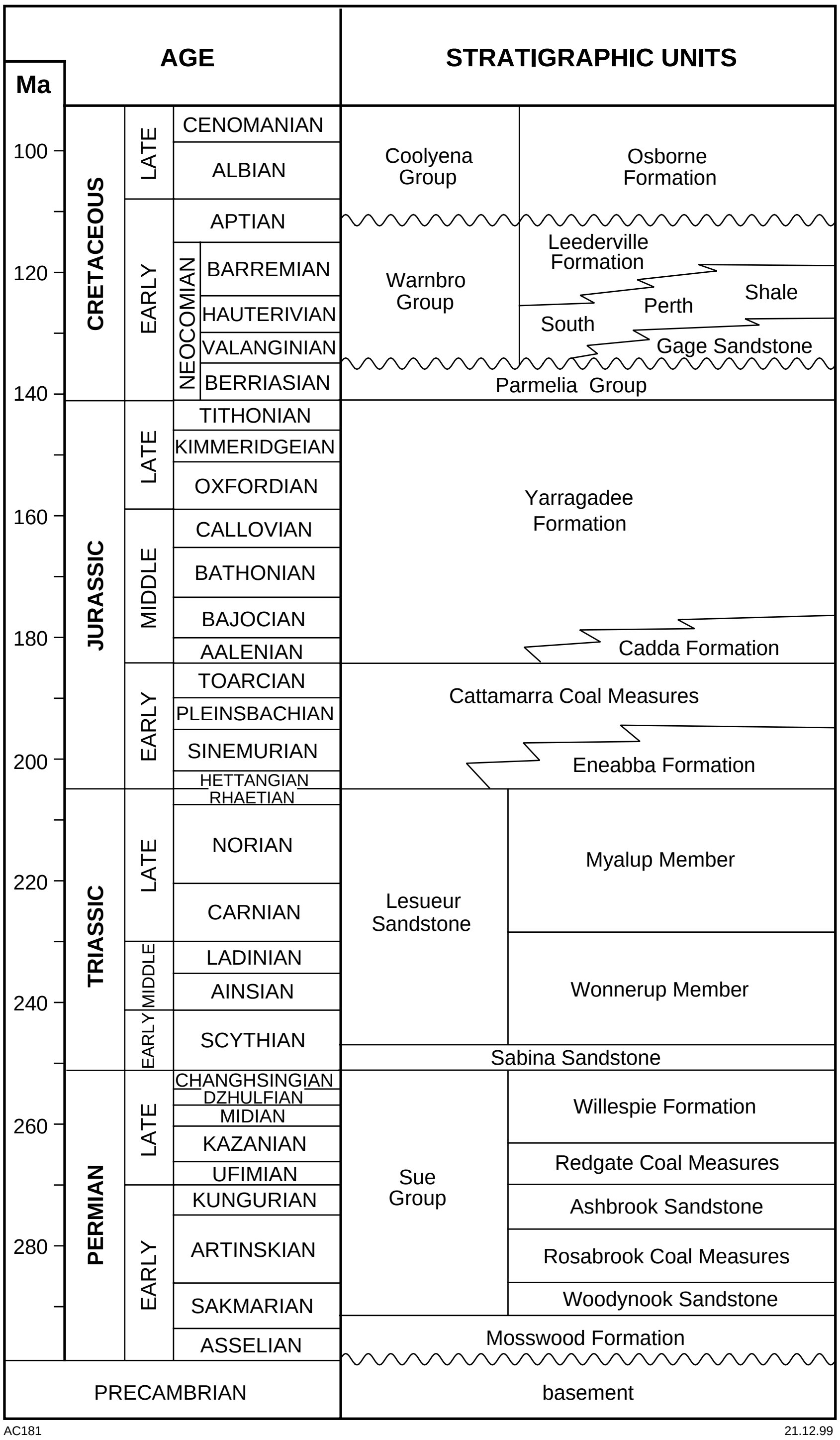

Figure 3. Stratigraphy of the central and southern Perth Basin. Sources: Playford et al. (1976) — Late Neocomian–Aptian; Crostella and Backhouse (this Report) — early Neocomian; Mory and Iasky (1996) — Jurassic and Triassic; Backhouse (1993) and Le Blanc Smith and Kristensen (1998) — Permian. The stratigraphy of the Carnac Formation is shown in Figure 17 and Plate 2

land, and the resulting separation of Australia from Greater India, produced transfer faults and substantial strike-slip movements associated with limited vertical throws and compressional anticlines. These early Neocomian transtensional movements imparted the present structural overprint to the basin, although the pre-existing rift faults can be recognized from variations in the thicknesses of the relevant stratigraphic intervals.

Hydrocarbon exploration activities

Apart from the three shallow wells drilled by Westralian Mining and Oil in 1902 (Warren River 1–3), which provided only limited information, petroleum exploration in the region commenced in earnest during the 1960s. As in other parts of Western Australia, Western Australia Petroleum Pty Limited (WAPET) was the protagonist of early activities, conducting geophysical surveys and drilling the first key exploration wells, both onshore and offshore, when the company was granted exploration permits over virtually the entire Vlaming Sub-basin. During this early stage of exploration, Union Oil Development Company (Unocal) focused its exploration activities in the Bunbury Trough. Wells drilled by WAPET, such as Gingin 1, Bullsbrook 1, Pinjarra 1, Lake Preston 1, Sue 1, Gage Roads 1, and Sugarloaf 1, and Unocal's wells, such as Whicher Range 1, provided the first extensive insight into the subsurface of the area. The results obtained from this early exploration, such as oil from Gage Roads and gas from Gingin and Whicher Range, focused later activity on these areas. After the withdrawal of WAPET and Unocal, companies such as Weaver Oil and Gas Corporation, BP Petroleum Development Australia, Mesa Australia, Phoenix Oil and Gas, Discovery Petroleum, and Amity Oil acquired onshore acreage, especially in the Bunbury Trough. Phillips Oil Company Australia, Esso Australia, Petrofina Exploration Australia, and Ampolex carried out exploration in the Vlaming Sub-basin. To date, a total of 38 wells have been drilled in the central and southern Perth Basin; 21 onshore and 17 offshore (Fig. 4).

Many geophysical surveys have been carried out (Appendix 1; Fig. 5), as well as geochemical analyses and palynological studies. Oil companies, other than those mentioned above, have expressed interest in the region by reviewing the hydrocarbon potential of selected areas and carrying out specific studies. The unpublished results of these studies are available from the Western Australian petroleum exploration and Western Australian petroleum information management system databases (WAPEX and WAPIMS).

Subsurface control is also provided by deep hydrogeological boreholes drilled by GSWA in several east–west traverses (Appendix 2), and by deep boreholes drilled in the area between Gingin and Mandurah for the Metropolitan Water Authority (Davidson, 1995). Data from companies interested in the coal potential of the Collie Basin and Vasse Shelf have been valuable for interpretation of the Permian intervals (Le Blanc Smith, 1993; Le Blanc Smith and Kristensen, 1998).

Regional framework

The Perth Basin has been subdivided into northern, central, and southern parts (Iasky, 1993; Mory and Iasky, 1996); a western part has also been introduced by Stein et al. (1989). For the purpose of this Report, the northern Perth Basin is informally defined as that part of the basin lying to the north of latitude 31°S, the central Perth Basin as that part lying between latitudes 31° and 33°S, and the southern Perth Basin as that part lying south of latitude 33°S (Fig. 4).

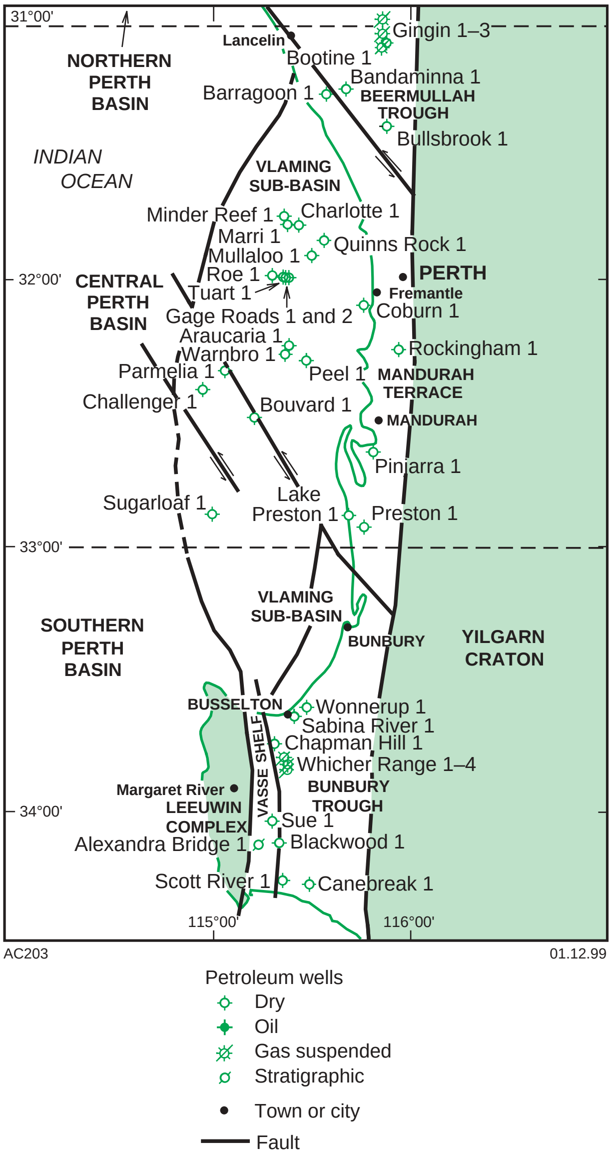

Figure 4. Well locations in the central and southern Perth Basin

In this Report, the central and southern parts of the basin are subdivided into five structural units: the offshore Vlaming Sub-basin, the partly onshore and partly offshore Mandurah Terrace, the onshore Beermullah and Bunbury Troughs, and the onshore Vasse Shelf (Fig. 2).

Beermullah Trough

The Cervantes Transfer separates the Dandaragan Trough from the Beermullah Trough (new name), which is bounded to the east by the Darling Fault, to the southwest by the Turtle Dove Transfer, and to the west by the Beagle

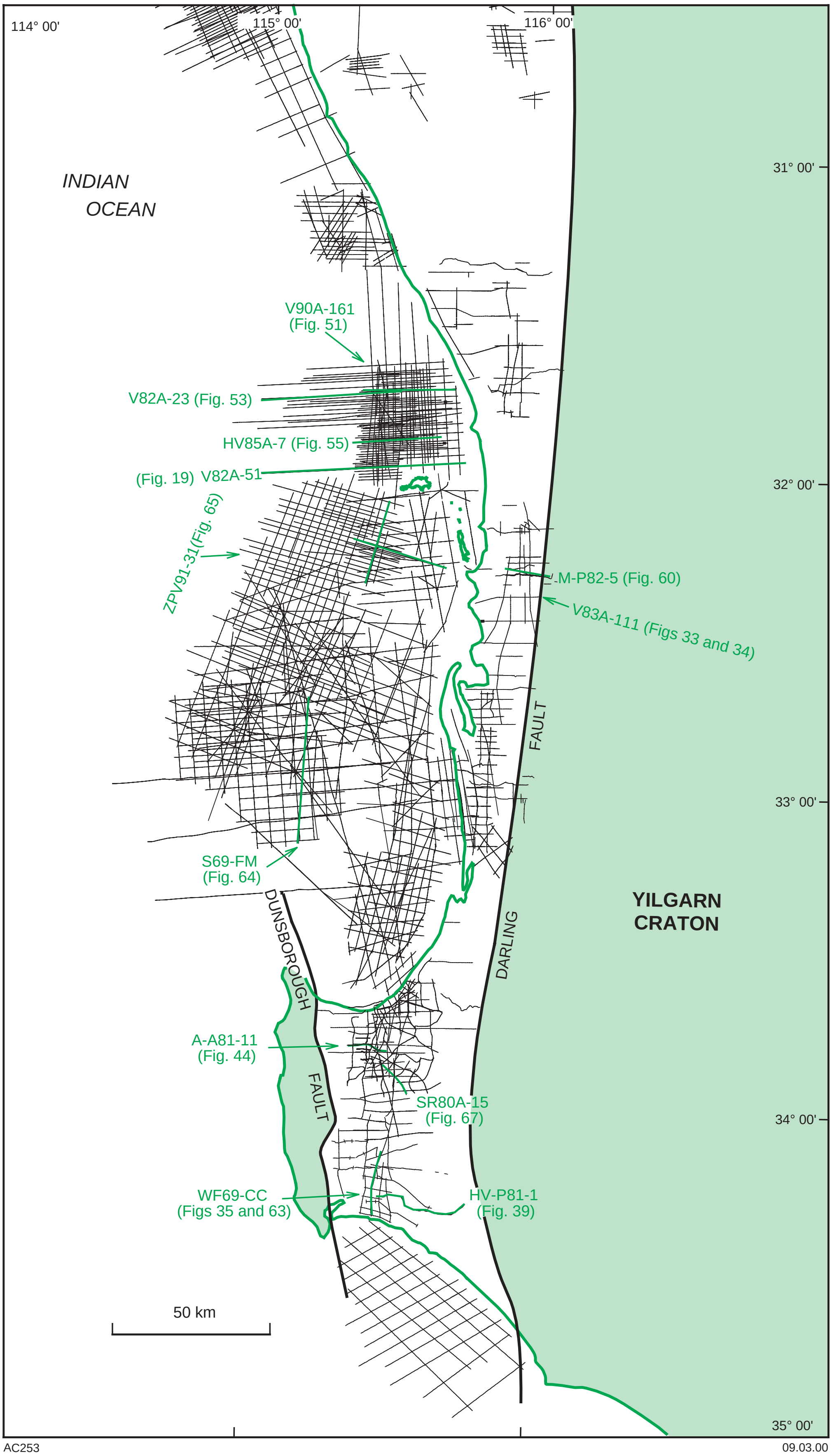

Figure 5. Map showing seismic control in the central and southern Perth Basin. The seismic lines illustrated in full or in part within this Report are identified

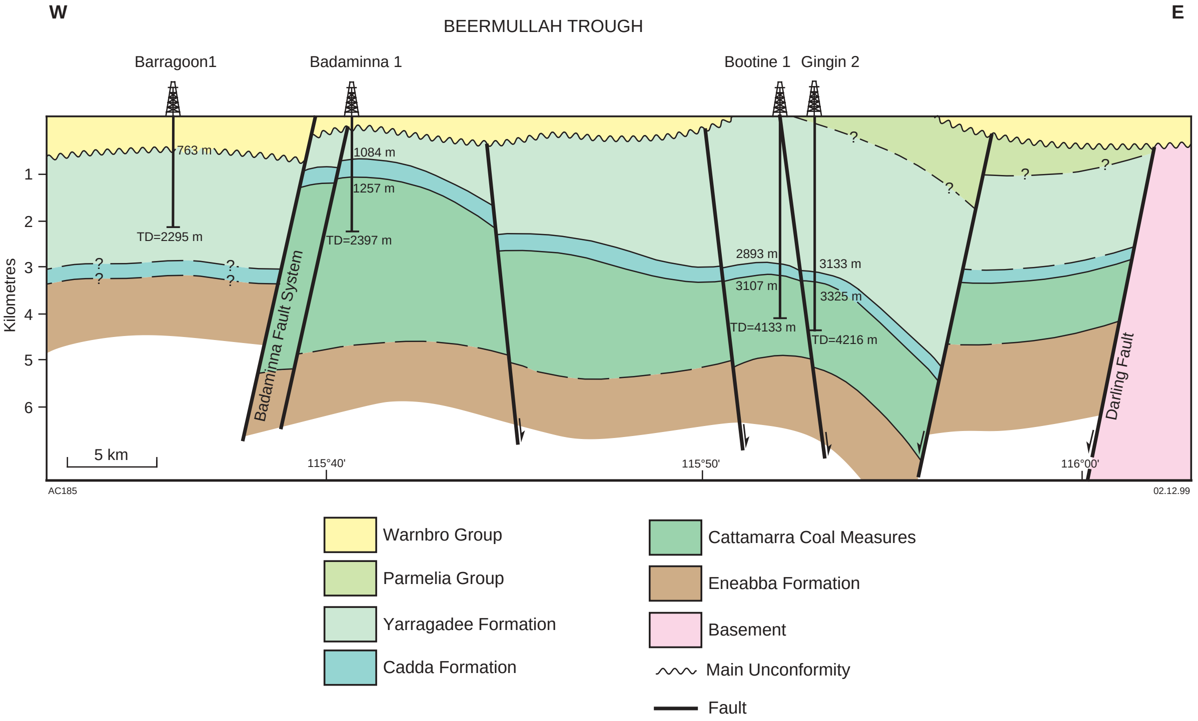

Figure 6. Schematic cross section showing Barragoon 1, Badaminna 1, Bootine 1, and Gingin 2

Ridge. The Beermullah Trough was originally included within the Dandaragan Trough. Both are large synclinal features in which the sedimentary succession thickens eastwards towards the Urella and Darling Faults. Structural closures have only been documented along the eastern flank of the Beermullah Trough (Mory and Iasky, 1996). The synclinal axis of the Dandaragan Trough abuts against the Muchea Fault slightly south of latitude 31°S (Fig. 2). In contrast, the axis of the depocentre of the Beemullah Trough lies further to the west. The Beermullah Trough is also characterized by anticlines that are virtually absent in the Dandaragan Trough. The structural setting of the Beermullah Trough is illustrated in Figures 6 and 7. There is an intermediate terrace between the Darling and Muchea Faults, and a thick section of the Yarragadee Formation, together with the basal part of the Parmelia Group, is present in the downthrown section west of the Muchea Fault. A characteristic northerly trending anticlinal axis is developed approximately 10 km to the west of the Muchea Fault, and the Cattamarra Coal Measures thickens substantially from east to west towards the Badaminna Fault System. The thickest section of the Yarragadee Formation and Parmelia Group is in the downthrown section to the west of the Muchea Fault System, implying that it was active during the Late Jurassic – early Neocomian.

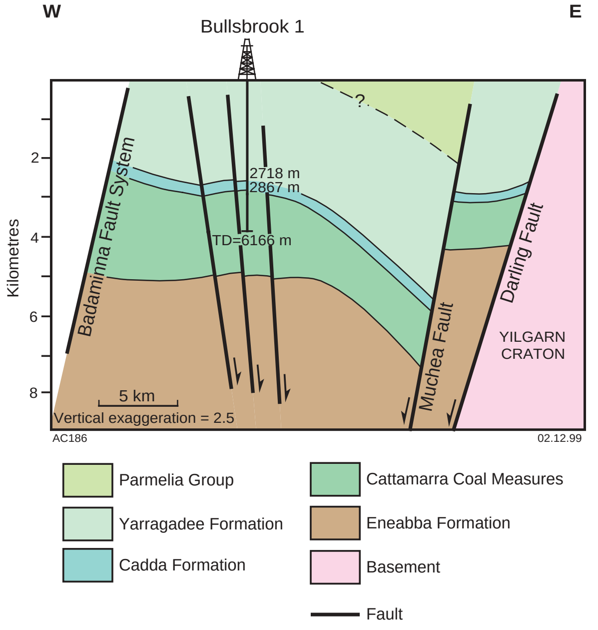

Figure 7. Section across the Bullsbrook structure

The large number of compressional anticlines within the Beermullah Trough (Fig. 8) are probably the result of the convergence of the Cervantes and Turtle Dove Transfers. Of these structures, only the Gingin–Bootine and Bullsbrook Anticlines have been tested. The Badaminna High is another fault-controlled anticlinal trend that has developed over the Lower Jurassic Cattamarra Coal Measures. These coal measures are thicker in this area than to the east (Fig. 6), and this is the only documented case of structural inversion within the Perth Basin. The oldest stratigraphic unit penetrated in the Beermullah Trough is the Lower Jurassic Cattamarra Coal Measures. The total combined thickness of sedimentary

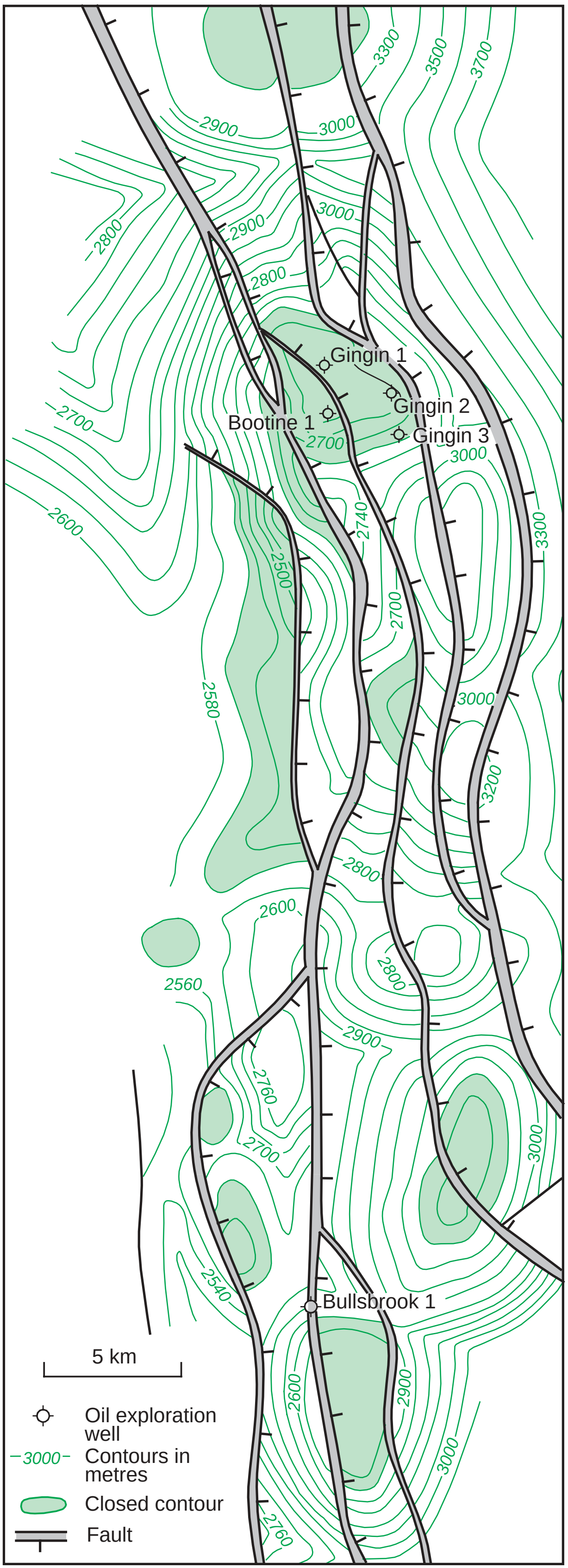

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Figure 8. **Structural configuration of the Gingin area on an intra-Cattamarra Coal Measures horizon (after American Shoreline Inc, 1990)**

rocks in the trough may reach 15 000 m. The geothermal gradient is low, averaging 19.5°C/km.

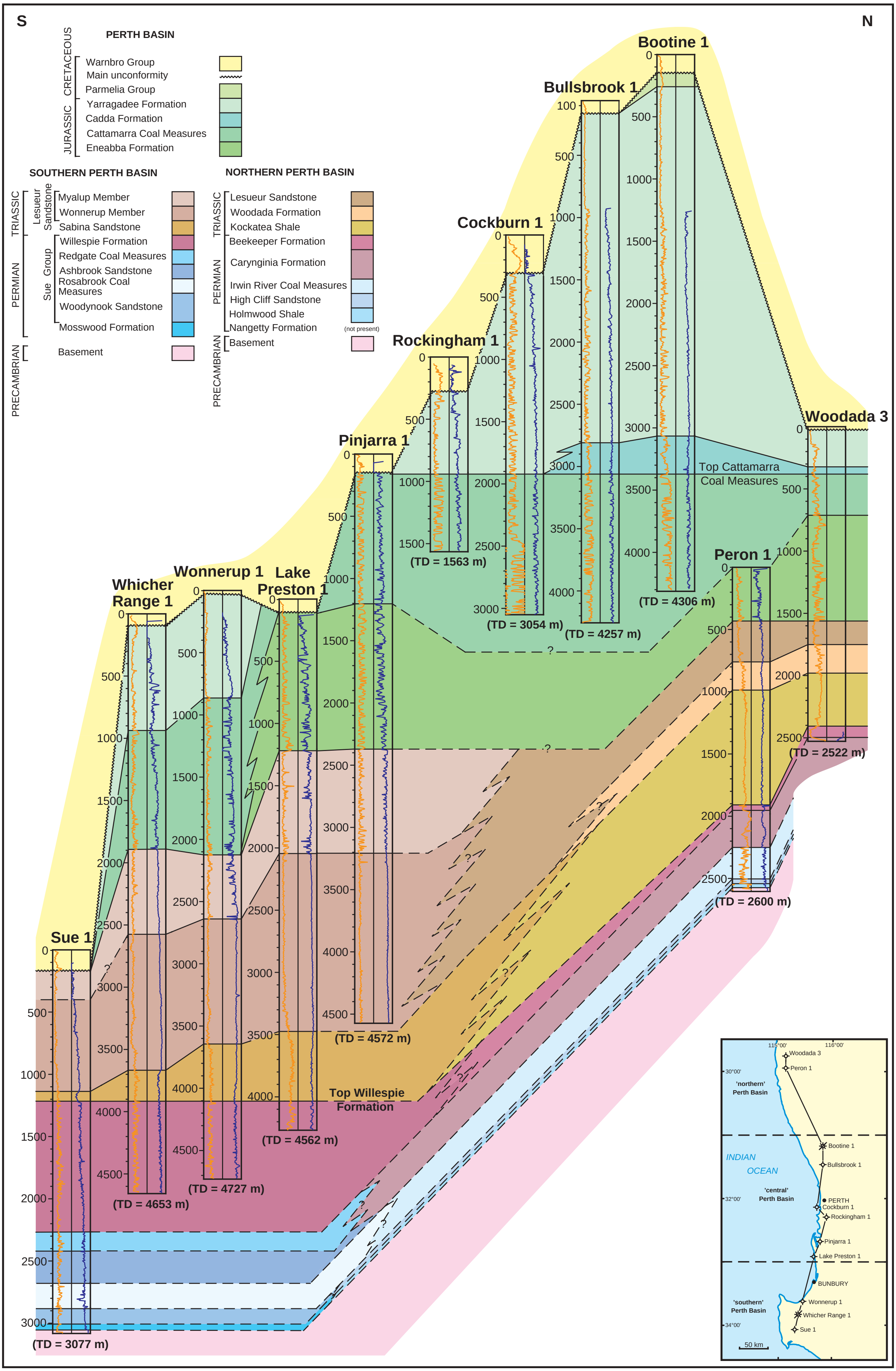
Mandurah Terrace

The Mandurah Terrace (new name) is bounded to the north and south by two transfer zones; the Turtle Dove and Harvey Transfers respectively (Fig. 2). The eastern boundary is the Darling Fault and the western boundary is the Badaminna Fault System. The Mandurah Terrace, previously regarded as a part of the Dandaragan Trough, forms a terrace in comparison to the Vlaming Sub-basin to the west. However, its relationship with the Beermullah and Bunbury Troughs to the north and south respectively has not yet been clearly established. Cockburn 1 and Rockingham 1 in the central part of the terrace (Fig. 4), and Pinjarra 1 and Lake Preston 1 in the southern part, penetrated the Mesozoic section at a higher structural level than in the adjacent Beermullah Trough, but this may be the result of local conditions. To date, only limited drilling has been carried out in the area, and its structural setting is poorly understood because of the limited, poor quality seismic control (Fig. 5). The southern part of the Mandurah Terrace is characterized by a thick Triassic – Lower Jurassic succession (Plate 1; Figs 4 and 9).

Vlaming Sub-basin

The Vlaming Sub-basin lies between latitudes 31°30' and 33°30'S, and extends westwards from the Mandurah Terrace and Bunbury Trough to the upper continental slope (Fig. 4). The eastern boundary of the Vlaming Sub-basin is along the Badaminna Fault System and its southern extensions, and the Turtle Dove Transfer separates this sub-basin from the Beermullah Trough to the north. Despite the numerous strike-slip faults that characterize the sub-basin (Marshall et al., 1993), the structural setting is mainly extensional; compressional anticlines, such as those in the Coomallo, Beermullah, and Bunbury Troughs, have not been identified in the area. The main high, the north-trending Roe High, is a west-dipping homocline that is separated by faults from the sub-parallel Rottnest Trough. The southernmost portion of the Vlaming Sub-basin, where the only well to be drilled is Sugarloaf 1, is separated by the Harvey Transfer from the main portion of the sub-basin, which contains the other 16 wells that have been drilled in this sub-basin.

The sub-basin is dominated by the very thick early Neocomian Parmelia Group, formerly the Parmelia Formation (Backhouse, 1984), which attains an estimated average thickness of 3200 m. The thickness of the Parmelia Group is controlled by the Badaminna Fault System (Fig. 2), which continued to develop during the early Neocomian and remained active after the breakup of Gondwana. The underlying succession has barely been reached by drilling, and to date only the top of the Upper Jurassic Yarragadee Formation has been penetrated. There is, however, no reason to believe that a Permian–Jurassic sequence, similar to that penetrated onshore, is not also present in the Vlaming Sub-basin. A total of approximately 15 000 m of sedimentary rocks is likely.



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Vasse Shelf

The Vasse Shelf contains up to 2000 m of Permian strata overlain by a maximum of 1000 m of Mesozoic rocks. It is bounded by the Busselton Fault to the east and the Dunsborough Fault to the west (Fig. 2). The term shelf, as used by Playford et al. (1976), is preferred to the Vasse Terrace of Hocking (1994) because the area occupies a marginal elongate position between the Leeuwin Complex and the downthrown Bunbury Trough. This structural setting is similar to that of the Peedamullah Shelf in the Carnarvon Basin and the Lennard Shelf in the Canning Basin. The relatively shallow basement of the Vasse Shelf, like the basement of the Peedamullah Shelf and Lennard Shelf, occupies an intermediate position between Precambrian rocks and the deep basement of the troughs, represented by the Bunbury Trough, Barrow Sub-basin, and Fitzroy Trough respectively. In each case, major faults separate the shelf areas from the downthrown troughs.

The stratigraphic succession thins to the west, and to the north it abuts against the southern extension of the Badaminna Fault System that separates it from the Vlaming Sub-basin. To the south, the Vasse Shelf extends offshore, and becomes thinner towards the continental margin. Two petroleum exploration wells, Sue 1 and Alexandra Bridge 1 (Fig. 4), have been drilled on the shelf, and extensive exploration for coal has been carried out in its northernmost part where the coal seams are shallow (Le Blanc Smith and Kristensen, 1998). Strike-slip faults and compressional features are common on the shelf. Vitrinite reflectance data indicate that the depth of burial of the Permian strata is insufficient for significant hydrocarbon generation (Iasky, 1993).

Bunbury Trough

The Bunbury Trough is bounded to the west by the Busselton Fault and the southern extensions of the Badaminna Fault System, and to the east by the Darling Fault that separates it from the Yilgarn Craton (Fig. 2). Up to 11 000 m of sediments have been interpreted within the trough, with the deepest part near the Darling Fault (Iasky, 1993). Triassic, Jurassic, and thin lower Neocomian sedimentary rocks overlie a thick Permian succession. A thin section (100–200 m thick) of post-breakup Lower Cretaceous strata is present over most of the trough. The temperature gradient is low, averaging 19°C/km. To the north, the Bunbury Trough is separated from the Mandurah Terrace by the Harvey Ridge. The trough shallows to the south where it reaches the continental margin. A large number of strike-slip induced compressional anticlines are present, probably because the relatively narrow trough between two basement highs (the Leeuwin Complex and Yilgarn Craton) offers limited relief to tectonic stresses. Vitrinite reflectance data indicate that the Permian strata have been buried sufficiently deeply to generate hydrocarbons, and on the western flank of the trough they are presently within the oil or the upper gas–condensate window (Iasky, 1993).

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Figure 9. South–north log correlation: Sue 1 to Woodada 3

Stratigraphy

The stratigraphy of the central and southern Perth Basin is summarized in Figure 3, based on the correlation of exploration wells (Plates 1 and 2; Figs 9 and 10). Formation tops for the wells drilled in the area are listed in Appendix 3.

Permian

The oldest known sedimentary rocks in the area are Permian in age. They have been intersected on the Vasse Shelf, in the Bunbury Trough, and on the southernmost part of the Mandurah Terrace (Plate 1; Figs 4 and 9). On the Vasse Shelf, Sue 1 reached granitic basement and provided a structurally undisturbed, well-sampled Permian section. In addition, a large amount of core from coal exploration within the Vasse River Coalfield allows a detailed examination of Permian strata, albeit faulted, on the northern part of the Vasse Shelf (Le Blanc Smith and Kristensen, 1998).

The Permian interval in Sue 1 was described by Williams and Nicholls (1966), and was formally established as the type section for the ‘Sue Coal Measures’ by Playford and Low (1972). Backhouse (1993) used Sue 1 as a reference section for Permian palynostratigraphic correlation, and recognized a 51 m-thick transgressive glacigene unit near the base of the well. He therefore restricted the type section of the Sue Coal Measures to the interval 1216–3003 m in Sue 1. Le Blanc Smith and Kristensen (1998) proposed a more detailed stratigraphy for the Permian strata of the Vasse River Coalfield, with type sections in coal exploration boreholes (Table 1). The basal glacigene unit was defined as the Mosswood Formation. The Sue Coal Measures was elevated to group status to become the Sue Group, and was subdivided into five formations that in ascending order are the Woodynook Sandstone, Rosabrook Coal Measures, Ashbrook Sandstone, Redgate Coal Measures, and Willespie Formation. The newly proposed stratigraphy is followed here, and the five units formally defined for the Vasse River Coalfield have been identified in Sue 1, where the thickness of all of the discrete formations can be measured precisely (Table 1). Palynological evidence has been used to correlate the Permian succession with units in the northern Perth Basin (Fig. 11). Previously, the boundary between the Early and Late Permian was placed at the base of the *Didecitriletes ericianus* Zone, but it is now placed at the base of the *Microbaculispora villosa* Zone, and as more data become available its position may be revised further. In the southern Perth Basin sedimentation within this interval is continuous, whereas in the northern Perth Basin a stratigraphic gap is present, at least locally.

During the Late Permian – Early Triassic, sedimentation in the southern Perth Basin appears to have been nearly continuous, with perhaps a short break at the top of the Sue Group. In the northern Perth Basin, near the Greenough River, a stratigraphic gap is indicated in the uppermost Permian, where the Lower Triassic Kockatea Shale disconformably overlies the Upper Permian Wagina Sandstone. Elsewhere in the northern Perth Basin, the

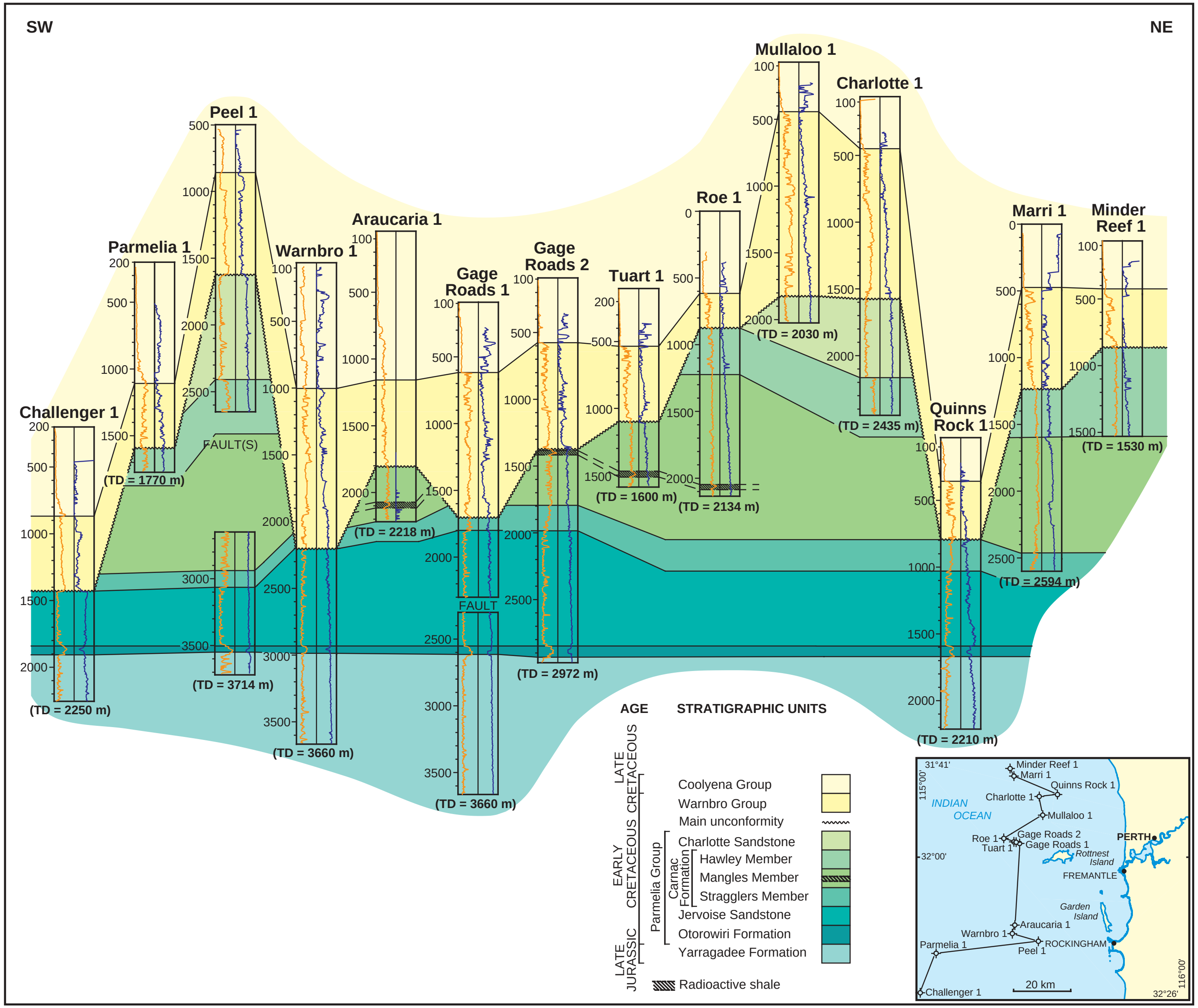

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Figure 10. Parmelia Group log correlation within the Vlaming Sub-basin: Challenger 1 to Minder Reef 1. Note that the boundary between the Late Jurassic and Early Cretaceous is at the base of the Parmelia Group, and not as shown on Plate 2

Table 1. Type sections for the Permian formations on the Vasse Shelf, southern Perth Basin

Formation	*Type section (Vasse River Coalfield; Le Blanc Smith and Kristensen, 1998)* Corehole	Coordinates	*Sue 1 interval (this Report)*	*Thickness (m)* Type section	Sue 1
Willespie Formation	CRA-MCH-1A (171–794 m) CRA-CRCH-3 (116–240 m)	30°43'23.91"S 115°08'6.475"E 33°42'41.50"S 115°11'50.59"E	1 216–2 276 m	>747	1 060
Redgate Coal Measures	CRA-CRCH-3 (240–405 m)	33°42'41.50"S 115°11'50.59"E	2 276–2 422 m	165	146
Ashbrook Sandstone	CRA-CRCH-3 (405–540 m)	33°42'41.50"S 115°11'50.59"E	2 422–2 684 m	135	262
Rosabrook Coal Measures	CRA-CRCH-3 (540–781 m)	33°42'41.50"S 115°11'50.59"E	2 684–2 882 m	241	198
Woodynook Sandstone	CRA-CRCH-1 (485–556 m)	33°45'50.42"S 115°10'55.46"E	2 882–3 003 m	71	121
Mosswood Formation	CRA-CRCH-1 (556–568 m) BMT-DDH-2 (175–198 m)	33°45'50.42"S 115°10'55.46"E 33°52'17.51"S 115°15'6.296"E	3 003–3 054 m	35	51

relationships of the Upper Permian Dongara Sandstone and Beekeeper Formation to the overlying Lower Triassic Kockatea Shale are still unresolved (Mory and Iasky, 1996). The Lower Permian successions in the northern and southern parts of the basin are broadly comparable, although the marine incursion characterized by the Carynginia Formation in the northern Perth Basin appears to correlate with the continental Ashbrook Sandstone in the southern Perth Basin. The Upper Permian Willespie Formation in the southern Perth Basin reaches a thickness of about 1000 m, whereas the Upper Permian of the northern Perth Basin reaches a maximum thickness of approximately 300 m (Fig. 9).

In the southern Perth Basin, seismic data suggest that the Permian sequence thickens eastwards towards the Darling Fault (Iasky, 1993), implying that the fault actively controlled sedimentation during that time. The limited control and poor quality of this data, however, made the seismic determination of top basement difficult. Conversely, palynostratigraphic data (Backhouse, 1993) suggest that there may be little difference in the thicknesses of the sedimentary rocks in the Lower Permian section in Sue 1 and the Lower Permian section in the Collie Basin, which implies that there may have been little movement on the Darling Fault during the Early – Middle Permian. Thinning of the Permian sedimentary rocks to the south suggests that its offshore extension is limited (Fig. 12), and that the alluvial-plain depositional system represented by the Sue Group drained to the north.

Mosswood Formation

The Mosswood Formation is a glacigene unit of earliest Permian age that was identified over the interval 3003–3054 m in Sue 1 by Backhouse (1993), who originally equated it to the Stockton Formation in the Collie Basin. Le Blanc Smith and Kristensen (1998) defined the basal Permian glacigene Mosswood Formation in the Vasse River Coalfield and placed it within the expanded Stockton Group. This usage is followed here. The type section is a composite of two coal exploration coreholes that contain a total of 35 m of section (Table 1), but the thickness of the unit varies significantly in accordance with the palaeotopographic surface it covers.

The Mosswood Formation consists of dark grey-brown to black argillaceous rocks, with subordinate siltstone and fine-grained sandstone. In Sue 1, a few granules and a small pebble of pink granite are present, embedded as erratics within an argillaceous matrix (Williams and Nicholls, 1966). On the Vasse Shelf, numerous pebble-sized, largely granitic erratics are evident in core. The depositional environment for the Mosswood Formation is considered to be fluviolacustrine, with the minor erratics indicating the presence of melting icebergs that dropped morainic material onto the basin floor. In comparison, some of the thick Permian glacigene deposits of the northern Perth and Carnarvon Basins may have a more marine origin.

A thin basal conglomerate in Sue 1 (core 35) contains pebbles and boulders of granulite set in a greenish, coarse-grained sandstone matrix, and rests unconformably on basement (Williams and Nicholls, 1966). This basal contact, between diamictite and granitic basement, was also cored in borehole BMT-DDH-2, just west of the Wirring Fault on the Vasse Shelf (Backhouse, 1993; Le Blanc Smith and Kristensen, 1998). The upper contact with the Sue Group is conformable and gradational, being

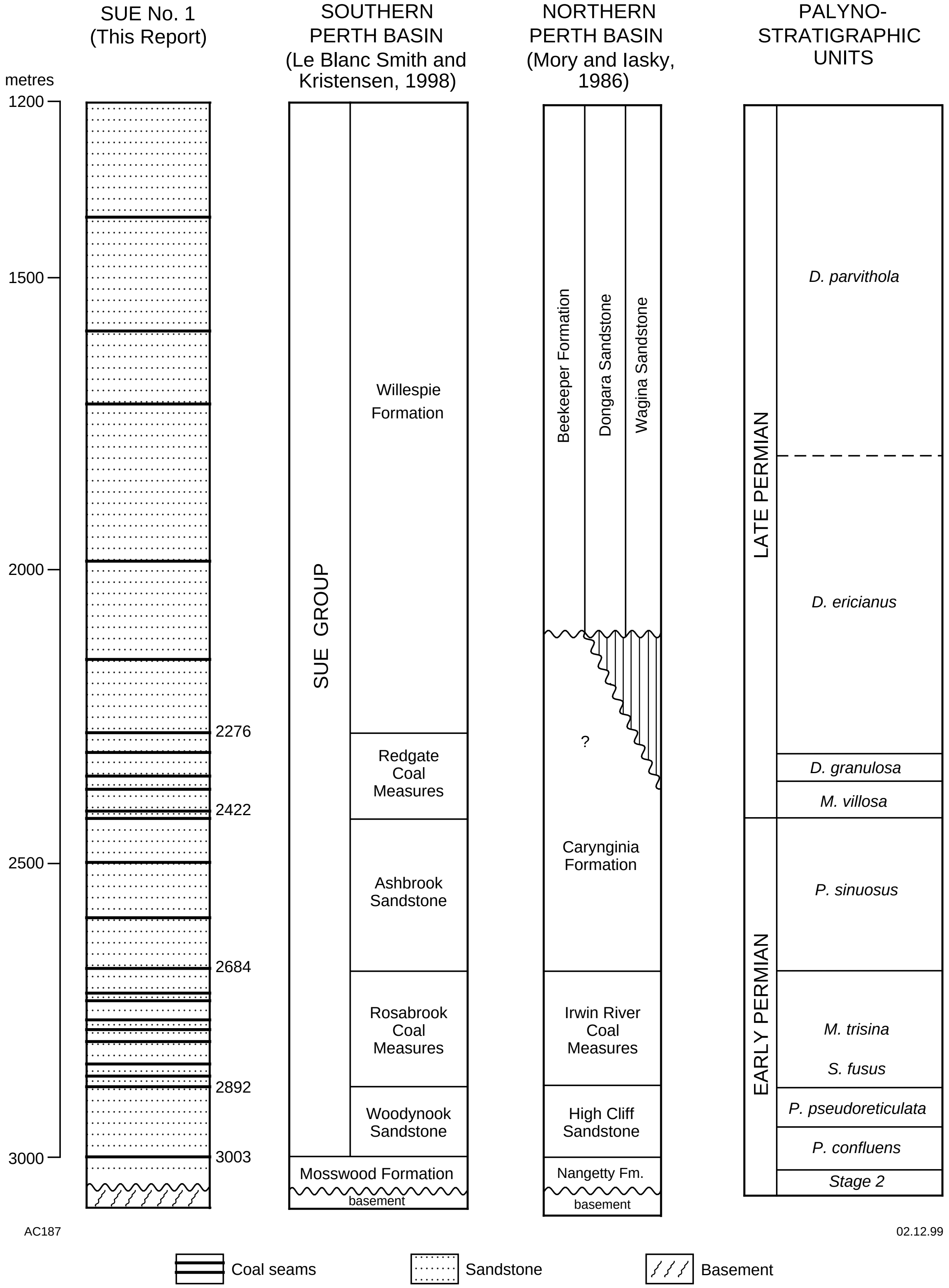


Figure 11. Stratigraphic correlation between northern and southern Permian sequences of the Perth Basin

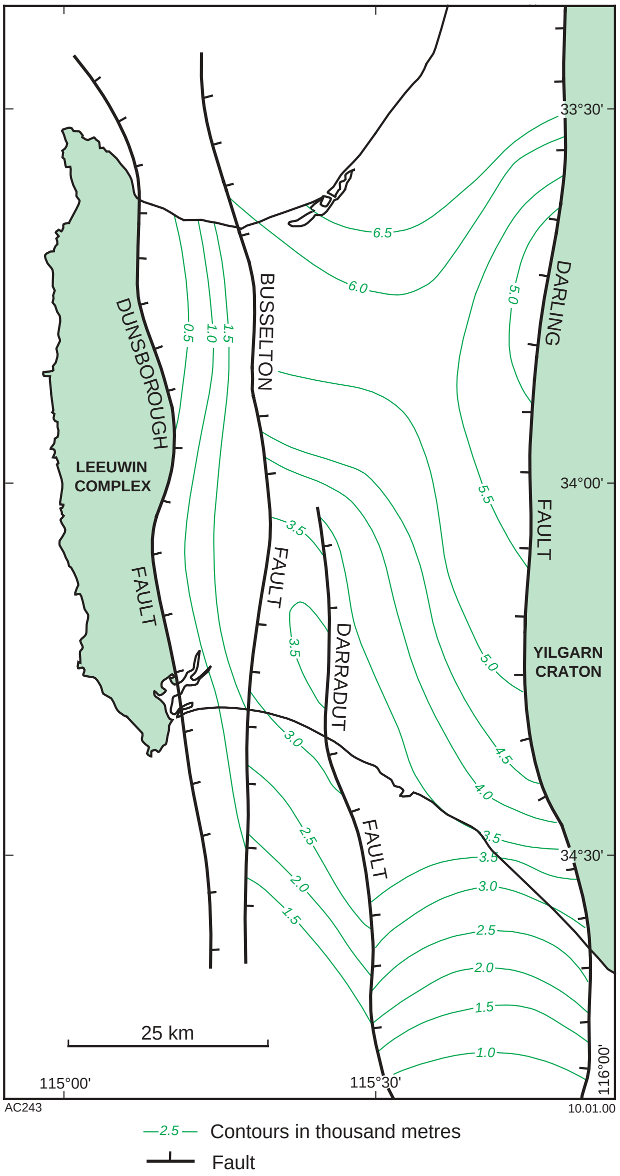


Figure 12. Isopach map of the Permian Mosswood Formation and Sue Group within the Vasse Shelf and Bunbury Trough (after Iasky, 1993; plates 9 and 11)

marked by a gradual increase of the sandstone component and a corresponding decrease in fine clastic material.

The Mosswood Formation in Sue 1 contains palynomorphs of the *Pseudoreticulatispora confluens* Zone and Stage 2 (Backhouse, 1993) that indicate an Asselian to early Sakmarian age.

Sue Group

The Sue Group contains, in ascending order, the Woodynook Sandstone, Rosabrook Coal Measures, Ashbrook Sandstone, Redgate Coal Measures, and Willespie Formation. Only brief descriptions of these units are given in this Report, but more detail is contained in Le Blanc Smith and Kristensen (1998).

Woodynook Sandstone

The Woodynook Sandstone consists predominantly of poorly sorted fluvial sandstone. The type section is 71 m thick (Table 1), whereas in Sue 1 it is 121 m thick.

The transitional upper contact with the Rosabrook Coal Measures is conformable, and is placed immediately beneath the stratigraphically lowest coal seam of that unit. In the type section, the top of the unit falls within the *Pseudoreticulatispora pseudoreticulata* Zone, but the base of the unit may be within the *P. confluens* Zone, although the evidence is equivocal. The unit is Sakmarian (Early Permian) in age. No reliable palynological samples are available from this interval in Sue 1 (Backhouse, 1993).

Rosabrook Coal Measures

The Rosabrook Coal Measures was introduced by Le Blanc Smith and Kristensen (1998) for the lower coal-bearing unit within the Permian sequence of the Vasse River Coalfield. In the type section (Table 1), the unit reaches a thickness of 241 m, whereas in Sue 1 it is 198 m thick. The Rosabrook Coal Measures is characterized by poorly sorted feldspathic sandstone intercalated with siltstone and carbonaceous shale grading upwards to coal. The seams of black and bituminous coal range from 0.1 to 4.5 m in thickness, and are the thickest and best quality Permian seams on the Vasse Shelf (Le Blanc Smith and Kristensen, 1998) Seams of similar thickness are present in Sue 1. The Rosabrook Coal Measures is interpreted to have been deposited in a fluvial-plain setting in which deltas prograded into a lacustrine environment.

The contact between the Rosabrook Coal Measures and Woodynook Sandstone is transitional, and the two units are lithologically similar. They are distinguished from each other by the presence of significant coal seams in the Rosabrook Coal Measures. The Rosabrook Coal Measures is conformably overlain by the Ashbrook Formation.

In corehole CRA-CRCH-1 on the Vasse Shelf, the unit ranges from the *Striatopodocarpites fusus* to the *Microbaculispora trisina* Zone, indicating a late Sakmarian to Artinskian age. In Sue 1 it appears to occupy a similar biostratigraphic level, although the data from this well are too poor to be conclusive (Backhouse, 1993). The unit is correlated lithologically and palynologically with the Irwin River Coal Measures of the northern Perth Basin (Fig. 11).

Ashbrook Sandstone

The Ashbrook Sandstone was formally introduced by Le Blanc Smith and Kristensen (1998) for the poorly sorted feldspathic sandstone unit, without major coal seams, that overlies the Rosabrook Coal Measures. In the type section within the Vasse River Coalfield the unit is 135 m thick, whereas in Sue 1 it is 262 m thick (Table 1). A lacustrine–deltaic environment of deposition is envisaged for the Ashbrook Sandstone. The Ashbrook Sandstone is conformably overlain by the Redgate Coal Measures.

Palynostratigraphically, the unit is characterized by the *Praecolpatites sinuous* Zone, which is now considered to be approximately Kungurian in age (Mory and Backhouse, 1997; Fig. 3).

Redgate Coal Measures

The Redgate Coal Measures was defined by Le Blanc Smith and Kristensen (1998) as a coaly, poorly sorted feldspathic sandstone overlying the Ashbrook Sandstone. The type section in the Vasse River Coalfield is 165 m thick, which is comparable to Sue 1, where it is 146 m thick (Table 1).

On the Vasse Shelf, the Redgate Coal Measures consists predominantly of sandstone with intercalations of siltstone, shale, and numerous thin coal seams, the thickness of which ranges from a few centimetres to 1.6 m. The coal is black and mainly bituminous, similar to that in the Rosabrook Coal Measures, but has a lower economic potential because of the limited extent of the seams, both vertically and horizontally. The sandstone beds fine upwards and are similar to those of the underlying Ashbrook Sandstone, albeit with more frequent and thicker argillaceous beds. The Redgate Coal Measures was deposited in an alluvial environment that ranged from braided streams to swamp and lacustrine deltas. The Redgate Coal Measures passes conformably upwards into the Willespie Formation (Fig. 11).

In Sue 1, the unit appears to range palynostratigraphically from the *Microbaculispora villosa* Zone into the lower part of the *Didecitriletes ericianus* Zone, an interval currently dated as Ufimian to Kazanian. The intermediate *Dulhuntyispora granulata* Zone was not identified by Backhouse (1993). In the Vasse River Coalfield, only the *D. ericianus* Zone has been proven to be present, but the palynological data are sparse.

Willespie Formation

The Willespie Formation (Le Blanc Smith and Kristensen, 1998) is a thick unit of poorly sorted feldspathic sandstone, with subordinate conglomerate, siltstone, shale, and sporadic thin, lenticular sub-bituminous coal that lies conformably above the Redgate Coal Measures. In the Vasse River Coalfield, the unit is at least 747 m thick, but has not been completely penetrated (Table 1), whereas in Sue 1 a complete section of 1060 m thickness is present. Like the Ashbrook Sandstone, the Willespie Formation is dominated by numerous upward-fining sandstone cycles. Lenticular coal seams are common, with thicknesses generally less than 0.5 m (Le Blanc Smith and Kristensen, 1998), although thicker beds are present, as in Scott River 1 where a 1.5 m-thick seam is present between 1920.5 and 1922 m. Sandstone porosity is fair to good, with local tight streaks. An alluvial to upper deltaic environment of deposition within a lacustrine setting is envisaged. The Willespie Formation in the Vasse River Coalfield is unconformably overlain by the Cretaceous Warnbro Group, but in Sue 1 and elsewhere in the southern Perth Basin it is overlain by the Triassic Sabina Sandstone, with an apparently conformable contact.

In Sue 1, the unit ranges from the *D. ericianus* to the *Dulhuntyispora parvithola* Zone, and Backhouse (1993) recognized the appearance of *Camptotriletes warchianus* and *Microbaculispora* sp. *A* as potentially useful biohorizons, but did not erect zones based on these species. There is an age correlation, based on similar palynofloras, between this unit and the Wagina Sandstone of the northern Perth Basin (Backhouse, 1993).

Triassic

The Permian succession appears to pass upwards into the Triassic with no break in sedimentation. However, a palynostratigraphic break is evident at about the top of the Willespie Formation. The contact has been cored in Whicher Range 2 (core 1), where at 3896 m Lower Triassic coarse clastic rocks of the Sabina Sandstone overlie Upper Permian fine clastic rocks interbedded with coal seams of the Willespie Formation. The boundary between the two units appears to be related to a transition from a quiet lacustrine environment (Willespie Formation) to an environment in which there was active transportation of material by running streams (Sabina Sandstone).

The marine Lower Triassic Kockatea Shale in the northern Perth Basin correlates with the continental Sabina Sandstone in the southern Perth Basin. In the northern Perth Basin, siltstone and fine-grained sandstone of the Middle – Upper Triassic Woodada Formation forms a transitional unit between the underlying marine Kockatea Shale and the overlying continental Lesueur Sandstone. In the southern Perth Basin, the Woodada Formation has not been recognized and the entire Middle – Upper Triassic succession has been assigned to the Lesueur Sandstone. In several wells, however, the Lesueur Sandstone has been informally subdivided into a lower sandstone member (Wonnerup Member), and an upper member (Myalup Member) that consists of fine clastic sediments interbedded with sandstone (Plate 1). This interval has not been penetrated in the central Perth Basin, and it does not readily correlate with the northern Perth Basin succession.

Sabina Sandstone

The Sabina Sandstone overlies the Willespie Formation with an apparently conformable contact, and is conformably overlain by the Lesueur Sandstone. The Sabina Sandstone was recognized as a distinctive unit in all the early oil exploration wells in the southern Perth Basin (Williams and Nicholls, 1966; Union Oil Development Company, 1968, 1969, 1972), although no formal or informal name was suggested. It was generally considered, on palynological evidence, to be an equivalent of the Lower Triassic Kockatea Shale of the northern Perth Basin. The name Sabina Sandstone was first applied by Young and Johanson (1973), and was formally defined by Playford et al. (1975). The type section in Whicher Range 1 is now revised to the interval 3450–3915 m. Thinning of the Sabina Sandstone to the west (Fig. 13) suggests that the depositional edge of the basin was within the Vasse Shelf during the Early Triassic. The maximum known thickness of the Sabina Sandstone is in Lake Preston 1 (561 m).

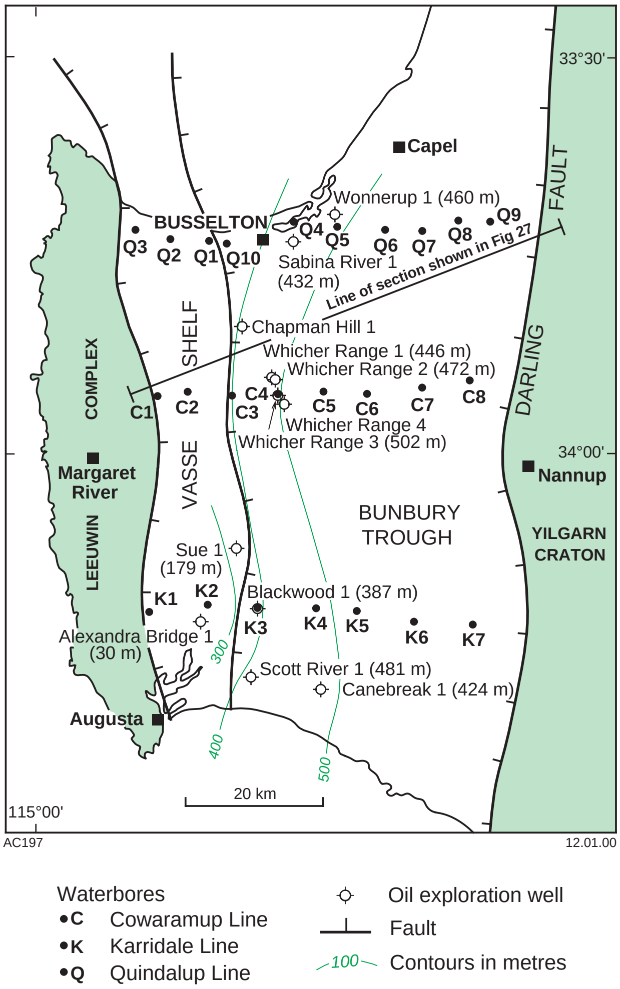


Figure 13. Isopach map of the Sabina Sandstone in the Bunbury Trough

The Sabina Sandstone consists predominantly of green-grey, micaceous, poorly consolidated sandstone, with interbedded grey shale and siltstone. The sandstone is moderately sorted and ranges from very fine to coarse grained. The green colour is due to the abundance of green mica and a greenish coating on the quartz grains (Williams and Nicholls, 1966).

The lower contact shows a distinct and abrupt change in lithology, with the most characteristic difference being the absence of coaly intervals in the Sabina Sandstone. The upper contact can be defined on sonic, gamma-ray, calliper, and electric logs. The sonic log indicates an increase in travel time, the gamma-ray log shows an increase in gamma radiation, the calliper log an increase on hole caving, and the electric logs reflect the presence of siltstone and minor claystone interbedded with the prevailing sandstone.

Backhouse (1993) identified pre-*Lunatisporites pellucidus* Zone assemblages in the Sabina Sandstone in Wonnerup 1 and Whicher Range 2. Other intervals of Sabina Sandstone were interpreted as belonging to the unequivocally Triassic *L. pellucidus* or *Protohaploxypinus samoilovichii* Zones. The Sabina Sandstone is treated here as entirely Early Triassic in age, although the lowest palynological interval has also been considered by Dolby and Williams (1973) to be latest Permian in age. In Whicher Range 2, core 1 (3890–3906 m) has yielded palynological assemblages now considered to be consistent with the *Protohaploxypinus microcorpus* Zone of Foster (1982). The age of this zone is still problematic; Foster (1982) placed the zone in the latest Permian, but it may be earliest Triassic in age. If this is the case, then the Permian–Triassic boundary would lie below 3906 m and probably above core 2 (3941–3951 m).

The report of marine palynomorphs (Playford et al., 1976) has not been substantiated by current work on the unit. Previous reports indicate a non-marine, possibly fluvial, environment of deposition for the Sabina Sandstone.

Lesueur Sandstone

The Lesueur Sandstone was introduced by Willmott, Johnstone, and Burdett (Willmott, 1964) for the medium to very coarse grained sandstone of Middle – Late Triassic age. The type section is the interval 264–1008 m in Woolmulla 1 in the northern Perth Basin (Mory and Iasky, 1996). The Lesueur Sandstone in the Vasse Shelf and Bunbury Trough ranges in thickness from 331 m in Alexandra Bridge 1, where it is eroded, up to 1995 m in Whicher Range 3. The isopach map of the unit shows depositional thinning to both the west and south (Fig. 14), whereas to the north, on the Harvey Ridge, the unit is 2292 m thick in Lake Preston 1.

In the southern Perth Basin, and in the southernmost part of the central Perth Basin, the fluvial Lesueur Sandstone may be differentiated into two members (Plate 1; Fig. 3), which is consistent with the description of the Lesueur Sandstone in Lake Preston 1 by Young and Johanson (1973). These members are here named the Wonnerup Member and the Myalup Member. The Wonnerup Member comprises homogeneous sandstone, whereas the Myalup Member includes sandstone with subordinate interbeds of finer clastic rocks. In the Wonnerup Member, the sandstone is feldspathic, poorly sorted, coarse to very coarse grained, generally unconsolidated, and light grey to colourless, in contrast to the Myalup Member, which is dark grey. The fine-grained clastic rocks are mostly siltstone beds up to 20 m thick.

The interval from 2640 to 3644 m in Wonnerup 1 (latitude 33°37'59", longitude 115°28'24") is nominated as the type section of the Wonnerup Member. The type section of the Myalup Member is nominated as the interval between 1219 and 2045 m in Lake Preston 1 (latitude 32°55'13", longitude 115°39'39"). The boundary between the two members is a good regional seismic marker. On wireline logs, the Myalup Member shows a similar character to the overlying Jurassic units.

The Lesueur Sandstone has not been penetrated in the central Perth Basin. The formation conformably overlies the Lower Triassic Sabina Sandstone in the southern part of the basin and the Early – Middle Triassic Woodada

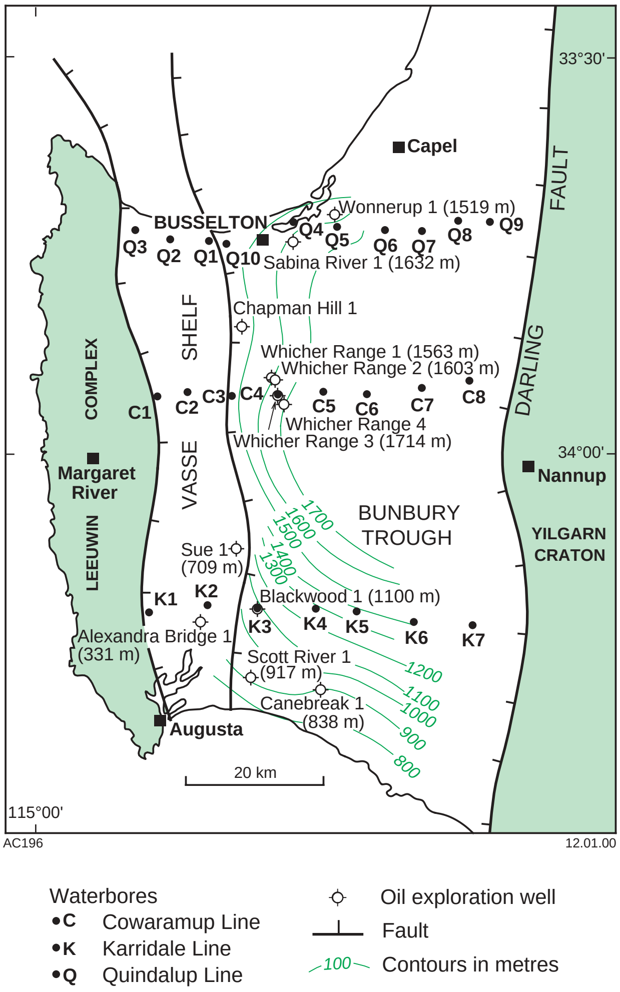


Figure 14. Isopach map of the Lesueur Sandstone in the Bunbury Trough

Formation in the northern Perth Basin. No stratigraphic hiatus, however, is implied, because Dolby and Williams (1973) have correlated the palynological assemblage between 3078 and 3094 m in Lake Preston 1 with assemblages typical of the Woodada Formation in the northern Perth Basin. In the southern Perth Basin, therefore, the lower part of the Lesueur Sandstone is approximately coeval with the Woodada Formation of the northern Perth Basin, whereas the upper part passes upwards into the Cattamarra Coal Measures. In the central part of the basin, the unit passes upwards into the Eneabba Formation (Plate 1; Fig. 9). In the northern Perth Basin, the Woodada Formation represents a depositional environment transitional between the underlying fine-grained marine Kockatea Shale and the overlying, predominantly sandstone, fluviatile Lesueur Sandstone. In the southern Perth Basin, the Wonnerup Member is lithologically closer to the Lesueur Sandstone, and the Myalup Member represents a transitional environment between the underlying Wonnerup Member and the overlying Cattamarra Coal Measures. On a wider scale, the Myalup Member appears to correlate with the uppermost part of the Mungaroo Formation of the Barrow–Dampier Sub-basin of the Northern Carnarvon Basin.

Balme (1966) suggested a Middle – Late Triassic age, on the basis of a poorly diversified palynological assemblage from the Lesueur Sandstone in Pinjarra 1. A similar age is indicated for the unit in Wonnerup 1 (Union Oil Development Company, 1972), Lake Preston 1 (Dolby and Williams, 1973), Sabina River 1 (Ingram, 1982), and in the northern part of the basin (Mory and Iasky, 1996).

Jurassic

A thick Jurassic succession extends over a wide area of the Perth Basin. It consists predominantly of continental deposits, with the exception of the relatively thin marine Cadda Formation, which is restricted to the northern and part of the central Perth Basin (Fig. 3). In the study area, more than 2000 m of Jurassic rocks have been penetrated in Pinjarra 1, where the top of the Yarragadee Formation has been eroded and the Cadda Formation appears absent. The thickest Jurassic section drilled to date is in Bootine 1 from 280 to 4306 m total depth (TD), even though the Eneabba Formation was not reached in this well. This well terminated in the *Callialasporite turbatus* Zone, which means that the lowest Jurassic *Corollina torosa* Zone lies between the lowest sample from this well and the top of the Triassic.

Eneabba Formation

The Eneabba Formation was elevated to formation status by Mory (1994). The type section is the interval 2320–2978 m in Eneabba 1 in the northern Perth Basin. This Lower Jurassic unit is characterized by the presence of multicoloured siltstone and shale interbedded within dominantly sandstone lithologies. In unpublished WAPET reports, the Eneabba Formation was originally referred to as the ‘Multicoloured Member’ of the Cockleshell Gully Formation, but this definition has been abandoned. The Eneabba Formation is widespread in the northern Perth Basin, and is also recognized in Lake Preston 1 and Pinjarra 1 within the central Perth Basin. However, this unit has not been identified in the southern Perth Basin, where the Cattamarra Coal Measures directly overlies the Lesueur Sandstone (Fig. 3). Based on the presence of the *Corollina torosa* Zone, Discovery Petroleum NL (1992a) interpreted the presence of the Eneabba Formation in Chapman Hill 1 and other wells in the Bunbury Trough. Although that interpretation is not followed here, it shows that there is a section in the Bunbury Trough that is a time equivalent to the Eneabba Formation. In this Report, that section is included within the Cattamarra Coal Measures because the multicoloured fine-grained clastic rocks characteristic of the Eneabba Formation are absent.

Lithologically, the Eneabba Formation consists of feldspathic, coarse to very coarse grained sandstone interbedded with local minor conglomerate, and multicoloured claystone and siltstone (Mory and Iasky, 1996). In the type section, the ratio between the multicoloured fine clastic rocks and the sandstones is approximately 1:5. This is assuming that the lower and upper boundaries are present at the first appearance and disappearance respectively of the very distinctive multicoloured sediments. The Eneabba Formation is conformably overlain by the Cattamarra Coal Measures.

A fluviatile environment is envisaged for the formation. The sandstone intervals probably represent channel-fill deposits. The multicoloured clastic rocks indicate an oxidizing environment and suggest episodes of subaerial exposure, and are interpreted as overbank floodplain deposts. In the northern Perth Basin, the Eneabba Formation contains assemblages assigned to the *Corollina torosa* Zone of Early Jurassic age (Mory and Iasky, 1996). Sparse palynological data in Lake Preston 1 and Pinjarra 1 indicate a similar age.

Cattamarra Coal Measures

The Cattamarra Coal Measures was originally named the Cattamarra Coal Member of the Cockleshell Gully Formation, with the sandy interval 1790–2302 m in Eneabba 1 as the type section (Willmott, 1964). Subsequently, the type section in Eneabba 1 has been modified to the interval 1554–2320 m (Mory and Iasky, 1996).

The greatest thickness of the unit is present on the downthrown eastern side of the Badaminna Fault System (Fig. 6) in the Beermullah Trough. The isopach map of the Cattamarra Coal Measures in the southern Perth Basin also shows a thickening to the east towards the Yilgarn Craton (Fig. 15), which suggests that the eastern boundary of the unit is controlled by the Darling Fault. The Cattamarra Coal Measures has conformable and gradual contacts with both the underlying Eneabba Formation and the overlying Cadda Formation or Yarragadee Formation. In the southern Perth Basin, the unit is the time equivalent of the Eneabba Formation of the central and northern Perth Basin.

The Cattamarra Coal Measures contains coarse-grained quartz sandstone interbedded with dark carbonaceous fine-grained clastic rocks and thick coal seams. The coal seams are good seismic markers, as they exhibit a strong density contrast with overlying sandstones. However, due to the lenticular nature of the seams, these markers cannot be followed over large distances, although the total interval with seams is useful in regional correlations. Tarabbia (1991) considered that the sandstone units were deposited in distributary channel fills within fluvial braided–meander–paludal complexes. On the other hand, the moderate sorting and poor rounding indicates transportation over short distances, and the coaly intervals indicate deposition in marshy embayments. In the northern Perth Basin, some marine influence is recognizable in the upper part of the formation.

Within the southern Perth Basin, the palynology of the Cattamarra Coal Measures in Chapman Hill 1 has recently been studied in some detail. Discovery Petroleum NL (1992a) found that the upper zone is characterized by the *Callialasporites turbatus* Zone and the lower zone by the *Corollina torosa* Zone. The suggested age is Aalenian–Toarcian for the upper zone and Toarcian–Pliensbachian for the lower zone.

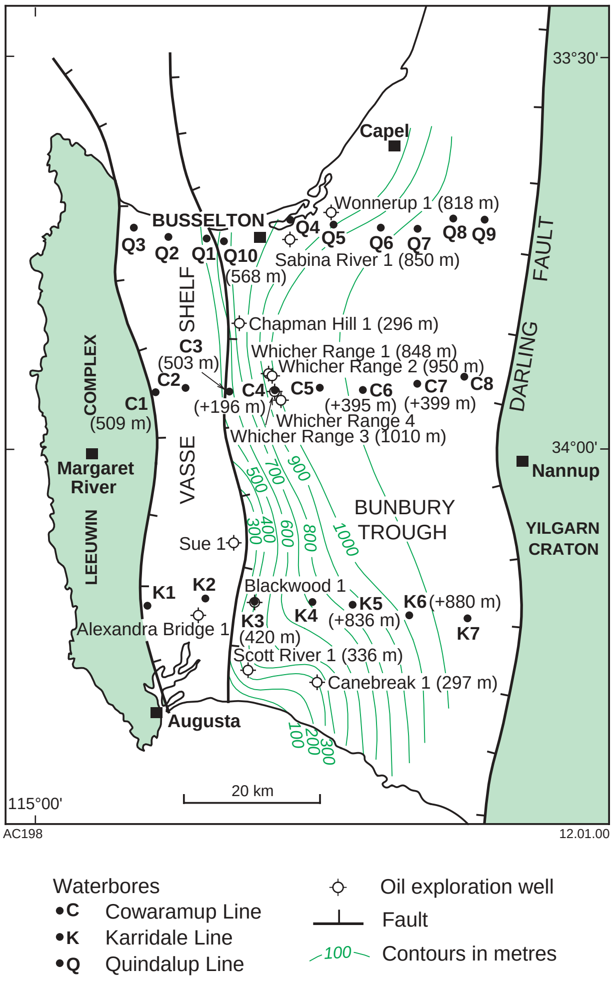


Figure 15. Isopach map of the Cattamarra Coal Measures in the Bunbury Trough

Cadda Formation

The Cadda Formation is a Middle Jurassic unit composed of marine clastics and fossiliferous limestone (Mory and Iasky, 1996). The formation is widespread in the northern Perth Basin and the Beermullah Trough. The equivalent time interval has not been penetrated in the Vlaming Sub-basin and the unit is absent in the Mandurah Terrace and Bunbury Trough, where the Yarragadee Formation directly overlies the Cattamarra Coal Measures. In the central Perth Basin, the unit is 200–300 m thick (Plate 1 and Fig. 9) and passes either upwards or laterally into the lowermost part of the Yarragadee Formation. The Cadda Formation was deposited in a shallow sea during a Middle Jurassic transgression that extended as far south as Rockingham 1. Palynology indicates an Aalenian to Bajocian age for the Cadda Formation in the northern Perth Basin (Mory and Iasky, 1996).

Yarragadee Formation

The Yarragadee Formation, as redefined by Backhouse (1984), is an Upper Jurassic sandstone succession of fluvial origin. The type section is the interval 356–3315 m in Gingin 1. In this well, the entire depositional thickness of the unit is preserved, but in many wells the upper part of the unit is eroded. In the southern Perth Basin, the Yarragadee Formation reaches a maximum known thickness of 1510 m in Karridale 6 near the Darling Fault, suggesting that this fault actively controlled the eastern margin of the basin throughout the Late Jurassic (Fig. 16). In the central Perth Basin, the Darling Fault plays the same bounding role to the east in controlling the thickness of the formation, whereas no information is available about the western margin. The Yarragadee Formation conformably overlies either the Cadda Formation or the Cattamarra Coal Measures, and it is overlain, also conformably, by the Otorowiri Formation of the Parmelia Group. Fine- to coarse-grained, poorly sorted feldspathic sandstone is the dominant lithology of the Yarragadee Formation. Thin beds of shale, siltstone, and minor conglomerate and coal are also present. Discrete horizons have limited horizontal continuity, thus hampering detailed correlations, but some regional correlations are possible in the northern part of the basin where there is more well control. The Yarragadee Formation is a predominantly fluvial deposit, with shales and coals representing minor overbank deposits, parts of the fluvial system, or swamps.

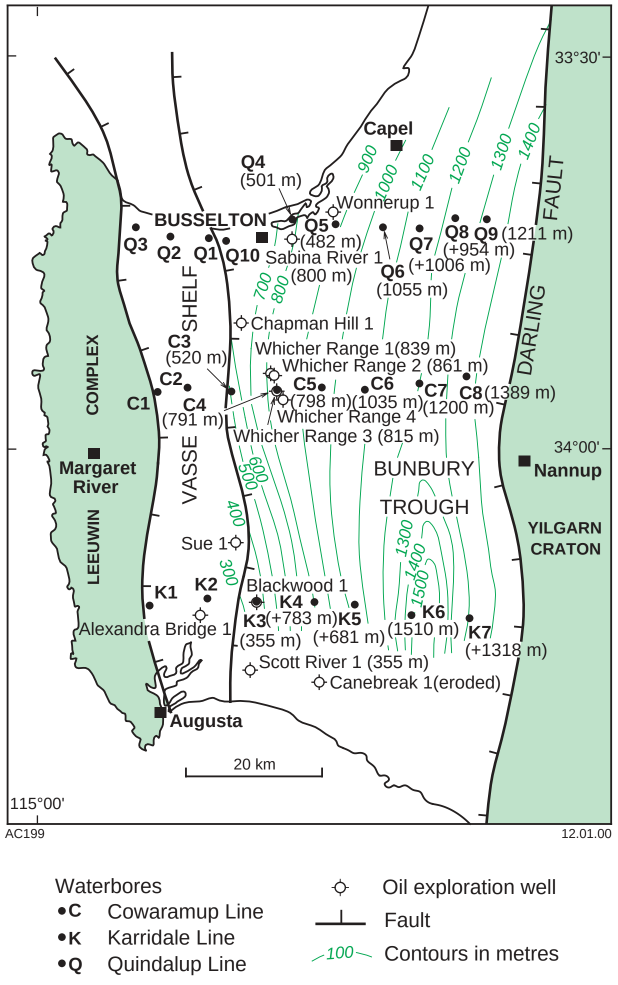


Figure 16. Isopach map of the Yarragadee Formation in the Bunbury Trough

The Yarragadee Formation ranges from the *Dictyotosporites complex* Zone (spore–pollen zone) to the *Retitriletes watherooensis* Zone (spore–pollen zone) of Bajocian to Tithonian age (Filatoff, 1975; Helby et al., 1987).

Cretaceous

Parmelia Group

The Parmelia Formation was established by Backhouse (1984) for an interval that had previously been included in the Yarragadee Formation. The Otorowiri Member was placed at the base of the formation, and a thick shale and siltstone unit within the formation was named as the Carnac Member. The predominantly sandstone successions between the Otorowiri and Carnac Members and above the Carnac Member were left as undifferentiated Parmelia Formation. The age of this succession was estimated to be Tithonian to Berriasian and the Main (breakup) Unconformity, then referred to as the late Tithonian–Berriasian (early Neocomian) unconformity, was identified immediately above the formation. Drilling in the Vlaming Sub-basin led oil companies to use a number of additional lithostratigraphic units in an attempt to identify discrete intervals within the Parmelia Formation. Some of the informal units, such as the ‘Charlotte Sandstone’ at the top of the Parmelia Formation, have been well described. However, others are poorly named, which has resulted in labels such as the ‘Lower Parmelia Sandstone’ between the Otorowiri and Carnac Members, the ‘Intra-Carnac Sandstone Sequence’ within the Carnac Member, and the ‘Y Shale’ and ‘X Shale’ derived from the acoustic impedance generated by the density contrast between a shaly interval and enclosing sandstones. The usage of these units has been inconsistent, partly because they lacked, or their instigators did not take into account, biostratigraphic control. Ingram (1991) made an attempt to divide the Parmelia Formation based on palynological criteria, and this work has been reassessed and is the basis for the stratigraphic correlation of the Parmelia Group in Figure 10 and Plate 2.

The Parmelia Formation is here raised to group status. Within the group, the Otorowiri and Carnac Members are given formation status, the name ‘Charlotte Sandstone’ is formalized, a new formation, the Jervoise Sandstone, is identified, and the Carnac Formation is subdivided into three new members (Fig. 17). The lithostratigraphic boundaries presented here are based on electric-log characters, with overall correlation based on palynostratigraphy. The revised stratigraphy is a prerequisite for the identification and correlation of various incomplete well intersections in the Vlaming Sub-basin.

The type section is the interval 1625–3551 m in Peel 1, as nominated by Backhouse (1988), who recognized that it was the only well to contain all the major subdivisions

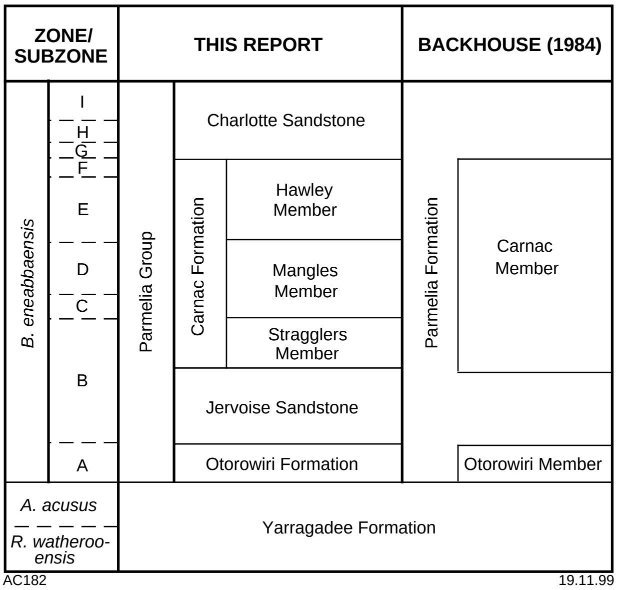


Figure 17. Parmelia Group stratigraphy and palynological subzones as described in Appendix 4

of the Parmelia Formation. It is now acknowledged that the thickness of the formation in this well is considerably reduced by faulting and, although it is still the only well in which the various formations are all present, more representative intervals for some of the various units recognized in this Report have been selected from other wells (Fig. 10; Plate 2).

The Parmelia Group has a wide distribution across the Perth Basin, but it is best developed and attains a maximum thickness in the offshore Vlaming Sub-basin. Onshore, the unit is largely eroded because it immediately pre-dates uplift associated with the early Neocomian breakup. The Parmelia Group was deposited virtually everywhere in the basin, including the Bunbury Trough. Figure 18 shows the area within the Bunbury Trough where Parmelia Group sediments are still present or are interpreted to have been eroded from the crest of a regional high. Onshore, the maximum known thickness of the Parmelia Group is 829 m in Gillingarra Line 7 (Moncrieff, 1989) in the Beermullah Trough.

Otorowiri Formation

The Otorowiri Formation (formerly Otorowiri Member) is named after Otorowiri Spring, 7 miles east of Arrino (Ingram, 1967). The type section is from 253 to 277 m (a thickness of 24 m) in Arrowsmith River 25 (latitude 29°33'25"S, longitude 115°32'00"E), which is located in the northern Dandaragan Trough. The original reference section from 1590 to 1647 m in Quinns Rock 1 is reinterpreted in this Report as 1591 to 1670 m (a thickness of 79 m). Lithologically, the Otorowiri Formation is a silty shale unit at the base of the Parmelia Group. More detailed descriptions have been provided by Ingram (1967, p. 123) and Backhouse (1984, p. 46).

The Otorowiri Formation is conformably overlain by the Jervoise Sandstone and conformably overlies the Yarragadee Formation. The precise age of the unit is not known and it has been interpreted previously as basal Cretaceous or Tithonian. For the purposes of this Report, it is accepted as earliest Cretaceous in age. This allows the whole Parmelia Group to be placed in the Lower Cretaceous (see the above discussion).

The Otorowiri Formation always lies at the base of the Parmelia Formation, and was deposited at the beginning of the tectonic activity that initially resulted in the flooding of the Perth Basin and ultimately resulted in the Neocomian fragmentation of Gondwana. The density contrast between the fine clastic rocks of the Otorowiri Formation, and the coarse clastic rocks of the Yarragadee Formation (below) and Jervoise Sandstone (above) produces an outstanding seismic horizon (Fig. 19) that has been referred to as the 131 maximum flooding surface by Seggie (1990).

Jervoise Sandstone

The Jervoise Sandstone is named after Jervoise Bay on the eastern side of Cockburn Sound. The type section is from

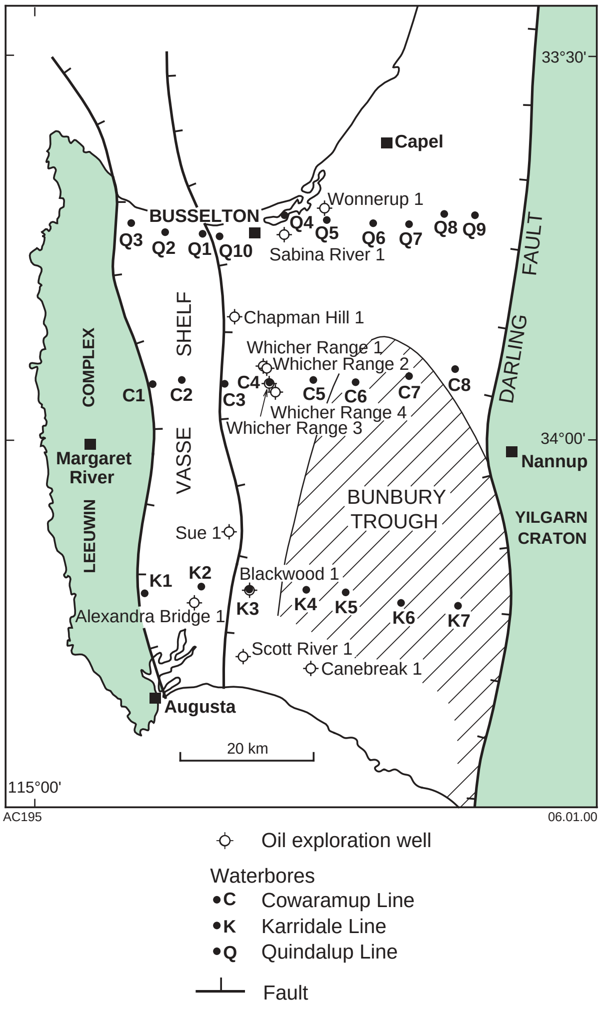


Figure 18. Extent of deposition of the Parmelia Group in the Bunbury Trough

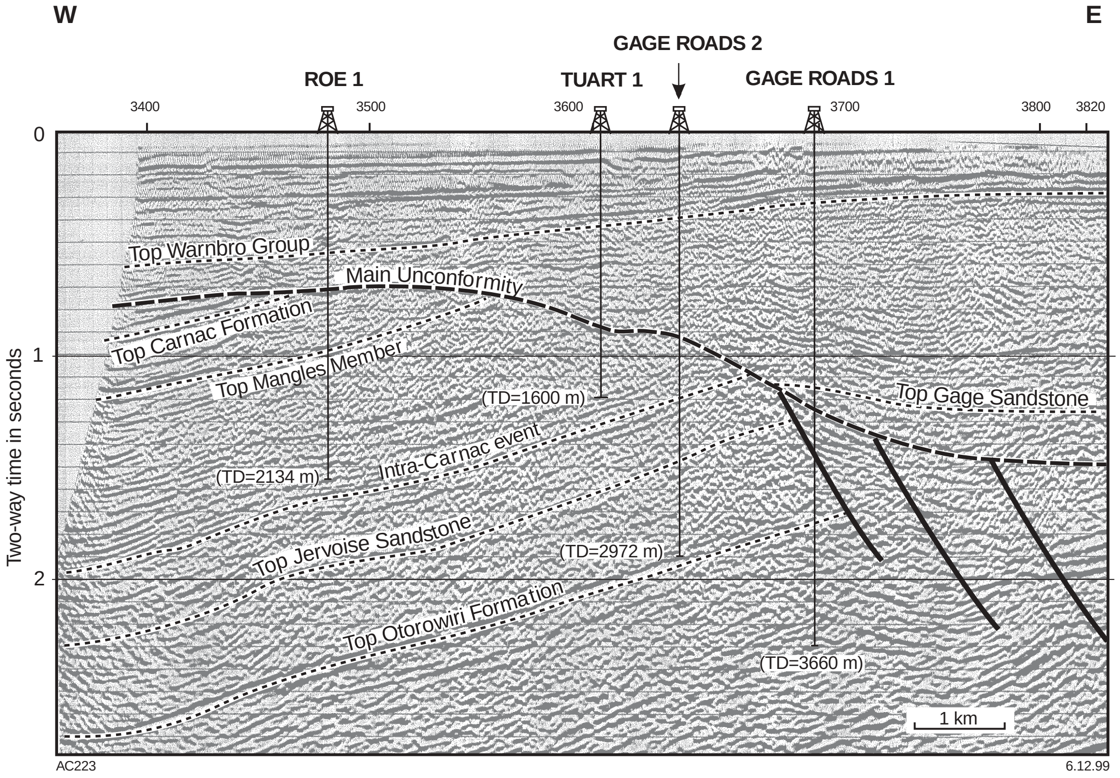


Figure 19. Seismic section V82A-51, showing the Lower Cretaceous horizons in the Roe High, Vlaming Sub-basin (after Seggie, 1990)

1985 to 2848 m (a thickness of 863 m) in Gage Roads 2 (latitude 31°57'08"S, longitude 115°21'53"E). This unit was loosely named as the ‘Lower Parmelia Sandstone’ in several unpublished well completion reports, although its upper boundary was never defined. Lithologically, the unit consists predominantly of sandstone, with minor siltstone and shale beds, particularly in the upper part.

The Jervoise Sandstone is conformably overlain by the Stragglers Member of the Carnac Formation and conformably overlies the Otorowiri Formation.

Carnac Formation

The name Carnac Formation (after Carnac Island) was originally informally introduced by WAPET, in unpublished reports, in order to define an early Neocomian unit that was mainly composed of fine-grained clastic rocks that were present in several wells in the Vlaming Sub-basin and Beermullah Trough. Backhouse (1984) redefined the unit as the ‘Carnac Member’ of the Parmelia Formation, and noted that the sandstone bodies within the member are thinner than in the rest of the Parmelia Formation. Further drilling indicated that it was practical to subdivide the Carnac Member into subunits because some of the sandstone bodies, such as the ‘Intra-Carnac Sandstone sequence’, were considered to be of economic significance.

Backhouse (1984) designated a type section for the Carnac Member in Peel 1 from 2408 to 3064 m (a thickness of 656 m). The unit is elevated here to formation status, and three new members are introduced. The three new members have type sections in other wells, and have a combined thickness of approximately 1800 m. The lowest is the Stragglers Member, which is characterized on wireline logs by an upward-fining sequence transitional between the Jervoise Sandstone and the overlying Mangles Member. The Mangles Member consists mainly of shale with minor sandy intervals that are interpreted to be lenticular, and it is locally characterized by a radioactive shale interval towards the base of the unit (Plate 2). The Mangles Member gradually passes upwards to the Hawley Member, which is more sandy. The seismically defined sequence boundary 128.5 of Seggie (1990) approximately coincides with the Stragglers–Mangles boundary, whereas his 127.5 maximum flooding surface approximately coincides with the Mangles–Hawley contact.

The Carnac Formation is overlain by the Charlotte Sandstone, with a possibly disconformable relationship, or unconformably by the Warnbro Group. It is conformably underlain by the Jervoise Sandstone. The Carnac Formation is interpreted as a widespread lacustrine deposit containing interspersed deltaic sediments.

Stragglers Member

The Stragglers Member is named after Stragglers Rocks, which are located 7 km north of Carnac Island. The type section is the interval 1794–1985 m (a thickness of 191 m) in Gage Roads 2 (latitude 31°57'08"S, longitude 115°21'53"E). This member is also well represented in Quinns Rock 1 between 794 and 1030 m. This unit is lithologically transitional between the mainly sandstone Jervoise Sandstone below and the predominantly shale and siltsone Mangles Member above. In Gage Roads 1, the member is sandy in the lower part and appears to be silty or shaly near the top.

Mangles Member

The name of this member is derived from Mangles Bay at the southern reach of Cockburn Sound. The type section is from 1598 to 2470 m (thickness 872 m) in Marri 1 (latitude 31°44'46"S, longitude 115°21'19"E). A 915 m-thick incomplete interval of this member is present in Roe 1 (1219–2134 m). The unit consists of shale and siltstone with a few thin sand beds.

Hawley Member

The name of this member is derived from Hawley Shoals, 6 km west of Garden Island. The type section is an incomplete interval from 864 m to total depth at 1530 m (a thickness of 666 m) in Minder Reef 1 (latitude 31°43'21"S, longitude 115°20'36"E). The upper part of this unit, and the contact with the overlying Charlotte Sandstone, is present in Charlotte 1 between 2165.0 and 2435.0 m (TD). The lower part of this member is present in Roe 1 from 872.0 to 1219.0 m. Lithologically, the member is predominantly shale and siltstone with a few thin, probably lensoid, sandstone beds.

Charlotte Sandstone

The name Charlotte Sandstone has been used informally in many unpublished reports for the massive sandstone at the top of the Parmelia Group. The unit is here given formal status and the type section is nominated as the interval 1576–2165 m (a thickness of 589 m) in Charlotte 1 (latitude 31°48'40"S, longitude 115°27'04"E).

The Charlotte Sandstone consists predominantly of sandstone with a few thin shale beds. Backhouse (1984) has given a brief description of this unit when discussing Peel 1. The unit is unconformably overlain by the Lower Cretaceous Warnbro Group. Backhouse (1984) assumed that this lithostratigraphic unit was conformable on the Carnac Member (Carnac Formation in this Report). However, the boundary between the Charlotte Sandstone and the underlying Hawley Member of the Carnac Formation corresponds to the 126 sequence boundary of Seggie (1990), who considered that the base of the Charlotte Sandstone represents a major unconformity with substantial eastwards onlap and minor eastward truncation of the underlying units. The relationship of the Charlotte Sandstone with the underlying units cannot be resolved until more data become available.

Bunbury Basalt

The Bunbury Basalt is a porphyritic basalt that has been extruded as lava flows over extensive areas of the eastern Bunbury Trough. In some areas these two flows are interbedded with a thin sedimentary interval. Traditionally, this basalt has been placed stratigraphically between the Yarragadee Formation and the Warnbro Group, with no record of the Parmelia Group either above or below it. However, palynological assemblages from between two flows in Bunbury Harbour are probably from the *Biretisporites eneabbaensis* Zone (spore–pollen zone) (Burgess, 1978; Backhouse, 1988) and imply extrusion during the latter stage of deposition of the Parmelia Group (?late Berriasian).

Warnbro Group

The Warnbro Group represents a predominantly marine unit of late Neocomian – early Aptian age that transgressed over the heavily faulted and eroded Parmelia Group and older units to produce a major angular unconformity. The unit was originally defined by Cockbain and Playford (1973), and the most recent stratigraphic revision (Davidson, 1995) recognized three formations: the Gage Formation, South Perth Shale, and Leederville Formation in ascending order. The group is very thin in the onshore northern and southern Perth Basin, but thickens in the Mandurah Terrace and Beermullah Trough, where its maximum known thickness onshore is 729 m in Gillingarra Line 2 (Moncrieff, 1989) within the Gingin Syncline. In the offshore Vlaming Sub-basin, to the west of the Badaminna Fault System, the Warnbro Group reaches a maximum penetrated thickness of 1382 m in Mullaloo 1. The depositional sequences of this marine group have been reconstructed by Spring and Newell (1993), based on the detailed dinoflagellate zonation available at this level. More recently, the group has been reviewed by Davidson (1995), and a number of new subunits have been proposed for the onshore area.

Gage Sandstone

The name Gage Sandstone Member was introduced by Bozanic (1969a) for the basal member of the South Perth Formation, for a sandstone interval penetrated in Gage Roads 1. The unit was formally recognized as a member of the South Perth Shale by Playford et al. (1976), who proposed the type section in Gage Roads 1 as 1588–1801 m, and it was elevated to Gage Formation by Davidson (1995). The authors prefer to retain the original descriptive name, Gage Sandstone, as it accurately reflects the arenaceous nature of the unit. The type section is redefined, on palynological evidence, as the interval in Gage Roads 1 between 1587 and 1704 m. The boundary between the Gage Sandstone and the Parmelia Group lies between palynological samples found at 1699.9 and 1705.1 m. The maximum known thickness of the Gage Sandstone is 259 m in Warnbro 1. Lithologically, it consists of fine-grained to granular feldspathic sandstone interbedded with shale and siltstone, which may be several metres thick in some wells.

The Gage Sandstone was deposited in the structurally lowest areas, unconformably overlies the Parmelia Group or older units, and is conformably overlain by the South Perth Shale. The unit pinches out against the Main Unconformity in the western part of the Vlaming Sub-basin (Fig. 19). Many references to this unit on the Mandurah Terrace and in the Beermullah Trough actually refer to younger sandstone beds that are present locally at the base of the Warnbro Group. The Gage Sandstone is characterized by the presence of the *Gagiella* *mutabilis* Zone (Backhouse, 1988). Ingram (1991) subdivided the zone into a lower and an upper part, differentiated by the presence of both *G. mutabilis* and *Senoniasphaera tabulata* in the upper part. An age somewhere in the Valanginian, possibly early Valanginian (early Neocomian), is indicated by the dinoflagellates, and a restricted marine environment is envisaged.

The top of the unit can be recognized on seismic sections as a sequence boundary (121.5 Ma; Seggie, 1990). Figure 19 shows the relevant seismic horizon onlapping on the eastern flank of the Roe High.

South Perth Shale

The name South Perth Shale was introduced by Fairbridge (1953) for the thick Lower Cretaceous shale in the Perth area. The type section is the interval between 498 and 567 m in South Perth 1, a deep borehole drilled for groundwater extraction. The maximum known thickness is 898 m in Mullaloo 1. Lithologically, the unit is dominated by shale that is glauconitic in part, with minor sandstone and siltstone. Sandstone beds are present in some areas within the unit, and generally silt and sand seem to become more common in higher parts of the unit. Sand beds increase in thickness and abundance northwards and over the Roe High to the west.

The South Perth Shale conformably overlies the Gage Sandstone, where present, or unconformably overlies pre-Main Unconformity units. In some areas it passes up into the Leederville Formation with a gradational contact, but in other places the boundary is more abrupt at the base of a thick sandstone bed. A shallow marine environment of deposition is envisaged for the unit.

According to Backhouse (1987, 1988), the main interval of the South Perth Shale is characterized by the *K. scrutillinum* and *P. lowryi* Zones in ascending order, although the unit may extend further upwards, depending on interpretation, to include the *A. alata* and *B. jaegeri* Zones. The two latter zones characterize either an upper section of the South Perth Shale or a lower section of the Leederville Formation, which are, in part, coeval units. The South Perth Shale is generally considered to be late Valanginian to Hauterivian in age. Several sequence boundaries that range in age from 116 to 120.5 Ma have been identified within the interval (Spring and Newell, 1993).

Leederville Formation

The name Leederville Formation was introduced by Fairbridge (1953) for a Lower Cretaceous sandstone, shale, and conglomerate interval distinguished from the underlying South Perth Shale by the predominance of sandstone. The type section is between 198 and 433 m in the Leederville Valley waterbore. The maximum known thickness is present within the Vlaming Sub-basin in Gage Roads 1, where the unit is 663 m thick. On the Mandurah Terrace, Davidson (1995) recognized three members, but they cannot be identified in other parts of the basin. The Leederville Formation is interpreted as mainly a shallow-marine deposit with areas where fluvial deposition was dominant.

The *A. alata, B. jaegeri,* and *F. monilifera* Zones are frequently present within the formation, thus indicating a Hauterivian to early Aptian (Early Cretaceous) age. Older zones may be represented, depending on lithostratigraphic interpretation, and late Aptian intervals are known, but are extremely rare. According to Spring and Newell (1993), sequence boundaries with ages of 112–116 Ma are present on seismic data within the unit in the Vlaming Sub-basin. The unconformity above the unit represents a stratigraphic gap of approximately 2.5 million years.

The Leederville Formation overlies the South Perth Shale with a gradational contact, and in places passes laterally into it. Where the latter unit is absent, the Leederville Formation unconformably overlies pre-Main Unconformity units. In most wells, the formation is separated from the overlying Coolyena Group by an Albian–Aptian unconformity.

Coolyena Group

The Coolyena Group was proposed by Cockbain and Playford (1973) for the succession comprising the Osborne Formation, Molecap Greensand, Gingin Chalk, and Poison Hill Greensand in ascending order. To the west, the group also contains the Lancelin Formation (Davidson, 1995). The group ranges in age from Albian to Maastrichtian (late Early – Late Cretaceous) and is transgressive over the Warnbro Group, although an angular relationship is not apparent on seismic sections.

The Coolyena Group and younger units were reviewed by Playford et al. (1976) and, more recently, by Davidson (1995). These younger rocks lie beyond the scope of this Report.

Structural features

Although the structural setting of the central and southern Perth Basin has been compiled mainly from geophysical data, direct geological input has been provided by Le Blanc Smith (1993) and Le Blanc Smith and Kristensen (1998) for the Collie and Vasse River Coalfields respectively. In these areas, where the Permian strata are affected by extensive faulting and low amplitude folding, extensive drilling and mining operations have provided a detailed insight into the stratigraphy and structure of the region. Fault displacements are highly variable and may change from 0 to 200 m within a strike length of 1 km, and reversals are displayed on several faults. A strike-slip regime is strongly indicated (Le Blanc Smith and Kristensen, 1998), and the Collie Basin itself is bounded by major strike-slip faults (Le Blanc Smith, 1993). Horizontal displacements are mostly sinistral, and the faults are oriented in a north-westerly direction. All deformations are post-depositional, and therefore are related to the early Neocomian breakup tectonism, since no other regional tectonism is known to have occurred in the area.

The regional structure of the central and southern Perth Basin can be illustrated by gravity images (Figs 20 and 21), magnetic images (Fig. 22), and regional depth-

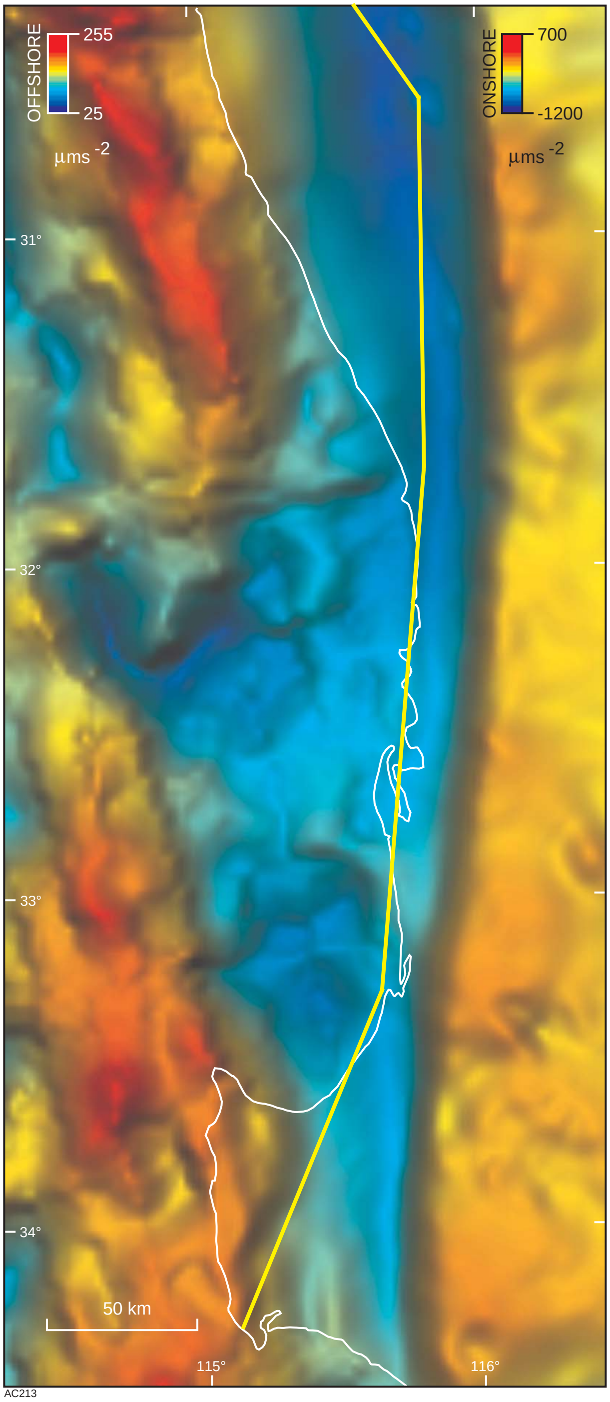


Figure 20. Gravity image of the central and southern Perth Basin corrected for Bouguer onshore and free-air offshore. For this reason, offshore and onshore anomalies have a different colour range. The yellow line shows the line of the gravity model and structural section shown in Figure 26

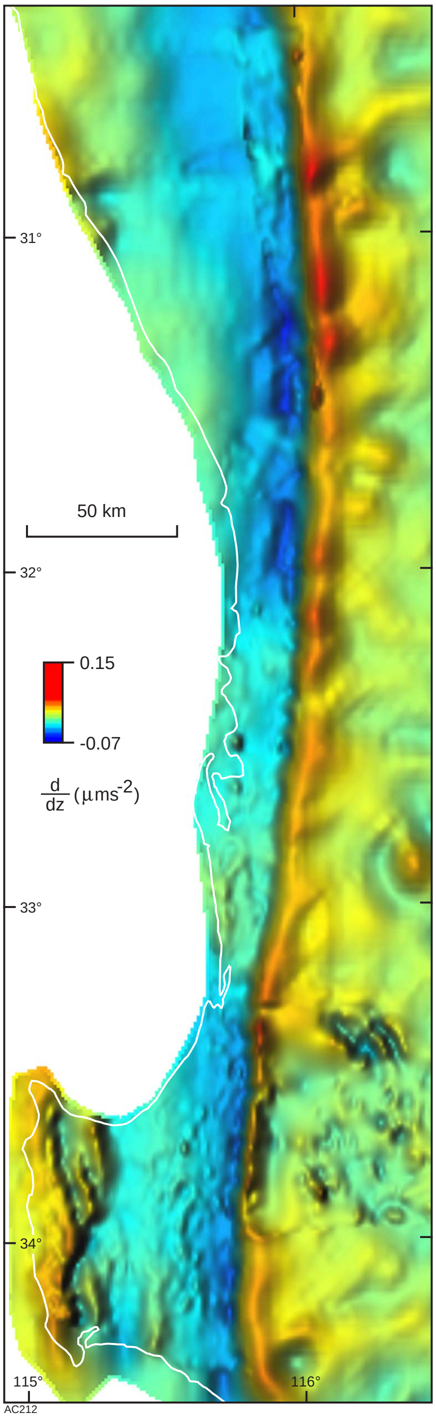


Figure 21. Gravity image of the first vertical derivative for the central and southern Perth Basin

structure maps for the Top Willespie Formation (Fig. 23), Top Otorowiri Formation (Fig. 24), and Base Warnbro Group (Fig. 25). A north–south model of the gravity data from Sue 1 to Arramall 1, utilizing well information and seismic data, was used to generate a schematic geological cross section along the axis of the Perth Basin (Fig. 26), although the density layers used in the gravity model represent increasing density with depth and are unrelated to geological formations. Data from regional structural interpretations by Iasky (1993), Marshall et al. (1993), and Heath et al. (1994) have also been utilized in the cross section.

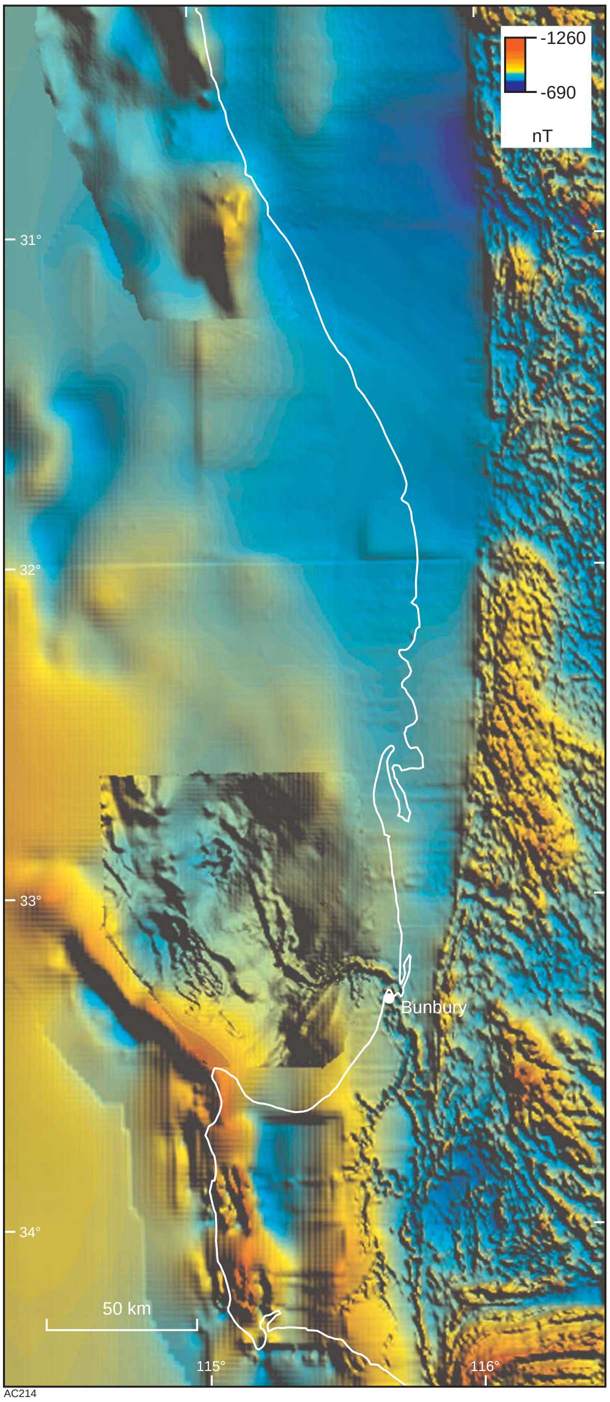


Figure 22. Total magnetic intensity image for the central and southern Perth Basin

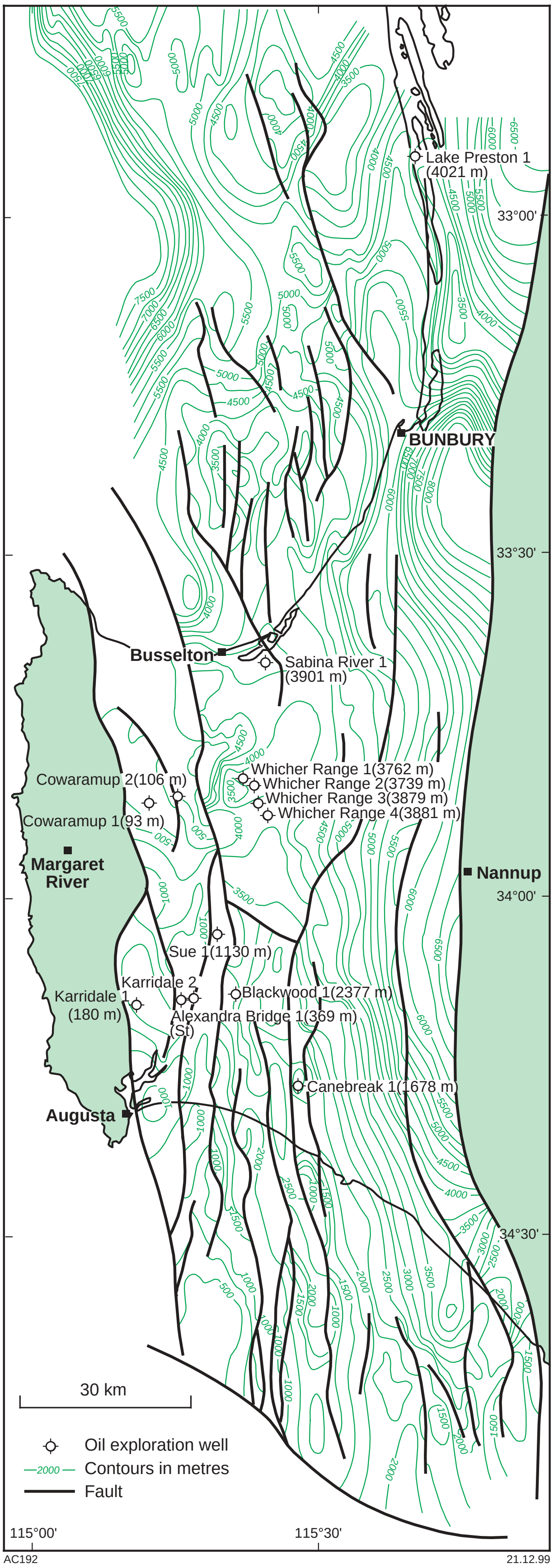


Figure 23. Regional depth-structure map of the Top Willespie Formation, Sue Group, within the southern Perth Basin (after Iasky, 1993)

The most outstanding feature of the region is the north-trending Darling Fault System, including the Muchea Fault, which forms the eastern boundary of the basin (Fig. 2). The fault system originated as a shear zone during the Archaean (Blight et al., 1981), reactivated during the development of a Proterozoic basin (Baxter and Harris, 1980), and further rejuvenated as a rift fault during the Early Permian, and possibly the Late Carboniferous, to form the Perth Basin. The Darling Fault developed as a

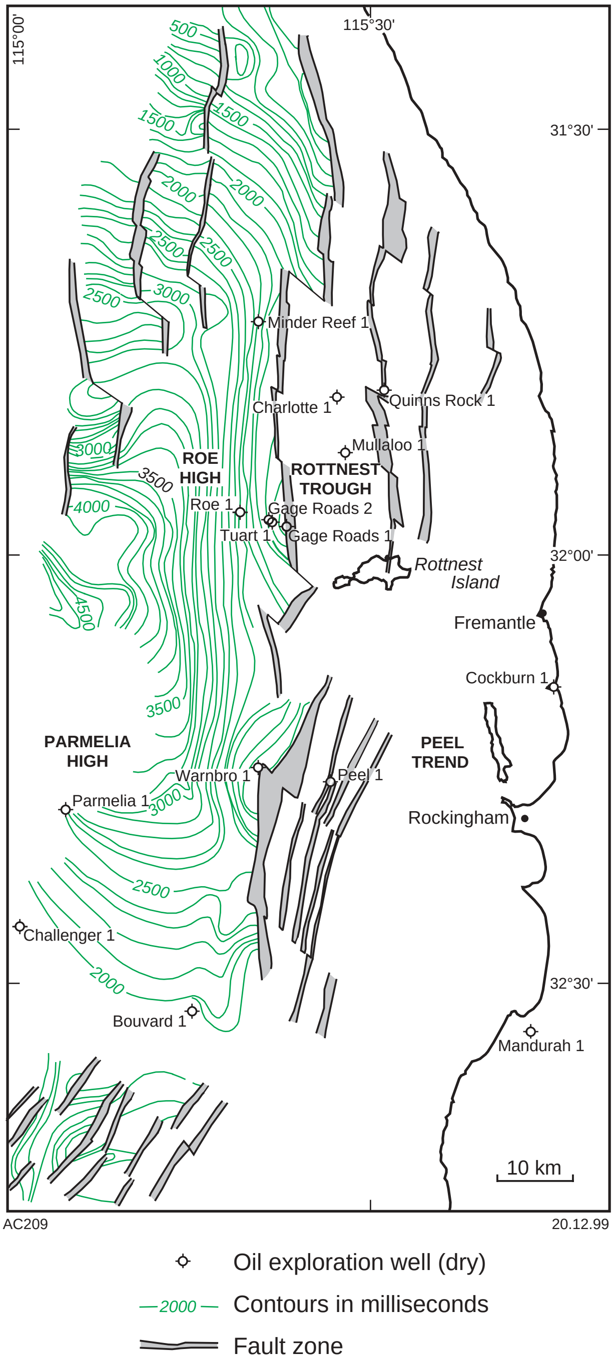


Figure 24. Regional time-structure map of the Top Otorowiri Formation within the Vlaming Sub-basin (after Marshall et al., 1993)

growth fault that allowed the deposition of a Permian to Neocomian succession that is thickest just west of the fault plane (Figs 12–16, 20, and 21), although the linearity of the fault may suggest significant strike-slip movements.

Within the Bunbury Trough, the Busselton and Dunsborough Faults are subparallel to the Darling Fault. These two faults are also interpreted as rift faults that control the western part of the basin. The Bunbury Trough is separated from the Vasse Shelf by the Busselton Fault (Fig. 27). The Permian section maintains a similar

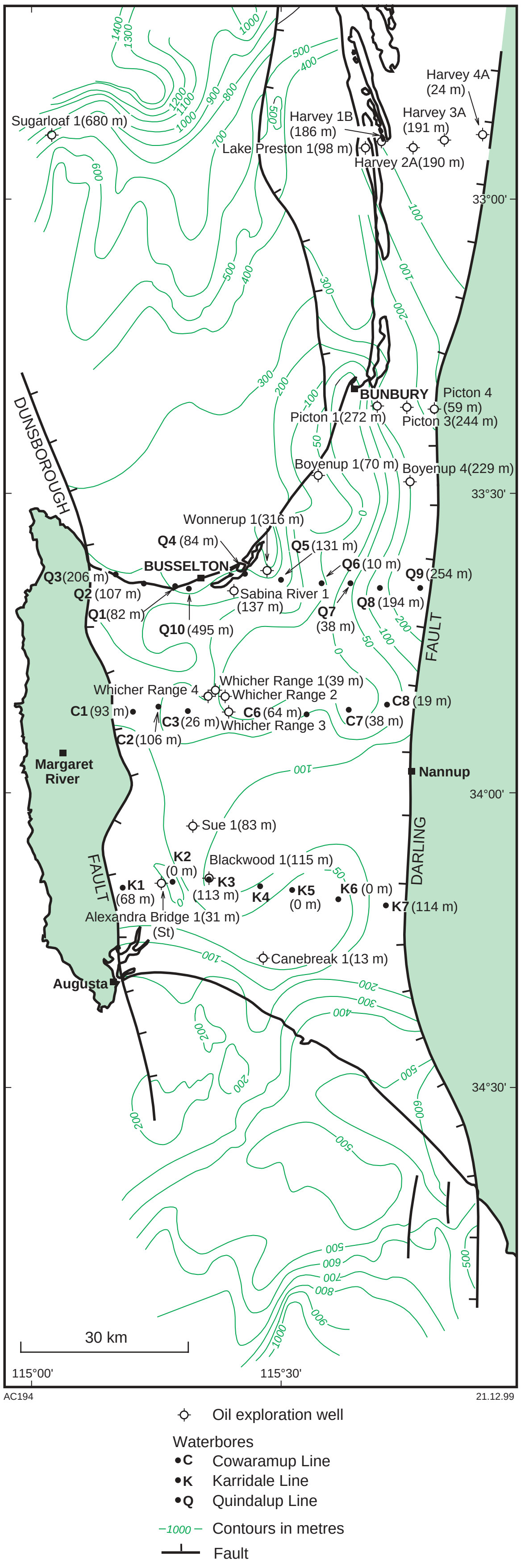


Figure 25. Regional depth-structure map of the Base Warnbro Group within the southern Perth Basin (after Iasky, 1993)

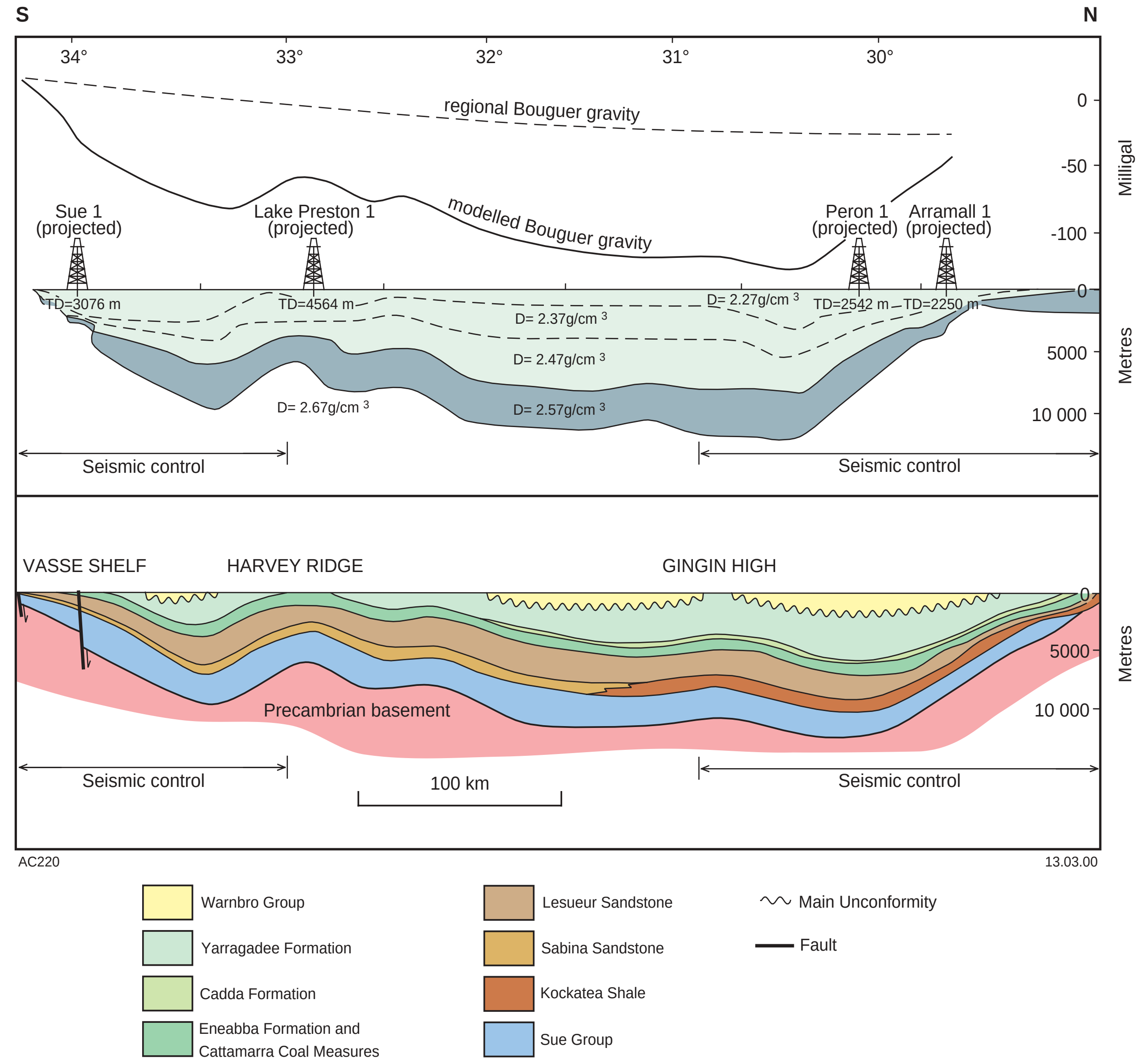


Figure 26. South–north gravity model and structural section along the Perth Basin. The line of the gravity model and structural section are shown in Figure 20

thickness across the fault, whereas the Mesozoic section is substantially thinner on the Vasse Shelf (Plate 1). Furthermore, vitrinite reflectance values (Iasky, 1993) indicate that the degree of maturation at the top of the Permian on the Vasse Shelf (Sue 1) was much lower than in the Bunbury Trough (Whicher Range 1), indicating a shallower depth of burial. Based on this line of reasoning, it appears that the Dunsborough Fault was active during the Permian.

Another fault relevant to the development of the Perth Basin is the mainly northerly trending Badaminna Fault and lesser unnamed associated faults that separate the offshore Vlaming Sub-basin from the Mandurah Terrace and Bunbury Trough. This fault was most active during the Early Jurassic when its eastern side was downthrown (Fig. 6), and from the late Tithonian to the Aptian when it was downthrown on its western side (Fig. 28).

Other features within the study area are all related to early Neocomian tectonism that culminated in the breakup of Gondwana and the separation of Australia from India. In the southern part of the Perth Basin, an important feature is the presence of basalt flows in the early Neocomian, probably during the last stages of deposition of the Parmelia Group. The Bunbury Basalt, a major basalt flow that extends south from the Bunbury area, is clearly recognizable on magnetic images (Fig. 22). The flows progressed firstly in a westerly direction and then northwards. The basalt flows are consistent with the gradual emersion of the area during deposition of the Parmelia Group. The extrusion of basalt before the Valanginian (mid-Neocomian) breakup has been discussed in detail by Heath et al. (1994).

In the Bunbury Trough, intense strike-slip movements during continental breakup resulted in the formation of

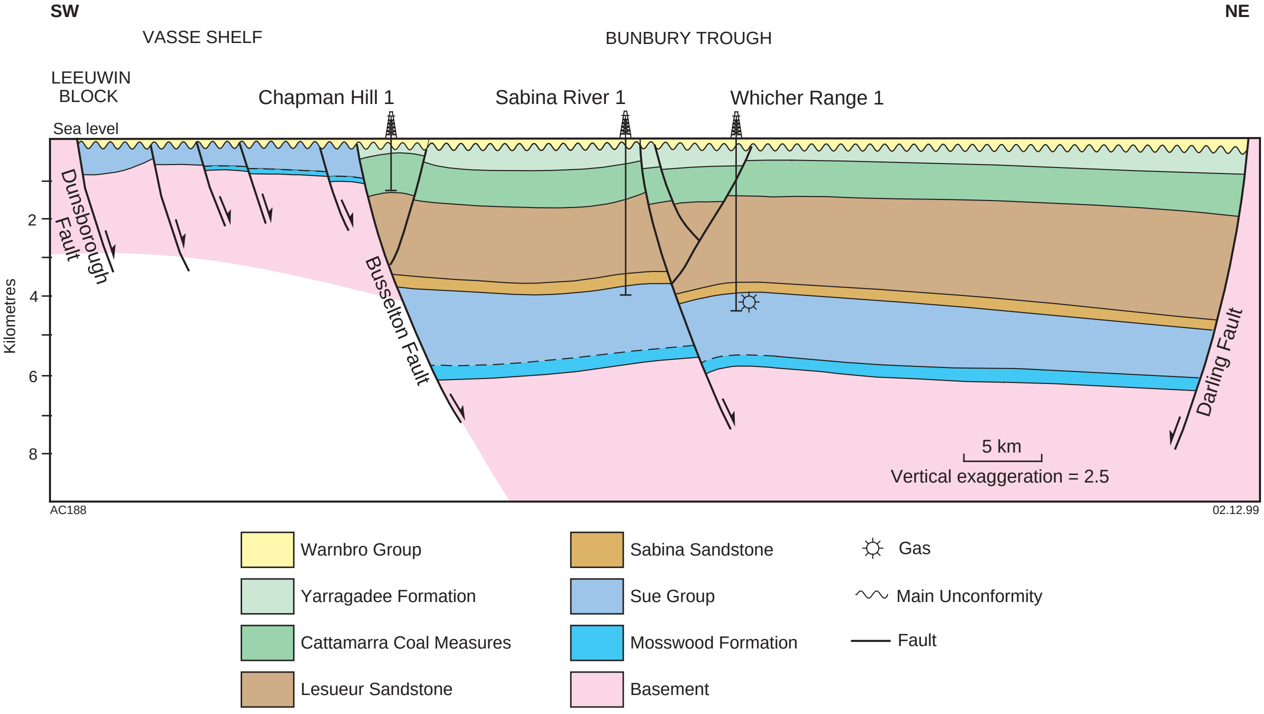


Figure 27. East–west structural section across the Vasse Shelf and Bunbury Trough. The section line is shown in Figure 13

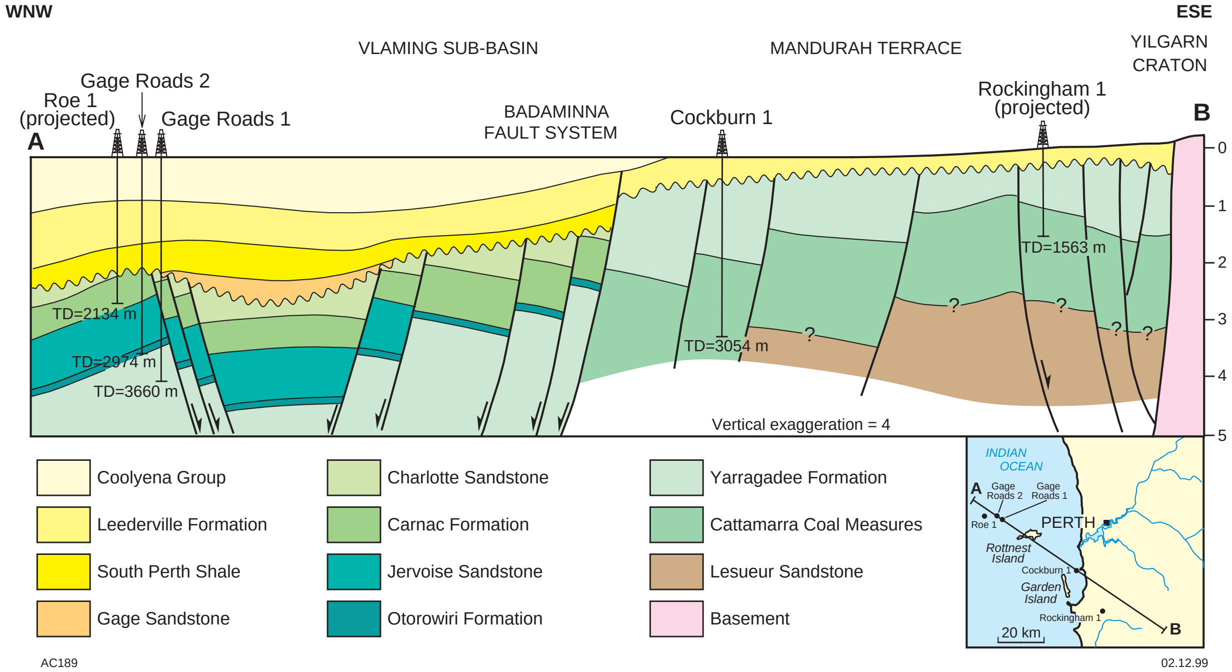


Figure 28. East–west structural section across the Vlaming Sub-basin and Mandurah Terrace

several large anticlines such as the Whicher Range Anticline, as well as en echelon northerly oriented faults (Fig. 23).

Also associated with continental breakup are some significant transfer zones. The left-lateral Harvey Transfer (Fig. 2) is recognizable on magnetic and gravity data, both offshore and onshore, and is associated with the Harvey Ridge structural high, which was penetrated by Lake Preston 1 (Fig. 23). Further north, the Turtle Dove Transfer also has a left-lateral movement and is associated with an onshore high called the Turtle Dove Ridge. These transfer zones trend approximately northwesterly, in contrast to the transfer zones further north, such as the Cervantes (Fig. 2) and Abrolhos Transfers, which trend west-northwesterly. The Beermullah Trough, between the Cervantes and Turtle Dove Transfers (Fig. 2), is characterized by a number of northerly trending strike-slip controlled anticlines, such as the one drilled by Gingin 1. The area just to the south of latitude 31°S is affected by northerly trending lineaments that intersect more fragmented north-northwesterly trending features (Heath et al., 1994; fig. 5). The Beermullah area does not appear to contain transfer zones, even though such faults are common further north.

The Vlaming Sub-basin narrows southward into the Bunbury Trough, and is contained between the Darling and Busselton Faults (Fig. 2). The prevailing structural elements in the Vlaming Sub-basin are northerly trending (Fig. 23), and run subparallel to the Darling and Badaminna Fault Systems. The faults all relate to Early Cretaceous tectonism, and there is no evidence of an earlier structural history. The main structural elements of the Vlaming Sub-basin are the Roe and Parmelia Highs (Fig. 2), and the Rottnest Trough and Peel Trend (Fig. 24). Strike-slip faults are the dominant faults, with the vertical throw generally more subdued. Compressional anticlines were not detected by Marshall et al. (1993, fig. 24), which indicates a prevailing extensional regime. However, the Rottnest Trough, which is interpreted as a collapsed arch between two facing faults, may well be defined as a strike-slip induced negative flower structure. The Roe High is a virtually unfaulted dominant westward-dipping monocline (Figs 19, 24, and 28). On the other hand, the Peel Trend is a positive feature marked by a number of fault blocks (Fig. 24). South of latitude 33°S the orientation of the faults is different, with the trend being northwest in the western part and northeast in the eastern part. Left-lateral transfer zones, such as the Harvey Transfer, can be identified by large horizontal offsets between corresponding tectonic lineaments (Fig. 2).

Only limited and poor structural data are available for the Mandurah Terrace, but it appears to be dominated by extensional faults, without clearly defined positive structures. Figure 28 shows an attempt to reconcile the structural setting of the Mandurah Terrace with the Beermullah Trough to the north (Fig. 6), and the Bunbury Trough to the south (Fig. 27) where compressional stresses prevailed. As the narrow onshore Mandurah Terrace is poorly covered by potential-field data, this problem cannot be resolved with the existing images.

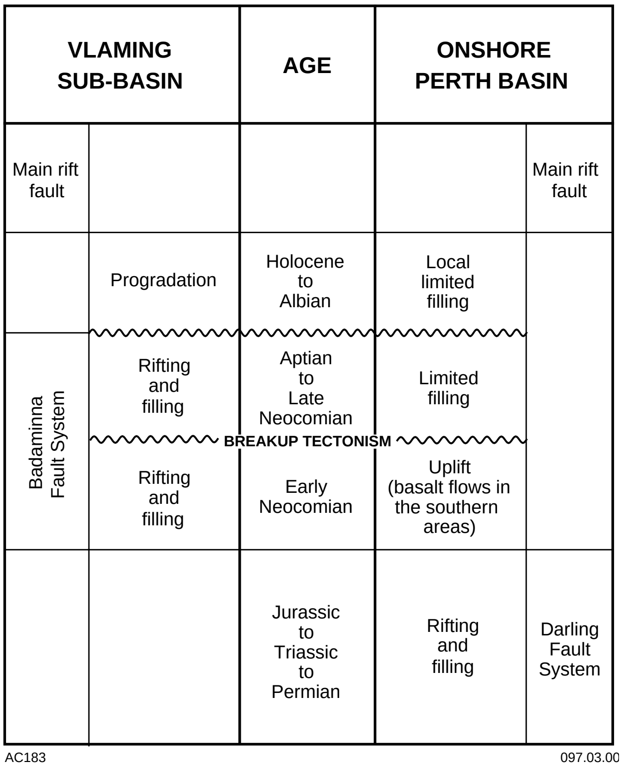
After continental breakup, the only structural features were palaeotopographic highs evident at the base of the Warnbro Group in the Bunbury Trough (Fig. 25) in the Vlaming Sub-basin (Marshall et al., 1993, plate 30), particularly the Roe High. The Badaminna Fault System, however, was still active in the Vlaming Sub-basin, as it has displaced the Warnbro Group. Within the Coolyena Group, only westwards progradation of the sedimentary succession is evident.

Basin evolution

The evolution of the central and southern Perth Basin can be reconstructed from the stratigraphy and structure discussed above (Fig. 29).

At the end of the Carboniferous, or in the Early Permian, north-trending regional rifting marked the beginning of sedimentation within the basin. The north–south Darling Fault System is the dominant feature of the Perth Basin, and was active until at least the late Berriasian, and possibly as late as the Barremian (Backhouse, 1988, p. 43).

During the Permian, Triassic, and Jurassic, the main eastern controlling faults continued to be active, which resulted in clastic sedimentation from the emergent Yilgarn Craton. After the Late Permian, faulting also took place within the margin of the Yilgarn Craton, and the Collie Basin and smaller associated intracratonic basins were formed. The similarity of the Lower Permian successions in the Collie Basin, the Yilgarn Craton, and in the southern Perth Basin indicates deposition in the same, or a closely connected, basin.



VLAMING SUB-BASIN		AGE	ONSHORE PERTH BASIN	
Main rift fault				Main rift fault
	Progradation	Holocene to Albian	Local limited filling	
Badaminna Fault System	Rifting and filling	Aptian to Late Neocomian	Limited filling	
		BREAKUP TECTONISM		
	Rifting and filling	Early Neocomian	Uplift (basalt flows in the southern areas)	
		Jurassic to Triassic to Permian	Rifting and filling	Darling Fault System

Figure 29. Tectonic evolution of the Perth Basin

The geological section in Figure 26 shows the gradual shifting of the depocentre of the basin from south to north. The Permian sequence is thickest within the Vasse Shelf and Bunbury Trough, the Triassic sequence within the Mandurah Terrace, and the Jurassic sequence on the Gingin High and generally in the northern Perth Basin. Rivers gradually filled up the north-trending continental downwarp from south to north.

Proper palaeogeographic reconstructions for the entire Perth Basin cannot be produced because adequate palynological control is lacking. However, during the Triassic in the southern Perth Basin, fluvial conditions were established (Wonnerup Member of the Lesueur Sandstone), while a transitional environment from marine to fluvial was present in the northern Perth Basin (Woodada Formation). Distributory channel fills within a fluvial environment were present in the southern Perth Basin (Myalup Member of the Lesueur Sandstone), whereas a more typical fluvial environment was present in the northern Perth Basin (undifferentiated Lesueur Sandstone). The deltaic environment of the Cattamarra Coal Measures commenced later in the northern and central Perth Basin than in the south because in the former area the lowermost Jurassic is represented by the Eneabba Formation, indicating an environment closer to land.

In the southern Perth Basin, Permian rocks are entirely continental, with widespread coal seams (Sue Group), whereas in the northern Perth Basin a marine transgression took place in the Early Permian, after the deposition of the Irwin River Coal Measures. The Early Triassic sequence is marine in the northern Perth Basin, whereas it is continental in the southern part of the basin. The thickness of the marine Kockatea Shale increases southwards in the northern part of the Perth Basin (Mory and Iasky, 1996, fig. 15); conversely, the thickness of the coeval Sabina Sandstone increases northwards in the southern part of the basin (Plate 1; Fig. 9). The large tract between is without well control, and the extent to which the Early Triassic sea transgressed into the central Perth Basin cannot be estimated.

The Middle – Late Triassic was characterized by continental sedimentation across the basin, and is represented by the thick sandstone successions of the Woodada Formation and Lesueur Sandstone. In the Early Jurassic, fluvial and marshy sedimentation (Eneabba Formation and Cattamarra Coal Measures) was widespread. A marine incurson from the north extended into part of the central Perth Basin in the Middle Jurassic (Cadda Formation), while continental sedimentation continued in the south. In the Late Jurassic, continental sedimentation (Yarragadee Formation) was widespread.

The two Mesozoic regressive continental phases in the Middle – Late Triassic (Lesueur Sandstone) and Middle – Late Jurassic (Yarragadee Formation), which followed marine episodes in the Early Triassic (Kockatea Shale) and Middle Jurassic (Cadda Formation), suggest major episodes of sea-level fall, with the Yilgarn Craton becoming, at least partly, the source for the two continental formations. Reworked Permian palynofloras within the Yarragadee Formation indicate that during the Late Jurassic some Permian sediments were being eroded.

The presence of reworked Devonian, Permian, Triassic, and Jurassic palynomorphs in the Otorowiri Formation of the Parmelia Group (Ingram, 1967; Backhouse, 1988) is evidence for emergence and erosion of some areas within the Perth Basin at the beginning of the Cretaceous. During deposition of the fluviolacustrine Parmelia Group, successive flows of basalt and associated dolerite sills (Sue 1, Whicher Range 2, Wonnerup 1, Sugarloaf 1, and ?Blackwood 1) are present in the Bunbury Trough and the southwestern part of the Vlaming Sub-basin (Fig. 22), which suggests that the rifting that resulted in the fragmentation of the Indo-Australian continent began in the southern part of the Perth Basin. While the onshore part of the Perth Basin was uplifted, with limited and probably discontinuous deposition, the offshore part continued to be filled with continental and lacustrine deposits (Backhouse, 1988). The Badaminna Fault System became the most active fault system in the region, and a rapid rate of deposition of approximately 500 m per million years took place in the Vlaming Sub-basin. This is based on the Australian Geological Survey Organisation time scale presented in Young and Laurie (1996), and assumes that the Parmelia Group was deposited entirely during the Berriasian.

The final separation of Australia from India occurred during the early Valanginian (mid-Neocomian, Early Cretaceous), and produced deeply seated wrenching transfer faults, strike-slip movements, and anticlines. A transtensional stress field produced extensional strike-slip faulting accompanied by compressional features. The most significant break in the Perth Basin succession happened during the breakup of Australia from Greater India, and it is commonly referred to as the Breakup Unconformity or the Main Unconformity (Woodside Offshore Petroleum, 1988). The event is characterized in seismic lines by a distinct angularity where sediments of appreciable thickness are present above the eroded continental pre-breakup section. Deformation is present only below the Main Unconformity, whereas the transgressive marine Warnbro Group and younger sedimentary rocks show a sub-horizontal setting throughout the basin, with only regional depositional features (Marshall et al., 1993, fig. 25, plates 31, 32). Limited rifting, however, took place offshore from the late Neocomian to the Aptian because the Badaminna Fault System was active during deposition of the Warnbro Group. Consequently, the Vlaming Sub-basin contains a thick post-breakup section.

From Albian to recent times, the western margin of the continent has been passive and has been characterized by the deposition of progradational shallow-water, mainly carbonate, rocks.

Post-mortems of hydrocarbon exploration wells

Information on the hydrocarbon exploration wells has been gathered from reports produced by exploration companies. The data analysed includes stratigraphy, petroleum engineering, seismic data, geochemistry, petrophysics, and palynology. The interpretation provided here is consistent with the reconstructed basin evaluation. This interpretation may or may not be consistent with that proposed by the relevant company, largely because of updated information and the regional approach of the present study. It is acknowledged that not all wells are treated in similar detail, but this weakness is dictated by the quality of the original reports and the amount of data provided, which vary greatly. In general, the more recent reports contain more detailed information.

Alexandra Bridge 1

Location

Alexandra Bridge 1 was drilled on the Vasse Shelf in 1965 by WAPET, at a location 56 km south of Busselton (Fig. 4).

Stratigraphy

The Main Unconformity was encountered at 70 m (Jones, 1965), and the well was terminated at 766 m in the Willespie Formation of the Sue Group.

Structure

Alexandra Bridge 1 is a stratigraphic well located on the upthrown side of the Alexandra Bridge Fault, outside of any closure (Figs 23 and 25). Core-derived dips range from 8° to 15°, and seismic data indicate a westerly direction.

Hydrocarbons

No hydrocarbon indications were reported by Jones (1965).

Reservoir potential

Core-derived porosities range from 20 to 27%, whereas permeabilities range from 50 millidarcies (md) to more than 1 darcy (D) (Figs 30 and 31).

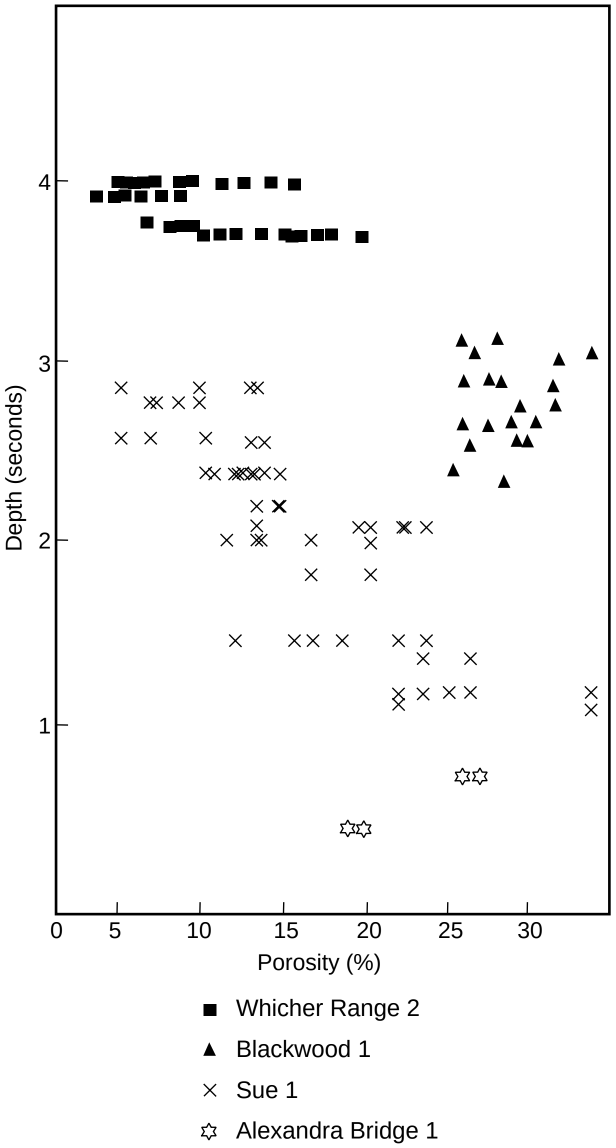


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Figure 30. A plot of porosity versus depth in selected wells in the Bunbury Trough (after Paton, 1994)

Araucaria 1

Location

Araucaria 1 was drilled offshore in the Vlaming Sub-basin in 1993 by Petrofina Exploration Australia S.A., at a location 45 km southwest of Fremantle (Fig. 4).

Stratigraphy

Araucaria 1 was terminated at 2218 m in the Mangles Member of the Carnac Formation (Parmelia Group). At 1796 m, the South Perth Shale directly overlies the Mangles Member, which is characterized by a highly radioactive shale interval (Plate 2 and Fig. 32).

Structure

Araucaria 1 is located on the Roe High, which is an eroded homocline dipping to the west. It is draped by post-breakup sediments and bordered to the west by the Rottnest Trough (Fig. 2). Fault movements were believed to have taken place sporadically, both before and after breakup, thus creating local structural highs such as that tested by Araucaria 1 (Petrofina Exploration Australia S.A., 1993; Fig. 33). The primary objective of the well was the pre-breakup Charlotte Sandstone of the Parmelia Group, which is sealed at the crest by the South Perth Shale. Secondary objectives were sandstone beds within the predominantly shaly lower Leederville Formation and intraformationally sealed sandstone of the Carnac Formation.

An alternative structural interpretation is that Araucaria 1 is located on a secondary strike-slip induced narrow asymmetric anticline that is controlled by a high-angle reverse-fault upthrust to the west (Fig. 34). The time section may give a distorted version of the true structural setting due to unresolved velocity problems.

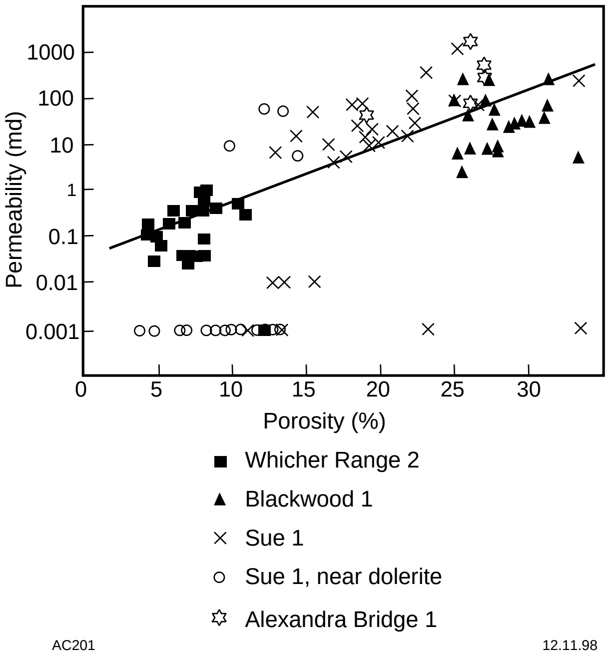

Figure 31. A plot of porosity versus permeability in selected wells in the Bunbury Trough (after Paton, 1994)

Hydrocarbons

The best show in the well was the presence of oil in core 1 (1807–1825 m), which was cut in the Mangles Member just below the Main Unconformity. The evaluation of the show was difficult due to the difference between drilled depth and log depth. The company concluded that an oil column of 7.5 m is present in the interval 1806–1813.5 m (log depth), but only 1.4 m of the oil-bearing section is permeable (1811.85–1813.25 m). No drillstem test (DST) was carried out.

Combined core and log analyses indicate a hydrocarbon saturation of less than 25% within the interval 1806–1813.5 m, which contains poor quality reservoirs composed of the Mangles Member. Minor oil shows were observed while drilling sandy stringers of the Leederville Formation between 1470 and 1578 m. Log analyses, however, indicate a water saturation of 100% across this interval. Gas shows containing up to 900 ppm of C_1 and 300 ppm of C_2 were observed while drilling the interval 1050–1180 m (Base Coolyena Group – Top Warnbro Group), but 100% water saturation was also calculated in this interval.

Reservoir potential and seals

The cored interval of 1807–1825 m contains thinly bedded argillaceous sandstone in which porosity ranges from 7.1 to 23.3%, with a mean of 15.8%, and permeability ranges from less than 0.01 to 168 md, with a mean of 6.4 md. The sealing potential of the rocks overlying the Main Unconformity was calculated by measuring the capillary pressure, but the results were inconsistent and no definite conclusions were drawn.

Geochemical data

The source-rock potential of the Parmelia Group is moderate. Total organic carbon (TOC) of up to 2.25% and hydrogen indices from 202 to 318 were measured. A mixed waxy oil – condensate source is considered likely. However, these source rocks are immature at the well location, and therefore the encountered hydrocarbons were generated from deeper source rocks. Furthermore, the high water saturation suggests that hydrocarbons are still migrating into the reservoirs.

Reasons for failing to discover a hydrocarbon accumulation

The degree of closure of the Araucaria anticlinal feature cannot be assessed precisely, based on present information, but it is considered to be minor. The intraformational seals within the Mangles Member appear to be truncated by the Main Unconformity. Ultimately, therefore, the sealing potential of the Araucaria structure depends on the impermeability of the South Perth Shale that unconformably overlies sandstone of the Mangles Member. The reservoir potential of the Mangles Member is poor because the sandstone beds are probably lenticular. Hydrocarbon indications are scattered over a long vertical section, and it is therefore concluded that the hydrocarbons encountered in Araucaria 1 are migrating hydrocarbons, and that the limited accumulations are present mainly in permeability traps, whereas the oil column of 7.5 m may be controlled by the anticlinal closure.

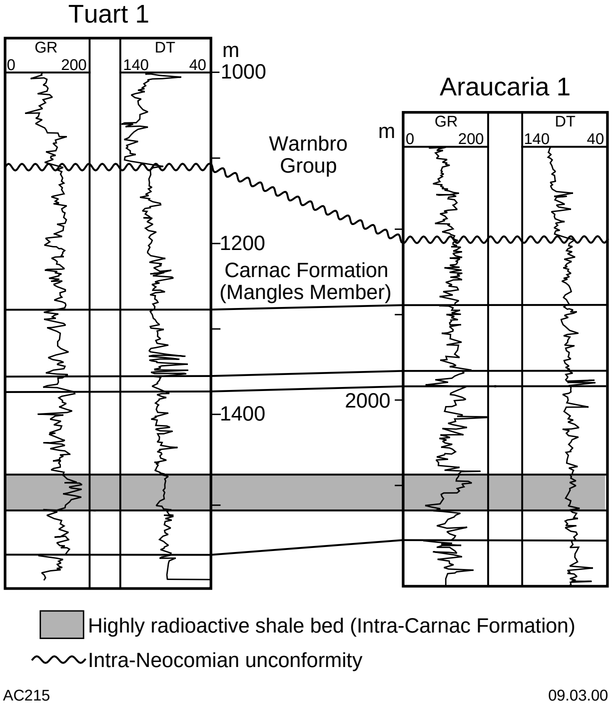

Figure 32. Log correlation between Araucaria 1 and Tuart 1 (after Petrofina Exploration Australia S.A., 1993)

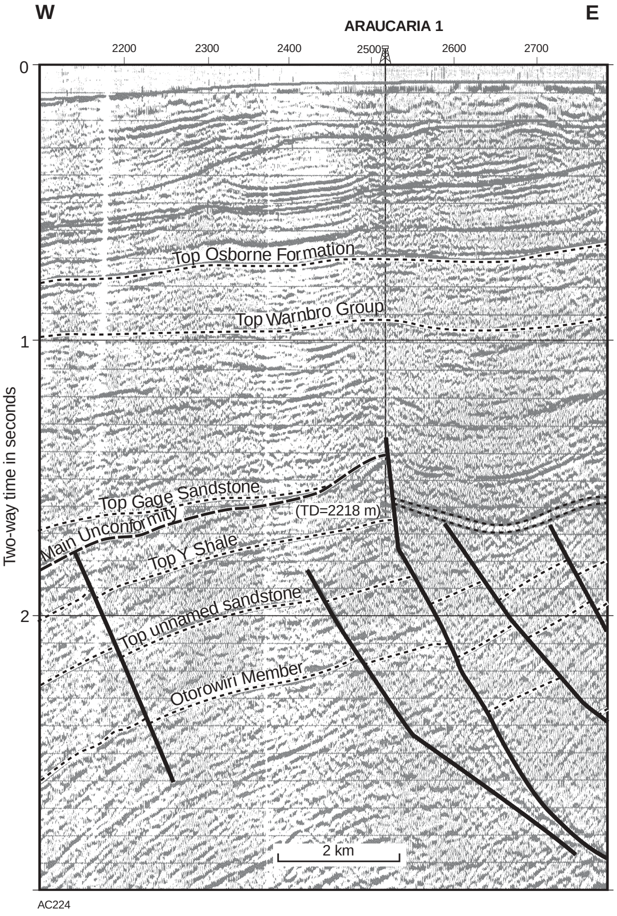

Figure 33. Seismic section V83 A-111, showing the structural setting of Araucaria 1 (after Petrofina Exploration Australia S.A., 1993)

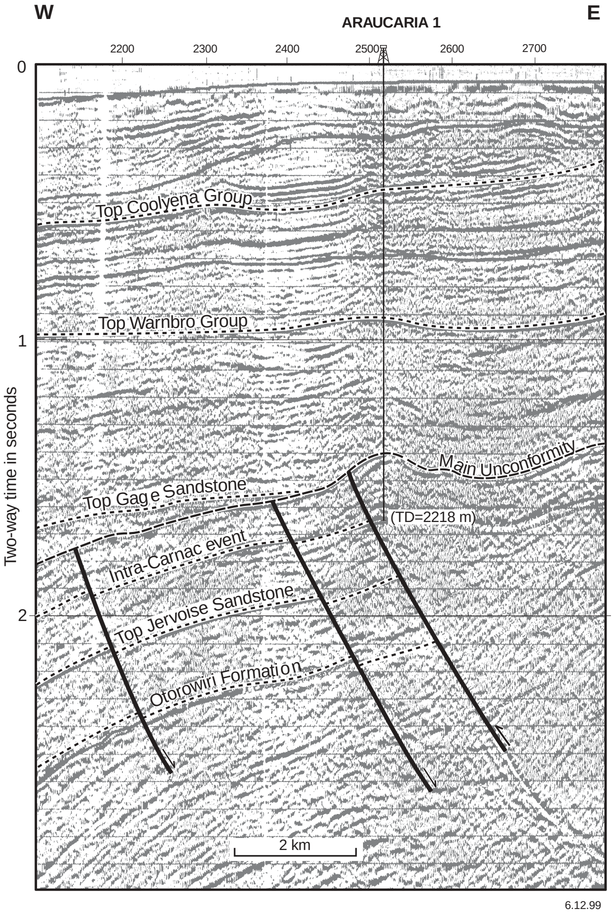

Figure 34. Seismic section V83 A-111, showing an alternative structural setting for Araucaria 1

Badaminna 1

Location

In 1967, Badaminna 1 was drilled by WAPET in the onshore Beermullah Trough, at a location 19 km southwest of Gingin and 80 km north of Perth (Fig. 4).

Stratigraphy

The regional intra-Neocomian Main Unconformity was reached at 288 m, and total depth is at 2438 m, within the Cattamarra Coal Measures. Williams (1967) assigned the interval 967–1298 m to the Cadda Formation. He included the interval 967–1125 m within the unit because of the presence of calcareous sandstone and microplankton that indicate a marine environment. The Yarragadee–Cadda boundary, however, is here placed at 1125 m in order to be consistent with the top of the Cadda Formation in Hill River 1, which was drilled near the main outcrops of the Cadda Formation. Cockbain and Lehmann (1971, figs 7 to 12) suggested that the Eneabba Formation is present at 2431–2438 m, but their statement cannot be substantiated. Furthermore, no wireline logs were run below 2429 m, as the hole had collapsed below that depth.

Structure

Badaminna 1 was drilled on a gravity anomaly near Yanchep, with limited seismic control, at an early stage of exploration in the region. A vertical closure of up to 230 m was mapped seismically over an area of more than 50 km^2. The results of the well indicate that the location was some distance to the east of the crest of the structure. The main attraction of the location was the presence of a section equivalent to the gas-bearing sandstone interval in Gingin 1, but which was found at a depth 2000 m closer to the surface. The Badaminna structure developed over a depositional low at the time of continental breakup, and is therefore an example of structural inversion (Fig. 6).

Potential reservoirs and seals

A core cut from sandstone within the lower part of the Yarragadee Formation (1037–1040 m) exhibits a range of porosities (27–37%) and permeabilities (7.9 md–2.8 D). Sonic-derived porosities decrease from 25–30% at 800 m to 20% at 1220 m. Below this depth, sandstone porosities in the Cattamarra Coal Measures range from 14 to 18%.

Intraformational seals are present both in the Yarragadee Formation and the Cattamarra Coal Measures. The Cadda Formation is the only significant regional seal. Log-derived formation-water salinities, however, increase only gradually from 1000 to 10 000 ppm at depths of 820–1783 m, whereas at 1844 m, within the Cattamarra Coal Measures, the water salinity reaches 32 000 ppm. Water salinities further increase with depth to a maximum of 50 000 ppm at 2350 m, which suggests that the sealing potential increases with depth in this area.

Hydrocarbons

Only minor amounts of gas were detected while drilling, and chromatographic analyses indicate only methane, except for very minor traces of ethane towards total depth. No oil fluorescence was noted.

Reasons for failing to discover a hydrocarbon accumulation

It is believed that the well did not test an effective trap because the limited amount and poor quality of the controlling seismic lines did not allow a satisfactory definition of the structural setting.

Barragoon 1

Location

Barragoon 1 is situated to the west of the Badaminna Fault System in the central Perth Basin, and therefore falls within the northernmost portion of the Vlaming Sub-basin, most of which, apart from this small area, is offshore. The well lies 70 km north-northwest of Perth (Fig. 4) and was drilled by WAPET in 1974.

Stratigraphy

The Main Unconformity was encountered at 803 m, below which the mainly sandy Jurassic Yarragadee Formation is present, with shale interbeds from 2210–2284 m. The well was terminated at 2335 m within the Yarragadee Formation.

Structure

Barragoon 1 is basically a stratigraphic test well located on a poorly defined anticlinal closure that has been mapped from limited poor-quality seismic data (Osborne and O’Shaughnessy, 1974). Poor data quality is a regional feature of the area because of outcropping or near-surface hard karstic eolian calcarenites that absorb a large percentage of the seismic energy. The available seismic data indicate an east–west reversal of dips, but do not confirm a structural closure (Fig. 6). Subsurface stratigraphic control suggests that the well is on a faulted terrace that is downthrown with respect to the Turtle Dove Ridge, but is upthrown with respect to the Rottnest Trough.

Hydrocarbons

No hydrocarbon shows were encountered in Barragoon 1.

Reservoir potential and seal

Sandstone beds in the Yarragadee Formation represent good potential reservoirs. Core 1 (1783–1802.1 m), however, has an average porosity of 20%, but because of the kaolin matrix this results in an average permeability of only 5 md and a limited maximum permeability of 12 md. The South Perth Shale, which is a regional seal, directly overlies sandstone of the Yarragadee Formation.

Reasons for failing to discover a hydrocarbon accumulation

Barragoon 1 did not test a valid trap because the post-breakup South Perth Shale, the only sealing horizon, is flat-lying. In addition, the pre-breakup structure is unclear.

Blackwood 1

Location

In 1969, Blackwood 1 was drilled in the Bunbury Trough by Union Oil Development, at a location 55 km south of Busselton (Fig. 4).

Stratigraphy

There is a thin interval of the Warnbro Group above the regional Main Unconformity, which is present at a depth of 186 m. Blackwood 1 was terminated at 3333 m in the Willespie Formation of the Sue Group. Volcanic sills may be present at 3069–3072 m and 3274–3279 m (Union Oil Development Company, 1969).

Structure

Blackwood 1 is located on the crest of the Whicher Range anticlinal axis (Fig. 2), which was formed by strike-slip fault movements. The Blackwood structure is a positive flower structure that shows compression at the top of the Sue Group. Compressional stresses decrease upwards and are not evident at the top of the Lesueur Sandstone (Fig. 35). Union Oil Development estimated a closure area of 17 km^2 and a vertical closure of 137 m for the downthrown anticline (Fig. 35). Remapping of the area (Irwin and Paton, 1995), however, indicated that Blackwood 1 was located off-closure down dip from Scott River 1 (Fig. 36). The regional map by Iasky (1993) is consistent with the latter interpretation (Fig. 23).

Hydrocarbons

Although shows of methane were recorded during drilling, three DSTs (2802–2846 m, 3035–3046 m, and 3001–3034 m) failed to recover any hydrocarbons (Table 2).

Potential reservoirs

The three DSTs proved that the tested intervals are tight. Porosity–depth and porosity–permeability plots, however, indicate that porosities ranging from 25

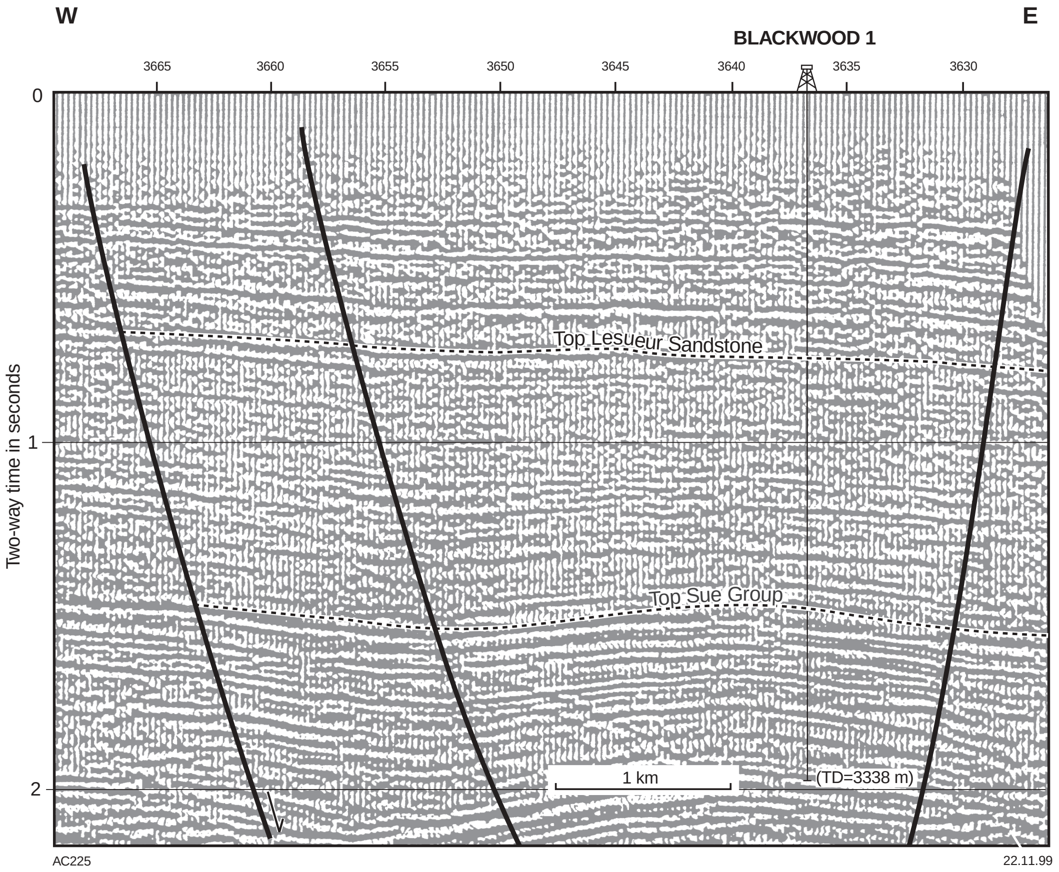

Figure 35. Seismic section WF69-CC, showing the structural attitude of the Blackwood structure (after Irwin and Paton, 1995)

to 35% and permeabilities ranging from 1 to more than 100 md are present (Figs 30 and 31). Union Oil Development Corporation (1969) stated that a few ‘moderately porous’ sandstones are correlatable with the gas-bearing sandstones in Whicher Range, but are water-wet in Blackwood 1.

Reasons for failing to discover a hydrocarbon accumulation

It is believed that Blackwood 1 did not test a closed structure. In any case, faults beyond seismic resolution would easily breach a potential trap relying only on thin intraformational seals such as those present in this well.

Bouvard 1

Location

Bouvard 1 is situated 47 km southwest of Fremantle, within the southern part of the offshore Vlaming Sub-basin. It was drilled in 1974–75 by WAPET.

Stratigraphy

The stratigraphy of Bouvard 1 is not well documented. Marine palynomorphs of Senonian to late Neocomian age were encountered down to 1100 m, which indicates that the Main Unconformity is below this depth at the well location. On weak lithological evidence, Young and McDermott (1975) placed the unconformity at 1276 m. Dipmeter data, however, do not indicate any difference within the logged 1148–1980 m (TD) interval. Therefore, it is considered likely that the Main Unconformity is higher and falls within the interval 1100–1148 m. Below the unconformity, the lithology is monotonously sandy, and it can only be reported that the well was terminated in the Parmelia Group.

Structure

Bouvard 1 was drilled on a seismically defined pre-Main Unconformity anticlinal feature that was expected to be sealed by the South Perth Shale of the Warnbro Group. The Bouvard structure lies close to the northern extremity of a string of anticlines stretching in a north-northeasterly direction from Sugarloaf 1 (Fig. 37). The elongate positive trend is separated from the north-trending Roe High by the Harvey Transfer (Fig. 2). Iasky (1993) and Marshall (1993), however, failed to recognize a structural closure at the Bouvard location.

Hydrocarbons

No indications of hydrocarbons were recorded.

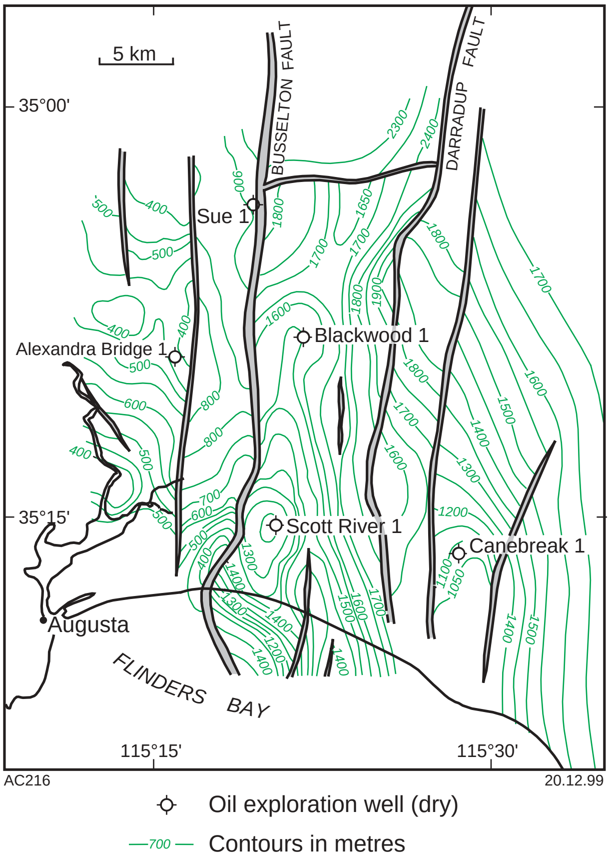

Figure 36. Configuration of the Scott River, Blackwood, Canebreak, and Alexandra Bridge structures in the Augusta area (after Paton, 1994)

Reasons for failing to discover a hydrocarbon accumulation

The Warnbro Group, which overlies the pre-Main Unconformity exploration objective, is represented here by sandstone of the Leederville Formation. No effective seal is therefore present to trap migrating hydrocarbons, whatever the Bouvard 1 structural setting may be.

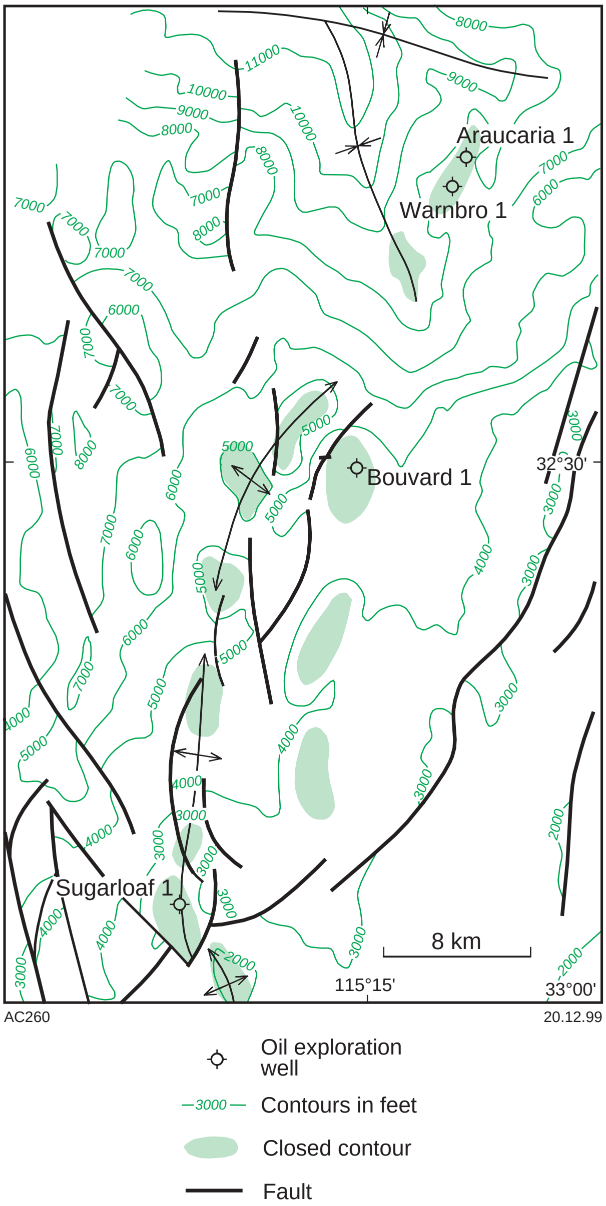

Figure 37. Structural map of a pre-Main Unconformity intra-Neocomian horizon of the Sugarloaf–Bouvard trend, southern Vlaming Sub-basin (after West Australian Petroleum Pty Limited, 1970)

Table 2. Results from Blackwood 1 drillstem tests

DST number	*Depth (m)*	*Formation*	*Recovery*	*Comments*
1	3 046–3 035	Willespie Formation Sue Group	1036 m water cushion 30 m filtrate and formation water	very weak blow
2A	3 034–3 001	Willespie Formation Sue Group	366 m freshwater	weak blow
3	2 846–2 802	Willespie Formation Sue Group	701 m water cushion 55 m muddy water	weak blow

Bullsbrook 1

Location

Bullsbrook 1 is situated onshore within the Beermullah Trough, in the central Perth Basin. It was drilled in 1972 by WAPET, at a location 51 km north of Perth and 37 km north of Gingin 1 (Fig. 4).

Stratigraphy

Bullsbrook 1 was planned in order to test sandstone in the Cattamarra Coal Measures, which is sealed both intraformationally and by the Cadda Formation (Osbsorne et al., 1973). The Main Unconformity was encountered in Bullsbrook 1 at 160 m, and the well was terminated within the Cattamarra Coal Measures at 4257 m. Several interbeds of shale and siltstone are present below 1816 m, within the mainly sandy Yarragadee Formation. The Cadda Formation (2809–3050 m) is lithologically quite similar to the lower part of the Yarragadee Formation, and its definition depends on palynological data indicating a Middle Jurassic marine environment. Marine influence is also indicated by palynological evidence from ditch cuttings within the uppermost Cattamarra Coal Measures.

Structure

Bullsbrook 1 is located on a large anticlinal structure that was estimated at the time of drilling to cover 166 km^2, although the tested fault compartment is relatively minor. The closure is well defined to the east, but thickening of the Cattamarra Coal Measures weakens the closure to the west (Fig. 7). The structural setting is comparable to that of the Gingin – Bootine Anticline (Crostella 1995, figures 6 and 56), but the Bullsbrook Anticline is structurally higher because the regional structural axes plunge to the north. The Muchea Fault separates the Beermullah Trough, in which the Bullsbrook structure lies, from an upthrown block adjacent to the Yilgarn Craton (Fig. 7). As is regionally the case, the structure and its related faults are the result of breakup tectonic movements.

Hydrocarbons

No hydrocarbon shows were recorded during drilling. Log analyses, however, indicated four discrete thin sandstone intervals with gas saturations greater than 43%, within the Cattamarra Coal Measures. These are present between 4050 m and total depth, for a total of 39 feet (12 m) (Fig. 38).

Potential reservoirs and seals

At Gingin, sonic-derived porosities are higher than those from gas-bearing sandstone. Sealing potential is offered throughout the entire pre-Main Unconformity section by numerous intervals of shale that increase with depth. A shale section between 3862 and 3991 m appears to act as an effective regional seal because the log-derived salinity decreases from 70 000 ppm above this interval to

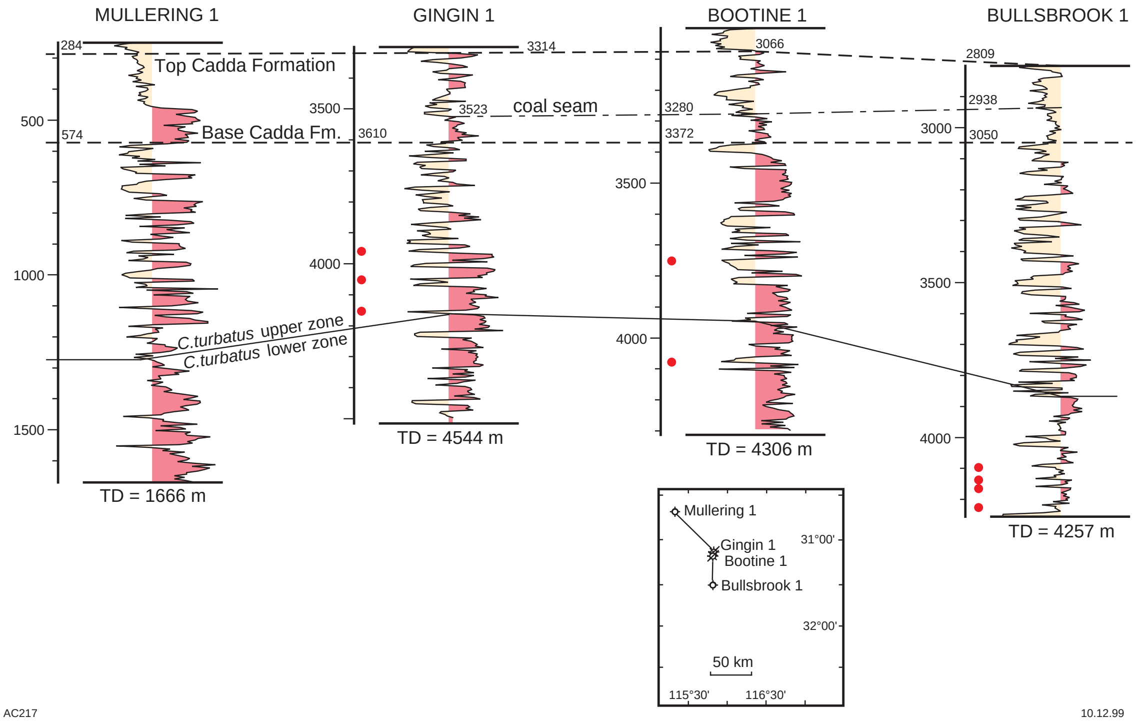

Figure 38. Stratigraphic correlation of Mullering 1, Gingin 1, Bootine 1, and Bullsbrook 1 (from gamma ray and palynology). Gas indications (shown by red dots) in Gingin 1 and Bootine 1 from testing and in Bullsbrook 1 interpreted from E-logs

10 000 ppm below it. This reflects the continental environment of deposition.

Comments

In Bullsbrook 1, the hydrocarbons indicated by log analysis have not been tested because, at the time, their potential was not considered to be of economic significance. A contributing factor to the decision not to test was reportedly the lack of any mud-log shows, although this only indicates that the pressure of the formation fluid was controlled by the mud weight.

It is interpreted that the gas indications with high water saturation reflect hydrocarbons migrating from deeper horizons. Owing to the regional increase in thickness of the Cattamarra Coal Measures, the western closure of the Bullsbrook structure increases with depth (Fig. 7). In addition, the frequency and thickness of sealing intervals also increase with depth where shaly sections, up to 64 m thick, are present (Fig. 38). As a consequence of these two positive factors, a definitive evaluation of the well results would require adequate testing of the log-derived hydrocarbon indicators. Even so, the structure cannot be considered exhaustively tested until the Lesueur Sandstone has been reached, because the lower part of the overlying Cattamarra Coal Measures and Eneabba Formation are considered to have the best regional sealing potential.

Canebreak 1

Location

Canebreak 1 is situated within the Bunbury Trough, at a location approximately 70 km south of Busselton (Fig. 4). It was drilled in 1982 by Weaver Oil and Gas.

Stratigraphy

Canebreak 1 was terminated at 2090 m in the Willespie Formation (Sue Group), below the Sabina Sandstone, although the latter unit was not recognized by Weaver Oil and Gas (Lowry, 1983). The basin-wide Main Unconformity was reached at 144 m, above the Bunbury Basalt.

Structure

Canebreak 1 was drilled to test the upper part of the Willespie Formation in a location that was thought to be on the crest of an elevated fault block (Figs 39a and 40). The well results, however, suggest that the location is on a downthrown fault compartment (Fig. 39b).

Potential reservoirs and seals

In Canebreak 1, the Sue Group has porosities ranging from 15 to 28% (Fig. 41). The Cattamarra Coal Measures and Lesueur Formation are without an effective seal

Fresh surface water circulates down to a depth of 1600 m, where salinities of less than 500 ppm have been estimated for the formation water. Salinities in the Willespie Formation are higher, although they cannot be properly estimated because the shale beds are insufficiently thick to develop a full spontaneous-potential (SP) response, and the resistivity logs appear to be affected by the incursion of drilling mud (Lowry, 1983). The Permian unit contains thin, discontinuous shaly and silty intervals that do not offer reliable sealing potential.

Hydrocarbons

Canebreak 1 did not encounter significant hydrocarbon indications.

Source rocks

The coal and carbonaceous siltstone of the Willespie Formation are expected to be good source rocks for gas and light oil. The maximum recorded temperature of 53.3°C at total depth, however, indicates that the Willespie Formation is immature for hydrocarbon generation at the well location. A very low temperature gradient of 1.5°C/100 m is estimated for the well.

Reasons for failing to discover a hydrocarbon accumulation

Lowry (1983) suggested that Canebreak 1 was located in a downthrown fault block (Fig. 39b). Paton (1994) claimed that the well was drilled off-structure and did not test a valid closure (Fig. 36), but Iasky's (1993) interpretation showed a four-way dip closure (Fig. 23). In any case, undetected faults are likely to be present in the area and they may well breach any possible trap. The locally very poor seismic data cannot define faults of less than 20 m of throw.

Challenger 1

Location

Challenger 1 is situated within the southwestern part of the offshore Vlaming Sub-basin, at a location 82 km southwest of Fremantle (Fig. 4). It was drilled by WAPET in 1975.

Stratigraphy

Challenger 1 was terminated at 2250 m in the Upper Jurassic Yarragadee Formation. The Main Unconformity at 1429 m can be seen in both dipmeter and palynological data, and is overlain by a 14 m-thick sandstone that was assigned by Barr and Bradley (1975) to the basal South Perth Shale, and is here assigned to the Gage Sandstone.

Structure

Challenger 1 is located on a four-way dip closure that is defined at the Main Unconformity level (Fig. 42). The closure represents a palaeotopographic culmination on the northwesterly trending positive axis of the southernmost Vlaming Sub-basin. Below the Main Unconformity, dipmeter data consistently indicate dips of between 10°

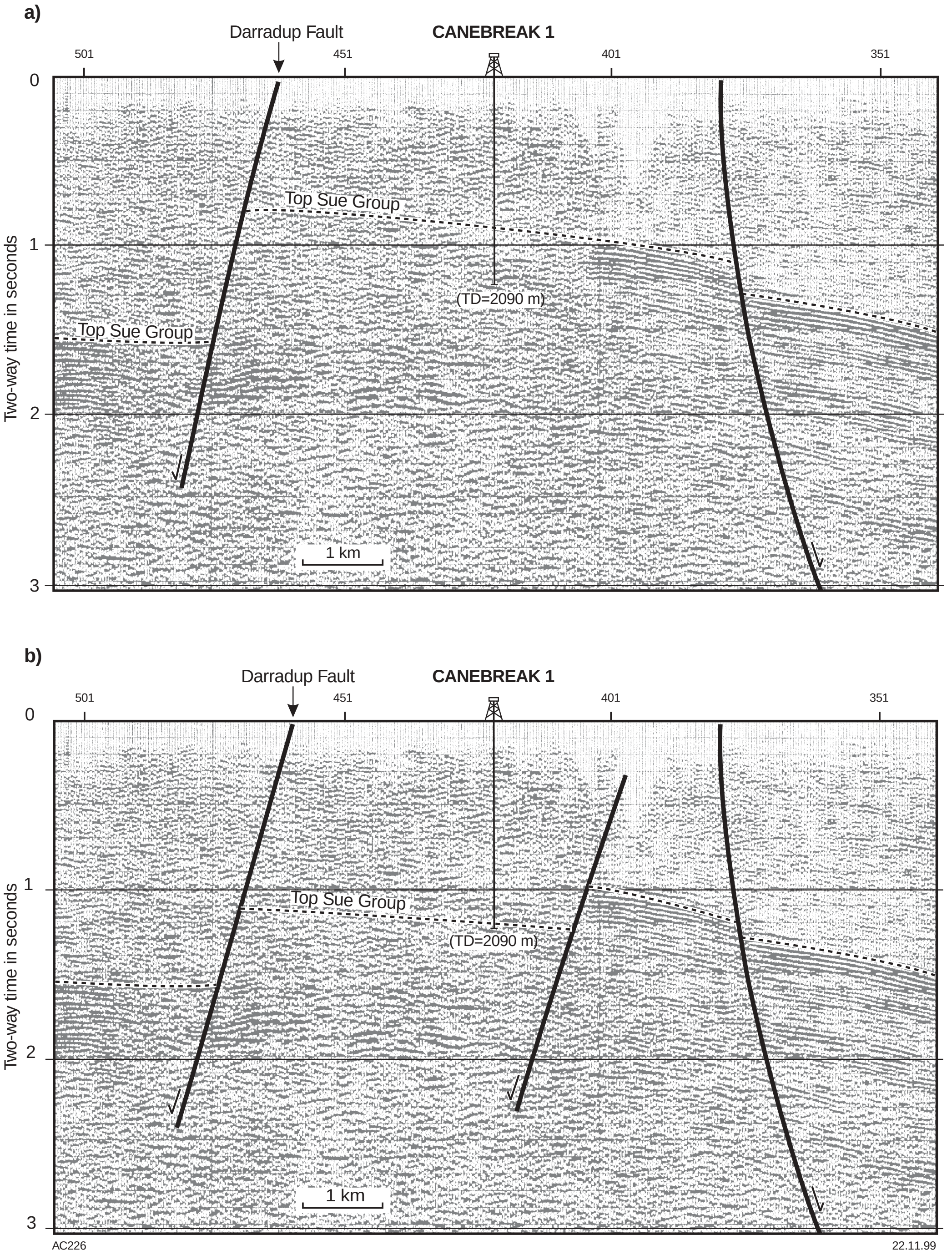

Figure 39. Seismic section HV-P81-1, showing the structural interpretation of the Canebreak structure: a) before drilling; b) after drilling (after Lowry, 1983)

and 22° to the east, although the most reliable dips, which are those within the Otorowiri Formation, are consistently 16° to the northeast. The Challenger prospect is virtually a truncation play because the expected seal above the Main Unconformity surface is not parallel to the underlying strata (Fig. 43).

Hydrocarbons

No significant hydrocarbons were detected.

Reasons for failing to discover a hydrocarbon accumulation

Only the tip of the Challenger feature appears to be sealed by the South Perth Shale. The Jervoise Sandstone, which was the exploration objective of Challenger 1, underlies the Gage Sandstone at the well location and also further downdip, thereby allowing migrating hydrocarbons to escape. The sandstone of the Yarragadee Formation is sealed vertically by the Otorowiri Formation, but there are no lateral seals (Fig. 43). It has been concluded that Challenger 1 did not test a valid trap.

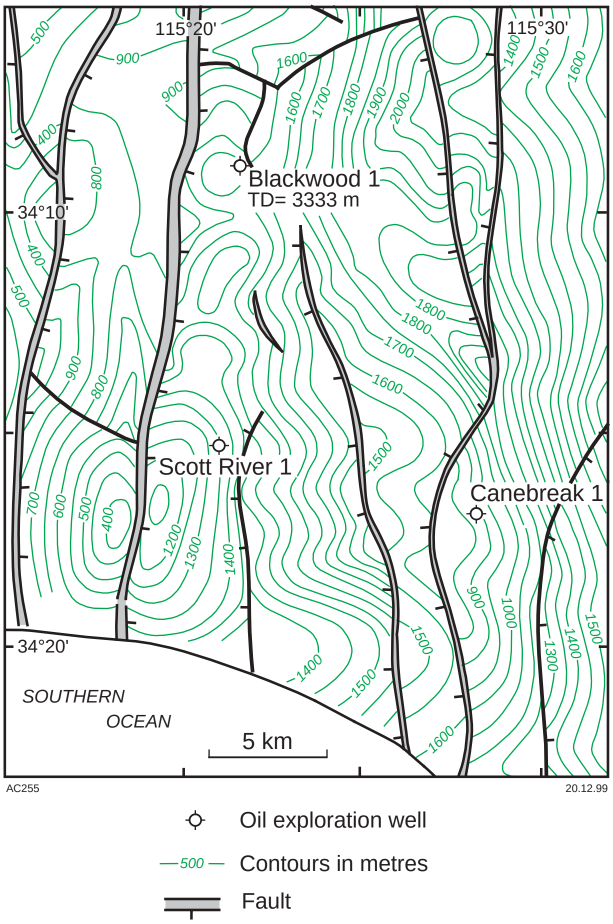

Figure 40. Pre-drilling structural interpretation of the Canebreak–Blackwood configuration at the Top Permian level (after Lowry, 1993)

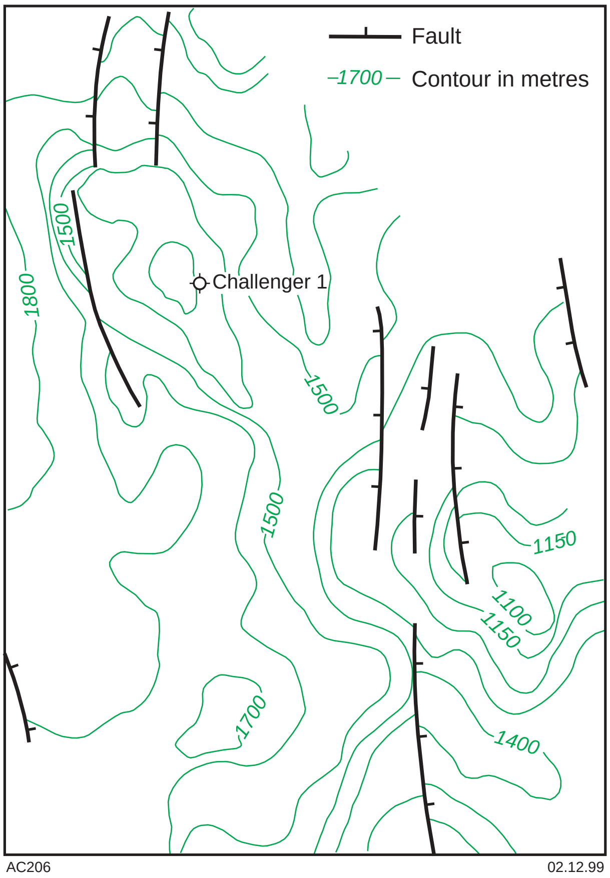

Figure 42. Structural map of a pre-Main Unconformity intra-Neocomian horizon in the Challenger 1 area

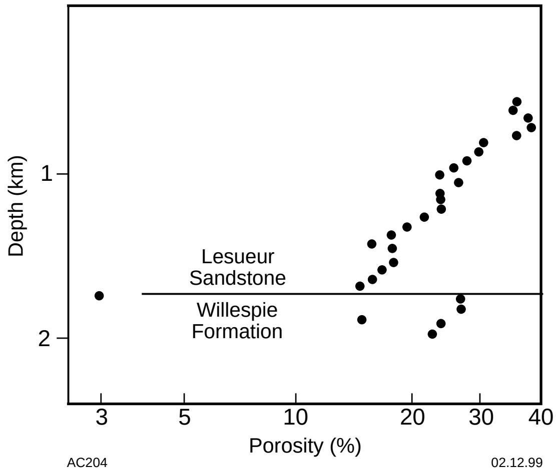

Figure 41. Sandstone porosities from a sonic log in Canebreak 1 (after Lowry, 1983)

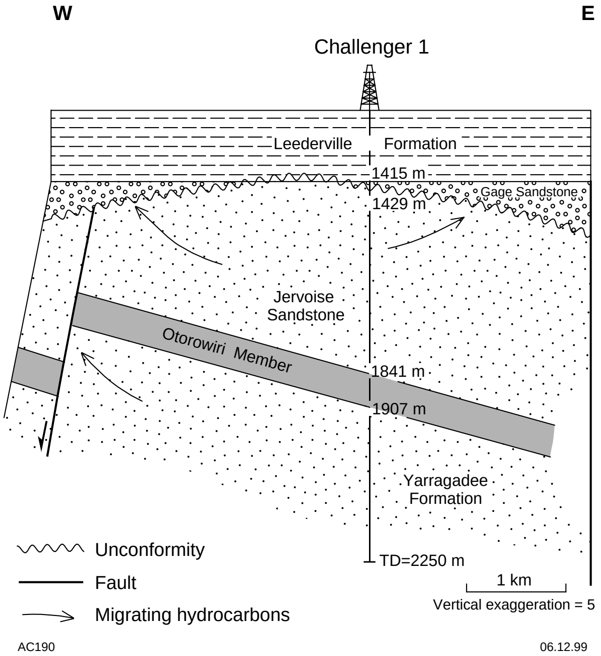

Figure 43. Structural section across the Challenger 1 area, based on seismic and well data

Chapman Hill 1

Location

In 1982, Chapman Hill 1 was drilled by Discovery Petroleum on the western flank of the Bunbury Trough, at a location 14 km south of Busselton.

Stratigraphy

The regional Main Unconformity is present at 240 m, and the well was terminated in the Cattamarra Coal Measures. The Eneabba Formation, contrary to the interpretation of Discovery Petroleum NL (1992a), is not present because the multicoloured shale and siltstone that characterize this formation have not been observed in the well. However, a detailed correlation for the interpreted Eneabba Formation between Sabina River 1, Chapman Hill 1, Whicher Range 1, and Wonnerup 1 (Discovery Petroleum NL, 1992a) supports the presence in the southern Perth Basin of sedimentary rocks equivalent to the Eneabba Formation.

Structure

Chapman Hill 1 tested an anticline that has developed on the downthrown side of the Busselton Fault. A seismic section across the anticline shows a flower structure (Fig. 44). The anticline is considered to be the result of the strike-slip faults that surround it, with minor vertical displacement. Figure 45 shows the area of the structural closure.

Potential reservoirs and seals

Sandstone beds in the Cattamarra Coal Measures, which were the primary objective of the well, have good porosities ranging from 18 to 30%. Good seals, albeit not too thick, are also present below 863 m, in the lower portion of the Cattamarra Coal Measures. Individually, the seals do not seem to represent a barrier to flushing, but collectively they appear to have influenced the degree of flushing because a major salinity increase to 22 000 ppm is present between 900 and 1100 m.

Hydrocarbons

No hydrocarbon shows were detected.

Geochemical data

The consistently low organic yields of the samples that have been examined palynologically suggests that the drilled rocks have very little source-rock potential. Furthermore, thermal alteration, as determined from palynomorphs, suggests that the rocks are immature or just within the oil window.

Reasons for failing to discover a hydrocarbon accumulation

Discovery Petroleum NL (1992a) concluded that no pathway exists from the deeper Permian source section to the shallower Cattamarra Coal Measures objective, and that this was the reason for the dry hole. However, the very high percentage of sand within the Jurassic, Triassic, and Permian intervals (Fig. 9; Plate 1) should facilitate hydrocarbon migration via faults, both horizontally and vertically. Seismic data allow the resolution of the major regional faults, but detailed work in discrete areas indicates that a large number of minor faults are also present (Le Blanc Smith, 1993; Le Blanc Smith and Kristensen, 1998). It is therefore concluded that Chapman Hill 1 did not test a valid trap because faulting juxtaposes sandstones against sandstones throughout the entire section.

Charlotte 1

Location

Charlotte 1 was drilled offshore in the Vlaming Sub-basin, at a location 3 km north-northwest of Fremantle (Fig. 4). It was drilled by WAPET in 1970–71 (Moyes, 1971a).

Stratigraphy

Charlotte 1 was terminated at 2435 m in the Hawley Member of the Carnac Formation (Parmelia Group). The Main Unconformity was encountered at 1576 m, and little stratigraphic interval is missing because the *G. mutabilis* Zone (the oldest post-breakup Cretaceous marine palynological zone) is present immediately above the Charlotte Sandstone, which is the youngest pre-breakup lithostratigraphic unit.

Structure

Charlotte 1 was located ‘on a major reversal’ developed within the central part of the Rottnest Trough (Moyes, 1971a). The meaning of this description is unclear.

Hydrocarbons

No indications of hydrocarbons were encountered by the well.

Potential reservoirs

Sandstone beds of reservoir quality were encountered in several units. The Gage Sandstone has log-derived porosities of 15–30%. The Charlotte Sandstone has a core-derived porosity of 22% and permeabilities of 11.5 to 395 md in core 3 (2125–2134 m). A sandy intercalation within the Hawley Member has core-derived porosities of 19.3 to 23.0% and permeabilities of 16.5 to 107 md in core 4 (2429–2435 m).

Reasons for failing to discover a hydrocarbon accumulation

The limited and poor-quality seismic data available did not allow a clear definition of the Charlotte prospect. However, the presence of a porous and permeable section (the Gage Sandstone) above the Charlotte Sandstone indicates that whatever structural closure may be present at the level of the unconformity, no vertical seal exists.

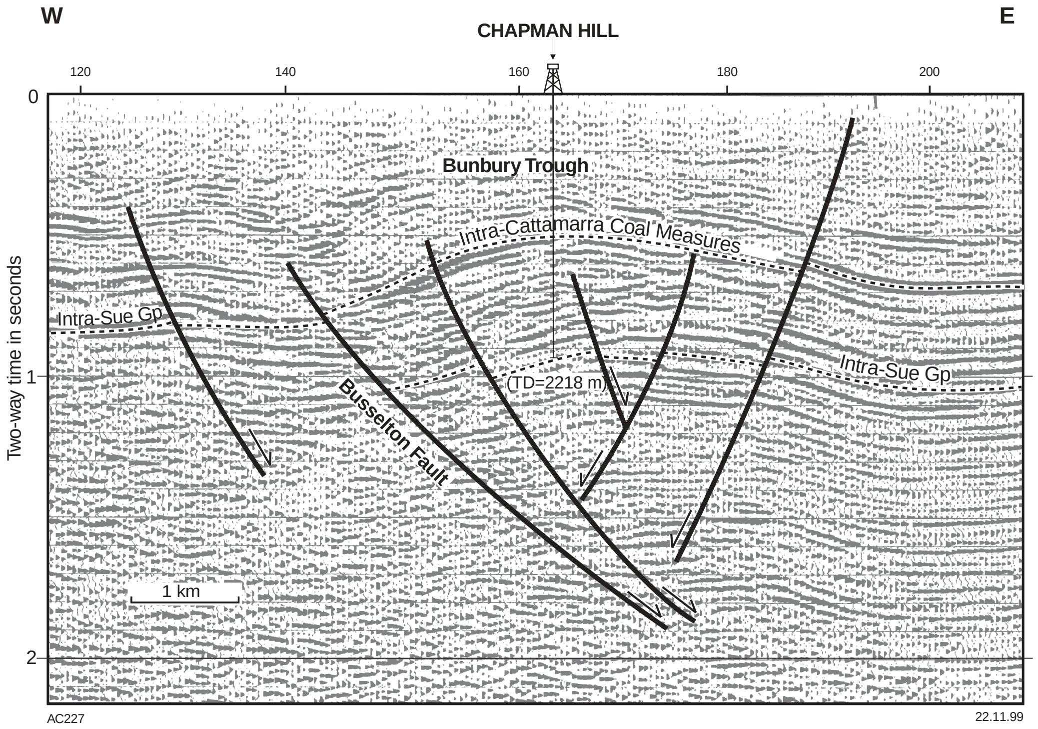

Figure 44. Seismic section A-A81-11, showing the Chapman Hill Anticline. The line of section is shown on Figure 45

Cockburn 1

Location

Cockburn 1 is situated in the Mandurah Terrace within Cockburn Sound, at a location approximately 7 km southwest of the port of Fremantle (Fig. 4). It was drilled by WAPET in 1967. A causeway about 800 m in length was built into Cockburn Sound in order to drill the well with a standard onshore rig.

Stratigraphy

The regional Main Unconformity is present at 313 m, and the well was terminated at 3054 m within the Cattamarra Coal Measures.

Structure

Cockburn 1 was drilled in order to evaluate the stratigraphy and hydrocarbon potential of the Cattamarra Coal Measures within the seismically defined Cockburn structure, which is closely associated with a gravity anomaly. Numerous geophysical surveys, carried out in 1965 and 1966, helped to mature the prospect to the drilling stage, but the drilling results indicated that the well was located on the southwestern flank of the structure.

Reservoir potential and seals

Core analyses indicate good porosity and permeability in the Yarragadee and Cadda Formations and, to a lesser degree, also in the Cattamarra Coal Measures. Core data are in good agreement with the log-derived data; porosities range from more than 30% in the shallower section above 600 m to 15% at about 2000 m, and 8–13% below this depth.

The upper part of the Yarragadee Formation has been flushed, as demonstrated by the low salinity of the formation waters (less than 1000 ppm). Formation water in the Cadda Formation has a salinity of approximately 30 000 ppm, which suggests that the unit has regional sealing capabilities.

Hydrocarbons

No indications of oil or gas were encountered.

Reasons for failing to discover a hydrocarbon accumulation

The well did not test an effective trap.

Gage Roads 1 and 2, and Tuart 1

Location

Gage Roads 1 and 2, and Tuart 1 are situated offshore within the Vlaming Sub-basin, at locations 35, 37, and 38 kilometres west-northwest of the port of Fremantle respectively (Fig. 4). Tuart 1 is located 700 m west of Gage Roads 2, 2.1 km west-northwest of Gage Roads 1, and 3.6 km east-southeast of Roe 1 (Fig. 46). Gage Roads 1 and 2 were drilled by WAPET in 1968–69 and 1971 respectively. Tuart 1 was drilled in 1991 by Ampolex.

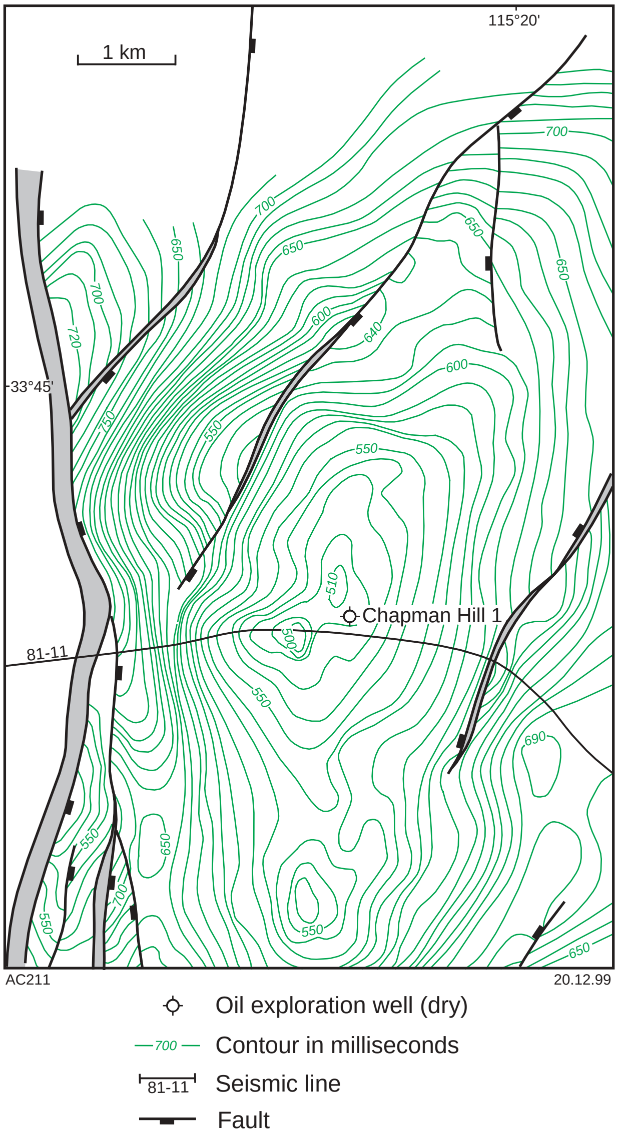

Figure 45. Time-structure map of the Chapman Hill Anticline, on an intra-Cattamarra Coal Measures horizon (after Discovery Petroleum NL, 1992a)

Stratigraphy

Gage Roads 1 and 2 were terminated at 3660 and 2974 m respectively in the Upper Jurassic Yarragadee Formation. Tuart 1 was terminated at 1600 m in the Mangles Member of the Carnac Formation. The regional Main Unconformity at the base of the Warnbro Group was reached at 1205 m in Gage Roads 1, at 1375 m in Gage Roads 2, and at 1107 m in Tuart 1. The Parmelia Group was included within the Yarragadee Formation by Bozanic (1969a) and Moyes (1971b), although its basal unit, the Otorowiri Member, was labelled as the Quinns Shale. The definition of the Main Unconformity, and that of the formations of the Parmelia and Warnbro Groups in the area, benefited from the palynological review by Ingram (1991), who resolved previous misinterpretations.

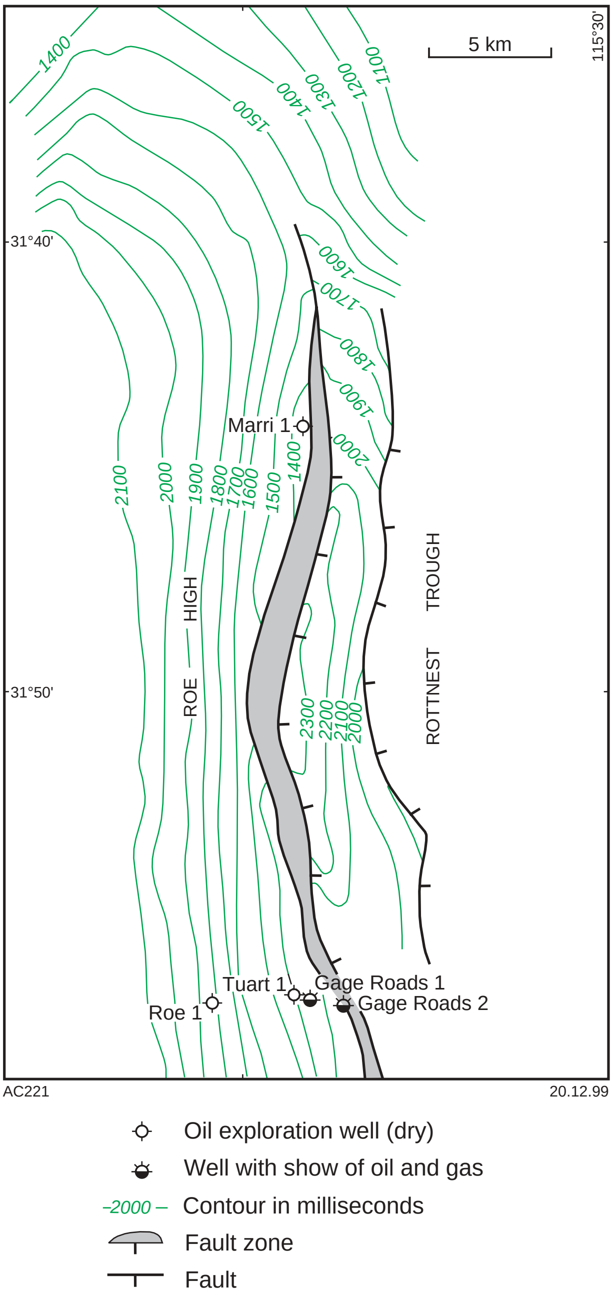

Figure 46. Time-structure map of the Roe High, on the Top Jervoise Formation (after Ampol Exploration Limited, 1991)

Structure

Gage Roads 1 was located on the eastern flank of the large north-trending and faulted homoclinal Roe High, which was formed during continental breakup (early Neocomian) (Fig. 46). Following the Gage Roads 1 oil discovery, Gage Roads 2 was planned to test the updip potential of a series of postulated stratigraphic-structural traps that ranged from the Warnbro to the Parmelia Group. The well encountered oil in the Gage Sandstone that pinches out against the underlying Parmelia Group. Subsequently, Tuart 1 was drilled further updip to test a truncation trap comprising sandstones of the Parmelia Group that are

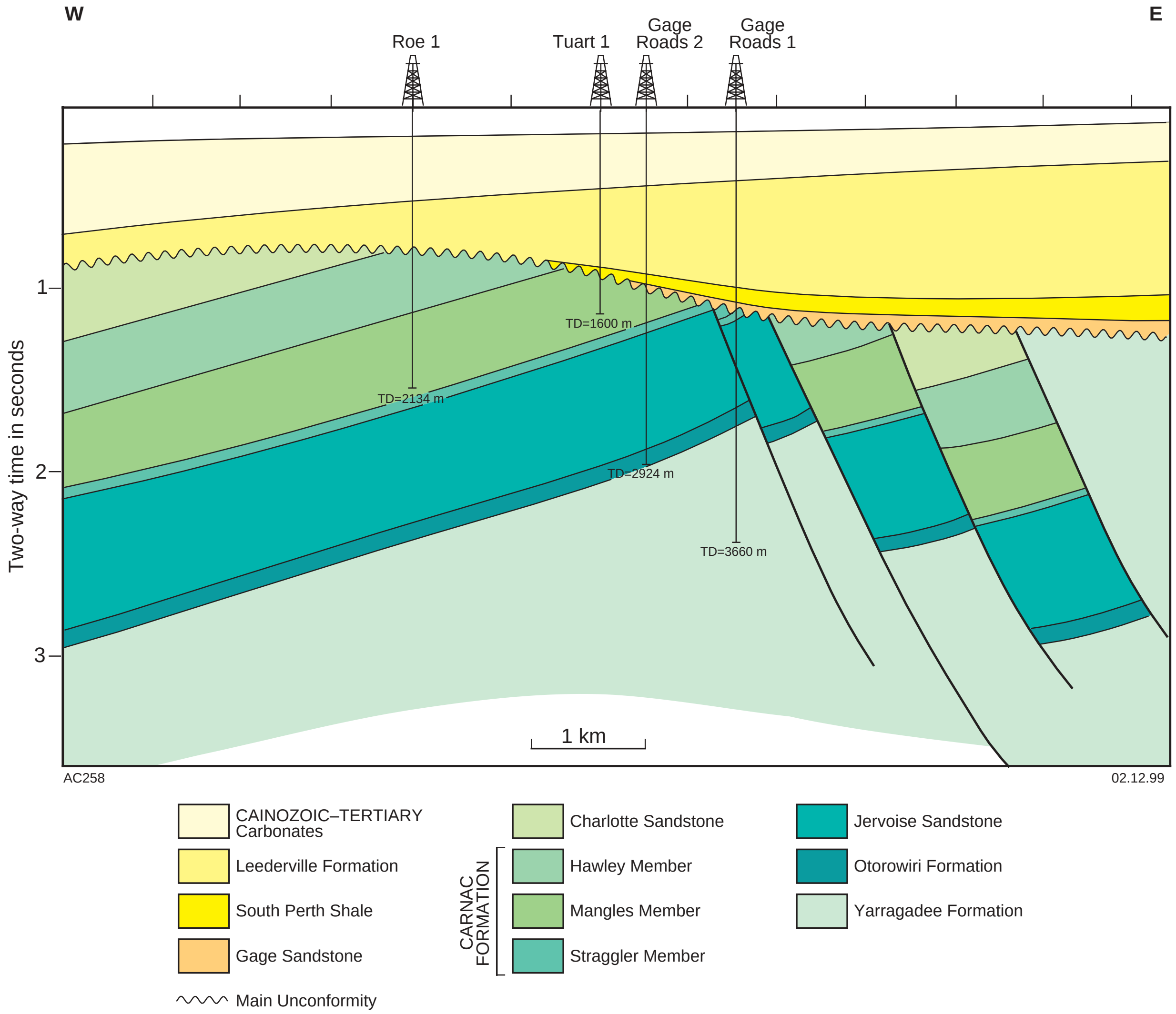

Figure 47. Cross section showing the structural and stratigraphic relationships between Roe 1, Tuart 1, Gage Roads 2, and Gage Roads 1

sealed intraformationally to the west and subcrop against the breakup unconformity (Malcolm, 1992). The truncation trap is overlain by easterly dipping South Perth Shale. The structural and stratigraphic relationships between the wells are shown in Figure 47. A small normal fault is interpreted within Gage Roads 1.

Reservoirs and seals

The Warnbro and Parmelia Groups offer good potential for both reservoirs and seals. The best reservoir potential is offered by the Leederville Formation and Gage Sandstone of the Warnbro Group, and the Charlotte and Jervoise Sandstones of the Parmelia Group. The two latter units have porosities up to 20%. The depositional environment of the Parmelia Group suggests that the sandstone beds are probably lenticular, and thus their reservoir potential may be minor. Petrophysical analyses of two selected intervals of the Mangles Member of the Carnac Formation indicate that their sandstone content is subordinate and that shale constitutes more than two thirds of the unit (Figs 48 and 49), which almost makes them seals. The presence of permeability barriers within the Mangles Member of the Carnac Formation is demonstrated by the different salinities of the two intervals analysed; 30 000–35 000 ppm in the upper interval and 20 000 ppm in the lower interval.

Proven effective reservoirs in these wells are the Gage Sandstone from which some oil was recovered in formation interval tests (FIT) in Gage Roads 2, and the Stragglers Member of the Carnac Formation, from which oil was produced in Gage Roads 1. The hydrocarbon zone in Gage Roads 1 has core-derived porosities ranging from 16 to 22% and permeabilities of 10 to 1100 md, with an average of 350 md from core 6 (1785–1793 m). The Gage Sandstone in Gage Roads 2 has core-derived porosities of up to 16% and permeabilities ranging from 0 to 10 md in core 2 (1359–1362 m). The highly porous and permeable Leederville Formation does not have an effective seal, whereas in Gage Roads 1 a difference in water salinity above (38 000 ppm) and below (15 000 ppm) the

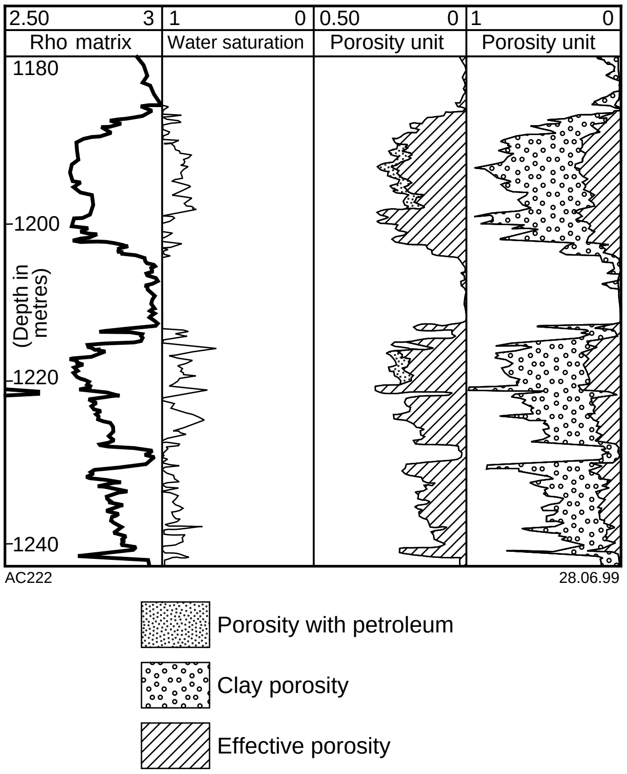

Figure 48. Potential reservoir characteristics in Tuart 1, 1180–1240 m interval

Otorowiri Formation proves that it offers a good seal to underlying sandstone of the Yarragadee Formation.

Hydrocarbons

DST 1A in Gage Roads 1 recovered 40 barrels of 37°API oil and 82 barrels (13 m^3) of water after swabbing two perforated intervals (1760–1762 m and 1765–1769 m) of the Stragglers Member in the Carnac Formation. DST 2A recovered 58.5 barrels (9 m^3) of 41.2°API oil and 25 barrels (4 m^3) of water from 1779–1782 m after swabbing. The calculated daily rate of flow was approximately 500 barrels (80 m^3) of oil from the upper zone and 350 barrels (56 m^3) from the lower zone. A gross oil column of 50 m is interpreted from the well log, with high water saturation in the shaly sandstone (Seggie, 1990). In addition, strong fluorescence and high gas readings were recorded within the Yarragadee Formation over the interval 2615–2652 m, with a possible hydrocarbon column of 35 m (Seggie, 1990).

In Gage Roads 2, hydrocarbon shows were encountered in the Gage Sandstone from 1351 to 1376 m. A log evaluation of this interval (Moyes, 1971b), however, suggested the presence of less than 2 m of net oil pay in the upper part. This small interval was not considered to be of commercial significance, and no drillstem tests were carried out.

In Tuart 1, strong hydrocarbon shows were detected from a 1.5 m-thick sandstone within the mainly shaly base of the Leederville Formation. This thin interval may contain residual hydrocarbon or, at best, less than 20% hydrocarbon saturation.

Geochemical data

Oil was extracted from a sample taken from 1056 m in Tuart 1. The sample was early mature, as indicated by the vitrinite reflectance (R_o) of approximately 0.65%, and was derived from terrestrial organic matter (Malcolm, 1992). Both geochemistry and palynology indicate that the South Perth Shale is the best source rock for oil in the Tuart 1 section. In contrast, the oil in Gage Roads 1 is sourced from the Upper Jurassic Yarragadee Formation, which is mature in the Vlaming Sub-basin. The oil in Gage Roads 1 is heavy, as indicated by its carbon isotope ratio, and contains a relatively high percentage of conifer-derived aromatic hydrocarbons (Kantsler and Cook, 1979; Summons et al., 1995).

Discussion

Hydrocarbons encountered in both Gage Roads 1 and Gage Roads 2 were considered at the time of drilling to be of no economic value. Dedman (1989), however, noted that there is a section with moveable oil between 1685 and 1745 m in Gage Roads 1 that falls partly above and partly below the Main Unconformity. This section was not tested at the time of drilling. Seggie (1990) was even more optimistic and suggested that high potential reserves may be associated with the Main Unconformity in the Gage Roads area. Seggie (1990) was also optimistic about the oil potential of the Gage Sandstone in Gage Roads 2. From a more general perpective, the Gage Roads structural-

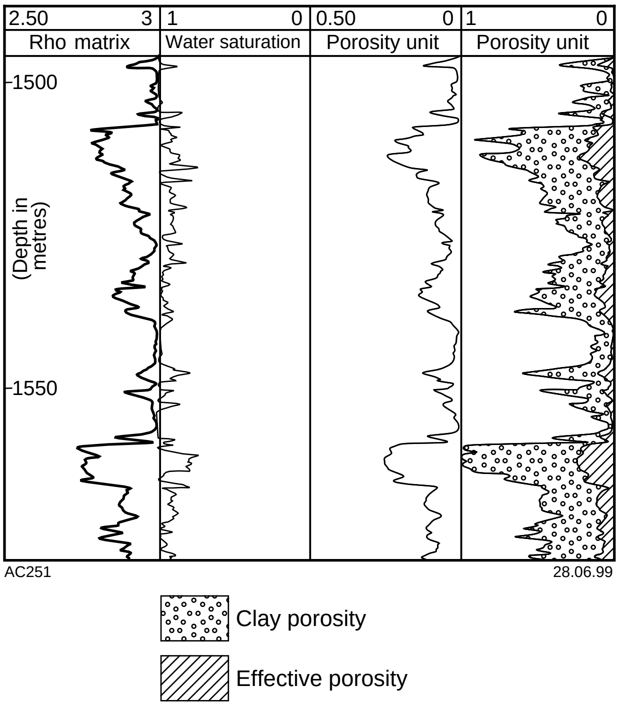

Figure 49. Potential reservoir characteristics in Tuart 1, 1493–1528 m interval

stratigraphic trap has been proved to be valid by DSTs 1A and 2A in Gage Roads 1. It is difficult to believe that the sandstone intervals tested are in a different trapping position to the overlying or underlying sandstone beds, and therefore further testing is recommended.

Until Dedman's (1989) and Seggie's (1990) hypotheses are either proved or disproved by testing, the Gage Roads pinch-out – truncation play (as shown in Figure 47) must be considered valid.

Malcolm (1992) suggested that Tuart 1 failed to encounter significant hydrocarbons because the thickness of the South Perth Shale is insufficient to provide a valid seal. However, seals of only a few metres can be quite effective and, in Tuart 1, the South Perth Shale is 38 m thick. The dipmeter readings for Tuart 1 indicate east-northeasterly dips within the South Perth Shale and southwesterly dips within the Parmelia Group, thus confirming the presence of an effective trap. An alternative explanation for the dry hole may be the lack of migration paths within the Carnac Formation, which may be an effective sealing horizon if its sand bodies are lenticular.

Gingin 1, 2, and 3, and Bootine 1

Gingin 1, 2, and 3, and Bootine 1 are situated within the Beermullah Trough, in the northernmost part of the onshore central Perth Basin (Fig. 4). Gingin 1 and 2 were drilled by WAPET in 1964–65 and 1965–66 respectively (Johnson, 1965; Brownhill, 1966), whereas Bootine 1 was drilled in 1981 (Mesa Australia Limited, 1982). Gingin 3 was drilled by Empire Oil in 1998. All four wells were designed to test the hydrocarbon potential of the upper part of the Cattamarra Coal Measures within the large Gingin Anticline. The results of the first three wells, as discussed in Crostella (1995), are summarized below.

The three wells are located on a large, heavily faulted, elongate northerly trending anticline within the Gingin area (Fig. 8). The western closure of the structure is critical, as it is diminished by regional thickening of Lower Jurassic strata to the west (Crostella 1995, figs 6 and 56). DSTs and production tests in Gingin 1 established the presence of gas-bearing reservoirs in the Cattamarra Coal Measures between 3864.9 and 4154.4 m, whereas Gingin 2 tested only non-commercial gas. Gas from Gingin 1 was fed into the Dongara–Perth pipeline at a rate of 5 million cubic feet (MMcf), which is about 140×10^3 m^3 per day, but production lasted only from March to December 1972. In June 1975, production was resumed at a much reduced rate, until it ceased completely in January 1976. In total, 1.72 billion cubic feet (Bcf) or 49×10^6 m^3 of gas and 20 000 barrels (3189 m^3) of condensate were produced. Bootine 1 also encountered gas-bearing reservoirs in the Cattamarra Coal Measures, but production tests indicated that the flow rates did not stabilize and production declined rapidly, which suggests a very limited accumulation of gas.

Data from Gingin 3, which had a total depth of 4200 m, are not yet in open file, although it can be reported that the Cattamarra Coal Measures objective was reached and tested. Good reservoir potential was shown by the deeper sands that proved, however, to be freshwater-bearing, and contained only gas in solution. Further drilling operations are planned for this area.

Comments

It is concluded that none of the four wells penetrated a trap of economic significance because intense faulting has probably breached whatever four-way dip closure may have been present. The uneconomic hydrocarbon zones were controlled by either limited fault traps or permeability barriers. These traps or barriers allowed the accumulation of gas in sandstones averaging 8% porosity and low permeability, within a generally impervious formation. Sandstones with better reservoir potential are present at shallower depths within the Cattamarra Coal Measures (Fig. 38), but they are water-bearing.

In the authors' opinion, the limited gas pockets indicate the migration of hydrocarbons from deeper horizons. This interpretation is supported by the results of a near-surface geochemical survey over the area, which suggests that gas is leaking from the reservoirs (Gole and Butt, 1985). Since the undrilled section of the Cattamarra Coal Measures becomes more shaly with depth, sandstone bodies that are better sealed could be present at a greater depth. Furthermore, these horizons are more likely to be within a closed structure (Crostella, 1995, figs 6 and 56). As with the Bullsbrook structure, a more exhaustive test should be drilled to the top of the Lesueur Sandstone, which represents the main potential reservoir in the region, and may be better sealed by the lower part of the Cattamarra Coal Measures and the Eneabba Formation. The possibility that the hydrocarbons have been generated by coal seams and carbonaceous shales of the Cattamarra Coal Measures cannot be excluded. Finally, a less faulted anticline may be considered for a future test. A geochemical survey should provide the relevant information on the retention capabilities of the sealing horizons.

Lake Preston 1

Location

Lake Preston 1 is situated 47 km north of Bunbury (Fig. 4), on the Harvey Ridge, which forms the boundary between the Bunbury Trough and the Mandurah Terrace in the onshore central Perth Basin. The well was drilled by WAPET in 1972–73.

Stratigraphy

The Main Unconformity was encountered in Lake Preston 1 at a depth of 112 m. The well was terminated at 4565 m, within the Willespie Formation of the Sue Group. The boundary between the Jurassic Eneabba Formation and Triassic Lesueur Sandstone can be identified with reasonable certainty on the wireline logs at 1219 m. The boundary between the Triassic Lesueur and Sabina Sandstones has been determined at 3511 m, where both gamma-ray and sonic log values increase. This depth corresponds to the top of an interval of green-grey, fine-grained sandstone that grades to siltstone. The Sabina Sandstone is thicker in this area than in the Bunbury Trough, which suggests a gradual shifting of the depocenter towards the north.

Vitrinite reflectance data suggest that the structure has been uplifted considerably (Iasky, 1993), which is consistent with the crestal erosion indicated by the presence of the Eneabba Formation immediately below the Main Unconformity. The pronounced discontinuity in the vitrinite reflectance values just below 4000 m may be related to a local Late Permian heat pulse (Iasky, 1993), or to a large normal fault.

Structure

Lake Preston 1 was drilled on a faulted anticlinal structure that, at the time, was interpreted to have 457 m of vertical relief and 130 km^2 of areal closure. The structure, which has four-way dip closure even though it is cut by several large faults, was first identified by gravity surveys, and then detailed with seismic lines. The seismic quality was considered acceptable at the time, despite unfavourable near-surface conditions as a result of coastal limestone and sand dunes. The Willespie Formation section proved to be disrupted by major faults. The regional seismic structure map for the top of the Willespie Formation (Fig. 23) shows that Lake Preston 1 was drilled on the northernmost tip of an elongated anticline, 1000 m downdip from the crest.

Hydrocarbons

No significant shows of hydrocarbons were recorded. Minor indications of methane and ethane were associated with the coal beds of the Willespie Formation.

Reservoir potential and seal

No seal occurs within the Mesozoic section, whereas thin shales and coal seams of Permian age, if unfaulted, may have sealing potential. Reservoir potential is poor, with porosities up to 14% in the Sabina Sandstone, decreasing to a maximum of 6% in the heavily faulted Willespie Formation.

Reasons for failing to discover a hydrocarbon accumulation

The lack of any hydrocarbon shows above the coal beds in the Willespie Formation suggests that no valid seal is present within the Lake Preston closure, probably because heavy faulting has breached the structure. The well was also poorly located within the structure (Fig. 23).

Marri 1

Location

Marri 1 was drilled in 1993 by Ampolex. It is located approximately 55 km northwest of Perth, in the offshore Vlaming Sub-basin (Fig. 4).

Stratigraphy

Marri 1 was terminated at 2594 m in the Stragglers Member of the Carnac Formation. The South Perth Shale directly overlies the Hawley Member of the Carnac Formation at 1326 m. The Gage Sandstone is absent.

The lithostratigraphy of the Carnac Formation, as proposed in this Report, differs substantially from that of Devereux (1993). Below the Main Unconformity, Devereux identified (in descending order) a mostly sandy ‘X Shale’, a largely shaly ‘Intra-Carnac Sandstone’, a ‘Y Shale’, a mostly shaly ‘Lower Carnac Sandstone’, and a sandy–shaly ‘Lower Parmelia Sandstone’. The palynology report in Devereux (1993) does not support the original interpretation, and is in much better agreement with the subdivisions proposed here (Fig. 50).

Structure

Marri 1 is located on the eastern edge of the northern part of the Roe High. The high is a westerly dipping faulted homocline within the pre-breakup section that is draped by the post-breakup South Perth Shale (Fig. 51). The main objectives of the Marri truncation play were sandstones of the ‘Intra-Carnac’, ‘Lower Carnac’, and ‘Lower Parmelia Sandstone’ that were sealed vertically by intraformational shales and laterally by shales of the ‘X Shale’ unit, and juxtaposed against the Roe Fault along the eastern boundary of the high. The Gage Sandstone pinches out between the pre-breakup ‘X Shale’ and the conformably overlying South Perth Shale, and was a secondary stratigraphic objective. The play was expected to be similar to that described for the Gage Roads area. The Roe Fault was interpreted to have a throw of 750 m.

The well was engineered to build a maximum hole deviation of about 44° in an easterly direction, in order to drill parallel to the high side of the Roe Fault and intersect the primary objectives in an optimal structural position.

Hydrocarbons

Wireline log data, gas peaks, pressure–depth data, and a segregated sample taken during a repeat formation test (RFT) that contained gas, all indicate the presence of a small accumulation of dry gas below 2250.8 m in poor reservoir-quality sandstone. No DST was carried out.

Reservoir potential and seal

Within the pre-breakup section, sandstone porosities range from 18 to 21%. Lack of intraformational sealing potential is suggested by the log-derived water salinities, which are consistently between 20 000 and 25 000 ppm.

Reasons for failing to discover a hydrocarbon accumulation

Devereux (1993) suggested that the lack of significant quantities of hydrocarbons in Marri 1 was due to the lack of seal, the inability of the Roe Fault to provide a fault-plane seal, or the low porosity and permeability of the reservoirs. As the sealing potential of a fault plane is

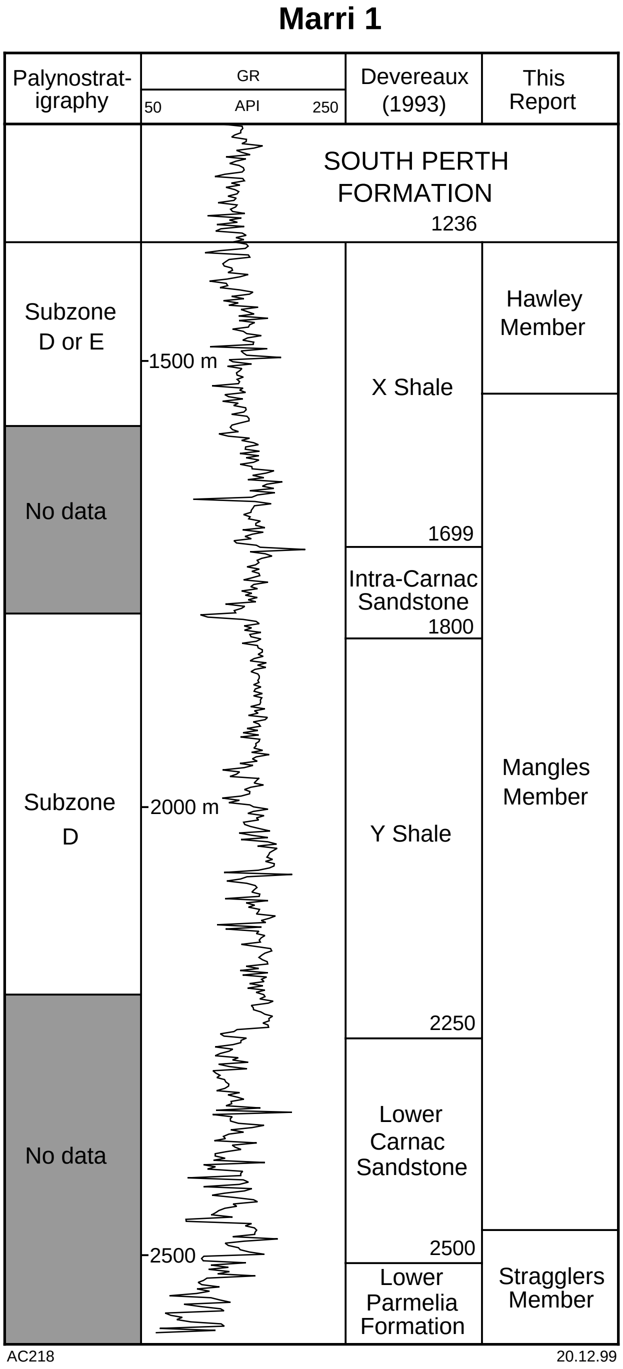

Figure 50. The Carnac Formation, Parmelia Group, in Marri 1

expected to be directly proportional to the sand to shale ratio of the abutting lithostratigraphic units, and the units in this well are predominantly sandstone, the Roe Fault has little sealing potential. Just as Gage Roads 1 showed that oil-bearing sandstone in the Parmelia Group may represent an effective reservoir, the lack of intra-formational seals in Marri 1 is accepted as the main reason for the failure of the well to discover hydrocarbons. The numerous faults intersected by the well are a further impediment to maintaining an effective seal. Devereux (1993) stated that these faults are below the resolution of the seismic data, but they would certainly be capable of juxtaposing discrete sandstone beds.

Minder Reef 1

Location

Minder Reef 1 was drilled on the Roe High in 1984 by Esso Australia, at a location 49 km northwest of Fremantle (Fig. 4).

Stratigraphy

No returns were obtained from the seabed (73 m) to a depth of 807 m, at which depth Minder Reef 1 was within the Leederville Formation. The underlying South Perth Shale is thin, and the clean porous sandstone bed at the base of the Warnbro Group, assigned to the *G. mutabilis* palynozone by Ingram (1991), is here assigned to the Gage Sandstone. The Main Unconformity was encountered at 866 m, below which the Hawley Member of the Carnac Formation is present to total depth at 1530 m.

Structure

Minder Reef 1 was located on the crest of a structure (Fig. 52) that was 'mapped with a reasonable degree of confidence' as being closed (Brooks, 1984a), within the northern extension of the Roe High on the western flank of the Rottnest Trough. The 'structural closure' corresponds to a palaeotopographic high, and strata of the Parmelia Group below the unconformity dip consistently to the west-northwest, thus forming a truncation play (Fig. 53). The seal was expected to be the horizontal South Perth Shale.

Hydrocarbons

No hydrocarbons were found.

Potential reservoirs

The sandstones of the Gage Sandstone have a log-derived average porosity of 22%. The porosity of sandstone in the Hawley Member of the Carnac Formation ranges from 12 to 25%.

Reasons for failing to discover a hydrocarbon accumulation

Brooks (1984a) attributed the failure of Minder Reef 1 to an inadequate seal. This opinion is confirmed by the presence of reservoir-quality sandstone of the horizontal Gage Sandstone immediately above the exploration objective.

Mullaloo 1

Location

Mullaloo 1 was drilled in the offshore Vlaming Sub-basin in 1984 by Esso Australia, at a location 35 km northwest of Fremantle (Fig. 4).

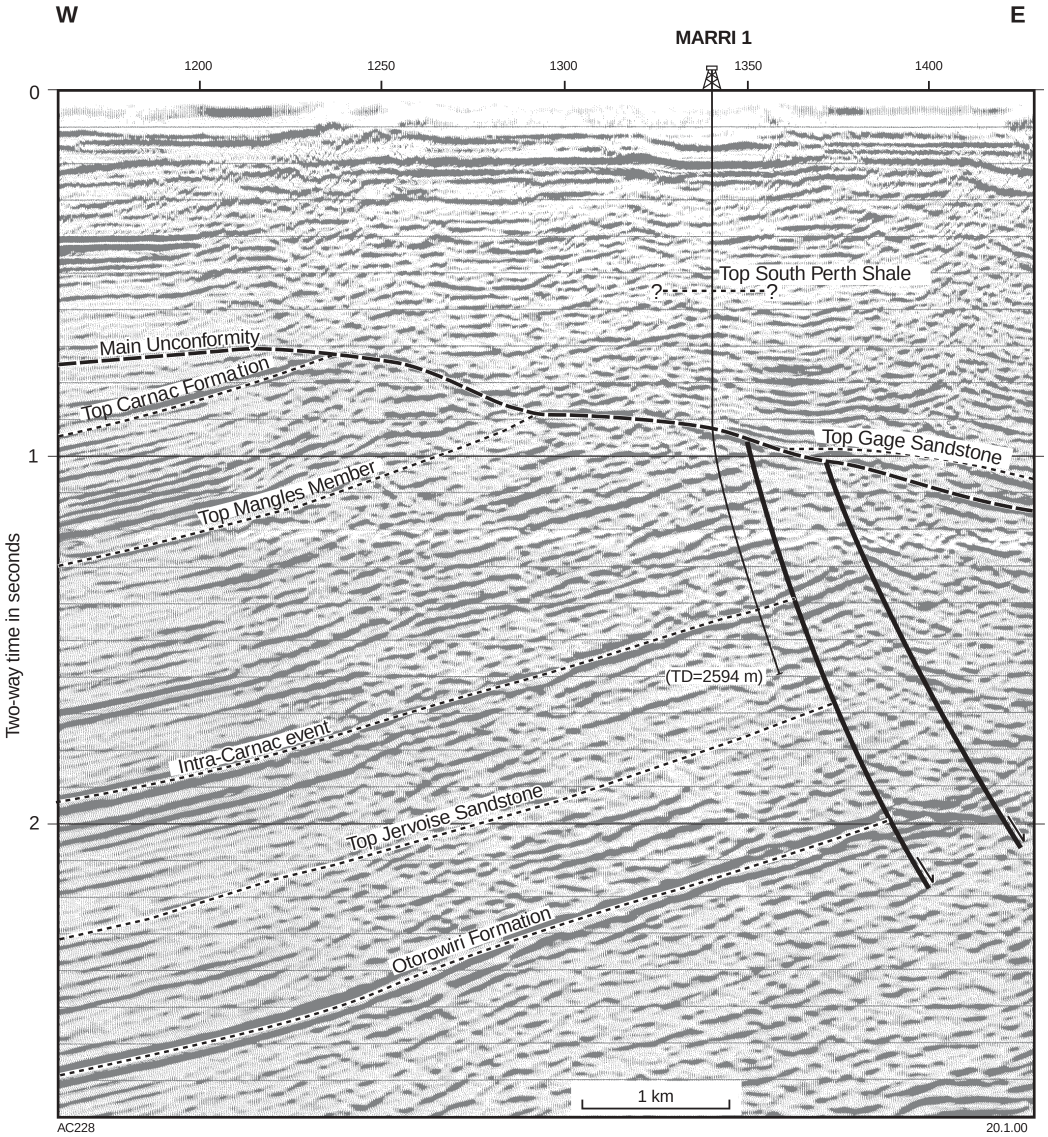

Figure 51. Seismic section V90A-161, showing the structural attitude of Marri 1

Stratigraphy

At total depth (2030 m), the well was within the Charlotte Sandstone. The shale section overlying the Gage Sandstone was included by Brooks (1984b) within the Gage Sandstone, but is here assigned to the South Perth Shale.

A palynological study by Ingram (1991) indicated that the Main Unconformity is between 1824.8 and 1888.5 m. No more precise definition is possible because no changes of lithology or structural attitude are indicated by the log or seismic data for this interval. In Mullaloo 1, little or no section appears to have been eroded from the top of the Parmelia Group, which is consistent with the well's position in the central part of the Rottnest Trough. The stratigraphy for the well has been revised in this Report (Plate 2; Fig. 10).

Structure

Mullaloo 1 tested a downthrown block interpreted to be part of a north-trending elongate dome that extends above the Main Unconformity (Fig. 54). The Gage Sandstone was expected to be sealed by the South Perth Shale, and additional seal would have been provided by faults.

Hydrocarbons

No indications of hydrocarbons were found.

Potential reservoirs

Log-derived porosities within the Gage and Charlotte Sandstones have a range of 14.7–19.7%.

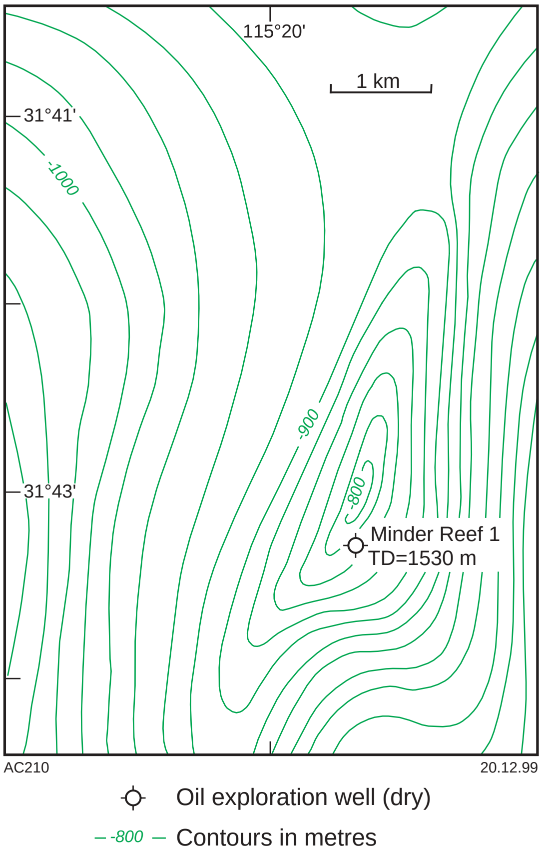

Figure 52. Time-structure map, at the level of the Neocomian unconformity, showing the Minder Reef palaeotopographic high (after Brooks, 1984a)

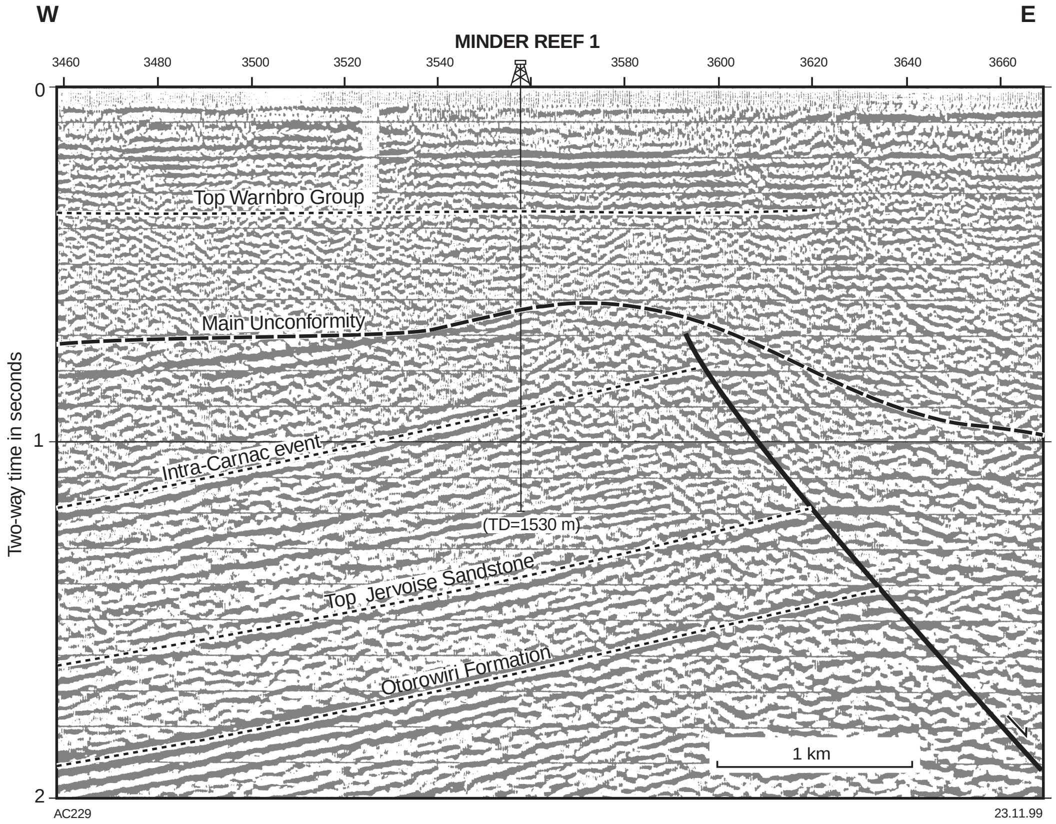

Figure 53. Seismic section V82A-23, showing the structural attitude of Minder Reef 1 (after Brooks, 1984a)

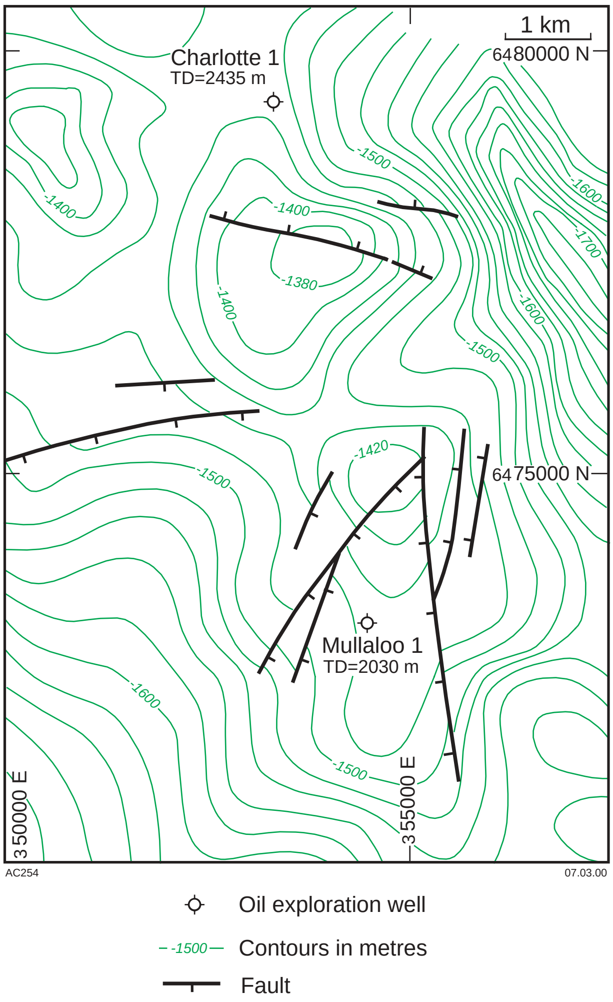

Figure 54. Pre-drill interpretation-structure map on the Top Gage Sandstone in the Mullaloo area (after Brooks, 1984b)

Reasons for failing to discover a hydrocarbon accumulation

Mullaloo 1 did not test a valid trap. A post-drill seismic reinterpretation shows that no closure exists at the Top Gage Sandstone level (Fig. 55).

Parmelia 1

Location

Parmelia 1 is situated offshore in the southwestern part of the Vlaming Sub-basin, at a location 70 km west-southwest of Fremantle (Fig. 4). It was drilled in 1981 by WAPET.

Stratigraphy

Parmelia 1 was terminated at 1770 m in the Mangles Member of the Carnac Formation. Dipmeter data indicate an angular unconformity at 1669 m (Crossing and Bundesen, 1983), but palynology (Crossing and Bundesen, 1983; Backhouse, 1978) constrains the Main Unconformity to a depth between 1517 and 1594 m. The Main Unconformity is here placed at 1593 m, at the base of a thick sandy interval.

Structure

Parmelia 1 was located, with the seismic control available at the time, on an interpreted four-way dip closure within the Parmelia High. Further seismic interpretation demonstrated that the well was located outside of any closure (Fig. 56). Below the Main Unconformity, Parmelia 1 penetrated a homocline dipping consistently at 30° to the north-northwest.

Potential reservoirs

Log-derived porosities for sandstone in the Mangles Member range from 14 to 21%.

Hydrocarbons

No significant hydrocarbon indications were encountered in the well.

Reasons for failing to discover a hydrocarbon accumulation

Parmelia 1 did not test a valid trap because no closed structure is present at this location. In addition, horizontal sandstone of the Leederville Formation directly overlies the Parmelia Group, which was the main objective. Therefore, no regional seal is present and no trapping potential exists in the area.

Peel 1

Location

Peel 1 was drilled in the Vlaming Sub-basin in 1977 by Phillips Australian Oil, at a location 39 km southwest of Fremantle (Fig. 4).

Stratigraphy

The well was terminated at 3714 m in the Yarragadee Formation (Phillips Australian Oil Company, 1978). The Main Unconformity, overlying the Charlotte Sandstone, was encountered at 1625 m, but a normal fault (or a set of normal faults) was intersected between 2600 and 2800 m. This fault has more than 1000 m of throw, and cuts out a substantial part of the Carnac Formation (Plate 2; Fig. 57). The part of the section below 2800 m can reliably be assigned to discrete lithostratigraphic units within the Parmelia Group because of the presence of the characteristic Otorowiri Formation at 3505 m.

Structure

Peel 1 was drilled to test an interpreted structural culmination to the west of the Rottnest Trough. The structure was poorly defined at the level of the Otorowiri

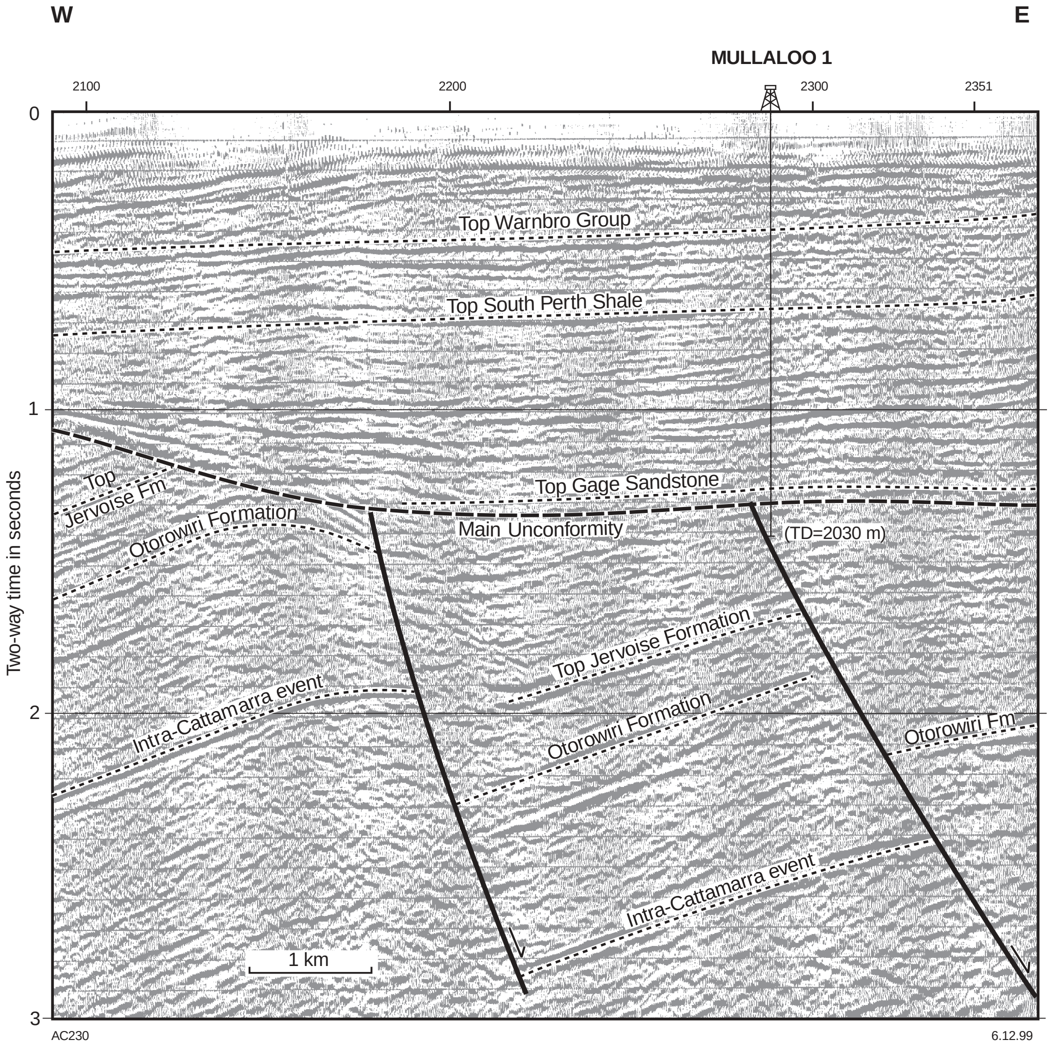

Figure 55. Seismic section HV85A-7, showing the structural attitude of Mullaloo 1

Formation (Fig. 58), within the highly faulted Peel Trend (Fig. 24). A revised structural-stratigraphic interpretation is presented in Figure 57.

Hydrocarbons

No hydrocarbon indications were encountered in the well.

Potential reservoirs

Beneath the Main Unconformity, the sandstones of the Parmelia Formation have log-derived porosities of 10 to 20%.

Reasons for failing to discover a hydrocarbon accumulation

No intraformational seal is present above the fault zone, nor is there any closure above the Main Unconformity throughout the Vlaming Sub-basin. Therefore, no valid trap exists at the level of the undeformed (subhorizontal) South Perth Shale that directly overlies massive sand-

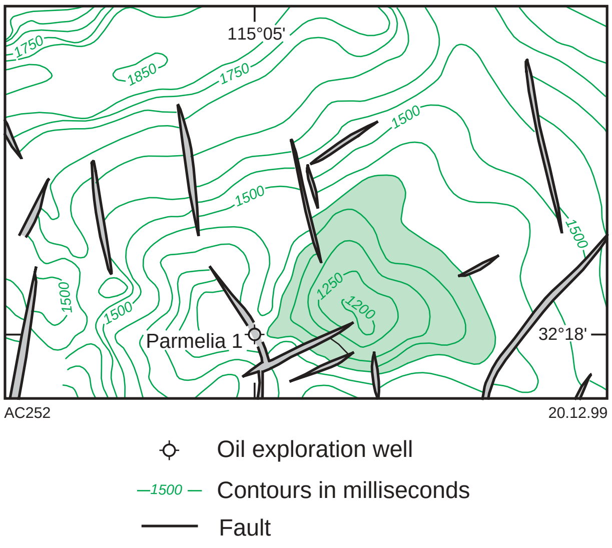

Figure 56. Structure map on a pre-Main Unconformity intra-Neocomian horizon of the Parmelia area (after Petrofina Exploration Australia S.A., 1993)

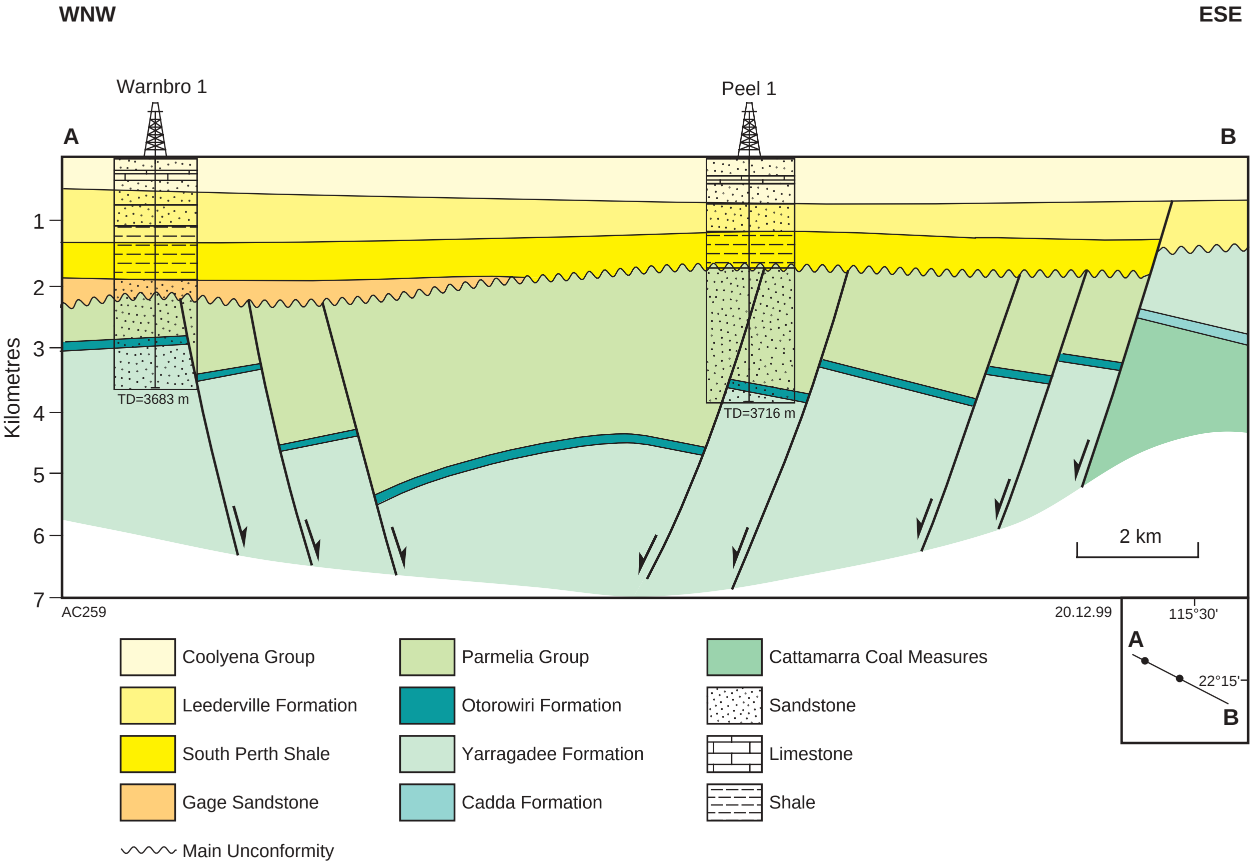

Figure 57. Section across the Rottnest Trough, showing the structural position of Peel 1 and Warnbro 1

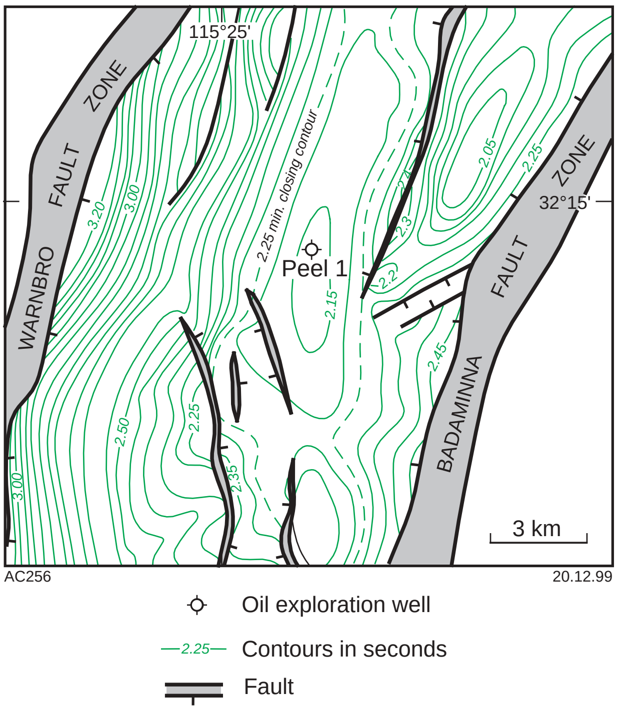

Figure 58. Time-structure map on the Top Otorowiri Formation of the Peel 1 area (after Phillips Australian Oil Company, 1978)

stones. In addition, the postulated play is invalid below the fault zone (Fig. 57).

Pinjarra 1

Location

Pinjarra 1 was drilled by WAPET in 1965, within the onshore part of the Mandurah Terrace, at a location 80 km south of Perth and 10.5 km west of Pinjarra (Fig. 4).

Stratigraphy

The Main Unconformity was intersected at 149 m, and drilling was terminated at 4572 m in the Lesueur Sandstone. A palynological review confirms that the lowest samples from the well are of Triassic age and that probably only the Middle – Late Triassic is represented.

Structure

According to Jones and Nicholls (1966), Pinjarra 1 was drilled on the northern segment of a north-plunging anticlinal nose, with the critical southern closure poorly defined and relying only on faulting (Fig. 59). The main aim of the well was to obtain stratigraphic information in an area lacking subsurface geological control.

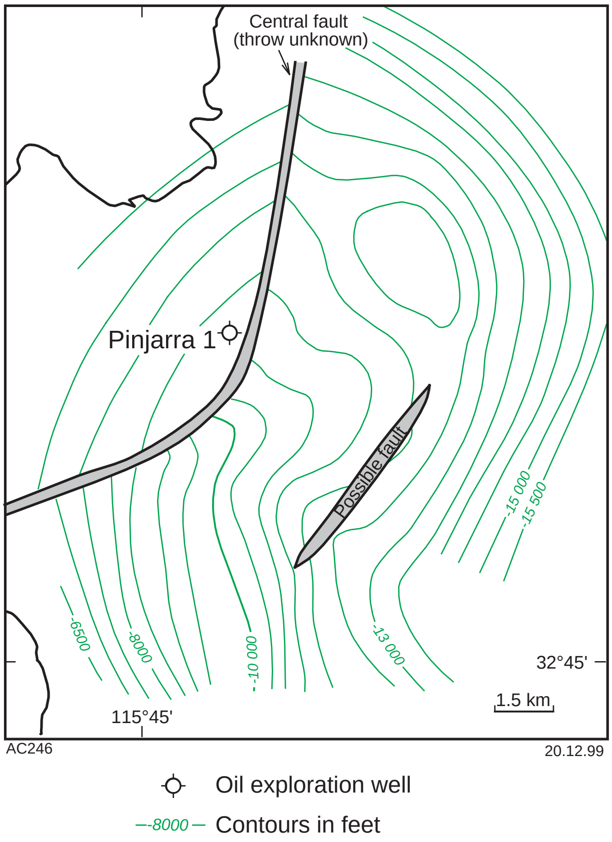

Figure 59. Configuration of the Pinjarra structure, on a phantom horizon (after Jones and Nicholls, 1966)

Hydrocarbons

No oil or gas shows were recognized in Pinjarra 1.

Reasons for failing to discover a hydrocarbon accumulation

Pinjarra 1 did not test a valid trap. Furthermore, the main regional Permian objective was not reached.

Preston 1

Location

Preston 1 was drilled in 1966 by WAPET, at a location 44 km north of Bunbury. It was drilled in the onshore part of the Harvey Ridge between the Bunbury Trough and Mandurah Terrace, in the onshore central Perth Basin (Fig. 4).

Stratigraphy

Preston 1, which was terminated at 765 m, encountered a similar stratigraphic succession to that found in the upper part of Lake Preston 1.

Structure

Preston 1 was a stratigraphic test that was drilled with no structural constraints (Lehmann, 1966).

Hydrocarbons

No hydrocarbon shows were encountered during drilling.

Quinns Rock 1

Location

Quinns Rock 1 was drilled in 1968 by WAPET. It was located 35 km north-northwest of Fremantle, in the Vlaming Sub-basin (Fig. 4).

Stratigraphy

Drilling was terminated at 2210 m within the Yarragadee Formation. The Main Unconformity was penetrated at approximately 794 m, at which depth a sand bed (correlated with the *P. lowryi* Zone) overlies the Stragglers Member of the Carnac Formation, indicating the presence of a large stratigraphic gap. The pre-Aptian stratigraphy of the well has been revised in this Report, utilizing logs and the palynological data of Ingram (1991).

Structure

The well was designed largely as a stratigraphic test, and was located on a poorly defined structural feature (Bozanic, 1969b).

Hydrocarbons

No hydrocarbon shows were encountered.

Reasons for failing to discover a hydrocarbon accumulation

Quinns Rock 1 did not test a valid trap.

Rockingham 1

Location

Rockingham 1 was drilled by Phoenix Oil and Gas in the onshore part of the Mandurah Terrace, at a location 20 km east of Rockingham (Fig. 4).

Stratigraphy

In Rockingham 1, the Leederville Formation was encountered at 65 m and the Main Unconformity at 287.5 m. Drilling was terminated at 1563 m, within the Cattamarra Coal Measures.

Structure

As mapped by Phoenix Oil and Gas, Rockingham 1 tested a feature bound to the west by an easterly dipping fault (Fig. 60) and controlled by a north–south rollover (Fig. 61).

Hydrocarbons

No hydrocarbon shows were observed throughout the interval drilled.

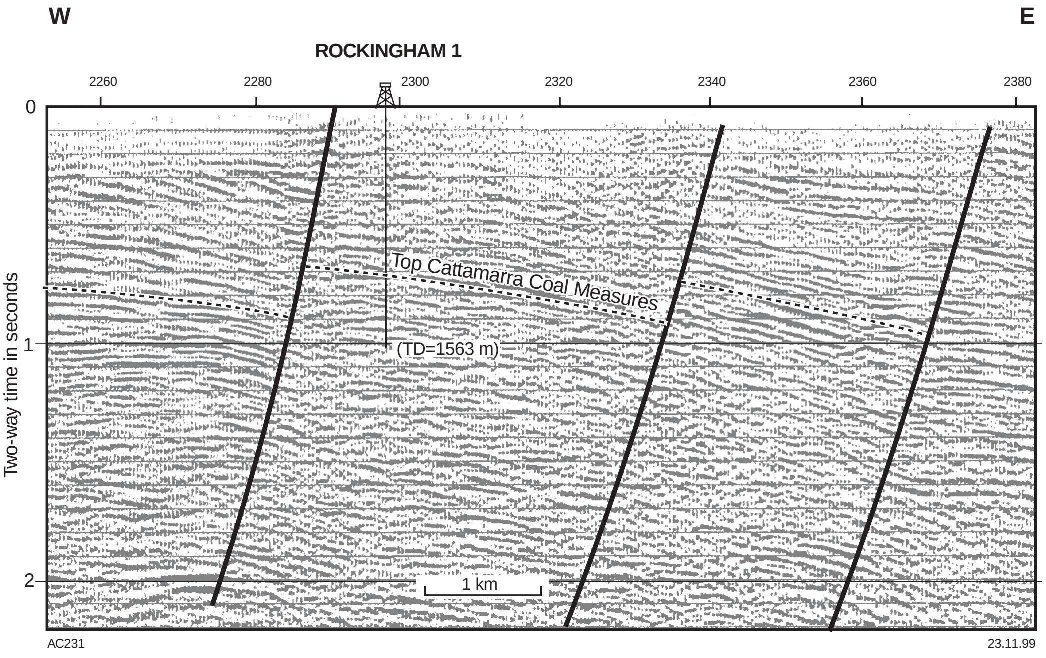

Figure 60. Seismic section M-P82-5, showing the fault block drilled by Rockingham 1

Reservoir potential and seal

A number of siltstone–shale intervals with good sealing potential were intersected within the Cattamarra Coal Measures, at a depth of 1028 to 1545 m. These shales overlie well-developed sandstones, with porosities ranging from 18 to 28%, that persist to total depth without any deterioration in reservoir quality. The sealing properties of the shaly intervals are confirmed by the marked change in water resistivity between discrete sand bodies (Marshall et al., 1983). As in Bullsbrook 1, the salinity of the formation water decreases with depth.

Reasons for failing to discover a hydrocarbon accumulation

The Rockingham prospect was critically dependent on the sealing potential of the fault controlling the closure to the east (Fig. 60). Rockingham 1 penetrated a section of the Cattamarra Coal Measures (the test objective) with a very high sand to shale ratio and relatively thin shaly intervals up to 35 m thick. It is conceivable that the drilled sandstones are juxtaposed against other sandstones along the fault plane, thus allowing migrating hydrocarbons to escape. It is believed that Rockingham 1 did not test a valid trap.

Roe 1

Location

Roe 1 is situated within the Vlaming Sub-basin, at a location approximately 32 km northwest of Fremantle (Fig. 4). It was drilled in 1970 by WAPET.

Stratigraphy

Roe 1 was terminated at 2134 m in the Mangles Member of the Carnac Formation. At 873 m, the Leederville Sandstone directly overlies the Hawley Member of the Carnac Formation (Fig. 47).

Structure

Roe 1 is located on the crest of the southernmost culmination of the Roe High, a major westerly tilted, fault-controlled homocline that has been upthrown from the Rottnest Trough (Fig. 46). The main exploration objectives were expected to be the post-breakup basal Gage Sandstone and pre-breakup sandstones within the Parmelia Group (Moyes, 1971c).

Hydrocarbons

No hydrocarbons were encountered.

Reservoir potential

At total depth, porosity is 10% and permeability ranges from 1 to 10 md.

Reasons for failing to discover a hydrocarbon accumulation

The shallower objective, the Gage Sandstone, is not present, and sandstone beds within the Carnac Formation lack a regional seal, which was expected to be the South Perth Shale.

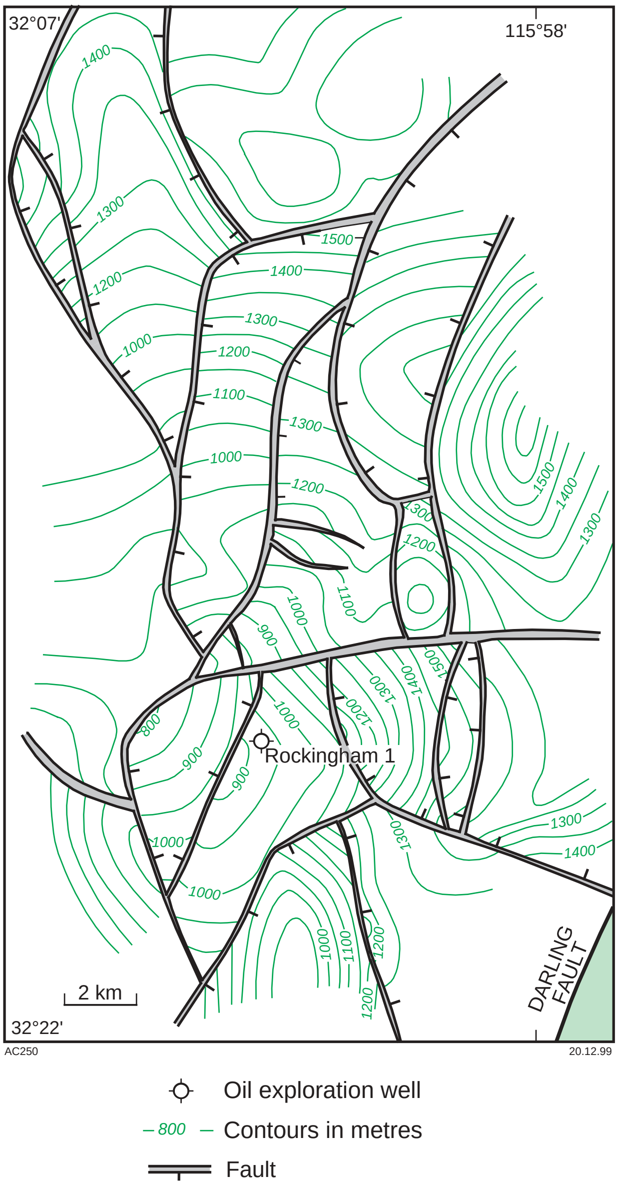

Figure 61. Time-structure map on the base of a shaly interval within the Cattamarra Coal Measures, showing the setting of Rockingham 1 (after Marshall et al., 1983)

Sabina River 1

Location

Sabina River 1 is situated within the Bunbury Trough, at a location 7 km east of Busselton (Fig. 4). It was drilled in 1982 by BP Petroleum Development Australia.

Stratigraphy

In Sabina River 1, the Main Unconformity was penetrated at 150 m, and total depth was reached at 4309 m within the Willespie Formation. The tops for the Cattamarra Coal Measures and Lesueur Sandstone have been revised in this Report.

Structure

Sabina River 1 was located in what was interpreted as a 'moderately large, southwesterly tilted fault block' (Nosiara and Hogg, 1982). Recent interpretations (Figs 23 and 62), however, indicate that the structure does not have a documented closure to the north, and relies entirely on fault seal to the east and northeast.

Hydrocarbons

Gas indications and some fluorescence were encountered within the Willespie Formation, initially at 3961 m and with increasing frequency with depth. Logs indicate a hydrocarbon saturation ranging from 15 to 30% throughout the interval of 4050 m to total depth. Log-derived hydrocarbon saturation reached 50% in two 1 m-thick sandstones at 4147 and 4234.5 m.

Reservoir potential and seals

Within the Permian Willespie Formation, which was the well's exploration objective, sandstones have porosities ranging from 9.5 to 16%, with an average of 12%. The presence of a regional seal is indicated by the resistivities of the formation waters. The resistivities grade from 0.08 to 0.14 ohms/m in the interval between the surface and 3915 m, are 0.17 – 0.22 ohms/m between 3915 and 4050 m, and then increase to 0.38 – 0.55 ohms/m from 4050 m to total depth.

Reasons for failing to discover a hydrocarbon accumulation

The well probably did not test a trap of economic significance. Small stratigraphic or fault-controlled traps

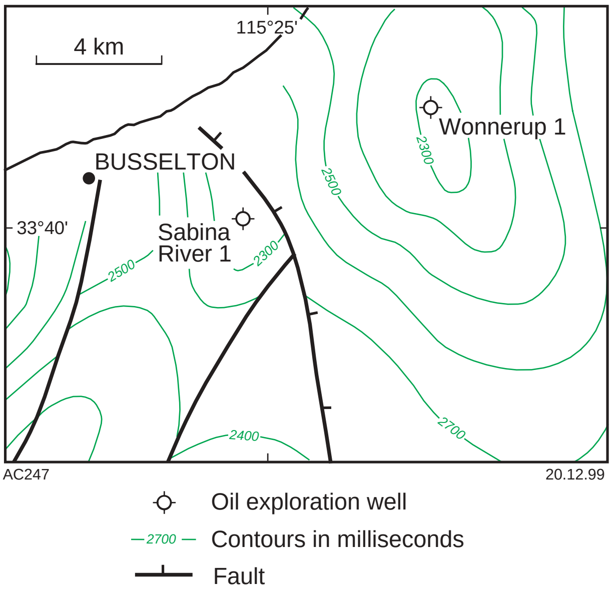

Figure 62. Structure map near the Top Williespie Formation, Sue Group, showing the configuration of the Sabina River 1 and Wonnerup 1 area. Many additional faults are not included due to poor quality data (after Discovery Petroleum NL, 1992b)

may, however, be present, and deepening the well may provide a more exhaustive test.

Scott River 1

Location

Scott River 1 is situated in the Bunbury Trough, at a location 68 km south of Busselton (Fig. 4). It was drilled in 1995 by Amity Oil.

Stratigraphy

In Scott River 1, a predominantly sandy unit, here referred to as the Cattamarra Coal Measures, was encountered below surficial Quaternary rocks. The well was terminated at 2370 m, in the Willespie Formation.

Structure

Scott River 1 tested a large faulted anticlinal closure that is defined at the near Top Permian (Willespie Formation) horizon (Fig. 36), and is present on the downthrown side of the Busselton Fault. As mapped by Amity Oil, the structural closure of the crestal part of the structure was not fault-dependent. Parallel bedding and a flower structure (Fig. 63) indicate that the anticline was formed as a result of strike-slip movements in the early Neocomian, after the deposition of Jurassic rocks that are present throughout the area.

Hydrocarbons

Significant gas shows of more than 0.6% methane were recorded from several sandstone intervals, with a total thickness of 116 m, within the Willespie Formation (Irwin and Paton, 1995). Wireline log analyses indicate gas saturation was up to 30% directly beneath the intraformational shales. A significant kick of 2.2% methane was detected at 2087 m. However, DST 1 over the interval 2075–2100 m (kelly bushing) recovered only 500 L of drilling fluids and 3000 L of saltwater. The gas indications are probably related to hydrocarbons migrating from either a deeper accumulation or source rocks that are still generating gas.

Potential reservoirs and seals

Measured porosities in several zones within the Willespie Formation range from 15 to 24%. The only seals present are intraformational, and the numerous shale and coal beds are generally less than 2 m thick, with only the occasional bed up to 5–7 m thick.

Reasons for failing to discover a hydrocarbon accumulation

The Scott River Anticline is thought to be intersected by a large number of faults. Although these faults are generally minor, and therefore cannot be detected seismically, a 10–20 m throw is more than sufficient to breach the thin seals that are present. It is therefore believed that no valid structural traps were tested by Scott River 1. The possibility of deeper traps, perhaps controlled by permeability barriers, cannot be discounted.

Sue 1

Location

Sue 1 is situated on the Vasse Shelf, at a location 32 km east of Margaret River (the nearest town) and 40 km south of Busselton (Fig. 4). It was drilled in 1966 by WAPET.

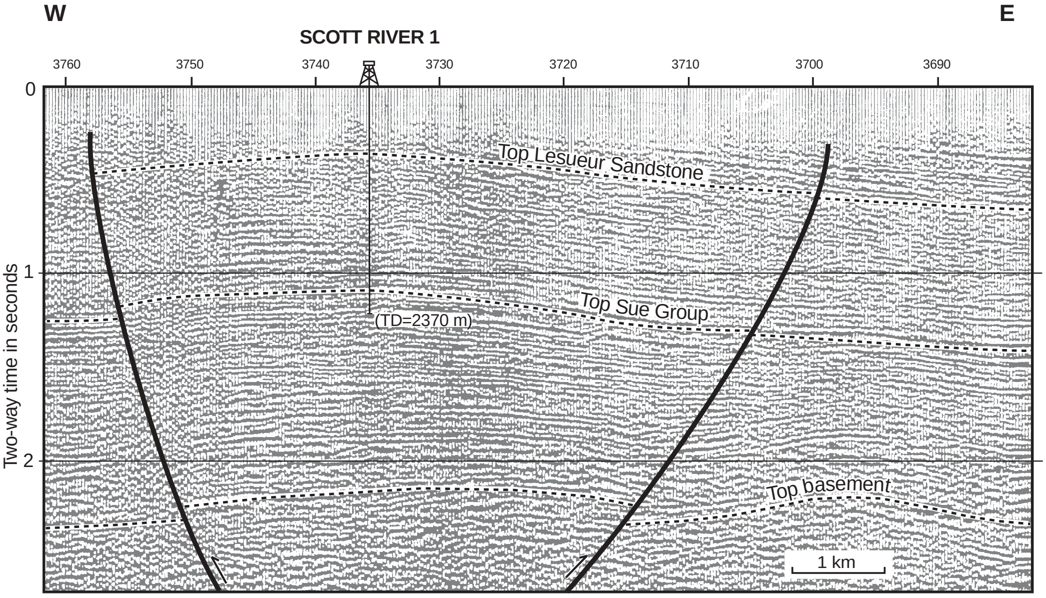

Figure 63. Seismic section WF69-CC, showing the structural setting of Scott River 1 (after Paton, 1994)

Stratigraphy

Sue 1 is the only oil exploration well in the study area that penetrated a complete Permian section and reached Precambrian basement. The Warnbro Group, which is the surface unit, unconformably overlies the Triassic Lesueur Sandstone at a depth of 169 m. Two members, namely the Wonnerup and Myalup Members, have been tentatively differentiated in the Lesueur Sandstone. The Triassic Sabina Sandstone and Permian Sue Group were encountered at 1137 and 1216 m respectively (Williams and Nicholls, 1966). A doleritic sill was present in the Rosabrook Coal Measures between 2862 and 2869 m. The sill is considered to be an intrusive phase of the Lower Cretaceous Bunbury Basalt. Below the Sue Group, the Permian Mosswood Formation was penetrated above the Precambrian basement in which the well was terminated at 3078 m. The Permian section between 1216 and 3003 m is the interval for the type section of the superseded Sue Coal Measures (Backhouse, 1993), and represents the only known virtually complete section of the Sue Group. On the basis of the detailed study by Le Blanc Smith and Kristensen (1998) that examined the Permian strata of the Vasse River Coalfield, the Sue Group penetrated by Sue 1 has been subdivided into five formations, and correlated with formations from the northern Perth Basin (Fig. 11).

Structure

Sue 1 was reportedly located near the crest of a seismically defined anticline, although WAPET defined the well as a ‘deep stratigraphic test’. The dipmeter readings indicate very low dips ranging from 0° to 2°. According to Irwin and Paton (1995), remapping indicated that Sue 1 did not test a valid structure (Fig. 36).

Hydrocarbons

In Sue 1, only minor shows of methane were recorded while drilling the carbonaceous sections of the Sue Group. The presence of ethane was registered in a low-porosity impermeable sandstone immediately below the dolerite sill in the Rosabrook Coal Measures.

Potential reservoirs

Core-derived porosities (Williams and Nicholls, 1966, appendix 2) for sandstones of the Sue Group decrease gradually from 33.6% at the top of the unit to an average of 10% in its lower part. Permeabilities vary greatly, with values of over 1000 md in the uppermost section that decrease to zero in the lowermost section (Figs 30 and 31).

Reasons for failing to discover a hydrocarbon accumulation

Sue 1 did not test a valid trap.

Sugarloaf 1

Location

Sugarloaf 1 was drilled in the southern part of the Vlaming Sub-basin in 1971 by WAPET, at a location 72 km northwest of Bunbury.

Stratigraphy

Drilling was terminated at 3660 m in the Yarragadee Formation. The Main Unconformity was tentatively selected at 710 m by Bird and Moyes (1971), and has been revised here to 875 m.

Structure

Sugarloaf 1 is located on a four-way dip anticline that has resulted from northerly trending sinistral strike-slip movements. The structure is one of a series of anticlines that constitute a north-plunging positive trend, and can be followed in a north-northwesterly direction to Bouvard 1 (Figs 37 and 64). This positive trend is separated from the Roe High by the Harvey Transfer.

Hydrocarbons

No significant hydrocarbon shows were encountered in Sugarloaf 1.

Reasons for failing to discover a hydrocarbon accumulation

No structural closure is shown at the level of the Main Unconformity (Iasky, 1993; Fig. 25), which is directly overlain by the sandy Leederville Formation. Furthermore, no reliable seal is present throughout the faulted porous and permeable pre-Main Unconformity section, in which the thickest shale interval is the 22 m-thick Otorowiri Formation. It is concluded, therefore, that Sugarloaf 1 did not test a valid trap.

Warnbro 1

Location

Warnbro 1 is situated offshore in the Vlaming Sub-basin, at a location 23 km southwest of Fremantle (Fig. 4). It was drilled in 1970–71 by WAPET.

Stratigraphy

The Main Unconformity was encountered at 2204 m, and total depth of 3660 m was reached in the Yarragadee Formation.

Structure

Warnbro 1 was planned in order to test a topographic anomaly on the southern part of the Roe High. The anomaly was interpreted as a major unfaulted anticline (Moyes, 1971d). Post-drilling reviews, however, do not support the original interpretation (Figs 65 and 66).

Hydrocarbons

The only hydrocarbon shows encountered were traces of residual oil at 2932–2952 m in the Otorowiri Formation (Dedman, 1989).

Potential reservoirs

Core porosities for the Gage Sandstone range from 9.5 to 21.8%, and permeabilities range from 0 to 1340 md.

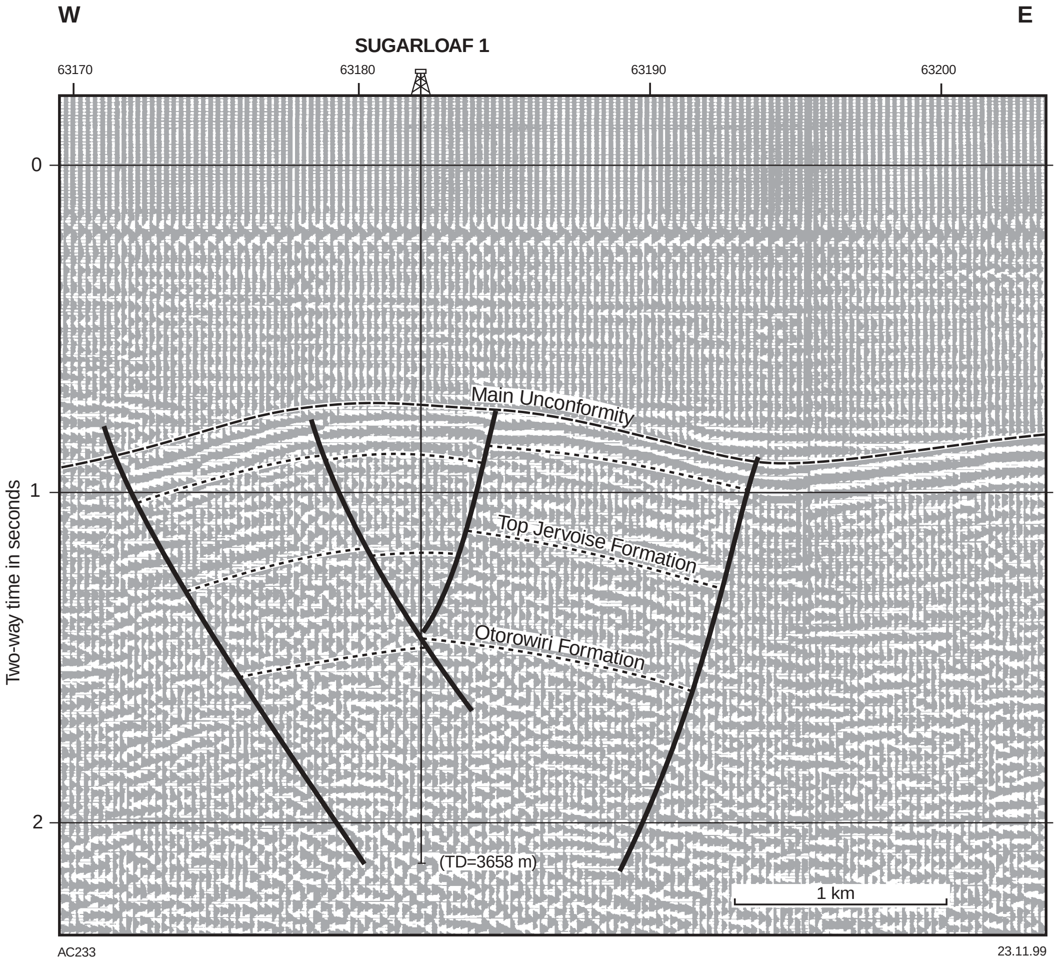

Figure 64. Seismic section S69-FM, showing the Sugarloaf structure

Within the Parmelia Group, core porosities vary from 15 to 21%, and permeabilities from 374 to 2031 md.

Reasons for failing to discover a hydrocarbon accumulation

No anticline is present at the Warnbro location. As unstructured sandstones of the Gage Sandstone overlie the Parmelia Group, which was the well objective, the potential truncation play is invalidated by the absence of a seal.

Whicher Range 1, 2, 3, and 4

Location

Whicher Range 1, 2, and 3 are situated 22 to 25 km south of Busselton (approximately 210 km south of Perth) in the Bunbury Trough (Fig. 4). The wells were drilled by Union Oil Development Corporation (Whicher Range 1), Mesa Australia (Whicher Range 2), and BP Petroleum Development Australia (Whicher Range 3) in 1968, 1980, and 1982 respectively. Basic information has been derived from the well completion reports by Union Oil Development Company (1968), Poynton and Hollams (1980), and Griffiths and Groombridge (1982) for Whicher Range 1, Whicher Range 2, and Whicher Range 3 respectively. Petrographic data have been provided by Stolper (1992).

A fourth well, Whicher Range 4, was drilled and tested in 1997–98 by a group led by Amity Oil. Their aim was to further evaluate the potential of the area where a gas volume of between 1 and 4 trillion cubic feet (28.3 and 113.3 billion cubic metres) was estimated to be present (Amity Oil NL, 1998). In 1997–98, the same group also carried out further testing in Whicher Range 1. Data on Whicher Range 4 and the re-entering of Whicher Range 1 are not yet on open file.

Stratigraphy

The shallowest non-superficial units in the Whicher Range wells consist of sandstone, siltstone, and lignite of the Warnbro Group. The Main Unconformity was encountered at 98 m in Whicher Range 1, at 108 m in Whicher Range 2, and was not identified in Whicher Range 3, but was below 185 m (Griffiths and Groombridge, 1982). In Whicher Range 2, four intervals of dolerite, totalling over 200 m in thickness, were penetrated in the Lesueur Sandstone, and one 10 m-thick

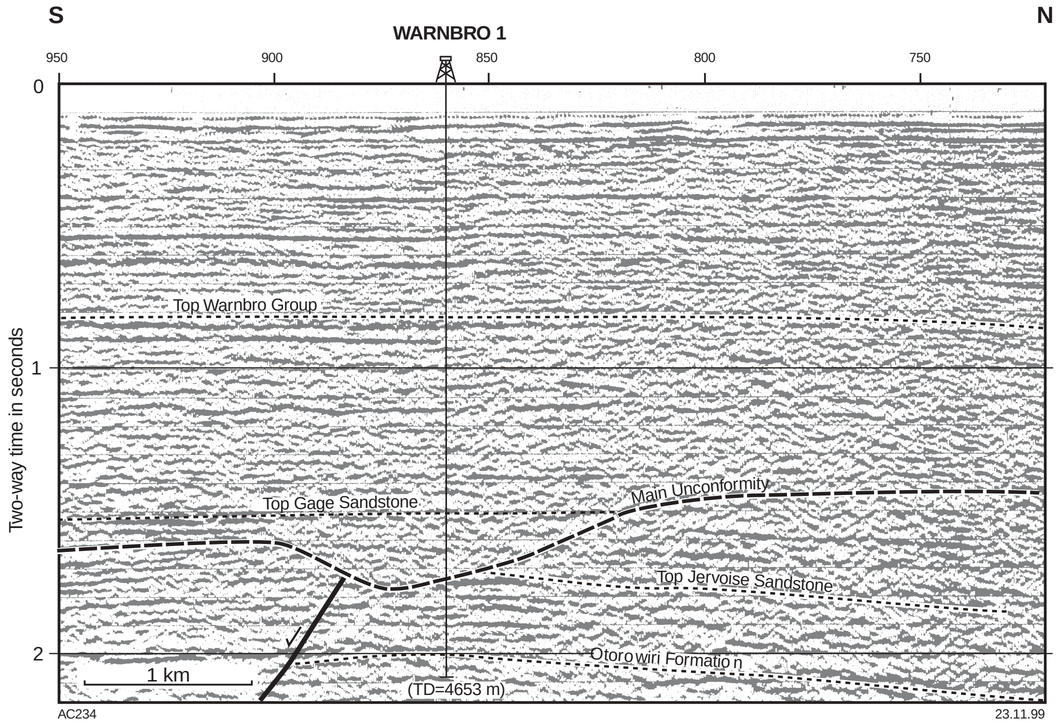

Figure 65. Seismic section ZPV91-31, showing the structural setting of Warnbro 1 (after Petrofina Exploration Australia S.A., 1992)

interval was encountered in the Yarragadee Formation. Total depth in the three wells was reached at 4653 m, 4330 m, and 4496 m respectively, in the Upper Permian Willespie Formation.

Structure

The Whicher Range wells were drilled within a large anticline (Figs 67 and 68) that was well defined by the 1967 (Sabina) and 1967–68 (Margaret River) seismic surveys. Based on these surveys, Poynton and Hollams (1980) calculated an areal closure of 400 km^2 at the top of the Sue Group, whereas Griffiths and Groombridge (1982) estimated 100 km^2 of closure. No faults were mapped over the structure. The areal closure mapped by Amity Oil NL (1998) was approximately 110 km^2 in size, and had a few faults intersecting it.

Hydrocarbons

Within the Sabina Sandstone, log interpretation indicates an absence of producible hydrocarbons in the few thin intervals that have some indications of gas, whereas the majority of the sandstones have 100% water saturation. The presence of methane (92%), with significant quantities of heavier hydrocarbons, was detected within the Whicher Range structure by the majority of DSTs and production tests carried out within the Willespie Formation. The best results were obtained from Whicher Range 1 DST 8 (Table 3), which produced up to 1.96 × 10^6 cubic feet (cf) or approximately 55.6 × 10^3 m^3 of gas per day through a ½" choke, although pressure declined immediately from 7200 to 900 pounds per square

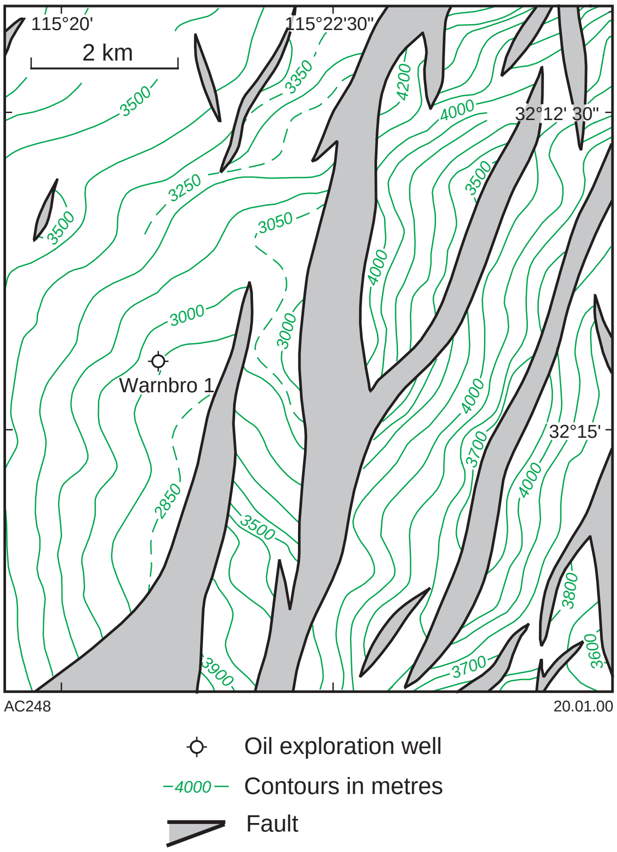

Figure 66. Depth-structure map of the Warnbro area, at the Otorowiri Formation level (after Petrofina Exploration Australia S.A., 1992)

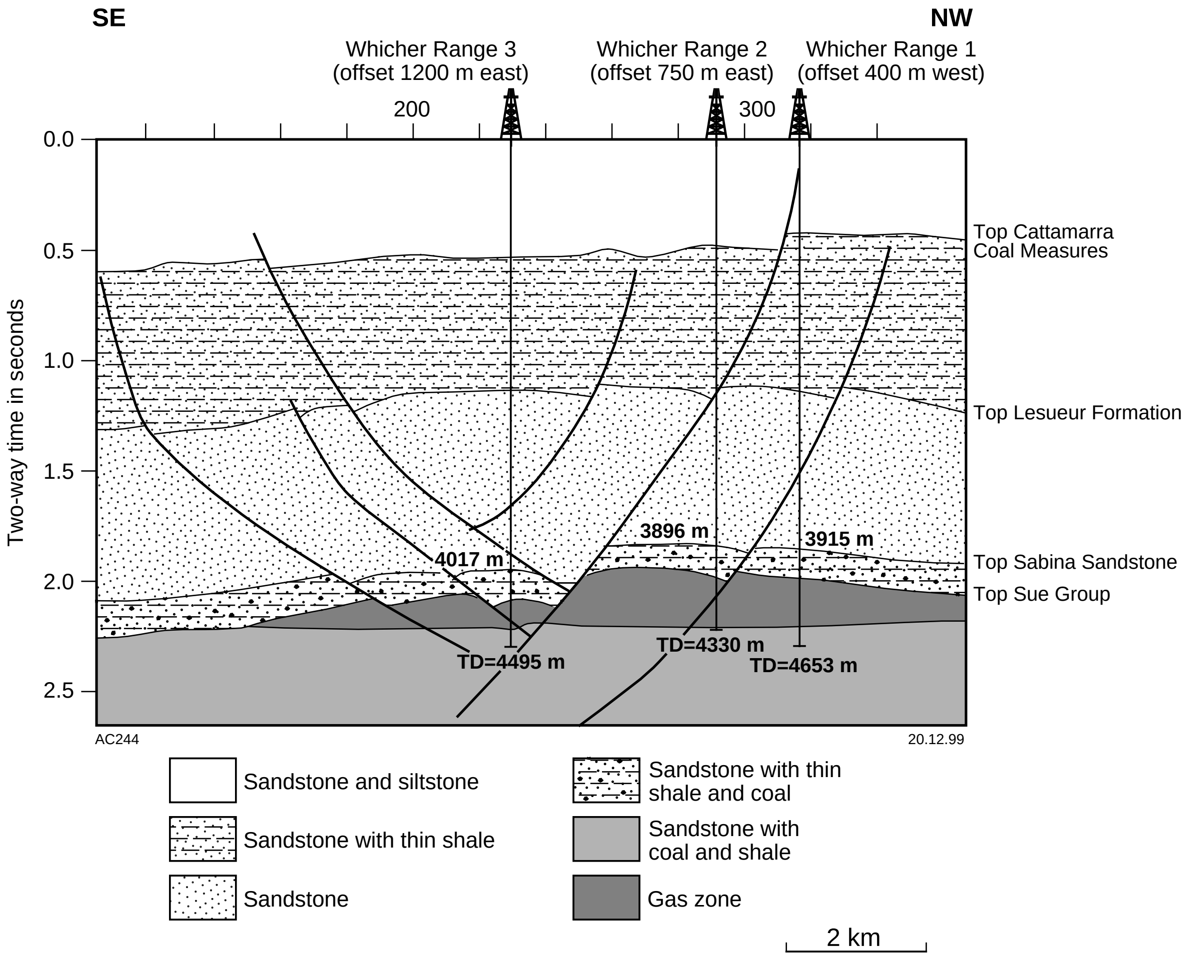

Figure 67. Diagrammatic cross section from seismic line SR80A-15, showing the attitude of the Whicher Range structure (after Petroleum Gazette, 1998)

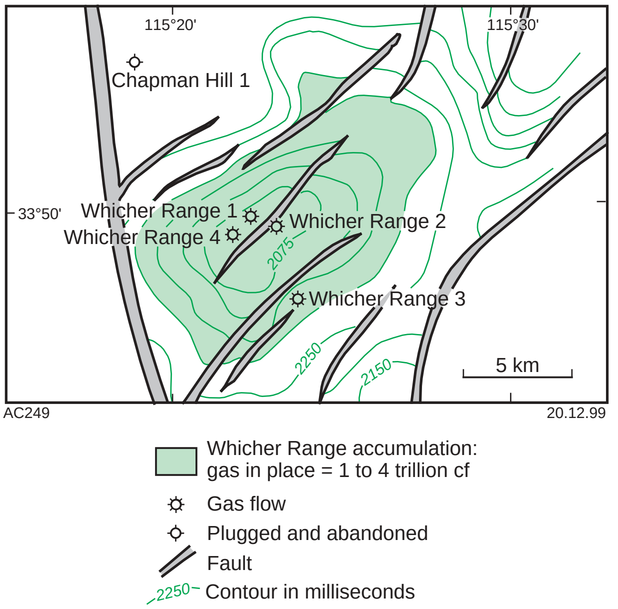

Figure 68. Configuration of the Whicher Range structure (after Amity Oil NL, 1998)

inch or 49 642 to 6205 kilopascals, even though the well was acidized and fractured. Two to four barrels of condensate were recovered from Whicher Range 1 DST 7. Although a gross flow rate of 5.82 × 10^6 cf (164 × 10^3 m^3) of gas per day was recorded in Whicher Range 1, a rapid decline of the flow rate was a feature of many of the successful tests.

A total of 11 production tests and six DSTs were carried out in Whicher Range 2 (Table 4), the reservoir characteristics of which are slightly worse than those in Whicher Range 1. Although some tests were performed after acidizing with 10 000 gallons of 15% HCl, they produced only minor amounts of gas. The best flow was 180 × 10^3 cf (5 × 10^3 m^3) of gas per day, which declined rapidly to zero. The six DSTs performed in the Whicher Range 3 reservoirs, which have similar porosity and clay content but lower permeability to those in Whicher Range 1, produced more modest results (Table 5). It was concluded that Whicher Range test flow rates were very low, especially when compared with log and core data.

Whicher Range 4 intersected 694 m of gas-bearing Willespie Formation sediments without encountering a

Table 3. Results from Whicher Range 1 drillstem tests

DST number		*Depth (m)*	*Formation*	*Recovery*
1A		3 968–3 950	Willespie Formation Sue Group	614×10^3 cf/d gas
2A		3 985–3 950	Willespie Formation Sue Group	550×10^3 cf/d gas
3B		4 025–4 004	Willespie Formation Sue Group	294×10^3 cf/d gas
4		4 059–4 056	Willespie Formation Sue Group	794×10^3 cf/d gas
5		4 169–4 164	Willespie Formation Sue Group	No measured flow
6	Test 1	4 169–4 164	Willespie Formation Sue Group	1.93×10^6 cf/d gas
	Test 2			1.50×10^6 cf/d gas
	Test 3			1.24×10^6 cf/d gas
	Test 4			1.21×10^6 cf/d gas
	Test 5			1.35×10^6 cf/d gas
7		4 205–4 200	Willespie Formation Sue Group	1.26×10^6 cf/d gas 2–4 bbls condensate
8	Test 1	4 273–4 164	Willespie Formation Sue Group	1.292×10^6 cf/d gas
	Test 2			1.242×10^6 cf/d gas
	Test 3			1.96×10^6 cf/d gas
	Test 4			1.86×10^6 cf/d gas
	Test 5			1.116×10^6 cf/d gas
	Test 6			1.098×10^6 cf/d gas
9		4 273–4 164	Willespie Formation Sue Group	11 stands water cushion 20 stands gas cut salty water 2 stands fracture beads
10		4 273–4 164	Willespie Formation Sue Group	11 stands water cushion 3 stands rat-hole mud 43 stands spent acid water

NOTES: cf/d: cubic feet/day
bbls: barrels

gas–water contact. Hydraulic fracture stimulation and testing of Whicher Range 1 and 4 produced stabilized gas flows from each well of about 1.4 MMcf/day (39 644 m^3) (Amity Oil NL, 1998). Although the gas flow rates were much lower than expected, it is possible that gas can be economically produced from the Whicher Range area using more effective reservoir-stimulation techniques.

Reservoirs and seals

In the Whicher Range area, hydrocarbons are present in sandstone beds in the Upper Permian Willespie Formation. The most porous sandstone is found in the coarser grained intervals at the base of individual upward-fining fluvial channels. Porosity and permeability measurements from Whicher Range 1 were carried out by Core Laboratories over the interval 3953.41 – 4211.745 m. Fifty-five samples from conventional cores and ten sidewall cores were measured. The porosities and permeabilities throughout the interval were found to be poor, although the average permeability in air is 8.7 md. Stolper (1992) stated that the effective porosity is 7–14% and the permeability 1–10 md, with a clay content of 2–11%. In Whicher Range 2, log-derived porosities in the lower portion of the Sabina Sandstone range from 10 to 15% on average, with some beds showing porosity as high as 20%. Core measurements confirm these data, with values ranging from 8.8 to 21.4%. In Whicher Range 2, log porosities for the Willespie Formation generally range from 4 to 9%, although a few beds reach 15%. Permeabilities are, in general, less than 1 md. Paton (1994) confirmed these values, although he reported a maximum permeability

Table 4. Summary of Whicher Range 2 production tests

Test	*Perforation interval (m)*	*Results*
1	4 281–4 287	No surface reaction
2	4 267–4 273	No surface reaction
3	4 231–4 237	No surface reaction
4	4 214–4 220	No surface reaction. Bled off to 1 000 psi through ¼" choke. No flow
5	4 188–4 194	No surface reaction. Bled off to 500 psi. No flow
6	4 168–4 174	No surface reaction. Pressured up to 6 900 psi, equivalent to 9 300 psi BHP. No leak off
7	4 129–4 135	No surface reaction. Bled off and achieved small gas flow. WHFP 75 psi. Shut in well. WHSP 75 psi
8	4 214–4 220	Reperforated Test 4 zone. Bled off to 400 psi on 3/8" choke. Bled off on 3/16" choke and attempted to flow well. WHFP 100 psi
9	4 051–4 045	Small gas flare on 3/16" choke. WHFP 30 psi
10	4 026–4 020	Approximate 5 000 cf/d on 3/16". WHFP 6 psi
11	4 009–4 015 3 951–3 957	Flowed well on 3/8" choke at 180 × 10^3 cf/d (145 psi WHFP) declining to zero

NOTES: Intervals tested are cumulative
Formation tested: Willespie Formation, Sue Group
BHP: Bottomhole pressure
WHFP: Wellhead flow pressure
WHSP: Wellhead shot-in pressure
cf/d: Cubic feet/day
psi: pounds/square inch

value of 6 md (Figs 30 and 31). In Whicher Range 3, core-derived porosities for the Willespie Formation range between 1 and 16.8%, whereas permeabilities are generally less than 1 md, with the exception of a 6 m-thick sandstone in which permeabilities ranging from 175 to 220 md were measured (core 6, 4415.4 – 4431.9 m). Test results indicate that there are no barriers to the vertical development of fractures into the Sabina Sandstone.

Intraformational siltstone, shale, and coaly beds overlie gas-bearing sandstone of the Upper Permian Willespie Formation. However, these seals are thin, seldom exceed 5 m in thickness, and may be breached by faults too small to be detected by seismic testing. No regional seal has been defined.

Source

The generation of gas is related to the presence of coal beds. Although the temperature gradient is low (19°C/km), substantial subsidence has allowed the vitrinite reflectance to reach a value of 1.01 near total depth (Iasky, 1993),

Table 5. Results from Whicher Range 3 drillstem tests

DST number	*Depth (m)*	*Formation*	*Recovery*	*Comments*
1	4 438–4 435 4 413–4 409	Willespie Formation Sue Group	200 b/d water	–
2	4 360–4 039	Willespie Formation Sue Group	10 × 10^3 cf/d gas 2 b/d water	Very selectively acidized
3	4 275–4 039	Willespie Formation Sue Group	5 × 10^3 cf/d gas 35 b/d water	–
4	4 275–4 039	Willespie Formation Sue Group	2 × 10^3 cf/d gas	Interval fractured
5	4 275–4 039	Willespie Formation Sue Group	1 × 10^3 cf/d gas 43 b/d water	Interval further fractured
6	4 275–4 235	Willespie Formation Sue Group	–	Mechanical failure

NOTES: Gas rates are very approximate
b/d: barrels/day
cf/d: cubic feet/day

which is sufficient for hydrocarbon generation. Furthermore, higher R_o values would be expected in the deeper parts of the Bunbury Trough (Fig. 23). Cook (1982) discussed the potential for oil generation by the coal and shaly coal beds in the Whicher Range wells. In particular, shaly coals are similar in chemical composition and mineral association to many accepted source rocks. In Whicher Range 3, the vitrinite reflectance is lower than in Whicher Range 1 and 2, and the interval 4030–4420 m lies within the principal zone of oil generation. Oil cuts and seeps from the coal seams are common, and their extent indicates significant oil generation. In addition, oil-related fluids have been able to migrate out of the numerous fractures within the coal.

Discussion

In places, sandstones in the Willespie Formation and the Sabina Sandstone show reservoir potential. However, in Whicher Range 1, 2, and 3 the best sandstones were considered to be water-bearing, with gas restricted to the poorer quality reservoirs. As the petrographic analyses indicate that the tested reservoirs should produce dry gas without stimulation (Stolper, 1992), rapid declines of the hydrocarbon flow during testing suggest the presence of limited accumulations. Although porosities are low, as would be expected at such depths, reservoirs with a porosity as low as 6% are generally considered to be capable of producing economic flows of gas.

No commercial accumulation of hydrocarbons has yet been proved to be present in Whicher Range. Amity Oil NL (1998) is confident that stimulation using a modified procedure to avoid fracture and formation damage would increase gas flows. Alternatively, it is possible that the gas is trapped either in reservoirs of limited extent and with seal integrity possibly compromised by faults, or within coal seams with high permeability fractures but a tight matrix. The evaluation of the economic potential of Whicher Range essentially depends on petroleum engineering studies. Deepening of the wells drilled in the structurally highest part of the anticline, especially Whicher Range 1, may disclose better trapping potential.

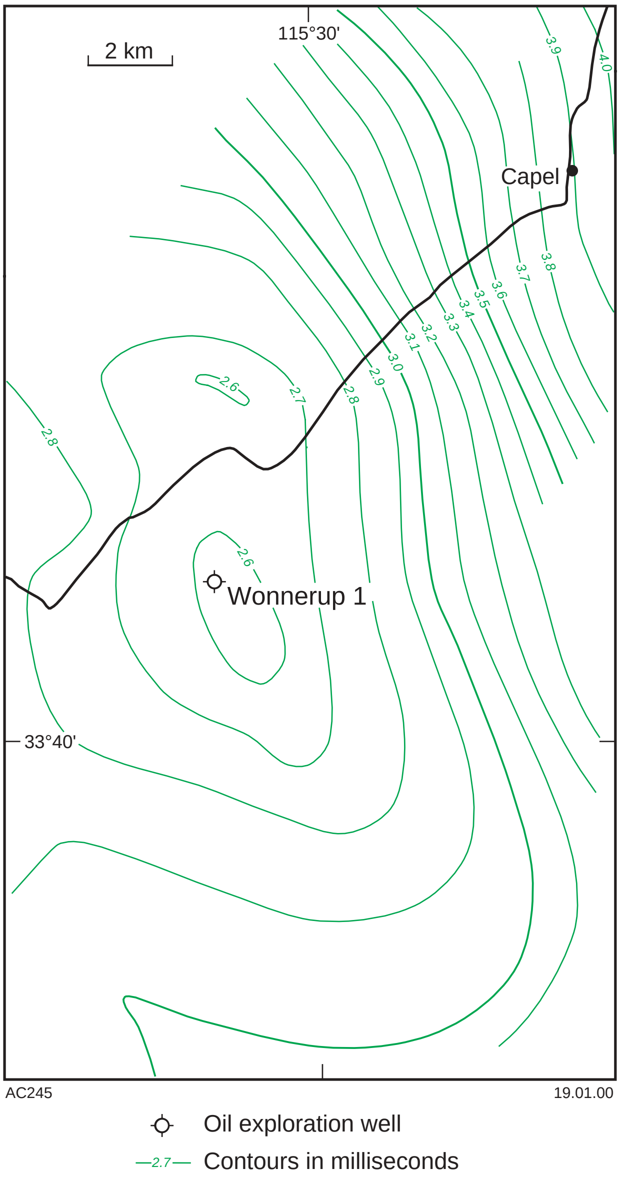

Figure 69. Structure map on an intra-Willespie Formation horizon of the Wonnerup structure (after Union Oil Development Corporation, 1972)

Wonnerup 1

Location

In 1972, Wonnerup 1 was drilled in the Bunbury Trough by Union Oil Development Corporation, at a location 12 km east of Busselton (Fig. 4).

Stratigraphy

The Warnbro Group was encountered at 17 m, beneath Quaternary continental sandstone, and the Main Unconformity at 341 m. Jurassic, Triassic, and Permian sections were penetrated below this level, and drilling was terminated at 4728 m in the Willespie Formation. Dolerite sills were intersected at 3248–3257 m in the Lesueur Sandstone, and at 4613–4626 m and 4675–4677 m in the Willespie Formation.

Structure

Wonnerup 1 was located on the crest of a large anticline with, as estimated at the time of drilling, an areal closure of 90 km^2 and a vertical relief of 550 m (Union Oil Development Corporation, 1972; Fig. 69). The structure is one of several anticlines associated with strike-slip movements present in the Bunbury Trough, and has been confirmed by recent interpretations (Fig. 62). Discovery Petroleum NL (1992b), however, noted that many additional faults could not be mapped due to poor quality data.

Hydrocarbons

Fair to good gas shows were encountered between 4279 m and total depth. Most of the gas was methane, but

Table 6. Porosity, permeability, and water saturation in selected Wonnerup 1 intervals

Depth (m)	*Porosity (%)*	*Permeability (md)*	*Water saturation (%)*
4 178.5	29.2	32	67.9
4 209.6	30.5	650	38.4
4 283.7	36.2	645	49.2
4 445.4	43.9	56	74.1

significant amounts of heavier fractions were recorded from some levels. The mud log indicates approximately 18 m of thin sands with records of gas.

Potential reservoirs

The Permian sandstones are generally tight, but numerous porous streaks are present, with some hydrocarbon saturation indicated by the wireline logs (Table 6). DST 1 and 1A (4322–4339 m) were mechanically unsuccessful (Table 7). Better porosities, ranging from 14 to 30%, are present in the shallower sandstones.

Discussion

The Wonnerup Anticline appears to be intersected by numerous faults, as is the general case in the Bunbury Trough. Although the faults cannot be recognized seismically, and therefore are of limited throw, they probably disrupt any thin Permian intraformational seals and breach the structure. Although Wonnerup 1 did not discover any hydrocarbons, the lack of a mechanically successful test prevents a definitive assessment.

Hydrocarbon potential

Reservoirs

Permian, Triassic, Jurassic, and early Neocomian (Early Cretaceous) rocks in the Perth Basin are all characterized by a high proportion of siliciclastic rocks with good reservoir potential. One of the major factors limiting the economic value of possible reservoirs in a faulted setting is the thickness and number of the discrete sandy intervals, because the presence of numerous sandy intervals is likely to decrease lateral seal across any fault, assuming a constant sand to shale ratio. Another major limiting factor is the depth of burial, because the porosity and permeability are inversely proportional to each other.

In the southern Perth Basin, the Permian section (especially the Upper Permian) has acceptable reservoir characteristics for gas, notwithstanding its depth of burial. Porosity and permeability data, as summarized in Figures 30 and 31 and discussed in the relevant well post-mortems, are based on a substantial number of core analyses. In the Bunbury Trough, the tight reservoirs that have been tested, without results of economic significance, appear to be minor and limited to thin beds. Other sandstone beds with better reservoir qualities have not been tested because they are water-bearing. The Triassic Sabina Sandstone and Lesueur Formation possess good reservoir potential because their dominant sandstone bodies retain significant porosities and permeabilities at depth.

In the Jurassic section, the Eneabba Formation contains sandstone beds with limited vertical and areal distribution, and poor reservoir potential. In contrast, the thickness of the sand bodies within the Cattamarra Coal Measures averages 15 m and may be up to 50 m. Porosity in these beds is good at shallow depths, but decreases with depth due to the development of illite (Tarabbia, 1991). In the Gingin area, however, porosities averaging 10% are still present at about 4000 m (Mesa Australia Limited, 1982) and would allow gas to be produced economically. In this area, the sand bodies are difficult to correlate because they lack continuity (Mesa Australia Limited, 1982; Fig. 38), although on a regional scale, sandstone beds below the major coal seams are more continuous.

The Yarragadee Formation is highly porous at shallow depth, where porosity may reach up to 40%. Even though porosity decreases with depth, sandstone beds in this unit should still be capable of producing gas to depths of at least 4000 m.

Two units within the Parmelia Group, the Jervoise and Charlotte Sandstones, exhibit excellent reservoir potential. In contrast, sandstones in the Carnac Formation appear to be thinner and lenticular, although occasionally they may be up to 25 m thick.

The Gage Sandstone at the base of the post-breakup Warnbro Group has good reservoir characteristics in the

Table 7. Results from Wonnerup 1 drillstem tests

DST number	*Depth (m)*	*Formation*	*Recovery*	*Comments*
1	4 322–4 339	Willespie Formation Sue Group	No recovery	Tool failed
1A	4 322–4 339	Willespie Formation Sue Group	No recovery	Tool failed

NOTES: Mud log indicates gas in thin sands totalling about 18 m; hole too badly caved to interpret water saturation confidently

Vlaming Sub-basin. In the Gage Roads area, porosities average 18%, with maximum values up to 30%.

Seals

In the sandstone-dominated Perth Basin, the lack of seals of regional extent represents the major risk for petroleum exploration. This has been discussed by Crostella (1995) for the northern Perth Basin, and is shown in Table 8 for the southern and central Perth Basin. In the northern Perth Basin, the main regional seal is the Lower Triassic Kockatea Shale, which reaches a maximum thickness of over 1100 m. This unit is the seal for the Dongara gas- and oilfield, which is the major hydrocarbon accumulation in the basin, as well as for the Mondarra, Yardarino, Beharra Springs, and Woodada – East Logue gasfields. The sealing potential of the Kockatea Shale is reduced north of latitude 29°30'S, where the unit is only a few hundred metres thick and interbedded sandstone members are present (Mory and Iasky, 1996).

The lithology of the Lower Triassic units in the central Perth Basin is unknown. Tenuous geophysical data from the central Perth Basin suggest that the Lower Triassic units are approximately 1000 m thick, which is consistent with the thickness of the Kockatea Shale in the northern Perth Basin. In the southern Perth Basin, the Kockatea Shale is absent, the lower Triassic is represented by the Sabina Sandstone, and no regional seal exists.

In the Jurassic section, a regional seal may be provided by the Lower Jurassic Eneabba Formation, where it is present, but the unit is predominantly sandstone and its potential as a seal needs to be confirmed. Above the Eneabba Formation, the mainly shaly Middle Jurassic Cadda Formation does not appear to provide a regional seal in wells in the faulted Gingin–Bullsbrook area.

Onshore, the Yarragadee Formation, which is largely sandstone, is virtually unconfined. Offshore, in the Vlaming Sub-basin, the Otorowiri and Carnac Formations may provide a seal for the underlying units, as suggested by the results from Gage Roads 1.

Table 8. Reasons for failing to discover an accumulation of hydrocarbons of economic significance in the petroleum wells of the central and southern Perth Basin

Well name	*Stratigraphic well*	*Lack of structural closure*	*Lack of seal*	*Hydrocarbon accumulation not yet assessed*
Alexandra Bridge 1	x	–	–	–
Araucaria 1	–	–	x	–
Badaminna 1	–	x	–	–
Barragoon 1	–	x	–	–
Blackwood 1	–	x	x	–
Bootine 1	–	–	x	–
Bouvard 1	–	–	x	–
Bullsbrook 1	–	–	–	x
Canebreak 1	–	–	x	–
Challenger 1	–	–	x	–
Chapman Hill 1	–	–	x	–
Charlotte 1	–	–	x	–
Cockburn 1	–	x	–	–
Gage Roads 1	–	–	–	x
Gage Roads 2	–	–	–	x
Gingin 1	–	–	x	–
Gingin 2	–	–	x	–
Lake Preston 1	–	–	x	–
Marri 1	–	–	x	–
Minder Reef 1	–	–	x	–
Mullaloo 1	–	x	–	–
Parmelia 1	–	x	x	–
Peel 1	–	x	x	–
Pinjarra 1	–	x	–	–
Preston 1	x	–	–	–
Quinns Rock 1	x	–	–	–
Rockingham 1	–	–	x	–
Roe 1	–	–	x	–
Sabina River 1	–	x	x	–
Scott River 1	–	–	x	–
Sue 1	x	–	–	–
Sugarloaf 1	–	–	x	–
Tuart 1	–	–	x	–
Warnbro 1	–	x	x	–
Whicher Range 1, 2, 3	–	–	x	–
Wonnerup 1	–	–	x	–

Thin intraformational seals are present within the Permian units, as shown by several northern Perth Basin hydrocarbon accumulations such as the Dongara Deep, Woodada, and Beharra Springs gasfields. Thin, intraformational shale intervals of the Lower Jurassic Cattamarra Coal Measures seal several oil-bearing horizons in the Mount Horner oilfield. To be effective, however, these intraformational seals appear to require virtually unfaulted structures or a fortuitous juxtaposition of the potential reservoir and the seal. As a result, the risk assessment for undrilled traps is high.

In the Vlaming Sub-basin, Gage Roads 2 demonstrated that shale beds in the Leederville Formation can provide an effective seal for stratigraphic traps in the Gage Sandstone.

Source rocks

Within the Perth Basin, hydrocarbons have been either produced or tested from several intervals (Table 9). Minor accumulations (Crostella, 1995) and shows (Mory and Iasky, 1996, appendix 3; this Report) have also been recorded in several unsuccessful petroleum wells. A few hydrogeological boreholes (Appendix 2) encountered minor hydrocarbon indications, for example Harvey Line 1B (gas), Binningup Line 1 (gas), and Quindalup Line 1 (oil). Therefore, there is evidence for the presence of hydrocarbons throughout the pre-breakup succession and in the basal part of the post-breakup succession.

The source rocks for the Permian gas occurrences in the southern Perth Basin are considered to be coal seams and carbonaceous shales of the Lower Permian Rosabrook and Redgate Coal Measures. These units also have some potential to generate oil. These coal seams and carbonaceous shales preserve significant volumes of terrigenous organic matter derived from plant debris. In comparison, in the northern Perth Basin the Lower Permian Carynginia Formation and Irwin River Coal Measures are the principal sources of methane (Summons et al., 1995). The source rock for both the Dongara and Mount Horner oil is the basal interval of the Lower Triassic Kockatea Shale, which may be present in the central Perth Basin. The gas and condensate present in the Gingin wells is believed to have migrated upwards from the basal Triassic units or the Permian coal measures. The lower geothermal gradient of the Beermullah Trough (Fig. 70) places the Triassic, and even the Permian, rocks still within the gas-generative zone, even though they may be at great depth. Summons et al. (1995) suggested that the Gingin gas was sourced from the Cattamarra Coal Measures, but their opinion may have been influenced by their postulated thickness of up to 10 000 m for the Jurassic rocks; a thickness that is not supported by our stratigraphic correlation (Plate 1; Fig. 9) or structural interpretation (Fig. 26). Furthermore, the temperature required to generate this gas had to be higher than that of the oil window, and the main gas-generation zone was not reached in any of the wells in this area (Fig. 71). In this context, similarities between Whicher Range 1, Walyering 1, and Gingin 1 condensates (Summons et al., 1995) support a common Permian, not Jurassic, origin because the Jurassic intervals in the wells in the Bunbury Trough are immature for oil generation (Fig. 72). According to Summons et al. (1995), the oil tested in the Gage Roads wells was sourced from the Upper Jurassic Yarragadee Formation or Lower Cretaceous Parmelia Group. However, in that area only the Yarragadee Formation is fully mature for hydrocarbon generation (Marshall et al., 1993). Therefore, it is evident that the principal source-rock intervals within the Perth Basin are the Permian Sue Group, the Lower Permian Irwin River Coal Measures and Carynginia Formation, the basal Triassic Kockatea Shale, the Lower – Middle Jurassic Cattamarra Coal Measures and, only offshore, the Middle – Upper Jurassic Yarragadee Formation.

The regional geothermal-gradient contour map (Fig. 70) shows that the onshore Perth Basin has dominantly low values, with a range of 20–25°C/km. Gradients increase northwards (Mory and Iasky, 1996, fig. 51) and to the west (Marshall et al., 1993, fig. 10). The low regional values are related to the high thermal

Table 9. Hydrocarbon-producing intervals within the Perth Basin

Stratigraphic unit	*Basin subdivisions*	*Hydrocarbon occurrence*	*Field or well*
Gage Sandstone	Vlaming Sub-basin	DST-oil	Gage Roads 2
Carnac Formation	Vlaming Sub-basin	DST-oil	Gage Roads 1
Cattamarra Coal Measures	Beermullah Trough	limited gas production	Gingin 1
Cattamarra Coal Measures	Allanooka High	oilfield	Mount Horner
Arranoo Member of Kockatea Shale	Allanooka High	oilfield (minor production)	Mount Horner
Arranoo Member of Kockatea Shale	Dongara Terrace	gas/oilfield	Dongara
Dongara Sandstone	Dongara Terrace	gas/oilfield	Dongara
Dongara Sandstone	Beharra Spring Terrace	gasfield	Yardarino
Dongara Sandstone	Beharra Spring Terrace	gasfield	Mondarra
Beekeeper Formation	Beharra Spring Terrace	gasfield	Beharra Spring
Beekeeper Formation	Cadda Terrace	gasfield	Woodada – East Lake Logue
Willespie Formation	Bunbury Trough	DST-gas	Whicher Range 1, 2, 3
Irwin River Coal Measures	Dongara Terrace	gas/oilfield	Dongara
Irwin River Coal Measures	Allanooka High	oilfield	Mount Horner

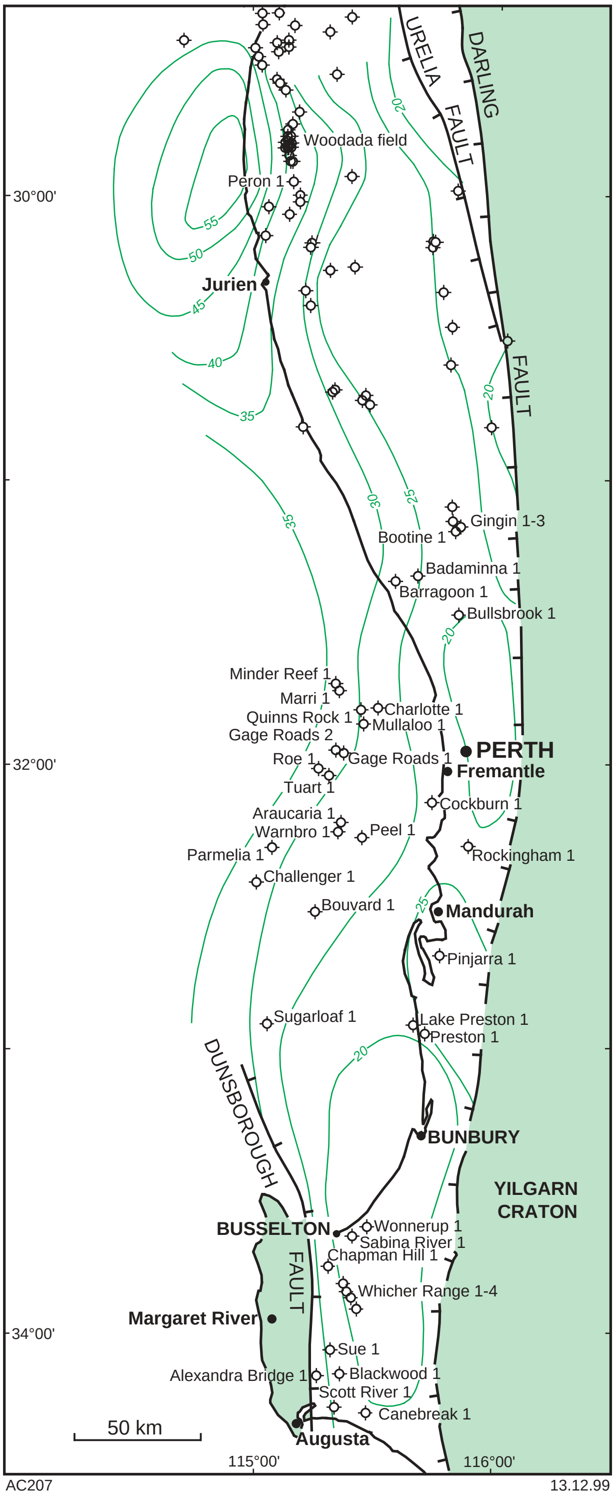

Figure 70. Geothermal-gradient (°C/km) contour map

conductivity of the thick coarse clastic rocks present in the Middle Triassic to Upper Jurassic units in the northern and central Perth Basin, and in the entire stratigraphic section in the southern part of the basin. In many parts of the Perth Basin, Triassic rocks have not been penetrated (Plate 1; Fig. 9), and geothermal gradients have been extrapolated from younger parts of the succession. If marine Lower Triassic shales extend southwards into the central part of the Perth Basin (Fig. 26), then the geothermal gradients for the lower part of the succession in this area are likely to be higher than shown in Figure 70.

The maturity map of the Top Permian section (Fig. 73), although poorly constrained, shows that the Permian and basal Triassic units are virtually mature for hydrocarbon generation over the entire Perth Basin, and are overmature only around Woolmulla 1 and Cadda 1. The maturity map of the Top Cattamarra Coal Measures (Fig. 74) shows that this unit is within the oil window over most of the onshore Perth Basin and the offshore Vlaming Sub-basin, excluding some areas in the northwest of the basin and in the Bunbury Trough.

Long-range migration of hydrocarbons is indicated by the Mount Horner oilfield, which is located in an area without mature source rocks.

Burial history and maturity calibration have been constructed for two key wells, Walyering 1 in the northern Perth Basin (Fig. 71) and Whicher Range 1 in the Bunbury Trough (Fig. 72), utilizing the BasinMod package of Plate River Associates. In Figures 71 and 72 it has been assumed that the vitrinite reflectance data from the Cattamarra Coal Measures in Walyering 1 are reduced by suppression or misreading, and that 2250 m of section have been eroded at the Main Unconformity in Walyering 1 and 750 m in Whicher Range 1. The results are consistent with others already published by Iasky (1993) and Mory and Iasky (1996), using a different program. The geological history of the two parts of the basin is strikingly similar, thus indicating a gradual increase in the depth of burial into the Early Cretaceous, as a result of basin rifting and infilling (Fig. 29). At the beginning of the Cretaceous, the uplift that resulted from the separation of Greater India from Australia commenced locally and continued into the mid-Neocomian. The geological history of the entire region, as documented in Figures 71 and 72, shows that source-rock maturity is essentially related to depth of burial.

Traps

Within the central and southern Perth Basin, several types of traps are present:

- anticlines
- fault-controlled traps
- subunconformity truncations
- palaeotopographic highs
- post-breakup pinch-outs
- permeability barriers

Anticlines

Compressional anticlines are common within the Bunbury Trough (Figs 23 and 67), the southernmost part of the Vlaming Sub-basin (Fig. 64), and the Beermullah Trough (Figs 6 and 8). Unfaulted anticlines provide highly reliable traps that require only thin seals and offer the potential

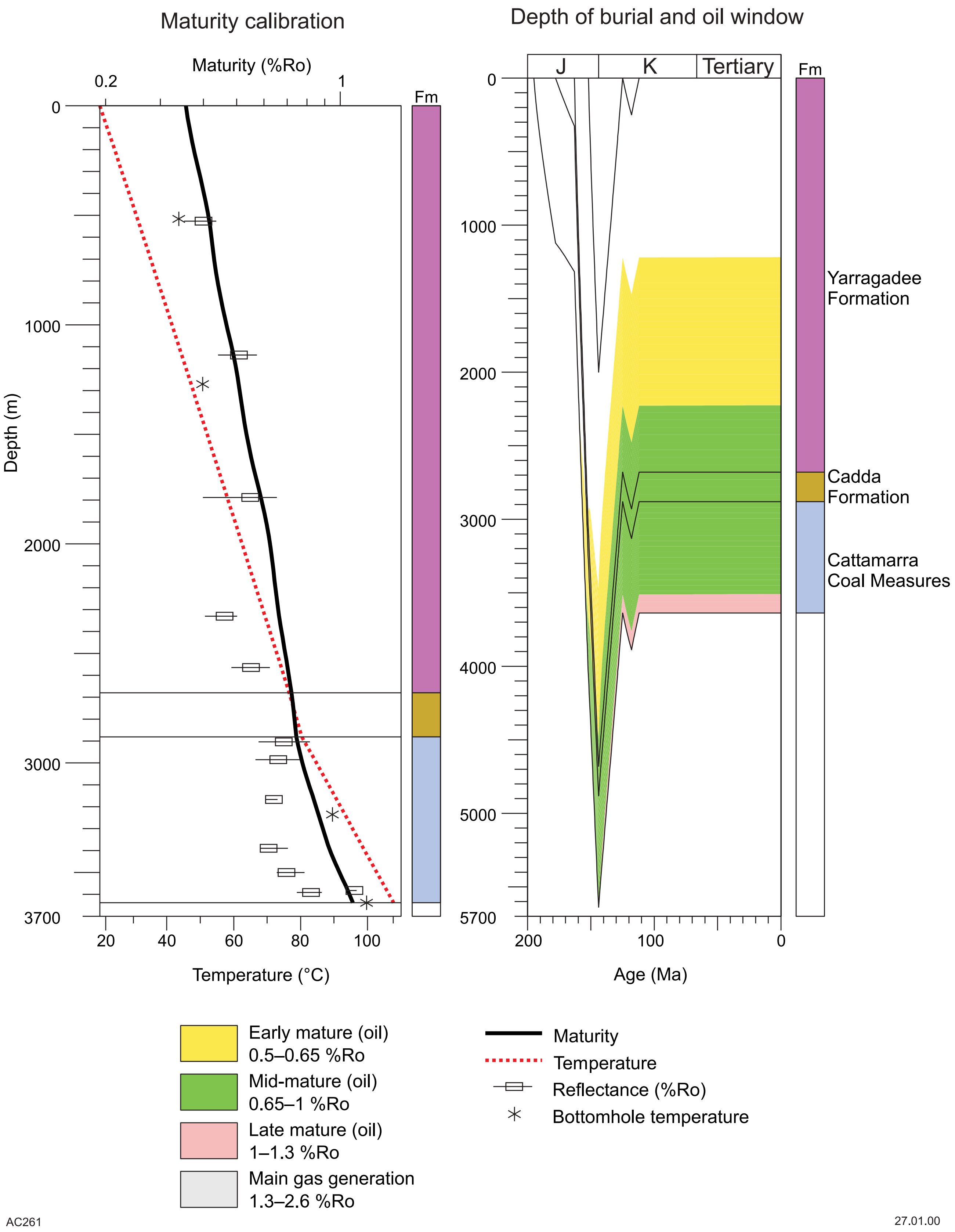

Figure 71. Depth of burial, maturity calibration, and oil window for Walyering 1

for several pools within the same structure (Fig. 75a). Faulted anticlines, however, are reliable only when thick regional seals cover the potential reservoirs, because thin seals, when faulted, readily allow sandstones to be juxtaposed against other sandstones, especially where the sand to shale ratio is high. Furthermore, seismic control

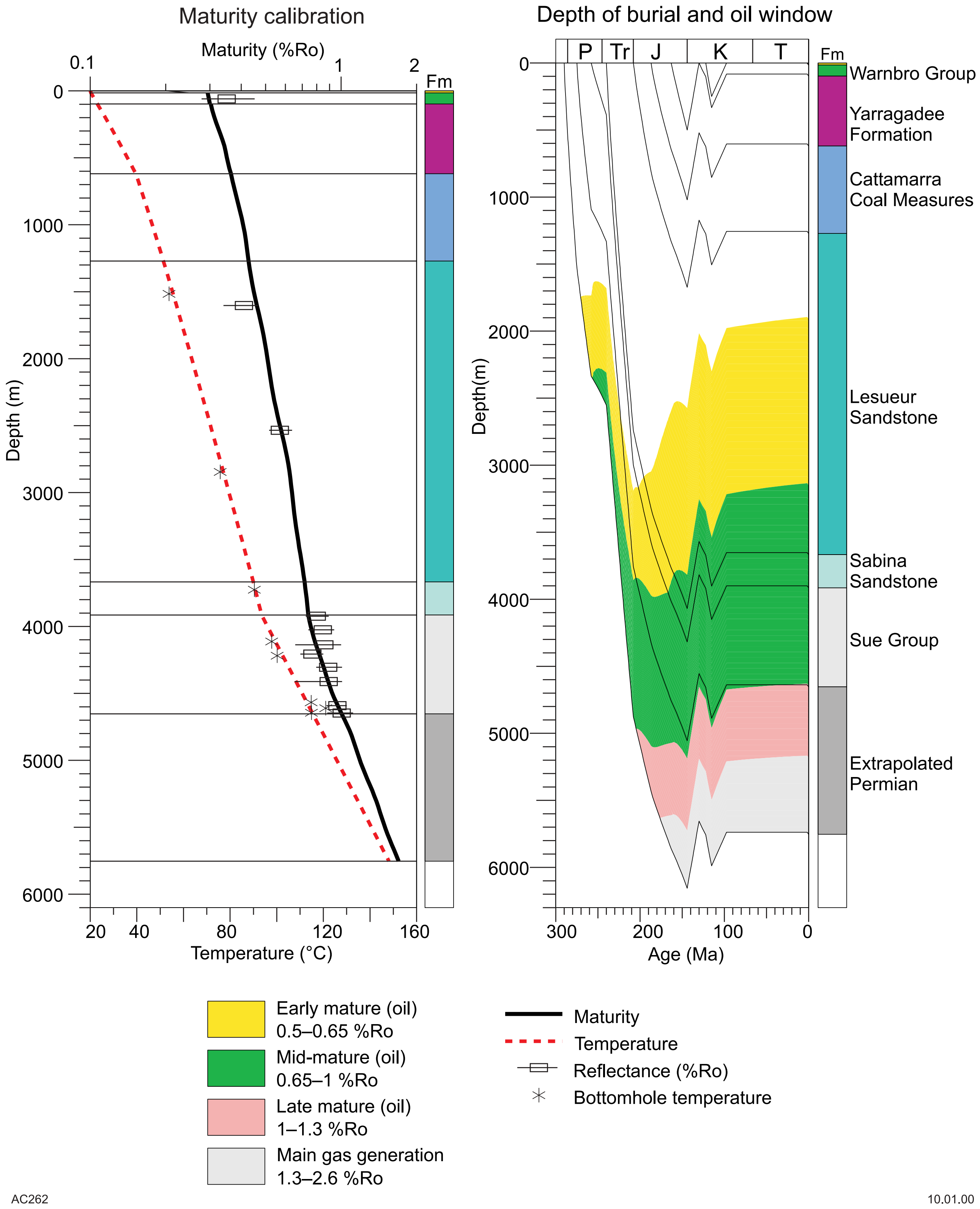

Figure 72. Depth of burial, maturity calibration, and oil window for Whicher Range 1

rarely resolves faults with a throw of less than 20 m, and the geometry of the potential reservoirs therefore cannot be adequately defined prior to drilling. Although seismic resolution can be improved with specific acquisition parametres, this approach is expensive and is usually only used at the development stage after additional information is obtained from drilling.

The Dongara oil- and gasfield in the northern Perth Basin is a good example of an anticline in which a thick

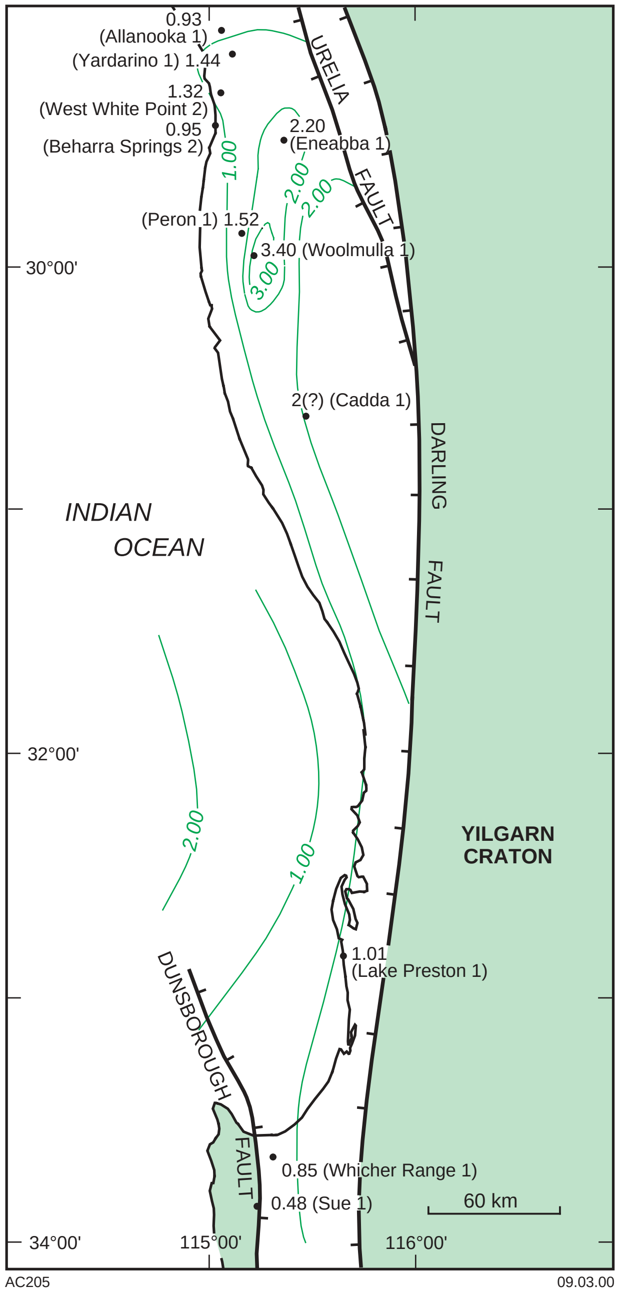

Figure 73. **Tentative maturity (vitrinite reflectance) map of the Top Permian in the Perth Basin. Sources: northern Perth Basin data from Mory and lasky (1996), southern Perth Basin from lasky (1993), Vlaming Sub-basin extrapolated from Marshall et al. (1993)**

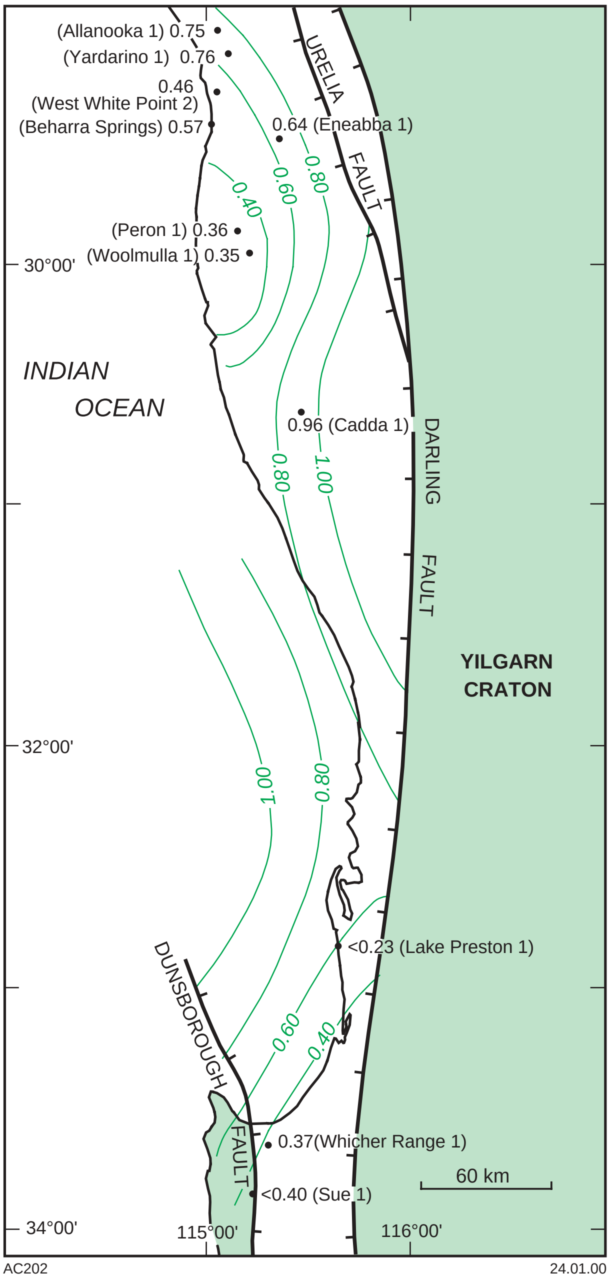

Figure 74. **Tentative maturity (vitrinite reflectance) map of the Jurassic rocks (Top Cattamarra Coal Measures) in the Perth Basin. Sources: northern Perth Basin data from Mory and lasky (1996),southern Perth Basin from lasky (1993), Vlaming Sub-basin extrapolated from Marshall et al. (1993)**

seal, the Kockatea Shale, controls a hydrocarbon accumulation (Crostella, 1995).

Fault-controlled traps

Faults may juxtapose sandstones against shales, thereby forming a trap (Fig. 75b). In the case of faulted anticlines, thick regional shales are the best guarantee for effective traps, whereas thin shales increase the chance of a weak or non-existent lateral seal. The effectiveness of a fault seal, however, is also dependent on other factors, such as shale smearing along the fault plane. The definition of a fault trap presents more problems than for an antiform structure because it essentially depends on correctly predicting the lithological succession. Reliance on a fault seal in sandstone-dominated successions, which are typical of the Perth Basin, carries a substantial risk.

In the northern Perth Basin, the Beharra Springs gasfield provides a good example of a hydrocarbon

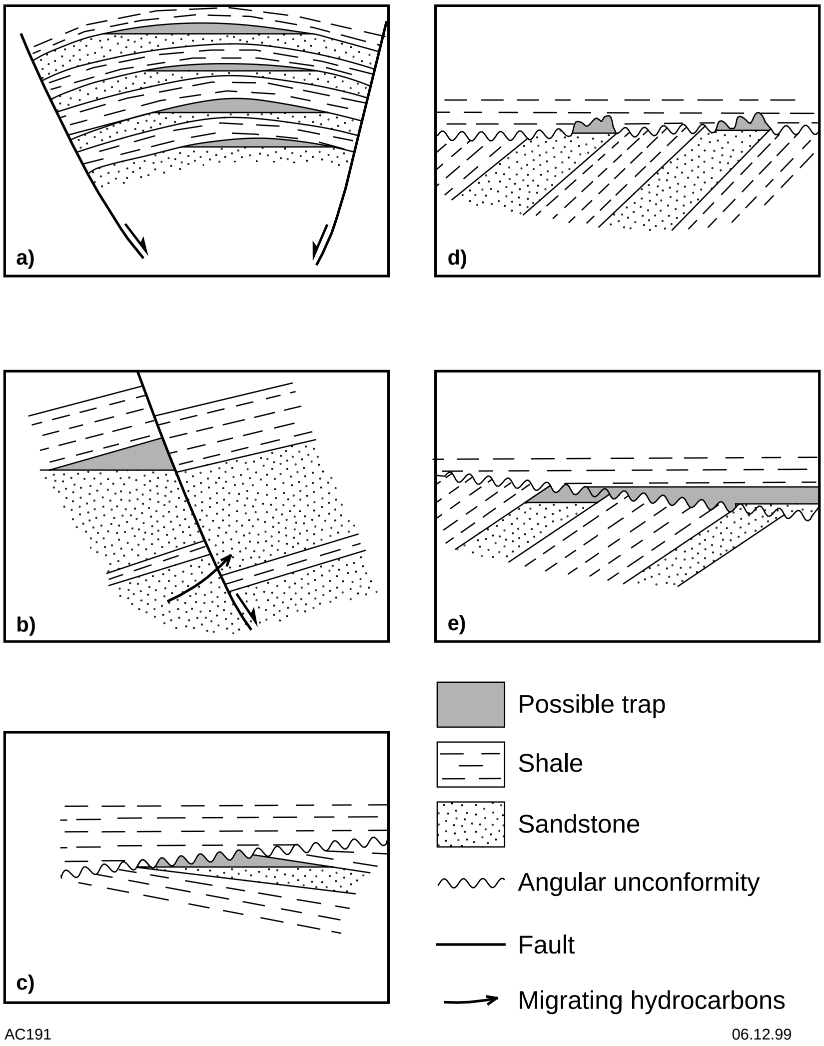

Figure 75. Type of traps present, or expected to be present, within the Perth Basin. a) anticlines, b) fault-controlled traps, c) subunconformity truncations, d) palaeotopographic highs, e) post-breakup pinch-outs

accumulation controlled by a fault trap that is sealed laterally by a thick shale (Kockatea Shale).

Subunconformity truncations

An angular unconformity may provide effective traps, even where the post-tectonic strata are unstructured, as long as both top and bottom shales seal the sandstone objective, and impervious rocks overlie the unconformity surface (Fig. 75c). Even though no commercial accumulation of hydrocarbons has been discovered within such a trap in the Perth Basin, the most prospective area for such an accumulation is the Roe High (Fig. 47).

Palaeotopographic highs

Sandy palaeotopographic highs, covered by post-tectonic shales, offer a suitable setting for entrapment of hydrocarbons (Fig. 75d). This type of trap has been tested within the Vlaming Sub-basin, with no commercial discoveries to date, but better quality and more closely spaced seismic control, together with a better understanding of the regional setting, may yet result in a successful test of this type of trap.

Post-breakup pinch-outs

Generally, the Gage Sandstone overlies the breakup unconformity surface in structurally depressed areas, but the absence of structural deformation following the intra-Neocomian transgression restricts the trapping potential of this unit to depositional features. The Gage Sandstone is covered by the South Perth Shale, and thus an effective trap may develop where a bottom seal is present (Fig. 75e). An example of this type of trap is the oil accumulation discovered in Gage Roads 2.

Permeability barriers

Among other possibilities, the presence of hydrocarbons in the Willespie Formation in the Bunbury Trough may be due to permeability barriers. This trapping mechanism may explain the limited deliverability of the tested intervals. In the event that the permeability of the reservoir is increased by further acidification or hydraulic fracture stimulation (or both), some gas production may be sustained sufficiently long enough to be of economic value, given the proximity to potential markets. A similar possibility exists in the Gingin area.

Migration paths and time of trapping

The high percentage of coarse clastic rocks, and the scarcity of regional seals in the region, minimize the relevance of conventional migration paths because large-scale vertical migration did, and still does, take place within the southern and central Perth Basin. Such migration takes place either through the thick sandy formations or along high-angle faults that are effective conduits for hydrocarbons.

Traps that may have formed within the study area are related to the Main Unconformity, and therefore it is expected that only hydrocarbons generated after that time accumulated in discrete fields. The main potential source rocks should still be generating hydrocarbons (Figs 73 and 74), as indicated by the hydrocarbon accumulations within the basin. Lack of pre-Main Unconformity traps prevents the possibility of older accumulations, which suggests that the low saturation levels found in the area are not residual, but are an indication that hydrocarbons are migrating within the section.

Conclusions

The pre-breakup Perth Basin is an intracontinental rift basin that was filled largely with non-marine sediments. In the narrow (40 km-wide) southern part of the basin, the depositional history was dominated mainly by Permian northward-flowing rivers (Fig. 26). The basin becomes progressively wider to the north, where the fluvial- to alluvial-plain Triassic and Jurassic deposits thicken, and where intervening Early Triassic and Middle Jurassic marine sedimentation is evident.

Based on the analysis of results of oil exploration drilling in the central and southern Perth Basin, the most prospective plays in each basin subdivision are summarized below.

In the Beermullah Trough, the most prospective plays are north-trending anticlines containing sandstone of the Cattamarra Coal Measures with intraformational seals, and Lesueur Sandstone sealed by shale of the overlying Eneabba Formation, both of which are filled with gas sourced from the Permian Irwin River Coal Measures. Such anticlines are numerous and are present over a distance of 50 km throughout the Beermullah Trough (Fig. 8). The results from Bullsbrook 1, Gingin 1 and 2, and Bootine 1 suggest that the hydrocarbons encountered to date accumulated in limited pools controlled by permeability characteristics, lenticular sandstones, or limited fault traps. The likely presence of thicker seals at depth suggests that large hydrocarbon accumulations may be present below the depths reached by existing wells. Furthermore, the effectiveness of the structural traps is expected to increase with depth (Fig. 6). If a valid trap can be proved, the Badaminna High may be another attractive exploration target (Fig. 6) because in this area the Cattamarra Coal Measures is 2000 m closer to the surface than in the Gingin–Bootine Anticline.

In the Vlaming Sub-basin, the most likely plays are the Jervoise Sandstone in unconformity-controlled truncations or palaeotopographic highs, the Charlotte Sandstone in palaeotopographic highs, and the Gage Sandstone in post-breakup pinch-outs. In addition, results from Gage Roads 1 suggest the presence of fault-controlled traps (Fig. 47). Oil is expected to have migrated upwards from the Upper Jurassic Yarragadee Formation or the Lower – Middle Jurassic Cattamarra Coal Measures, both of which are within the oil window in this area (Fig. 72). In the event that new seismic control identifies structures with limited faulting, an additional play may be provided by anticlines in the southern part of the sub-basin.

Within the poorly understood Mandurah Terrace, the most viable play is gas reservoired within sandstones of the Cattamarra Coal Measures, Eneabba Formation, and Lesueur Formation, within fault-controlled traps. Cockburn 1, Rockingham 1, Pinjarra 1, and Lake Preston 1 show that, at least in selected areas, these objectives are at drillable depths.

No economically viable play has been confirmed yet in the Vasse Shelf or Bunbury Trough. It is not yet proven, at least in that part of the Sue Group drilled in the Bunbury Trough, whether faulted anticlines, although widespread in the region, control accumulations of economic significance in Permian sandstones deposited near now mature source rocks. These anticlines have been extensively tested by wells such as Whicher Range 1, 2, 3, and 4, Scott River 1, and Wonnerup 1. No viable younger objectives are present in the area.

In conclusion, the hydrocarbon potential of the Perth Basin is highest where the percentage of marine sediments is high. In the study area, the Beermullah Trough provides the best chance to discover very large gasfields. Such fields are probably present at depths of around 5000 m or greater. The Vlaming Sub-basin is expected to provide the best chance for discovering oilfields at depths of 3000 m or less. Such fields, however, would be controlled by less conventional traps, of types as yet unproven within this basin. The Mandurah Terrace has been very poorly explored and should be considered a frontier area. The fairly well-tested Bunbury Trough is poorly rated, not because of its perceived poor reservoir potential, but because of its poor potential for effective traps.

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Appendix 1

Surveys conducted for petroleum exploration in the central and southern Perth Basin

Survey name	*Year*	*Company*	*Tenement*	*Survey type*	*Km*	*GSWA WAPEX no.*	*Microform no.*
Aeromagnetic S. of the Perth Basin	1957	BMR	PE-27-H	Aeromagnetic	35 406	S152	–
Aeromagnetic S. WA-228-P	1992	Woodside	WA-228-P	Aeromagnetic	10 453	S10107V1	
Alexander Bridge Reconnaissance S.S.	1964	WAPET	PE-27-H	2D Reflection	51	S132V1	12, 43
				2D Refraction	14		
Ambergate S.S.	1980	Mesa	EP 130	2D Reflection	388	S1751	629, PES1751
Augusta 1st Order Regional Magnetic S.	1970	BMR	EP 50	Magnetic	0	S3009V2	–
Augusta–Moora Gravity S.	1963	WAPET	PE-27-H	Gravity	0	S54V1	10
Badaminna S.S.	1990	Barrack	EP 337	2D Reflection	73	S10004	
Barragoon Reconnaissance S.S.	1970	WAPET	EP 21,23,24,25	2D Reflection	666	S622	6, 41, 87
Beagle (West) Aeromagnetic S.	1969	WAPET	PE-27-H	Aeromagnetic	4 467	S495	PES495
Blackwood S.S.	1965	WAPET	PE-27-H	2D Reflection	56	S206	17, 43, 62
				2D Refraction			
Bouvard (DW) M.S.S., Gravity and Magnetic S.	1972	WAPET	WA-13,14-P	2D Reflection	252	S803V1	(313,634) PES803
				Gravity	128		
				Magnetic	256		
Broadwater M.S.S.	1980	Mesa	EP 130	2D Reflection	49	S1737	(629) PES1737
Bullsbrook 1964 S.S.	1964	BMR	PE-27-H	2D Reflection	37	S3002	–
Bullsbrook Reconnaissance S.S.	1965	WAPET	PE-27-H	2D Reflection	177	S253	40, 86
				2D Refraction	19		
Bunbury M.S.S.	1967	WAPET	PE-27-H	2D Reflection	97	S393	21, 311
Busselton S.S.	1956	BMR	PE-27-H	2D Reflection	64	S3007	–
Canebreak S.S.	1982	Weaver	EP 112	2D Reflection	113	S2010	628
Cape Leeuwin M.S.S.	1980	Wainoco	WA-135-P	2D Reflection	768	S1749	(636-7) PES1749
Central Perth Basin Gravity S.	1963	WAPET	PE-27-H	Gravity	2 534	S54V2	10
Cervantes (DW) M.S.S.	1972	WAPET	WA-13-P	2D Reflection	116	S803V2	(21, 313, 634) PES803
				2D Refraction	57		
				Gravity	211		
				Magnetic	341		
Challenger Detail M.S.S., Gravity and Magnetic S.	1971	WAPET	WA-13,14-P	2D Reflection	418	S611V1	(21, 53, 309, 312, 633) PES611
(part of Perth Basin M.S.S.)				Gravity			
				Magnetic			
Chapman Hill S.S.	1991	Discovery	EP 340	2D Reflection	30	S10056	
Charla S.S.	1966	WAPET	PE-27-H	2D Reflection	37	S278	40
Charlotte M.S.S.	1967	WAPET	PE-27,225-H	2D Reflection	567	S360	(311) PES360
Cockburn Sparker M.S.S.	1966	WAPET	PE-27-H	2D Reflection	656	S309	21, 53, 86,3 11
Coogee Detail S.S.	1966	WAPET	PE-27-H	2D Reflection	33	S326	86
Cookernup S.S.	1955	BMR	PE-27-H	2D Reflection	71	S3005	–
				2D Refraction			
Coventry M.S.S.	1966	WAPET	PE-27-H	2D Reflection	253	S325	(21, 86, 311) PES325
				2D Refraction	16		

Appendix 1 (continued)

Survey name	*Year*	*Company*	*Tenement*	*Survey type*	*Km*	*GSWA WAPEX no.*	*Microform no.*
Dandaragan 1981 S.S.	1981	Mesa	EP 100	2D Reflection	117	S1867	PES1867
Dandaragan East Flank Detail S.S.	1971	WAPET	EP 23,24	2D Reflection	372	S684	41
Darradup S.S.	1964	WAPET	PE-27-H	2D Reflection	131	S132V2	12, 43, 62
Direction Bank M.S.S.	1968	WAPET	PE-27,225-H	2D Reflection	1 628	S388	21, 312
Flinders Bay M.S.S.	1972	WAPET	WA-13-P	2D Reflection	155	S803V3	(21, 634) PES803
				Gravity	155		
				Magnetic	289		
Four Mile Hill S.S.	1981	BP	EP 130	2D Reflection	46	S1991	629, PES1991
Gingin Anticline North S.S.	1955	BMR	PE-27-H	2D Reflection	32	S3003	–
Gingin Bullsbrook D1 S.S.	1971	WAPET	EP 24,25	2D Reflection	406	S683	41, 86
Gingin Detail S.S.	1963	WAPET	PE-27-H	2D Reflection	319	S83V1	14, 40, 42
				2D Refraction			
Gingin Reconnaissance S.S.	1956	WAPET	PE-27-H	2D Reflection	84	S83V2	14, 40
Gingin S.S.	1955	WAPET	PE-27-H	2D Reflection	84	S457V2	
Gravity S. of the Perth Basin	1951	BMR	PE-27-H	Gravity		S3001	
Green M.S.S.	1982	Balmoral	WA-171-P	2D Reflection	697	S2214	PES2214
Happy Valley S.S.	1981	Weaver	EP 112	2D Reflection	194	S1614	628
Harvey D1 S.S.	1969	WAPET	PE-27-H	2D Reflection	136	S526	41
Harvey S.S.	1969	WAPET	PE-27-H	2D Reflection	65	S471V2	41-3, 62
Harvey Gravity S.	1969	WAPET	PE-27-H	Gravity		S471V1	41, 43, 62
Karnup Reconnaissance S.S.	1966	WAPET	PE-27-H	2D Reflection	143	S277	
Kerrie M.S.S.	1991	Ampol	WA-220-P	2D Reflection	409	S10076	
Koombana–Wedge Island M.S.S.	1969	WAPET	WA-13, 14-P	2D Reflection	379	S520V1	21, 312
Koombana 3 M.S.S. and Magnetic S.	1975	WAPET	WA-14-P R1	2D Reflection	498	S1115	(313, 636-7) PES1115
				Magnetic			
Koombana M.S.S.	1969	WAPET	WA-13, 14-P	2D Reflection	1 319	S456	21, 312
Korijekup S.S.	1991	Petroz	EP 344, 345	2D Reflection	199	S10054	
Lake Preston S.S.	1964	WAPET	PE-27-H	2D Reflection	74	S133V1	12, 39, 40
				2D Refraction	7		
Lancelin (SW) M.S.S.	1972	WAPET	WA-14-P	2D Reflection	210	S788V1	21, 312, 639
Lancelin 3 S.S.	1973	WAPET	EP 24	2D Reflection	122	S841V1	41
Lancelin Exp. S.S.	1970	WAPET	PE-27-H	2D Reflection	39	S579	41
Leeuwin Aeromagnetic S.	1969	WAPET	WA-13, 14-P	Aeromagnetic	3 701	S503	PES503
Margaret River S.S.	1967	Union	PE-261-H	2D Reflection	357	S396	43, 62
Medina 1981 S.S.	1981	Phoenix	EP 204	2D Reflection	34	S1862V1	PES1862
Medina S.S.	1982	Phoenix	EP 204	2D Reflection	46	S1862V2	PES1862
Mersey M.S.S.	1975	WAPET	WA-13-P R1	2D Reflection	85	S1117	(310-1, 636) PES1117
Moore River S.S.	1971	WAPET	EP 24	2D Reflection	88	S624	41
Mullering S.S.	1973	WAPET	EP 24	2D Reflection	74	S841V2	
Namban (Lancelin) S.S.	1969	WAPET	PE-27-H	2D Reflection	69	S478	6, 41
Naturaliste 1974 M.S.S.	1974	WAPET	WA-13-P	2D Reflection	127	S966	(313, 635-6) PES966
				Magnetic	127		
Naturaliste 1993 M.S.S.	1993	Woodside	WA-227-P	2D Reflection	1 417	S10185	

Appendix 1 (continued)

Survey name	*Year*	*Company*	*Tenement*	*Survey type*	*Km*	*GSWA WAPEX no.*	*Microform no.*
Pauline 1994 M.S.S.	1994	Ampol	WA-220-P	2D Reflection	429	S10233	
Peel M.S.S. and Magnetic S.	1974	WAPET	WA-13-P	2D Reflection Magnetic	285	S967	(313, 635-6) PES967
Perth Basin Gravity S.	1956	WAPET	PE-27-H	Gravity		S416	39
Perth M.S.S.	1965	WAPET	PE-27-H	2D Reflection	592	S243	(21, 311) PES243
Perth South M.S.S. (part of Perth Waters M.S.S.)	1970	WAPET	WA-13, 14, 20-P	2D Reflection	834	S626V1	(21, 53, 309, 312) PES626
Pinjarra Detail S.S.	1965	WAPET	PE-27-H	2D Reflection	46	S186	17, 40
Pinjarra Reconnaissance S.S.	1964	WAPET	PE-27-H	2D Reflection	144	S133V2	12, 39, 40
Preston D1 S.S.	1971	WAPET	EP 25	2D Reflection	29	S666	41
Preston Detail (1971) S.S.	1971	WAPET	WA-14-P	2D Reflection	153	S788V2	312, 639
Preston Detail S.S.	1970	WAPET	EP 25	2D Reflection	88	S608	41
Preston M.S.S.	1966	WAPET	PE-27-H	2D Reflection	323	S269V1	21, 311
PV91 M.S.S.	1991	Petrofina	WA-221-P	2D Reflection	2 426	S10068	
Rockingham 2 Detail S.S.	1975	WAPET	EP 25	2D Reflection	40	S984	86
Rockingham Reconnaissance S.S.	1972	WAPET	EP 25	2D Reflection 2D Refraction	149	S792	41, 86
Rockingham–Mundijong S.S.	1956	BMR	PE-27-H	2D Reflection	34	S3004	
Roe M.S.S.	1982	WAPET	WA-13-P R2	2D Reflection	121	S2196	(635) PES2196
Rottnest M.S.S.	1966	WAPET	PE-27-H	2D Reflection	see S269V1	S269V2	21, 311
Sabina Reconnaissance S.S.	1964	WAPET	PE-27-H	2D Reflection	35	S132V3	12
Sabina S.S.	1967	Union	PE-261-H	2D Reflection	79	S356	43
Scientific Investigation 5/1988–89	1989	Amoco	Vacant acreage	Geochemical	1 800	S3655V3	
Scientific Investigation 6SL (Petrel Roving)	1972	Shell	WA-13, 43, 44, 47, 50, 51-P	2D Reflection Gravity Magnetic	6 194	S779	24, 31 (637) PES779
Scientific Investigation 7SL/88-89 (Vlaming ALF)	1988	BP	Vacant acreage	Spectrometer	1 593	S3611	
Seabird I M.S.S.	1980	Strata	WA-113-P	2D Reflection	132	S1748	(638) PES1748
Seabird II M.S.S.	1981	Haoma	WA-113-P	2D Reflection	111	S1941	(638) PES1941
Seabird III M.S.S.	1982	Strata	WA-113-P	2D Reflection	38	S2188	(639) PES2188
Smokebush S.S.	1966	WAPET	PE-27-H	2D Reflection	37	S317	41
Southern Perth Basin Gravity S.	1963	WAPET	PE-27-H	Gravity	2 317	S54V3	10
Stirling Rapids S.S.	1980	Mesa	EP 130	2D Reflection	314	S1580	628-9, PES1580
Sugarloaf M.S.S.	1968	WAPET	WA-13, 14-P	2D Reflection	515	S437	(21, 312) PES437
Two Rocks M.S.S. and Gravity S.	1972	WAPET	WA-13-P	2D Reflection Gravity	189 219	S825V2	(21, 309, 312, 634) PES825
V82A M.S.S.	1982	Esso	WA-170-P	2D Reflection	2 542	S2085	PES2085
V83A M.S.S.	1983	Esso	WA-170-P	2D Reflection	971	S2302	PES2302
V85A M.S.S.	1985	BHP	WA-170-P	2D Reflection	545	S2791	PES2791
V90A M.S.S.	1990	Norcen	WA-220-P	2D Reflection	1 502	S10034	
WA-174-P 1982 M.S.S.	1982	BP	WA-174-P	2D Reflection	1 633	S2030	PES2030(B&I)
WA-174-P 1983 M.S.S.	1983	BP	WA-174-P	2D Reflection	378	S2328	PES2328
WA-227-P 1993 Aeromagnetic S.	1993	Woodside	WA-227-P	Aeromagnetic	10 000	S10157	
White Lakes S.S.	1984	Phoenix	EP 204	2D Reflection	53	S2728	PES2728

Appendix 1 (continued)

Survey name	*Year*	*Company*	*Tenement*	*Survey type*	*Km*	*GSWA WAPEX no.*	*Microform no.*
Wonnerup–Flinders S.S.	1969	Union	PE-261-H	2D Reflection	131	S462	43
Yanchep S.S.	1965	WAPET	PE-27-H	2D Reflection	95	S259	40

NOTES: All surveys listed are open file
Alpha numeric numbers represent microfiche, two or three digit numbers represent microfilm rolls
Microfilm rolls listed in brackets indicate data is also available on microfiche
S: Survey
S.S.: Seismic survey
M.S.S.: Marine seismic survey
DW: Deep water
SW: Shallow water

Amoco:	Amoco Australia Petroleum Company
Ampol:	Ampol Exploration Ltd
Balmoral:	Balmoral Resources NL
Barrack:	Barrack Energy Management Pty Ltd
BHP:	BHP Petroleum Pty Ltd
BMR:	Bureau of Mineral Resources
BP:	BP Petroleum Development Australia Pty Ltd
Discovery:	Discovery Petroleum NL
Esso:	Esso Australia Ltd
Haoma:	Haoma Goldmines NL
Mesa:	Mesa Australia Ltd
Norcen:	Norcen International Ltd
Petrofina:	Petrofina Exploration Australia S.A.
Petroz:	Petroz NL
Phoenix:	Phoenix Oil and Gas NL
Shell:	Shell Development (Australia) Pty Ltd
Strata:	Strata Oil NL
Union:	Union Oil Development Corporation
Wainoco:	Wainoco International Inc.
WAPET:	West Australian Petroleum Pty Ltd
Weaver:	Weaver Oil and Gas Corporation of Australia
Woodside:	Woodside Petroleum Pty Ltd

Appendix 2

Waterbores drilled in the central and southern Perth Basin by the Geological Survey of Western Australia

Well name	*Year*	*Latitude (S)*	*Longitude (E)*	*Total depth (m)*	*Reference*
Abba River 1	1956	33°43'24"	115°29'59"	522	Low, 1956
Abba River 2	1956	33°44'12"	115°26'33"	226	
Abba River 3	1956	33°44'54"	115°27'40"	464	
Harvey Line 1B	1983	32°54'43"	115°42'05"	605	Deeney, 1989a
Harvey Line 2A	1983	32°55'08"	115°45'57"	810	
Harvey Line 3A	1983	32°54'31"	115°49'29"	603	
Harvey Line 4A	1984	32°53'51"	115°54'08"	602	
Binningup Line 1	1984	33°08'51"	115°41'46"	807	Deeney, 1989b
Binningup Line 2	1984	33°08'59"	115°44'28"	600	
Binningup Line 3	1984	33°09'37"	115°48'15"	801	
Binningup Line 4	1984	33°09'42"	115°51'09"	803	
Picton Line 1	1978	33°20'44"	115°41'36"	1 200	Wharton, 1980
Picton Line 2	1978	33°20'07"	115°38'42"	782	
Picton Line 3	1978	33°20'55"	115°45'08"	794	
Picton Line 4	1978	33°20'59"	115°48'30"	824	
Boyanup Line 1	1981	33°28'13"	115°34'18"	1 000	Smith, 1982
Boyanup Line 2	1981	33°28'29"	115°36'36"	1 000	
Boyanup Line 3	1981	33°29'21"	115°40'01"	1 000	
Boyanup Line 4	1981	33°28'36"	115°45'33"	998	
Quindalup Line 1	1966	33°39'36"	115°17'41"	588	Wharton, 1981
Quindalup Line 2	1967	33°39'26"	115°13'55"	551	
Quindalup Line 3	1967	33°38'37"	115°10'30"	453	
Quindalup Line 4	1967	33°38'13"	115°26'00"	585	
Quindalup Line 5	1967	33°38'38"	115°30'22"	613	
Quindalup Line 6	1974	33°38'56"	115°35'02"	1 118	
Quindalup Line 7	1979	33°39'05"	115°38'39"	1 044	
Quindalup Line 8	1979	33°38'17"	115°42'12"	1 158	
Quindalup Line 9	1980	33°39'06"	115°46'52"	1 465	
Quindalup Line 10	1979	33°39'53"	115°19'26"	1 064	
Cowaramup Line 1	1988	33°52'15"	115°12'23"	500	Appleyard, 1991
Cowaramup Line 2	1988	33°51'58"	115°15'22"	759	
Cowaramup Line 3	1988	33°52'24"	115°19'07"	1 055	
Cowaramup Line 4	1988	33°52'18"	115°24'15"	1 072	
Cowaramup Line 5	1988	33°52'09"	115°28'44"	1 500	
Cowaramup Line 6	1988	33°52'22"	115°33'04"	1 494	
Cowaramup Line 7	1988	33°51'56"	115°38'28"	1 668	
Cowaramup Line 8	1988	33°51'24"	115°43'08"	1 448	
Karridale Line 1	1989	34°09'52"	115°11'12"	655	Baddock, 1994
Karridale Line 2	1989	34°09'22"	115°16'58"	1 171	
Karridale Line 3	1989	34°09'06"	115°21'36"	1 203	
Karridale Line 4	1989	34°09'46"	115°27'42"	1 207	
Karridale Line 5	1989	34°10'06"	115°31'40"	1 165	
Karridale Line 6	1989	34°10'55"	115°37'19"	1 602	
Karridale Line 7	1989	34°11'21"	115°43'10"	1 686	

NOTE: In addition, several hundred hydrogeological boreholes have been drilled in the Perth region (Davidson, 1995, tables 3, 4, 5 and 8)

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Appendix 3

Formation tops for petroleum wells in the central and southern Perth Basin

Well name	*Onshore/ offshore*	*Kelly bushing/ rotary table*	*Leederville Formation*	*South Perth Shale*	*Gage Sandstone*	*Charlotte Sandstone*	*Hawley Member*	*Mangles Member*	*Stragglers Member*	*Jervoise Sandstone*	*Otorowiri Formation*	*Yarragadee Formation*
Alexandra Bridge 1	Onshore	39	3	–	–	–	–	–	–	–	–	–
Araucaria 1	Offshore	18	1157	–	–	–	–	1 806	np	np	np	np
Badaminna 1	Onshore	41	61	241	–	–	–	–	–	–	–	288
Barragoon 1	Onshore	40	213	699	–	–	–	–	–	–	–	803
Blackwood 1	Onshore	71	–	18	–	–	–	–	–	–	–	186
Bootine 1	Onshore	173	ni	–	–	–	–	–	–	–	–	257
Bouvard 1	Offshore	12	650	ni	ni	1 137	ni	ni	ni	ni	ni	np
Bullsbrook 1	Onshore	91	92	–	–	–	–	–	–	–	–	160
Canebreak 1	Onshore	31	–	16	–	–	–	–	–	–		–
Challenger 1	Offshore	12	868	1 110	1 415	–	–	–	–	1 429	1 841	1 907
Chapman Hill 1	Onshore	36	–	18	–	–	–	–	–	–	–	240
Charlotte 1	Offshore	30	450	869	1 488	1 576	2 165	np	np	np	np	np
Cockburn 1	Offshore	7	–	40	–	–	–	–	–	–	–	313
Gage Roads 1	Offshore	21	617	1 280	1 587	–	–	–	1 704	1 800	2 553	2 616
Gage Roads 2	Offshore	30	577	1 147	1 350	–	–	1 374	1 794	1 985	2 848	2 932
Gingin 1	Onshore	203	94	–	–	–	–	–	–	189	319	356
Gingin 2	Onshore	266	ni	–	–	–	–	–	–	280	401	430
Lake Preston 1	Onshore	15	42	–	–	–	–	–	–	–	–	–
Marri 1	Offshore	33	474	792	–	–	1 326	1 598	2 470	np	np	np
Minder Reef 1	Offshore	30	475	789	828	–	864	np	np	np	np	np
Mullaloo 1	Offshore	30	443	772	1 670	1 825	np	np	np	np	np	np
Parmelia 1	Offshore	21	1 108	–	–	–	–	1 593	np	np	np	np
Peel 1	Offshore	30	859	ni	ni	1 625	2 409	f	?2 995	3 064	3 505	3 551
Pinjarra 1	Onshore	10	24	–	–	–	–	–	–	–	–	–
Preston 1	Onshore	8	25	–	–	–	–	–	–	–	–	–
Quinns Rock 1	Offshore	24	357	611	775	–	–	–	794	1 030	1 591	1 670
Rockingham 1	Onshore	16	65	–	–	–	–	–	–	–	–	287
Roe 1	Offshore	30	616	–	–	–	872	1 219	np	np	np	np
Sabina River 1	Onshore	13	61	–	–	–	–	–	–	–	–	150
Scott River 1	Onshore	27	–	–	–	–	–	–	–	–	–	–
Sue 1	Onshore	86	6	–	–	–	–	–	–	–	–	–
Sugarloaf 1	Offshore	30	450	–	–	–	–	–	875	ni	ni	2 099
Tuart 1	Onshore	21	535	1 069	–	–	–	1 107	np	np	np	np
Warnbro 1	Offshore	25	1 003	1 408	1 945	–	–	–	–	2 204	2 932	2 987
Whicher Range 1	Onshore	153	–	15	–	–	–	–	–	–	–	98
Whicher Range 2	Onshore	157	–	ni	–	–	–	–	–	–	–	108
Whicher Range 3	Onshore	138	–	ni	–	–	–	–	–	–	–	ni
Wonnerup 1	Onshore	24	17	ni	–	–	–	–	–	–	–	36

NOTES: ni: not identified
np: not penetrated
f: faulted out

Appendix 3 (continued)

Well name	*Cadda Formation*	*Cattamarra Coal Measures*	*Eneabba Formation*	*Lesueur Sandstone*	*Sabina Sandstone*	*Willespie Formation*	*Redgate Coal Measures*	*Ashbrook Sandstone*	*Rosabrook Coal Measures*	*Woodynook Sandstone*	*Mosswood Formation*	*Precambrian basement*	*Total depth*
Alexandra Bridge 1	–	–	–	70	401	431	np	np	np	np	np	np	766
Araucaria 1	np	np	np	np	np	np	np	np	np	np	np	np	2 218
Badaminna 1	1 125	1 298	np	np	np	np	np	np	np	np	np	np	2 438
Barragoon 1	np	np	np	np	np	np	np	np	np	np	np	np	2 335
Blackwood 1	–	541	ni	961	2 061	2 448	np	np	np	np	np	np	3 333
Bootine 1	3 066	3 372	np	np	np	np	np	np	np	np	np	np	4 306
Bouvard 1	np	np	np	np	np	np	np	np	np	np	np	np	1 980
Bullsbrook 1	2 809	3 050	np	np	np	np	np	np	np	np	np	np	4 257
Canebreak 1	–	150	ni	447	1 285	1 709	np	np	np	np	np	np	2 090
Challenger 1	np	np	np	np	np	np	np	np	np	np	np	np	2 250
Chapman Hill 1	–	438	1 234	np	np	np	np	np	np	np	np	np	1 350
Charlotte 1	np	np	np	np	np	np	np	np	np	np	np	np	2 435
Cockburn 1	1 725	1 914	np	np	np	np	np	np	np	np	np	np	3 054
Gage Roads 1	np	np	np	np	np	np	np	np	np	np	np	np	3 660
Gage Roads 2	np	np	np	np	np	np	np	np	np	np	np	np	2 972
Gingin 1	3 314	3 610	np	np	np	np	np	np	np	np	np	np	4 544
Gingin 2	3 399	3 591	np	np	np	np	np	np	np	np	np	np	4 482
Lake Preston 1	–	–	112	1 219	3 511	4 035	np	np	np	np	np	np	4 561
Marri 1	np	np	np	np	np	np	np	np	np	np	np	np	2 594
Minder Reef 1	np	np	np	np	np	np	np	np	np	np	np	np	1 530
Mullaloo 1	np	np	np	np	np	np	np	np	np	np	np	np	2 030
Parmelia 1	np	np	np	np	np	np	np	np	np	np	np	np	1 770
Peel 1	np	np	np	np	np	np	np	np	np	np	np	np	3 714
Pinjarra 1	–	149	1 203	2 373	np	np	np	np	np	np	np	np	4 572
Preston 1	–	–	205	np	np	np	np	np	np	np	np	np	765
Quinns Rock 1	np	np	np	np	np	np	np	np	np	np	np	np	2 210
Rockingham 1	730	939	np	np	np	np	np	np	np	np	np	np	1 563
Roe 1	np	np	np	np	np	np	np	np	np	np	np	np	2 134
Sabina River 1	ni	950	ni	1 800	3 432	3 914	np	np	np	np	np	np	4 309
Scott River 1	–	7	ni	403	1 320	1 801	np	np	np	np	np	np	2 370
Sue 1	–	–	–	169	878	1 216	2 276	2 422	2 684	2 882	3 003	3 054	3 077
Sugarloaf 1	2 126	np	np	np	np	np	np	np	np	np	np	np	3 658
Tuart 1	np	np	np	np	np	np	np	np	np	np	np	np	1 600
Warnbro 1	np	np	np	np	np	np	np	np	np	np	np	np	3 660
Whicher Range 1	ni	937	ni	1 887	3 450	3 916	np	np	np	np	np	np	4 653
Whicher Range 2	ni	969	ni	1 817	3 420	3 987	np	np	np	np	np	np	4 330
Whicher Range 3	ni	791	ni	1 801	3 515	4 017	np	np	np	np	np	np	4 496
Wonnerup 1	ni	854	ni	2 125	3 644	4 104	np	np	np	np	np	np	4 727

NOTES:
ni: not identified
np: not penetrated
f: faulted out

Appendix 4

Palynostratigraphy and age of the Parmelia Group

The upper limit on the age of the Parmelia Group is based on the age of the oldest part of the Warnbro Group. The lowest fully marine dinoflagellate zone in the Perth Basin zonation of Backhouse (1987, 1988) is the *Kaiwaradinium scrutillinum* Zone, which approximately corresponds to the *Senoniasphaera tabulata* Zone of Helby et al. (1987). The age of these zones is considered to be Valanginian (Helby et al., 1987; Backhouse, 1988). In the Vlaming Sub-basin, the *K. scrutillinum* Zone is underlain by the *Gagiella mutabilis* Zone, which contains a facies-controlled dinoflagellate assemblage. Backhouse (1988) considered this zone to be Valanginian, although there is no direct evidence for such an age. Therefore, the oldest intervals of the Warnbro Group are considered to be Valanginian, and by extrapolation it seems unlikely that the top of the underlying Parmelia Group can be much younger than late Berriasian.

The base of the *Biretisporites eneabbaensis* Spore–pollen Zone has previously been placed in the Tithonian, based on tenuous extrapolation from rare ammonite occurrences (Backhouse, 1988). Other workers have placed the base of the zone at the Jurassic–Cretaceous boundary (Helby et al., 1987). On the available data, it is not possible to date the base of this zone more precisely than approximately at the Jurassic–Cretaceous boundary, or within the Tithonian. For ease of usage it is appropriate to place the base of the *B. eneabbaensis* Zone, and therefore the base of the Parmelia Group, at the start of the Cretaceous, while accepting that this position may be revised.

From the above discussion, it follows that the entire Parmelia Group is regarded as Berriasian in age for the purposes of this Report.

Backhouse (1988) outlined the distribution of various dinoflagellate species in the *Fusiformacysta tumida* Zone (which corresponds to the Parmelia Group), but stated that no subdivision had been attempted at that stage, although there was potential to do so. All of the Parmelia Group falls within Backhouse's (1988) *Biretisporites eneabbaensis* Spore–pollen Zone and, unlike the dinoflagellates, there is no evidence to suggest that this zone is amenable to subdivision. Therefore, any biostratigraphic subdivision of this thick and relatively uniform succession must depend largely on differential distribution of the unusual non-marine dinoflagellates that are to be found in many samples. An unpublished report prepared for Ampol Exploration by Ingram (1991) subdivides the Parmelia Group of the northern Vlaming Sub-basin into nine subzones, partly by utilizing variations in dinoflagellate distribution described by Backhouse (1988), but also using quantitative changes of reworked palynomorphs and the simple, spherical alete pollen *Spheripollenites*. Ingram's report is the basis for the palynological subdivision presented here. The boundaries between the subzones are necessarily gradational, and in most cases they are somewhat arbitrary. The subdivision works best over long intervals, where a sequence of subzones can be observed, and where lithostratigraphic changes are also apparent. The subzones should not be regarded as formal biostratigraphic units, but rather they are loosely defined units that have shown some utility in the Vlaming Sub-basin. Application of this zonal scheme has been found to work on a broad scale, and in the absence of alternatives, except log correlation, it is the basis for the well correlation presented in this Report (Fig. 10; Plate 2). The scheme has not been applied outside the Vlaming Sub-basin, and it is unlikely that most of the subzones can be recognized in other parts of the Perth Basin, or in other basins. Indeed, many of the subzones are known with certainty from only one or two wells, and are untested even within the Vlaming Sub-basin. A fuller description of the subzones is provided by Ingram (1991).

Subzone A

This is the basal subzone in which various lagoonal dinoflagellates are present, together with diverse reworked palynomorphs, particularly in the lower part. Lithologically it corresponds to the Otorowiri Formation. A reference section is present in Gage Roads 1 between 2566.5 and 2612 m (sampled interval).

Subzone B

In this subzone, shale beds contain infrequent dinoflagellates and relatively few reworked forms, which are more frequent in the upper part. Lithostratigraphically, this zone approximates the Jervoise Sandstone, and a reference section is present in Gage Roads 2 from 1792 to 2836.5 m.

Subzone C

This is a tenuously defined subzone that is nevertheless identifiable in at least two wells. It is an interval in which the small alete pollen *Sheripollenites psilatus* Couper is more abundant than usual (it is present in many other samples). Dinoflagellates and reworked palynomorphs may be present in relatively small numbers. This subzone is present in the lowest interval of the Carnac Formation, for example in Gage Roads 2 at 1771 m.

Subzone D

In subzone D, lagoonal dinoflagellates of the genus *Moorodinium* are predominant, particularly in the upper part. This subzone is best represented by the interval in the lower Carnac Formation from 1339.5 to 2114.5 m in Roe 1, where Backhouse (1988) recorded a high percentage of *Moorodinium* spp., but few reworked palynomorphs compared with higher levels in the Carnac Formation in this well.

Subzone E

This subzone is represented by the interval from 876.5 to 1285.5 m in the upper part of the Carnac Formation in Roe 1, where reworked Permian and Triassic palynomorphs, especially acritarchs, are abundant. *Moorodinium* spp. may be present, but they are fewer in number than in the underlying subzone D. The transition from subzone D to E is particularly arbitary because of fluctuations in the the proportion of reworked palynomorphs between samples and between wells.

Subzone F

The top few metres of the Carnac Formation in Charlotte 1 (2166 to 2179.5 m) contain abundant *Pentafidia* sp., an undescribed form with a membraneous autophragm that is slightly different from the two described species of the genus, *P. charlottensis* and *P. punctata*. The presence of this dinoflagellate in significant numbers, together with a dramatic decrease in the number of reworked palynomorphs, is used to define subzone F. However, it is only known, to date, from Charlotte 1.

Subzone G

This subzone is identified in Charlotte 1, at 2057 m, in a shale band in the lower part of the Charlotte Sandstone. *Pentafidia punctata* is abundant at this level (Backhouse, 1988) and reworked palynomorphs are virtually absent.

Subzone H

The replacement of *P. punctata* by *P. charlottensis* is the basis for recognizing this subzone. *P. charlottensis* is a robust dinocyst that is common in samples from 1932 to 1975.5 m in Charlotte 1.

Subzone I

In this subzone, which falls in the highest known interval in the Charlotte Sandstone, Ingram (1991) noted that *Tetrachacysta baculata* is the most common dinoflagellate, although *Moorodinium* spp. and *P. charlottensis* are also present. Reworked palynomorphs are present, but rare, and the interval has no other distinguishing characters except that it lies above subzones G and H. The subzone has been identified from 1588.6 to 1826.5 m in Charlotte 1.

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PERTH BASIN

CRETACEOUS	Warnbro Group	▨
	Main unconformity	〰
	Parmelia Group	▨
JURASSIC	Yarragadee Formation	▨
	Cadda Formation	▨
	Cattamarra Coal Measures	▨
	Eneabba Formation	▨

SOUTHERN PERTH BASIN

TRIASSIC	Lesueur Sandstone	Myalup Member	▨
		Wonnerup Member	▨
		Sabina Sandstone	▨
PERMIAN	Sue Group	Willespie Formation	▨
		Redgate Coal Measures	▨
		Ashbrook Sandstone	▨
		Rosabrook Coal Measures	▨
		Woodynook Sandstone	▨
		Mosswood Formation	▨
PRECAMBRIAN		Basement	▨

NORTHERN PERTH BASIN

TRIASSIC	Lesueur Sandstone	▨
	Woodada Formation	▨
	Kockatea Shale	▨
PERMIAN	Beekeeper Formation	▨
	Carynginia Formation	▨
	Irwin River Coal Measures	▨
	High Cliff Sandstone	▨
	Holmwood Shale	▨
	Nangetty Formation	(not present)
PRECAMBRIAN	Basement	▨

PALYNOLOGICAL ZONES USED IN THIS PLATE

	ABBREVIATION	ZONE NAME
JURASSIC	***M. flor***	*Murospora florida*
	C. cook	*Contignisporites cooksoniae*
	C. turb	*Callialasporites turbatus*
	C. tor	*Corollina torosa*
TRIASSIC	***S. quad***	*Staurosaccites quadrifidus*
	T. play	*Triplexisporites playfordii*
	P. sam	*Protohaploxypinus samoilovichii*
?	***P. micr***	*Protohaploxypinus microcorpus*
PERMIAN	***D. parv***	*Dulhuntyispora parvithola*
	D. eric	*Didecitriletes ericianus*
	M. vill	*Microbaculispora villosa*
	P. sin	*Praecolpatites sinuosus*
	M. tris	*Microbaculispora trisina*
	S. fus	*Striatopodocarpites fusus*

Note: Determinations for Woodada 3 are extrapolated from Woodada 1 and East Lake Logue 1

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
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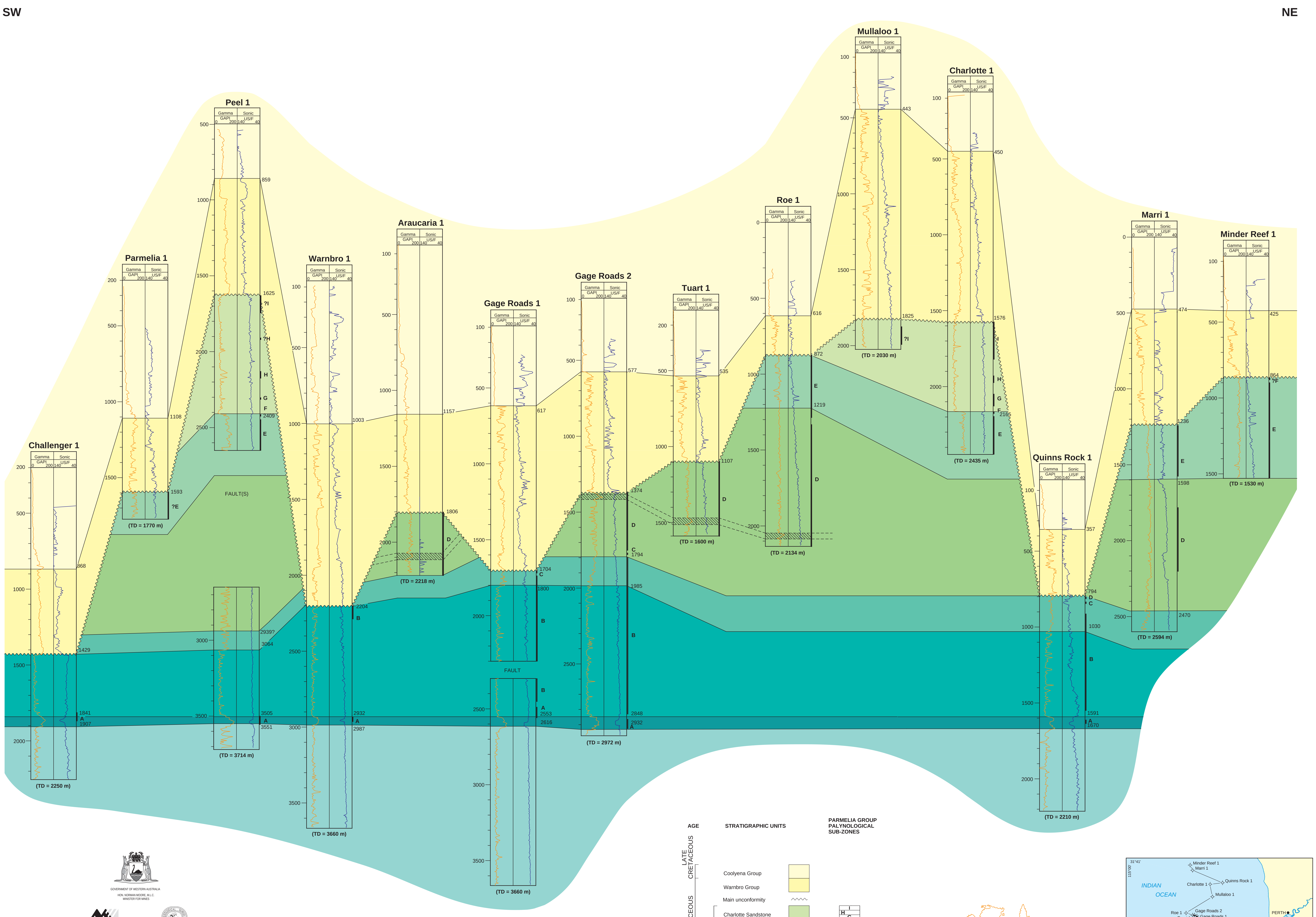
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
REPORT 57 PLATE 1

SOUTH–NORTH LOG CORRELATION:
SUE 1 TO WOODADA 3



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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
REPORT 57 PLATE 2

PARMELIA GROUP LOG CORRELATION WITHIN THE VLAMING SUB-BASIN: CHALLENGER 1 TO MINDER REEF 1

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AGE			STRATIGRAPHIC UNITS		PARMELIA GROUP PALYNOLOGICAL SUB-ZONES
LATE CRETACEOUS			Coolyena Group	🟨	
EARLY CRETACEOUS			Warnbro Group	🟨	
			Main unconformity	〰	
	Parmelia Group		Charlotte Sandstone	🟩	I H G F
		Carnac Formation	Hawley Member	🟩	E
			Mangles Member	▨	D
			Stragglers Member	🟩	C
			Jervoise Sandstone	🟦	B
LATE JURASSIC			Otorowiri Formation	🟦	A
			Yarragadee Formation	🟦	

▨ Radioactive shale