# More sources for gas and oil in Perth Basin

## Study highlights potential for multiple petroleum systems

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**Perth Basin has been intermittently explored for the last few decades, resulting in the production of gas and oil from several onshore fields. The bulk of known hydrocarbon reserves has been produced, however, and new ideas are needed for Perth Basin to contribute to Australia's petroleum stock in the future. Notwithstanding this long exploration history, the accepted sources for gas have been based on minimal geochemical data; even the generally accepted major Early Triassic Kockatea Shale source for oil has been questioned recently.[1] To improve understanding, carbon isotopic and biomarker analyses of gases, condensates and oils have been analysed as part of AGSO's South and South-west Regional Project. The study has documented numerous oil families from Permian, Triassic and Jurassic sources and positively identified, for the first time, both Permian and Triassic sources for gas in the Perth Basin.**

Perth Basin is a deep, linear north–south trending trough extending more than 1000 kilometres from Geraldton in the north to the south coast of Western Australia (figure 1). The basin covers an area of approximately 45 000 square kilometres onshore and 98 000 square kilometres offshore and contains sediments of Permian to Cainozoic age. A generalised stratigraphy for Perth Basin is shown in figure 1.

The basin is bounded to the east by the north–south trending Darling Fault and this has been downthrown on its western side.[2,3] The main depocentre is the Dandaragan Trough, where up to 15 kilometres of Permian and Mesozoic sediments were deposited. The succession shallows to the north and west, where it is bounded by Beagle Ridge. To the south, Dandaragan Trough is separated from Bunbury Trough by Harvey Ridge. Offshore and to the north, the Abrolhos Sub-basin contains sediments of Early Permian to Late Cretaceous age. Offshore and to the south and west of the city of Perth, the Vlaming Sub-basin contains about 10 kilometres of Cretaceous and Tertiary sediments.

The structural history of the basin is recognised as being very complex with none of the existing models giving completely satisfactory explanations for all tectonic elements.[4] There are considerable problems in accurately dating the Permian sections and this adds to the difficulties in reconstructing the basin history. Mory and Iasky recognise two major phases in the structural evolution of Perth Basin related to the breakup of Australia and India.[5] The first of these began with north–south extension in the Early Permian resulting in east–west trending normal faults and probable sinistral strike-slip faults along the Darling Fault. The Late Jurassic extension and subsequent Early Cretaceous separation of Greater India from Australia caused reactivation of these faults and major uplift and erosion. This second event was probably associated with increased heatflow.

### Petroleum systems

The onshore Perth Basin has yielded volumes of 4.2 million barrels, 1.4 million barrels and 0.7 trillion cubic feet of oil, condensate and gas, respectively.[6] The bulk of these reserves have already been produced. The Dongara field contains more than half the oil and gas reserves, while approximately 85 per cent of the condensate is found in the Beharra Springs field.

#### *Sources*

Petroleum accumulations in the Perth Basin are believed to originate from sources within the terrestrial source rocks of the Early Permian Irwin River Coal Measures and some marine mudstone source rocks of the Early Permian Carynginia Formation, Permian Wagina Sandstone and Early Triassic Kockatea Shale.[1,7,8] Organic matter in these sediments is considered to be the source of gas, condensate and oil in the Beharra Springs, Mondarra, Woodada, Dongara, Mount Horner and Whicher Range fields of the onshore Perth Basin.[8–11] In contrast, oil in offshore Gage Roads-1 is thought to originate from Late Jurassic rift-related sediments of the Yarragadee and/or Parmelia Formations.[8,12–14] Liquids from the Gingin and Walyering Gas fields of the onshore Dandaragan Trough were probably sourced from the Cattamarra Coal Measures.[8]

#### *Reservoirs*

Lithostratigraphic units with reservoir potential are widespread throughout the entire sedimentary succession.[15,16] The Lower Permian sandstones of the Irwin River Coal Measures produce gas of economic significance in the Dongara field. Discontinuous thin sandstones in the Carynginia Formation reservoir gas in the Dongara field and on Beagle Ridge, while the Woodada gas field is found in thick carbonates of the Carynginia Formation. The Wagina Sandstone produces gas in the Dongara and Mondarra fields. The best reservoir potential is present in the Upper Permian Dongara Sandstone and Beekeeper Formation. These reservoirs, together with the high-grade reservoirs in the basal Triassic sandstone of the Kockatea Shale, contain the bulk of hydrocarbons discovered in the basin. There are minor accumulations in the sandstones of the Lower Triassic Arranoo Member (gas and oil in Dongara and oil in Mount Horner). Several thin sandstone horizons of the Lower to Middle Jurassic Cattamarra Coal Measures produce oil from the Mount Horner field.

#### *Seals*

Regional seals are provided by the Cadda Formation and by some intervals within the Cattamarra Coal Measures, but mainly by the thick and laterally extensive Kockatea Shale.[15,16] Shales in the Carynginia Formation may provide a seal to the Irwin River Coal Measures, or juxtaposition of Kockatea Shale and intra-formational seals of the Carynginia Formation across fault boundaries can provide compartmentalisation of hydrocarbon.[16,17] Seals for the sandstone reservoirs within the Cattamarra Coal Measures/Eneabba Formation are either intra-formational or provided by the regional Cadda Formation, while the Yarragadee Formation is sealed by the Parmelia Formation in the Dandaragan Trough.

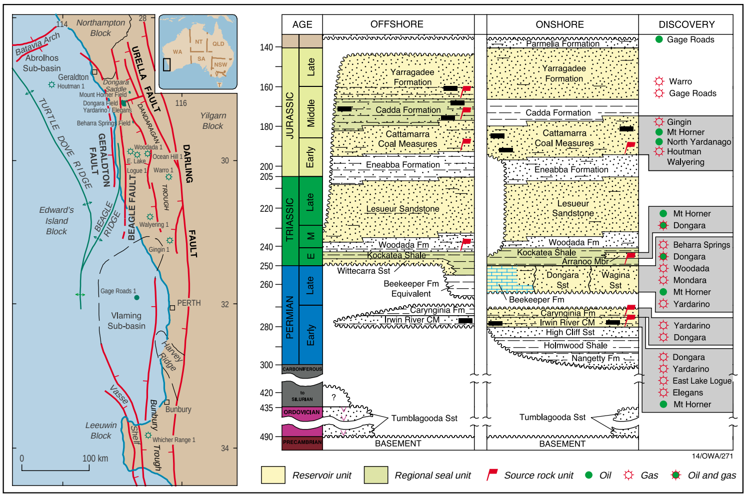


**Figure 1.** Tectonic elements, selected well locations and generalised stratigraphy in the Perth Basin. Note: stratigraphy modified after Owad-Jones and Ellis[15] and Crostella[25].

## Present investigation

### *Gas composition*

The highest $CO_2$ content is seven per cent in gas from Houtman-1 in the offshore Northern Perth Basin, which is similar to the average composition of Australian natural gas,[18] whereas Whicher Range-1 and Yardarino-3 have only trace amounts (figure 2a). A much better appreciation of the origin of $CO_2$ is seen using the relationship between $CO_2$ content and carbon isotopic composition of the $CO_2$ (figure 2b). The strong relationship between increasing $CO_2$ content and enrichment in $^{13}C$ is governed by the degree of mixing of isotopically light thermogenic, organic-derived and isotopically heavy inorganic (mantle and/or igneous)-derived $CO_2$. Very high $N_2$ content is found in Yardarino-3 while all other wells (figure 2a) are below the average of 3.2 per cent for Australian natural gases.[18]

Maturity is the principal control on the composition of the gaseous hydrocarbons and is reflected in the strong relationship between the ratio $\%C_1/\%C_1–C_5$ and the ratio $\%C_2/\%C_3$ (figure 3a). The bulk of the gases have high ratios suggesting relatively high maturities. This is supported by the carbon isotopic composition of individual gaseous hydrocarbons (figure 3b), which suggests gas generation at vitrinite reflectance (VR) >1.1 per cent. The considerable 'scatter' around the predicted maturity trend indicates that the isotopic composition is also governed by source effects.[18] Figure 3c shows the carbon isotopic composition of individual $C_1–C_5$ gaseous hydrocarbons in relation to the range in carbon isotopes of Australian natural gases.[18]

### *Oil geochemistry*

Of the 10 oils analysed for C33-alkylcyclohexane (C33ACH; table 1), a characteristic biomarker of the organic matter in the Kockatea Shale, relatively high amounts were found in North Erregulla-1, Woodada-3 and Mt Horner-1, and in somewhat lower abundance in Erregulla-1. Although its presence confirms a major contribution from the Early Triassic Kockatea Shale, its absence is equivocal. On the other hand, carbon isotopes are one of the most diagnostic indicators of source in the Perth Basin (see below).

The results of the analysis of aromatic hydrocarbons for methylated naphthalenes, methylated benzenes and higher plant-derived biomarkers are listed in table 1. The naphthalene parameters TMNr, TeMNr and PMNr for all oils fall in or close to the centre when plotted in a ternary diagram (figure 4).19 Since none of the samples deviates appreciably from the 'maturity centre' there is no positive indication, within the limitations of the technique, of any significant in-reservoir mixing of oils of different maturities, biodegradation or migration contamination.

The oils from Dongara-4, East Lake Logue-1, Erregulla-1 and Mount Horner-1, sourced predominantly from the Kockatea Shale, have relatively low abundances of the land-plant markers retene and *i*p-iHMN.[20,21] The high HPI for the oil from Woodada-3 suggests an additional input from allochthonous terrestrial organic matter to the extensively marine depositional environment of the Kockatea Shale.

The oils from Gage Roads-1 and Gingin-1 contain relatively abundant conifer-derived retene, consistent with a source from the Late Jurassic Yarragadee Formation and Early Jurassic Cattamarra Coal Measures, respectively.[8]

The HPF for Whicher Range-1 is unexpectedly weak for oil derived from a Permian land-plant source. The HPF for Walyering-2 is similar to marine-sourced oil from North Erregulla-4 but its high TeMBr may indicate an additional input from a terrestrial source biased towards the low molecular weight components (see below).

### *Gas-to-oil-to-source correlation*

The most reliable approach for assigning source rocks for the various natural gases firstly involves defining gas-to-oil correlations and secondly, by using better understood oil-to-source correlations, extrapolating to the desired gas-to-source correlations. The critical step relies on the utility of the *n*-alkane carbon isotope profile of oil as a good diagnostic tool in oil-oil and oil-to-source correlations.[8,22] The $>C_{7+}$ *n*-alkane carbon isotopic ratios for representative oils from Perth Basin are shown in figure 5. A range in $\delta^{13}C$ of <2 ‰ for *n*-alkanes of the same carbon number but from different oils is typical for variations in organic facies from essentially the same source rock interval. To unravel the source of the gas, the position and shape of an extended *n*-alkane carbon isotope profile is used, involving the combination of the carbon isotopic data for gas ($C_1$, $C_2$ $C_3$, $n$-$C_4$, $n$-$C_5$) components and the $>C_{7+}$ *n*-alkane carbon isotopes from accompanying oils and condensates (figure 5).

For East Lake Logue-1 and Dongara field gas and oil there is a fairly smooth trend (i.e. continuity) across the carbon number range $C_4$ to $C_9$, which defines the gas to oil transition zone (figure 5). This trend supports the idea that the gas and oil are genetically related, both generated from the Early Triassic Kockatea Shale. Gases from the Beharra Springs field, Indoon-1 and Woodada-6 are also thought to have a major contribution from Early Triassic rocks. Oils from Mount Horner-1 (figure 5), North Erregulla-1 and Yardarino-1 are extremely isotopically light (depleted in $^{13}C$) compared with oils from older Permian (Whicher Range-1) and younger Jurassic sources (Gage Roads-1 and Gingin-1).[8] The rather flat (constant carbon isotopes) profile for the $C_{15+}$ *n*-alkanes is typical of marine-sourced oil.[23] A flat profile is also characteristic of the lacustrine source (Gage Roads-1), while increasing isotopic lightness with increasing carbon number is typical of a land plant source.[8,23]

The oils from Erregulla-1, Woodada-3 and Walyering-2 show 'intermediate' *n*-alkane carbon isotope profiles (figure 5).[8] The first two oils are isotopically similar and most likely from the same source. Summons et al. suggest an Early Triassic Kockatea Shale source, albeit from slightly different organic facies.[8]

The Woodada-3 oil was described as a 'vagrant'—that is, it stood alone compared with the other Perth Basin oils using statistical principal component cluster analysis based on biomarker ratios and bulk carbon iotopes.[24] The additional biomarker data in table 1 also support the unusual composition of this oil. If this interpretation is correct, then the Kockatea Shale source can give rise to a wide isotopic variability in the same *n*-alkane (e.g. 3.5 ‰ for *n*-$C_{15}$).

The gas isotope data for Woodada-6 indicate that the gas is from the more common organic facies of the Kockatea Shale source, indicating a rather complex charge history.

It is apparent that the carbon isotopic composition of the wet gas components in Elegans-1 (a later re-entry of Yardarino-1) is heavier (enriched in $^{13}C$) compared to the other Perth Basin gases as well as to the shallower oil from the original well on the same site (Yardarino-1). This enrichment in $^{13}C$ is attributed to a source effect and is consistent with either a Jurassic or Permian source. The geological setting and regional maturation profiles indicate a Permian source for the gas.[15]

**Table 1.** Results from biomarker analyses

| HPF | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **HPI** | **% ret** | **% cad** | **% iHMN** | **TMNr** | **TeMNr** | **PMNr** | **136/ 137** | **TeMBr** | **DBT/ 1367** | **C33ACH** |
| Dongara-4 | 0.27 | 3 | 96 | 1 | 0.82 | 0.75 | 0.60 | 1.10 | 0.64 | 0.10 | |
| East Lake Logue-1 | 0.12 | 0 | 100 | 0 | 0.91 | 0.86 | 0.59 | 1.29 | 0.78 | 0.45 | |
| Erregulla-1 | 0.07 | 0 | 100 | 0 | 0.75 | 0.80 | 0.70 | 1.45 | 0.49 | 0.15 | + |
| Gage Roads-1 | 0.67 | 70 | 25 | 5 | 0.53 | 0.56 | 0.41 | 1.23 | 0.74 | 0.14 | |
| Gingin-1 | 0.18 | 38 | 62 | 1 | 0.74 | 0.71 | 0.63 | 1.16 | 0.75 | 0.12 | |
| Mt Horner-1 | 0.10 | 0 | 100 | 0 | 0.76 | 0.75 | 0.61 | 1.42 | 0.48 | 0.20 | ++ |
| North Erregulla-1 | 0.12 | 30 | 70 | 0 | 0.72 | 0.70 | 0.52 | 1.49 | 0.47 | 0.05 | ++ |
| Walyering-2 | 0.13 | 32 | 68 | 0 | 0.83 | 0.85 | 0.74 | 1.26 | 0.73 | 0.28 | |
| Whicher Range-1 | 0.13 | 9 | 90 | 1 | 0.67 | 0.65 | 0.58 | 1.10 | 0.70 | 0.30 | |
| Woodada-3 | 0.72 | 12 | 85 | 3 | 0.67 | 0.70 | 0.55 | 1.37 | 0.51 | 1.07 | ++ |

HPI : Higher plant index = (retene + cadalene + *i*p-iHMN) /1,3,6,7-TeMN
HPF: Higher plant fingerprint
%ret = retene / (retene + cadalene + *i*p-iHMN); % cad = cadalene / (retene + cadalene + *i*p-iHMN); %iHMN = *i*p-iHMN / (retene + cadalene + *i*p-iHMN)
TMNr = 1,3,7-TMN / (1,3,7-TMN + 1,2,5-TMN)
TeMNr = 1,3,6,7-TeMN / (1,3,6,7-TeMN + 1,2,5,6-TeMN)
PMNr = 1,2,4,6,7-PMN / (1,2,4,6,7-PMN + 1,2,3,5,6-PMN)
136/137 = 1,3,6-TMN / 1,3,7-TMN
TeMBr = 1,2,3,5-TeMB / (1,2,3,5-TeMB + 1,2,3,4-TeMB)
DBT/1367 = DBT / 1,3,6,7-TeMN
$C_{33}$ACH = $C_{33}$ alkylcyclohexane

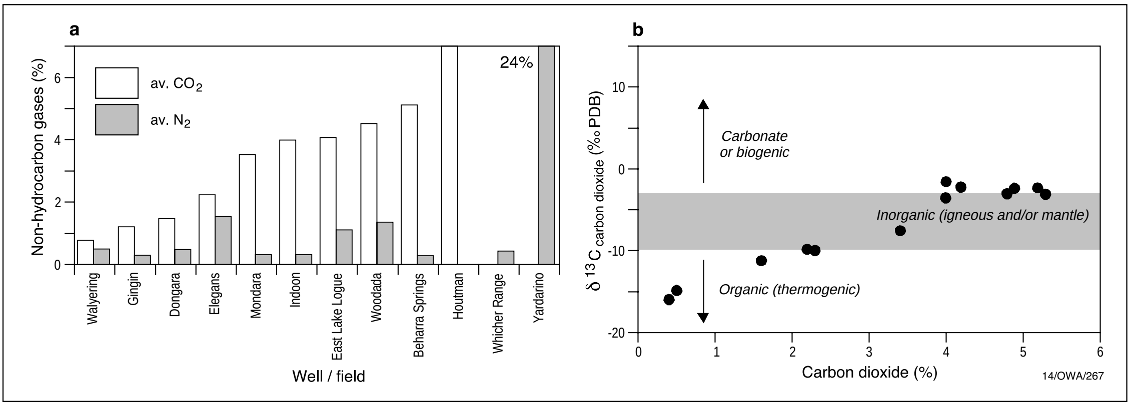


**Figure 2.** Plots showing **a.** average molecular percentage of $CO_2$ and $N_2$ and **b.** carbon isotopic composition of $CO_2$ versus molecular percentage of $CO_2$ for natural gases from Perth Basin.

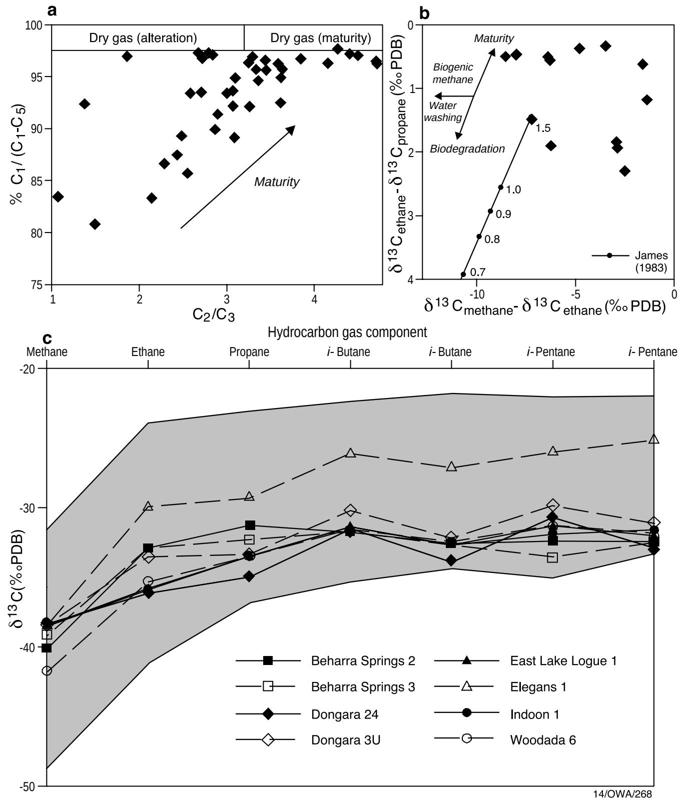


**Figure 3.** Plots of
**a.** Percentage methane%/(methane% + ethane% + propane% + *iso*- & *n*-butane% + iso & n- pentane%) versus ethane%/propane%; (%$C_1$/$C_1$–$C_5$ vs $C_2$/$C_3$)
**b.** $\delta^{13}C_{methane}$ minus $\delta^{13}C_{ethane}$ versus $\delta^{13}C_{ethane}$ minus $\delta^{13}C_{propane}$ (the predicted evolution of carbon isotopic difference[26])
**c.** $\delta^{13}C$ of individual $C_1$–$C_5$ gaseous hydrocarbons for natural gases from the Perth Basin (the shaded area is the range in carbon isotopes for unaltered Australian gases[18]).

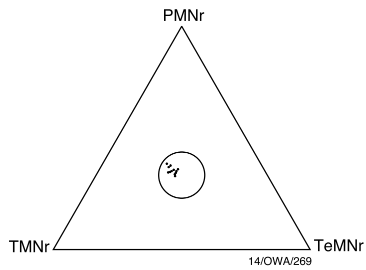


**Figure 4.** Triangular plot of TNMr, TeMNr and PMNr. The circle defines the 'maturity centre' representing a 10 % variability in the ratios.[19]

## Implications for exploration

This study identified numerous oil families and petroleum systems in Perth Basin. It also positively identified, for the first time, both Permian and Triassic sources for gas in Perth Basin.

The Early Triassic Kockatea Shale is the principal source for oil, and it is of the highest quality in the onshore Northern Perth Basin. Carbon isotopic evidence for gas indicates that the Kockatea Shale is also the major source for gas onshore. Gas generation should still have occurred offshore, even though the Kockatea Shale has diminished potential for oil.[24] The Permian, and to a lesser extent, Jurassic sediments are also gas sources in Perth Basin. The existence of leaky Permian seals for gas leads to a large scale 'gas flush' in the subsurface, compounding the widespread gas-stripping of oil in Perth Basin.[17] However, this re-mobilisation of hydrocarbons should result in long-range migration and a mechanism for emplacement of petroleum higher in the section.

In summary, the identification of Permian and Triassic sources for gas in the onshore Perth Basin, coupled with recognised oil and gas potential in the Mesozoic sediments offshore,[25] highlight the potential for multiple petroleum systems active in the region and points to new exploration opportunities.

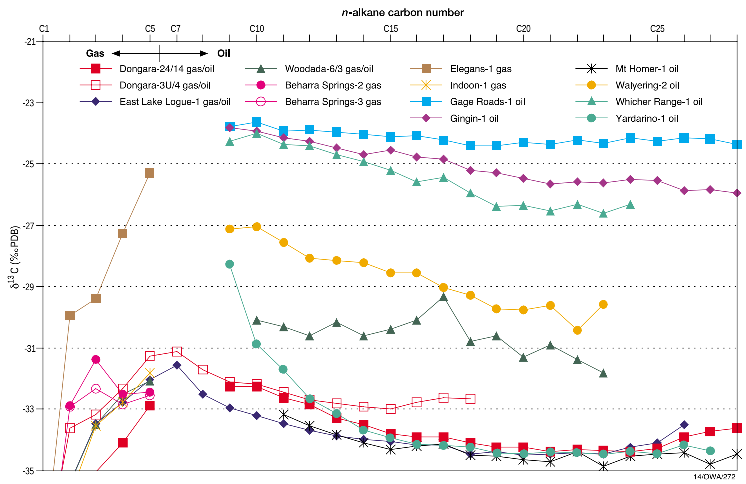


**Figure 5.** Carbon isotope profile for *n*-alkanes from gases and oil in the Perth Basin

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