Petroleum geochemistry, burial history and shale gas potential of the Goldwyer Formation – Canning Basin, Western Australia

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Abstract: Several organic-rich shale horizons in the Canning Basin, Western Australia, acted as source rocks for conventional oil and gas fields. The aim of this study is to investigate one of its units, the Goldwyer Formation (Ordovician in age, as the Utica Shale in USA) as a potential shale gas play. Geochemical analysis such as Rock-Eval pyrolysis and total organic carbon (TOC) estimation, as well as thermal and burial history modelling were used. The organic matter is mixed type II/III kerogen and the total organic carbon

(TOC) values range between 0.16 and 4.8 wt%. Tmax values between 335°C and 471°C and vitrinite reflectance values between 0.71 and 1.3 Ro% point to the main oil to wet and dry thermogenic gas zones, with a trend of increasing maturity in the west-central part of the basin. The results of this study show that the Goldwyer shale may be considered as potential shale-gas play. [Received: September 3, 2016; Accepted: March 2, 2017]

Keywords: shale gas; burial history; thermal modelling; Canning Basin; Goldwyer Formation.

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1 Introduction

Shale gas is natural gas produced from shale source rocks as 'unconventional' reservoirs. This has become an increasingly important source of natural gas in the USA over the past decade, and interest has spread to potential shale gas plays in Canada, Europe, Asia, and Australia. Some analysts expect shale gas to supply as much as half of the natural gas production in North America by 2020 (Polczer, 2009). The potential for shale gas production has grown dramatically in recent years due to the improved technologies of horizontal drilling and multistage fracturing. The shale gas production in Australia is in its infancy, with a few big players and several smaller companies carrying out active exploration through Joint Ventures. However, the magnitude of the 'unconventional' gas reserves in Australia is largely unknown (e.g., Karimian Torghabeh et al., 2015).

Organic-rich sediments occur throughout the stratigraphic column in the Canning Basin, but the focus of this paper is to evaluate the potential for successful exploration of the Ordovician Goldwyer Formation as a potential candidate for shale gas play. The approach is the one detailed in Triche and Bahar (2013), utilising extensive geochemical data and thermal/burial history modelling to identify and characterise important volumes of shales with significant content well matured organic matter transformed into gas contained within those shales.

1.1 Geological framework

The Canning Basin in the North West Australian shelf, with several other associated basins were for most of their early geological history, shallow intra-cratonic basins located in northern Gondwana (Metcalf, 1996). First extensional phase in Canning basin was in Early Ordovician and then in Late Devonian, followed by uplifting phase in Permian-Early Triassic and final break-up in northern and western margin of Australia to take its present form in the Late Jurassic – Early Cretaceous (Edwards et al., 1997).

The Canning Basin covers an area of about 595,000 km^2 (Haines, 2004) (Figure 1). This basin preserves a complex depositional history from the Early Ordovician to the Cenozoic (Kennard et al., 1994; Shaw et al., 1994). The Canning Basin has been internally subdivided into a series of sub-basins, platforms, shelves, and terraces bounded by northwesterly-southeasterly trending faults (Shaw et al., 1994; Middleton, 1991). The basin developed between the Kimberley Craton to the N and the Pilbara Craton to the South, with two major northwest-trending depositional troughs, separated by a mid-basinal arch (Figure 1).

Deposition in the Canning Basin began in the EarlyOrdovician in response to extensionaltectonics (Cook and Totterdell, 1990) (Figure 2). Subsidence and marine transgression in the Early Ordovician resulted in deposition of shallow marine sandstones, shales, siltstones, and carbonates of the Nambeet Formation and carbonates of the Willara Formation. At Mid Ordovician, clastics and carbonates of the Goldwyer and carbonates of the Nita Formation were deposited in shallow marine to subtidal/intertidal environments (Brown et al., 1984; Nicoll et al., 1994). The lower Ordovician to lower Silurian succession is a relatively conformable package of sediments deposited in marine, marginal marine and terrestrial environments. From the late Ordovician to early Silurian, a period of sub-aerial exposure and non-deposition occurred. Intra-cratonic rifting in the Silurian led to the formation of the Fitzroy Trough and the Kidson Sub-basin. The succession is unconformably overlain by Devonian, Carboniferous, or Permo-Triassic strata. The post-Triassic section consists of late Middle Jurassic marine sandstones and Cretaceous continental sandstones, with a thin Quaternary cover of alluvial sediments (Jonasson, 2001).

Figure 1 Location of the studied area in Western Australia (see online version for colours)

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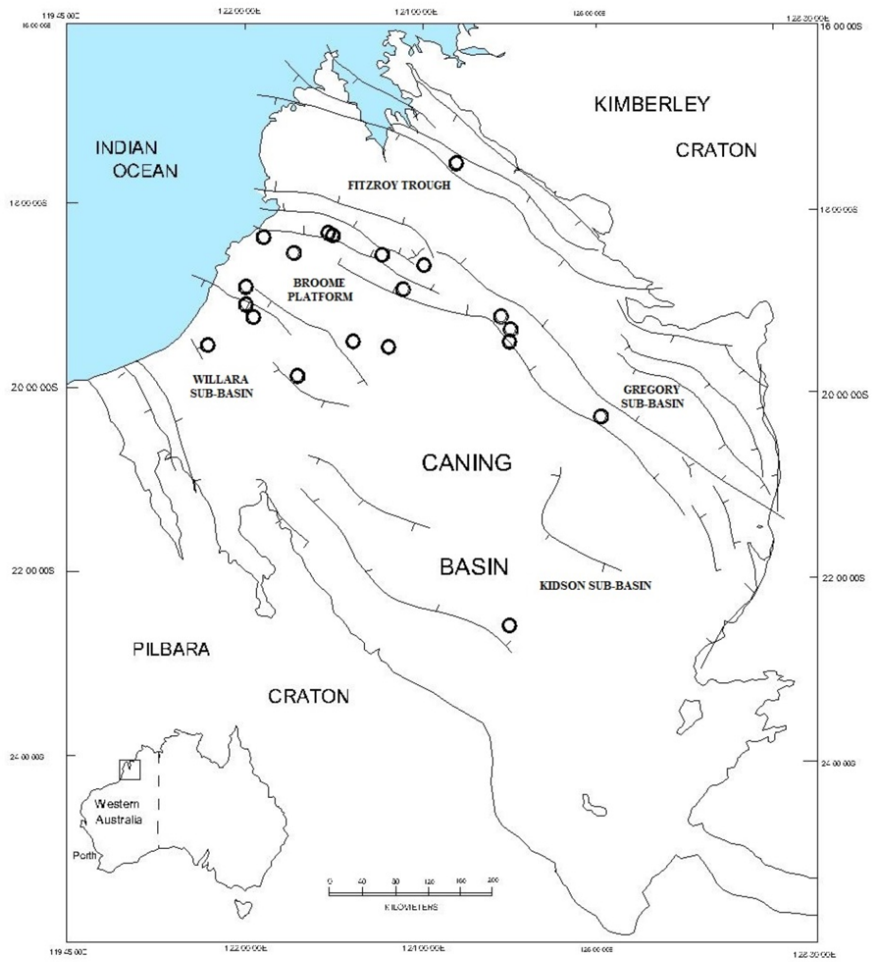
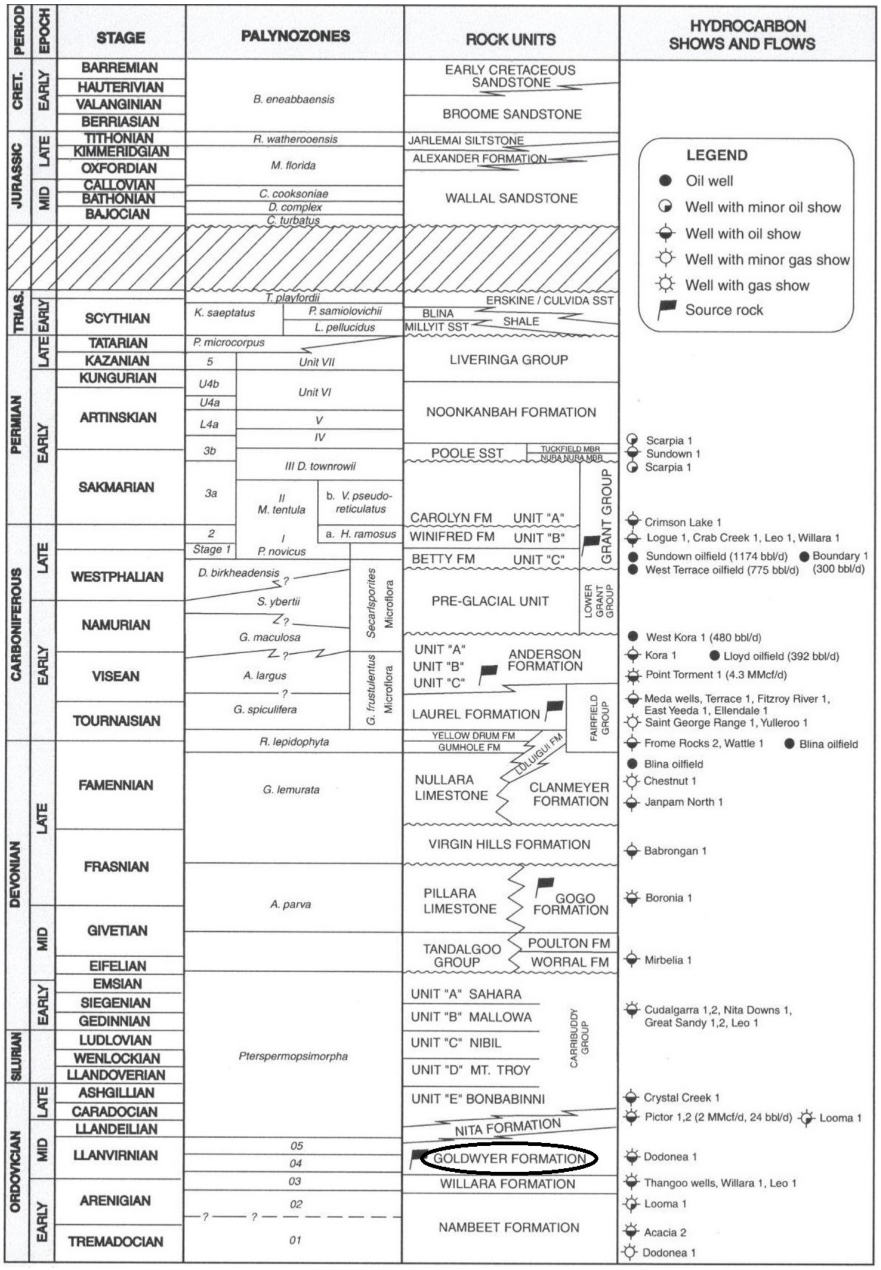


Source: Modified from Purcell (1984)

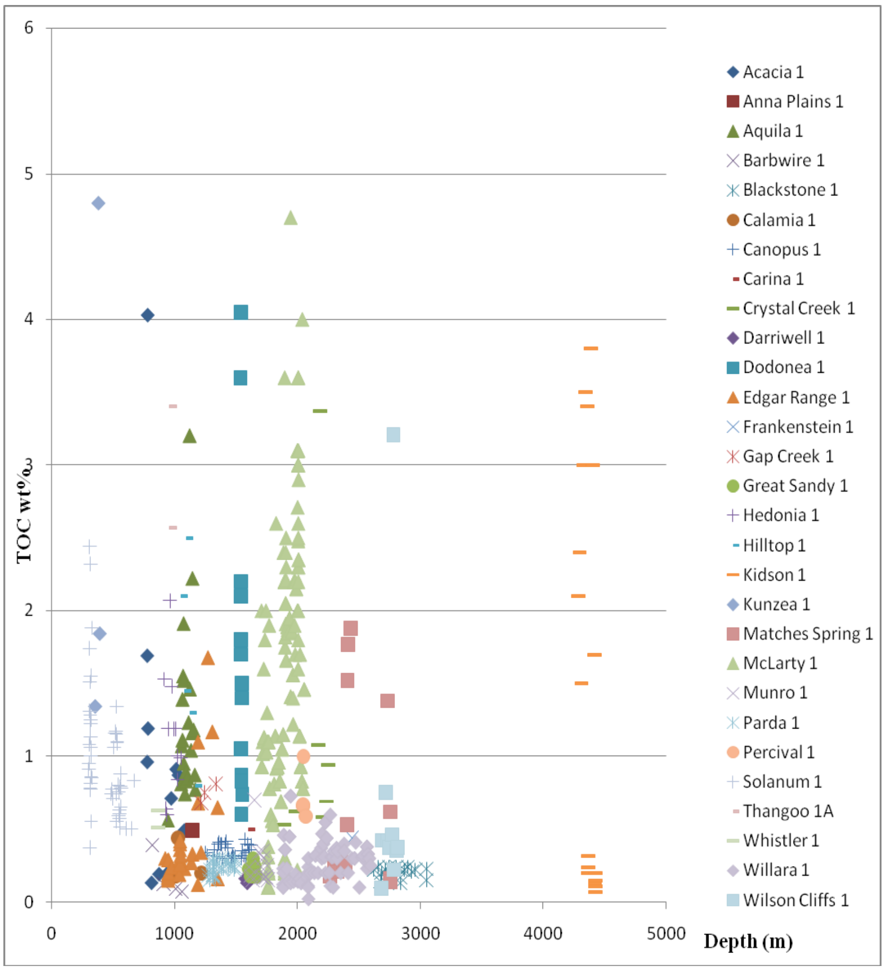
Figure 2 Stratigraphic column of the Canning Basin in Western Australia



Source: Goldstein (1989) and Kimberley OIL NL (1997)

The Goldwyer Formation is the focus of this study and is dominated by mudstones and carbonates. Mudstone varies in average grain size from claystone to siltstone, with minor fine-grained sandstones, increasing towards the southeastern margin of the basin. Carbonates were despoited in sub-tidal environments and include dolomites and some major organic build-ups.

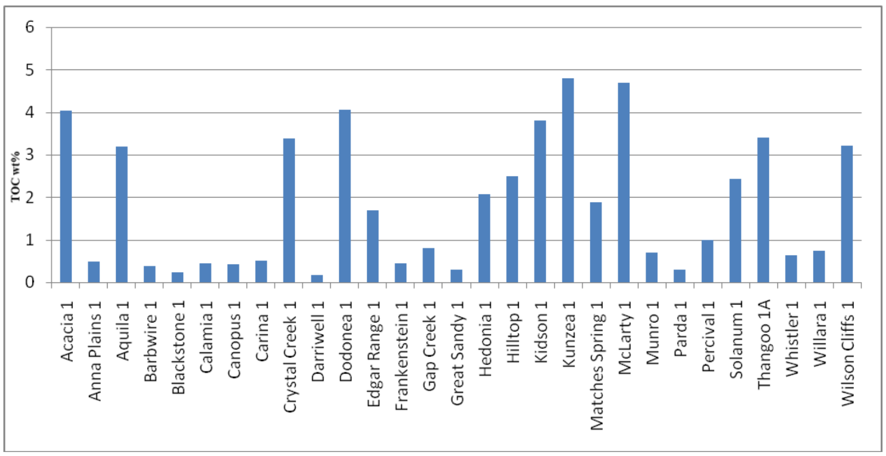
Figure 3 Total organic carbon richness (TOC, wt%) of the Goldwyer Formation samples (see online version for colours)



1.2 Exploration activities and petroleum systems

The Canning Basin is one of the Australian's largest onshore sedimentary basins, but until now largely underexplored concerning it petroleum potential. Petroleum exploration activity in the Canning Basin began in 1922, when the Freney Kimberley Oil Company began drilling a series of wells. Exploration was followed by the Bureau of Mineral Resources (BMR; now Australian Geological Survey Organization – AGSO) and West Australian Petroleum (WAPET) in the early 1950s, which conducted a series of magnetic, gravity and seismic surveys in the northern and western parts of the Canning Basin (Jonasson, 2001).

Figure 4 Variation of organic carbon richness (TOC, wt%) in the studied wells (see online version for colours)



During the1980s an extensive phase of petroleum exploration resulted in the acquisition of many thousands of kilometres of seismic data, much in hitherto little explored areas, and the drilling of many additional wells, but this intensive exploration has yielded little commercial success. Up until the mid-1980s, exploration largely focused on the northern and central basin areas with wells drilled on the Lennard Shelf, Broome Platform and Jugurra Terrace. Many exploration wells had shows, especially of oil, with few commercial quantities of hydrocarbons. In 1981, Home Energy Company Ltd. made the first commercial oil discovery with the Blina 1 exploration well (Jonasson, 2001). The southern Canning Basin, on the other hand, has undergone very little exploration. Oil has been recovered from the Ordovician sequence and the sub-salt Ordovician play has been the target of companies such as Shell, who recovered hydrocarbons at their Looma 1 discovery in the southern Canning Basin. The basin is substantially under-explored, with low well density and a small percentage of valid structural tests. As at 30 June 2000, 247 wells have been drilled onshore in the basin, of which 164 were new field wildcats and 62 were stratigraphic wells.

One of the most important prospective areas of the Canning Basin includes the Broome Platform. The sub-salt discovery at Looma 1 was the first evidence of mature, migrated oil from a southern Canning Basin kitchen (King, 1998). In addition, a new post-salt exploration play, with over 1,900 GL (12 billion barrels) of proven oil in place in a similar geologic setting [Shell, in Petro Ventures/DME WA, (2000), p.5] has been mapped by Shell in the southern Canning Basin. In the south, there is potential for gas generation from the Permian and pre-Ordovician carbonaceous shales and for oil expulsion from the Ordovician Goldwyer shales (Scott, 1998). The oil and gas recovered from Pictor 1 and in place in the Looma structure is sourced from Willara through Goldwyer Formations. Potential reservoirs are considered to be the Nita Formation, Devonian reef complexes, Tandalgoo Formation, Yellow Drum Formation (Fairfield Group), Anderson Formation and Permian sandstones. Salt diapirism is evident in the region and may provide traps in areas that lack major block faulting.

Four petroleum systems have been identified in the onshore Canning Basin (Kennard et al., 1994; Cadman et al., 1993). The marine shales of the Ordovician Goldwyer Formation and the Devonian Gogo Formation are considered to provide the best prospects for liquid hydrocarbons (e.g., Blina oilfield). The Lower Carboniferous Fairfield Group, especially the Lower Laurel Formation, also contains proven source rocks. Oil and minor gas have been produced from the Lower Carboniferous. Point Torment 1 recorded the highest gas flow in the basin with a stabilised flow rate in the order of 121,000 m3/d (4.3 Mcf/d) from the Anderson Formation (Jonasson, 2001).While past exploration has shown large late-formed structures in the Canning Basin to have poor potential for petroleum, early-formed structures on the Lennard Shelf, Jurgurra and Barbwire Terraces, and the Broome platform may be prospective targets (Crostella, 1998).

2 Materials and methods

2.1 Burial history and thermal modelling

Geochemical and stratigraphic data from 20 wells have been used to address the burial history and thermal modelling and to evaluate the potential of shale gas in the Canning Basin.

Burial history modelling reflects the cumulative subsidence of selected chronostratigraphic horizons encountered in a well and therefore stratigraphy, geochemical and borehole data were used for this study. Data required for thermal modelling include the depths and ages of the formation tops; the lithology of each unit; the bottom-hole temperatures and kerogen type and measured vitrinite reflectance values (e.g., Littke et al., 2011). The measured depth of each unit's top at each well location has been combined with an estimated heat flow value, to compute the theoretical vitrinite reflectance (Ro) for that horizon as a function of geological time. The estimated Ro has then been compared with the observed vitrinite profile and used to determine the real heat flow and to proceed with thermal modelling. Vitrinite-like macerals have been used, since real vitrinites do not occur in such Ordivician rocks. Pars Basin Modeler (PBM) software was used for burial and thermal history modeling, using all the above-mentioned parameters (Karimian Torghabeh and Rezzae, 2016).

Measured maturity values (Ro and T_{max}) indicate the present-day status of hydrocarbon generation. Hydrocarbon generation potential (GP) and timing of hydrocarbon generation can be predicted using the Lopatin Time Temperature Index or TTI (Lopatin and Bostick, 1973). In this study, we used burial history curves to calculate the maturity of organic matter using a TTI, Easy Ro model (Sweeney and Burnham, 1990) and geochemical diagrams.

2.2 Geochemical analysis

Geochemical analyses were performed on core and cutting samples from 20 wells of the Canning Basin, mostly from Broome platform (Figure 1 and Table 1). About 600 Rock-Eval data from the studied wells are analysed to evaluate their hydrocarbon potential generation geochemical analysis included the determination of the total organic carbon (TOC) content and Rock-Eval pyrolysis carried out by the Curtin University Shale Gas Consortium sponsors. These unpublished data were plotted to evaluate their hydrocarbon potential generation (Figures 5, 6, 7 and 8).

Table 1 Location of the studied wells and main data (thickness, average TOC and average T_{max}) for the Goldwyer Formation in the Canning Basin

Well name	*Latitude (ºsouth)*	*Longitude (ºeast)*	*Thickness (m)*	*av. TOC (wt%)*	*av. T_{max} (ºCelsuis)*
Acacia 1	–19.329	124.995	354.00	4.03	439
Aquila 1	–18.581	122.670	370.00	3.2	439
Blackstone 1	–17.585	124.353	387.09	0.24	335
Calamia 1	–19.579	121.797	304.00	0.44	433
Canopus 1	–18.946	123.868	398.00	0.43	435
Carina 1	–19.353	123.080	52.50	0.5	419
Crystal Creek 1	–18.556	123.602	460.00	3.37	453
Darriwell 1	–19.588	122.105	21.20	0.16	477
Hilltop 1	–18.292	122.290	227.30	2.5	447
Kidson 1	–22.616	125.009	128.63	3.8	364
Kunzea 1	–19.533	124.991	100.00	4.8	437
Matches Spring 1	–18.689	124.051	557.48	1.88	443
McLarty 1	–19.394	123.656	373.08	4.7	442
Munro 1	–19.863	122.489	717.00	0.7	436
Parda 1	–18.933	122.009	311.51	0.3	434
Percival 1	–20.330	126.083	51.50	1	453
Solanum 1	–19.364	124.962	331.00	2.44	442
Thangoo 1A	–18.362	122.886	211.84	3.4	443
Whistler 1	–18.370	122.896	120.50	0.63	440
Willara 1	–19.181	122.072	736.09	0.73	440

Figure 5 Modified Van Krevelen Diagram, plotting HI versus T_{max} for all the samples from the Goldwyer Formation, indicating the type of organic matter and maturity levels of the analysed samples (see online version for colours)

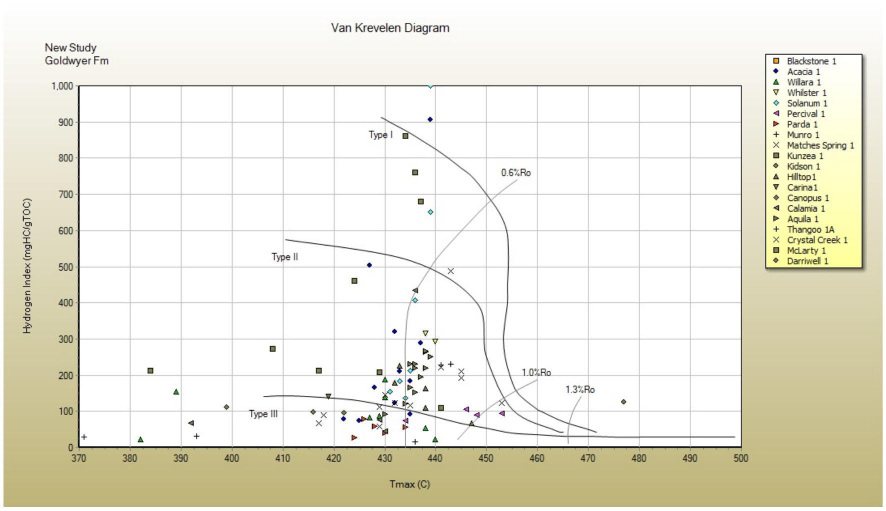


Figure 6 Modified Van Krevelen Diagram, plotting HI versus T_{max} for six wells sampled at the Willara sub-basin, indicating maturity levels (see online version for colours)

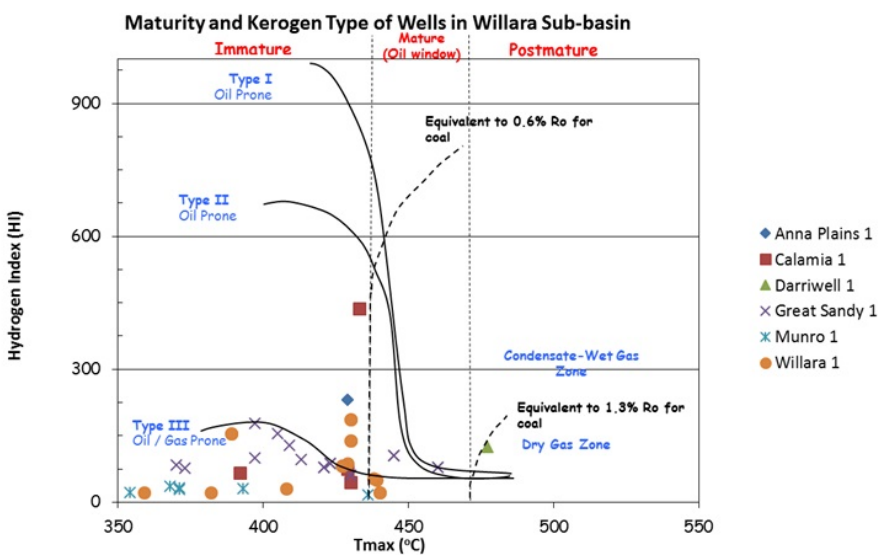


Figure 7 Thermal maturation indicators as production index (PI) in studied wells (see online version for colours)

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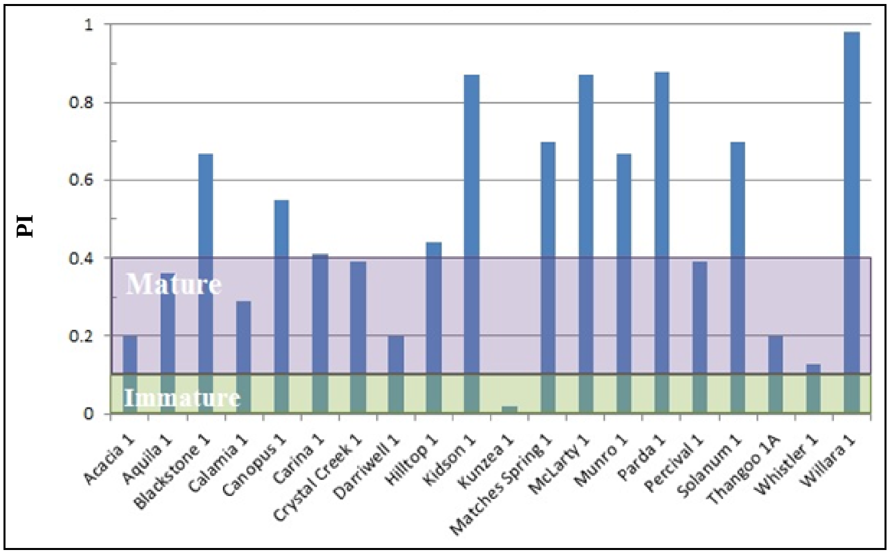


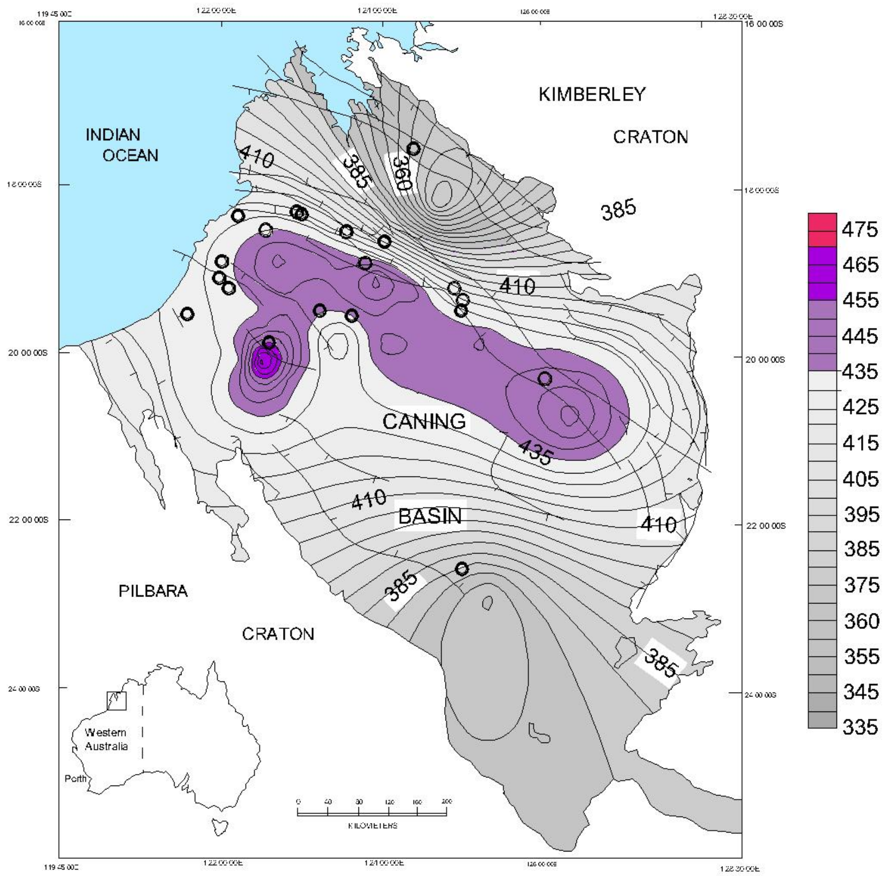
Note: PI < 0.1 show immature stage, 0.1–0.3 mature stage and PI > 0.3 show over mature stage.

Rock-Eval pyrolysis is a geochemical technique that can be used for the characterisation of shale gas interval, providing information on the quantity of hydrocarbons contained in the rock, the quantity of producible hydrocarbons and the quality and maturity of the kerogen. Rock-Eval pyrolysis consists of heating (initially at 300°C then up to 550°C with a temperature gradient of 25°C per minute) of a small quantity of rock (100 mg) (Jones, 1976). During the heating process, different fractions of hydrocarbons are detected (S1 and S2), using a flame ionisation detector (FID). S1 is the quantity of hydrocarbons (expressed as mg of hc/g of rock) thermally desorbed at 300°C; S2 is the quantity of hydrocarbons (expressed in mg of HC/g of rock) produced by thermal cracking (pyrolysis from 300 to 550°C) of the kerogen; and S3 is the amount of CO_2 released during heating to 390°C. These values are combined with TOC values to provide the information necessary to calculate the hydrogen index (HI) (HI = 100 × S2/TOC in milligrams hydrocarbon per gram of TOC) and the oxygen index (OI = 100 × S3/TOC in milligrams CO_2 per gram of TOC). The temperature of maximum hydrocarbon release during pyrolysis (T_{max}) is also obtained and provides a measure of organic matter thermal maturity.

The production index (PI), calculated as S1/(S1 + S2), and Genetic Potential (S1 + S2) indicate the presence of migrated or indigenous hydrocarbons and total production potential of the shale.

Vitrinite reflectance has also been studied for all the samples, using laboratorial industry facilities, within the mentioned consortium.

Figure 8 Thermal maturation, based in T_{max} (values in ºC) for the Goldwyer Formation (see online version for colours)



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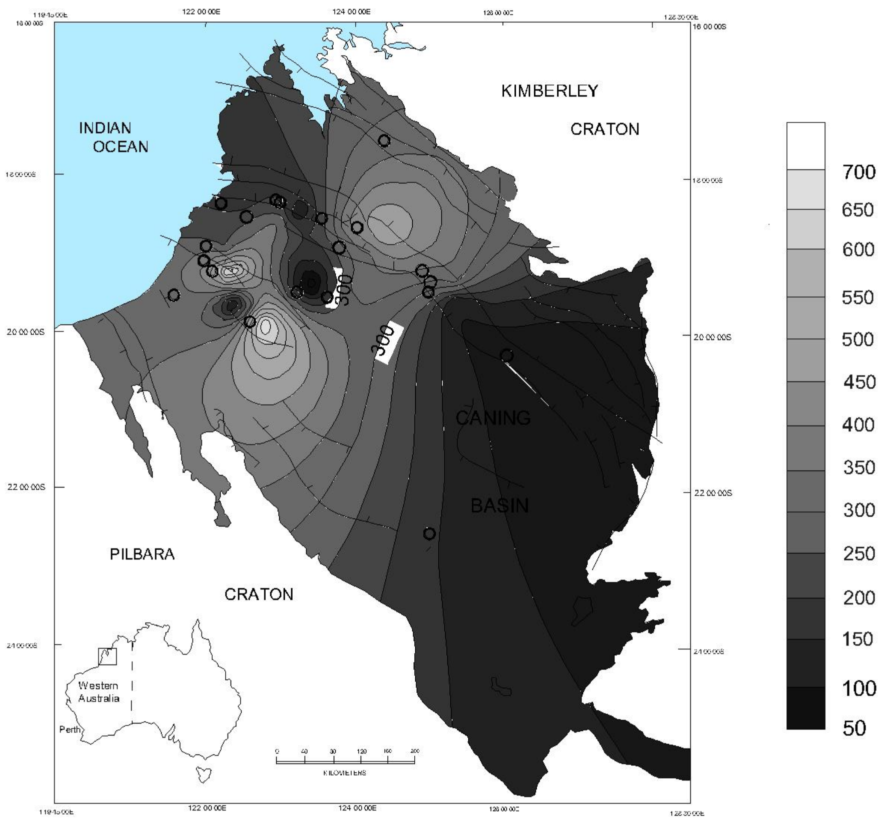
3 Results

3.1 Burial history and thermal modelling

The Goldwyer Formation sediments show variable thicknesses along the Canning Basin. From the analysis of the studied wells, these values are estimated to range from a few hundred at the SE part of the Basin to over 500 meters at the Fitzroy Trough and Willara sub-basin (Figure 9).

Figure 9 Thickness map (values in meters) of the Goldwyer Formation in the Canning Basin (see online version for colours)



Burial history curves of the Goldwyer Formation show, for all the studied wells, a steady subsidence with deposition of different stratigraphic overburden units until the end of the Permian, broadly similar to the evolution of the Perth Basin in Western Australia (Karimian Torghabeh et al., 2014a). Different unconformities, such as in Early Devonian, Early Carboniferous, Early Permian to Mid Jurassic and Early Cretaceous have been identified several wells, such as Darriwell 1 (Figure 14).These unconformities and some disconformities could be the result of different stages of rifting and extensional phase in the Canning basin. In Late Cretaceous to recent final rifting stages there is no sedimentation in onshore of Canning Basin. Thermal history shows maturation of the Goldwyer Formation for most wells, such as Darriwell 1 (Figure 15). Thermal modelling for this well shows that maximum subsidence and overburden has been attained at the end of the Permian, followed by an important uplift before the Mesozoic rifting. A geothermal pulse and increased heat flow is due to the initial Late Triassic to Jurassic rifting and higher gradients near spreading ridges (Mory and Iasky, 1996), while from the Late Cretaceous break-up onwards, with the separation of the continents, it was assumed that temperature gradients would quickly drop to no lower than present gradients.

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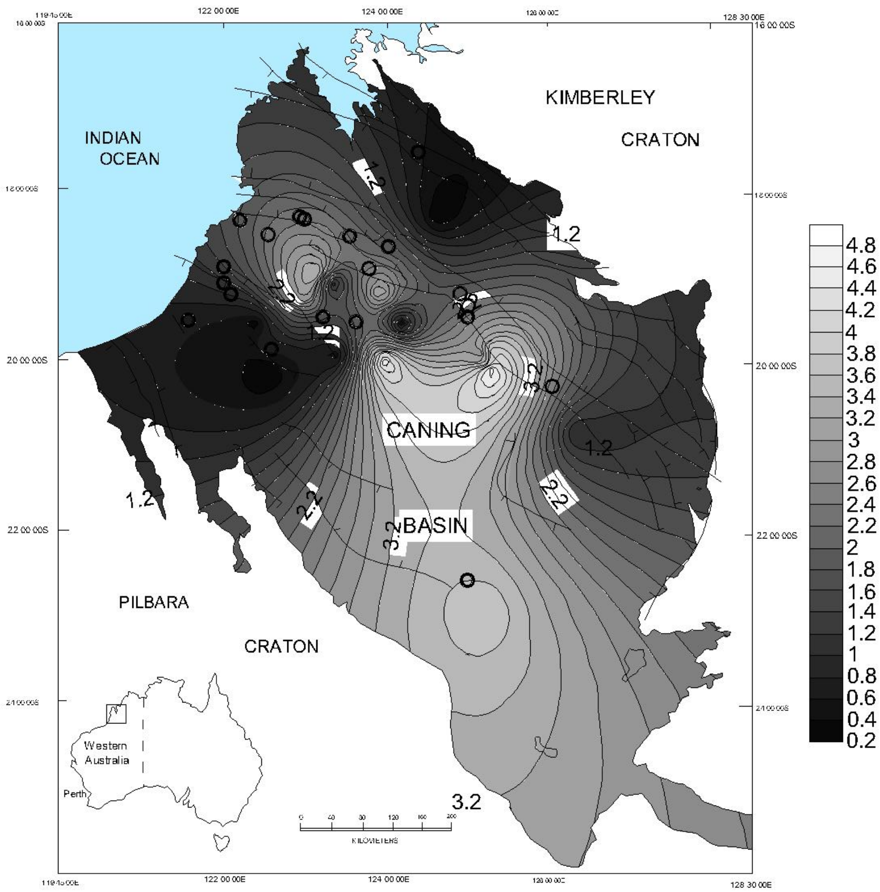
3.2 Geochemical results

The shale gas potential is estimated by using the TOC content, estimated HI, kerogen type, thermal maturity, thickness, and the presence of upper and lower boundary conditions.

3.2.1 TOC

TOC values between 0.5 and 1 wt.% indicate poor generative potential, values from 1.0 to 2.0 wt.% show fair generative potential and greater than 2.0 wt.% refer good, above 4wt.% very good generative shale (Maky and Ramadan, 2008). Most of the studied samples reveal mainly fair to good, with some very good source rock samples (Figures 3 and 4). Looking at regional distribution, the Boone Platform and the areas from there towards SE, appear as the most organic rich areas (Figure 10).

Figure 10 Regional TOC (values in wt.%) map for the Goldwyer Formation in the Canning Basin (see online version for colours)



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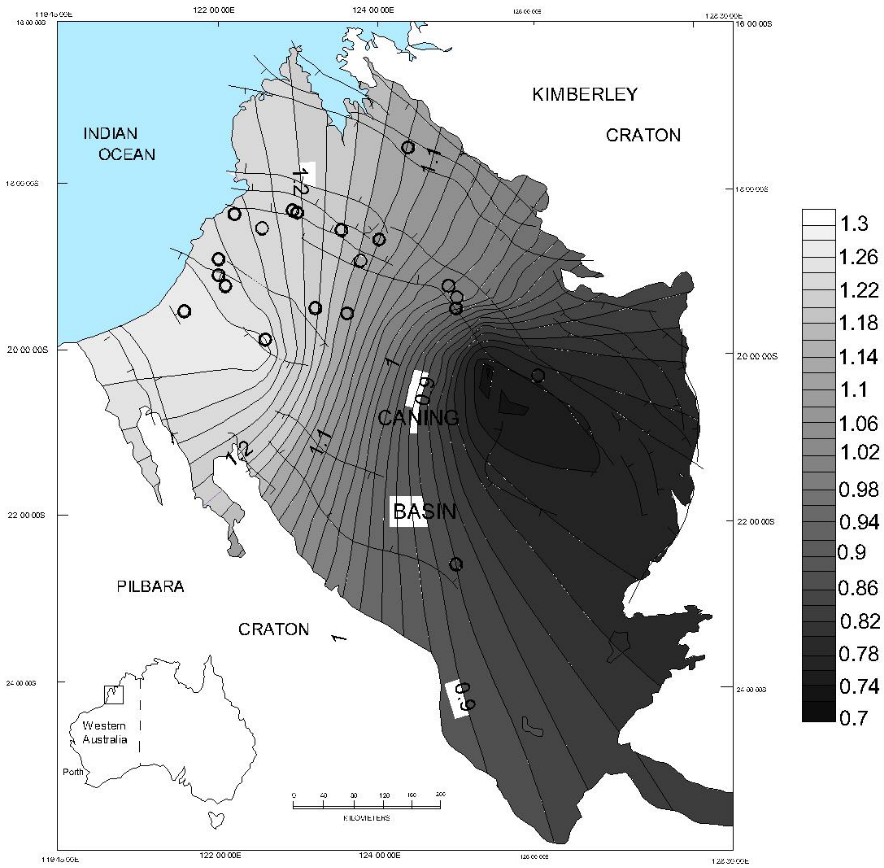
3.2.2 Kerogen type

Kerogen type is one of the important factors in evaluating shale gas potential and hydrocarbon production (Barker, 1996). This information may be estimated using a modified Van Krevelen Diagram, plotting T_{max} versus HI. For an immature source rock, HI for gas prone organic matter is less than 150, gas-oil-prone organic matter is ranged between 150-300 and oil-prone organic matter is more than 300 (Maky and Ramadan, 2008). The HI versus T_{max} graph on a modified Van Krevelen diagram shows for the studied Goldwyer samples that the target shale contains mature to highly mature organic matter, containing mixed kerogen types II–III (Figure 5).

Figure 11 Maturation map based in vitrinite reflectance (values in Ro % equivalent) for the Goldwyer Formation in the Canning Basin (see online version for colours)



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3.2.3 Thermal maturity

Different parameters may be used to evaluate thermal maturity of the analysed samples, such as the measured or estimated vitrinite reflectance (Hunt, 1996) or PI and T_{max} derived, both obtained from Rock-Eval analysis (Maky and Ramadan, 2008). Vitrinite reflectance measurements range from 0.71–1.3% Ro, clearly increasing towards the NW coastal areas (Figure 11) indicating that the analysed shales have entered the oil and even the gas generation windows. PI data show most of the samples in the mature rank (Figure 7) and T_{max} values (Figures 5 and 6) show values above 435ºC and therefore maturation at the Broome Platform and Willara sub-basins.

3.2.4 Generation potential

The GP of the studied samples may be interpreted from (S1 + S2) plotted against TOC (Figure 11). Most of the studied samples have poor to fair GP. These data are also supported by the presence of high content of type III and some type II Kerogen in the studied samples. Therefore, samples in the studied wells are rather gas-prone than oil-prone (Figure 13).

Figure 12 GP of the Goldwyer Formation, based on TOC versus S1 + S2 plotting (see online version for colours)

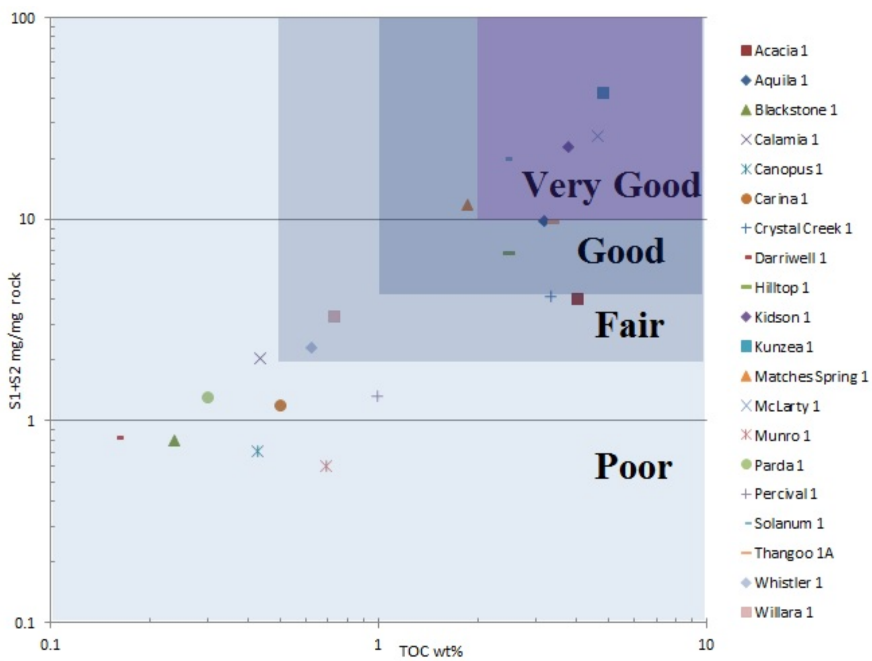


Figure 13 GP of the Goldwyer Formation, based on the S2/S3 proportion (see online version for colours)

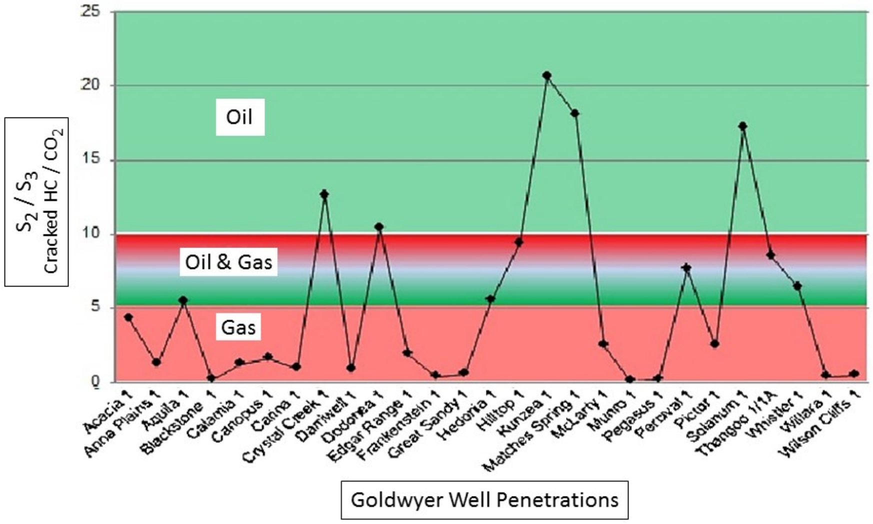


Figure 14 Burial History curve for well Darriwell 1, showing burial story of Goldwyer Formation in this well (see online version for colours)

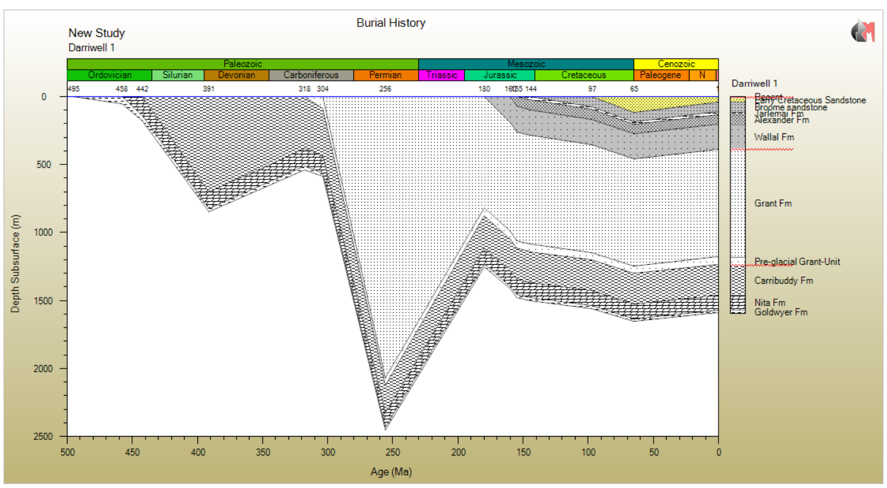
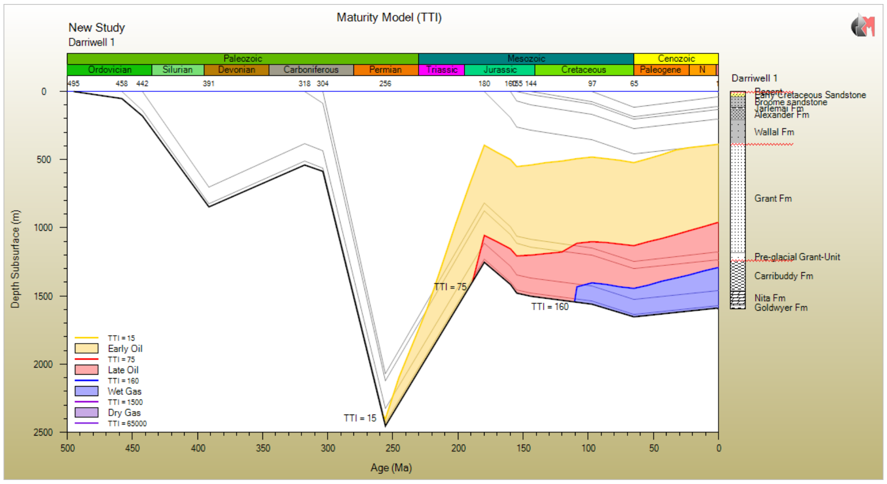


Figure 15 Thermal history of the potential shale gas for well Darriwell 1 in the Canning Basin (see online version for colours)



4 Conclusions

The organic carbon content in 20 wells ranges from 0.16 to 4.8 wt% and in general the studied shale interval can be considered good in terms of organic carbon richness (averages in Table 1). Kunzea 1 and McLarty 1 and Acacia have a very good potential, with TOC values above 4 wt%, while Crystal Creek 1, Hilltop 1 and Kidson 1 have a good potential, with values above 2.5 wt%.

Their HI is mostly less than 150 that reflect gas producing organic matter. Percentage of type II kerogen was determined by the relationship between HI and T_{max} that shows less than 30% of type II kerogen associated with type III kerogen in some samples. Van Krevelen diagram show that some wells such as Pervical 5 and Darriwel 6 reached into gas generation stage and some wells such as Willara 1 reached into oil windows with type III kerogen.

Ro data are promising, as wells such as Willara 1 reached into the gas generation stage, while wells such as Kunzea 1 and Acacia 1 are not mature for gas generation. PI data show that most wells, such as Kidson 1, Matches Sprige 1, McLarty 1, Willara 1 and Darriwell 1 reached into mature to overmature stages, while other wells such as Kunzea 1 are in the immature stage. Based on the maturity profile in the burial history curves, most of the wells are placed in the gas generation window for the target shale.

Geochemical data for the studied wells show that the wells in the west-central part of the Canning Basin, in Willara and Broome sub-basins have a good to very good gas shale potential because they have been buried deeply enough, although some factors such as thickness and organic richness may be negative factors in some wells in these regions.

A general trend shows that maturity increases toward the west central part of the basin. High values of T_{max}, TTI, and Ro in west central part of the Canning Basin show that the target shale is reached into gas generation stage. The results of Rock-Eval analysis associated with TTI, PI and Ro also indicate that west-central part of the

Canning basin reached into the gas window and may therefore be looked as a promising area, regard in shale gas exploration. This study also shows that how interdisciplinary techniques can be used to evaluate shale gas potential in similar basins and tectonic settings.

The most promising area is in NW Caning Basin, corresponding to the Broome Platform and Willara Through. The area with significant maturation extends for around 20.000 square km (Figure 6) and Goldwyer Formation thicknesses are around 500 metres (Figure 9) with TOC average around 2% (Figure 10). However, detailed volume estimations (including net-to-gross, generation rates, etc.) are needed evaluate the potential of this unit as a shale-gas play. Main uncertainties are related to lateral variations in TOC and, whereas exploration risks may be related to the (unknown) petrophysical behaviour of the Goldwyer Shale's layers.

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