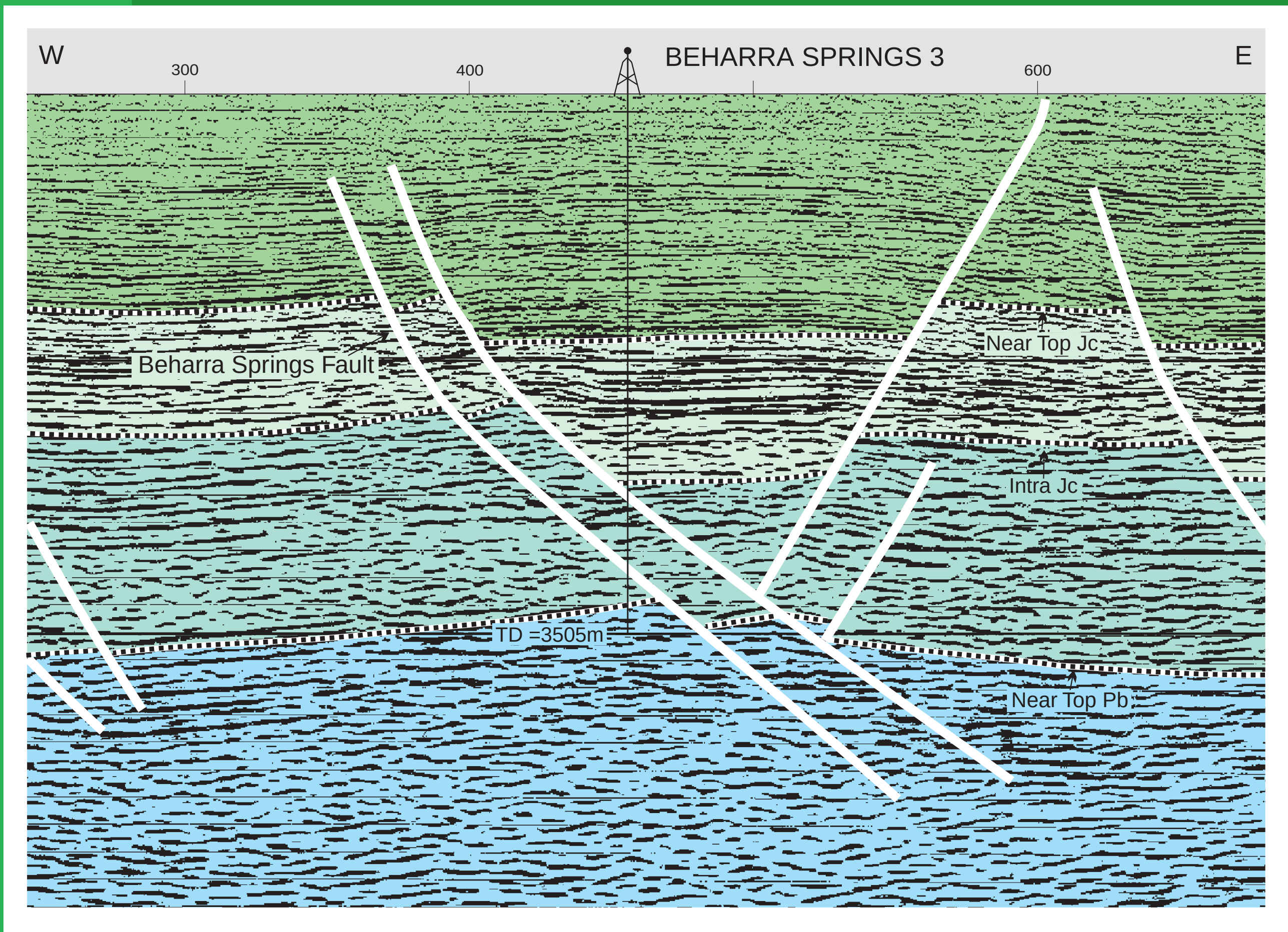
REPORT
43

AN EVALUATION OF THE HYDROCARBON POTENTIAL OF THE ONSHORE NORTHERN PERTH BASIN WESTERN AUSTRALIA

by A. Crostella



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 43

AN EVALUATION OF THE HYDROCARBON POTENTIAL OF THE ONSHORE NORTHERN PERTH BASIN, WESTERN AUSTRALIA

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A. Crostella

Perth 1995

MINISTER FOR MINES
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Copy editor: J. A. Mikucki

REFERENCE

The recommended reference for this publication is:

CROSTELLA, A., 1995, An evaluation of the hydrocarbon potential of the onshore northern Perth Basin: Western Australia Geological Survey, Report 43, 67p.

National Library of Australia
Cataloguing-in-publication entry

Crostella, A. (Angelo), 1929–.
An evaluation of the hydrocarbon potential of the onshore northern Perth Basin, Western Australia

Bibliography.
ISBN 0 7309 4471 9

1. Petroleum — Geology — Western Australia — Perth Basin.
2. Petroleum — Prospecting — Western Australia — Perth Basin.
3. Perth Basin (W.A.).

I. Geological Survey of Western Australia.
II. Title. (Series: Report (Geological Survey of Western Australia); no. 43).

553.28099411

ISSN 0508–4741

Cover picture: **Part of an interpreted seismic line (Yandanooka Seismic Survey, line S92-11) across the Beharra Springs gasfield showing the Beekeeper Formation (Pb) and Cattamarra Coal Measures (Jc). Modified from Beharra Springs 3 well-completion report.**

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An evaluation of the hydrocarbon potential of the onshore northern Perth Basin, Western Australia

by

A. Crostella

Abstract

Intracratonic sedimentation commenced in the onshore northern Perth Basin in the Early Permian and continued until the fragmentation of Gondwanaland in the Early Cretaceous, with only local interruptions. Structurally, the basin is characterized by basement-related regional faults with a history of growth. The main faults were rejuvenated by breakup tectonism, which caused horizontal displacements, wrench-induced anticlines, and further faults.

Exploration for hydrocarbons commenced in the fifties and resulted in the discovery of six hydrocarbon fields of economic significance. Three discoveries were made in the late 1960s, two in the 1980s and one so far in the 1990s, in direct relation to exploration efforts. The present rate of success is estimated to be one out of ten. Analysis of the lithostratigraphic units, structural setting, oil and gas accumulations, and hydrocarbon shows indicates that mature source rocks are widespread, that reservoirs are abundant, and that structures are well timed for hydrocarbon entrapment. A critical factor is considered to be the seal, since the structures covered by shales that are thinner than the throw of the faults may lose their trapping potential. This is important due to the intense faulting and high sand/shale ratio of the post-Early Triassic sequence.

Seven main basin subdivisions are proposed, namely the Allanooka High, Dongara Terrace, Beharra Springs Terrace, Cadda Terrace, Donkey Creek Terrace, Coomallo Trough, and Dandaragan Trough. The high source-rock potential for both oil and gas, the presence at drillable depth of Early Triassic seals and Late Permian objectives, and the abundance of anticlinal structures, suggest that the first four sub-basins as listed offer the best chances for further hydrocarbon discoveries. Exploration efforts should be particularly rewarding when directed towards the faulted flanks of the anticlines, which provide gas-bearing traps for the Mondarra and Beharra Springs fields. The crests of the anticlines have been the main drilling target since the early stages of exploration, but the structures could be better defined in areas that presently have limited seismic coverage. Hydrocarbon potential is also offered by the remaining sub-basins; they may offer interesting, albeit high-risk prospects.

Keywords: petroleum potential, regional geology, hydrocarbon accumulations, oil wells, structural traps, reservoirs, source rock, north Perth Basin, Western Australia

This report on the hydrocarbon potential of the onshore northern Perth Basin complements the basin analysis by Mory and Iasky (in prep.) who discussed the structure and stratigraphy of the area. The study is the first of a series in which the stratigraphy and structure of each Western Australian basin will be analysed in relation to oil and gas potential. The hydrocarbon potential of the onshore northern Perth Basin is reviewed by assessing the six known accumulations of economic significance, by producing post-mortems of selected wells, and by analysing traps, sources, reservoirs, and seals.

It is intended that the analysis in this report will stimulate the current thinking in petroleum exploration of the onshore northern Perth Basin. As elsewhere, discoveries in this basin can be related to new ideas and new companies entering the exploration arena (Table 1).

Previous regional reviews of the area have been produced by Playford et al. (1976), who dealt chiefly with the geological aspects; Jones (1976), whose main interest was the hydrocarbon occurrences; Thomas (1984), who discussed in particular the relationships between hydrocarbons and source rocks; and Hall (1989), who

Table 1. Hydrocarbon discoveries of economic significance in the onshore northern Perth Basin

Year	*Field*	*Company*
1964	Yardarino	WAPET
1966	Dongara	WAPET
1968	Mondarra	WAPET
1980	Woodada	Hughes and Hughes
1982	East Lake Logue	Hudbay Oil (Australia)
1987	Mount Horner (Main Pool)	Barrack Petroleum
1990	Beharra Springs	Barrack Petroleum

emphasized the promising future of petroleum exploration in the basin. Albeit indirect, the most important contribution to the structural understanding of the north Perth Basin has come from the offshore part of the basin, where a large amount of good quality, recent data is available. The tectonic framework of the offshore north Perth Basin has been discussed and illustrated in detail by Smith and Cowley (1987), Marshall et al. (1989), and Stein et al. (1989). An exhaustive review of previous work can be found in Mory and Iasky (in prep.).

Regional framework

The north-trending Perth Basin extends from the Darling Fault in the east as far as the continental slope. Figure 1 shows the subdivisions of the basin, as proposed by Stein et al. (1989): the western margin, which lies beneath the Indian Ocean in deep water, is ill-defined.

The stratigraphy of the onshore northern Perth Basin is well known, from both the detailed surface mapping, carried out in particular by the Geological Survey of Western Australia, and from more than 150 wells drilled for hydrocarbon exploration in the region. An in-depth analysis and discussion of the stratigraphy is presented by Mory and Iasky (in prep.). Figure 2 illustrates the relationships between the lithostratigraphy and the petroleum geology.

Stratigraphy and geological history

Intracratonic sedimentation commenced in the Early Permian, with the melting of the Gondwana ice cap and the subsequent rise in sea level. Throughout Permian time, north-trending regional growth faults marked the progressive rifting of the basin. Figure 3, which is derived from the structural maps of Mory and Iasky (in prep.), shows the major tectonic elements of the northern Perth Basin, whereas Figure 4 indicates the location of regional geological cross sections and seismic sections. The growth faults controlled the differential downwarp of the discrete subdivisions of the basin.

Deposition of the continental sedimentary rocks at the base of the Permian Nangetty Formation was followed by continental and marine sedimentation, with deposition of the Holmwood Shale, the High Cliff Sandstone, the Irwin River Coal Measures, and the Carynginia Formation (in ascending order) during the Early Permian. The sedimentary succession was interrupted in parts of the basin by Mid–Late Permian tectonic activity, which resulted in the uplifting of tilted fault blocks. Subaerial exposure and subsequent erosion then followed in the uplifted area. The best examples of the tilted fault blocks can be seen offshore, as in the seismic sections of Smith and Cowley (1987). Onshore, there is evidence of uplift in the outcropping Northampton Complex. In that part of the north Perth Basin which surrounds the complex, uplift is documented by extensive erosion of Permian sedimentary rocks (Mory and Iasky, in prep., plate 12). The erosion is progressively more intense approaching the Northampton Complex. Uplifted or tilted fault blocks of Late Permian age have not been recognized elsewhere in the seismic sections. In large tracts, however, Permian sedimentary rocks have not been reached and therefore no firm conclusions can be made.

The Wagina Formation was deposited either without stratigraphic hiatus, or transgressed over the Early Permian sedimentary rocks. Bergmark and Evans (1987) discussed the depositional aspects of the unit. The sandstone of the Wagina Formation is thicker near the Urella–Darling Fault System: this was probably the result of an increasing Mid–Late Permian movement along the plane of the fault. Such movement was contemporaneous with the tectonic activity in other parts of the basin, and caused a sudden increase of coarse clastic sediments in the area that came from the Yilgarn Craton. Following the most recent usage (Hall and Kneale, 1992; Tupper et al., 1994), the Wagina Formation is considered to also comprise the unit previously called the Basal Triassic Sandstone or Yardarino Sandstone.

The Beekeeper Formation is mainly represented by a bioclastic shelf limestone that is coeval with the Wagina Formation. The Beekeeper Formation was deposited along the western margin of the basin as far south as the Cadda 1 and Woolmulla 1 wells, as suggested by Mory and Iasky (in prep.). The transition between the two units is gradual and occurs between the Mondarra and Beharra Springs gasfields. Limestone in the Beekeeper Formation is related to a western source, as discussed by Tupper et al. (1994). Such a distribution suggests that vertical movement along the Beagle Fault at the time of sedimentation was of lower magnitude than the movement along the Urella–Darling Fault System.

The rifting activity progressed until the Early Triassic, when a marine environment was re-established, as indicated by the deposition of the Kockatea Shale. The presence of a second hiatus between the Late Permian and the Early Triassic is suggested by the absence of some palynological zones. However, this can be alternatively explained by either insufficient sampling or that the sandstones in the time-equivalent section are undatable. The standard palynological zonation may not be applicable to the Perth Basin. It is worth noting that the remarkably

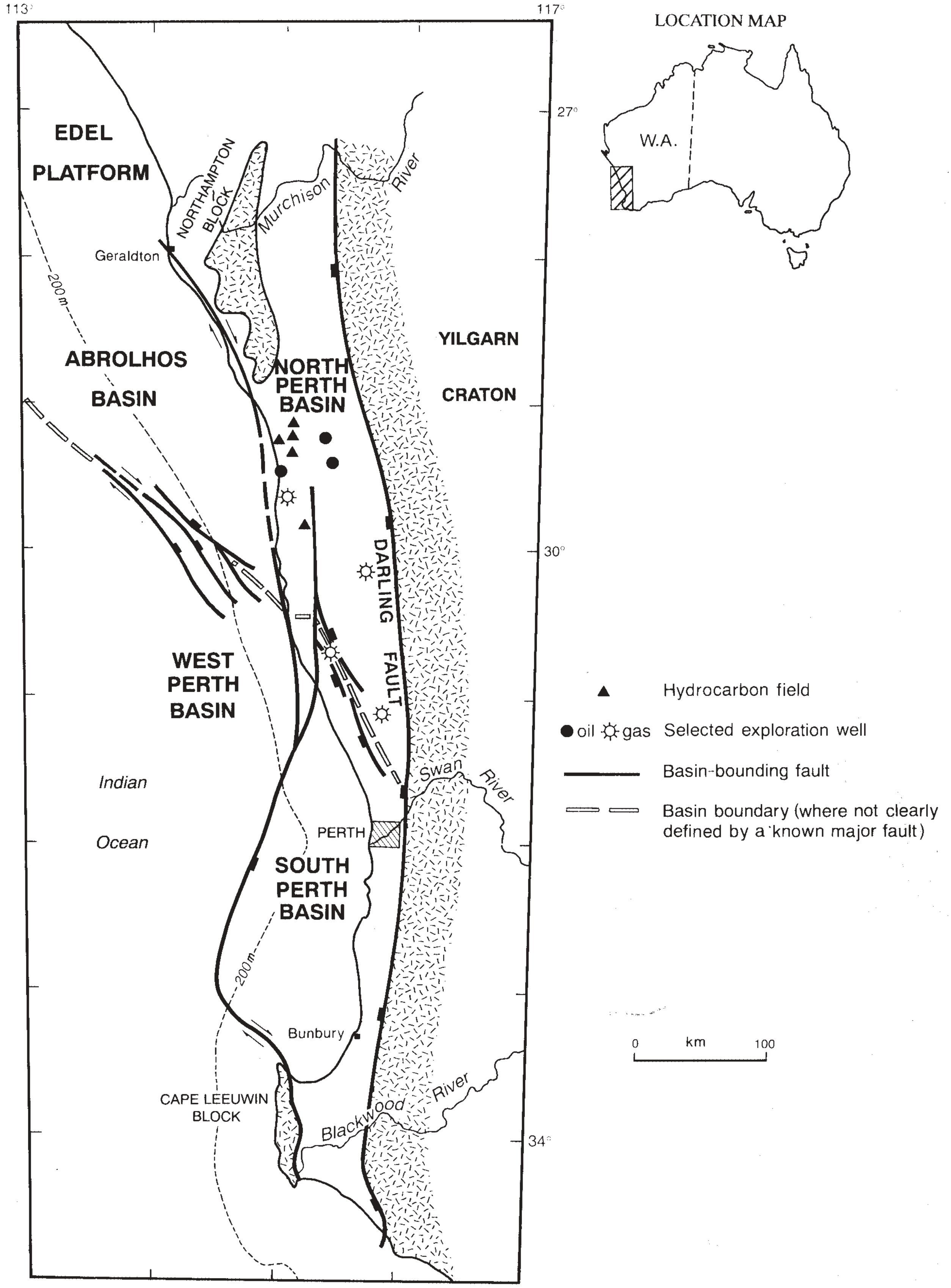

Figure 1. Regional setting of the Perth Basin (after Stein et al., 1989)

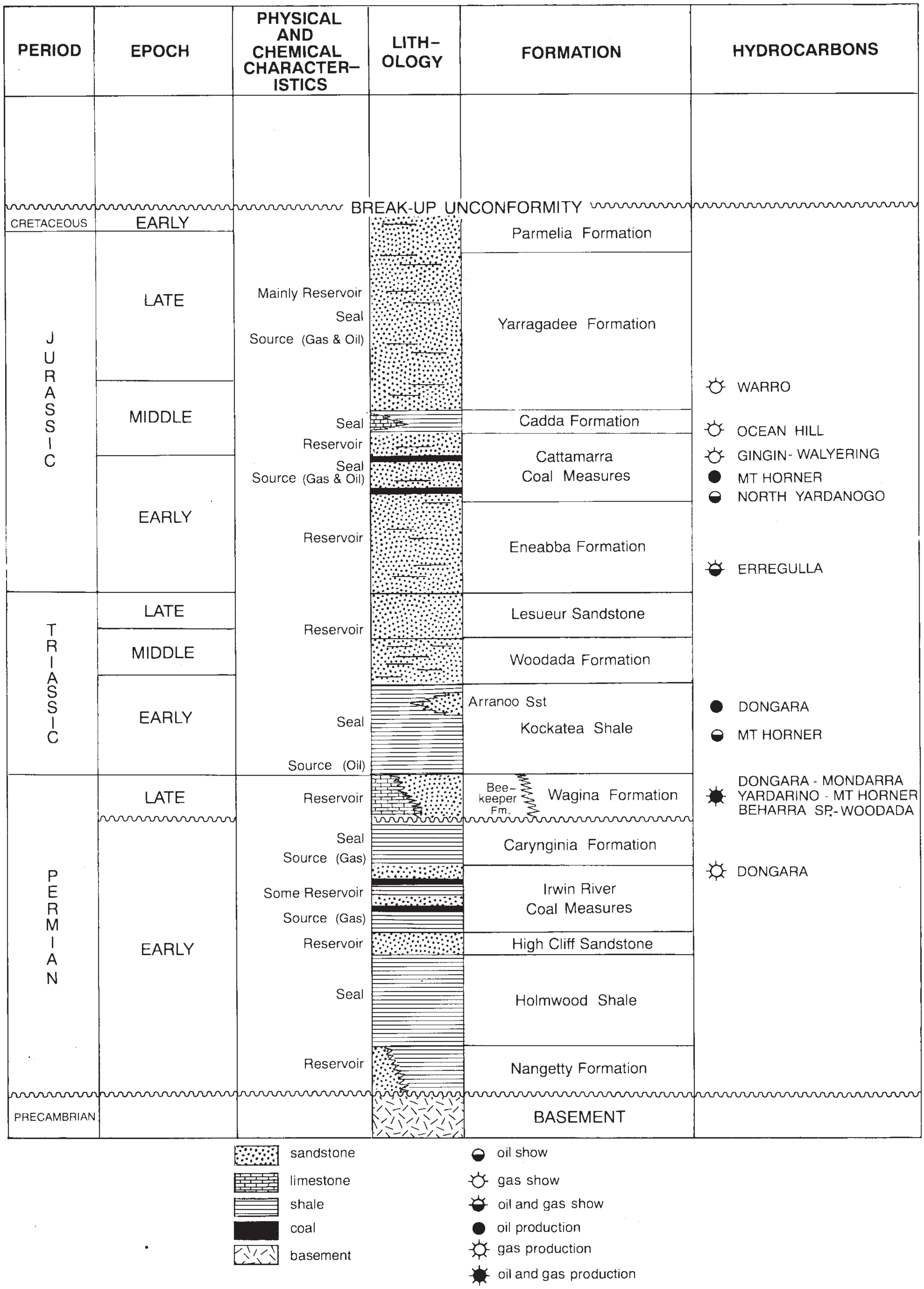

Figure 2. Generalized stratigraphy of the Perth Basin

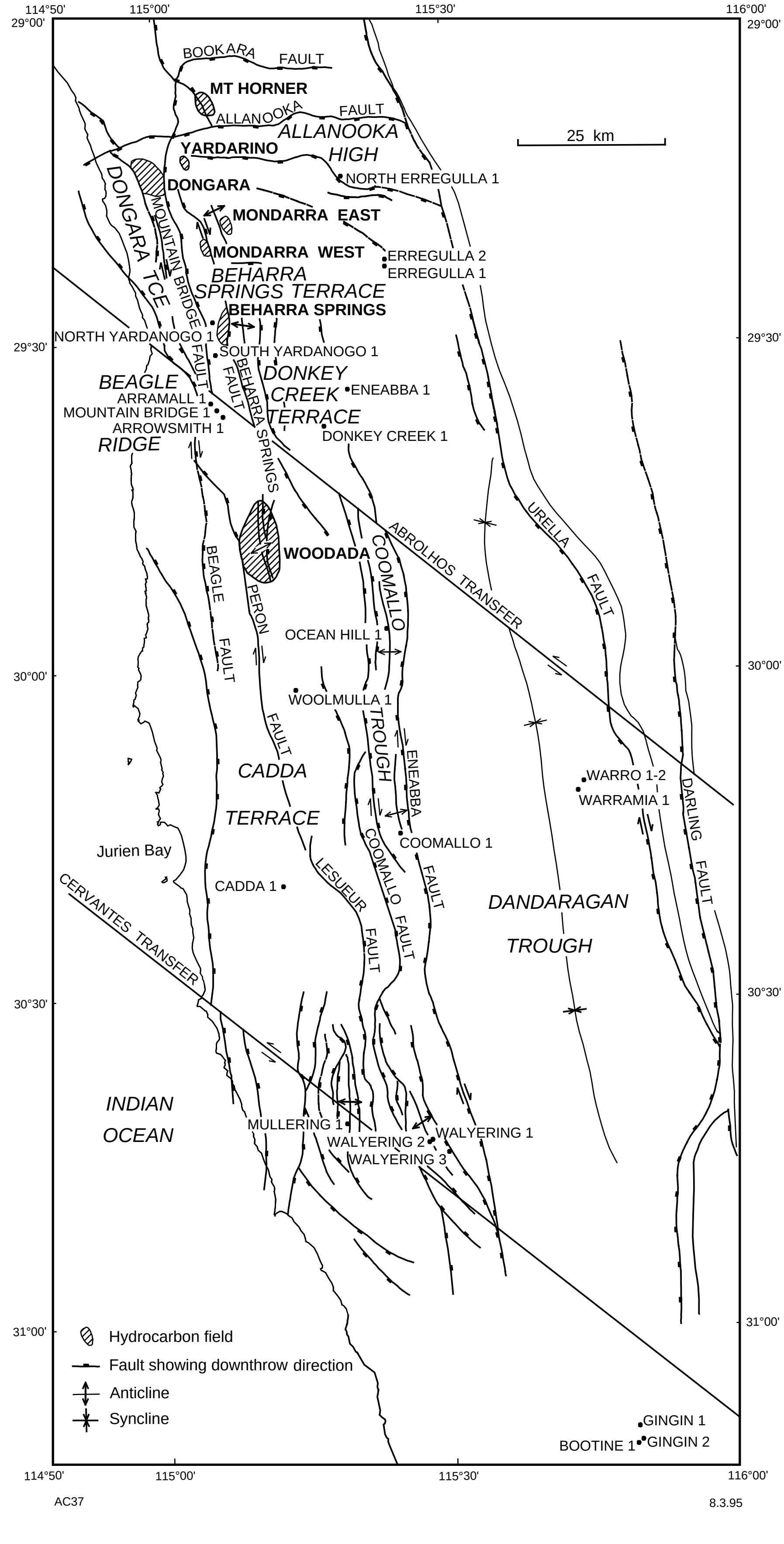

Figure 3. Onshore northern Perth Basin: tectonic elements, hydrocarbon fields, and selected exploration wells

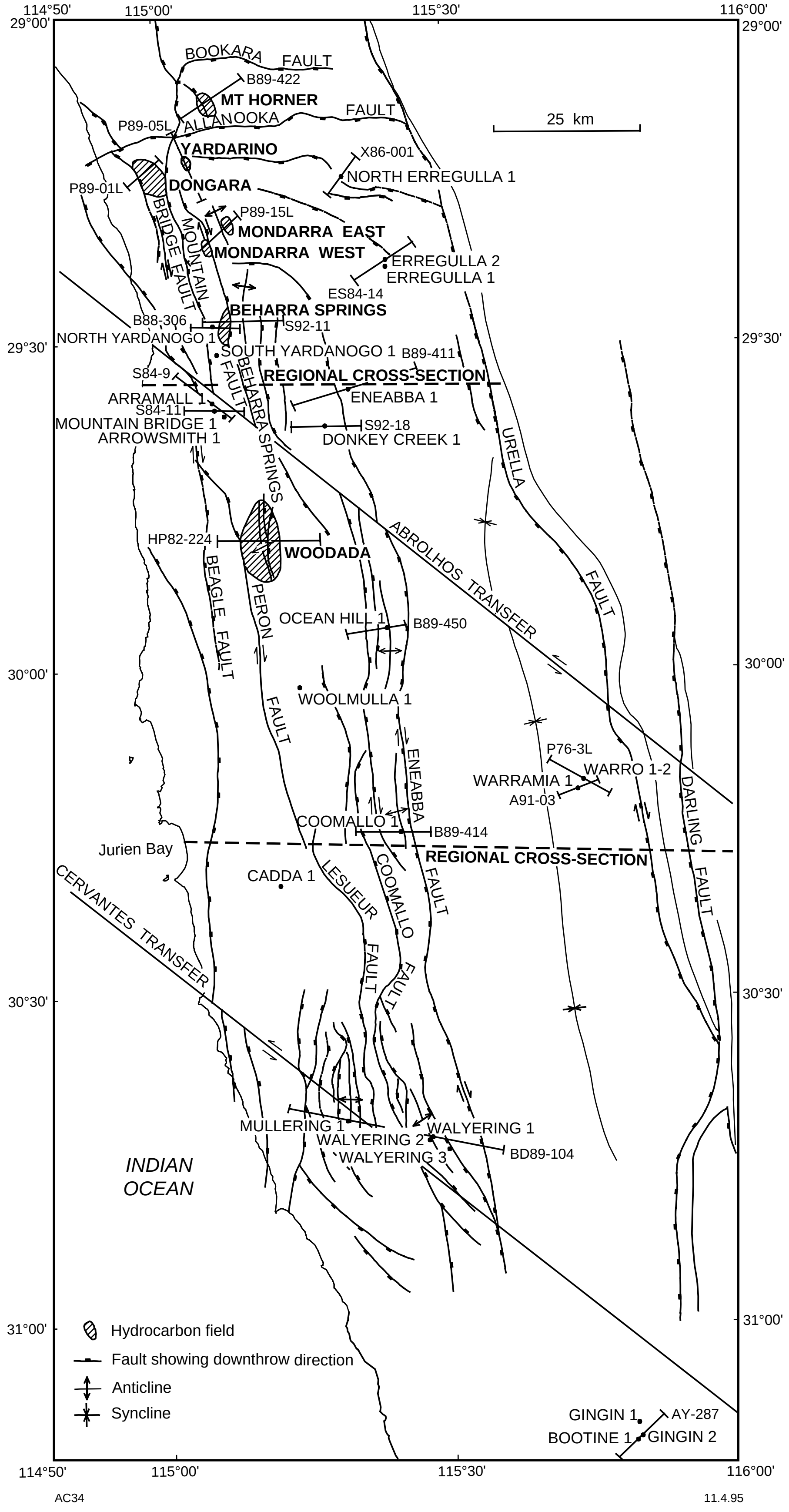

Figure 4. Index map showing regional cross sections and seismic sections

constant thickness of the Beekeeper Formation over the Woodada area suggests that the contact with the overlying Kockatea Shale is conformable.

Subsidence continued throughout Triassic and Jurassic times, controlled by major down-to-the-basin normal faults. Movements along the fault planes gradually became smaller in magnitude during the Triassic and earliest Jurassic.

The marine Kockatea Shale (Early Triassic) and the marginally marine Woodada Formation (Middle Triassic) were overlain in the Late Triassic by the continental Lesueur Sandstone. North of the Allanooka Fault, part of the Triassic – Early Jurassic sequence is missing, suggesting that during this time subsidence ceased altogether in this area. The fact that the Woodada Formation is either absent, probably due to erosion, or disconformably overlain by the Eneabba Formation or the Cattamarra Coal Measures, suggests a Late Triassic emergence. In the Jurassic, sediments either progressively onlapped the exposed Triassic beds, or were deposited on the Lesueur Formation without hiatus. The sequence evolved from a continental environment (Eneabba Formation) to a marginal marine environment with fluvial influence (Cattamarra Coal Measures), to a marine environment (Cadda Formation). Fault-controlled subsidence, related to renewed rifting, increased rapidly during the Middle to Late Jurassic: the Yarragadee Formation is up to 4000 m thick along the eastern margin of the basin (Warro wells; Fig. 5). At the end of the Jurassic the basin was close to its present form, with a very thick eastern section. The present shape of the basin is commonly described in the literature as a half graben, although its eastern part is characterized by the Dandaragan Trough, which is actually a syncline. In effect, the thickest sedimentary sequence in the onshore north Perth Basin covers the entire area between the Darling and Coomallo Faults (i.e. virtually half of the onshore north Perth Basin; Fig. 3).

Further to the south, at the latitude of the Gingin wells, depositional thickening has occurred from east to west (Fig. 6). The only well that has been drilled in the area to the west of the Gingin structure (Badaminna 1) did not penetrate the entire thickness of the Cattamarra Coal Measures, but seismic data indicate a substantial thickening of the formation. This would imply that the vertical movements along the Beagle Fault System at the latitude of the Gingin wells occurred at an earlier stage than those along the Urella–Darling Fault System. This differential basinal downwarp is related to the gradual shallowing of the Dandaragan Trough and the decreasing throw of the Eneabba Fault in the southern part of the area. As Figure 6 demonstrates, both the depositional and structural setting of the Gingin area differ from those to the north.

The seismic data suggest that there are no unconformities in the Triassic to Jurassic sequence. The continental Parmelia Formation was deposited on the Yarragadee Formation until the sedimentary cycle was interrupted by continental breakup in the early Neocomian.

Structure

The rate of sedimentation within the basin was related to downwarp controlled by the growth of the main regional faults. In turn, the growth reflected the magnitude of the rifting-related extensional movements. The only interruptions prior to breakup are represented by the Mid–Late Permian tectonism and by the Late Triassic – Early Jurassic hiatus, both of which are of local significance only.

Breakup tectonism was characterized by dextral strike-slip movements along the main regional north-trending faults, and also, in the Allanooka High, along the east–west striking faults. These horizontal displacements, however, cannot be identified on seismic sections. Transfer faults, such as the Abrolhos and Cervantes Faults, are also related to breakup tectonism. They show a sinistral horizontal displacement (Fig. 3).

The location of the transfer faults cannot be directly distinguished on the onshore seismic lines, but several considerations allow their definition. From west to east, the Beagle Fault in Figure 3 shows a marked bend, whereas the Mountain Bridge and Beharra Springs Faults do not extend to the south of the interpreted line of the Abrolhos Transfer Fault. Further to the east the area between the Beharra Springs anticline and the Eneabba Fault is characterized by normal extensional faults, whereas to the south of the transfer fault compressional anticlines extend eastwards to the Eneabba Fault. The Dandaragan syncline is well defined only to the south of the Abrolhos Fault. Finally, the Urella Fault also shows a sharp bend at the intersection with the Abrolhos Fault.

Horizontal displacements along the pre-existing regional faults resulted in additional secondary faulting and anticlines, produced by wrenching. The Early Cretaceous age of the anticlines is supported by the lack of significant pre-Cretaceous breaks in the sedimentary sequence: all pre-breakup strata that can be recognized in the relevant seismic sections are essentially parallel. In the northernmost section of the basin, the north-trending regional faults are represented only by the Mountain Bridge and Urella Faults, whereas there is good evidence of the easterly trending faults such as the Allanooka Fault. The breakup tectonism masked evidence of previous tectonic events in the basin, and determined its present structural setting. The northern Perth Basin can therefore be defined as a strike-slip basin, in which horizontal movements resulted from deeply seated wrench tectonism. This interpretation is consistent with the fact that the primary environment of wrench-fault assemblages are areas near plate boundaries, characterized by transform faults. The strike-slip movements were distributed throughout a set of subparallel faults. Marshall et al. (1989) discussed the structural style of the north Perth Basin and concluded that the extensions, which are characterized by strike-slip faults, are oblique. Although oblique movements are certainly present, due to the trend of the Abrolhos and Cervantes Transfer Faults (Fig. 3), horizontal displacements are subparallel to strike along the Urella, Eneabba, Coomallo, Beharra Springs, Peron, and Beagle Faults.

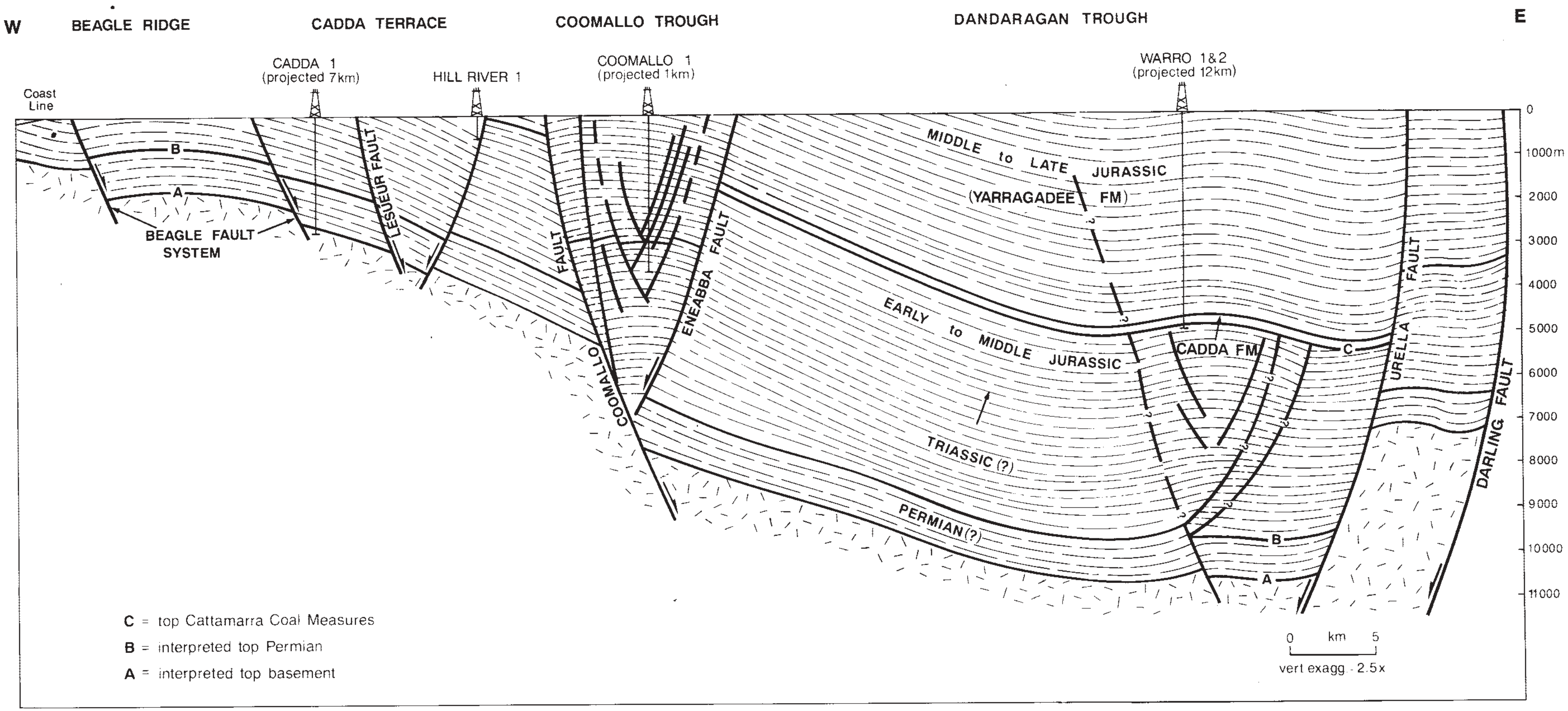

Figure 5. Southern regional cross section: Beagle Ridge – Cadda Terrace – Coomallo Trough – Dandaragan Trough. Section location is shown on Figure 4

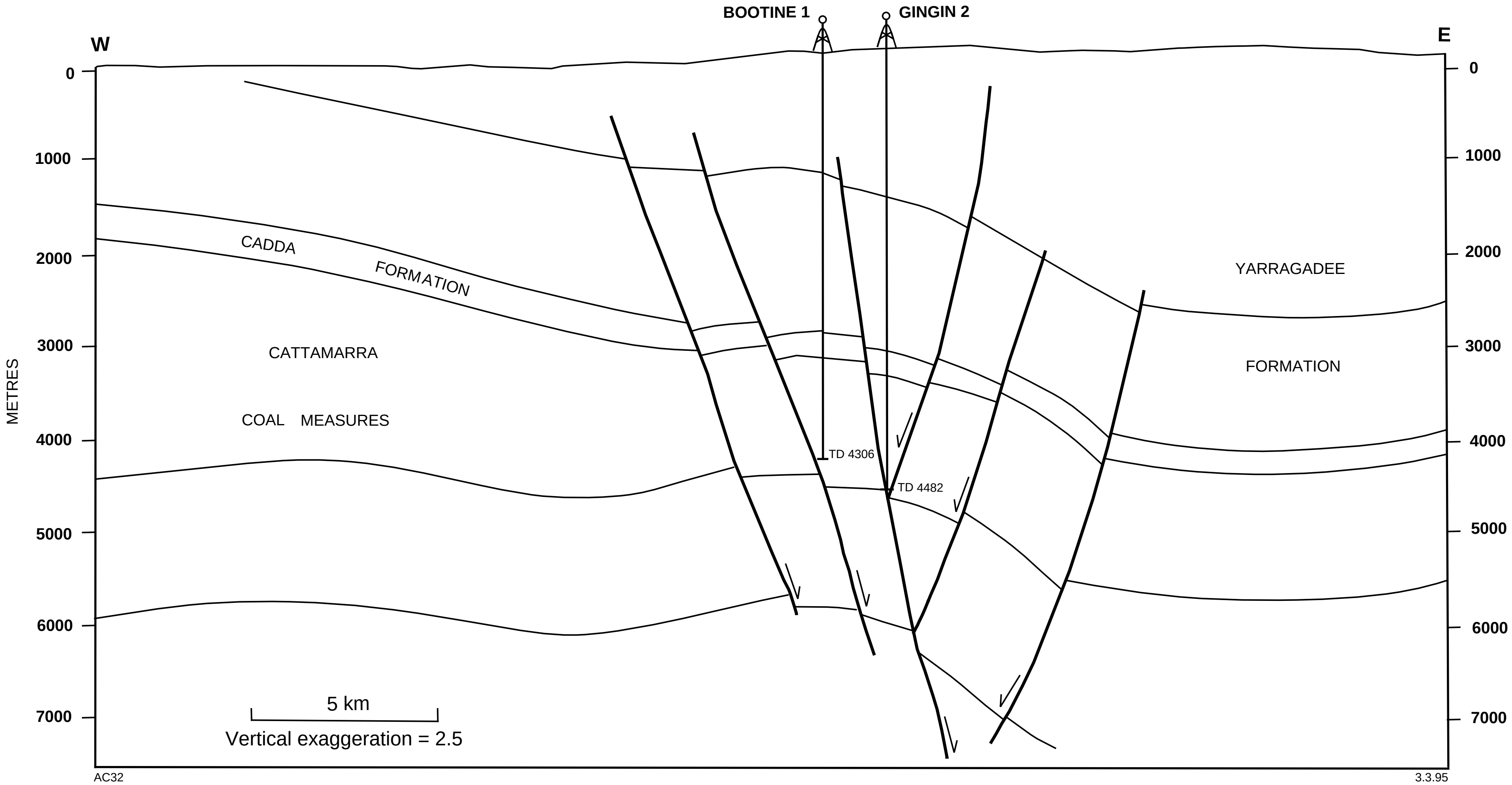

Figure 6. Cross section showing the Gingin structure within its regional context. Part of section AY–287 on Figure 4

It is hypothesized that the northern Perth Basin is characterized by divergent or side by side wrenching. Normal faults delineate the anticlinal features, as illustrated by the numerous seismic sections included in this Report. The proposed interpretation is corroborated by the similarity between the sag structures; the synchronous origin of anticlinal features; the presence of continuous, linear, lengthy trends, suggesting basement involvement (e.g. the Beharra Springs anticlinal trend and the Coomallo Trough; Fig. 3); the local presence of deeply eroded structures (e.g. Mullering); the symmetry of the anticlines, whose subvertical, planar axes intersect the controlling fault(s) at depth (e.g. North Yardanogo 1 and Beharra Springs wells); the widespread negative-flower structures; the absence of slow continuous growth; the largely present parallelism between folds and wrench zones; and the collapse of the central part of the anticlines.

Whereas the faults can be readily determined in the shallower part of the section, the poor seismic data available do not allow for a full investigation of the relationships between faults and basement. It is evident, however, that the maximum principal compressive stress is vertical.

The dramatic result of the tectonic events related to breakup is very evident in the offshore seismic sections presented by Smith and Cowley (1987). The breakup unconformity is clearly the result of the major event in the geologic history of the area. Onshore, the virtual lack of post-tectonic sedimentary rocks prevents a similar visual effect: the Jurassic structures mentioned in the literature are related to the early Neocomian breakup.

Within each major structural element, the depositional thickness of each discrete lithostratigraphic unit is fairly constant. The only exception appears to be the Wagina Formation.

Basin subdivisions

The above discussion of the tectonic evolution of the basin allows the introduction of more detailed basin subdivisions than previously proposed. Figure 7 illustrates the proposed subdivisions of the onshore north Perth Basin west of the Urella Fault, which facilitate a more detailed evaluation of the hydrocarbon potential. The subdivisions are defined below.

The ***Greenough Shelf***, as introduced by Mory and Iasky (in prep.), is the area of shallow basement between the Dongara Terrace to the north, the Allanooka High to the east, the outcropping Northampton Complex to the north, and the Abrolhos Sub-basin to the west.

The ***Allanooka High*** is characterized by easterly trending faults, a sedimentary sequence that becomes progressively thicker from north to south, and a higher geothermal gradient than that in the Dandaragan Trough (Fig. 8). To the west, the boundary between the Allanooka High and the Greenough Shelf is marked by the Mountain Bridge Fault. The northern boundary lies to the north of the study area. The eastern boundary is represented by the Urella Fault, whereas to the south the gradual transition to the Dandaragan Trough is tentatively drawn to correspond with the westerly trending section of the Eneabba Fault. Such a section marks the remaining part of the southern boundary. The boundary between the Allanooka High and the Beharra Springs Terrace to the west is taken to correspond with the easternmost fault intersecting the Beharra Springs – Mondarra – Yardarino trend. The geothermal gradient averages 3°C/100 m, although it gradually decreases southwards. Gentle anticlines on the downthrown section of the normal controlling faults are typical features of the Allanooka High (Mount Horner oilfield), the Dongara Terrace (Dongara oil- and gasfield), and the northern part of the Cadda Terrace (Woodada gasfield).

The ***Dongara Terrace*** is bounded to the north by the Allanooka Fault, to the east by the Mountain Bridge Fault, to the south by the Abrolhos Transfer Fault, and to the west by the Beagle Fault. The Dongara Terrace represents a structurally intermediate area between the Beagle Ridge and the Beharra Springs Terrace. The geothermal gradient is high, ranging from 3 to 3.5°C/100 m and locally reaching 4°C/100 m. Depth to basement is in the order of 2000 m.

The ***Beharra Springs Terrace*** is structurally intermediate between the Dongara Terrace to the west and the Donkey Creek Terrace to the east. It is bounded to the west by the Mountain Bridge Fault, to the north by the Allanooka Fault, to the east by the easternmost fault intersecting the prominent Beharra Springs – Mondarra – Yardarino trend, and to the south by the Abrolhos Transfer Fault. The geothermal gradient averages 3.5°C/100 m. Depth to basement is more than 4000 m. Large, very gentle, normal-faulted folds with a collapsed central portion are typical of the Beharra Springs Terrace, and are productive in the Mondarra and Beharra Springs fields.

The ***Donkey Creek Terrace*** is structurally in between the higher Beharra Springs Terrace and the lower Dandaragan Trough. It is bounded to the north and to the east by the Eneabba Fault, to the south by the Abrolhos Transfer Fault, and to the west by the easternmost fault intersecting the Beharra Springs – Mondarra – Yardarino trend. Structurally, it is characterized by down to the west north-trending normal faults, which provide steps that interrupt the regional dips to the east (Fig. 9). The compressional anticlines to the south, west, and north do not extend over the Donkey Creek Terrace. Probably no or limited strike-slip movement occurred in the region: the Donkey Creek Terrace covers an area where north-trending faults disappear and into which east-trending faults do not extend. To a certain extent it is a junction of divergent faults, acting like a pivot.

The ***Cadda Terrace*** is here defined as the area limited to the north by the Abrolhos Transfer Fault, to the east by the Coomallo Fault, and to the west by the Beagle Fault. To the south the terrace extends outside the study area. The geothermal gradient is comparable to that of the Dongara Terrace, ranging from 3 to 4°C/100 m. Depth to basement increases from west to east and from north to south, ranging from 2000 to 8000 m.

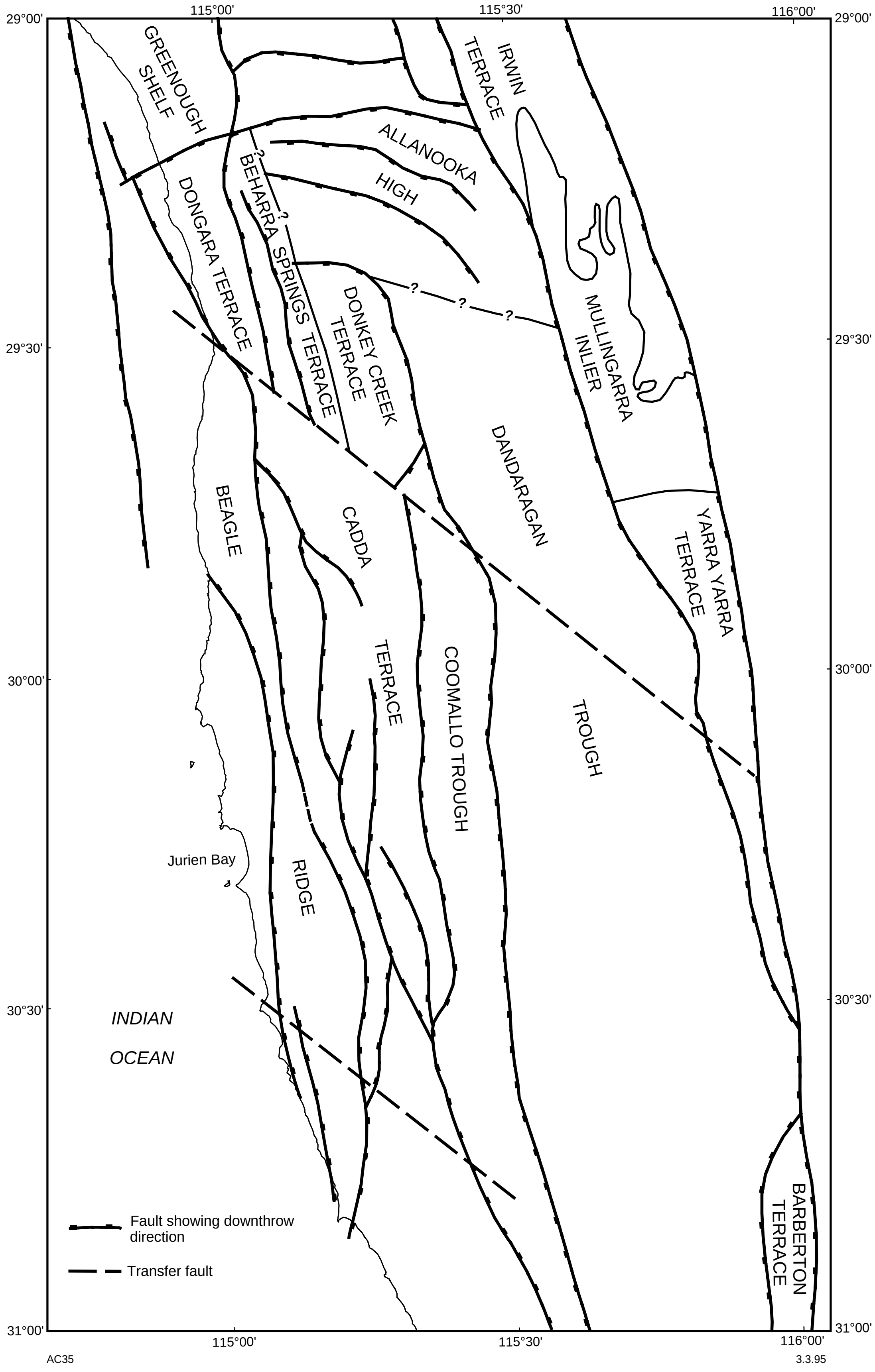

Figure 7. Subdivisions of the onshore northern Perth Basin

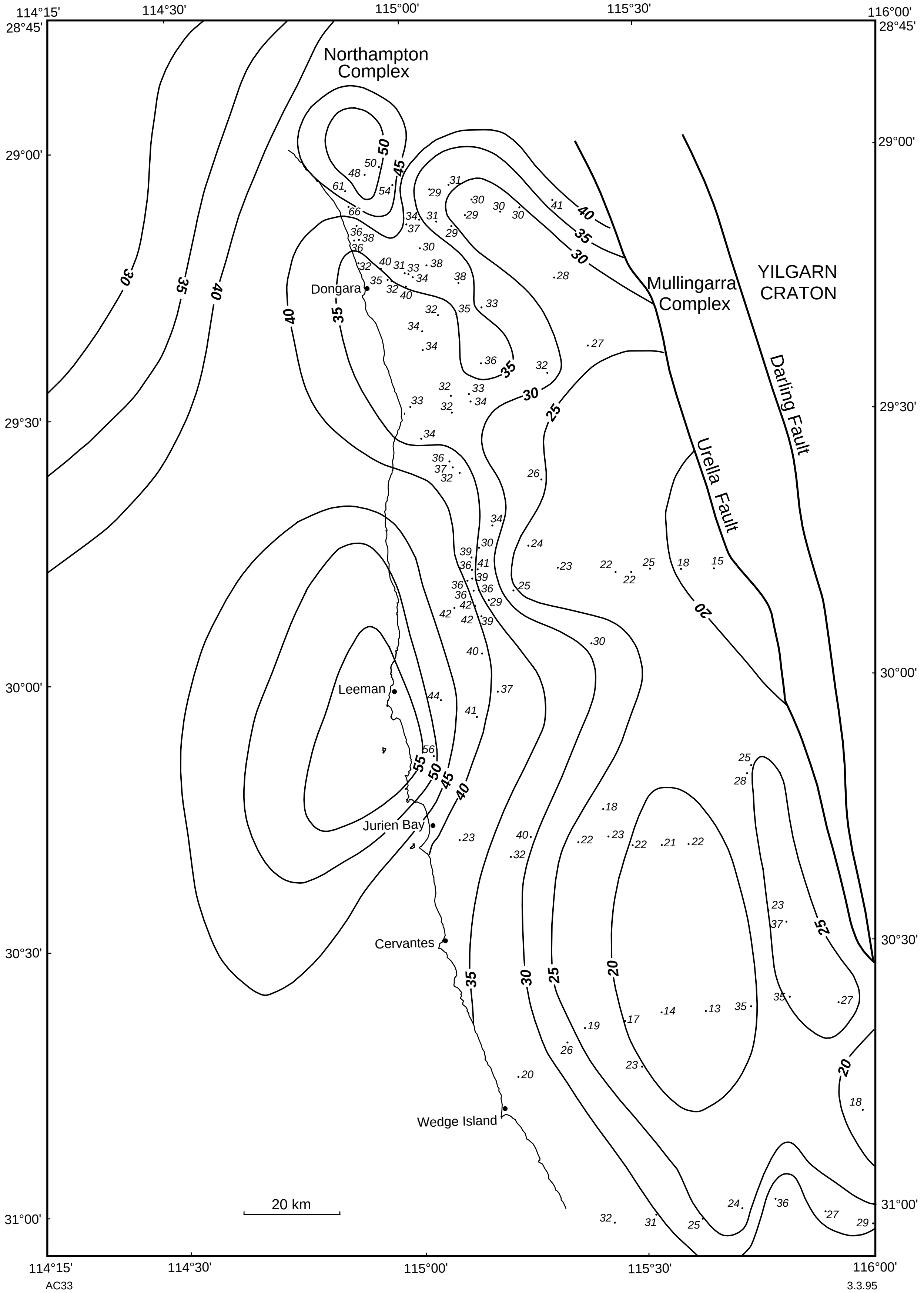

Figure 8. Generalized geothermal-gradient map from corrected bottom-hole temperature for the onshore northern Perth Basin (from Mory and Iasky, in prep.). Contours in °C/km

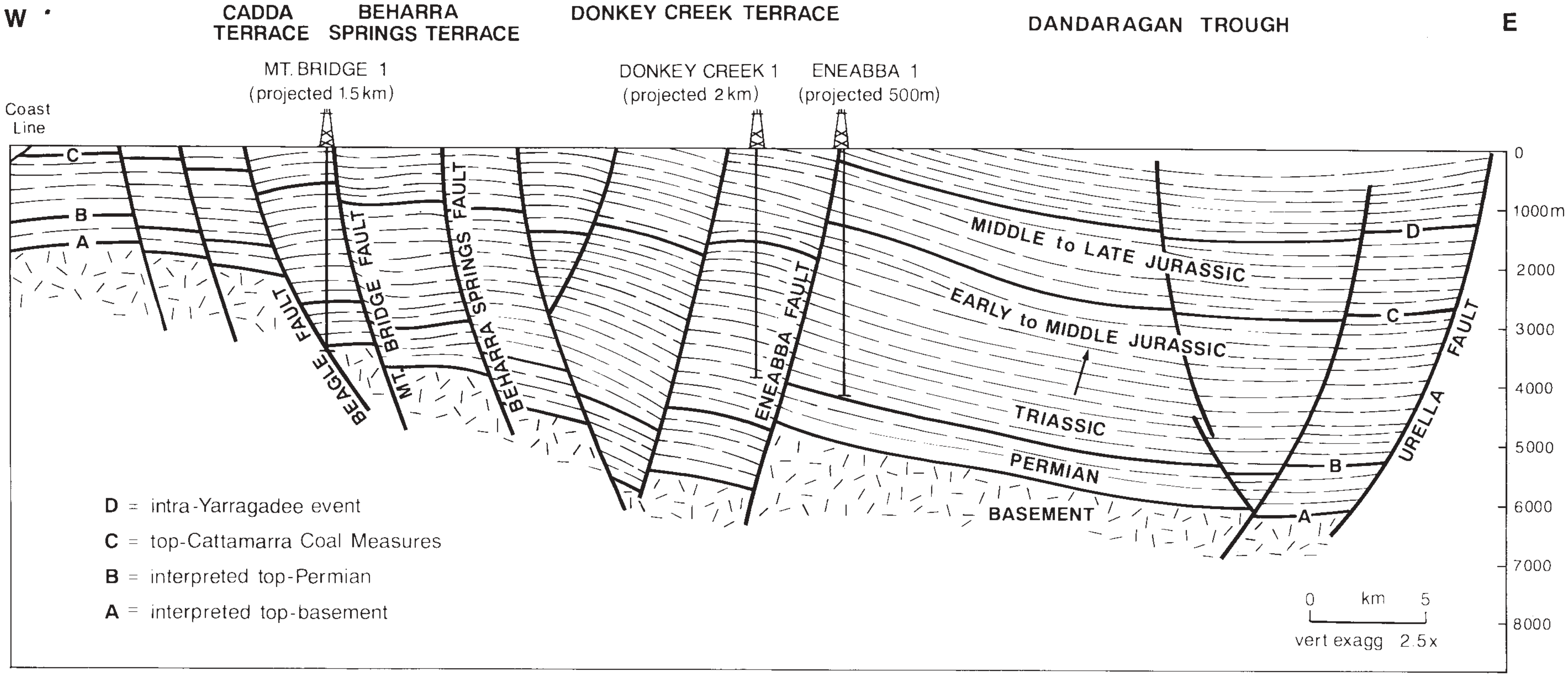

Figure 9. Northern regional cross section: Cadda Terrace – Beharra Springs Terrace – Donkey Creek Terrace – Dandaragan Trough. Section location is shown on Figure 4

The ***Coomallo Trough*** is an elongated depression (Figs 3 and 5) bounded to the north by the Abrolhos Transfer Fault, to the east by the Eneabba Fault, and to the west by the Coomallo Fault. The southern limit is not well defined within the study area. The throw of the Eneabba Fault decreases to the south, suggesting its gradual disappearance in that direction. At the latitude of the Gingin wells the Coomallo Trough is not recognizable (Fig. 6). Bounded by two north-trending faults downthrown towards the axis of the trough, the Coomallo subdivision has characteristics in between those of the Cadda Terrace and the Dandaragan Trough. Wrench anticlines are present, as in the Cadda Terrace (Figs 3 and 5), but the thickness of the sedimentary rocks is as great, and the geothermal gradient as low, as in the Dandaragan Trough. Large, enhanced anticlines, intersected by many normal faults with a collapsed central portion, such as those intersected by Ocean Hill 1, Coomallo 1, and Walyering 1, characterize the Coomallo Trough.

The ***Dandaragan Trough*** is here redefined as the depocentre of the basin. The trough is essentially represented by a huge syncline (Fig. 5) comprising a sequence that is more than 12 000 m thick. Structural highs are limited to its eastern flank. The poorly controlled geothermal gradient appears to range from 2 to 2.5°C/100 m. The boundaries of the Dandaragan Trough are represented to the east by the Urella Fault, and to the west by the Eneabba Fault. The trough shallows towards the south. The northern boundary is tentatively taken at the latitude of the west-trending section of the Eneabba Fault. The faulted Warro anticline exemplifies the few structural highs of the Dandaragan Trough.

Hydrocarbon fields

In the northern Perth Basin, the usage of the term ‘field’ has historically been extended to quite small hydrocarbon accumulations. For the purpose of this study, ‘fields’ are defined accumulations capable of sustaining the production of more than 10×10^7 m^3 of gas or the equivalent amount of oil. Minor accumulations are discussed in **Post-mortems of selected wells.**

This section and those that follow make use of unpublished well-completion reports held as S-series Open File reports at the Department of Minerals and Energy (DME). A full list of all relevant wells and the S-series numbers of the corresponding well-completion reports is contained in the **Appendix.** References other than these are made as appropriate in the text and listed under **References.** All reserve and production figures are quoted in the units in which they were originally reported, and the metric equivalent is also provided where appropriate.

Mount Horner oilfield

Location

The Mount Horner field is located in the Allanooka High, north of the east-trending Allanooka Fault and to the east of the north-trending Mountain Bridge Fault (Fig. 3). The discovery well was drilled in 1965 by West Australian Petroleum (WAPET), although the economic value of the field was not proven until 1987 when Barrack Energy (presently Discovery Petroleum) drilled Mount Horner 7.

Trap

An anticline with four-way dip closure, resulting from a minor Early Cretaceous wrench movement on a pre-existing fault, controls the main pools on the downthrown section of the fault (Figs 10, 11, and 12). Deeper accumulations are at a slight variance. The Arranoo pool is on the upthrown side of the fault (Fig. 13).

The field has been exhaustively discussed by Warris (1988).

Wells drilled

A total of 16 wells have been drilled on the field to date: as at 31 December 1993, eight wells were producing, two shut in, and six plugged and abandoned.

Reserves (original recoverable)

222 600 kL of oil (DME, 1993), of which one million barrels has already been produced.

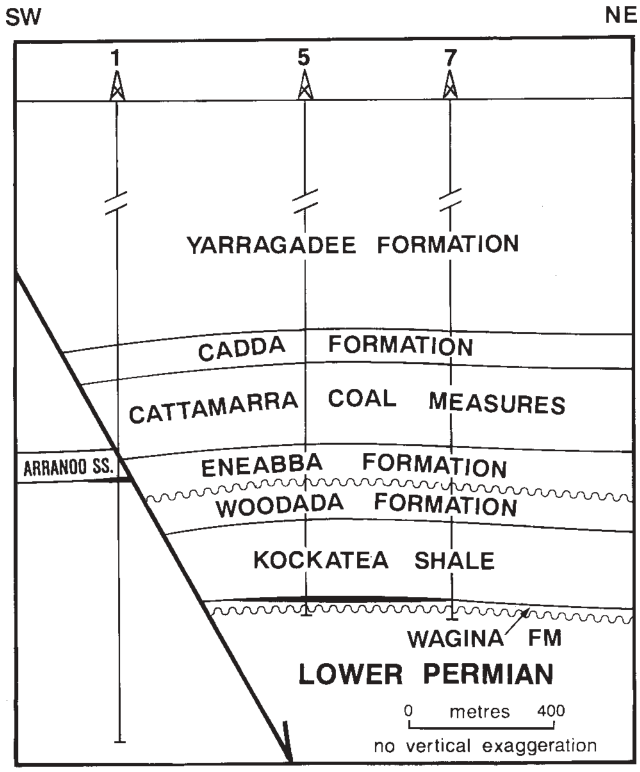

Figure 10. Structural cross section of the Mount Horner oilfield (after Warris, 1988)

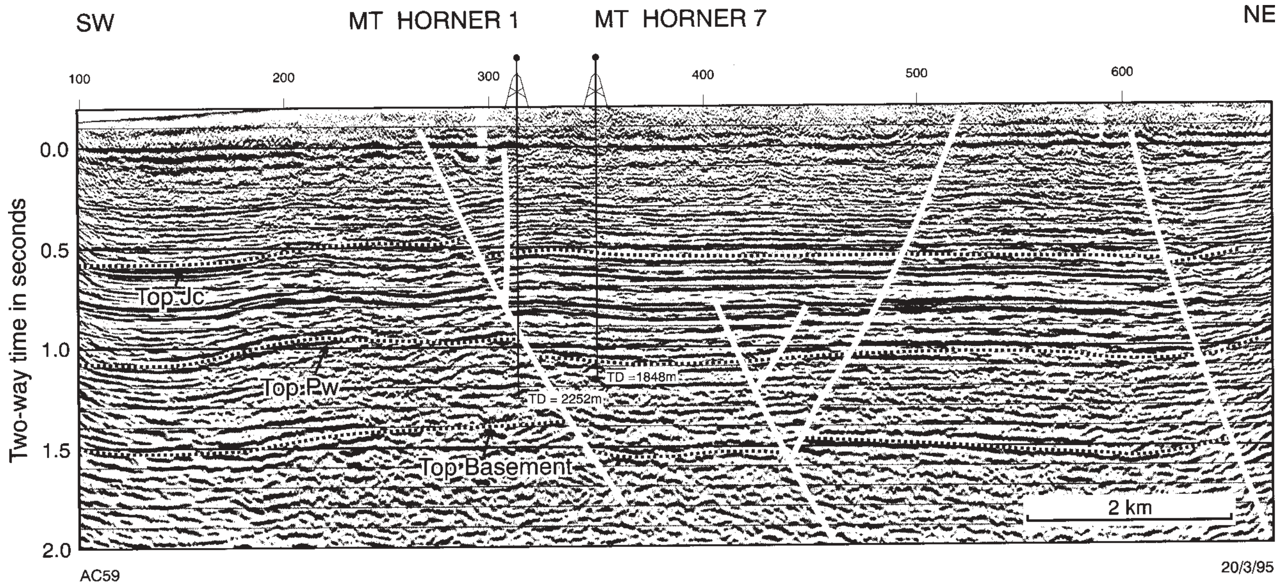

Figure 11. Seismic line B89-422, Georgina Seismic Survey, across the Mount Horner oilfield structure. Jc — Cattamarra Coal Measures; Pw — Wagina Formation. Location of section is shown on Figure 4

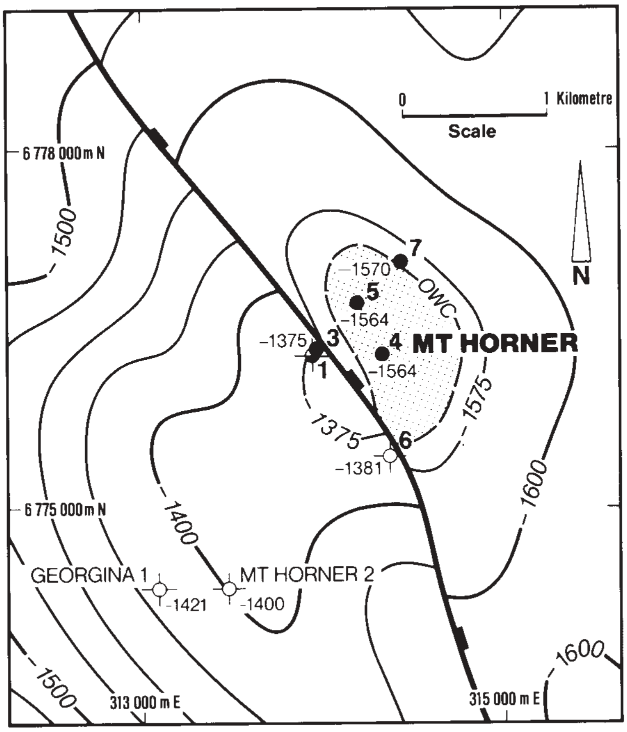

Figure 12. Structure map of the top of the Wagina Formation, Mount Horner oilfield (from Warris, 1988)

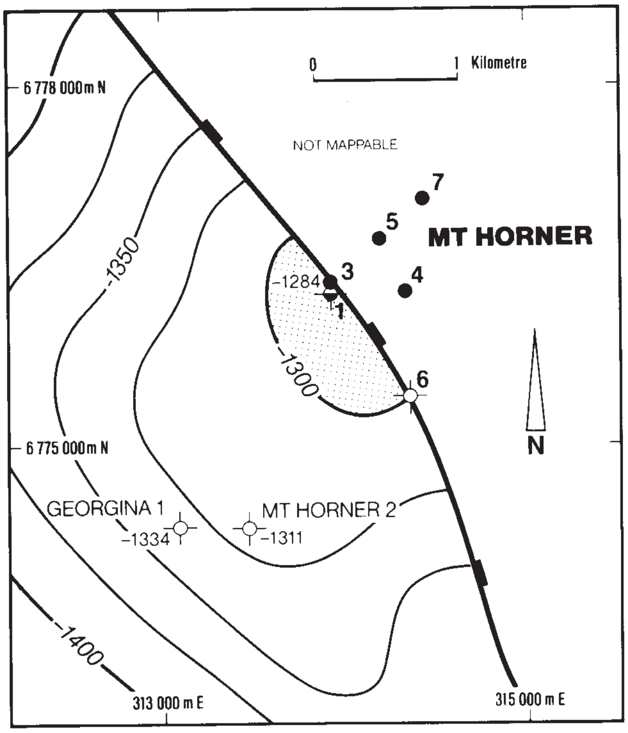

Figure 13. Structure map of the top of the Arranoo Sandstone Member, Mount Horner oilfield (from Warris, 1988)

No gas is associated with the oil accumulation. The 34°API (American Petroleum Institute) oil has a high wax content.

Reservoirs

The oil is found in several discrete pools that are listed below:

- 'B' Sand, within the Early to Middle Jurassic Cattamarra Coal Measures.
- 'F' Sand, within the Early to Middle Jurassic Cattamarra Coal Measures.
- 'K' Sand, within the Early to Middle Jurassic Cattamarra Coal Measures.
- Arranoo Sandstone Member of the Early Triassic Kockatea Shale.
- Late Permian Wagina Formation.

A few barrels of oil have also been tested from the Irwin River Coal Measures. Mount Horner 13 discovered oil in the 'K' sand in 1993.

Source

The basal Early Triassic Kockatea Shale is believed to be the source of the oil.

Dongara oil- and gasfield

Location

The Dongara oil- and gasfield is located on the Dongara Terrace, adjacent to the Mountain Bridge Fault (Fig. 3). The field was discovered in 1966 by WAPET, which has maintained operatorship to the present.

Trap

The structural attitude of the northwest-trending Dongara field is shown in Figures 14 and 15. A wrench movement controlled a gentle anticlinal feature on the downthrown section. Due to the thickness of the pay zone and the gently dipping strata, the field extends in a northeast direction towards a secondary culmination. The fault-controlled secondary high is known as the 'North Block'. Many faults intersect the Dongara structure such that its setting is very complex and difficult to define in detail. Only the main controlling faults are shown in Figure 14. A common GOC (gas/oil contact) at -1654.5 m and OWC (oil/water contact) at -1673.7 m are accepted for the whole field, although the level of the OWC varies slightly locally. Soon after production commenced, the rising watertable split the hydrocarbon accumulation into two discrete parts, the North Block, and the main part of the field, and a pressure differential between the two pools became established.

The easterly trending Allanooka Fault lies to the north of the Dongara hydrocarbon accumulation, whereas the northerly trending Mountain Bridge Fault constrains the field to the east.

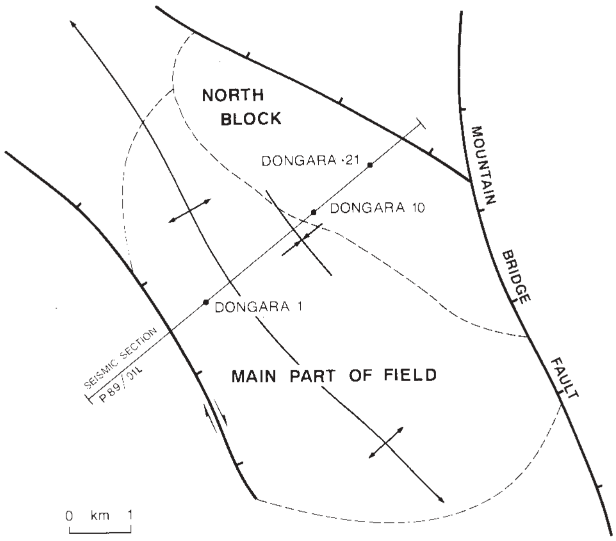

Figure 14. Simplified structural setting of the Dongara field

All sedimentary beds are conformable throughout the pre-Quaternary sequence (Fig. 15). An Early Cretaceous age for the Dongara anticline is therefore postulated. This is consistent with the regional geologic history, as described in **Regional framework**.

Wells drilled

Twenty-seven wells have been drilled on the field to date: as at 31 December 1994, seven are plugged and abandoned, seven shut in, ten in production, and three re-completed to produce from the Arranoo reservoir (Table 2).

Reserves (original recoverable)

2 479 153 kL of oil; original oil in place — 16 595 476 kL. 12 747 477 × 10^3 m^3 of gas; original gas in place — 14 277 520 × 10^3 m^3 (DME, 1993).

Production commenced in 1971.

The gas in place was originally calculated at approximately 500 billion cubic feet (Bcf; Cope, 1972), which is about 14.2 × 10^9 m^3, and this figure has changed little with time. Oil reserves were considered to be of secondary importance because an identified gas market existed when the Dongara field was discovered. Oil reserves, as cited above, include probable and possible resources, which WAPET plans to produce utilizing horizontal-well technology.

The gas (dry, not in equilibrium with the oil) is composed of about 96% methane. The oil is waxy, with 35°API gravity.

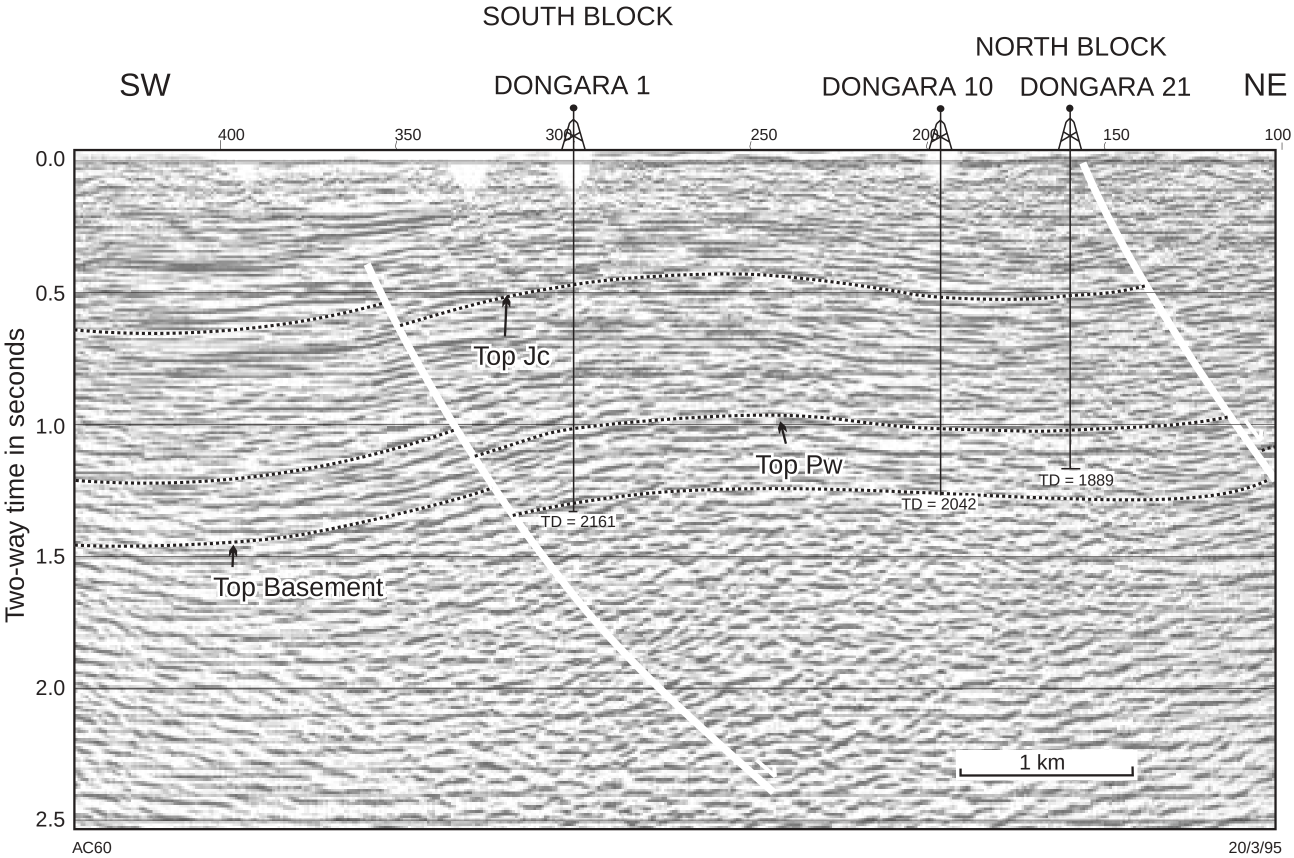

Figure 15. Seismic line P89-01L, Dongara Experimental 2 Seismic Survey, showing the structural setting of the Dongara field. Jc — Cattamarra Coal Measures; Pw — Wagina Formation. Location of section is shown on Figures 4 and 14

Reservoirs

Three reservoir sections occur within the Dongara field, namely:

- The Early Triassic Arranoo sandstones, which contain very minor oil and less than 1% of the gas reserves.
- The Late Permian Wagina Sandstone, representing the main reservoir and containing both oil and gas. The gross thickness of the unit averages 40 m. The net pay-thickness of the gas-bearing reservoir ranges from 0.9 to 11 m; the net pay-thickness of the oil reservoir averages 3.5 m. Porosity averages 20%; permeability averages 100 md. It is reported that at present the fluid pressure of the north block is considerably higher than the average pressure in the south block.
- The Early Permian sandstones of the Carynginia Formation / Irwin River Coal Measures, which contain approximately 5% of the gas reserves. Porosity ranges from 5.4 to 9%; permeability averages less than 1 md.

Sources

The Early Triassic Kockatea Shale generated the oil in the field, which lacks light ends, suggesting an early phase of oil generation. Interbedded Early Permian shales and coals generated the gas (Thomas, 1979).

Yardarino oil- and gasfield

Location

The Yardarino oil- and gasfield is located in the northern section of the Beharra Springs Terrace, east of the Mountain Bridge growth fault (Fig. 3), and 4 km south of the Allanooka Fault. The field was discovered in 1964 by WAPET, which is still the operator.

Trap

The hydrocarbons in the Yardarino field are trapped in a wrench-induced anticline intersected by faults both to the south and north of the hydrocarbon accumulation. The very limited seismic control available does not allow any comments on the fault pattern and structural position, as shown by Jones (1976; Figs 16 and 17). Better seismic data may, however, indicate a positive trend more consistent with the controlling fault. Figure 18 shows the limited rollover of the productive section of the Yardarino structure in a north–south direction. The age of the trap is correlated with Early Cretaceous continental breakup.

Wells drilled

Four wells have been drilled in the Yardarino area, of which two proved to be productive (Yardarino 1 — gas;

Table 2. Dongara field well-completion status, December 1993

Well	*Reservoir*	*Pool*	*Type*	*Status*
1	Dongara/Wagina	S	Gas	Shut in
2	Dongara/Wagina	S	Gas	Abandoned
3U	Dongara/Wagina	S	Gas	**Active**
3L	Caryngninia/IRCM	–	Gas	Shut in
4	Dongara/Wagina	S	Gas	Shut in
5	–	–	–	Drilled and abandoned
6	–	–	–	Drilled and abandoned
7	–	–	–	Drilled and abandoned
8	Dongara/Wagina	N	Oil	Shut in
9U	Dongara/Wagina	N	Gas	Recompleted to Arranoo
9L	Dongara/Wagina	N	Gas	Recompleted to Arranoo
9A	Arranoo		Gas	**Active**
10	Dongara/Wagina	N	Gas and oil	**Active**
11	Dongara/Wagina	S	Gas	**Active**
12	Dongara/Wagina	N	Gas	**Active**
13	–	–	–	Drilled and abandoned
14	Dongara/Wagina	N	Oil	Recompleted to Arranoo
14A	Arranoo		Gas and oil	Abandoned
15U	Dongara/Wagina	S	Gas	Shut in
15L	Dongara/Wagina	S	Gas	Shut in
16	Dongara/Wagina	S	Gas	Recompleted to Arranoo
16A	Arranoo	–	–	Abandoned
17	Dongara/Wagina	S	Oil	Shut in
18	Dongara/Wagina	S	Gas	**Active**
19	Dongara/Wagina	S	Oil	Shut in
20	Dongara/Wagina	S	Gas and oil	**Active**
21	Dongara/Wagina	N	Gas	Recompleted to Arranoo
21A	Arranoo		Oil	Shut in
22	Dongara/Wagina	–	–	Suspended
23U	Dongara/Wagina	S	Gas	**Active**
23L	Caryngninia/IRCM		Gas	**Active**
24	Dongara/Wagina	N	Gas	Recompleted to Arranoo
24A	Arranoo		Oil	**Active**
25	Dongara/Wagina	N	Gas	**Active**
26	–	–	–	Drilled and abandoned
27	–	–	–	Drilled and abandoned

Source: Department of Minerals and Energy files
Note: 'Dongara' is equivalent to WAPET's Basal Triassic Sandstone
N: north block
S: south block
IRCM: Irwin River Coal Measures

and Yardarino 3 — oil). The field is not producing at present.

Reserves (original recoverable)

2 629 kL of oil; 137 947 × 10^3 m^3 of gas (DME, 1993).

Reservoir

The hydrocarbons of the Yardarino field are in the Late Permian Wagina Formation. Porosity averages 15%; permeability averages 150 md.

Sources

By analogy with the Dongara field, the gas comes from the Early Permian Irwin River Coal Measures and the Caryngninia Formation, whereas the oil was probably generated by the Early Triassic Kockatea Shale.

Mondarra gasfield

Location

The Mondarra gasfield is located east of the Mountain Bridge Fault, within the Beharra Springs Terrace (Fig. 3). The depth to basement in the area is around 4 km. The field was discovered in 1968 by WAPET, which has maintained the operatorship.

Trap

The structural setting of Mondarra is illustrated in Figure 19. The main producing well, Mondarra 1, penetrated the eastern flank of a gentle anticline with an axis close to a northerly orientation, bounded to the west-northwest by a fault that is downthrown towards the east. The fault represents the northernmost section of the Beharra Springs Fault, a few kilometres to the south of the point where it peters out.

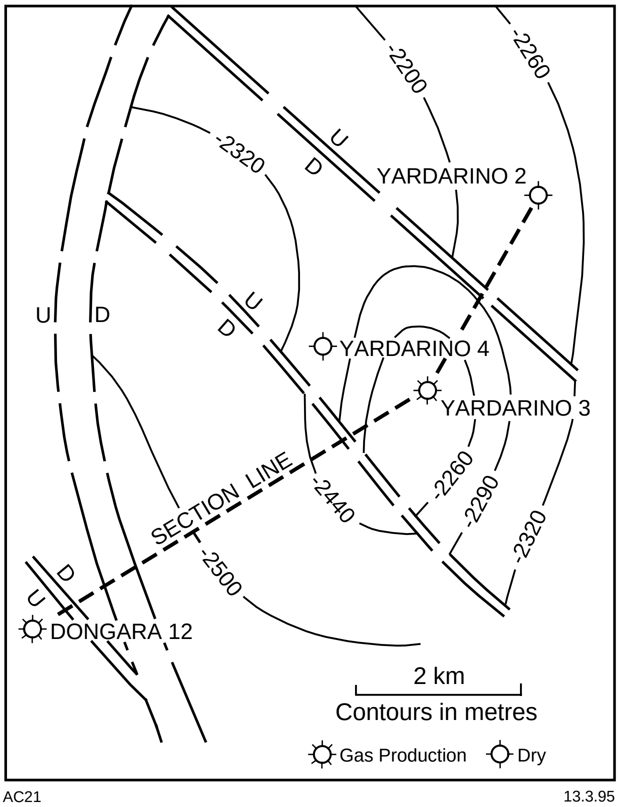

Figure 16. Structure map of the top of the Wagina Formation, Yardarino field (from Jones, 1976)

Limited seismic control and obsolete regional geologic knowledge hampered the original interpretation.

The interpretation shown in Figure 19 is proposed on the basis of the following data:

- the succession penetrated by Mondarra 2 (Table 3);
- the Mondarra field structural cross section, from Jones (1976; Fig. 20);
- the seismic section P89-15L, interpreted by R. P. Iasky (Fig. 21);
- the seismic section S92-11, interpreted by SAGASCO (Beharra Springs 3 well-completion report), shown in Figure 22.

The structural setting of the two above-mentioned seismic sections is strikingly similar: in both cases wrench movements produced a large open anticline characterized by collapse at the crest.

It was assumed by WAPET (Jones, 1976) that Mondarra 2 penetrated a major unconformity that cut out the Basal Triassic Sandstone and a large part of the Late Permian Wagina Sandstone (both of which are included within the Wagina Formation in the present study). Such an interpretation is not supported by the available seismic data and is inconsistent with the stratigraphic successions that have been penetrated in the area by the 27 Dongara wells, the four Yardarino wells, the other three Mondarra

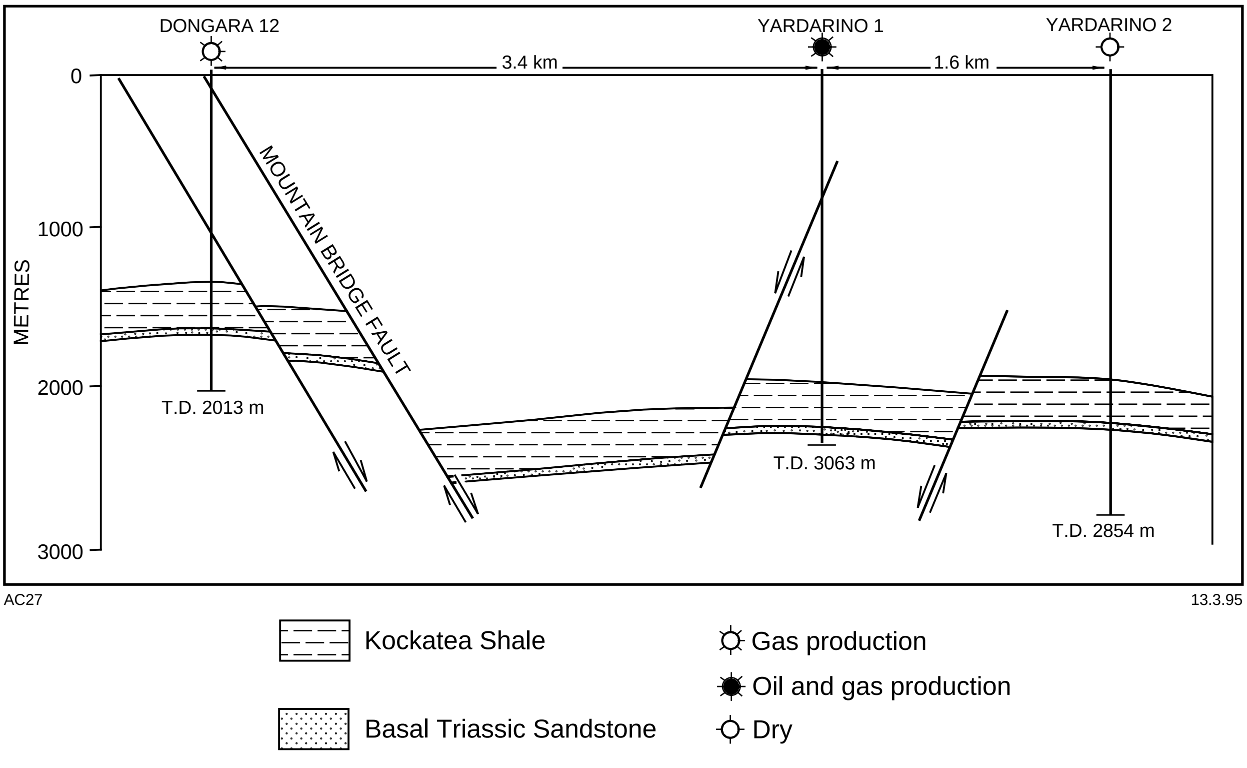

Figure 17. Structural cross section across the Yardarino field (from Jones, 1976). Location of section is shown in Figure 16

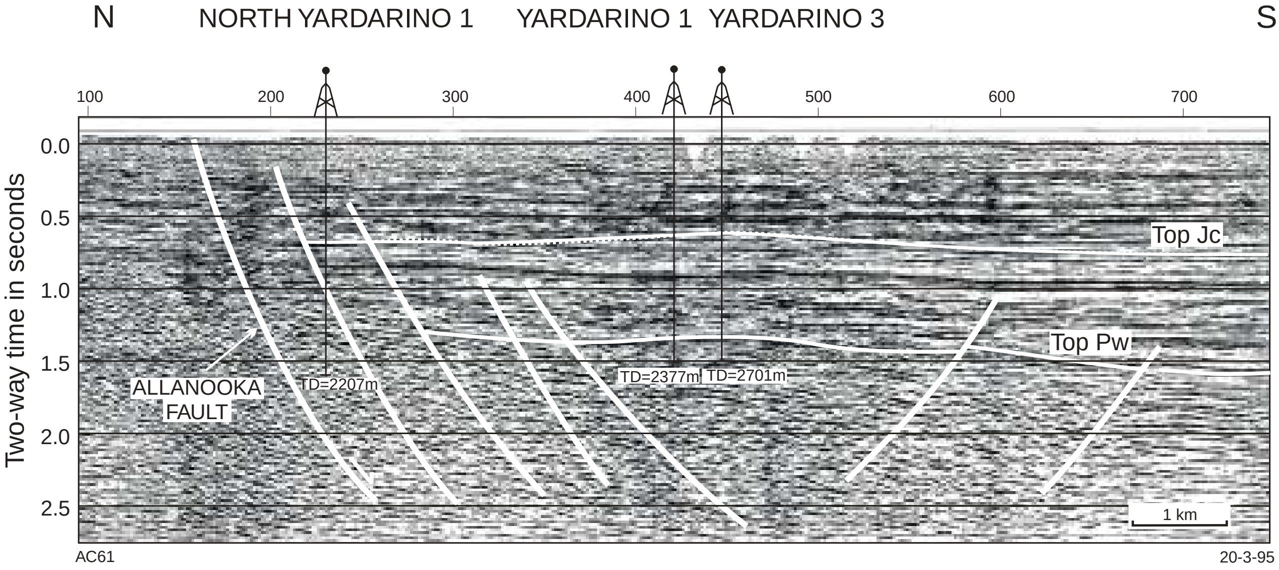

Figure 18. Seismic line P89-05L, Dongara 3 Seismic Survey, showing the north–south structural setting of the Yardarino area. Note that the projected Yardarino 3 appears structurally higher than Yardarino 1, whereas it is actually 10.5 m lower. Jc — Cattamarra Coal Measures; Pw — Wagina Formation. Location of section is shown on Figure 4

wells, and five dry holes. It is suggested that in Mondarra 2 some 70–80 m of the Late Permian Wagina Sandstone have been cut out by a fault of the Beharra Springs Fault System, as shown in Figure 21. The absence of the Woodada Formation and the thin Kockatea Shale confirm that Mondarra 2 penetrated several faults related to the Beharra Springs system.

The Mondarra 1 trap formed in the Early Cretaceous, as suggested by the seismic data and the regional setting.

Wells drilled

Four wells have been drilled, one of which was productive (Mondarra 1) and another of which was suspended following limited production (Mondarra 2).

Reserves (original recoverable)

690 800 × 10^3 m^3 of gas (DME, 1993).

Reservoir

In the Mondarra field the hydrocarbons are in the Late Permian Wagina Sandstone. The porosity of the sandstone is up to 25% and the permeability is up to 135 md. The averages are 12.5% and 70 md respectively.

Silicification has rendered the lower part of the Late Permian sandstone in Mondarra 1 tight (Mondarra 1 well-completion report). The zone is interpreted to be water-bearing.

Sources

The Early Permian shales and coals generated the dry gas, whereas the source of the oil is thought to be the Kockatea Shale.

Further potential

The cross section (Fig. 19) illustrates the potential of the trap below the Beharra Springs Fault: the Wagina Sandstone can probably be encountered in its entirety, and structurally higher, a few hundred metres to the southwest of Mondarra 2. Other more speculative plays between the two wells are also suggested by the interpretative cross section.

It should also be worth testing the Early Jurassic Eneabba Formation in the Mondarra 1 well, in which good 36°API oil shows occur in cores with good porosity: two drillstem tests (DSTs) have been unsuccessful. Thin oil columns proved to be of economic value in other northern Perth Basin wells, such as the Mount Horner wells.

Beharra Springs gasfield

Location

The Beharra Springs gasfield is located on a well-defined northerly trending positive high, which is characterized by the Beharra Springs Fault (Fig. 3). The Beharra Springs anticlinal trend also comprises the Mondarra and Yardarino positive structures. It lies within the Beharra Springs Terrace. The Dongara field is some 35 km to the northwest.

The field was discovered with the drilling of Beharra Springs 1 in 1990 by Barrack Energy. The present operator is SAGASCO.

Trap

The Beharra Springs gasfield is structurally trapped in a truncated anticline, limited by dip in three directions and by the Beharra Springs Fault to the east (Fig. 23).

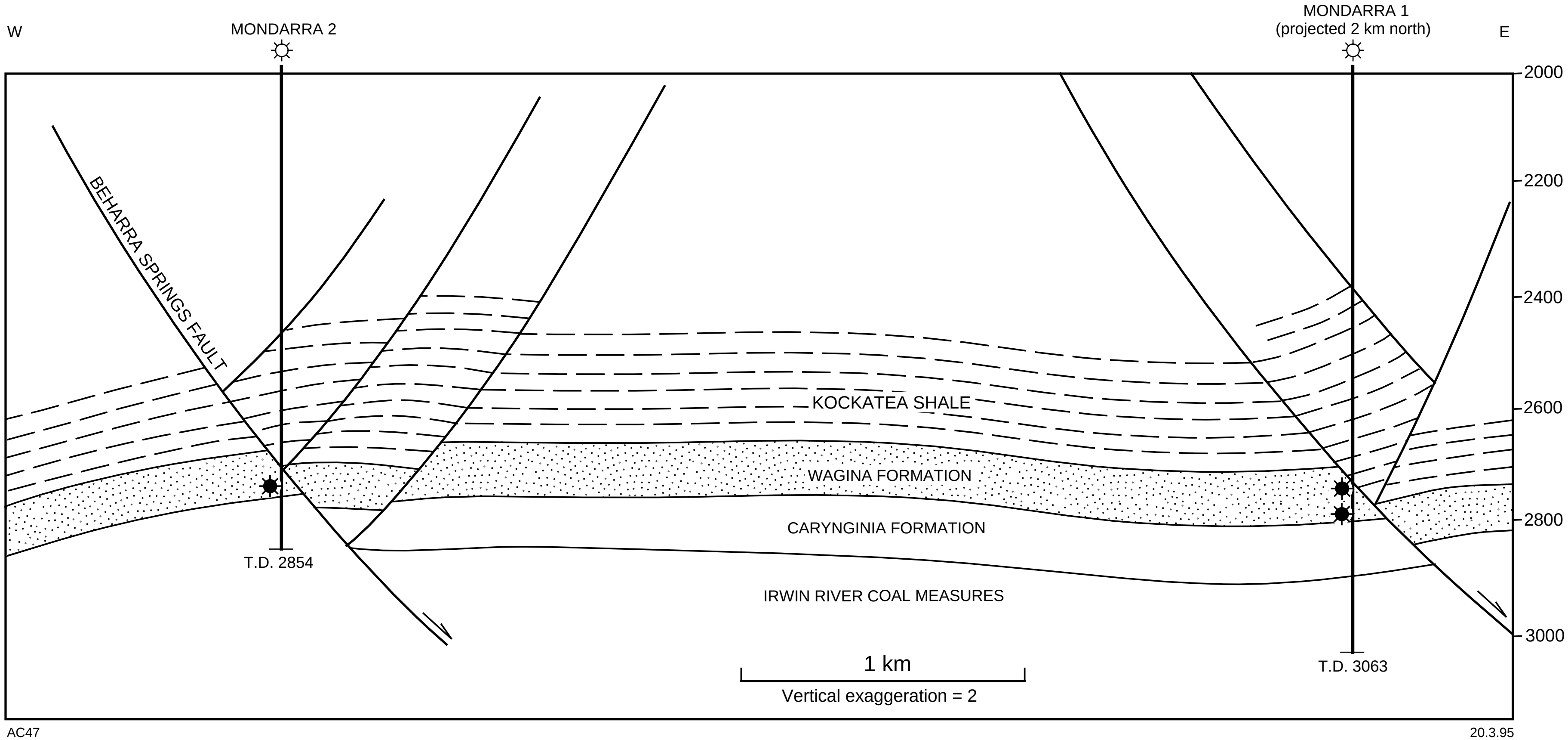

Figure 19. Cross section showing the structural relationships of the Kockatea Shale and the Wagina Formation between Mondarra 1 and 2

Table 3. WAPET well index sheet for Mondarra 2, revised 1 July 1970

COMPANY:	West Australian Petroleum Pty Ltd			WELL:	Mondarra 2
SPUDDED:	19 December 1968			BASIN:	Perth
COMPLETED:	18 February 1969	TD:	2854 m	TENEMENT:	P.L.1
		GL/SF:	27 m	LATITUDE:	29°21'09"
		KB:	31 m	LONGITUDE:	115°06'12"

Formation/Marker	***Key***	***Tops (m)***		***Lithologic summary***	***Remarks/Shows***
		Drill	***Sub Sea***		
Yarragadee Formation	KJy	282	251	Sandstone, siltstone, shale	
Cadda Formation	Jmd	?1 159	1 128	Shale, sandstone, siltstone	
Cattamarra Coal Measures	Jloc	?1 274	1 243	Sandstone, shale, siltstone, coal	
Eneabba Formation	Jloe	1 829	1 798	Sandstone, claystone, siltstone	Trace gas (ML)
Lesueur Sandstone	Rul	2 306	2 275	Sandstone, siltstone, shale	
Woodada Formation	Rmw	F	F		
Kockatea Shale	Rlk	2 475	2 444	Shale, siltstone, trace sandstone, limestone	Trace gas (ML)
Wagina Formation	Puw	2 726	2 695	Sandstone, siltstone	2 m gas
Caryngina Formation	Pay	2 762	2 731	Siltstone, shale	
TD		2 854	2 823		

	No.	***Depth (m)***	***Rec***	***Lithology***	***No.***	***Depth (m)***	***Rec***	***Lithology***
CORE	1	2738–2741	3 m	Sandstone				
	2	2740–2750	9 m	Sandstone				

Information source: WAPET files

DST 1, 1A & 1B: 2729–2741 m: Unsuccessful due to fill on bottom.
Choke 3/8"

Production test: 2736–2740 m: acidized; estimated gas flow — 14 x 10^6 m^3/day.
Choke 1/2", fractured–treated, flow 91 x 10^6 m^3/day.

TD: Total depth
GL/SF: Ground level
KB: Kelly bushing
ML: Microlog
F: Faulted out
Rec: Recovery

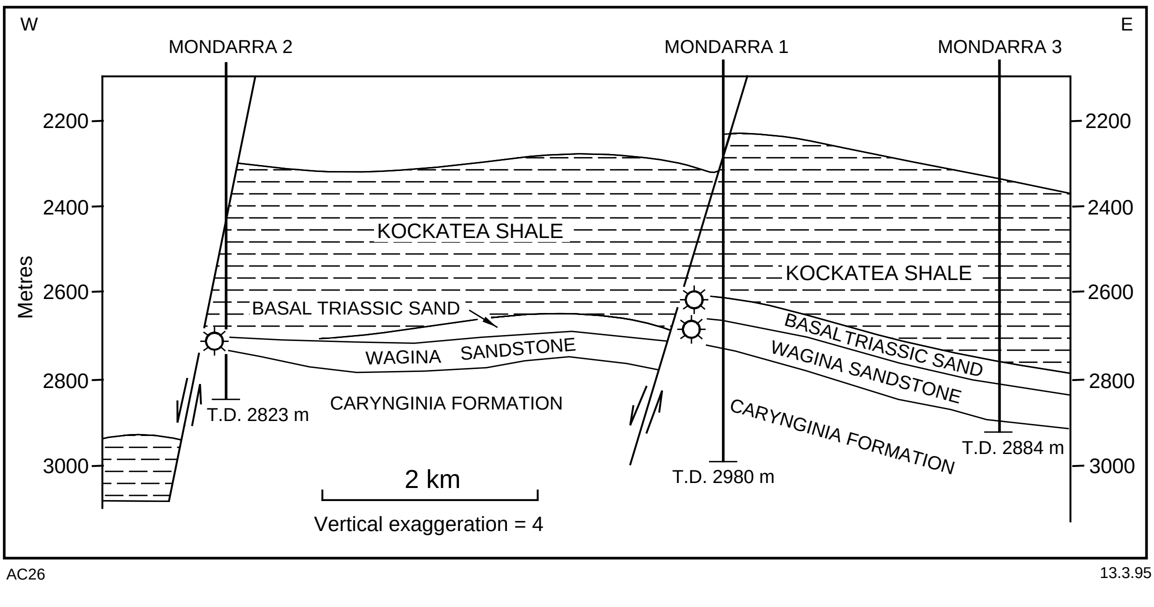

Figure 20. Structural cross section of the Mondarra field (from Jones, 1976)

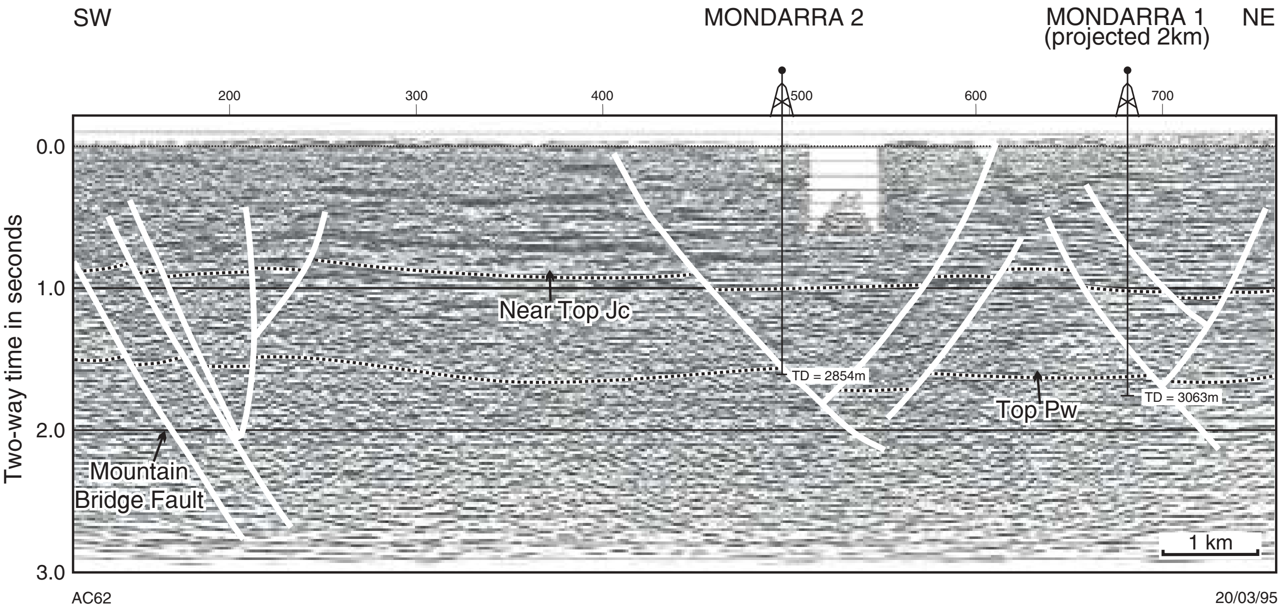

Figure 21. Seismic line P89-15L, Dongara 3 Seismic Survey, showing the structural setting of the Mondarra area. Jc — Cattamarra Coal Measures; Pw — Wagina Formation. Location of section is shown on Figure 4

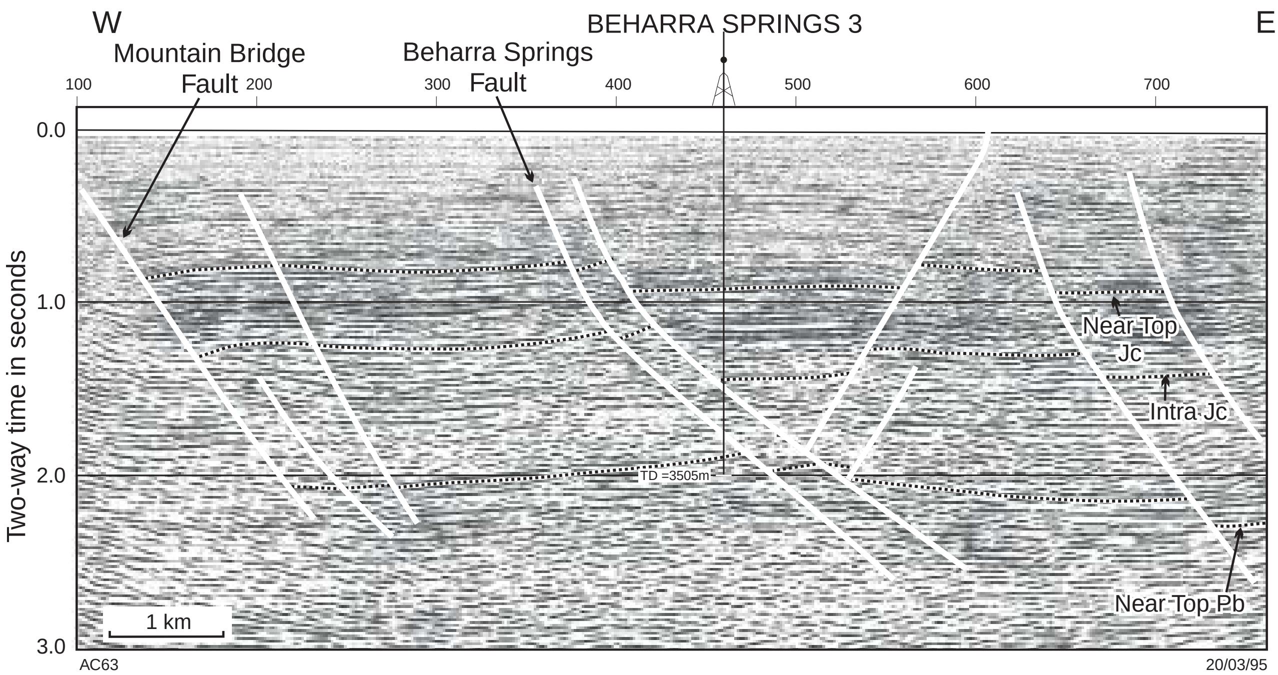

Figure 22. Seismic line S92-11, Yandanooka Seismic Survey, showing the structural setting of the Beharra Springs gasfield (after Beharra Springs 3 well-completion report). Jc — Cattamarra Coal Measures; Pb — Beekeeper Formation. Location of section is shown on Figure 4

The anticline is intersected by minor faults. Pressure data indicate that the faults do not entirely compartmentalize the hydrocarbon accumulation, which is subdivided into two pools. The northern pool has been penetrated by Beharra Springs 1 and 3, whereas the southern pool has been penetrated by Beharra Springs 2.

The gentle anticlinal shape of the trap suggests that it has been generated by minor wrench movements related to the Beharra Springs Fault, that it is pre-Cretaceous in age, and is downthrown to the east (Fig. 22). The Beharra Springs Fault was probably rejuvenated during the Early Cretaceous breakup, and experienced some strike-slip movement.

Wells drilled

Three (all productive): Beharra Springs 1, 2, and 3.

Reserves (original recoverable)

The field commenced limited production in January 1991 from Beharra Springs 1. Production increased following the drilling of two additional wells and the upgrading of production facilities. Volumetric estimates (assuming that the field is full to the spill point), and pressure data indicate original gas in place was approximately 1.9–2.3 × 10^9 m^3. A recovery of 1.9 × 10^9 m^3 of raw gas is considered to have a 50% chance of being achieved (DME, 1994). The average gas composition is as follows:

carbon dioxide	5%
nitrogen	<1%
methane	91%
other hydrocarbons	3%

Reservoir and seal

The gas in the Beharra Springs field occurs in a clastic interval within the Permian succession. The interval is quartzitic grading to calcarenitic with calcareous cement. Limited palynological data suggest that the reservoir section may be correlated with the Late Permian Beekeeper Formation.

Net reservoir thicknesses are as follows:

Beharra Springs 1	13.6 m
Beharra Springs 2	9.7 m
Beharra Springs 3	16 m

The porosity of the 5–6 m-thick upper zone ranges from 10 to 11%; that of the lower zone ranges from 4 to 5.8%. The reservoir is sealed both vertically and laterally across the Beharra Springs Fault by the Kockatea Shale.

Source

The source of the gas from Beharra Springs 1 is probably the Permian Carynginia Formation and Irwin River Coal Measures.

Further potential

By analogy with Mondarra 1 (Fig. 19), there is potential for a gas accumulation approximately 4 km to the east of the Beharra Springs gasfield, below the fault plane limiting the anticlinal feature to the northeast, and possibly also below the plane of the fault antithetic to the Beharra Springs Fault.

Woodada/East Lake Logue gasfield

Location

The Woodada/East Lake Logue gasfield is located to the east of the Beagle Ridge, on the northern part of the Cadda Terrace (Fig. 3).

The discovery well was drilled in 1980 by Hughes and Hughes. The present operator is Consolidated Gas.

Trap

Structurally, the Woodada/East Lake Logue gasfield consists of a north-plunging anticlinal feature (Figs 24 and 25). The anticlinal nose is intersected by minor splay faults and by a major north–south fault, generating two discrete compartments: the western main Woodada pool and the eastern East Lake Logue pool. Differing gas compositions indicate that the north–south fault acts as a seal.

The boundaries of the field are dip-controlled to the north and west, whereas the gas-bearing reservoir thins out to zero to the south and east. The zero line shown in Figure 24 is tentative. Work in progress may lead to an extension of the reservoir to the south. Figure 26 is a conceptual north–south cross section through the Woodada pool. Water influx and expansion provide the depletion mechanism.

Early Cretaceous wrench movements related to the Peron Fault are considered to have resulted in the formation of the Woodada/East Lake Logue anticlinal nose. The same tectonic stresses may also be responsible for the faults cutting the competent Permian sequence and disappearing in the overlying incompetent Early Triassic sequence.

Wells drilled

Fourteen, of which seven were productive at 31 December 1993.

Reserves (original recoverable)

Volumetric reserves range from 1.9 × 10^9 m^3 (90% probability) to 3.3 × 10^9 m^3 (DME, 1994). Pressure data would, however, suggest that the western (Woodada) pool may contain 100 Bcf (2.8 × 10^9 m^3) and the eastern (East Lake Logue) pool may contain 9 Bcf (0.26 × 10^9 m^3) of gas. The field is intersected by numerous gas-bearing subvertical faults and fractures that peter out upwards into

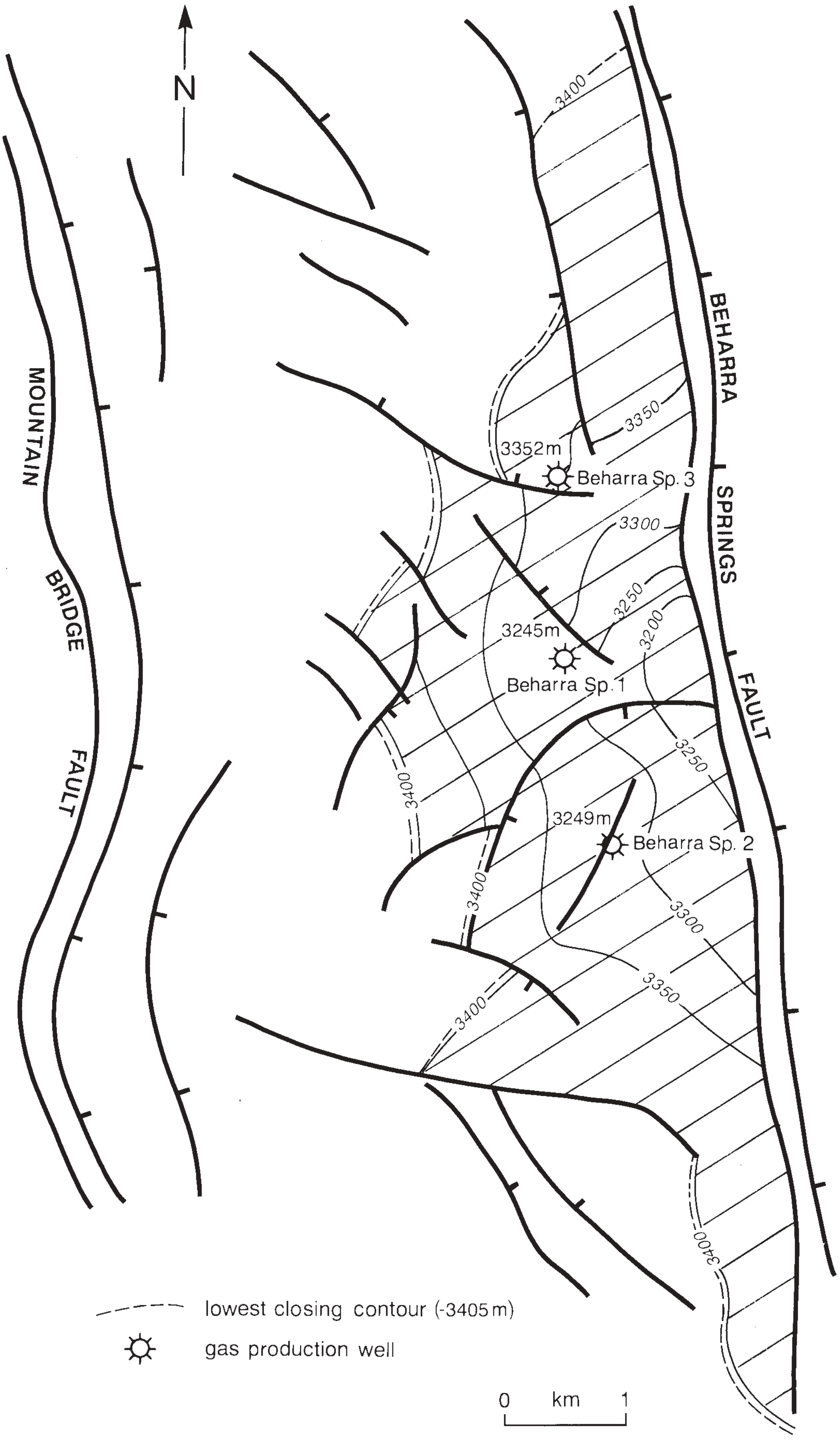

Figure 23. Structural map of the top of the reservoir, Beharra Springs gasfield (Beharra Springs 3 well-completion report)

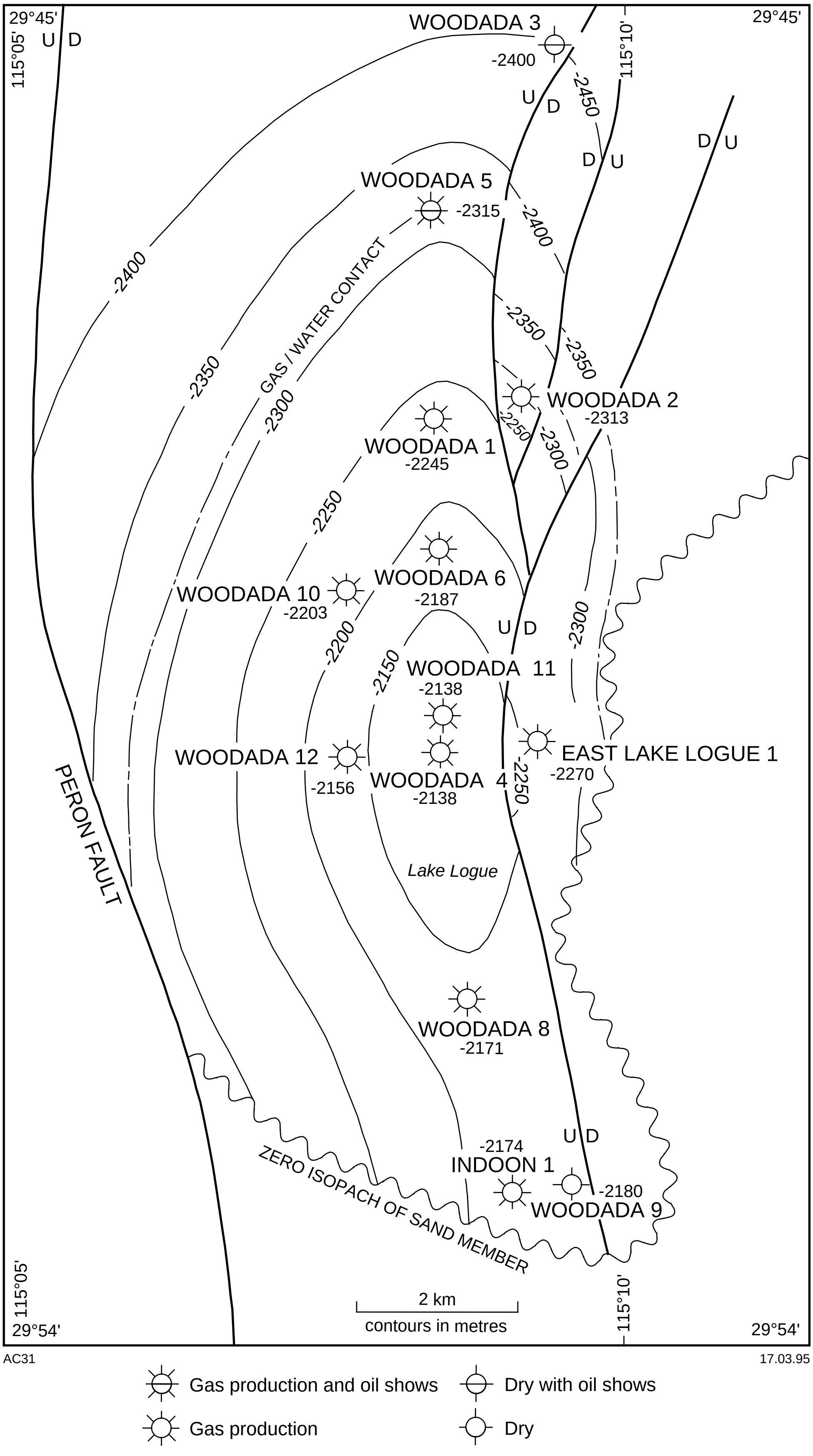

Figure 24. Structural map of the top of the reservoir, Woodada gasfield (modified from Lane and Watson, 1985)

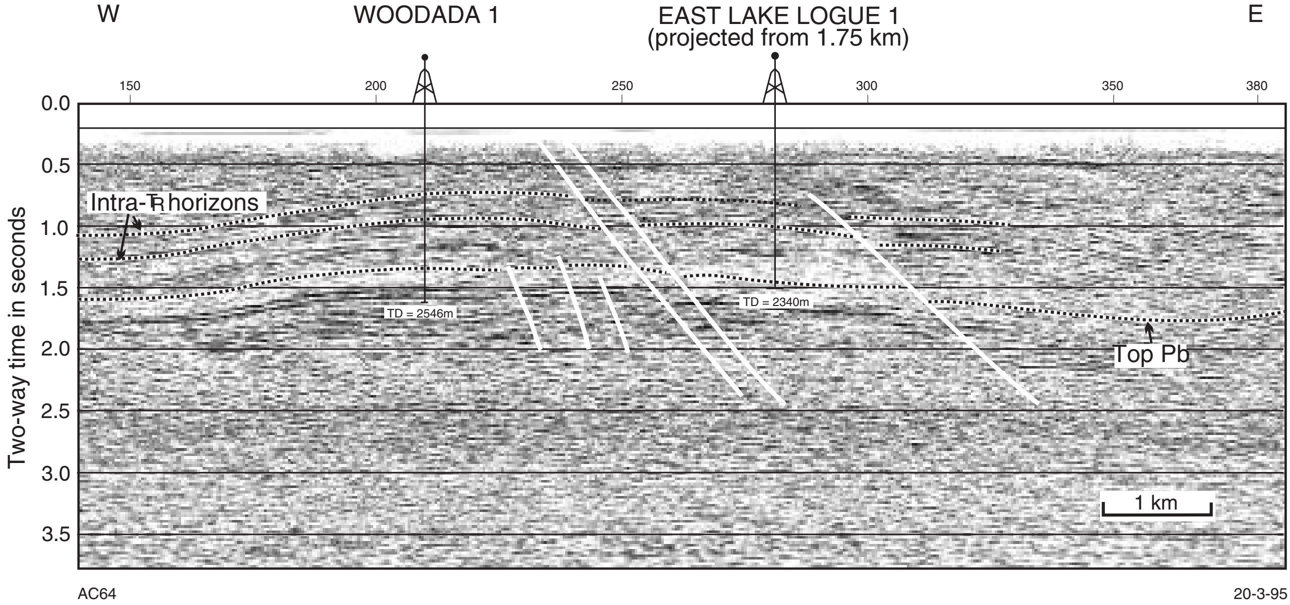

Figure 25. Seismic line HP82-224, Coorow Seismic Survey, showing the anticlinal setting of the Woodada gasfield. Ʀ — Triassic; Pb — Beekeeper Formation. Location of section is shown on Figure 4

the Kockatea Shale, which therefore seals them. The contribution to the field by these fractures is not quantified, although the higher reserves suggested by the pressure data may be related to them. Refilling of reservoirs by active migration is not unknown. It is possible that more than 100% of the presently estimated volumetric reserves will eventually be produced.

Gas from the Woodada field contains 91% methane and 7% inert gases. The gas/oil ratio (condensate) is 1.68 barrels/million cubic feet (MMcf; approximately 0.01%). East Lake Logue gas contains 4% more nitrogen than gas from other wells.

Reservoir

As indicated by the well-completion reports, the productive horizon is represented by a clastic interval referred to as the Permian Beekeeper Formation: the interval is defined as a dolarenite, ranging in thickness from 1 to 13 m. Gas is also released by the tight limestone matrix into the formation fractures. Porosity ranges from 2 to 15%, averaging 7%. Permeability averages 5 md in the Woodada pool and 460 md in the East Lake Logue pool. The high permeability in the latter well may, however, suggest that the only control well is located near or on a fault zone. Water saturation approximates 20%.

Source

The pressures accompanying the intense fault system suggest a deep source (Early Permian Carynginia Formation and Irwin River Coal Measures) for the hydrocarbons.

Post-mortems of selected wells

Erregulla 1 and 2

Location

Erregulla 1, located in the southeastern part of the Allanooka High (Fig. 3), was drilled by WAPET in 1966. Erregulla 2 was drilled 200 m to the north of Erregulla 1 in 1980 by Mesa Australia.

Stratigraphy

Erregulla 1 was spudded in the late-Middle Jurassic Yarragadee Formation, penetrated the Middle Jurassic Cadda Formation, the Early–Middle Jurassic Cattamarra Coal Measures, the Early Jurassic Eneabba Formation, a lacunose Triassic sequence, the Early Permian Carynginia Formation, and bottomed in the Early Permian Irwin River Coal Measures at 4244 m. Erregulla 2 penetrated a similar sequence down to the Triassic series, in which the well bottomed at 3577 m.

Structure

Figure 27 indicates that Erregulla 1 tested a very broad anticline, first penetrating the collapsed crest and then the main structure (Figs 28 and 29). This interpretation was originally suggested by Jones (1976; Figs 28 and 29). Due to the poor quality of the data below a coaly section within the Cattamarra Coal Measures (known locally as the Donkey Creek Coal Horizon), the structural setting of the deeper horizons cannot be defined.

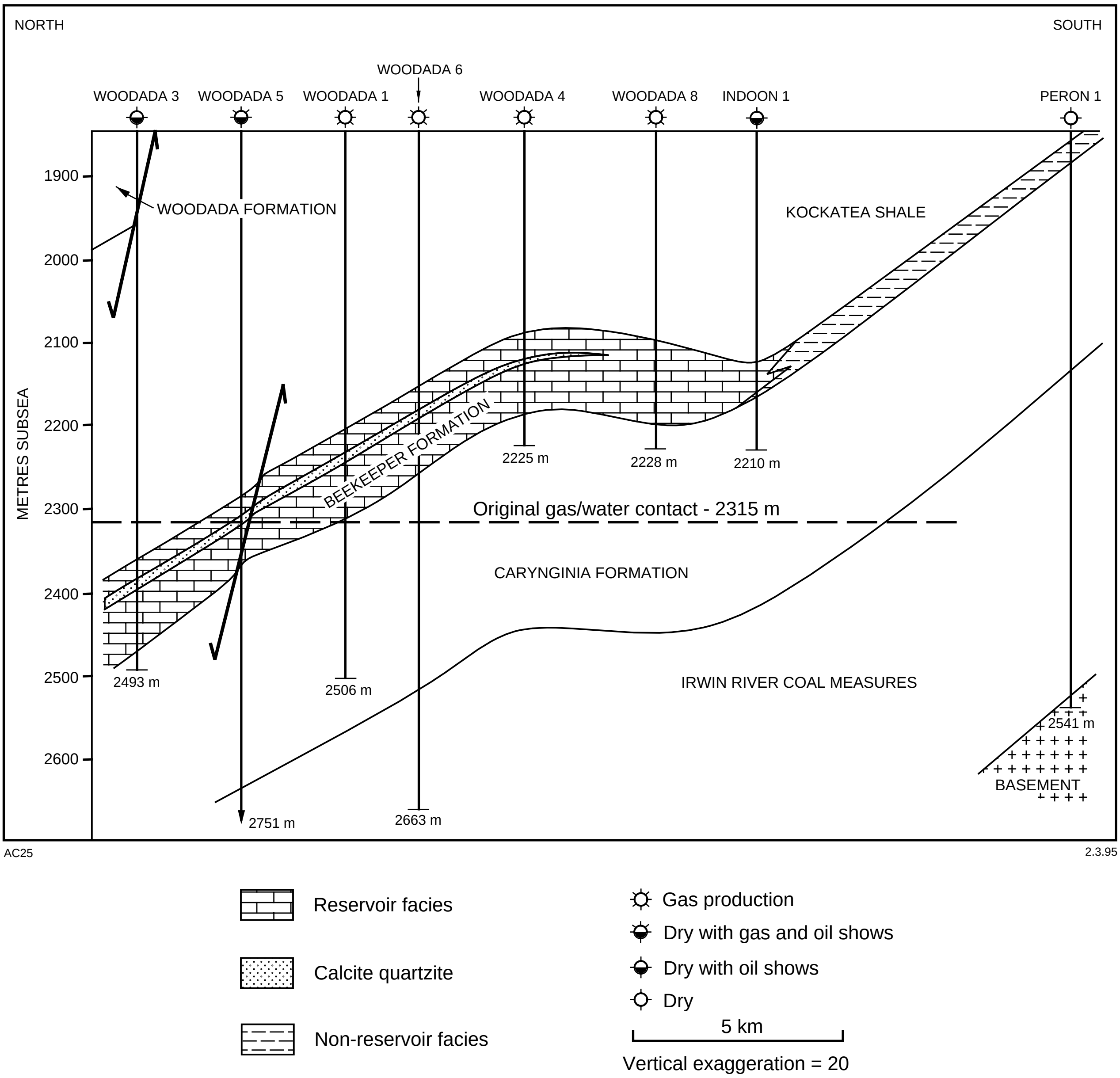

Figure 26. Cross section across the Woodada gasfield (from Lane and Watson, 1985)

Erregulla 2 is interpreted to have been drilled outside the collapsed crest, as shown in Figure 30.

Reservoirs and seals

The sandstones of the Yarragadee and Cadda Formations have porosities ranging between 15–34%. A good seal is present between 1770 m and 1870 m in the Cadda Formation: below this depth, water salinity increases to 30 000 ppm NaCl. Porosities within the Eneabba Formation range between 8 and 26%. Permeabilities are variable, locally reaching 109 md. The highest values have been obtained from core analyses of the oil-bearing tested intervals.

The visual porosity of the Lesueur Sandstone ranges from 12–15%, whereas the Woodada Formation has a porosity range of 5–15%. The sandstones within the Permian section proved tight and impermeable. The sandy sections throughout the entire sequence are covered by intraformational shales.

Hydrocarbons

Gas shows and fluorescence were detected in the entire sequence below the Cadda Formation. These occurrences prompted several drillstem tests to be carried out. A small gas flow, too small to measure, was obtained from an interval in the Permian sequence.

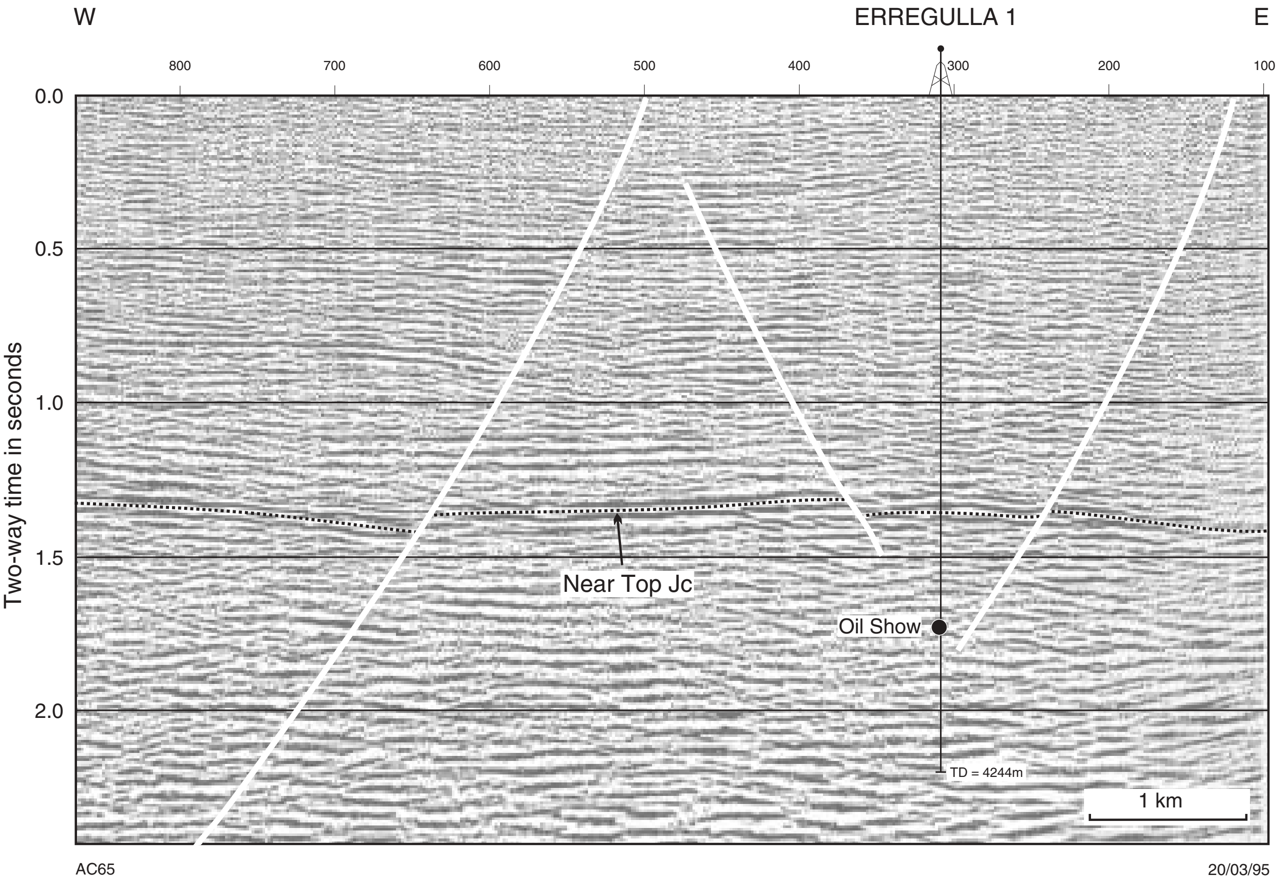

Figure 27. Seismic line ES84-14, Erangy Springs Seismic Survey, showing the structural setting of the Erregulla prospect. Jc — Cattamarra Coal Measures. Location of section is shown on Figure 4

Twenty-two and a half barrels of 47°API oil were recovered from the perforated interval 3174–3181 m (Eneabba Formation) on a first swabbing attempt. Following re-perforating (twice), hydrojetting (once), acidizing (twice), and oil squeezing (once), a further 36 barrels were obtained. No significant hydrocarbon indications were found in Erregulla 2 and all sands were water wet.

Source

The source of the Erregulla 1 oil is considered to be the Kockatea Shale.

Reasons for failure

The Erregulla area has good reservoir and seal potential. Hydrocarbons have been generated in the area, migrated in the structure, and are locally trapped.

The water-wet sands of Erregulla 2, which was drilled only 200 m from Erregulla 1, indicate that no valid trap of economic value occurs in the tested area. The oil recovered from Erregulla 1 is likely to be residual, locally trapped in a limited fault trap. The small volume recovered may also be due to some formation damage and limited effectiveness of perforations.

Remaining potential

A valid trap may exist in the general Erregulla area, which possesses all the parameters required for an oil accumulation. Better seismic data would allow a more precise definition of the Erregulla anticline and its fault planes below the Cattamarra Coal Measures. Tentatively, the crest of the structure seems to be about 2 km north of the drilled area. It is stressed that a clear definition of the deeper horizons is required in order to understand the structure.

North Erregulla 1

Location

North Erregulla 1 was located sixteen kilometres north-northwest of Erregulla 1 and Erregulla 2, within the Allanooka High of the Perth Basin (Fig. 3). The well was drilled in 1967 by WAPET, as a follow-up to Erregulla 1.

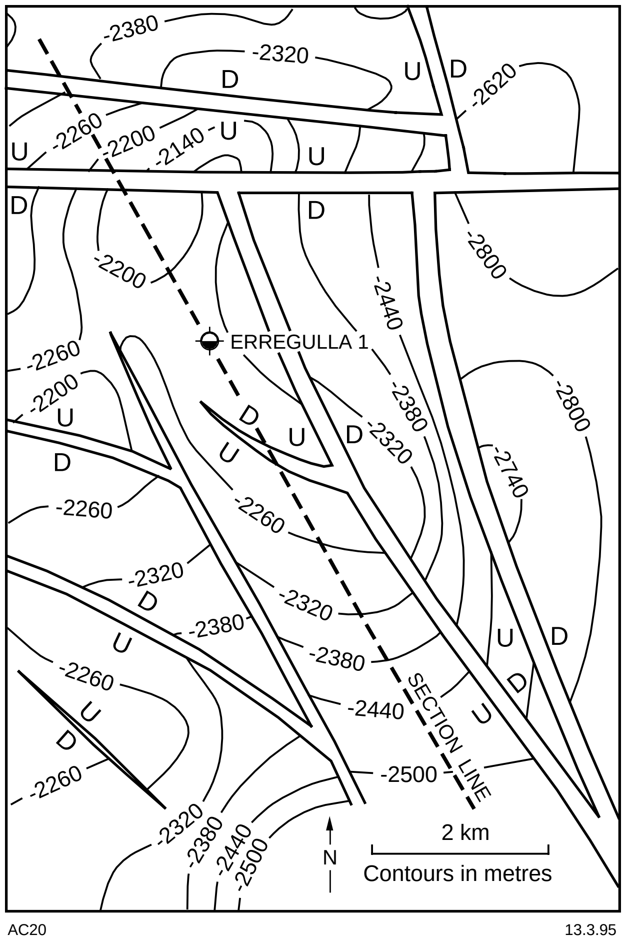

Figure 28. Early Jurassic structure map of the Erregulla prospect (from Jones, 1976)

Stratigraphy

Below poorly defined post-breakup sediments, North Erregulla 1 encountered a Jurassic to Permian stratigraphic succession from the Yarragadee Formation to the Irwin River Coal Measures. Part of the Lesueur Sandstone, the Woodada Formation, and the Caryngina Formation are not represented, although no formational thinning is suggested by the seismic data.

Structure

Poor seismic data (Fig. 31) suggest that the North Erregulla 1 well was located in the heavily faulted crest of an open fold. The stratigraphic succession, seismic sections, and inconsistent structural dips indicated by a dipmeter survey (North Erregulla 1 well-completion report) suggest that several faults have been encountered, cutting out parts of the succession.

Since the oil-saturated formations are tight and the water-bearing ones are permeable, it is considered that no structural trap is present. Permeability barriers may have trapped the small amount of oil that has been recovered.

Reservoirs and seals

Cores cut in the Kockatea Shale, Wagina Sandstone (which Mory and Iasky, in prep., correlate with the Irwin River Coal Measures), and Irwin River Coal Measures indicate good porosity, but no or poor permeability. The best reservoir sandstones have been encountered in the Lesueur Formation, where porosity ranges from 18 to 25% and permeability is between 90 and 946 md.

Hydrocarbons

Moderate gas shows and fluorescence were encountered below the Cadda Formation to total depth.

Oil is present in the upper part of the Early Triassic Kockatea Shale: DST 1 recovered 20 gallons (91 L) of 38°API oil in a one hour test. A second oil-saturated interval occurs at the top of the Permian succession, from which DST 2 recovered 8 gallons (36 L) of 38°API oil during a 30 minute test. Three metres below the oil sands, DST 3 recovered 22 barrels of salt water during a one hour test.

Source

A marginally mature Kockatea Shale is expected to have generated the oil present in both the Early Triassic and Late Permian units, as is regionally the case.

Reasons for failure

It is likely that no worthwhile trap is present in the heavily faulted section of the structure that has been tested.

Remaining potential

All conditions required for an oilfield are present in the North Erregulla area. A reinterpretation of the North Erregulla anticline is more than justified, and could possibly be followed by additional seismic coverage. In the event that a folded closure that is not dependent on fault sealing is substantiated, a second exploration well may be warranted.

North Yardanogo 1

Location

North Yardanogo 1 was drilled early in 1990 by Barrack Energy within the Beharra Springs Terrace (Fig. 3), 1.5 km to the east of the surface expression of the Mountain Bridge Fault and some 25 km to the south of the Dongara field. The well was designed to test a Jurassic rollover anticline (Fig. 32).

Stratigraphy

North Yardanogo 1 was spudded in the Middle Jurassic section of the Yarragadee Formation, encountered the Middle Jurassic Cadda Formation at 1092 m, the Early–Middle Jurassic Cattamarra Coal Measures at 1142 m, the

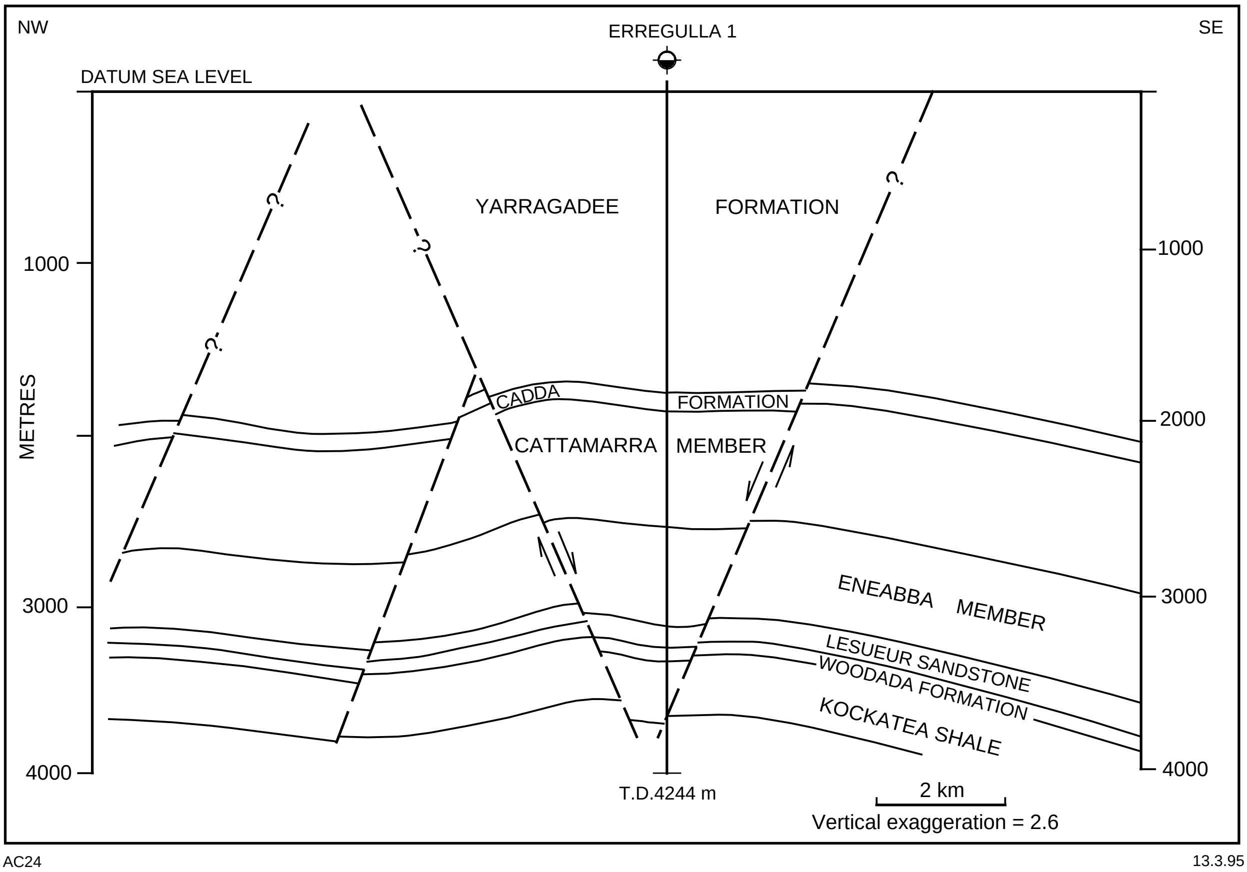

Figure 29. Structural cross section of the Erregulla prospect (from Jones, 1976)

Early Jurassic Eneabba Formation at 1774.5 m, and the Late Triassic Lesueur Sandstone at 2354 m. The well bottomed at 2387 m in the latter unit.

Structure

The interpreted presence of an effective trap down to total depth is not supported by the well results. The sandy intervals that were penetrated proved to be water wet, with the only exception a 1 m-thick oil-bearing sandstone within the Cattamarra Coal Measures. The vertical closure to the south and east, as mapped (Fig. 33), is very small. Additionally, a number of faults intersect the structure.

The north–south North Yardanogo Trend rises structurally southwards. It is therefore conceivable that no dip closure exists at the North Yardanogo location: the oil-bearing sandstone may pinch out nearby, creating a stratigraphic trap. This possibility is discussed in the North Yardanogo 1 well-completion report. Alternatively, the well may have encountered the high permeability sandstone interval either within a more extensive but poorer quality reservoir rock, or in a minor fault trap.

Reservoir and seals

The porosity of the sandstone that the well penetrated from the Yarragadee Formation to total depth is good, although it decreases with depth. Permeability appears to be good across the entire Yarragadee Formation, whereas at deeper levels the permeability is inferred to be poor, consistent with the porosity trend. Interbeds of clean sandstone interpreted to have good permeability are, however, present.

The regional seal over the structure appears to be related to an impervious bed within the Yarragadee Formation, which was encountered at 920 m, and beneath which a dramatic increase in salinity occurs. Further intraformational seals are present throughout the entire lithostratigraphic succession.

Hydrocarbons

A thin stringer of oil-bearing sandstone was penetrated between 1639.5 and 1640.5 m. The interval was drillstem tested and 118 barrels of oil were recovered: of this 26.3 barrels flowed to the surface in 34 minutes, and from this figure a rate of 1200 barrels (approximately 200 m^3) of oil per day was calculated. The oil had an API gravity of 34°, with a high pour-point.

The high productivity and evidence of stable pressure within the reservoir convinced the operator to case and production-test the well. The test results indicate that an oil/water contact is located very close to the well and

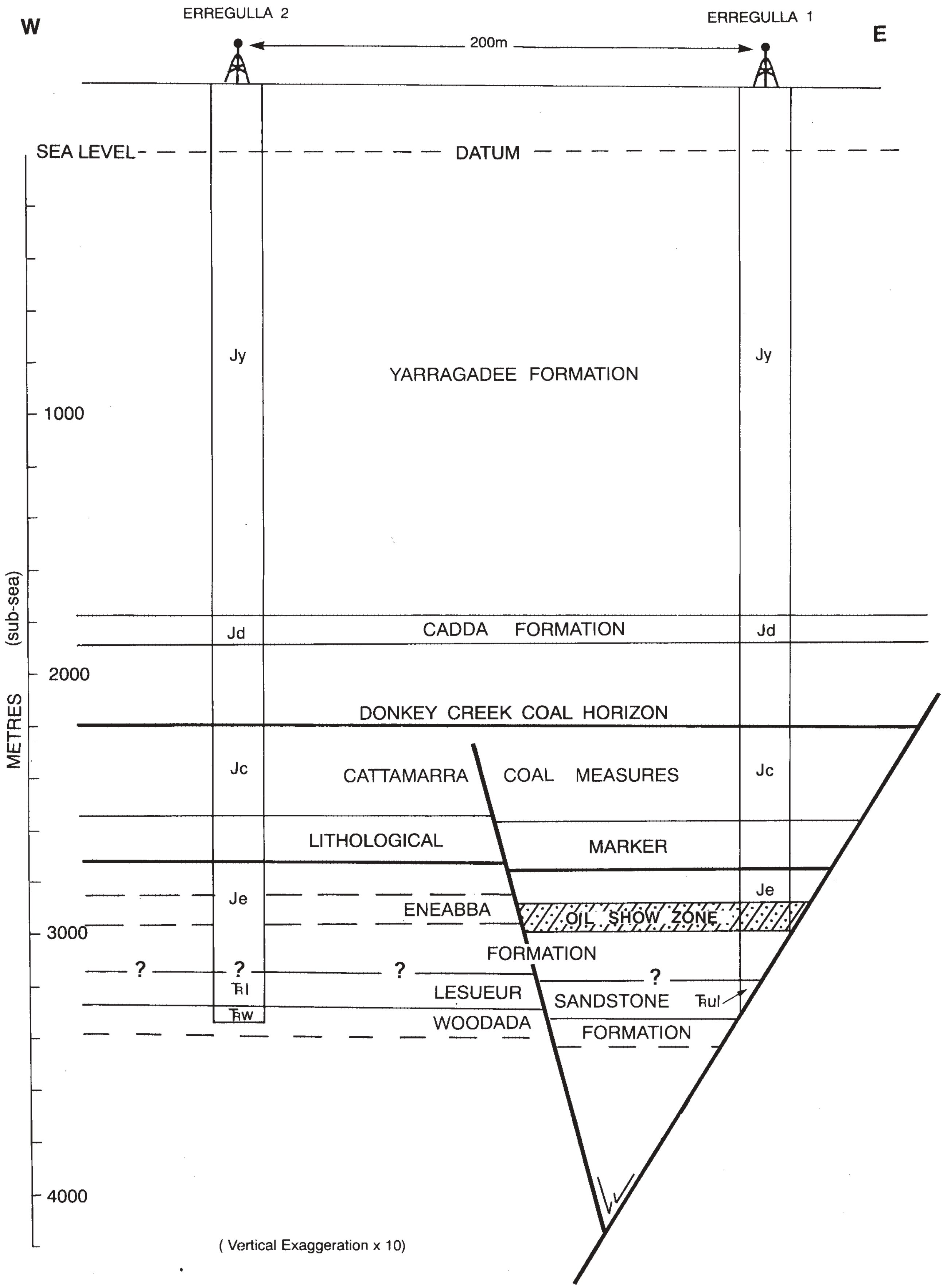

Figure 30. Cross section through Erregulla 1 and 2 (from Erregulla 1 well-completion report)

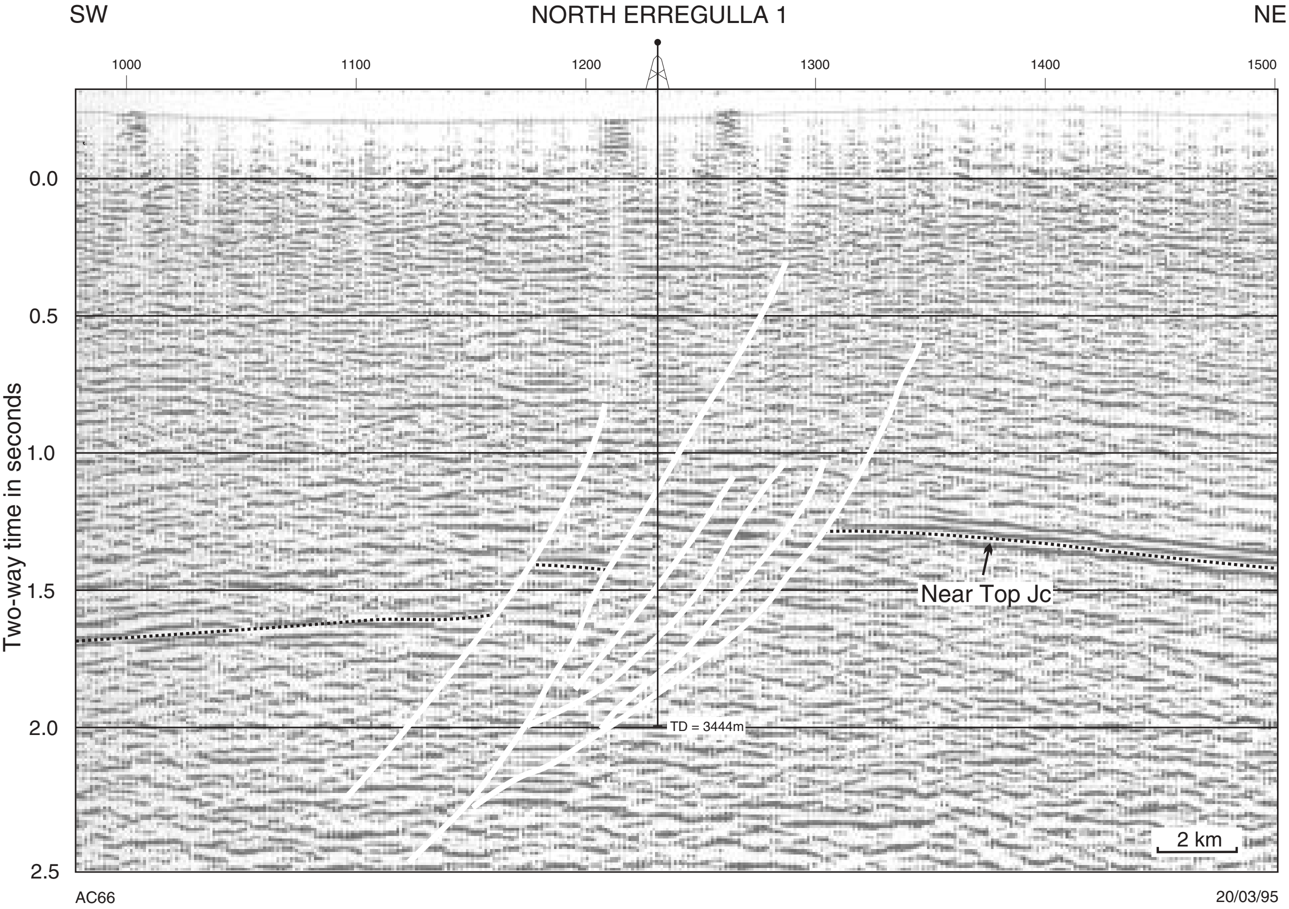

Figure 31. Seismic line ES84-14, Erangy Springs Seismic Survey, showing the North Erregulla 1 faulted location. Jc — Cattamarra Coal Measures. Location of section is shown on Figure 4

minimal reserves can be mapped downdip. The oil has a very low gas/oil ratio, too small to be measured, and a high water-cut. During the production tests, the percentage of water increased steadily.

Source

Geochemical analyses indicate a source in the Early Triassic Kockatea Shale. The very low gas/oil ratio (GOR) suggests that the source rock is only marginally mature.

Reasons for failure

North Yardanogo 1 probably did not test a valid trap. The recovered oil occurred in a very small stratigraphic, permeability or, more likely, fault trap.

South Yardanogo 1

Location

South Yardanogo 1 was drilled late in 1990 by Arrow Petroleum within the Beharra Springs Terrace, 3.75 km south of North Yardanogo 1 and 1.5 km to the east of the Mountain Bridge Fault (Fig. 3). The well was designed to test a Jurassic rollover anticline, similar to that tested by North Yardanogo 1.

Stratigraphy

South Yardanogo 1 penetrated a succession closely correlatable to that penetrated by North Yardanogo 1. A total depth of 2350 m was reached.

Structure

The interpreted existence of a valid trap down to total depth is not supported by the well results, since all sandy intervals proved to be water wet. It is suggested that either an anticlinal closure is not present at the depth of the critical objective or the rollover anticline was breeched by a crestal fault and the hydrocarbons migrated upwards. The presence of normal faults within the drilled area is also indicated by Arrow Petroleum in the South Yardanogo 1 well-completion report.

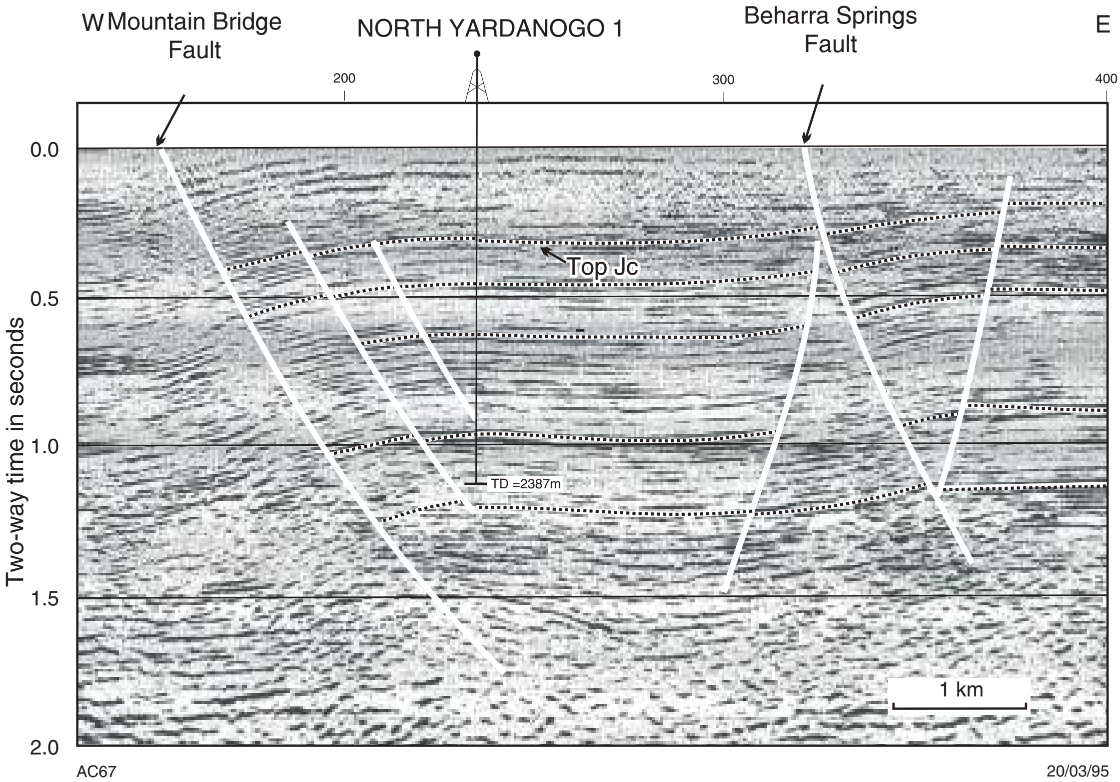

Figure 32. Seismic line B88-306, Yardanogo Seismic Survey, across the North Yardanogo prospect. Jc — Cattamarra Coal Measures. Location of section is shown on Figure 4

Reservoirs and seals

Good sandy reservoirs are present throughout the lithostratigraphic succession and intraformational seals are also common.

Hydrocarbons

No shows were detected throughout the entire section. Minor traces of methane were present below 2070 m.

Source

The widespread Early Triassic Kockatea Shale, which was the source of the oil recovered in North Yardanogo 1, should also be locally present.

Reason for failure

Migration paths from nearby kitchen areas are similar to those which allowed oil migration to the rocks intersected by North Yardanogo 1. It is thus concluded that the South Yardanogo 1 well did not test a valid trap.

Remaining potential

The Yardanogo area has good reservoir characteristics, good sealing potential, and lies within migration paths from a kitchen that is mature for oil generation. An additional test seems to be justified in the area, contingent on the reinterpretation of the seismic data and their depth conversion.

The two plays that can possibly be tested in the area are:

- Jurassic–Triassic sandstones in a valid structural closure. In the event that such a closure is substantiated, the well should test the entire stratigraphic succession above the Mountain Bridge Fault;
- Triassic–Permian sandstones below the Mountain Bridge Fault plane, trapped by truncation against the fault: this play may or may not be tested from the same surface location as the above-mentioned play.

Arrowsmith 1, Arramall 1, and Mountain Bridge 1

Location

Arrowsmith 1, Arramall 1, and Mountain Bridge 1 were all located within a short distance of each other in the northernmost part of the Cadda Terrace, close to the Abrolhos Transfer Fault, some 40 km south of the Dongara field and 4–5 km east of the Beagle Fault (Fig. 3). Arrowsmith 1 was drilled in 1965 by Australian Aquitaine Petroleum, Arramall 1 in 1989 by Barrack Energy, and Mountain Bridge 1 in 1993 by SAGASCO.

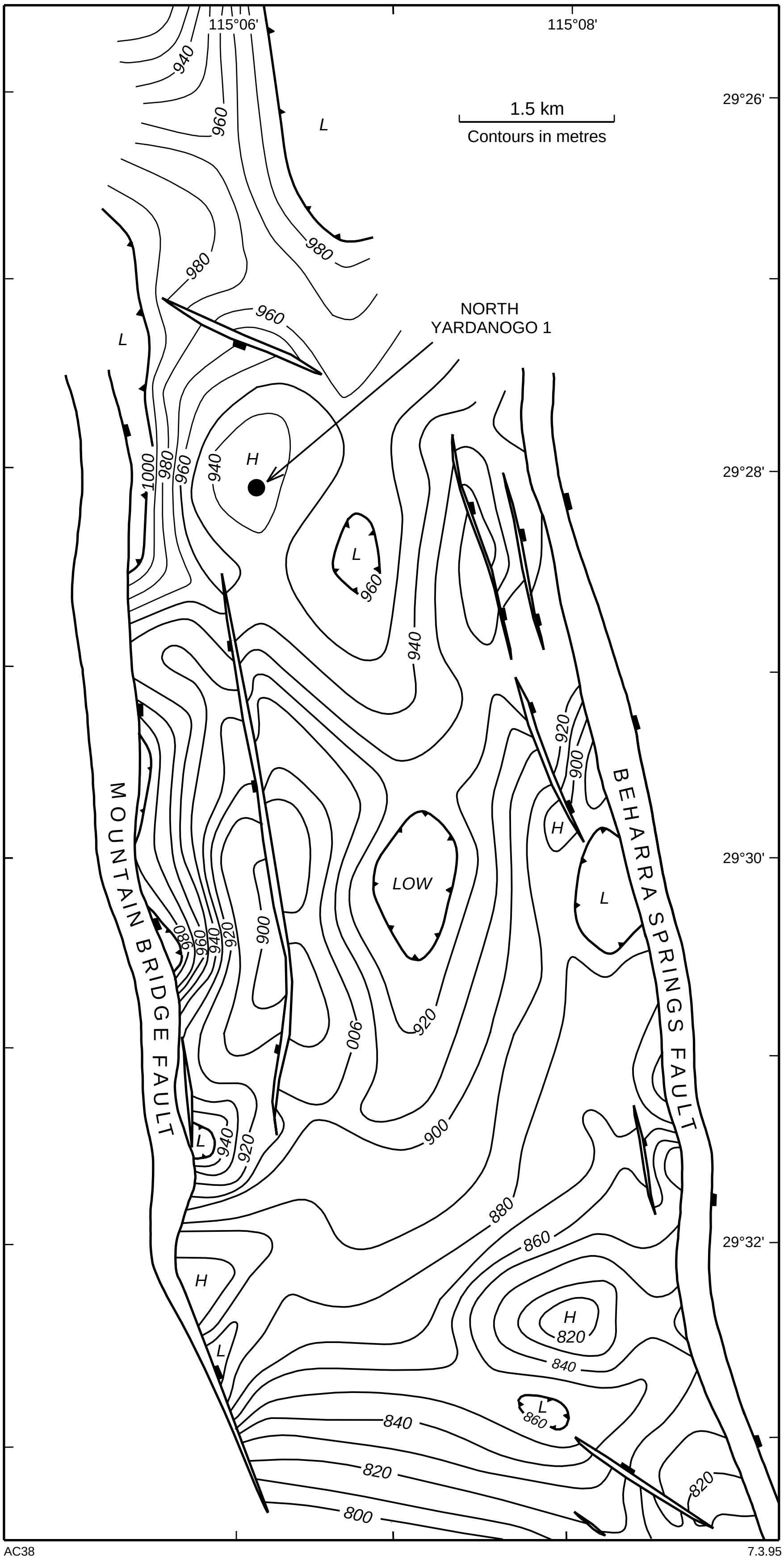

Figure 33. Time-structure map, near-top Coaly Unit horizon, North Yardanogo area (from North Yardanogo 1 well-completion report)

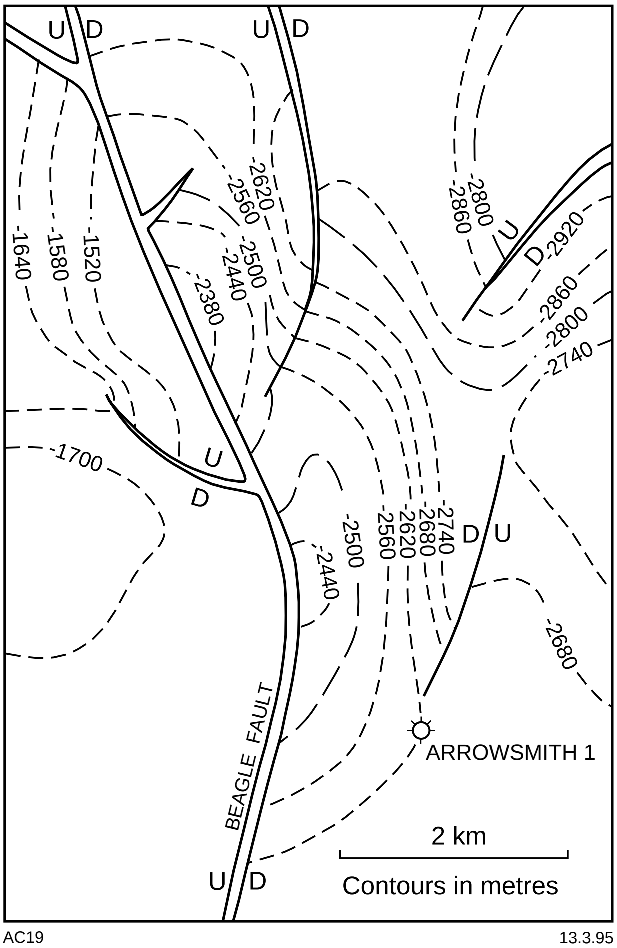

Figure 34. Permian structure map of the Arrowsmith area (from Jones, 1976)

History of exploration

Arrowsmith 1 was planned to test a seismically delineated structure. It penetrated a continuous stratigraphic succession from the Yarragadee Formation to granitic basement at 3420 m and terminated at 3446 m. In the well-completion report, Aquitaine concluded that Arrowsmith 1 was ‘probably’ drilled near the top of the structure, although within the text of the report it is stated that the well ‘has been drilled on the eastern flank of the structure.’ Jones (1976; Fig. 34) shows that Arrowsmith 1 at top Permian level was actually located to the east of a mapped closure, 200–250 m downdip.

The most important result from Arrowsmith 1 was the gas recovered from DST 3 and DST 4, which tested sandstone near the top of the Early Permian Caryngnia Formation. The gas flowed at an estimated rate of approximately 10^5 m^3 per day. The well was completed as a gas producer, but in production tests the gas volume and pressure declined rapidly. Arrowsmith 1 was finally abandoned in 1981.

Arramall 1 was planned to test a Jurassic rollover, 3 km northwest of Arrowsmith 1 (Fig. 35). The well bottomed in the basement at 2250 m, after the Beagle Fault was crossed below the Kockatea Shale at 2220.5 m (Fig. 36). Between the Kockatea Shale and basement a thin sliver of the Irwin River Coal Measures was penetrated. Minor shows of oil and gas were encountered, but after logging the well was plugged and abandoned without testing.

Arramall 1 did not penetrate the main objectives of the area and therefore was not conclusive.

Mountain Bridge 1 was designed to test both the Mesozoic and Palaeozoic succession. The well was located 1 km to the southeast of Arramall 1, and 2 km to the northwest of Arrowsmith 1. The shallower horizons intersected were within the eastern flank of an anticline controlled by the Beagle Fault to the west. Deeper down, the plane of the axis of the anticline is increasingly closer to the plane of the Beagle Fault. Consequently, the trap at Permian level becomes a truncation trap, because the controlling fault cuts out the western portion of the anticline. Such a fault was postulated to be sealing. The play is illustrated in Figure 37.

Mountain Bridge 1 penetrated an unfaulted stratigraphic succession from the Yarragadee Formation to granitic basement, which was encountered at 3385 m. The well reached total depth at 3416 m.

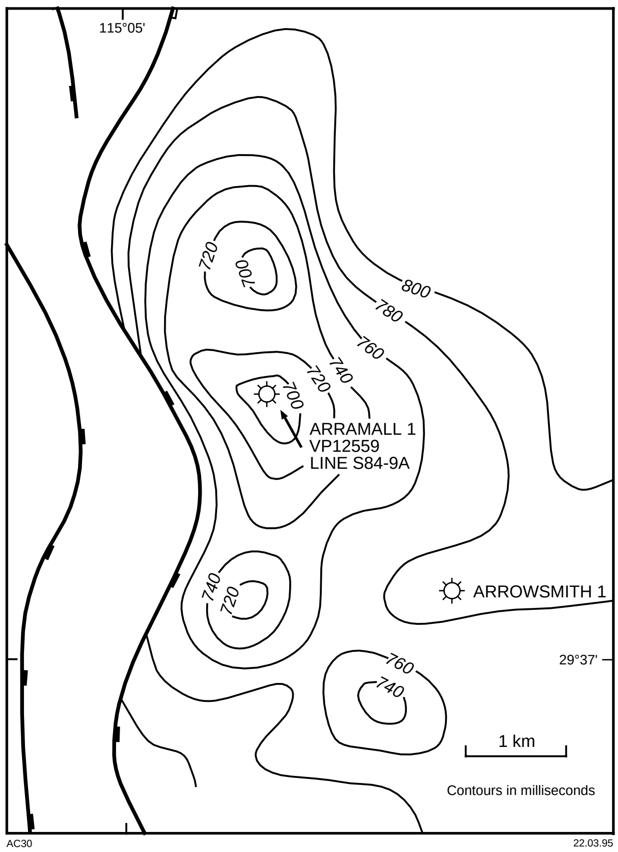

Figure 35. Structure map of near-top Eneabba Formation, Arrowsmith area, constructed prior to the drilling of Arramal 1 (from Arramal 1 well-completion report)

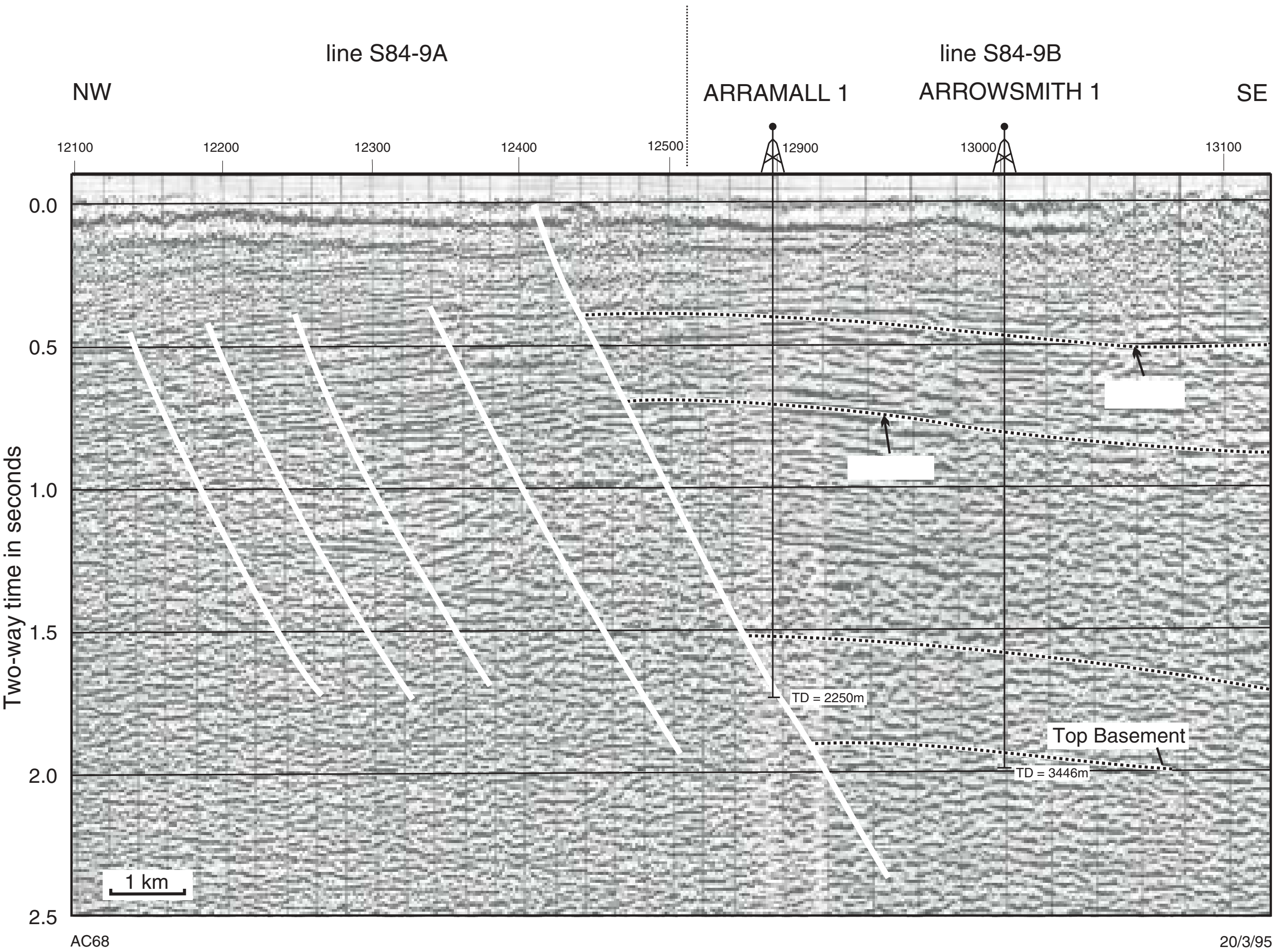

Figure 36. Seismic line S84-9A/9B, Eneabba Seismic Survey, across the Arrowsmith area showing Arramall 1 and Arrowsmith 1 (from Arramall 1 well-completion report). Jc — Cattamarra Coal measures. Location of section is shown on Figure 4

Stratigraphy

Table 4 shows a summary of the stratigraphy intersected by Mountain Bridge 1. The stratigraphic sequence penetrated by Mountain Bridge 1 is closely correlatable with that of Arrowsmith 1.

Structure

The gas-bearing section in Arrowsmith 1 may have been fed by fractures, as is common in the Woodada gasfield. It is therefore inferred that the well encountered a limited volume of fractured rocks.

Interpretation by SAGASCO (Mountain Bridge 1 well-completion report) indicates that the Mountain Bridge Fault merges with the Beagle Fault (Fig. 37). In contrast, the interpretation of Mory and Iasky (in prep.; Fig. 3) indicates that the Arrowsmith, Arramall, and Mountain Bridge area is intersected by the Abrolhos Transfer Fault. In particular, the Mountain Bridge Fault disappears to the south of the Abrolhos Fault, as do the Beharra Springs Fault and other features.

The structural setting of the area is therefore considered to be radically different from the setting that has been accepted to date. It is possible that all three wells did not test a valid closure: hydrocarbons may have migrated southward to the Woodada field or been trapped nearby in a different setting.

Reservoir and seals

In Arrowsmith 1, sandstones of the Yarragadee and Eneabba Formations have good porosity, with values ranging from 20–30%. Also, the permeability is very high, as the results of DST 1 (water flow) indicate.

The 5 m-thick gas-bearing ‘unconsolidated sand’ penetrated near the top of the Carynginia Formation has good porosity. Although the upper section was caved, a porosity of 24% was calculated for the lower section from logs. As discussed above, there is a strong possibility that the Arrowsmith reservoir is represented by fractured rocks.

DST 6 in Arrowsmith 1, which was run across the Irwin River Coal Measures, was dry. The Early Permian sandstones proved to be tight, although the log-derived porosity ranges from 9 to 14%. In Mountain Bridge 1, the Permian sandstones seem to maintain fair reservoir potential, although three out of four valid

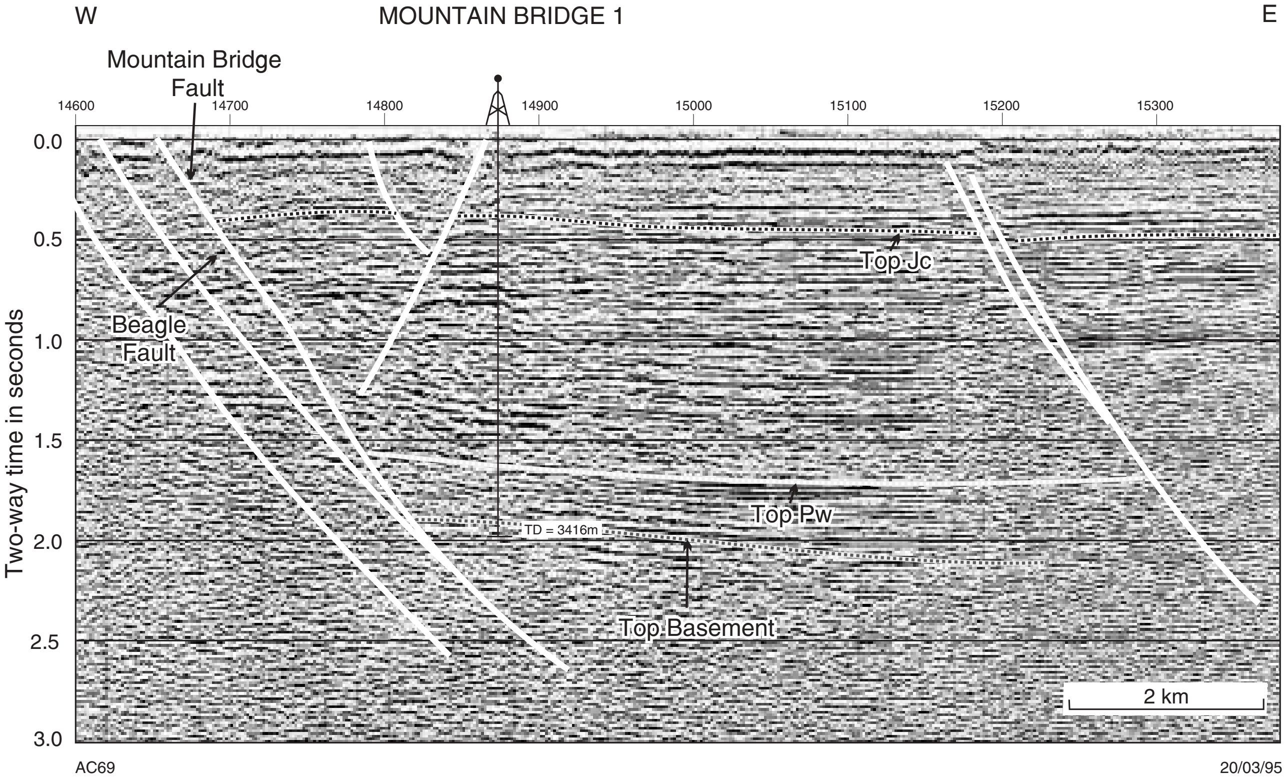

Figure 37. Seismic line S-84-11, Eneabba Seismic Survey, across the Arrowsmith area, showing Mountain Bridge 1 (from Mountain Bridge 1 well-completion report). Jc — Cattamarra Coal Measures; Pw — Wagina Formation. Location of section is shown on Figure 4

tests did not result in flow to the surface. The fourth DST in Mountain Bridge 1 (DST 2A) recovered 2000 barrels of water and 0.25 MMcf of gas per day (respectively some 3.20×10^5 m^3 of water and 7×10^3 m^3 of gas).

The Early Triassic Kockatea Shale and intraformational Permian shales provide seals to the major objectives, which are potential Permian reservoirs.

Hydrocarbons

In Arrowsmith 1, the first fluorescence appeared 50 m below the top of the Kockatea Shale: increasing amounts of gas and some fluorescence were detected throughout the entire formation. Gas on surface was obtained from both DST 3 and DST 4, which tested sandstones near the top of the Carynginia Formation. Chromatograph analyses were reported in the well-completion report as follows:

methane	45.84%
ethane	38.47%
propane	7.86%
butane	3.51%
isobutane	2.81%
other hydrocarbons	0.41%

The well-completion report stated that ‘very important oil fluorescence’ was apparent throughout both the Early Permian Irwin River Coal Measures and the High Cliff Sandstone.

In Mountain Bridge 1, many gas peaks were encountered during drilling of the Early Triassic Kockatea Shale, confirming the local presence of hydrocarbons: C_1 to C_5 were recorded some 100 m below the top of the unit. The gas shows were related to fractures and faults. The gas ratio of the shows encountered across the Kockatea Shale indicates an oil-prone formation. Below 2540 m the formation produced wet gas with an increased total-gas background. The gas became progressively drier with depth across the Permian sequence. The Early Permian High Cliff Sandstone contains the driest gas in the well.

In conclusion, it appears that a setting for hydrocarbons similar to that of the Woodada field is present in the area, without the advantage of a valid trap.

Source

The gas that was produced from the Carynginia Formation sandstones in Arrowsmith 1 was probably generated by both the Carynginia Formation and the underlying Irwin River Coal Measures.

Table 4. Mountain Bridge 1, SAGASCO well index sheet

COMPANY:	SAGASCO Resources Ltd	WELL:	Mountain Bridge 1
SPUDDED:	11 March 1993: 1200 hours	BASIN:	Perth
RIG RELEASED:	17 May 1993: 0800 hours	TENEMENT:	EP100(1)
TD:	3416 m	LATITUDE:	29°36’04.833"S
GL/SF:	39 m	LONGITUDE:	115°06’06.059"E
KB:	46 m	NORTHING:	6 723 872
STATUS:	Plugged and abandoned	EASTING:	316 166

Formation/Marker	*Seismic TWT*	*Tops (m)*		*Lithologic summary*	*Remarks/Shows*
		Drill	*Sub Sea*		
Surficial deposits and Yarragadee Formation	Surface	7.0	+39	Sandstone, shale	
Cadda Formation		577	–531	Sandstone, shale	
Cattamarra Coal Measures	445	658	–612	Sandstone, shale, coal	
Eneabba Formation	854	1 275	–1 229	Sandstone, claystone	
Lesueur Sandstone	1 116	1 731	–1 685	Sandstone	
Woodada Formation	–	1 984	–1 938	Sandstone	
Kockatea Shale	1 329	2 160	–2 114	Claystone	Trace oil fluorescence
Wagina Sandstone	1 566	2 647	–2 601	Shale, sandstone	Trace oil fluorescence; moderate–strong gas shows
Beekeeper Formation	1 595	2 670	–2 624	Limestone	Trace oil fluorescence; moderate–strong gas shows
Carynginia shale	1 598	2 679	–2 633	Shale	Moderate gas shows
Irwin River Coal Measures	1 702	2 886	–2 840	Shale, coal, sandstone	Trace oil fluorescence
High Cliff Sandstone	1 854	3 218	–3 172	Sandstone	Weak gas shows
Holmwood Shale	1 866	3 248	–3 202	Shale	
Basement	1 922	3 385	–3 339	Granite	
TD	1 930	3 416	–3 370		

Drillstem tests

DST 1	2667–2680 m	NFTS
DST 2	3185–3235 m	Misrun — packers deflated
DST 2A	3185–3235 m	2000 BWPD + 0.25 MMCFGD
DST 3	2755–2790 m	Misrun — packers failed to inflate
DST 3A	2755–2790 m	Tight
DST 4	2625–2660 m	Misrun — pump malfunction
DST 4A	2630–2662.5 m	Misrun — ruptured top packer
DST 5	3184–3217.5 m	NFTS

Plugs

Plug 1	3230–3150 m
Plug 2	2648–2588 m
Plug 3	2241–2161 m
Plug 4	625–525 m
Plug 5	20 m–surface

TD: Total depth
GL/SF: Ground level
KB: Kelly bushing
NFTS: No fluid to surface
BWPD: Barrels of water per day
MMCFGD: Million cubic feet gas/day
TWT: Two-way time

An evaluation of the shows encountered by the two deep wells suggests that the units above the Kockatea Shale are immature for hydrocarbon generation and that the Kockatea Shale is marginally mature and oil prone, whereas the Permian succession is mature and gas prone.

Reasons for failure

It is likely that Arrowsmith 1, Arramall 1, and Mountain Bridge 1 did not test valid traps. Furthermore, Arramall 1 did not penetrate the Permian objectives.

Remaining potential

From an exploration point of view, the Arrowsmith, Arramall, and Mountain Bridge area is very attractive. Three dry tests to basement, however, represent a heavy draw back.

A reinterpretation of the seismic data that takes into consideration the above described structural setting should be carried out. If justified, additional seismic data may be acquired. A more prospective location than those already drilled may then possibly emerge.

Eneabba 1

Location

Eneabba 1 was drilled in 1961 by WAPET in the northwestern part of the Dandaragan Trough (Fig. 3), the western margin of which is generally taken to be represented by the Eneabba Fault. This boundary is poorly defined near Eneabba 1 due to the lack of a secondary depression, such as the Coomallo Trough.

Stratigraphy

Eneabba 1 was spudded in the Yarragadee Formation, encountered the Cadda Formation at 1442 m, the Cattamarra Coal Measures at 1554 m, the Eneabba Formation at 2320 m, the Lesueur Sandstone at 2978 m, the Woodada Formation at 3270 m, and the Kockatea Shale at 3402 m, bottoming in the latter at 4179 m. The lithostratigraphy is similar to that in Donkey Creek 1.

Structure

The well was designed to test the hydrocarbon potential of an interpreted trap on the east side of the Eneabba Fault. The regional dip towards the axis of the northern extension of the Dandaragan Trough indicated the presence of the dip closure to the east. Small dip closures were mapped both to the north and south, and the critical closure to the west depended on the Eneabba Fault acting as seal (Fig. 38). A simplified cross section illustrates the basinal position of Eneabba 1 (Fig. 39).

The Eneabba feature appears to be the highest along the trend, as shown by the WAPET seismic interpretation (Fig. 38) and confirmed by Mory and Iasky (in prep.). The seismic line B89-411 illustrates the setting of the Eneabba play within the regional context (Fig. 40).

Reservoirs and seals

The highly porous and permeable sandstones of the Yarragadee Formation contain fresh water: no effective seal is present. Both the Cattamarra Coal Measures and the Eneabba Formation have good reservoir potential. The lower part of the Cattamarra Coal Measures has a porosity of 17% and a horizontal permeability of 23 md.

The Cadda Formation provides a regional cover, whereas intraformational shales provide local cover.

Hydrocarbons

Numerous traces of gas and oil were detected in the succession below the Cadda Formation. Strong flows of wet gas associated with fracture zones occurred throughout the Kockatea Shale. No DSTs were carried out because the well had to be abandoned due to technical problems. The drillpipe became stuck and 2806 m of drilling string were left in the hole.

Source

The Kockatea Shale is marginally mature at the well location and certainly fully mature within the migration paths to the well. It is expected that the wet gas detected in Eneabba 1 was generated in the Early Triassic formation, although contribution from the Early Permian sedimentary rocks cannot be excluded.

Reason for failure

The Eneabba 1 well did not test a valid trap. The Jurassic and Triassic potential reservoirs lack a lateral seal against the Eneabba Fault, being juxtaposed against younger permeable sand units.

Remaining potential

The presence of strong flows of wet gas within fractured zones of the Kockatea Shale is similar to the Woodada area. The shows are a good indication of a hydrocarbon accumulation at depth. The thick impervious Kockatea Shale should have better potential for lateral sealing than the thinner intraformational shales of the younger lithostratigraphic units. An exploration well located close to the Eneabba Fault at top-Permian level appears to be warranted in order to test the hydrocarbon potential of the Permian succession.

Donkey Creek 1

Location

Donkey Creek 1 was drilled in 1966 by French Petroleum Company (Australia) in a north-trending faulted compartment within the Donkey Creek Terrace of the Perth Basin (Fig. 3). The faults interrupt the gradual eastward dip of the strata from the Beharra Terrace towards the axis of the northern extension of the Dandaragan Trough.

Stratigraphy

Donkey Creek 1 was spudded in the Late Middle Jurassic Yarragadee Formation, penetrated the Middle Jurassic Cadda Formation, the Early–Middle Jurassic Cattamarra Coal Measures, the Early Jurassic Eneabba Formation, the Middle–Late Triassic Lesueur Sandstone, the Middle Triassic Woodada Formation, and bottomed in the Early Triassic Kockatea Shale at 3855 m.

The well encountered a stratigraphic succession closely correlatable with that in Eneabba 1, drilled 7.5 km to the northeast. It is noteworthy that the outstanding event on seismic sections in the area, namely a coal horizon within the Cattamarra Coal Measures (Fig. 41) intersected by Donkey Creek 1, does not occupy the same stratigraphic position that it occupies in Eneabba 1. The most distinct seismic marker is not, therefore, a reliable stratigraphic marker, and a seismic interpretation based on character correlation across faults may not be valid in the area.

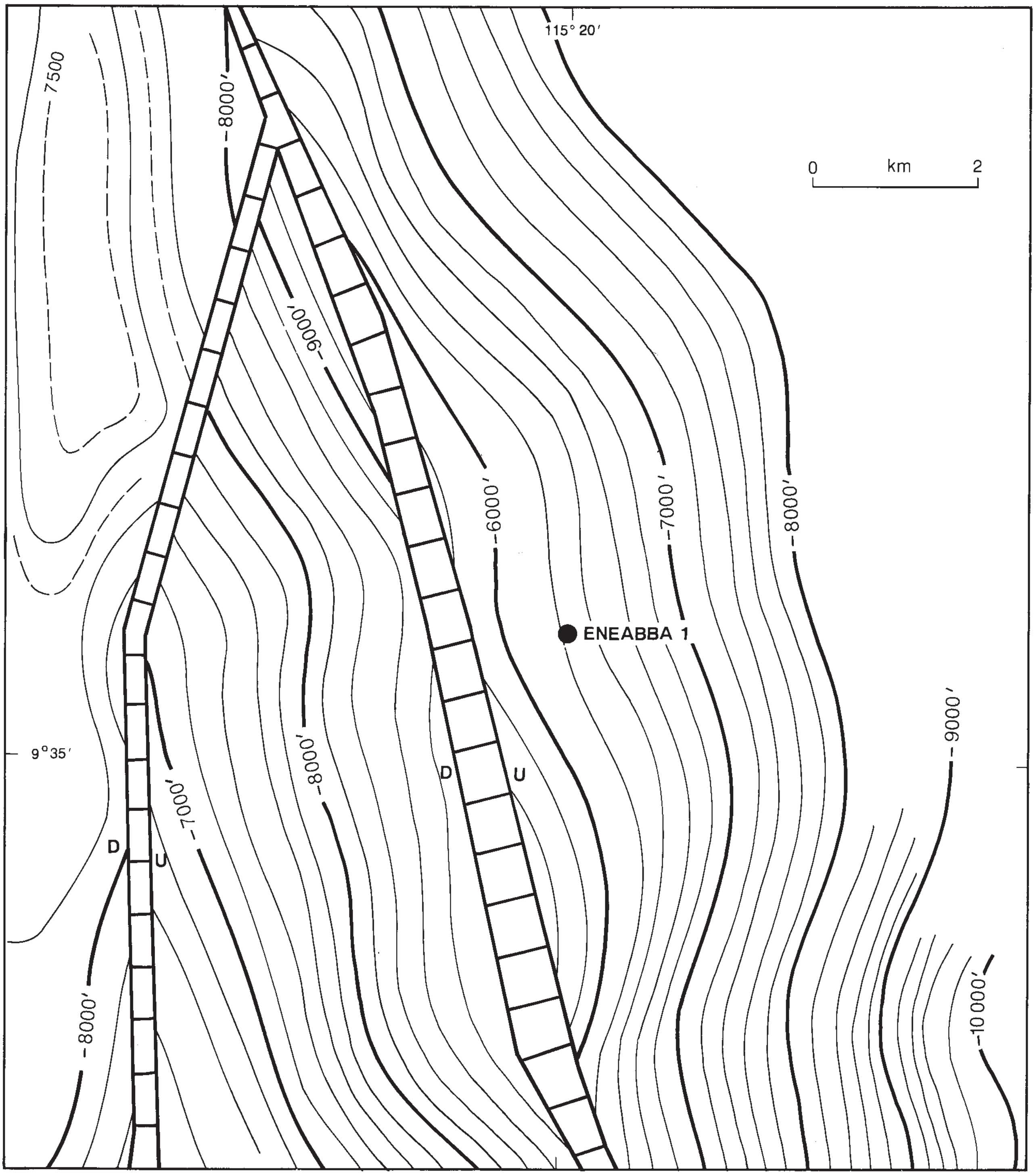

Figure 38. Structure map of the Jurassic coal horizon, Eneabba prospect (from Eneabba 1 well-completion report)

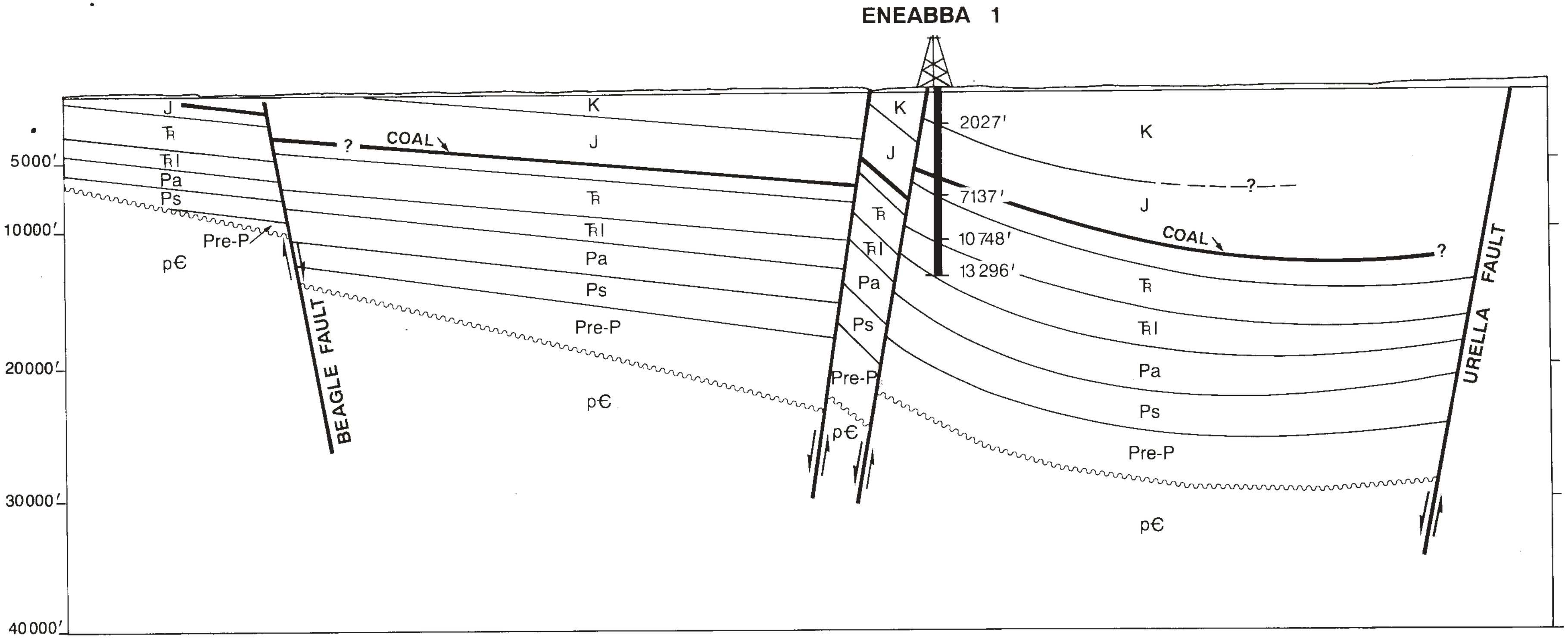

Figure 39. Regional cross section of the Eneabba prospect (from Eneabba 1 well-completion report)

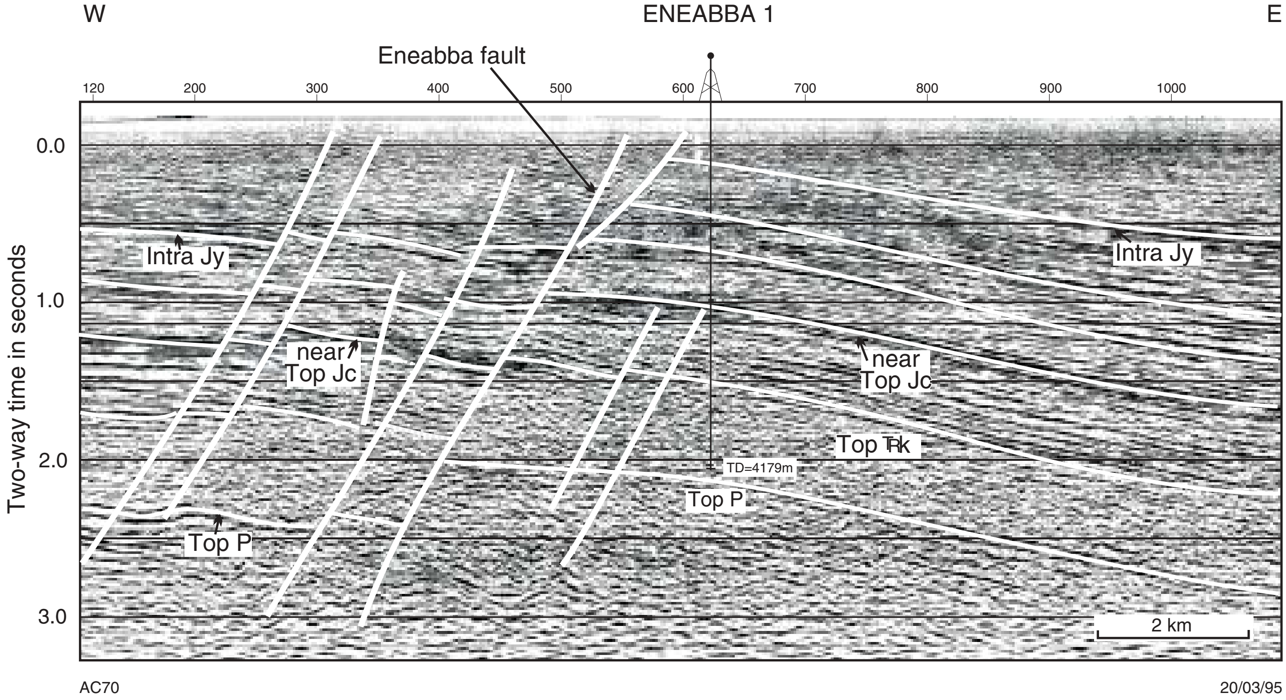

Figure 40. Seismic line B89-411, Correy Seismic Survey, across the Eneabba prospect, illustrating the hydrocarbon play within its regional context. Note how the Yarragadee Formation thickens towards the Dandaragan syncline. P — Permian; Ŧk — Kockatea Shale; Jc— Cattamarra Coal Measures; Jy — Yarragadee Formation. Location of section is shown on Figure 4

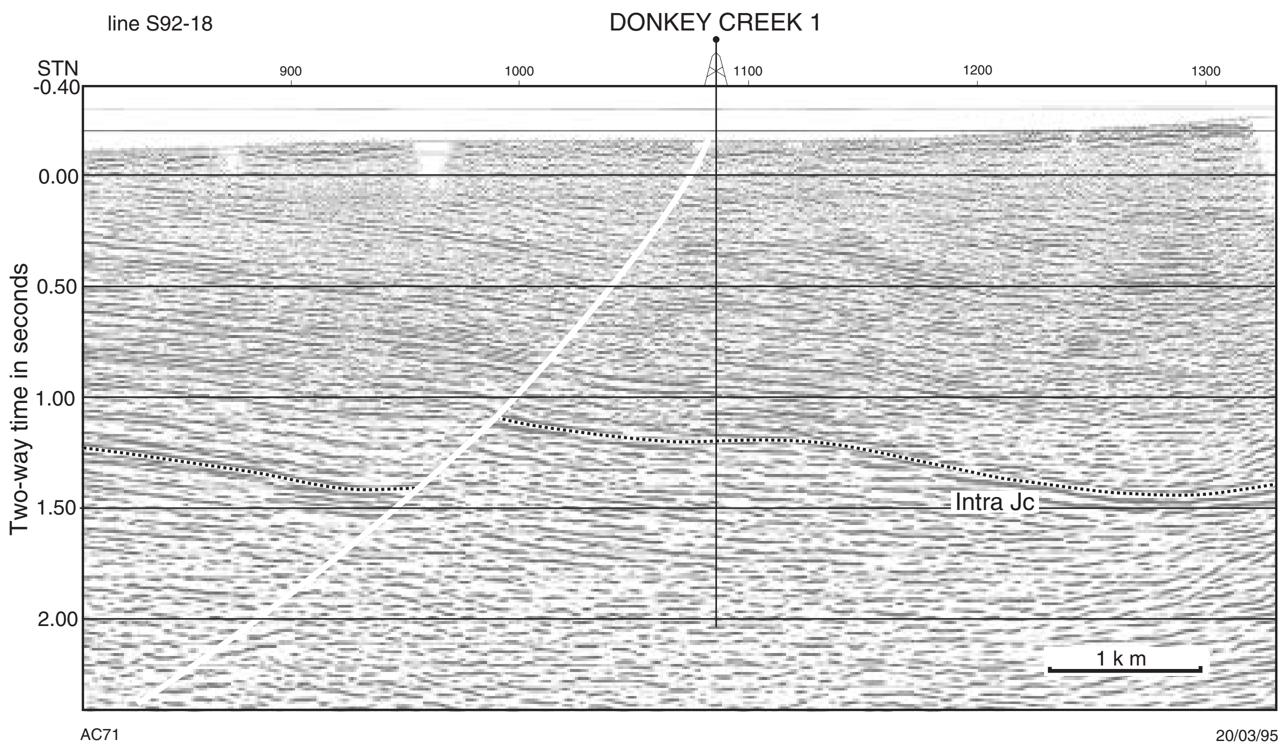

Figure 41. Seismic line S92-18, Yandanooka Seismic Survey, across the Donkey Creek prospect, showing Donkey Creek 1. Jc— Cattamarra Coal Measures. Location of section is shown on Figure 4

Structure

The area is characterized by an east-dipping monocline, with normal faults resulting in downthrown steps (Figs 40 and 41). Donkey Creek 1 was drilled to test an interpreted closure against the large fault intersecting the monocline to the west of the well. A sealing fault was therefore postulated. Figure 41 shows that, at the level of the main objectives, the well was drilled approximately 300 m downdip from the structurally highest point of the assumed fault trap.

Reservoirs and seals

Good potential sandstone reservoirs occur throughout the entire succession. The highest porosity values occur in the Eneabba Formation, the Lesueur Sandstone, and the top of the Woodada Formation; a porosity of 14.5% and a permeability of 4.8 md were measured in core from the latter.

The highest effective seal was encountered towards the base of the Yarragadee Formation, where a substantial increase in salinity occurs. Below, vertical seals are offered by the Cadda Formation and by intraformational shales.

Hydrocarbons

Minor shows of gas were encountered in the Lesueur Sandstone and the Woodada Formation. Fluorescence occurred in the lower unit of the Woodada Formation but no traces of free oil were detected.

Source

Taking into account the geothermal gradient, the most reliable sources of hydrocarbons for the area should be the Early Triassic Kockatea Shale and the Early Permian Carynginia Formation and Irwin River Coal Measures.

Reasons for failure

Apart from the Cadda Formation and the Kockatea Shale, Donkey Creek 1 encountered a sandy–shaly succession. In particular, the Eneabba Formation and the Lesueur Sandstone are predominantly sandy. The lateral seal that was thought to be provided by the critical fault appears not to exist. No valid trap was thus tested.

Remaining potential

The Donkey Creek area does not contain any anticlinal closures, which to date represent the most effective traps in the basin.

Assuming that the dip closures to the north and south are confirmed, a well has the best chance to test a valid fault-sealing trap when deepened below the thick impermeable Kockatea Shale. A location as close as feasible to the intersection of the plane of the critical fault with the top-Permian level should be chosen.

Ocean Hill 1

Location

Ocean Hill 1 exploration well was drilled by Arrow Petroleum in 1991 within the northern section of the Coomallo Trough (Fig. 3), 4 km west of the Eneabba Fault at top-Cadda Formation level.

Stratigraphy

Ocean Hill 1 was spudded in the Yarragadee Formation, encountered the Cadda Formation at 2959 m and the Cattamarra Coal Measures at 3248 m. The well bottomed on the latter unit at 3840 m.

Structure

As shown in Figure 42, Ocean Hill 1 was designed to test a highly faulted anticline. The fold has a northerly orientation and presents a four-way dip closure. The structurally highest point falls within the crestal collapsed portion of the anticline.

Strike-slip movements are known to have taken place during continental breakup and probably formed the Ocean Hill anticline, as well as other anticlines in the area.

Reservoirs and seals

Sandstones of reservoir quality are present in the Cattamarra Coal Measures. The potential reservoirs are sealed vertically by the Cadda Formation, which represents the regional seal, and also by intraformational shales. It is worth noting that the zones with hydrocarbon indications proved to be tight in DSTs, whereas zones with better reservoir quality were water-wet.

Hydrocarbons

Background gas up to pentane was detected in the Cadda Formation to total depth, and good gas shows were present. The best show was from a DST in the Cadda Formation, over the interval 3070–3130 m, and resulted in a flow of gas that lasted for 104 minutes. The flow rate was calculated to be 700 000 cubic feet (cf), approximately 2.0×10^4 m^3, per day. Fluorescence was also noted throughout the Cadda Formation and Cattamarra Coal Measures.

Following the encouraging DST results, SAGASCO fully financed the casing and testing of Ocean Hill 1. Seven discrete zones were tested. No commercial flows of hydrocarbons were obtained. Small amounts of gas reached the surface but the gas-rate was too small to be measured, except for over the 3099.5–3039.7 m zone, which flowed at a rate of 300 000 cf (approximately 8.5×10^3 m^3) per day. The poor results are interpreted to be due to very low permeability.

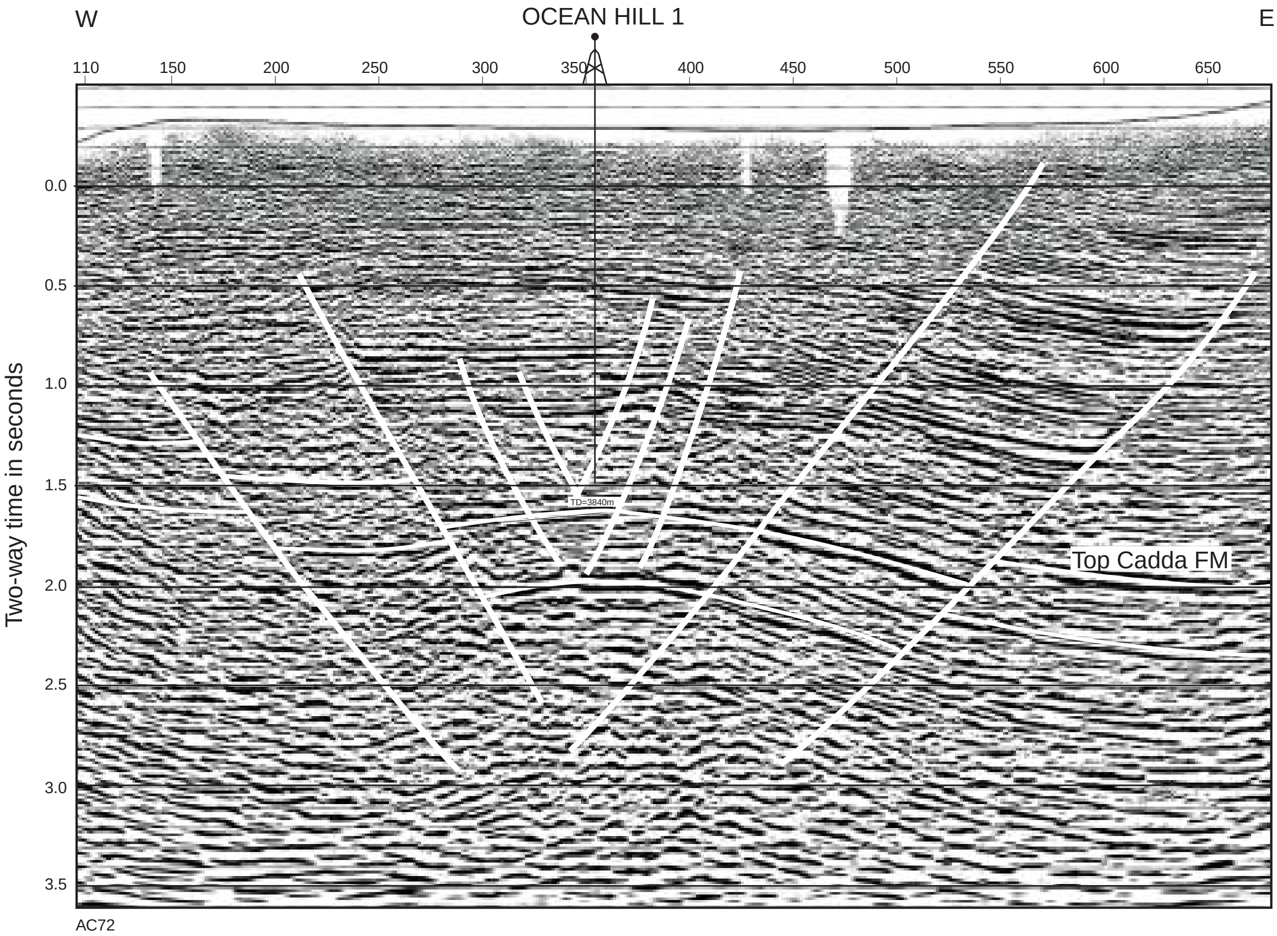

Figure 42. Seismic line B89-450, Coomallo Detailed Seismic Survey, across the Ocean Hill prospect, showing the structure rollover (modified after Ocean Hill 1 well-completion report). Location of section is shown in Figure 4

Source

Although the Cattamarra Coal Measures may have generated the hydrocarbons encountered in the well, a deeper source cannot be disregarded as a possibility.

Reasons for failure

The highly faulted Ocean Hill 1 anticline may not offer a valid trap at the very sandy levels tested due to the lack of lateral seal across the faults. The very small amounts of gas recovered may be trapped by a permeability barrier.

Remaining potential

At depth, the thick Early Triassic Kockatea Shale may offer better sealing potential for possible Permian objectives, but these are probably too deep to be of interest in the current economic conditions. Furthermore, the presence of Permian sedimentary rocks within the Coomallo and Dandaragan Troughs is only inferred. A regional Permian isopach map (Mory and Iasky, in prep.) indicates that the interval thins from the Allanooka High to the south. Also, seismic data significantly deteriorate at depth and structural interpretation becomes highly speculative. Regionally, the depressed structural setting of the Coomallo Trough may hamper migration from the largest kitchen areas to the east.

Coomallo 1

Location

Coomallo 1 was drilled by WAPET in 1974 within the central section of the Coomallo Trough, 5 km to the west of the surface expression of the Eneabba Fault (Fig. 3).

Stratigraphy

Coomallo 1 was spudded in the Yarragadee Formation, encountered the Cadda Formation at 2972 m and the Cattamarra Coal Measures at 3202 m. The well bottomed in the latter unit at 3526 m.

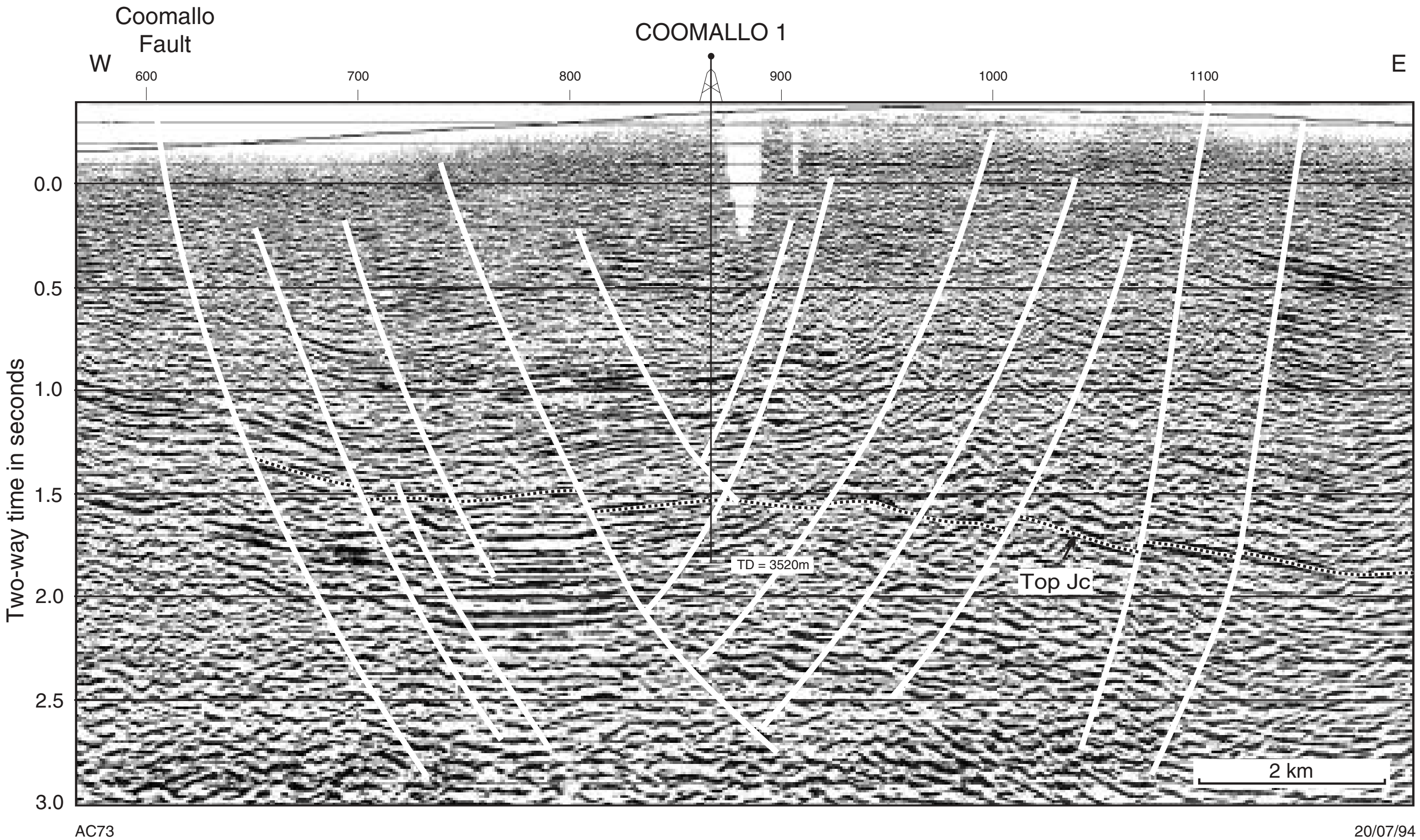

Figure 43. Seismic line B89-414, Coomallo Hill Seismic Survey, across the Coomallo prospect, showing Coomallo 1. Jc — Cattamarra Coal Measures. Location of section is shown in Figure 4

Structure

Coomallo 1 tested the hydrocarbon potential of a highly faulted anticline. The trend of the structure is controlled by north-trending faults, limiting the area of the objective (Fig. 3). Figure 43 shows that the well penetrated two fault compartments before testing a truncation play on the western flank of the anticline. Seismic data and the regional setting indicate that the anticline was formed during the Early Cretaceous continental breakup.

Reservoirs and seals

The section penetrated by Coomallo 1 is predominantly sandy with good porosity, although the porosity decreases with depth. Only minor interbeds of shale are present. The thin Cadda Formation represents an exception, being composed mainly of siltstone and shale, and provides the only potential seal.

Hydrocarbons

No hydrocarbon shows were detected during drilling, apart from gas peaks associated with coal beds.

Reasons for failure

No effective trap is likely to be present in the Coomallo 1 structure at the levels that have been penetrated. The very limited sealing potential appears to have been destroyed by the high number of faults present.

Remaining potential

Although it is possible that the structure may present some potential at depth where the thickness of the shale units is thought to increase, no further exploration activity seems to be justified.

Comments for the Ocean Hill anticline are also valid for the Coomallo structure.

Warro 1 and 2, and Warramia 1

Location

Warro 1 and 2 were drilled in 1977–78 by WAPET in the eastern flank of the central part of the Dandaragan Trough, less than 10 km to the west of the Urella Fault (Fig. 3). Because of their close proximity the two wells represent virtually only one test. Warramia 1 was drilled by Ampolex in 1992, 2 km south-southwest of the Warro wells.

Stratigraphy

Warro 1 was spudded in the uppermost section of the Yarragadee Formation and reached the Cadda Formation at more than 4340 m, encountering the thickest section of the Yarragadee Formation within the onshore northern Perth Basin. Warro 1 bottomed in the Cadda Formation at 4495 m, whereas Warro 2 was deepened further and penetrated 145 m of the Cadda Formation before bottoming in the Cattamarra Coal Measures at 4854 m.

Abnormal formation pressures were encountered in both the Warro wells below about 4300 m. WAPET calculated that the pressure was 22 787 KPa, in excess of the normal pressure for the depth.

Warramia 1 only penetrated sedimentary rocks of the Yarragadee Formation, reaching a total depth of 1498 m.

Structure

Two seismic surveys have been carried out in the Warro area. The first in 1976 (Winchester 2 Seismic Survey carried out by WAPET) led to the perforation of the two Warro wells, whereas the second in 1991 (Warramia 2 Seismic Survey carried out by Ampolex) was followed by the drilling of Warramia 1. The 1976 data are very limited and of very poor quality. A better understanding of the structural setting of the area may result from seismic information obtained after drilling of the Warro wells.

The Warro wells tested a very large north-northwesterly trending anticline, intersected by several faults (Figs 44 and 45). The structure is younger than the Yarragadee Formation, and its formation can therefore be attributed to the Early Cretaceous breakup, as can the majority of structures within the basin. Although no definitive assessment of the validity of the two Warro tests can be made on present knowledge, the Warro structure might have been tested some 200 m downdip from the crest at the level of the most valid objectives (Fig. 46).

Reservoirs and seals

The Yarragadee Formation is mainly sandy, but has both reservoir and sealing potential. The Yarragadee sandstones may therefore be sealed vertically by intraformational seals. An additional vertical seal may be provided by the Cadda Formation. The lateral seal across the numerous faults is, however, problematic.

Thirty-one cores from the Warro 2 Yarragadee Formation were petrophysically studied by Amdel (1978). All of the sandstones are compacted and contain angular quartz crystals derived from the original grains by post-depositional recrystallization. Five samples of cores were examined by Chevron Oil Field Research Company (1978), with results similar to those of Amdel. The cause of the recrystallization was not determined.

Hydrocarbons

Warro 1 encountered gas shows from 3750 m to total depth. A total of 178.5 m of possible gas pay were calculated from logs, with porosity ranging from 8 to 10%. Four tests were run, but no flow to surface resulted.

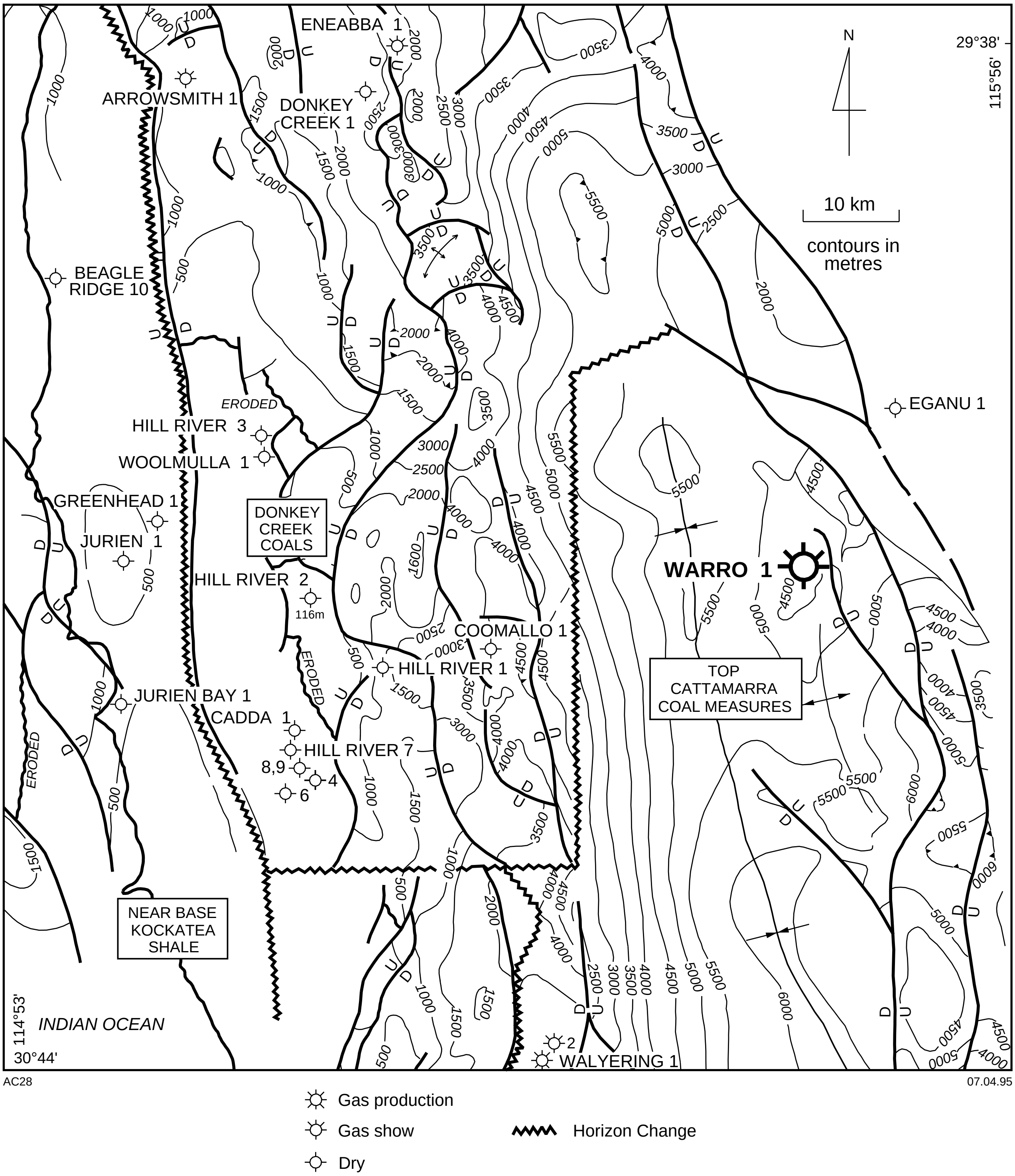

Figure 44. Generalized composite-structure map of the Warro prospect (from Warro 1 well-completion report)

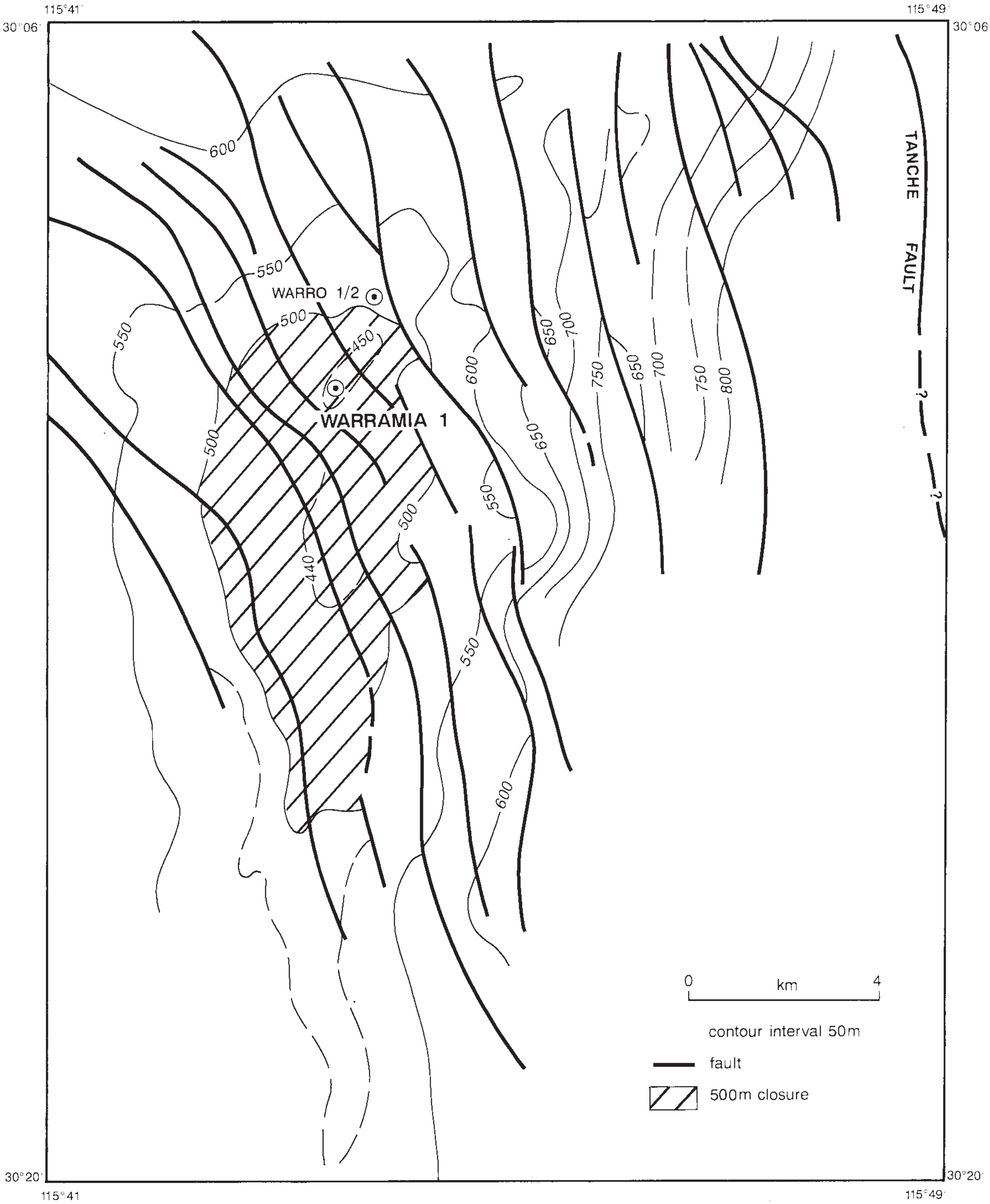

Figure 45. Time-structure contour map of the near-base Parmelia Formation for the Warro prospect, showing the location of Warro 1 and 2, and Warramia 1 (after Ampolex, 1992)

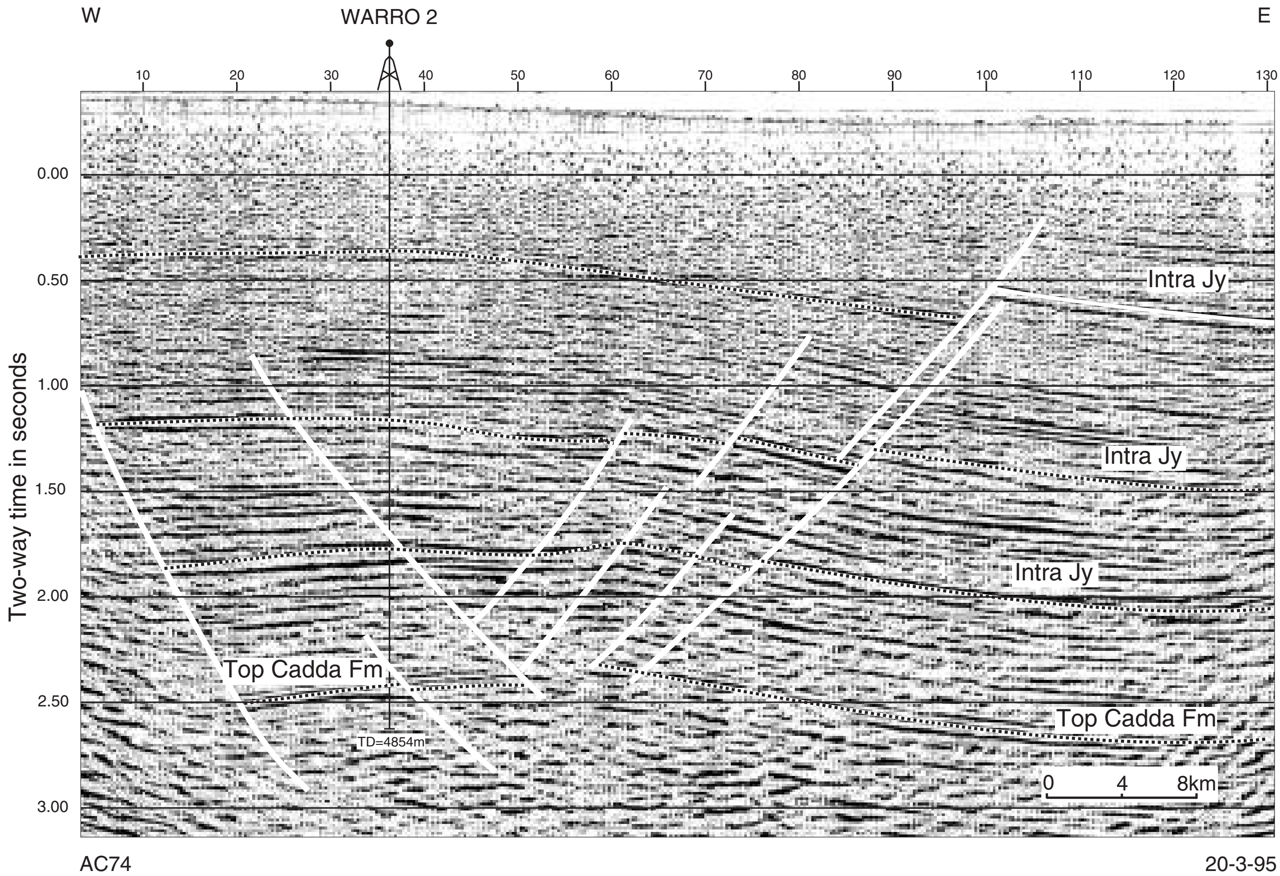

Figure 46. Seismic line P76-3L, Winchester 2 Seismic Survey, across the Warro prospect, reprocessed by Barrack Energy Limited, showing the location of Warro 2. Jy — Yarragadee Formation. Location of section is shown in Figure 4

The negative tests were attributed to the heavy mud that was used to drill the deeper Cadda Formation section in order to counterbalance its abnormal pressure. It was considered possible that deep filtrate invasion, and perhaps whole mud invasion, had occurred in most of the sandstones, causing damage to the formation and destroying the permeability to gas. A plan to plug the deep, abnormally pressured zone and re-drill the interval of interest with lighter mud failed.

Warro 2 was drilled immediately after, and 270 m west of, Warro 1 in order to exhaustively test the interval with gas indications. No attempt to re-map the structure was made. In Warro 2 a section very similar to that of Warro 1 was penetrated. Persistent high gas readings were recorded from 3780 m to total depth. The gas sandstones had an average porosity of 9–10%, with a maximum of 13.9%.

Two zones within the Yarragadee Formation, each comprising a number of sandstone beds, were tested. The tests were carried out after breaking down perforations and fracture treatment. No significant flow of gas could be sustained from either zone, as the permeability was too low.

Warramia 1 was planned to test the potential on the shallower flanks of the Warro structure, where improved porosities were expected; however, the only test carried out flowed water.

Some gas was recovered from Warro 2. A list of elements identified in the chromatographic analysis is shown below:

nitrogen	0.141%
carbon dioxide	1.52%
methane	92.15%
ethane	3.81%
propane	1.21%
isobutane	0.18%
n-butane	0.29%
isopentane	0.098%
n-pentane	0.108%
hexanes	0.225%
heptanes	0.198%
octanes	0.048%

Furthermore, the presence of a gas chimney is suggested in Figure 47, about 1 km to the northeast of Warramia 1.

Source

The hydrocarbons encountered by the Warro wells may have been generated by the Yarragadee Formation itself, down dip from the drilled section. Alternatively, they may have been generated by deeper horizons that are regionally known to have source potential.

The potential of the large and thick Dandaragan Trough as a regional kitchen is enormous.

Ampolex (1992) has calculated that the oil window in the area commences at approximately 3300 m and the onset of gas generation at around 4500 m (Warramia 1 drilling proposal). Gas presently continues to be generated at great depth.

Reason for failure

Warro 1 and 2 encountered hydrocarbons from 3750 m to total depth in tight reservoirs. It is conceivable that the potential reservoirs are tight due to the recrystallization of water-bearing sections. The gas present may be trapped by permeability barriers.

Above 3750 m there is no valid seal. Below 3750 m the Warro wells either tested the structure too far downdip of the crest, or faults have destroyed the lateral sealing

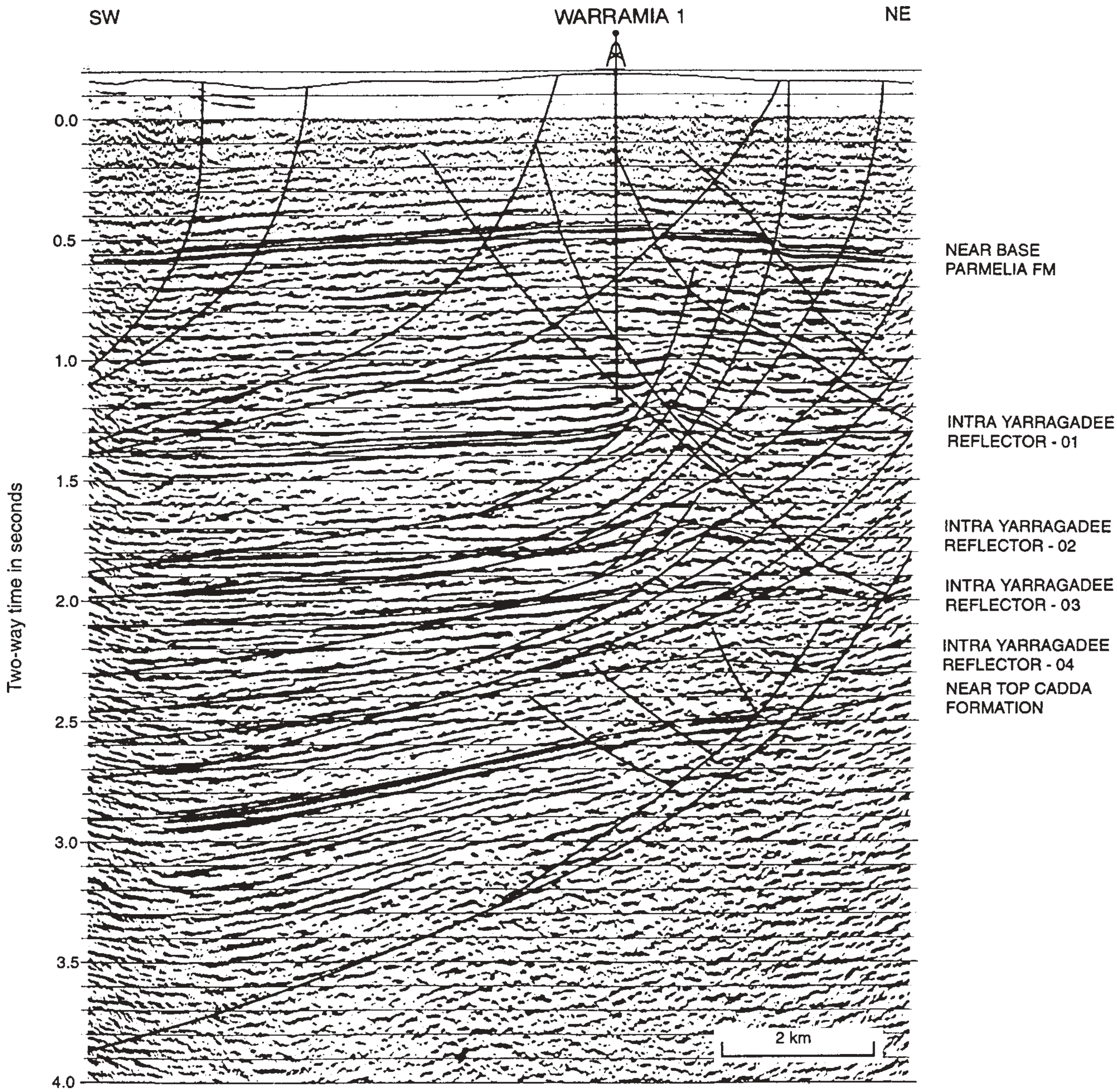

Figure 47. Seismic line A91-03, Warramia Seismic Survey, on the Warro prospect, showing the location of Warramia 1 (from Ampolex, 1992). Location of section is shown on Figure 4

potential of both the Yarragadee Formation and the thin Cadda Formation.

Remaining potential

Further exploration in the area appears to be justified. Seismic coverage over a larger area is required before any further drilling proposals can be made. Additional petrographical studies should also be carried out, in order to clarify the possible reasons for the lack of reservoir quality.

Walyering 1, 2, and 3

Location

The Walyering wells are located on the southern part of the Coomallo Trough (Fig. 3). WAPET drilled Walyering 1 and 2 in 1971, and Walyering 3 in 1972.

Stratigraphy

Walyering 1 was spudded in the Middle–Late Jurassic Yarragadee Formation, penetrated the Middle Jurassic Cadda Formation at 2685 m, and the Early–Middle Jurassic Cattamarra Coal Measures, which was the objective, at 2885 m. It bottomed in the Cattamarra Coal Measures at 3643 m. The appraisal wells, Walyering 2 and 3, bottomed respectively at 4115 and 4191 m.

Structure

The structural interpretation of the Walyering area by Mory and Iasky (in prep.) confirms other published information (Beddoes, 1973; Figs 48 and 49; Jones, 1976; Figs 50 and 51) and indicates that the Walyering wells tested a faulted, northerly trending anticlinal closure within the Coomallo Trough. Wrench movements, possibly occurring along the Coomallo Fault during the Early Cretaceous, resulted in the Walyering feature. The cross section in Figure 49 and

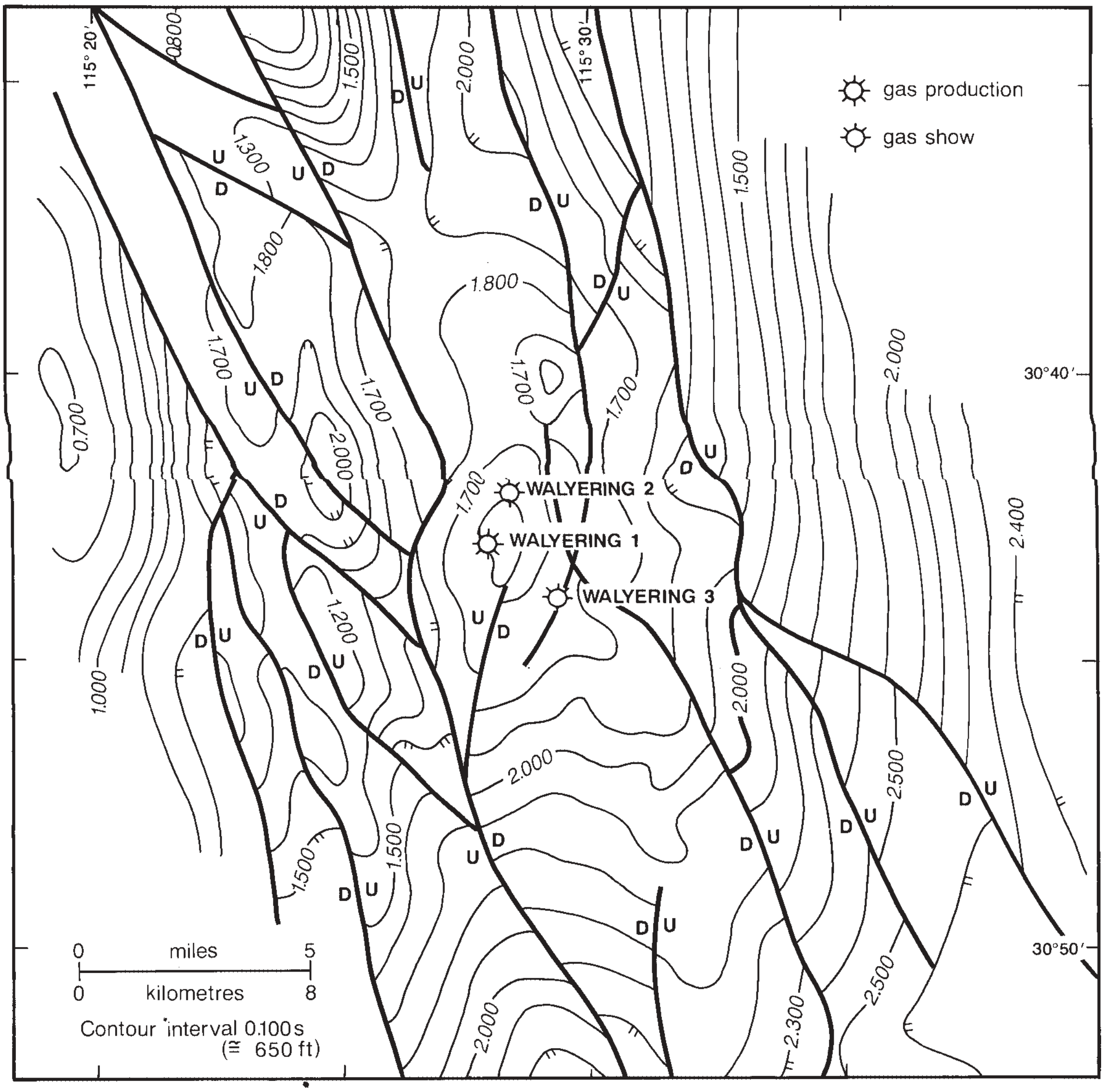

Figure 48. Early Jurassic structure map of the Walyering prospect (from Beddoes, 1973)

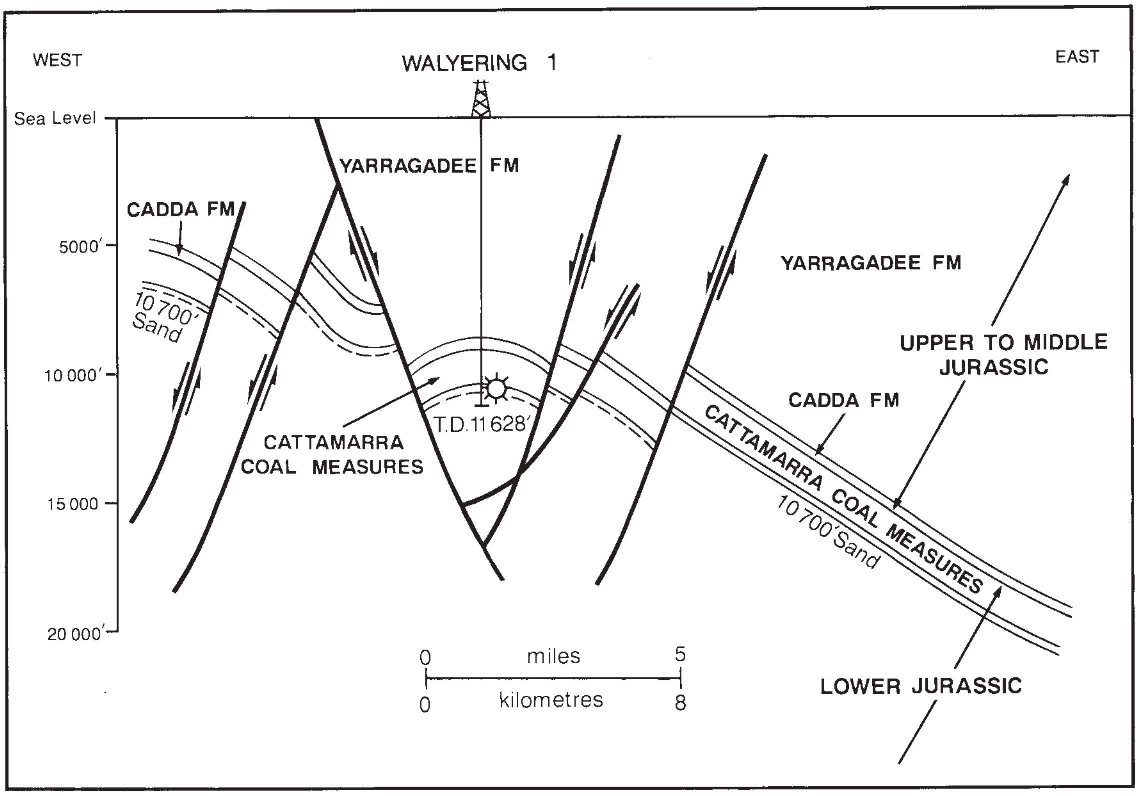

Figure 49. Early Jurassic structural cross section of the Walyering prospect (from Beddoes, 1973)

the seismic section in Figure 52 suggest that the Walyering wells were drilled in an area of crestal collapse. Another similar, faulted anticline is indicated between the Coomallo and Peron Faults. This structure is structurally higher than the Walyering structure, as is the case for all the structures near the Beagle Ridge with respect to structures to the east. It was tested by Mullering 1 (Arrow Petroleum), which bottomed in the Cattamarra Coal Measures at 1566 m, and was plugged and abandoned as a dry well.

Reservoir and seals

The discovery well encountered two gas-bearing zones in the Cattamarra Coal Measures. The quartzitic sandstone reservoirs have been rated as poor, although porosity ranges from 4.4 to 14.8% and permeability is up to 93 md, with an average effective value of 5.2 md. Such petrophysical characteristics should allow sustained production, if supported by a sizeable accumulation.

Hydrocarbons

The reservoir sandstone of the Walyering 1 lower interval (top at 11 050'; approximately 3368 m) flowed gas during the first test (DST 1) at 13.5 MMcf (about 4.0 ×

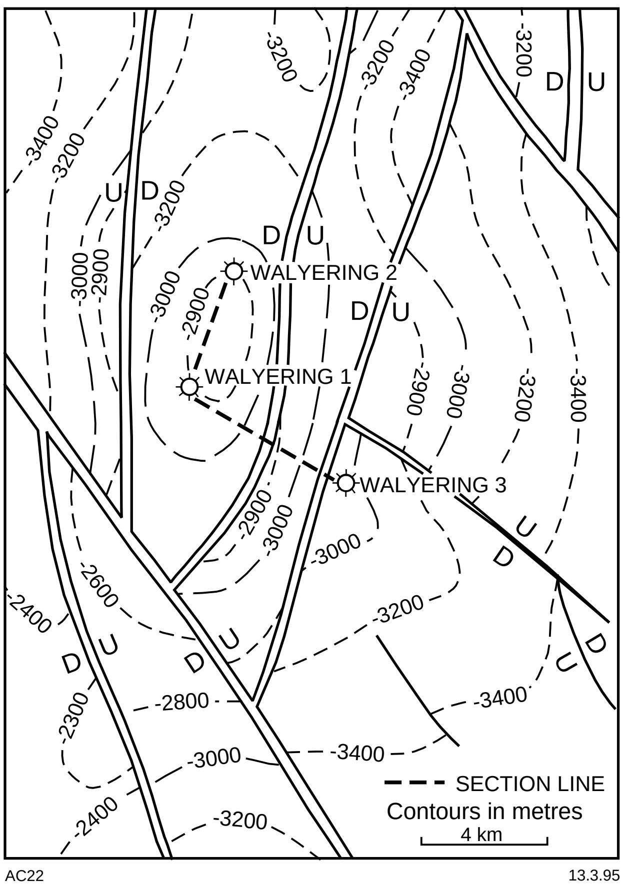

Figure 50. Early Jurassic structure map of the Walyering prospect (from Jones, 1976)

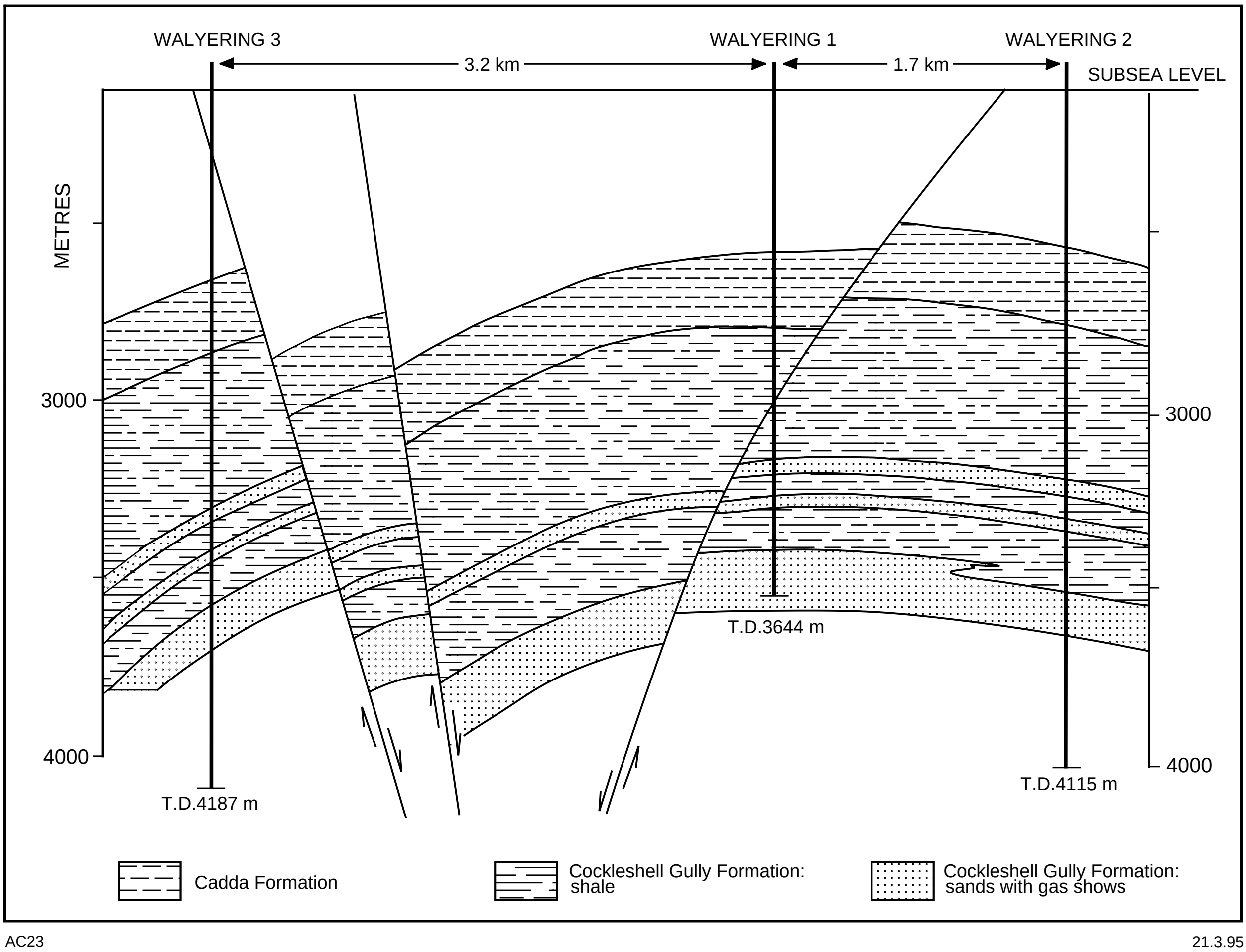

Figure 51. Early Jurassic structural cross section of the Walyering prospect (from Jones, 1976)

10^5 m^3) per day. The first production tests initially produced 10.6 MMcf (approximately 3.0 × 10^5 m^3), but afterwards the flow decreased, ranging from 2.5 to 8.1 MMcf (approximately 0.7 to 2.4 × 10^5 m^3; Jones, 1976). Minor 44.9°API condensate and some water was also produced.

The upper zone of Walyering 1 (top at 10 700'; approximately 3261 m) and Walyering 2 had lower flow rates. The zones of interest in Walyering 3 were water-bearing, although weak flows of 0.6 MMcf (16 × 10^3 m^3) and 0.2 MMcf (5 × 10^3 m^3) of gas were obtained from two deeper, overpressured, discrete zones.

Walyering 1 was linked to the Dongara–Perth pipeline, but production and pressure declined rapidly and the well was shut in after only four months production. A total of 260.5 MMcf (7.377 × 10^6 m^3) of gas and 1493 barrels (237 × 10^3 kL) of condensate were produced.

Source

It is likely that the Walyering gas is generated by interbedded Early Jurassic shales of the Cattamarra Coal Measures.

Reasons for failure

The Walyering wells probably did not test a valid trap. The sealing potential of the faults both on the crest and the flanks is rated low. The fairly fresh formation-water, which contains approximately 6000 ppm NaCl, supports this rating. Similar considerations are also valid for the Mullering anticline. The gas encountered in Walyering 1 was probably trapped by a permeability barrier. A similar hypothesis was made by Beddoes (1973). Additionally, the Coomallo Trough is basically a synclinorium; therefore, the hydrocarbons generated in the area are more likely to migrate out than in.

Remaining potential

A more detailed reinterpretation of seismic data from the Walyering area may result in the definition of better (unfaulted) traps. Since hydrocarbon generation post-dated the formation of the structure, the time of migration would allow an accumulation of hydrocarbons, at least at the shallower levels that have not been subjected to diagenesis. Multi-pay potential also exists. Traps would, however, have limited economic potential due to their position with respect to the kitchen areas.

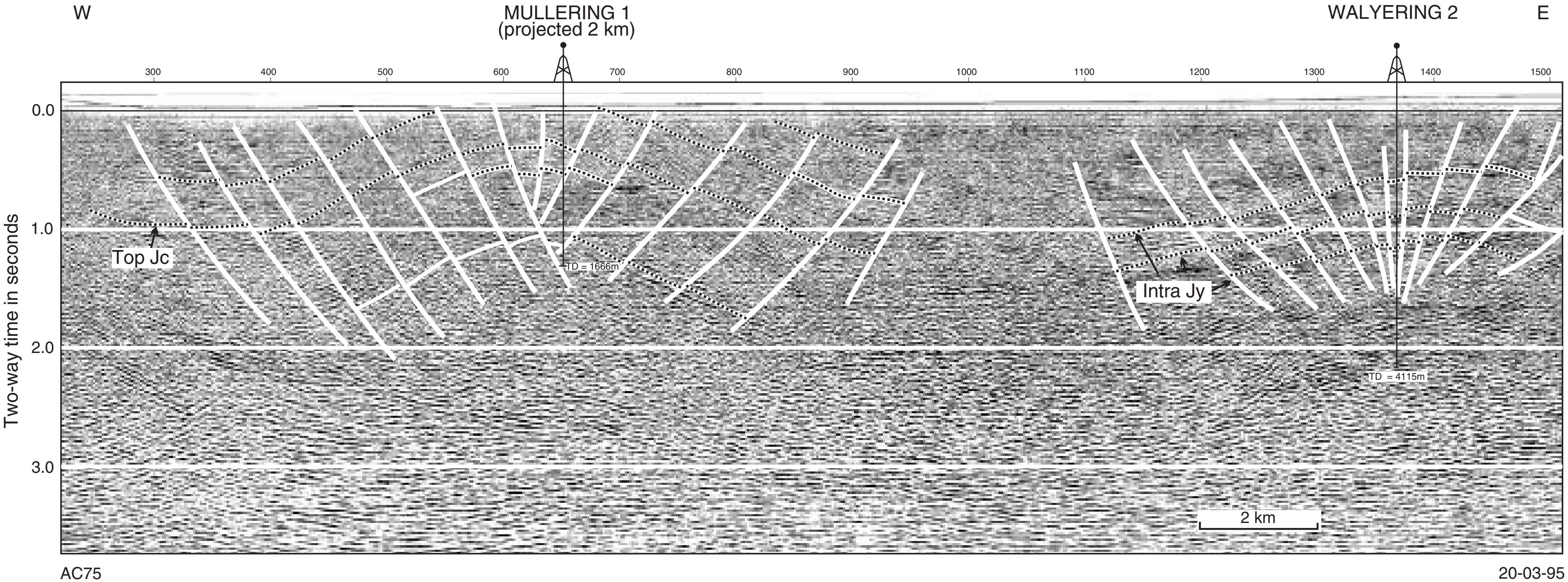

Figure 52. **Walyering seismic line BD89-104, Duggan Seismic Survey, tying the Walyering and Mullering structures. The form lines emphasize the similarity of the two structures and the considerable crestal erosion on the Mullering structure, where the Yarragadee Formation is only 270 m thick. No attempt is made to root the shallower faults into a vertical system. Jc — Cattamarra Coal Measures; Jy — Yarragadee Formation. Location of section is shown on Figure 4**

Gingin 1 and 2, and Bootine 1

Location

Gingin 1 and 2, and Bootine 1 were each designed to test the hydrocarbon potential of the large Gingin anticline, which lies towards the southeastern flank of the depocentre of the Perth Basin (Fig. 3). The geological setting of the Gingin area differs from that of the area to the north (Fig. 6).

Stratigraphy

The three wells penetrated a closely correlatable stratigraphic succession. Each was spudded in the later Jurassic Yarragadee Formation, penetrated the Middle–Late Jurassic Cadda Formation, and bottomed in the Early–Middle Jurassic Cattamarra Coal Measures. Due to their basinal position, the penetrated lithostratigraphic units are very thick: Gingin 1 reached a total depth of 4544 m, Gingin 2 reached 4482 m, whereas the total depth of Bootine 1 was 4306 m.

Structure

Gingin 1 was drilled in 1964–65 by WAPET to test what was considered a simple, large, northerly trending, elongated anticline (Fig. 53).

The encouraging results of Gingin 1 led to further drilling in the area and in 1965–66 WAPET drilled Gingin 2, which encountered more gas indications. A revised structural interpretation (Fig. 54) shows that the Gingin anticline is intersected by several normal faults, subparallel to the axis of the structure.

Although not economically viable, the Gingin discovery attracted further interest and in 1981 Mesa Australia produced their interpretation of the structural setting of the area (Fig. 55; Bootine 1 well-completion report). The Gingin anticline appeared to be compartmentalized by normal faults striking north. Both Gingin 1 and 2 penetrated the same compartment; another undrilled, structurally higher compartment is present to the west. In 1981, Mesa Australia drilled Bootine 1, 4 km south of Gingin 1, and 2 km west-southwest of Gingin 2, in order to test the highest section of the structure. Bootine 1 encountered similar hydrocarbon occurrences to the two Gingin wells.

In the mid-1980s, other companies became interested in the area and a number of seismic sections were reprocessed. Figure 56 shows an interpreted portion of line AY-287, reprocessed by Barrack Energy; Figure 6 is a regional geological cross section of the area, which has been derived from the same seismic line.

The large Gingin anticline is interpreted to be the result of Early Cretaceous basement-wrench tectonism, as is the general case in the north Perth Basin. Normal faults downthrown towards the crest control its structural configuration (Fig. 56). The regional thickening of the Jurassic succession to the west (Fig. 6), however, is a

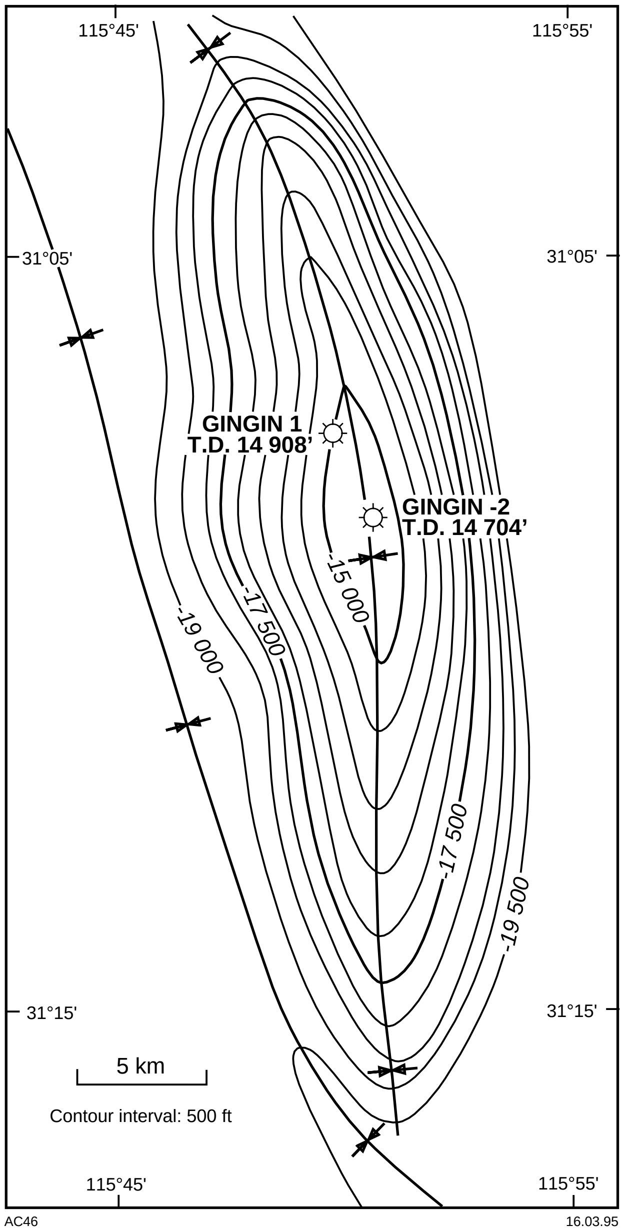

Figure 53. Structural setting of the Gingin structure (from Beddoes, 1973)

peculiar feature of the Gingin field. The thickening makes the structure asymmetric and weakens its western closure. At younger levels the anticlinal closure to the west gradually becomes a saddle that contains predominantly flat strata with easterly dips on both its western and eastern sides. The structural setting of the entire region is a monocline. A positive high is present at the extreme west of the section, where Badaminna 1 was drilled. The Gingin anticline represents the northernmost feature of an elongated, positive, northerly trending axis, which extends to the south for several tens of kilometres. Several anticlinal features occur along the trend.

Reservoirs and seals

The Yarragadee Formation is reported to have a regional porosity of up to 35% and a permeability of up to

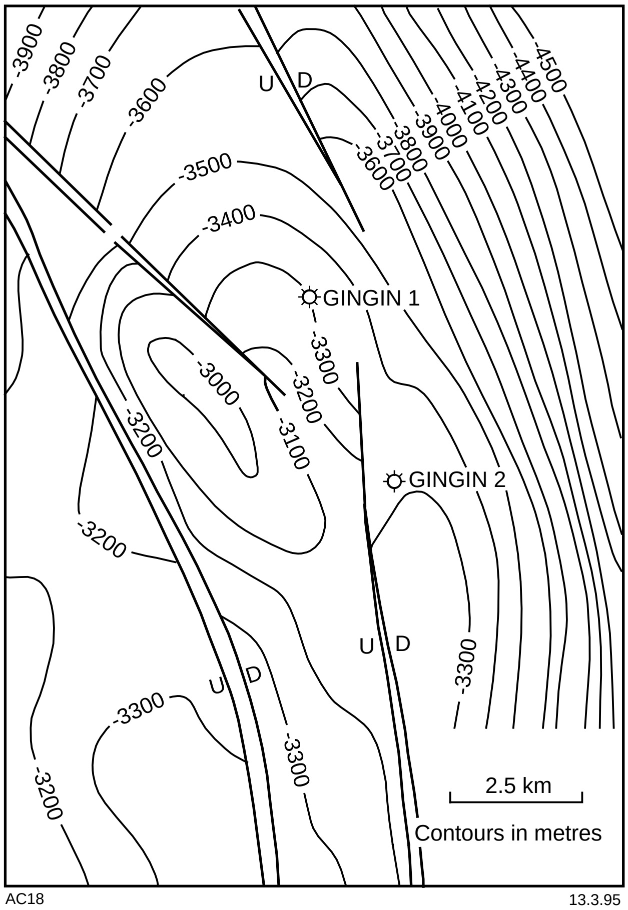

Figure 54. Early Jurassic structure map over the Gingin structure (from Jones, 1976)

3000 md. These values are of little significance in the Gingin area, since the sharp increase of salinity in Gingin 1 at 2740 m indicates that the upper portion of the stratigraphic succession is flushed. Above 2740 m, the water is fresh with a salinity of up to 5200 ppm NaCl. Below, the salinity increases to 33 000 ppm NaCl. Only the interval below 2740 m in Gingin 1 should therefore be considered to have hydrocarbon potential.

The Cattamarra Coal Measures also has good reservoir potential, with a porosity of 5–40%, averaging 23%, and permeabilities up to 7870 md. In Gingin 1, the sandstones of the Cattamarra Coal Measures are generally tight, have a poor porosity, averaging 8%, and low permeability. Permeability up to 99 md has, however, been determined at 3818 m. Bootine 1 encountered sandstones with porosity ranging from 15 (Yarragadee Formation) to 13 (Cadda Formation) to 10% (Cattamarra Coal Measures).

The sandstones of the Yarragadee Formation and Cattamarra Coal Measures may be sealed by intra-formational shales.

Hydrocarbons

During the drilling of Gingin 1 several occurrences of gas and oil were detected in the Cattamarra Coal Measures. These shows and log interpretations prompted 19 DSTs, plus four repeats. The six intervals of Gingin 1 with the best results, all within the Early Jurassic Cattamarra Coal Measures, are listed in Table 5.

Production tests were carried out on four intervals. The best result was up to 3.85 MMcf (approximately 100×10^3 m^3) of gas per day with some 46°API condensate. The follow-up Gingin 2 step-out well tested only non-commercial gas; the production rate declined rapidly and the well was abandoned.

In 1971, three producing intervals in Gingin 1 were fractured and, after clean up, the well flowed 13 MMcf (3.2×10^5 m^3) of gas per day on a short test (Jones, 1976).

In 1972, long-term production tests were undertaken and gas was fed into the Dongara–Perth gas-transmission line at 5 MMcf (1.4×10^5 m^3) of gas per day. Production lasted for only a few months (March–December 1972) and the well was shut in at the end of 1972. Production resumed in June 1975 at a much reduced rate until, at the end of January 1976, the Gingin field failed to sustain further production. Restricted permeability was considered the limiting factor. Cumulative production was 4.8561×10^7 m^3 of gas, 3164 m^3 of condensate, and 3498 m^3 of water.

Bootine 1 encountered noteworthy hydrocarbon shows in both the Cadda Formation and the Cattamarra Coal Measures. Several DSTs were attempted across the three zones considered worth testing, but without success. In late 1981 and in 1982 the well was successively tested by Mesa Australia with work-over rigs. Following swabbing, re-perforating, and acid stimulation the best results were as follows:

3746.5–3752.5 m — 2.25 MMcf (approximately 6.0×10^4 m^3) of gas, with 2 barrels (approximately 300 L) of condensate.

4078.5–4083 m — 0.25 barrels (approximately 40 L) of 38.7°API oil.

Additional testing was carried out in 1983 by WAPET. Gas, condensate, and water were recovered from between 3745.5 and 3752.5 m. Flow rates were not stabilized and hydrocarbons declined rapidly during the two-week production test.

Table 5. Drillstem test results from the most productive intervals in Gingin 1

Test interval	*Gas*		*Condensate*		*Water*	
(m)	*MMcf*	*10^3 m^3*	*barrels*	*m^3*	*barrels*	*m^3*
3864.9–3879.5	2.38	70	28.5	4.5	14.6	2.3
3871.0–3879.5	3.85	100	23.4	3.7	13.0	2.0
3950.8–3956.3	2.25	60	23.4	3.7	13.0	2.0
3956.3–3961.8	3.03	85	–	–	420	67.0
4151.4–4154.4	3.39	95	73.2	11.6	37.4	6.0
4047.1–4052.6	3.84	100	47	7.4	10	1.6

Note: Original figures quoted in MMcf and barrels. Metric equivalents quoted here are approximations only.

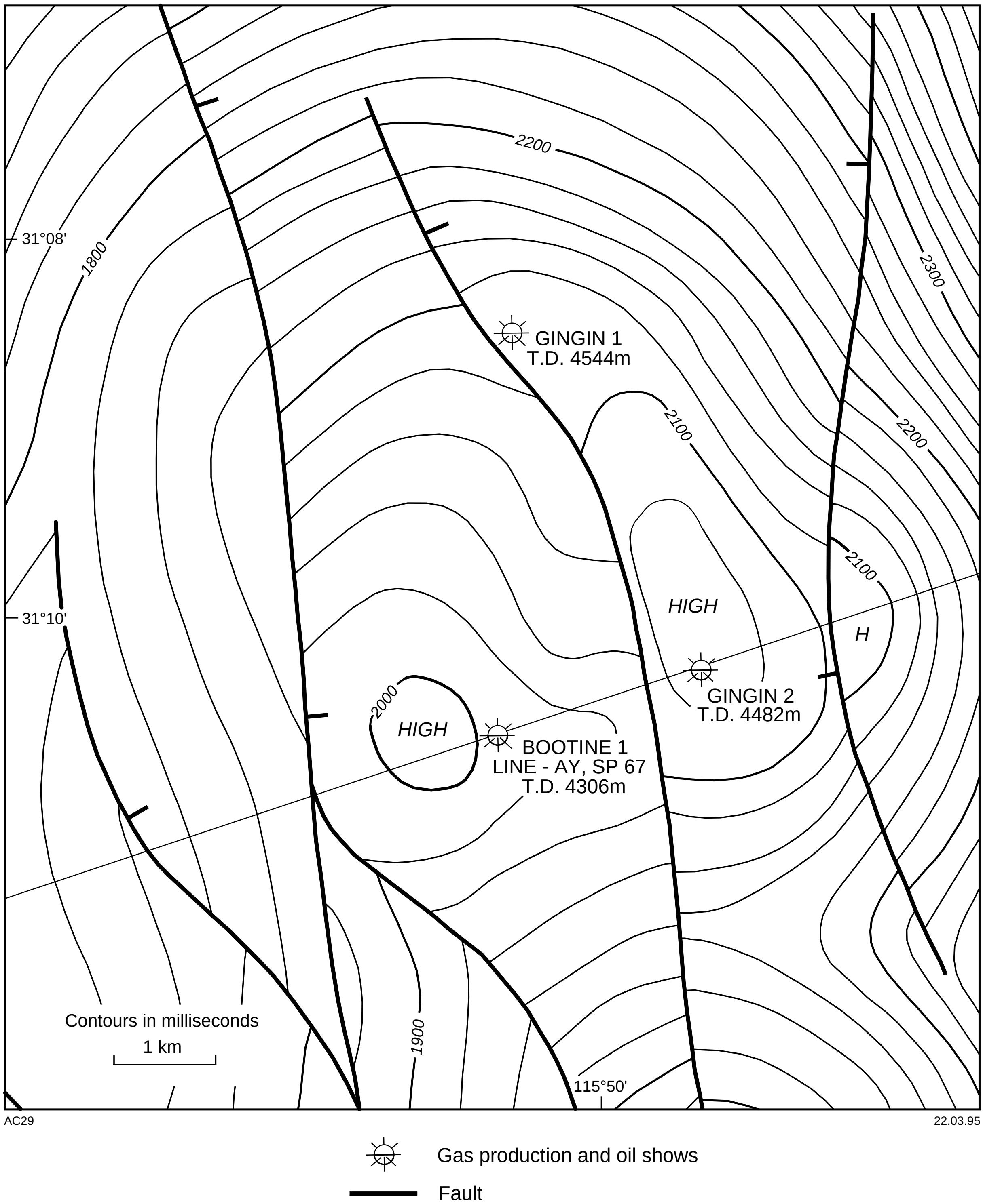

Figure 55. Time-structure map of top of pay for the Gingin structure (from Mesa Australia, 1980)

Source

Apart from the proven potential of the Cattamarra Coal Measures, it appears that hydrocarbons can also be generated by the Cadda and Yarragadee Formations. Stein et al. (1989) considered the Yarragadee Formation to be the best Mesozoic oil-source rock for the north Perth Basin area. The formation is probably sufficiently deeply buried in the relevant kitchen area to have reached maturity. Although very deep, the Kockatea Shale should still have potential for hydrocarbon generation.

Reasons for failure

The three wells drilled in the Gingin anticline down to the Cattamarra Coal Measures did not penetrate valid structural traps. The intense faulting probably breached

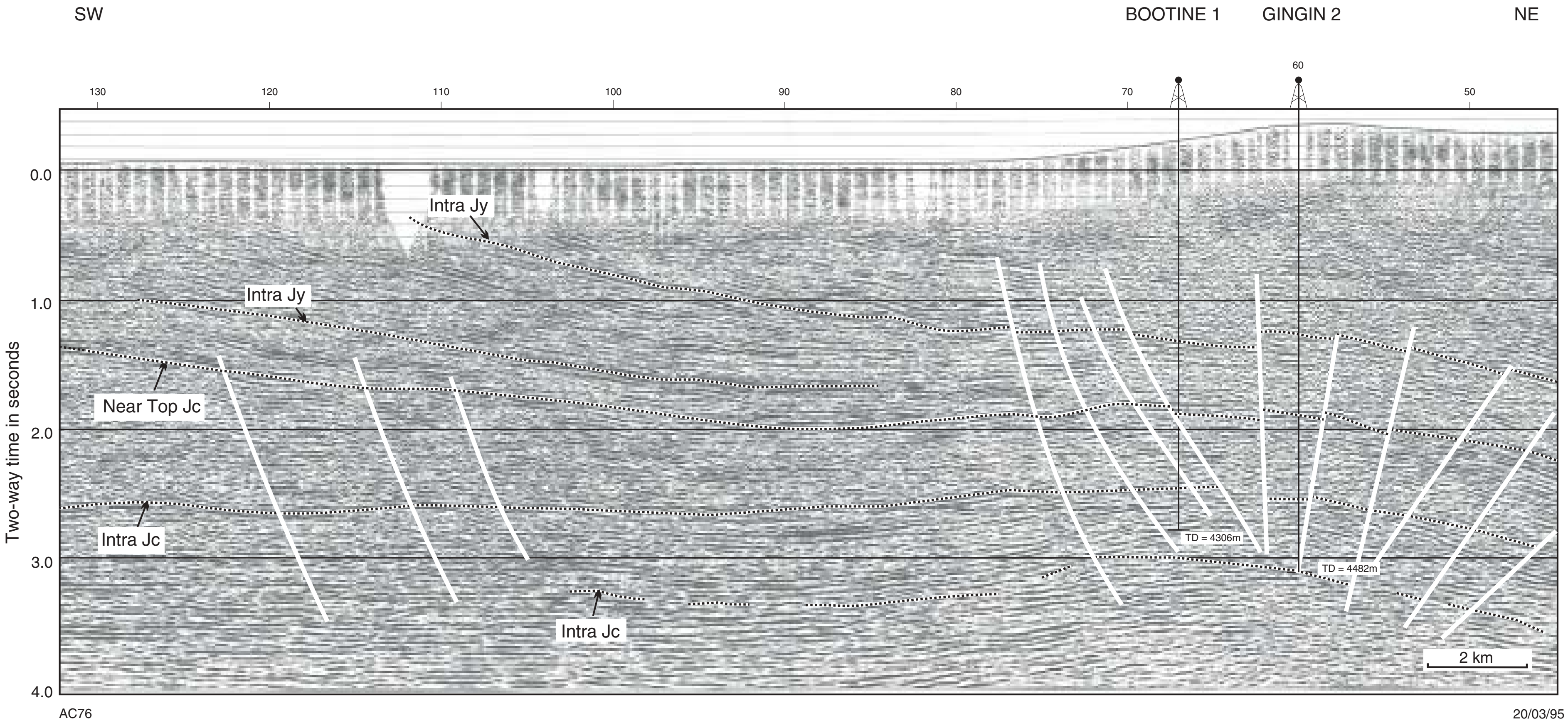

Figure 56. Seismic line AY-287, Barragoon Seismic Reconaissance Survey, across the Gingin structure, showing the location of Bootine 1 and Gingin 2. Jc — Cattamarra Coal Measures; Jy — Yarragadee Formation. Location of section is shown on Figure 4

whatever structural closure may have been present across the sandy–shaly Jurassic succession.

It is likely that the uneconomic hydrocarbon accumulations were controlled by permeability barriers. Poor permeability allowed limited local accumulations of hydrocarbons in zones of relatively high porosity (8%) within an overall impervious formation. This interpretation is consistent with the presence of separate gas/water interfaces in each of the six Gingin sandstone zones. The high water-saturation of the Gingin 1 and Bootine 1 gas-bearing zones further supports this conclusion. Furthermore, the interpretation is corroborated by the differing results obtained from Gingin 1 and 2. Alternatively, limited fault traps may be present.

Remaining potential

A valid structural trap is considered to exist in the Gingin structure. The thick Early Triassic Kockatea Shale should provide an effective seal for underlying Permian sandstones, if present. The large potential of such a play is, however, counterbalanced by the depth of the objective, which is probably prohibitive in the present economic climate. Other positive structures on the Gingin trend may provide better targets, if faulting results in better sealing potential. A four-way dip closure would provide the best chance of success.

Controlling factors for hydrocarbon accumulations

Traps

Traps in all of the six hydrocarbon fields in the northern Perth Basin are controlled by compressional anticlines of early Neocomian age.

Two fields, the main Mount Horner and Dongara fields, fall within the crest of such anticlines. Both structures are located within the eastern downthrown side of a strike-slip fault against which the structures developed (Figs 11 and 15).

The Mondarra East field is located in the downthrown eastern flank of an anticline (Figs 19 and 21), whereas the Beharra Springs field lies below the Beharra Springs Fault in the downthrown western flank of the structure (Fig. 22). The structural position of the Yardarino field is not entirely clear, but it is possible that it is positioned on the crest.

The Woodada field is in the northern nose of an elongate anticline, with the southern closure of the trap provided by a permeability barrier (Fig. 24).

In the Mount Horner, Dongara, and probably the Yardarino fields, closure is provided by four-way dip. In the Woodada field, the closure is dip-controlled in three directions, and lateral variations of the reservoir characteristics provide the closure in the remaining direction.

In the Mondarra and Beharra Springs fields, dip closure exists in three directions, whereas a fault provides the lateral seal in the fourth direction. The Beharra Springs field appears to be sealed laterally by the Kockatea Shale, whereas the lateral boundary of the Mondarra East field is open to three different interpretations. Either the field extends further to the west or a minor fault juxtaposes the Kockatea Shale to the reservoir or the controlling fault provides a seal on its own. Faults with substantial horizontal movement are more likely to have sealing potential.

In five fields out of six, structural features are critical to the trap. Of these five, three depend entirely on dips, and one on the critical presence of the thick impermeable Kockatea Shale. The critical feature in the fifth case cannot be determined.

It is therefore concluded that in the northern Perth Basin, apart from the obviously less risky trapping mechanism represented by an unfaulted anticline, the next best situation for an effective trap in faulted structures is provided by the juxtaposition of the Early Triassic Kockatea Shale with the main objective. In structural traps, other hydrocarbon occurrences may occur; however, these are more risky and more difficult to predict.

Twelve dry holes have been examined, but as their selection was based either on the occurrence of some hydrocarbons or on their regional position, no statistical value can be given to the reason for their failure.

South Yardanogo 1, Ocean Hill 1, Coomallo 1, Walyering 1, 2, and 3, Gingin 1 and 2, and Bootine 1 tested crests of faulted anticlines at very sandy Jurassic levels. South Yardanogo 1 also tested the sandy Late Jurassic Lesueur Sandstone. Eneabba 1 and Donkey Creek 1 tested a fault trap relying on a lateral seal: the Jurassic and Triassic objectives were juxtaposed to very sandy horizons of younger age. No effective seal is present in all these cases. A revision of the geophysical interpretation would be justified only in the event that a deep well, aimed at testing the hydrocarbon potential of the Late Permian objective, is considered.

The Erregulla, North Erregulla, North Yardanogo, Arrowsmith, Mountain Bridge, and Warro prospects would all probably be better understood through better seismic control and a revision of the structural interpretation.

The best potential for a stratigraphic trap is offered by the Wagina Sandstone, where it thins out to the northwest below the Kockatea Shale.

Stratigraphic distribution of source rocks

Several papers discuss the source-rock potential of the northern Perth Basin; the most informative remain those of Thomas (1979, 1982, 1984) and Thomas and Brown (1983). If all available data are taken into account, it appears that several lithostratigraphic units possess potential for the generation of hydrocarbons. Source rocks rich in land plants are widely distributed through the Permian, Triassic, and Jurassic formations.

The source potential of these formations is summarized in Table 6 (Fig. 2).

Maturity of source rocks

In evaluating the maturity of source rocks, three main factors are considered: time, geothermal gradient, and depth.

In the northern Perth Basin, vitrinite-reflectance values generally show an increase with depth without major rank breaks. The burial of the sediments was basically continuous. Only minor breaks have occurred and then only locally, related to the Mid–Late Permian and Late Triassic emergences. The basin was subject to long-term thermal subsidence and only one major heating event took place, which was due to continental breakup. Therefore, the time factor is considered to be relatively unimportant for the area.

The geothermal gradient ranges from low values in the Coomallo and Dandaragan Troughs (Fig. 8), to medium values in the Cadda (main part) and Beharra Springs Terraces, to high values in parts of the Cadda Terrace, Dongara Terrace, and Allanooka High. Basement tends to have a high geothermal gradient because of its lower geothermal-conductivity properties. Therefore, assuming no volcanic activity, the geothermal gradient of the sedimentary basin is mainly related to its sedimentary thickness or to the depth of basement. The presence of thick sandy sections in the younger units, however, facilitates the heat outflow.

Thomas and Brown (1983) attempted to plot maturity maps for the main source-rock intervals (Figs 57, 58 and 59). Although only generalized, these maps still provide a useful reference. In the northern Perth Basin source rocks are still immature, with a vitrinite reflectance (R_o) of 0.68. Generation of oil is reached at a R_o of 0.85. The main phase for oil generation is at R_o = 1–1.1. In the northern Perth Basin post-peak maturity for the oil is reached at R_o = 1.53, which is a higher value than the generally accepted R_o of 1.30.

The Permian source rocks appear to be mature for gas generation in large tracts of the northern Perth Basin, either because of a relatively high geothermal gradient or because of their depth of burial. Where source rocks are not mature, lateral migration may still lead to hydrocarbon accumulation. A possible exception is the northernmost part of the Allanooka High, which is considered too far from the hydrocarbon kitchen. The Greenough Shelf (Fig. 7) appears not to have been reached by migration paths.

The oil-prone Early Triassic Kockatea Shale has also reached maturity for hydrocarbon generation over most of the basin. Locally, as in the Allanooka High and Dongara Terrace, maturation is only marginal. In the Dongara, Mondarra, and Yardarino fields, the oil is without light ends; in the Mount Horner, Erregulla, and North Erregulla wells the oil is without gas. Secondary migrations make the evaluation of the characteristics speculative. Conversely, where the formation is deeply buried, the Kockatea Shale source beds may be below the oil window and the unit may generate only gas. The gas threshold has been calculated to occur in the synclinal areas of the basin at 112°C (Thomas, 1979).

The Jurassic source rocks are largely immature in the northern and western parts of the northern Perth Basin, due to their shallow depth. In the Dandaragan and Coomallo Troughs the Cattamarra Coal Measures, and marginally also the lower part of the Yarragadee Formation, are mature.

Age of trap versus migration

As discussed previously, the only proven, effective trapping mechanism in the northern Perth Basin is represented by anticlines and related secondary traps, which resulted from continental breakup in the early Neocomian.

Hydrocarbons are still being generated from all the mature lithostratigraphic units with source potential. In the northern Perth Basin, maximum bottom-hole temperatures of 140–150°C have been calculated but such temperatures have only been reached locally (Mount Adams 1 and Warradong 1). Thomas (1979) estimated that thermal destruction is well advanced when the temperature reaches 200°C. At this temperature the potential for additional gas

Table 6. Generalized source potential of formations in the onshore northern Perth Basin

Formation	*Source potential*
Yarragadee Formation	potential for both gas and oil, mainly related to coaly layers
Cadda Formation	evidence not conclusive
Cattamarra Coal Measures	potential for both gas and oil, mainly related to coaly layers
Eneabba Formation	no potential of economic significance
Lesueur Sandstone	no potential of economic significance
Woodada Formation	no potential of economic significance
Kockatea Shale	potential for oil, mainly in the basal condensed section
Wagina Formation/Beekeeper Formation	no potential of economic significance
Carynginia Formation	potential for gas
Irwin River Coal Measures	potential for gas
Holmwood Shale	evidence not conclusive

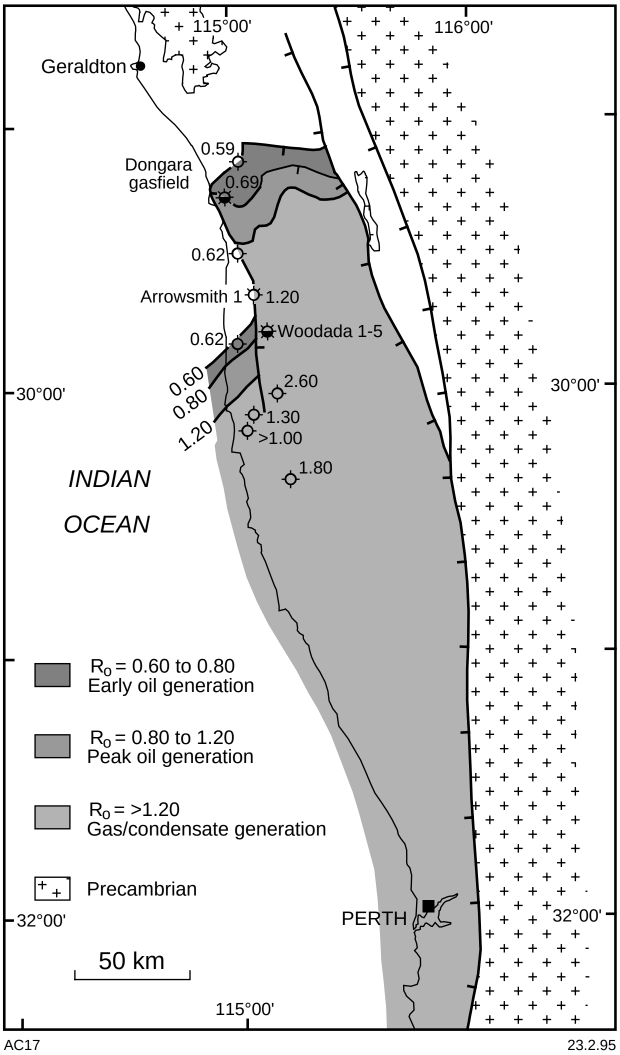

Figure 57. Maturity map, top of Permian (from Thomas and Brown, 1983)

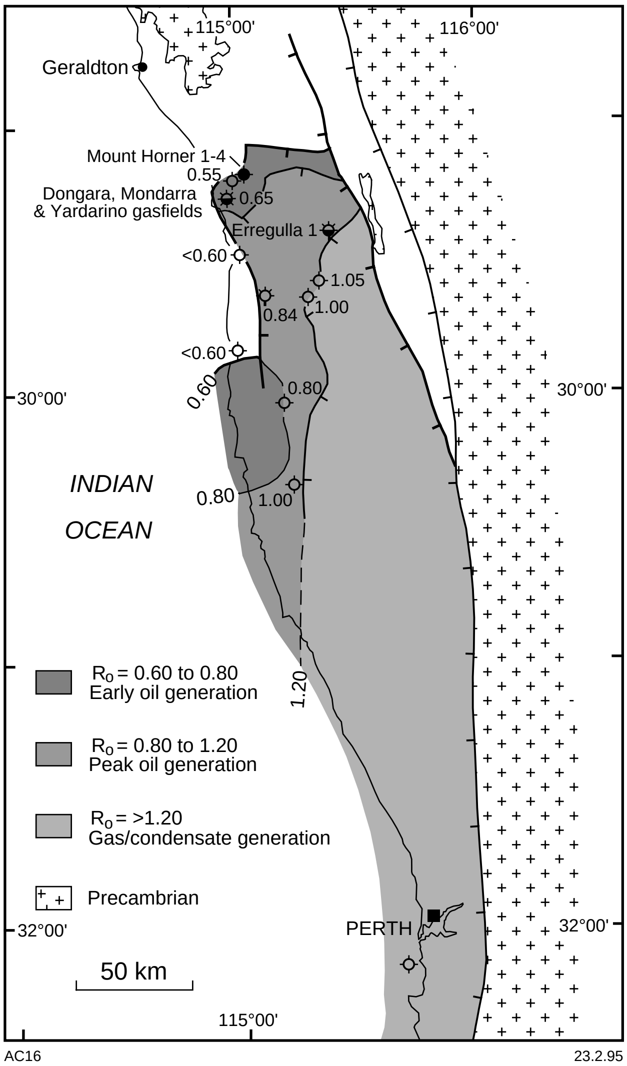

Figure 58. Maturity map, top of Kockatea Shale (from Thomas and Brown, 1983)

generation becomes limited. Similarly, it is generally accepted that gas is still being generated by rocks with a R_o above 2.0. Stein et al. (1989) reproduced vitrinite-reflectance data from 22 wells in the Perth Basin, and only in one case, namely Woolmulla 1, had the threshold for no more generation of gas been reached, and this was limited to Permian source rocks. In Cadda 1 vitrinite-reflectance values are similar to those of Woolmulla 1 (Thomas, 1979). Some hydrocarbons may therefore have escaped from the hottest parts of the basin, but certainly at least gas has been generated after the formation of traps. It can be concluded that virtually no trap post-dated the generation of hydrocarbons.

The balance is more delicate for oil because it ceases to be generated at much lower temperatures. In the parts of the basin with the highest geothermal gradient, or where the Kockatea Shale is very deeply buried, the likelihood is that the hydrocarbons present are only gaseous. Hall (1989) maintained that part of the Kockatea source rocks entered the gas-only window in the Late Cretaceous. In this case there is ample potential for the existence of oil-filled traps, although the statement is quite general.

Some oil may also have been generated by the Jurassic source rocks.

Reservoirs

The depositional environments of each discrete formation have been discussed in detail by Mory and Iasky (in prep.) and will not be repeated here.

Lithostratigraphic units with reservoir potential are widespread across the entire depositional succession. The Early Permian sandstones of the Irwin River Coal Measures have a low permeability, but still produce gas in the Dongara field. Their contribution to the total production of the field has, however, been modest.

The best reservoir potential is offered by the Late Permian Wagina and Beekeeper Formations, and is related

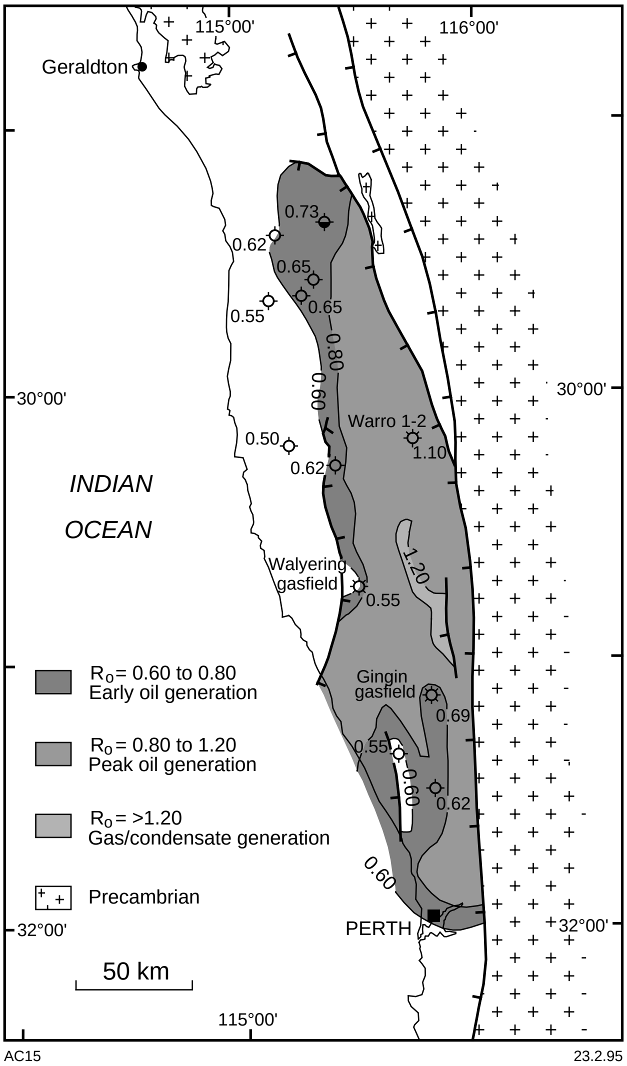

Figure 59. Maturity map, top of Cattamarra Coal Measures (from Thomas and Brown, 1983)

to the presence of the thick overlying sequence of the Early Triassic Kockatea Shale. Late Permian reservoirs contain the large majority of hydrocarbons discovered within the basin to date.

Some minor accumulations also occur in the Early Triassic Arranoo Sandstone (Dongara and Mount Horner) and in several thin horizons of the Early to Middle Jurassic Cattamarra Coal Measures (Mount Horner).

The tremendous reservoir potential of the Woodada Formation, Lesueur Sandstone, Eneabba Formation, and Yarragadee Formation has, to date, been hampered by the lack of an effective trap at that level.

An open problem is presented by the tight reservoirs that have been encountered in several wells, such as the Erregulla wells (Eneabba Formation), the Gingin, Bootine, and Walyering wells (Cattamarra Coal Measures), and the Warro wells (Yarragadee Formation). The reservoirs are tight, not because of depositional characteristics, but because of diagenesis. The hydrocarbons that have been produced from these wells always seem to have been trapped in permeability traps. The petrophysical features of the diagenesis are strikingly similar for all the formations involved, independent of their age. This may be related to the similarity in composition between all sandstones in the northern Perth Basin.

Relationships between diagenesis and reservoir quality have been discussed in detail by Tupper et al. (1994). Although the discussion refers specifically to the Late Permian succession, the conclusions reached by the authors are also valid for other intervals. Kaolinization, chloritization, and illitization do not prevent the existence of excellent reservoirs. The main factors reducing porosity and permeability are silicification, in the case of quartz sandstones, and carbonate cementation, in the case of calcareous sedimentary rocks.

No definitive reasons have been identified for silicification, and it is generally accepted that some parts of the basin are characterized by tight reservoirs. These areas, however, do not have high geothermal gradients, nor are the reservoirs particularly deeply buried. If clay crystallizes from solutions that were able to move freely throughout the pore spaces, the sandstones become tight due to the presence of water. The Wagina Formation of the Mondarra field, for example, has gas-bearing sandstones with good reservoir characteristics, and tight water-bearing sandstones.

The presence of hydrocarbons prevents the inhibition of porosity in the northern Perth Basin. In some cases the time span between the deposition of the potential reservoirs and the formation of the traps is quite short. For example, the basal Yarragadee Formation in the Warro area was deposited in the Middle–Late Jurassic and the structure was formed in the Early Cretaceous. Migration of hydrocarbons is thought to have occurred throughout the entire time span. It appears worthwhile to investigate the structures with hydrocarbon indications further, aiming to define an assured trap to be tested at the crest.

Seals

Seals of regional distribution are represented by the Cadda Formation, by some intervals within the Cattamarra Coal Measures, and mainly by the thick, laterally extensive Kockatea Shale. As noted above, the occurrence of the Kockatea Shale at the relevant depth may be critical to hydrocarbon accumulation. Some anticlines breached at the shallower and sandier levels by minor faults may provide effective traps at depth in the event that the throw of the faults is less than the thickness of the Kockatea Shale.

The shales of the Carynginia Formation may provide intraformational seals to local sandstones, such as the Irwin River Coal Measures. In undisturbed four-way dip closures, widespread intraformational seals can be effective, as demonstrated in the minor pools of the Mount Horner and Dongara fields.

Hydrocarbon potential

Dongara Terrace

The Dongara Terrace, with an area of 500 km^2, has proven potential for both oil and gas accumulations. Several faults occur with subordinate elongated folds. Further discoveries on the terrace are considered likely, although their size is expected to be smaller than that of the Dongara field. Traps on both the downthrown and upthrown sides of the controlling faults are possible, with independent hydrocarbon–water contacts. Sandstones of the Wagina Formation provide an excellent primary objective, whereas the thinner and less permeable sandstone of the Irwin River Coal Measures is a secondary target. Shallower minor objectives, like the Early Triassic Arranoo Sandstone, are also present.

Beharra Springs Terrace

The Beharra Springs Terrace, which also covers some 500 km^2, is characterized by large, gentle, north-trending anticlines that are intersected by major faults. Three gasfields have been discovered in the area, each in a different structural position with respect to the anticlinal axis.

An understanding of the structural model, the acquisition of good-quality seismic data, and careful interpretation should lead to additional discoveries. In order to understand the model, it may be advisable to firstly unravel the main structural characteristics of the entire terrace, focusing on the Yardarino, Mondarra, and Beharra Springs fields and the post-mortems of dry wells. The evaluation of a specific prospect in this sub-basin should be carried out only after such a review. It is critical to differentiate the key controlling faults, such as the Beharra Springs Fault and the corresponding fault to the east of the anticlinal axis, from the minor splay faults.

Sandstones within the Wagina Sandstone and limestones of the Beekeeper Formation are present within the Beharra Springs Terrace; the sandstones occur to the north and the limestones to the south. While the Late Permian objectives are the primary ones, shallower objectives within the Triassic and Jurassic are also present and may provide economic rewards.

The source rocks have reached a stage of maturation that should allow the discovery of both oil- and gasfields. Good migration paths exist from deeper buried source rocks that occur to the east and south.

Allanooka High

The Allanooka High shows differing characteristics over its 2000 km^2, from north to south and from west to east. The stratigraphic succession has important lacunae to the north of the Allanooka Fault, which are most enhanced to the northwest, in the area closer to the Northampton Complex. In general, the stratigraphic differences are controlled by growth faults.

Only one field has been discovered to date in the area, namely the Mount Horner oilfield. The Allanooka High is characterized by important faults and related anticlines, offering a wide spectrum of trapping mechanisms. The high percentage of coarse clastics with respect to fine clastics possibly reduces the potential for traps of the highly faulted and fairly thin succession to the north of the Allanooka Fault. To the south, faulting is less intense and the stratigraphic sequence thickens. These factors should increase the trapping potential of the area.

The Allanooka High offers perhaps the best chance for additional discoveries in the basin, especially in the southern part where long-range migration of hydrocarbons from the Dandaragan depocentre is thought to have occurred. The maturity of the source rocks and likelihood of lateral migration indicate potential for both oil and gas accumulations.

The objectives range from the Cattamarra Coal Measures, which are oil-bearing in the Mount Horner field, to the Irwin River Coal Measures.

Donkey Creek Terrace

The structureless Donkey Creek Terrace, which covers 600 km^2, is considered to have poor potential for hydrocarbons. Fault traps provide the only potential trapping mechanism. Only a 4500 m-deep hole may offer the chance of a hydrocarbon discovery, due to the high sand/shale ratio of the post-Kockatea Shale succession. In this case a gas accumulation is likely.

Cadda Terrace

The Woodada field is the only hydrocarbon accumulation within the Cadda Terrace. The terrace is large, with an area greater than 3000 km^2, and only sparsely explored. Many structural features have been recognized, providing interesting targets, although some constraints are present.

A limiting factor is related to the high vitrinite-reflectance values measured in Cadda 1 and Woolmulla 1 (Thomas, 1979). These values eliminate the possibility that the Early Permian source rocks generated hydrocarbons in the area after the formation of the traps. The potential for the generation of oil and gas by younger source rocks, however, is rated as good.

Early Permian sandstones are likely to be tight, whereas the Late Permian carbonates should provide an interesting objective, especially where fractured, as in the Woodada field. Shallower objectives are also considered to be of interest, in the event that they are unfaulted. A few structures closer to the Beagle Fault System may lack an effective seal.

Following the geophysical delineation of a prospect, a very critical geological appraisal of all relevant parameters should offer a good opportunity to find accumulations of hydrocarbons. The size of some of the structures provides scope for significant fields. Potential for both oil and gas discoveries exist.

The Cadda Terrace, especially its northern part, is rated as one of the most attractive subdivisions of the north Perth Basin, where the risks in exploring a new field appear to be balanced by potential rewards.

Coomallo Trough

The north-elongated Coomallo Trough, which covers 1500 km^2 between the Cadda Terrace and the Dandaragan Trough, has been tested by several exploration wells. It is attractive due to the presence of large anticlines, but no discoveries have been made to date.

As discussed in **Post-mortems of selected wells**, many prospects are considered to have poor trapping potential, although effective sources, reservoirs, and seals occur. The Walyering area requires specific consideration because of the tight reservoirs that have been encountered.

The Coomallo Trough has some basic regional weaknesses. Firstly, the scope for migration of hydrocarbons from kitchen areas to the potential traps is limited. The trough is a depressed area, bounded by faults downthrown towards the axis of the anticlines. Secondly, the rollover anticlines are accompanied by crestal collapse and therefore invalidate the location of crestal exploration wells, whereas other targets are too deep. Thirdly, regional strike-slip faults are likely to be sealing on their own, but the minor faults accompanying the folds cannot be expected to provide effective seals. The large percentage of sandstones in the Jurassic sequence results in the juxtaposition of sandstones against sandstones, and thus the sealing potential at these levels is minimal. Conversely, the oldest objectives are very deep within the entire trough.

The potential for hydrocarbon accumulations in the Coomallo Trough is rated as poor, unless the drilling of very deep wells is considered acceptable.

Dandaragan Trough

The Dandaragan Trough, which covers more than 5000 km^2, is the major depocentre in the northern Perth Basin. The potential of the huge, up to 12 000 m-thick, downwarp as a hydrocarbon-generation area is enormous. The virtually unfaulted syncline should allow extensive migration of hydrocarbons from the kitchen towards structural highs.

Unfortunately, the limited tectonism also has a negative aspect: only a couple of potential prospects have been identified. Furthermore, the very thick and sandy Jurassic sequence makes the existence of lateral seals at reasonable depth unlikely.

A positive aspect of the Dandaragan Trough is the size of the prospects delineated to date, which demand the attention of a courageous explorer who is not afraid of taking risks. The Dandaragan Trough has to be considered a true ‘frontier area’.

Conclusions

Sixty to seventy exploration wells have been drilled in the northern Perth Basin; the approximation is due to the unclear definition between exploration and development wells. The present success rate is one out of ten, since there are six fields that sustained reasonable production. Reserves discovered to date in the basin approximate 20×10^9 m^3 of gas and 3×10^9 kL of oil.

The main reasons for failing to find hydrocarbons of economic value are considered to be either structural weakness or ineffective seals. Another possible reason for dry wells at the margins of the basin, as in the northernmost belt, is the lack of migration paths from the kitchen areas, although this applies only to a few cases. Variable reservoir quality represents an additional problem.

Half of the basin’s area of 14 000 km^2, as here reviewed, contains all the requirements for hydrocarbon accumulations. The most prospective areas for further discoveries of hydrocarbons are in the Allanooka High or Cadda Terrace. While the source-rock potential is rated high within the entire basin, the structural setting of the Donkey Creek Terrace and Dandaragan Trough is unfavourable, and in the Coomallo Trough the more attractive objectives are very deep. The virtually unexplored Beagle Ridge may also have some hydrocarbon potential.

Acknowledgments

The permission of Ampolex Limited, Discovery Petroleum, and SAGASCO Resources Limited to use seismic sections not yet on open file is gratefully acknowledged.

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Appendix

List of well-completion reports used to compile this Report

Well name	Operator	Year	S-no.
Arramall 1	Barrack	1989	3 442
Arrowsmith 1	French	1965	203
Beharra Springs 1	Barrack	1990	20 009
Beharra Springs 2	Arrow	1991	20 061
Beharra Springs 3	SAGASCO	1992	20 092
Bootine 1	Mesa	1981	1 781
Coomallo 1	WAPET	1974	953
Dongara 01	WAPET	1966	303
Dongara 02	WAPET	1966	307
Dongara 03	WAPET	1966	319
Dongara 04	WAPET	1967	347
Dongara 05	WAPET	1967	386
Dongara 06	WAPET	1967	395
Dongara 07	WAPET	1968	401
Dongara 08	WAPET	1969	465
Dongara 09	WAPET	1969	466
Dongara 10	WAPET	1969	485
Dongara 11	WAPET	1969	490
Dongara 12	WAPET	1969	496
Dongara 13	WAPET	1969	499
Dongara 14	WAPET	1969	506
Dongara 15	WAPET	1969	501
Dongara 16	WAPET	1969	524
Dongara 17	WAPET	1969	529
Dongara 18	WAPET	1970	535
Dongara 19	WAPET	1970	538
Dongara 20	WAPET	1974	1 005
Dongara 21 St1	WAPET	1980	1 591
Dongara 22	WAPET	1980	1 607
Dongara 23	WAPET	1981	1 753
Dongara 24	WAPET	1981	1 799
Dongara 25	WAPET	1981	1 823
Dongara 26	WAPET	1990	20 006
Dongara 27	WAPET	1990	20 007
Donkey Creek 1	French	1966	320
Eneabba 1	WAPET	1961	34
Erregulla 1	WAPET	1966	293
Erregulla 2	Mesa	1980	1 584
Gingin 1	WAPET	1965	181
Gingin 2	WAPET	1965	225
Mondarra 1	WAPET	1968	445
Mondarra 2	WAPET	1969	451
Mondarra 3	WAPET	1969	464

Well name	Operator	Year	S-no.
Mondarra 4	WAPET	1969	491
Mountain Bridge 1	SAGASCO	1993	20 156
Mount Horner 01	WAPET	1965	195
Mount Horner 02	WAPET	1965	204
Mount Horner 03	XLX	1980	1 707
Mount Horner 04	XLX	1981	1 730
Mount Horner 04a	Barrack	1988	3 272
Mount Horner 05	XLX	1981	1 793
Mount Horner 05a	Barrack	1988	3 279
Mount Horner 06	Barrack	1983	2 476
Mount Horner 07	Barrack	1987	3 132
Mount Horner 08	Barrack	1988	3 312
Mount Horner 09	Barrack	1988	3 302
Mount Horner 10	Barrack	1989	3 377
Mount Horner 11	Barrack	1989	3 715
Mount Horner 12	Arrow	1992	20 134
Mount Horner 13	Discovery	1993	20 153
Mount Horner 14	Discovery	1993	20 194
North Erregulla 1	WAPET	1967	383
North Yardanogo 1	Barrack	1990	3 995
Ocean Hill 1	Arrow	1991	20 066
South Yardanogo 1	Barrack	1990	20 055
Walyering 1	WAPET	1971	627
Walyering 2	WAPET	1971	643
Walyering 3	WAPET	1972	673
Warramia 1	AMPOLEX	1992	20 121
Warro 1	WAPET	1977	1 331
Warro 2	WAPET	1978	1 370
Woodada 01	Hughes	1980	1 624
Woodada 02	Hughes	1980	1 667
Woodada 03	Hughes	1981	1 742
Woodada 04	Hughes	1981	1 778
Woodada 05	Hudbay	1982	2 028
Woodada 06	Hudbay	1982	2 091
Woodada 08	Strata	1983	2 456
Woodada 09	Strata	1984	2 535
Woodada 10	Strata	1984	2 547
Woodada 11	Congas	1991	20 076
Woodada 12	Congas	1991	20 090
Yardarino 1	WAPET	1964	154
Yardarino 2	WAPET	1964	163
Yardarino 3	WAPET	1964	169
Yardarino 4	WAPET	1964	183

S-no.: Geological Survey of Western Australia S-series number

AMPOLEX: AMPOLEX Ltd
Arrow: Arrow Petroleum
Barrack: Barrack Petroleum
Congas: Consolidated Oil and Gas
Discovery: Discovery Petroleum
French: French Petroleum Company (Australia)
Hudbay: Hudbay Oil (Australia) Ltd
Hughes: Hughes and Hughes
Mesa: Mesa Petroleum (Australia)
SAGASCO: South Australian Gas Company
Strata: Strata Oil NL
WAPET: West Australian Petroleum Pty Ltd
XLX: XLX NL