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REPORT
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PETROLEUM SOURCE POTENTIAL OF THE ORDOVICIAN NAMBEET FORMATION, CANNING BASIN: EVIDENCE FROM PETROLEUM WELL OLYMPIC 1

by LS Normore and LM Dent

EXPLORATION
INCENTIVE SCHEME

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Cover photograph: DDH1 drilling rig #31 onsite during Olympic 1 drilling operations

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Petroleum source potential of the Ordovician Nambeet Formation, Canning Basin: evidence from petroleum well Olympic 1

by

LS Normore and LM Dent

Abstract

The recently drilled Olympic 1 petroleum well has provided new insights into the petroleum source potential of the Ordovician Nambeet Formation in the Canning Basin. The well cored a 319.53 m section that revealed two distinct organic-rich mudstone intervals in the upper part of the Nambeet Formation. A suite of geochemical analyses confirmed fair to very good source quality, with total organic carbon (TOC) reaching a maximum of 3.28%, and fair to good hydrocarbon generating potential with a maximum S_2 of 5.05 mg HC/g rock.

Although the Ordovician age of the Nambeet Formation precludes the presence of Type III kerogen, preliminary geochemical analysis suggests these potential source intervals do comprise gas-prone, Type II/III marine kerogen. This contradiction between kerogen-type assessments can be influenced by the level of maturity, the environment of deposition, organic richness or matrix mineralogy. Thermal maturity predicted from T_{max} indicates maturity in the oil-generation window. T_{max} and production index (PI) data also indicate significant enrichment of free hydrocarbons (S_1) throughout the cored interval, potentially due to naturally migrated hydrocarbons.

The Nambeet Formation has been identified as a possible source interval in previous work. However, the poor data and limited sampling have provoked little interest. These new data from Olympic 1 provide evidence that the Nambeet Formation holds true potential as a source interval for the Canning Basin. Furthermore, correlation of the two source intervals identified in the Olympic 1 well across the Canning Basin indicates good lateral continuity of this prospective source. Recommended further work includes more detailed characterization of the kerogen types, kinetics measurements to better understand the potential timing of hydrocarbon generation, and additional geochemical sampling on other cored sections of the Nambeet Formation to better understand spatial variations in this source interval.

KEYWORDS: oil window, organic geochemistry, Ordovician, source rock analysis, TOC

Introduction

The pre-Permian Canning Basin is an asymmetric sedimentary basin oriented northwest–southeast in the northern part of Western Australia. The basin has an onshore surface area greater than 430 000 km^2 and contains a sequence of mainly Paleozoic sedimentary rocks more than 10 km thick (Fig. 1). Despite nearly a century of sporadic petroleum exploration, the Canning Basin has relatively insignificant oil and gas production in comparison to the basin's size and apparent petroleum potential (Ghori, 2013). Five distinctive potential petroleum source-rock intervals have been previously identified in the basin from the Ordovician to the Permian (Fig. 2). The Goldwyer and Bongabinni Formations represent two separate petroleum source intervals that formed in the Middle Ordovician during the Larapintine petroleum supersystem L2 (Romine et al., 1994; Kennard et al., 1994a). Larapintine supersystem L3 also has two interpreted petroleum source intervals: the Upper Devonian Gogo Formation and the lower Carboniferous Laurel Formation. A final prospective petroleum source-rock interval in the Canning Basin is the Permian Noonkanbah Formation from the Gondwanan supersystem G1.

Recent drilling of petroleum exploration well Olympic 1 on the central Broome Platform by Buru Energy (May–June 2015) has confirmed the presence of a sixth possible petroleum source-rock interval in the upper Nambeet Formation of the Canning Basin (Fig. 2). Olympic 1 continuously cored Ordovician strata from 1128.00 – 1447.53 m for a total of 319.53 m of 63.5 mm diameter core. The majority of the core was drilled through the Nambeet Formation from 1175.25 – 1447.53 m. The 272.28 m of Nambeet Formation cored during drilling of Olympic 1 equates to an increase of 18% over the pre-existing 1522.80 m of core available for this sedimentary succession for the entire Canning Basin (Fig. 3 and Appendix 1).

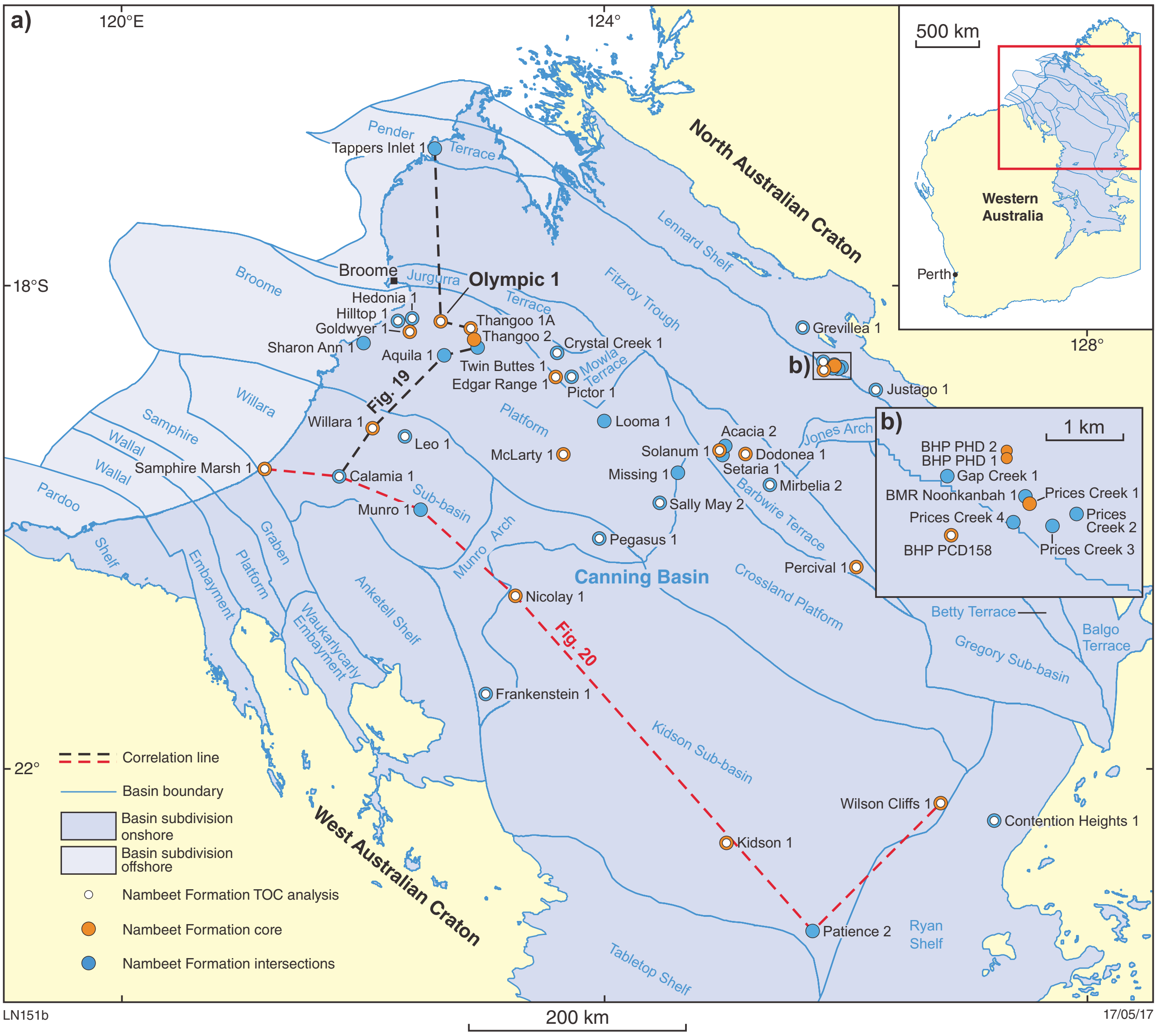

Figure 1. **Tectonic map of the Canning Basin showing the location of petroleum wells that intersected the Nambeet Formation, obtained core in the Nambeet Formation, and where organic geochemistry analysis was undertaken. Inset (b) gives details of closely spaced wells in the northeast Canning Basin**

A total of 158 samples was collected over two mudstone intervals in the upper Nambeet Formation and these were analysed for total organic carbon (TOC; Appendix 2). Where TOC >0.5%, Rock-Eval analysis was completed, resulting in 151 data points. Initial geochemical results indicate a Type II/III, gas-prone petroleum source with fair to good petroleum potential.

Geological setting

The Canning Basin encompasses two main northwest-trending asymmetric troughs separated by a mid-basin high with shelf regions to the north and south. The basin has been divided into more than 20 distinct structural elements (Fig. 1; Hocking, 1994). It is bounded by the Kimberley region to the northeast and the Pilbara Craton to the southwest, and onlaps the Musgrave Province to the southeast. It overlaps the Officer Basin to the southeast and extends into the offshore towards the west where it transitions into the Roebuck and Browse Basins of the North West Shelf. Predominantly Paleozoic sedimentary rocks form the bulk of the Canning Basin onshore, with a thin Mesozoic and Quaternary cover.

This Report focuses on the oldest Paleozoic sedimentary rocks currently known in the Canning Basin, the Lower Ordovician Nambeet Formation. This unit was deposited during initial rifting and associated rapid subsidence during the Samphire Marsh extensional event which lasted 70 Ma, culminating with the Prices Creek movement (Romine et al., 1994). The Nambeet Formation, along with the overlying Willara and Goldwyer Formations, constitutes the preliminary depositional supersequence of the Canning Basin (Romine et al., 1994; Kennard et al., 1994a).

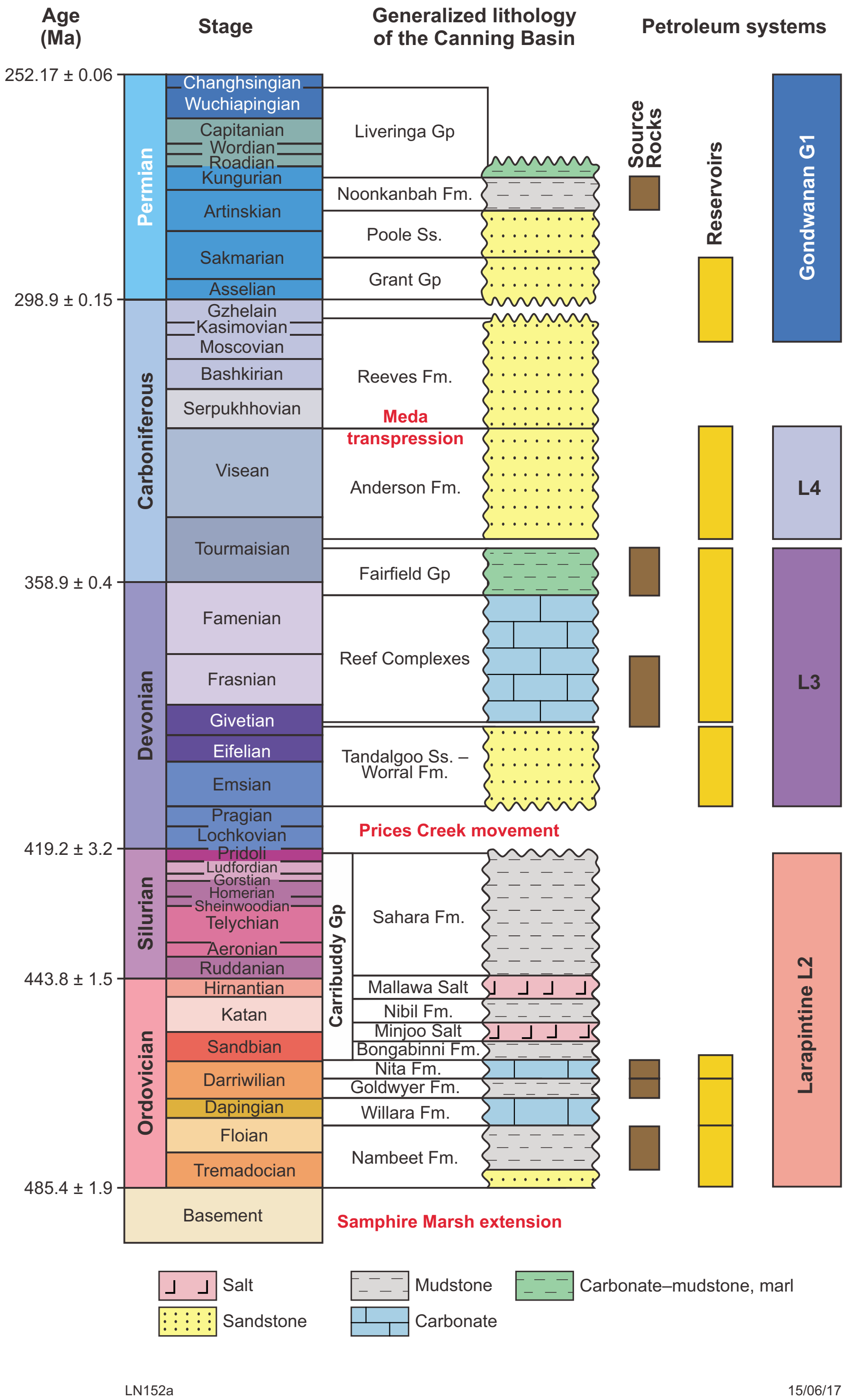

Figure 2. Stratigraphy of the Canning Basin showing the location of the upper Nambeet Formation source interval in relation to the distribution of other source and reservoir rocks and petroleum systems. Modified after Ghori (2013); time scale after International Commission on Stratigraphy (2013)

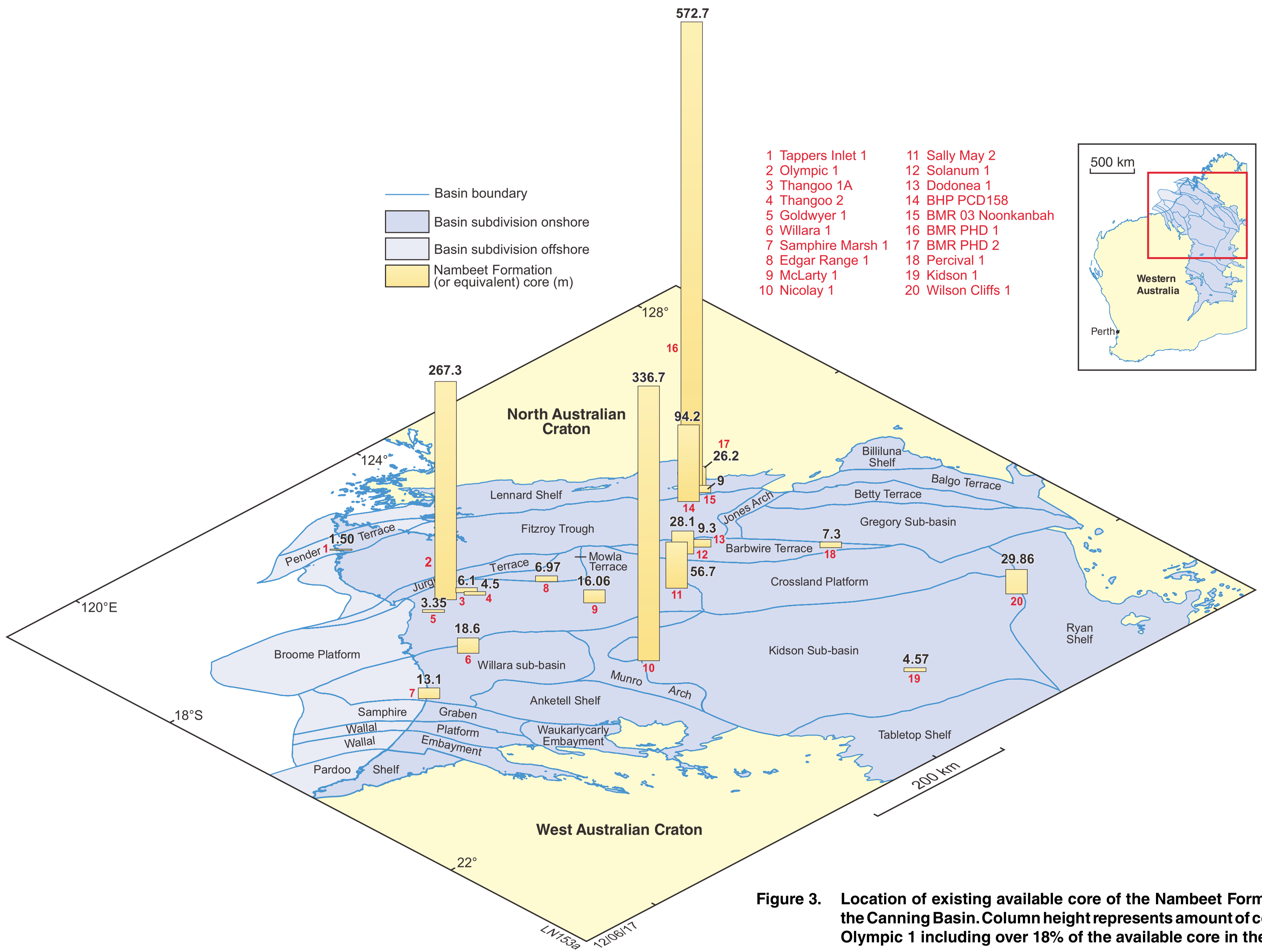

Figure 3. Location of existing available core of the Nambeet Formation in the Canning Basin. Column height represents amount of core, with Olympic 1 including over 18% of the available core in the basin

Nambeet Formation

The Nambeet Formation comprises a unit of dark-grey mudstones with interbedded light-grey carbonates overlying a basal sequence of light-grey to white, fine-grained subarkosic sandstone. Petroleum exploration well Samphire Marsh 1 (Fig. 1) was drilled in 1958 on the southern edge of the Willara Sub-basin (Johnstone, 1961, 1966) and contains the type section of the Nambeet Formation which was named after a nearby water well. Samphire Marsh 1 intersected 775 m of 'Lower Ordovician' sedimentary rocks from 1240 to 2015 m (Johnstone, 1961).

The Nambeet Formation was first informally proposed in 'General notes on the Ordovician Sediments in the Canning Basin' (Johnstone, 1966), a follow-up to the original well completion report (Johnstone, 1961). It was also published in cross-sections to illustrate the regional stratigraphy of the southern Canning Basin by Koop (1966) but not formally defined until Playford et al. (1975) completed a review on the entire basin. Bellis (1987) subdivided the Nambeet Formation on the Broome Platform into a lower sandstone unit and a 40–50 m thick upper shale unit, which makes a good wireline log marker due to the contrasting lithology with the overlying carbonate-dominated Willara Formation. In the type section, the top of the Nambeet Formation is truncated by the basal Grant Group unconformity. In deeper parts of the Canning Basin, the Nambeet Formation is overlain by the Willara, Goldwyer and Nita Formations, in ascending order. The Nambeet Formation represents initial sedimentation in the Canning Basin and unconformably overlies Precambrian granite, gneiss and metasedimentary basement rocks. Correlative intervals include parts of the Prices Creek Group of the Lennard Shelf (Nicoll et al., 1993) and the Wilson Cliffs Sandstone of the eastern Canning Basin (Haines and Wingate, 2007).

The Nambeet Formation has been intersected by 42 petroleum wells (Appendix 1), and has been identified in nine of the Canning Basin structural subdivisions. It has also been intersected in numerous mineral exploration holes in the Lennard Shelf area, three of which have been included in Appendix 1 because available core exists at the Department of Mines and Petroleum (DMP) core library (BHP PHD 001, 002, and PCD 158). The stratigraphic log from Olympic 1 over the cored interval demonstrates the broad subdivision of this formation into an upper unit dominated by mudstone and carbonate, and a lower sandstone-dominated unit (Fig. 4). The lower Nambeet Formation is a very fine- to fine-grained subarkosic sandstone unit with minor calcareous cement, capped by a nodular limestone. The upper Nambeet Formation is a mudstone-dominated interval with two distinct packages where mudstone grades into carbonate. These two mudstone packages comprise two separate potential hydrocarbon source intervals in the upper Nambeet Formation and are hereafter informally referred to as the upper mudstone unit and the lower mudstone unit.

Previous work on source potential of the Nambeet Formation

The hydrocarbon source potential of the mudstones of the upper Nambeet Formation has been briefly discussed in previous literature. Assessments have ranged from potential for oil generation (Taylor, 1992; Kennard et al., 1994a) to limited ability to assess source potential due to the presence of migrated hydrocarbons and drilling contaminants (Edwards et al., 1997). Although the Nambeet Formation has been encountered in 45 wells in the Canning Basin, only 18 of these wells have cored intervals (Fig. 3 and Appendix 1). Extensive mineral exploration on the Lennard Shelf drilling for Mississippi-valley type lead–zinc deposits has resulted in numerous intersections through the Prices Creek Group. This is outside the scope of this study but is acknowledged for future studies.

A study of Ordovician source rocks by the Bureau of Mineral Resources (now Geoscience Australia) indicated that three potential source intervals were encountered in the Ordovician sequence of the Canning Basin: Nambeet Formation (five wells), lower Goldwyer Formation, and upper Goldwyer Formation (Taylor, 1992). Analysis results from that report are included in Appendix 2, which also lists all currently available open-file TOC and Rock-Eval data from the Nambeet Formation, including more recent data from Olympic 1. TOC was measured in 30 petroleum wells and Rock-Eval data were available from 20 wells. The dataset of 279 samples is plotted in Figure 5 using standard industry parameter cut-offs to determine source potential (TOC ≥0.5% and S_2 ≥2 mg HC/g rock; Fig. 5).

More than 75% of samples taken from the Nambeet Formation across the basin prior to Olympic 1 were identified as having no source potential based on TOC alone (Fig. 5a). Those samples that identified hydrocarbon source potential, ranged from fair (0.5 – 1% TOC) to very good, with the best result of 2.06% TOC from a cuttings sample at 2650–2600 m in petroleum exploration well Tappers Inlet 1. While many samples had fair to good TOC content (Fig. 5a) only one sample had a suitable S_2 value to be classified as having hydrocarbon source potential (Fig. 5b). This sample had an S_2 value of 3.68 mg HC/g rock and was recovered from the mineral exploration well BHP PCD158 at 114 m. It should be noted that geochemical results have been deemed unreliable in some petroleum exploration wells in the past (Kidson 1, Matches Spring 1, McLarty 1 and Wilson Cliffs 1) due to contamination during drilling (Kennard et al., 1994b). Sample contamination was identified based on re-analysis of washed cuttings samples and the 'whole oil' extract gas chromatogram that gave results characteristic of fractionated crude oil.

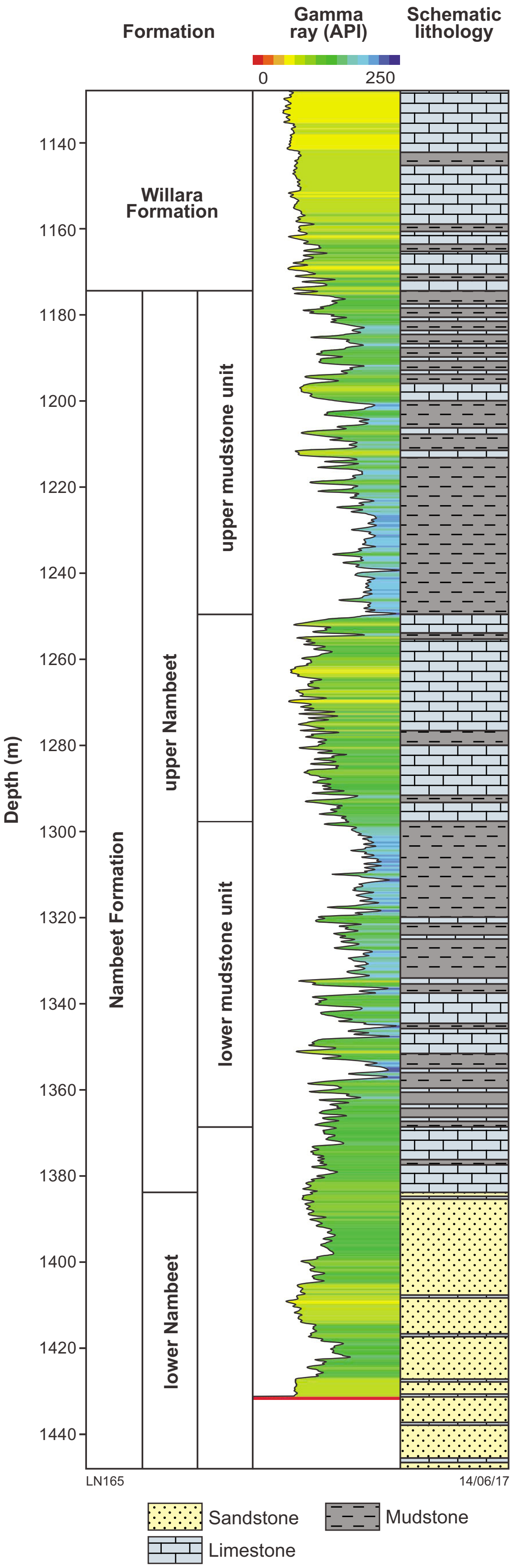

Figure 4. Stratigraphy of core (1128.0 – 1447.2 m) taken through the Willara and Nambeet Formations, Olympic 1, showing coloured gamma ray log and schematic lithology

During compilation of this Report, another possible source interval has been identified in strata interpreted as basement rocks (Fig. 6) to the Canning Basin. Appendix 3 lists TOC results for 21 samples of basement rock in six petroleum wells, of which a sample from 1935 m in Edgar Range 1 has the highest TOC value at 2.39%. Only four samples had Rock-Eval results, none of which indicates source potential based on S_2 values. These rocks are probably over mature for petroleum generation and may be weakly metamorphosed.

Olympic 1 results: petroleum source-rock parameters

Source quantity

To define the amount of organic matter in the upper Nambeet Formation in Olympic 1, 158 samples were analysed for TOC (Fig. 7a). TOC samples were acid digested in preparation for analysis on filtered crucibles, using a LECO Carbon/Sulphur Analyser. A total of 151 (96%) of these samples measured over 0.5% TOC (Fig. 7a) and these were analysed for Rock-Eval pyrolysis (Fig. 7b). The TOC and Rock-Eval results are included in Appendix 2 and the Rock-Eval pyrograms are given in Appendix 4. The results for TOC and Rock-Eval from Olympic 1 are also displayed as a geochemical log (Fig. 8).

Based on TOC alone, the organic richness or amount of kerogen (Jarvie, 1991) for the Nambeet Formation in Olympic 1 plots primarily in the petroleum source zone (Fig. 7a). More than one-third of these samples (56 of 158) classify as fair on the TOC organic richness scale, measuring between 0.5 and 1% TOC. Over 40% of the samples rank as good in the 1–2% range (68 of 158), and 17% are in the very good TOC range 2–4% (27 of 158). The highest TOC measured in the upper Nambeet Formation in Olympic 1 was 3.28% at 1337.54 m (GSWA sample 221829).

The hydrocarbon generating potential of the Nambeet Formation in Olympic 1, as measured by Rock-Eval pyrolysis and expressed as S_2 (Espitalié et al., 1985; Peters, 1986; Bordenave et al., 1993), is shown in Figure 7b. A total of 60% of the samples analysed by Rock-Eval for the upper Nambeet Formation of Olympic 1 (91 of 151) are ranked as poor or non-source, based on S_2 values less than 2 mg HC/g rock. This demonstrates the difficulties of source-rock evaluation using TOC values alone. Nearly 40% of the remaining samples analysed (59 of 151) fall into the fair hydrocarbon generating potential S_2 range of 2–5 mg HC/g rock. One sample measured 5.05 mg HC/g rock at 1316.45 m (GSWA sample 221438) and classifies as having good hydrocarbon source potential, defined as S_2 = 5–10 mg HC/g rock. For the crossplots that follow, the focus is on source rocks as defined by the 'source quantity' parameters of TOC >0.5% and S_2 >2 mg HC/g rock.

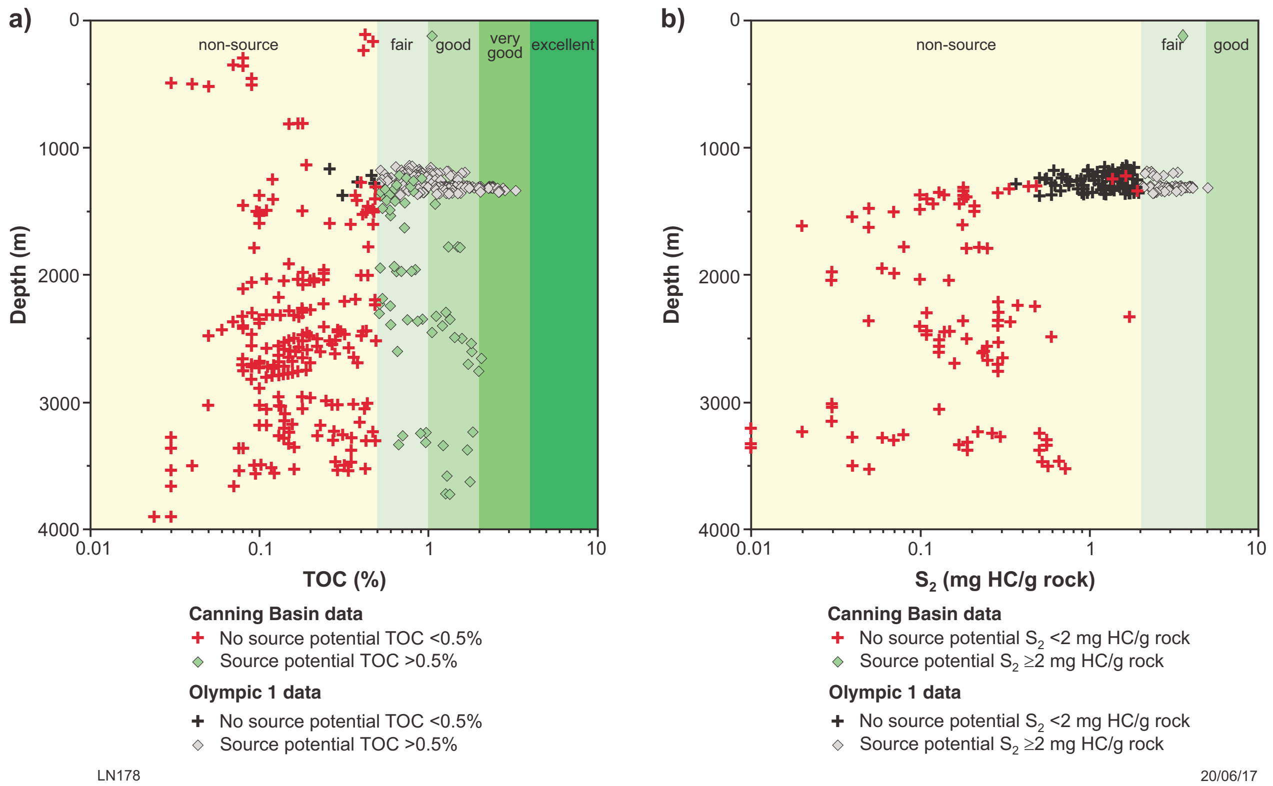

Figure 5. **Crossplots of all available open-file well data from the Nambeet Formation in the Canning Basin: a) TOC with depth; b) S_2 with depth. Samples with petroleum source potential are determined as those with TOC ≥0.5% and S_2 ≥2 mg HC/g rock. These crossplots highlight the assessment of poor source potential for the Nambeet Formation based on previous analysis results prior to drilling Olympic 1**

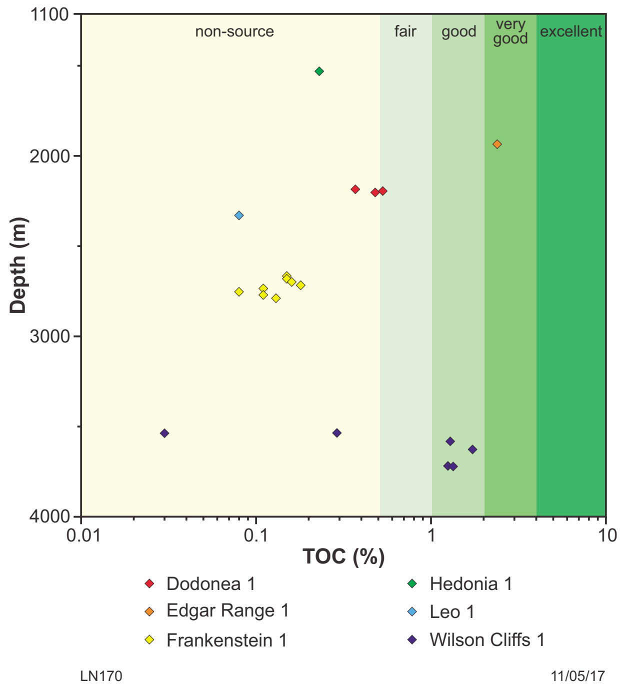

Figure 6. **Crossplots of TOC with depth for all available open-file geochemical data from basement rocks in the Canning Basin. Samples with petroleum source potential are determined as those with TOC ≥0.5%. This crossplot highlights the fair source potential of the basement rocks based on previous analysis results**

Thermal maturity

The method used for detailed thermal maturity determination of Olympic 1 source-rock samples is given in Dent and Normore (2017). This study focuses on the Rock-Eval pyrolysis parameters, temperature maximum (T_{max}) and production index (PI) for thermal maturity estimates. When all T_{max} data for Olympic 1 are plotted versus depth, the expected trend of increasing T_{max} with depth is not observed (Fig. 9). Typically, T_{max} values will increase with depth reflecting an increase in thermal maturity downhole due to the Earth's geothermal gradient. This lack of trend with depth combined with such high variations in the T_{max} value, suggests that a portion of the data is unreliable as a thermal maturity indicator.

The level of free hydrocarbons (S_1) present can have a major influence on the T_{max} values recorded. Enrichment in S_1 leads to an increase in PI which translates to a suppression of T_{max} values. If S_1 is depleted then T_{max} will be anomalously high. To determine if S_1 is enriched or depleted in these samples, PI was plotted against T_{max} (Fig. 10). Analysis results that diverge from the normal maturity trend could indicate alteration caused either by naturally migrated hydrocarbons or other factors such as oil-based contaminants added during the drilling process.

A normal maturity trend with a 10°C range was plotted onto a T_{max} and PI crossplot. The data from Olympic 1 indicate the majority of the samples fall in the S_1 enrichment zone.

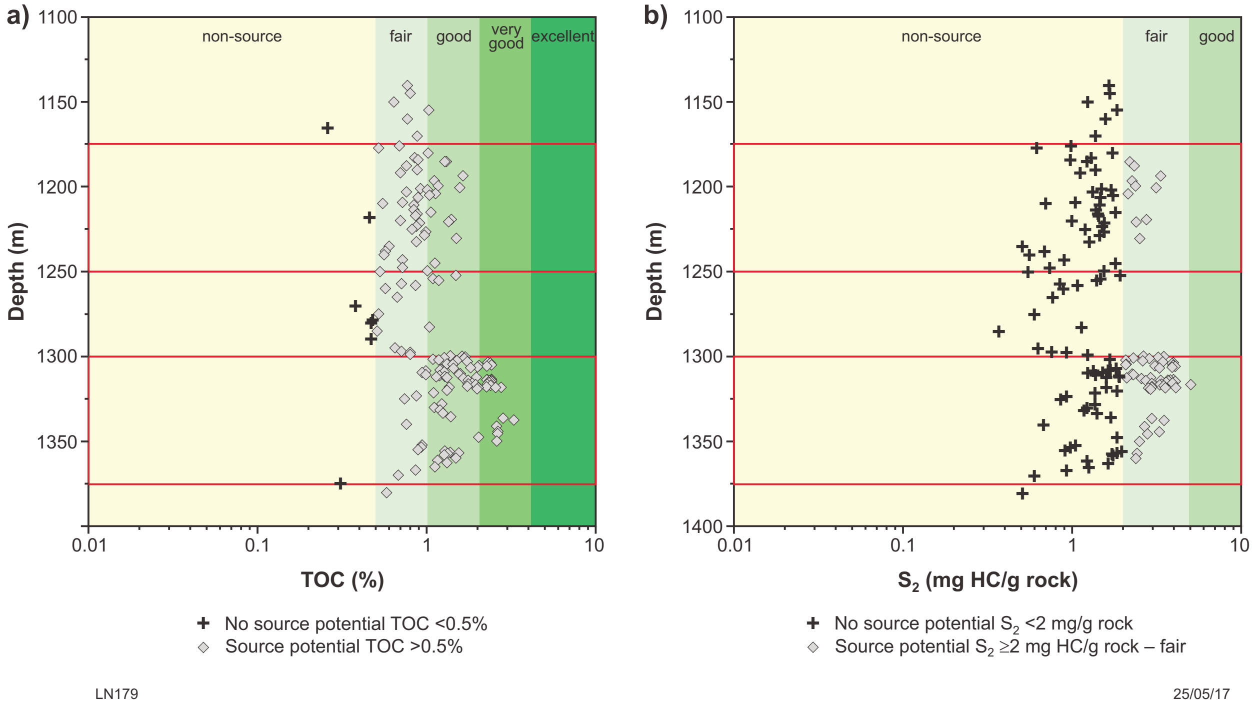

Figure 7. **Crossplot of TOC and S_2 against depth, Olympic 1. Discrimination between source and non-source samples from core samples in petroleum well Olympic 1. Red frames mark source intervals: a) total organic carbon (TOC) greater than 0.5% is considered potential source rock; b) Rock-Eval pyrolysis S_2 peak is equivalent to remaining petroleum potential and is considered a potential source rock with values greater than 2 mg HC/g rock. Note the higher source-rock potential in the lower mudstone unit (1300–1365 m) compared to the upper mudstone unit (1180–1250 m), based on both TOC and Rock-Eval pyrolysis**

Reliable samples are those located between the normal maturity trend lines (shaded box in Fig. 10). When all samples identified as 'altered' (either depleted or enriched in S_1) were removed and the remaining reliable points replotted on depth vs T_{max} (Fig. 11a) and depth vs PI (Fig. 11b) crossplots, most of the scatter (greyed out data points) was eliminated from the data. A trend emerges of a slight increase in both T_{max} and PI with depth; T_{max} for the selected subset of data ranges from 440–448°C and PI ranges from 0.17 – 0.25. For both parameters, the selected data plot within the oil-generative window.

Water-based drilling mud was used during the drilling of Olympic 1, and core rather than cuttings was recovered; these factors indicate that enrichment of free hydrocarbons is the result of natural hydrocarbon migration from a nearby petroleum source rock or in situ generation. Small hydrocarbon shows and bleeds of oil observed in the cored section indicate that generated hydrocarbons are present in some sections.

Source quality

Van Krevelen diagrams of the Rock-Eval results were created to define the kerogen types present in the Nambeet Formation (Stach et al., 1982; Van Krevelen, 1993). A crossplot of hydrogen index (HI) and oxygen index (OI) data from Olympic 1 does not clearly identify kerogen source type, which falls within either Type I or Type II kerogen (Fig. 12). However, there is a systematic decrease in HI and OI between the upper and lower mudstone units, and this is indicative of increasing thermal maturity with depth. Plotting HI versus T_{max} results in a spread of data over both Type II and Type III kerogens (Fig. 13). This represents the geochemical expression of kerogen type rather than the palynological kerogen type, as these Ordovician source rocks should not have a Type III kerogen which is produced from the humic components of higher plants (Tissot and Welte, 1978). Other factors such as maturity and levels of oxidation or environment of deposition can alter the geochemical signature of kerogen type.

To determine what primary petroleum product will be generated, the quality (HI) was plotted versus the quantity (TOC) (Fig. 14). This indicates that most samples are gas prone. Samples from the upper mudstone unit plot as lean to fair gas-prone source potential; whereas, the lower mudstone unit includes samples that plot as fair to rich gas-prone source potential.

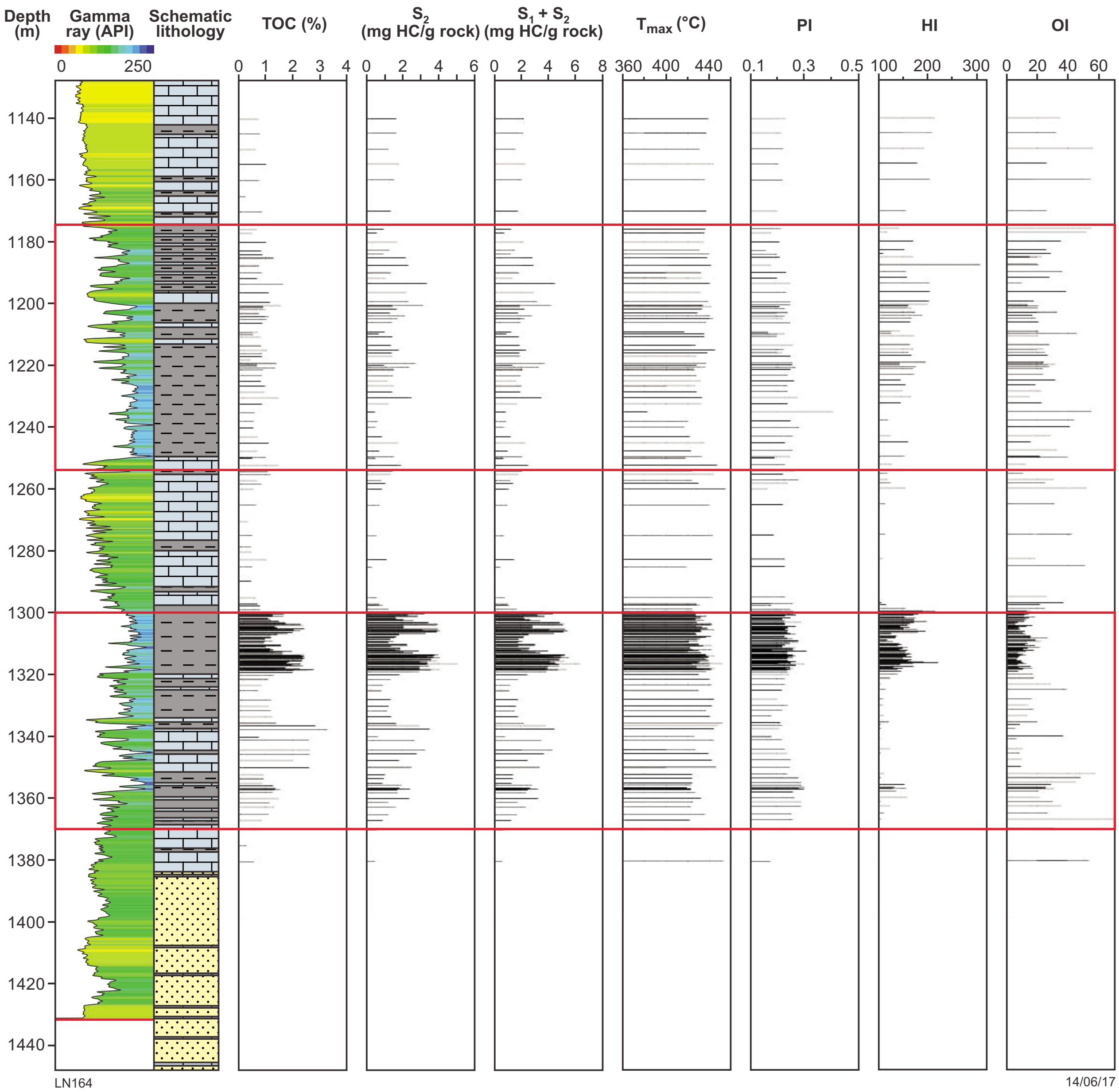

Figure 8. Composite log of organic geochemistry. TOC and Rock-Eval pyrolysis data from core samples in petroleum well Olympic 1. Red frames mark source intervals

Discussion

Two potential source intervals in the upper Nambeet Formation

The upper and lower mudstone units in the upper Nambeet Formation correlate with two potential source-rock intervals that can be readily identified in the core. Figure 15 shows a representative core tray from each mudstone unit with the development of carbonate horizons and concretions clearly visible in the lower unit (Fig. 15b). Unaltered source-rock samples are located at the following depths in Olympic 1 (Fig. 16): a lower source from 1300–1355 m (rectangle A in Figure 16) and an upper source from 1180–1220 m (rectangle B in Figure 16). Data from the lower source (A) average higher TOC values than the upper source (B) (Figs 7, 16).

The mudstones of the upper Nambeet Formation were deposited prior to the development of land plants; therefore, the organic matter would normally be restricted to Type I or Type II kerogen, based on the kerogen classification scheme of Tissot and Welte (1978). Previously, kerogen type for Ordovician sedimentary rocks (including the Nambeet Formation) in the Canning was interpreted as Type I (Taylor, 1992), based on assuming a comparable source to the *Gloeocapsomorpha prisca* source in the upper Goldwyer Formation.

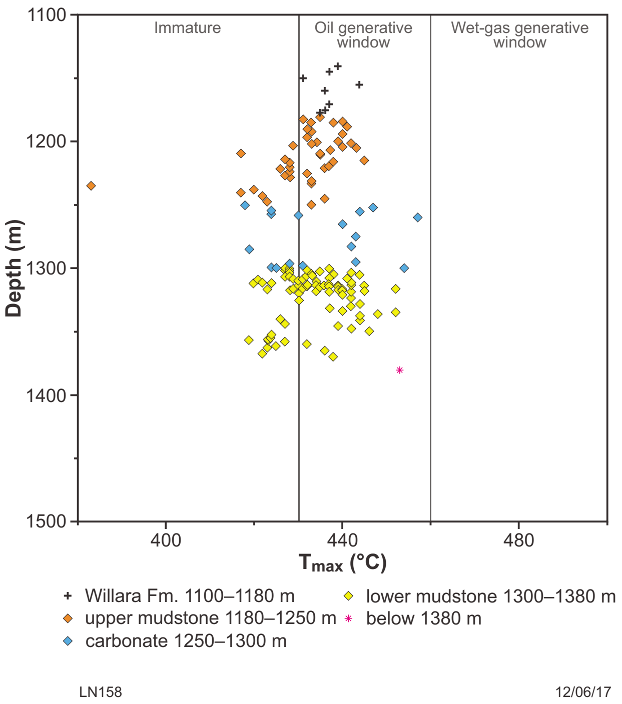

Figure 9. Crossplot of depth vs T_{max} for Olympic 1. This plot shows the maturity for hydrocarbon generation of all samples taken from the Nambeet Formation in Olympic 1. Samples are either immature or are classified as mature for oil generation. The expected trend of increasing maturity with depth is not seen in this dataset

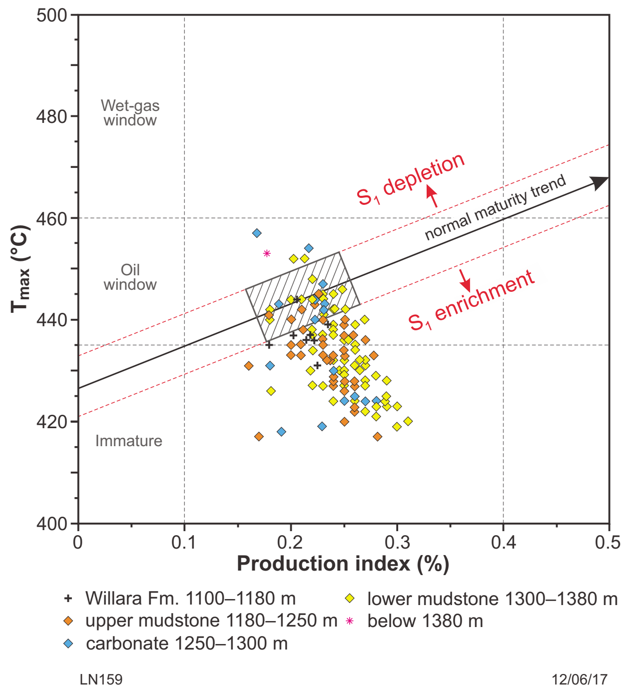

Figure 10. Crossplot of T_{max} vs PI for Olympic 1. This plot highlights which samples from the Nambeet Formation in Olympic 1 were altered due to migration of free hydrocarbons. The shaded box defines the samples that are not enriched or depleted with regard to S_1

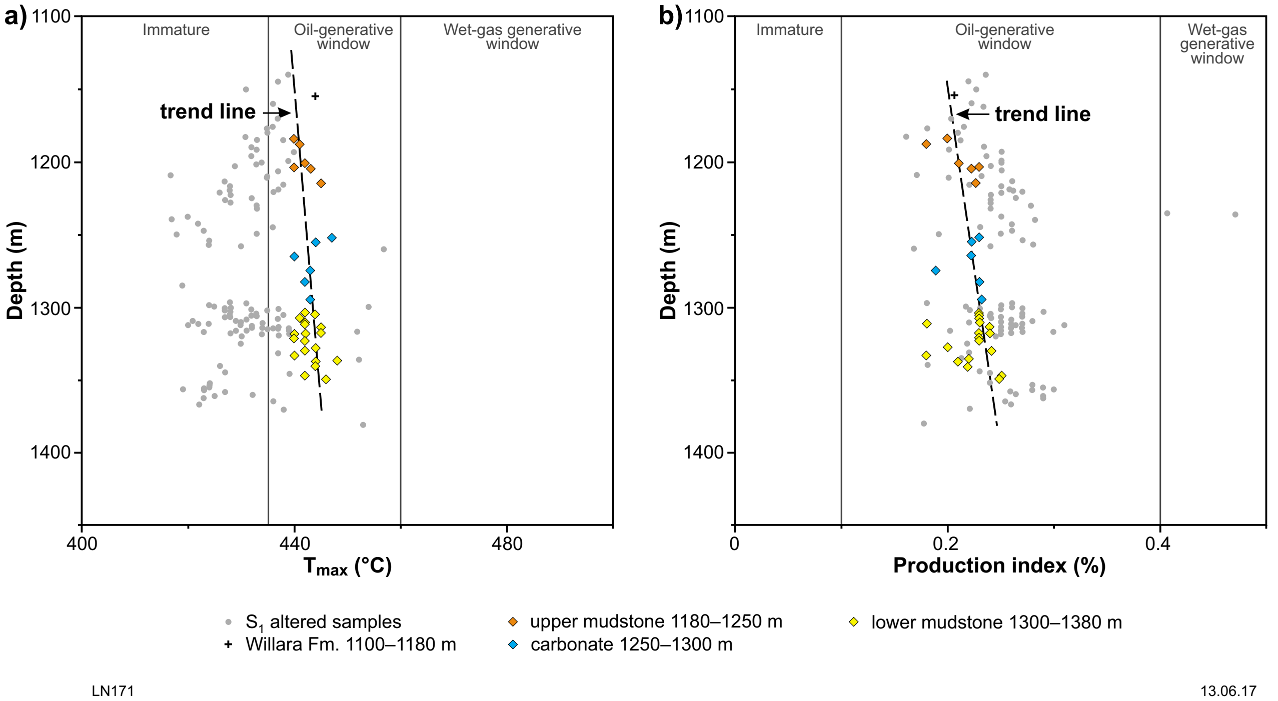

Figure 11. Crossplots of depth vs T_{max} and PI for unaltered samples from Olympic 1: a) depth vs T_{max}; b) depth vs PI. Altered samples (grey data points) as defined in Figure 10 are not considered for interpreting trends in the data. Both plots show a trend of increasing maturity with depth and unaltered samples plot within the oil window

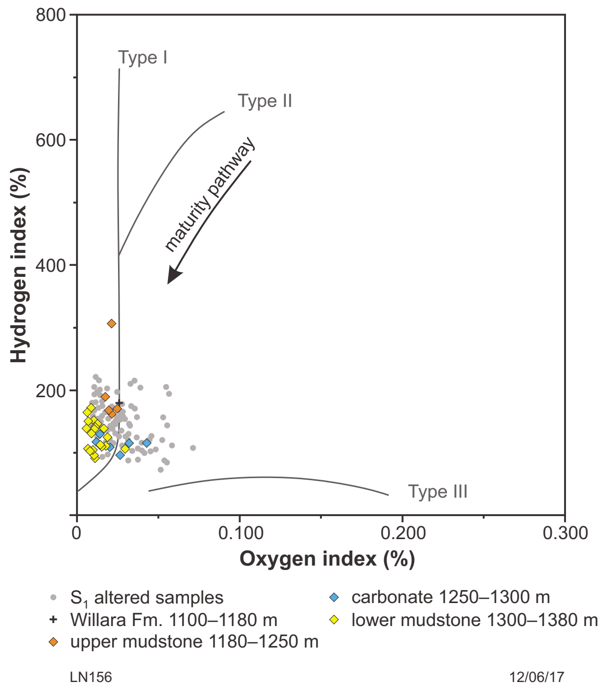

Figure 12. Crossplot of HI vs OI (van Krevelan diagram) for Olympic 1 to determine kerogen type based on Rock-Eval data

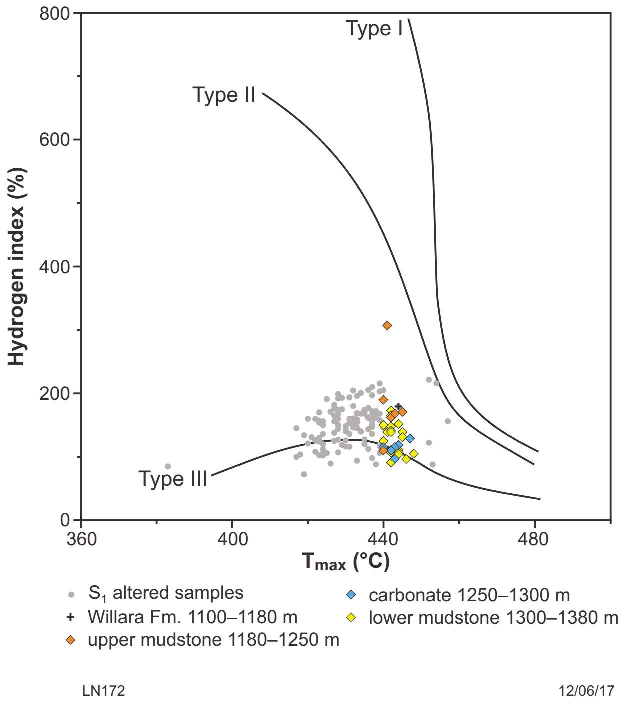

Figure 13. Crossplot of HI vs T_{max} for Olympic 1. Kerogen type straddles the boundary of Type II and Type III kerogens for the Nambeet Formation source rocks

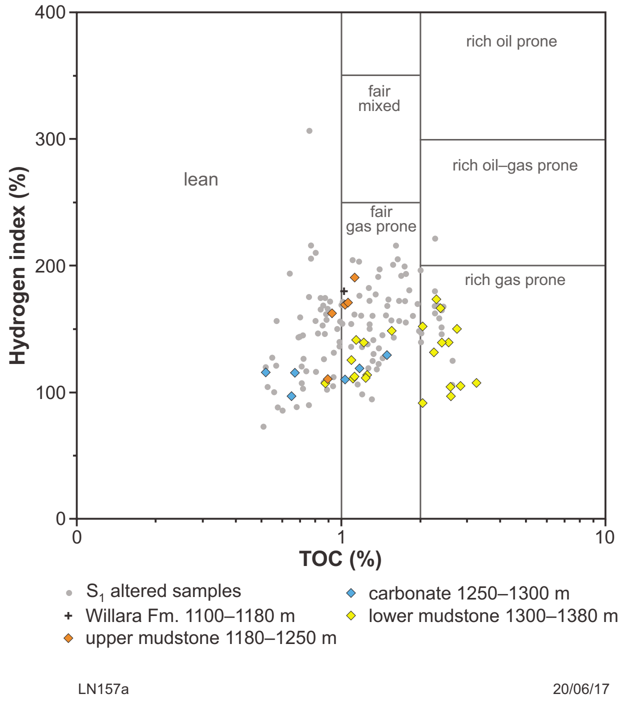

Figure 14. Crossplot of HI vs TOC for Olympic 1. This crossplot classifies the petroleum source-rock quality for each sample, showing the Nambeet Formation source rocks are gas prone. The lower mudstone unit includes rich gas-prone samples; the upper mudstone samples are lean to fair gas prone

By comparison, Kennard et al. (1994b) indicated a mixture of Type I and Type II kerogens for the Nambeet Formation mudstones, assuming a correlation with the lower Goldwyer Formation. Despite the previous determinations, Rock-Eval data from Olympic 1 indicate kerogen in the upper Nambeet Formation is Type II/III. Combining the results from HI vs OI (Fig. 12), HI vs T_{max} (Fig. 13) and HI vs TOC (Fig.14) classifies the organic matter from this interval as a gas-prone Type II/III source, originating from plankton or bacteria in a marine environment.

Although Kennard et al. (1994a,b) suggested the original source richness and kerogen types within Ordovician source intervals have significant spatial and temporal variability, they did not provide kinetic data for this source interval. Misleading kerogen-type assessment can also be affected by the level of organic enrichment and matrix mineralogy (Katz, 1983). Accurate determination of kerogen type would benefit from kinetic kerogen and biomarker analysis from a variety of maturity ranges across the Canning Basin.

Hydrocarbon yield in the upper Nambeet Formation

Previous studies have disagreed on the generation and expulsion of hydrocarbons from the upper Nambeet Formation throughout the Canning Basin. Taylor (1992) suggested the Nambeet Formation, grouped with the

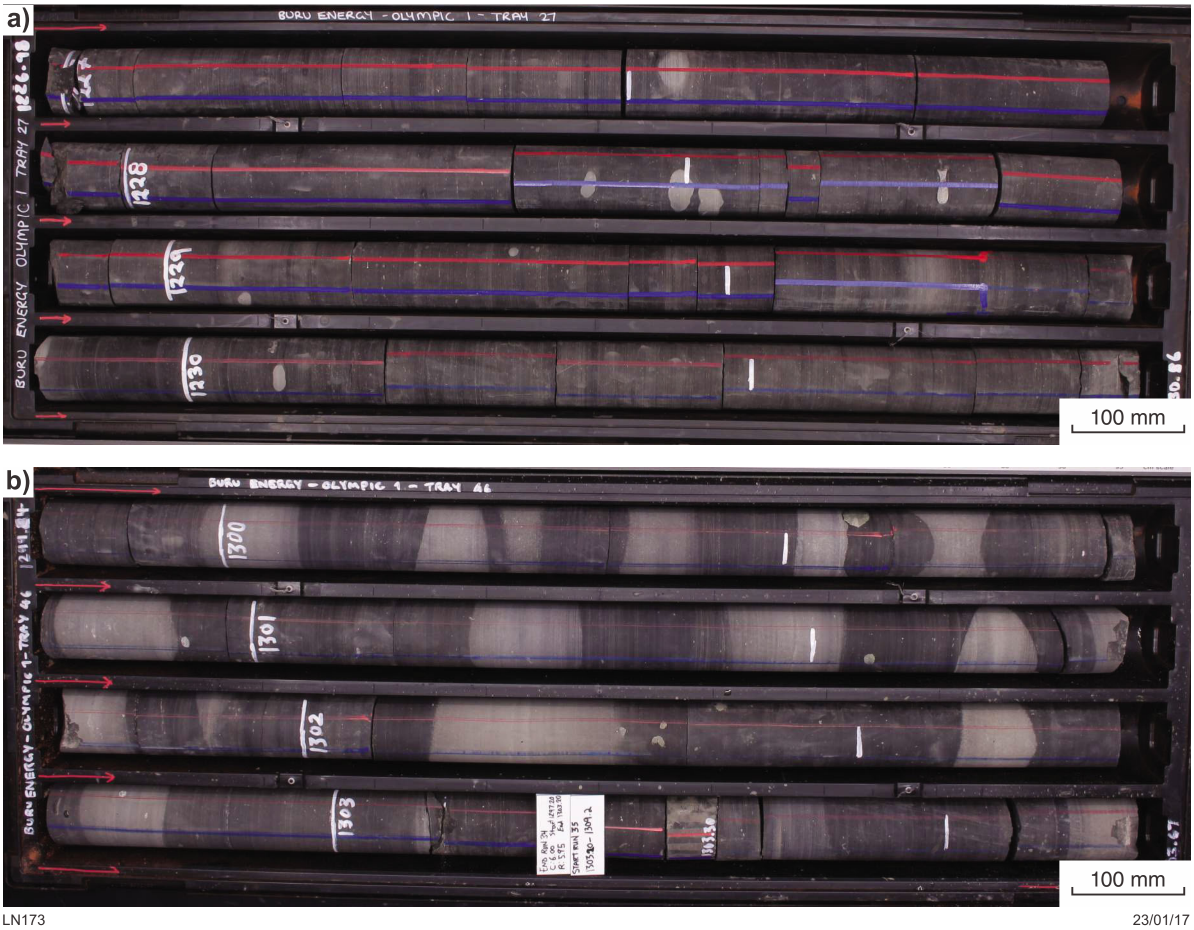

Figure 15. Examples of core from the upper Nambeet Formation: a) core from upper mudstone interval; tray 27 1226.98 – 1230.86 m; b) core from lower mudstone interval; tray 46 1299.84 – 1303.67 m

lower Goldwyer Formation, had the potential to generate large volumes of oil on the Broome Platform during the Ordovician–Silurian depositional cycle. Kennard et al. (1994b), on the other hand, proposed that the upper Nambeet Formation was immature on the Broome Platform, and hydrocarbon generation and expulsion was limited to the Jurgurra and Barbwire Terrace, and the northern Fitzroy Trough.

Suppression of the Rock-Eval pyrolysis yields of Ordovician source rocks in the Canning Basin has been previously observed (Kennard et al., 1994b). The adsorption of heavy hydrocarbons on active mineral sites, or 'mineral matrix effects', has been determined by plotting S_2 against TOC on all Rock-Eval data reported in Kennard et al. (1994b). Trend lines that pass through the zero intercept do not have mineral matrix effects. If the trend line intersects TOC >0, HI values are suppressed due to mineral matrix effects. By contrast, the best-fit trend line from Olympic 1 data of S_2 vs TOC indicates a slight HI enhancement. Calculation of the slope of the linear trend line allows for an HI correction to be applied, which equates to an average HI of 115 mg HC/g TOC for the Olympic 1 dataset (Fig. 17). The HI correction assumes constant organic-matter type (Kennard et al., 1994b).

Plotting corrected S_2 vs TOC% can also provide an indication of hydrocarbon yield for a petroleum source interval. When data from Olympic 1 are plotted on a logarithmic scale of S_2 vs TOC%, samples fall in the negligible to fair yield ranges of 0.1 – 4 mg HC/g rock (Fig. 18). Only samples from the lower source interval plot in the fair range. An S_2 value of 3 mg HC/g rock is the indicative hydrocarbon expulsion threshold. This is the initial amount of hydrocarbon required to saturate source-rock pore space. Only three unaltered samples from the lower mudstone interval, corrected for S_2 enrichment, are found above this threshold (Fig. 18). A more detailed study is required to determine the variability of hydrocarbon expulsion in the Nambeet Formation.

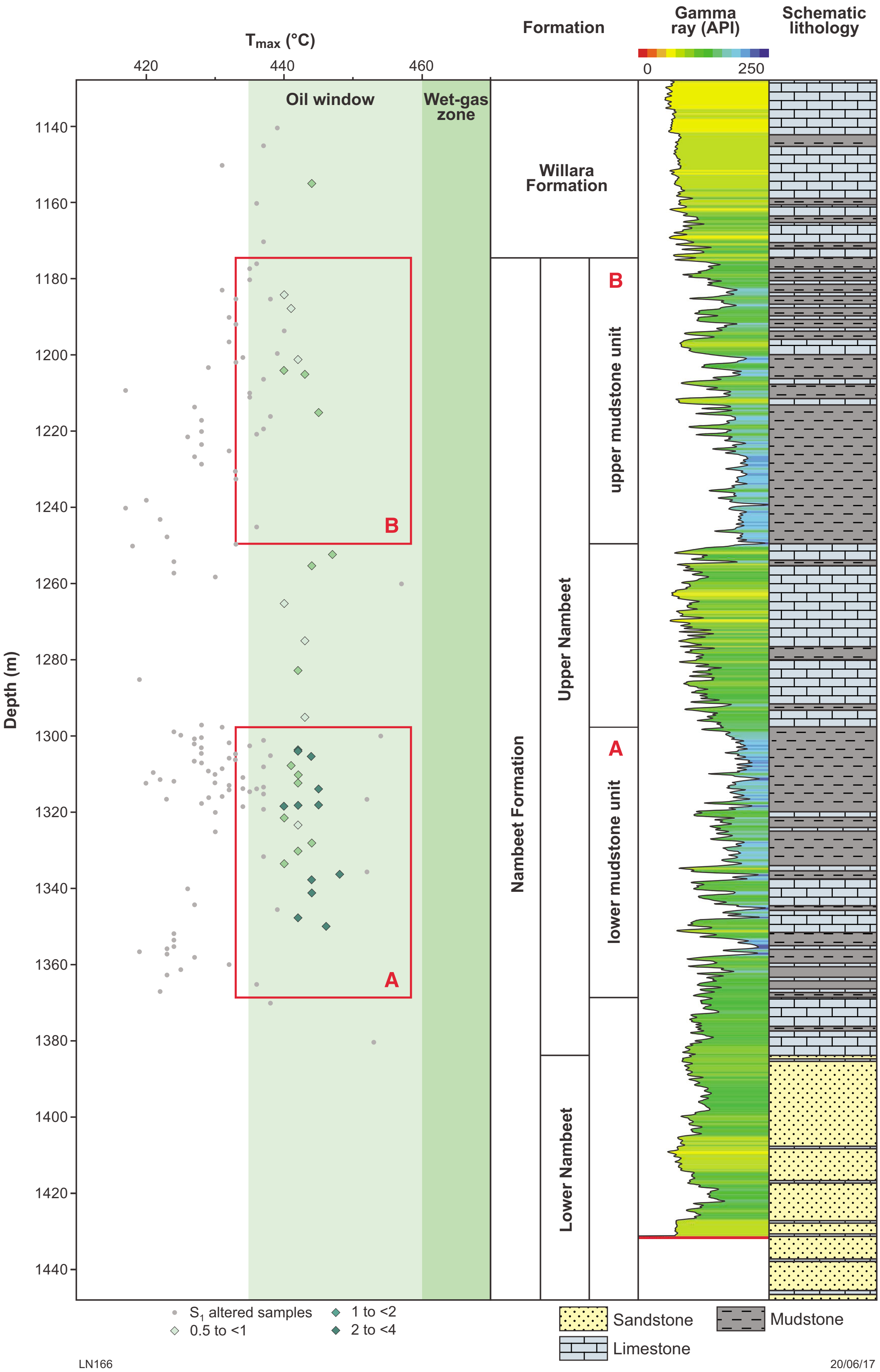

Figure 16. Source-rock intervals compared with gamma ray log and lithology in Olympic 1. Two potential source zones can be identified, indicated by boxes A and B. These two zones correlate with two regionally extensive mudstone units that are evident in well logs and core from Olympic 1. TOC in the depth range 1175.25 – 1220 m is on average 0.5 – 2%. From 1300 to 1355 m, TOC values of 2–3% are common

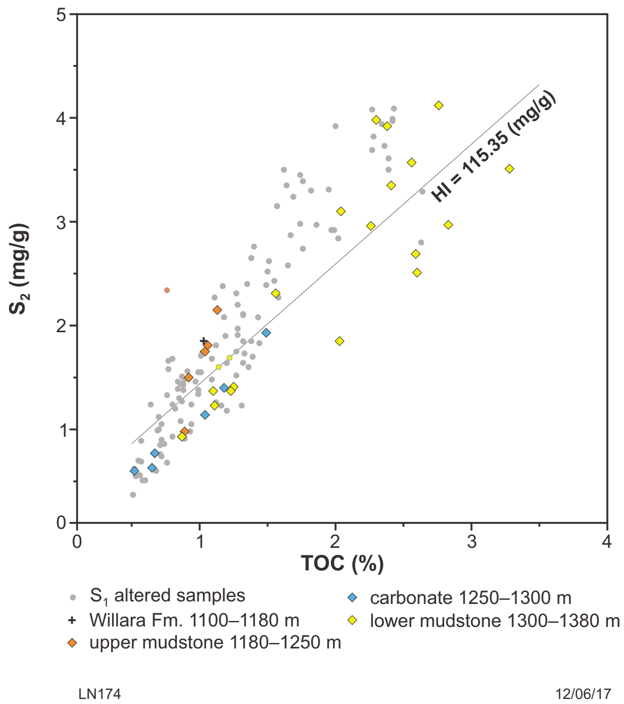

Figure 17. Crossplot of S_2 versus TOC to define mineral matrix effects and the amount by which HI supresses enrichment. The trend line for this crossplot indicates HI average value is slightly enriched

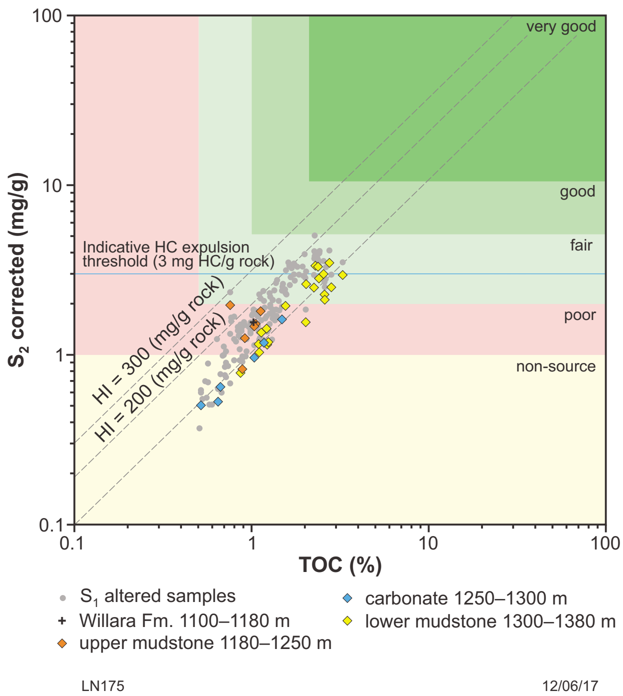

Figure 18. Crossplot of S_2 (corrected) vs TOC for Olympic 1 samples compared to an indicative hydrocarbon expulsion threshold (3 mg/g rock). S_2 correction is based on the HI average enrichment calculated from Figure 17. This crossplot indicates that the upper zone has poor generating potential while the lower zone ranges from negligible to fair generating potential

Regional extent of upper Nambeet Formation

Two correlation sections across the Canning Basin were created to illustrate the extent of the two source-rock intervals within the upper Nambeet Formation. The first correlation includes wells across the width of the Willara Sub-basin, Broome Platform and Fitzroy Trough from Calamia 1 in the southwest to Tappers Inlet 1 on the Pender Terrace in the northeast (Fig. 19). This demonstrates the widespread distribution of both mudstone intervals in the upper Nambeet Formation for over 300 km, with the thickest accumulation of mudstones seen in Willara 1 on the northern side of the Willara Sub-basin. The second correlation is subparallel to the axis of the southern Canning Basin along the length of the Willara Sub-basin into the Kidson Sub-basin, starting with the original type section, Samphire Marsh 1, in the northwest and ending in the southeast at Wilson Cliffs 1 (Fig. 20). These correlations highlight the anomalous thickness of the upper Nambeet Formation at the type section and the regional areal distribution of the mudstone interval almost 600 km from the middle of the Willara Sub-basin, thinning towards the southern end of the Kidson Sub-basin.

Future work

With geochemical results confirming the petroleum source potential of the upper Nambeet Formation in Olympic 1, a systematic review and further analysis should be conducted on existing Nambeet Formation samples from other wells. The depth of the potential source intervals in all Nambeet Formation petroleum wells should be first determined using correlation of available wireline logs.

A regional estimation of TOC from wireline logs should be undertaken using techniques such as the Schmoker or Passey methods (Schmoker, 1981; Passey et al., 1990), using Olympic 1 as a baseline due to the large dataset of TOC analysis. TOC estimation from wireline models can also be followed up by resampling of available core and cuttings. Although better analytical techniques have evolved over time, sample degradation and drilling-induced contaminants may be an issue with older samples.

The fact that this source interval was deposited prior to the evolution of land plants may be the reason there is a variety of interpretations available for these kerogen types. A detailed assessment of kerogen types is required by analysing maceral composition, pyrolysis-gas chromatography (Py-GC), extraction of organic matter (EOM), gas chromatography mass spectrometry (GC-MS) and kerogen kinetics. These analyses will not only identify organic facies but help with oil-to-oil and oil-to-source correlations.

Limited sample spacing throughout the Nambeet Formation may be one explanation for perceived variations in original source richness and kerogen type. Additional analysis such as GC-MS, isotopes and diamonoid biomarkers combined with thermal maturity modelling may help to understand regional source potential beyond the Olympic 1 well.

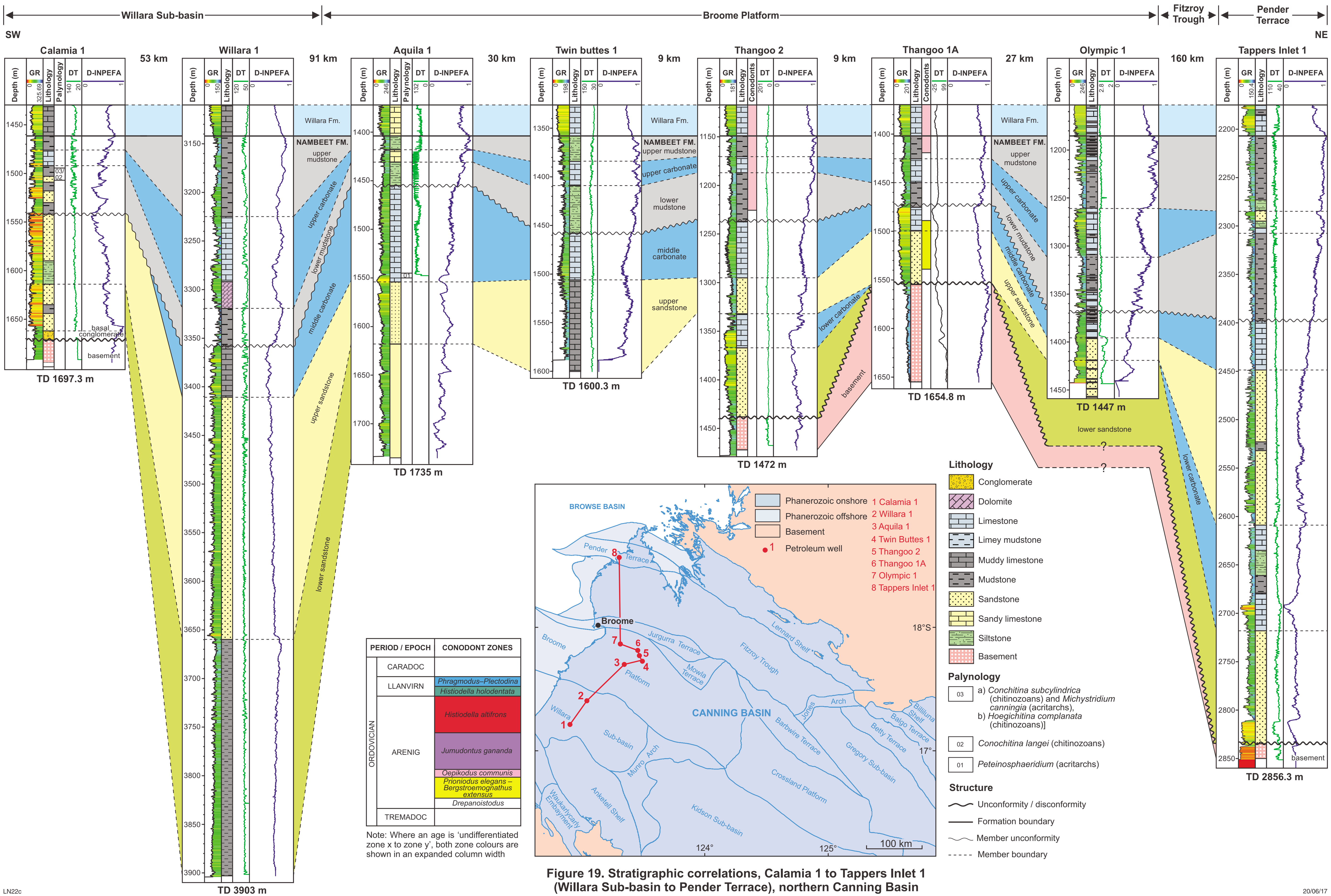

Figure 19. Stratigraphic correlations, Calamia 1 to Tappers Inlet 1 (Willara Sub-basin to Pender Terrace), northern Canning Basin

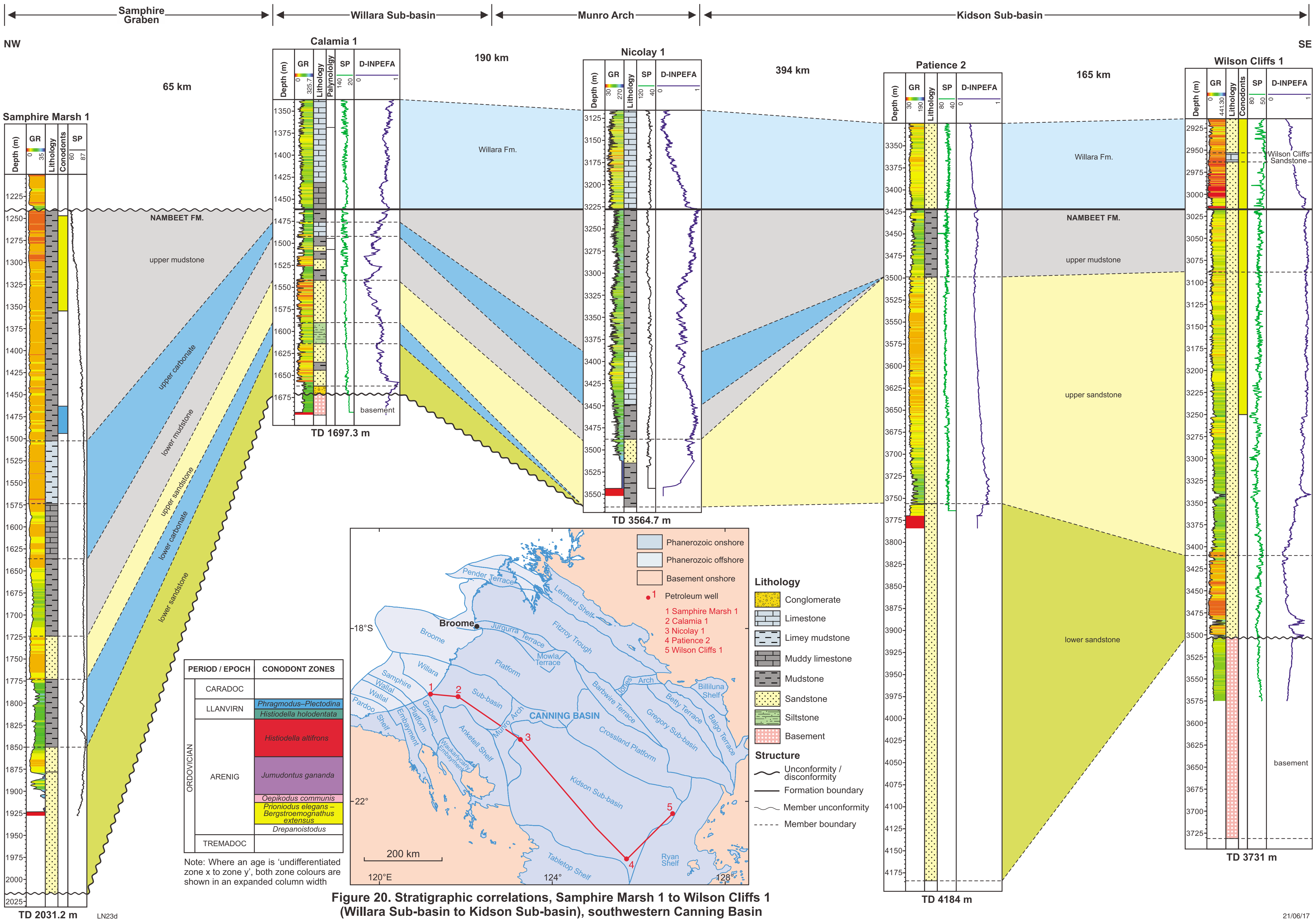

Figure 20. Stratigraphic correlations, Samphire Marsh 1 to Wilson Cliffs 1 (Willara Sub-basin to Kidson Sub-basin), southwestern Canning Basin

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Glossary

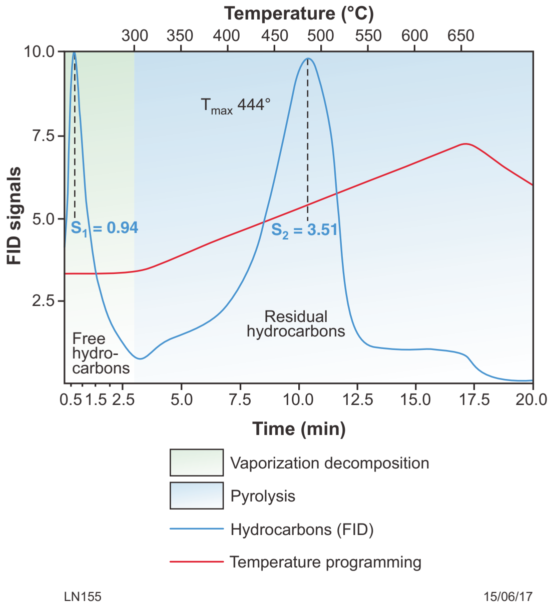
hydrogen index (HI)
: Measures the hydrogen richness of a source rock; it is the ratio of S_2 (mg HC/g rock) to TOC (g) and is calculated using the following equation: HI = S_2/TOC x 100 (mg HC/g rock)

kerogen
: The disseminated organic matter in sediments that is made up of a mixture of compounds containing carbon, hydrogen and oxygen (Selley, 1985). Petroleum studies classify kerogen based on their carbon, hydrogen and oxygen content as Type I, Type II or Type III (Tissot and Welte, 1978; Selley, 1985; van Krevelen, 1993). Types I and II mainly generate oil with minor gas and are known as sapropelic kerogen. Type I is produced mainly from an algal source, producing waxy oil. Type II can be subdivided into two types: liptinitic (Type IIA) kerogen forms in a marine environment producing light oil and gas; exinite (Type IIB) kerogen is found in terrestrial environments producing waxy oil and gas from the waxy components of higher land plants (Preston, 2016). Type III has vitrinite or humic kerogen produced from the lignin of plants and primarily generates gas with some waxy oil

oxygen index (OI)
: Measures the amount of oxygen relative to the amount of organic carbon; it is the ratio of S_3 (mg HC/g rock) to TOC (g) and is calculated using the following equation: OI = S_3/TOC x 100 (mg CO_2/g rock)

production index (PI)
: A measure of the hydrocarbons already produced relative to the total quantity of hydrocarbons that could be produced. It is calculated using the following equation: PI = $S_1/(S_1 + S_2)$

Rock-Eval analysis
: Controlled combustion of a sample to measure the hydrocarbon potential of a petroleum source rock. This analysis gradually heats up the sample until the free hydrocarbons are burned and measured which corresponds to the S_1 peak. S_1 = volatile hydrocarbon (mg/g rock). The second burning event at higher temperatures is the S_2 peak and represents the residual hydrocarbons that may still produce if maturation continues. Thus, S_2 = hydrocarbon generating potential (mg/g rock) ranked as follows: S_2 = 0–2 ranked as poor; 2–5 mg/g rock as fair; 5–10 mg/g rock as good; 10–20 mg/g rock as very good; greater than 20 mg/g rock as excellent. S_3 = organic carbon dioxide (mg/g rock)



thermal maturity
: Based on the increase in temperature due to geothermal gradient during progressive burial of sedimentary rock. Thermally immature source rocks occur below 435ºC, with thermal 'maturity' correlating to the 'oil window' from 435–470ºC and post-thermal maturity above 470ºC . T_{max} is the temperature at which the maximum amount of hydrocarbon is produced during pyrolysis. For sample analysis during this project, T_{max} was calculated by subtracting 40ºC from the peak S_2 temperature

total organic carbon (TOC)
: Quantity or amount of organic matter in a petroleum source rock is measured by the TOC as wt% of rock (Jarvie, 1991). Organic carbon is derived from biogenic matter as opposed to inorganic carbon which originates from mineral matter. To be considered a potential source rock, a minimum value of 0.5% TOC is required, with 0.5 – 1% classified as fair organic richness, 1–2% as good, 2–4% as very good, and over 4% as excellent

van Krevelen diagrams
: Originally developed to characterize coals, van Krevelen diagrams plot HI vs OI to differentiate kerogen types

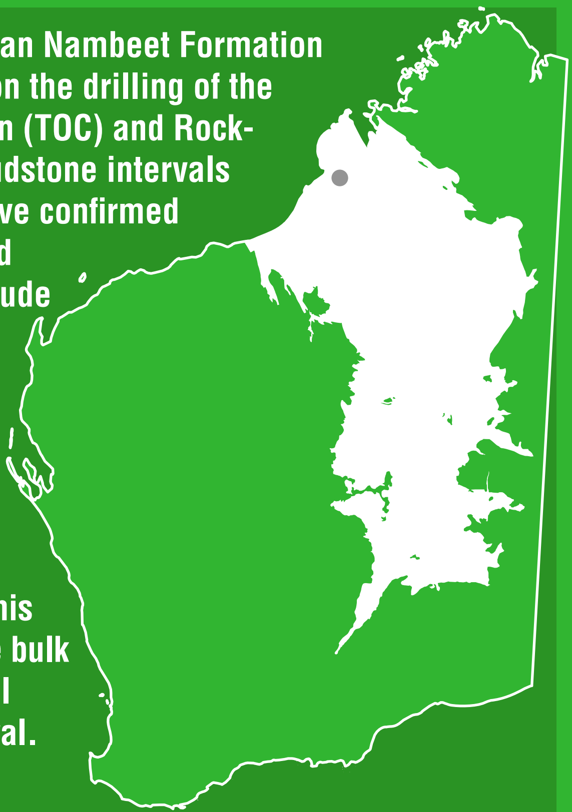
Appendix 1

Petroleum exploration, mineral exploration and stratigraphic wells intersecting the Nambeet Formation

Well or drillhole name	*TD date*	*MGA Easting*	*MGA Northing*	*Total depth (m)*	*Nambeet top (m)*	*Nambeet base (m)*	*Nambeet interval (m)*	*Core available (m)*	*TOC analysis*	*Rock-Eval analysis*	*Additional comments*
Acacia 2	06/07/1982	709638	7861481	1573	1277	1502.5	225.5				
Aquila 1	01/11/1982	465230	7945457	1735	1364	1735	371				
BMR 03 Noonkanbah	26/10/1987	806221	7934278	247	10.7	180.7	170	9			Also known as BMR 3 Prices Creek: Kudata Dolomite 10.7 – 99.1 m; Kunian Sandstone 99.1 – 180.7 m
BHP PCD 158	21/02/2001	804669	7933025	213.8	113.1	205.8	92.7		1	1	Gap Creek 111.6 – 115 m; Emanuel Formation 115–145 m; Kudata Dolomite 145 – 173.5 m; Kunian Sandstone 173.5 – 205.8 m
BHP PHD 001	06/07/1990	804378	7940190	668.1	70.9	643.6	572.7	572.7	11	11	Emanuel Formation 70.9 – 465 m; Kudata Dolomite 465 – 550 m; Kunian Sandstone 550 – 643.6 m
BHP PHD 002	27/07/1990	804374	7941164	119.2	93	119.2	26.2	26.2			Emanuel Formation 93 – 119.2 m
Calamia 1	04/06/1956	373897	7834662	1697.3	1461.4	1671.4	210		8	2	
Contention Heights 1	02/12/1987	317476	7519023	1790.7	1580.39	1790.7	210.31		2	1	Wilson Cliffs Sandstone 1580.39 – 1790.7m
Crystal Creek 1	23/09/1973	563550	7948172	2504	2403	2504	101		1	1	WCR has Willara Formation to TD
Dodonea 1	15/09/1988	727068	7855145	2215	1910	2185	275	9.3	15	3	
Edgar Range 1	25/09/1985	562751	7926116	1968.1	1754	1968.1	214.1	9.4	7	7	
Frankenstein 1	13/09/1968	501774	7635716	2803	2560	2666	106		29		
Gap Creek 1	07/11/1988	796615	7937683	1541.2	1392.5	1527.8	135.3		5	2	
Goldwyer 1	12/06/1988	434964	7967720	1439	1388	1420.4	32.4	3.35	1	1	
Grevillea No. 1	25/10/1958	778219	7968975	2586	1953	2556.5	603.5		6		Gap Creek 1953–2165 m; Emanuel Formation 2165 – 2399 m; Kudata Dolomite 2399–2466 m with; Kunian Sandstone 2466 – 2556.5 m
Hedonia 1	11/09/1982	436865	7979254	1543	1290	1501	211		19	15	
Hilltop 1	20/06/1984	424964	7977340	1770	1418	1736	318		7	7	
Justago 1	08/08/1987	208869	7911673	3150	3050.5	3150	99.5		4	1	
Kidson 1	12/02/1985	706087	7497918	4431.49	4412.5	4431.49	19.5	4.57	17	10	Wilson Cliffs Sandstone at 4412.5 m from GSWA Record 2011/11
Leo 1	20/07/1966	431229	7871682	2411	2253	2319.5	66.5		6		
Looma 1	15/08/1988	604574	7885202	2535	2305	2494	189				
McLarty 1	31/08/1996	569388	7855388	2591	2341	2590.8	249.8	16.06	1	1	
Mirbelia 2	29/07/1968	747695	7825644	2818	2547	2818	271		24		
Missing 1	20/11/1988	668167	7837589	1810	1746	1810	64				
Munro 1	07/11/2001	445112	7803740	2116	2015	2105.9	90.9				
Nicolay 1	30/06/1972	526953	7725419	3564.7	3228	3564.7	336.7	336.7	30	19	WCR has top of Nambeet Formation at 3468 m
Olympic 1	18/10/2012	461936	7976659	1447.2	1175.25	1447.53	272.28	272.28	158	151	
Patience 2	19/06/2015	773192	7414254	4184	3422	4184	762				3163.5 m for top of Wilson Cliffs Sandstone; 3322 m from base of Wilson Cliffs Sandstone; TD at 3322 m
Pegasus 1	10/08/1988	599574	7777610	2995	2916	2995	79		1		
Percival 1	15/07/1985	195442	7749224	2448	2280	2447.6	167.6		14		
Pictor 1	20/09/1984	575468	7925243	2146	1932	2121	189		9		
Prices Creek 1	01/12/1922	807676	7932623	307	0	307	307				Emanuel Formation 0–307 m
Prices Creek 2	15/05/1923	810473	7932483	104	25	104	79				Emanuel Formation 25–104 m
Prices Creek 3	15/05/1923	808088	7930921	247	4	247	243				Emanuel Formation 4–247 m
Sally May 2	13/08/2009	652665	7809838	1994.1	1938.5	1994.1	55.6	55.6	4		

Well or drillhole name	*TD date*	*MGA Easting*	*MGA Northing*	*Total depth (m)*	*Nambeet top (m)*	*Nambeet base (m)*	*Nambeet interval (m)*	*Core available (m)*	*TOC analysis*	*Rock-Eval analysis*	*Additional comments*
Samphire Marsh 1	04/05/1958	309341	7840588	2031.2	1240	2015	775	12.6	3		
Setaria 1	23/05/1989	707475	7853633	956	627.5	955	327.5				
Sharon Ann 1	07/08/1994	394611	7956828	1830	1768	1830	62				
Solanum 1	06/03/1984	706178	7857615	834	805.9	834	28.1	28.1	3		
Tappers Inlet 1	05/08/1971	456407	8135985	2856.28	2202.5	2834.6	632.1	1.5	28	28	
Thangoo 1A	17/02/1960	488025	7969738	1654.76	1450	1554.5	104.5	10.98	1	1	
Thangoo 2	30/05/1973	490531	7961030	1472	1150	1438	288	4.5			
Twin Buttes 1	12/07/1987	494331	7953353	1600.3	1359	1600.3	241.3				
Willara 1	21/08/1968	402754	7879008	3903	3142	3656	514	18.6	16	6	
Wilson Cliffs 1	29/11/1968	271590	7534937	3722.22	2963	3503	540	29.86	29	9	
							Totals	1522.8	453	277	

The petroleum source potential of the Ordovician Nambeet Formation in the Canning Basin has been revised based on the drilling of the Olympic 1 petroleum well. Total organic carbon (TOC) and Rock-Eval analysis over two distinct organic-rich mudstone intervals in the upper part of the Nambeet Formation have confirmed fair to very good source quality and fair to good hydrocarbon generating potential. Results include a maximum TOC of 3.28% and maximum S_2 of 5.05 mg HC/g rock.



Continuous coring of Olympic 1 over the upper Nambeet Formation has provided a complete record of these two organic-rich mudstone intervals. Previous drilling of this interval in other wells is limited, but lateral continuity of this prospective source can be correlated across the bulk of the Canning Basin, establishing a large aerial extent for this potential petroleum source interval.

TOC estimation using wireline interpretation techniques on regional petroleum wells intersecting the Nambeet Formation are required to understand the potential of this source interval. Further geochemical analysis such as gas chromatography mass spectrometry (GC-MS), kerogen kinetics and maceral composition, is also required to define the kerogen type in this source interval. This will provide correlations to known hydrocarbon shows in the Nambeet Formation, and permit Nambeet Formation source rocks to be distinguished from other Ordovician petroleum source rocks in the Canning Basin.

Further details of geological products and maps produced by the Geological Survey of Western Australia are available from:

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NORMORE AND DENT

PETROLEUM SOURCE POTENTIAL OF THE ORDOVICIAN NAMBEET FORMATION, CANNING BASIN: EVIDENCE FROM PETROLEUM WELL OLYMPIC 1

REPORT 169