Source rock geochemistry of the McArthur Basin, northern Australia

Rock-Eval pyrolysis data release

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GEOSCIENCE AUSTRALIA
RECORD 2018/024

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Executive summary

Exploring for the Future is an initiative by the Australian Government dedicated to boosting investment in resource exploration in Australia. The four-year program led by Geoscience Australia focusses on northern Australia and parts of South Australia to gather new data and information about the potential mineral, energy and groundwater resources concealed beneath the surface. The new pre-competitive data and information will be made publicly available and released over the next three years to support and de-risk resource decision-making and investment. As part of the Exploring for the Future Programme, this study aims to improve our understanding of the petroleum resource potential of Northern Australia. As a component of this project, collaboration between the Onshore Energy Branch, Geoscience Australia and the Northern Territory Geological Survey (NTGS) is designed to produce pre-competitive information to assist with the evaluation of the petroleum prospectivity of onshore Northern Territory basins.

This report characterises the organic richness, kerogen type and thermal maturity of source rocks in the Velkerri, Barney Creek, Wollogorang and McDermott formations of the McArthur Basin based on new Rock-Eval pyrolysis data analysed at Geoscience Australia in 2017-2018. This data is provided in preparation for future work to generate statistics quantifying the spatial distribution, quantity and quality of McArthur Basin source rocks, providing important insights into the hydrocarbon prospectivity of the basin.

The Velkerri Formation has poor to excellent potential to generate both oil and gas based on TOC in the range 0.1-7.5 wt % and associated HI values in the range 13–256 mg HC/g TOC. Thermal maturity for the samples range from immature to the late oil window (Tmax 387°C-465°C, depth 9m-599m). The Barney Creek Formation samples have only a fair potential to generate gas, in spite of good organic richness (TOC average = 1.6 ± 1.0 wt %; HI average = 29 ± 11 mg HC/g TOC). Thermal maturity for the samples range from immature to peak oil mature (Tmax = 418°C-449°C, depth 108.4m-335.8m). The Wollogorang Formation samples analysed in this study have poor to good source potential to generate gas (TOC = 0.1-2.5 wt %; 50 <HI < 150 mg/g TOC). Thermal maturity for the samples range from immature to mature (Tmax = 420°C-446°C, depth 249.6m-280.8m). The McDermott Formation samples analysed in this study have a poor potential to generate gas (TOC = 0.2-0.7 wt%; HI = 49-160 mg HC/g TOC). Thermal maturity is within the early oil window (Tmax = 438°C-439°C, depth 24.1m-34.1m).

Future work will consist of collating this data with existing data from the Northern Territory Geological Survey and Geoscience Australia’s ORG CHEM databases to generate statistics quantifying the spatial distribution, quantity and quality of McArthur Basin source rocks in addition to mapping the distribution of source rocks. This will provide important insights into the hydrocarbon prospectivity of the greater McArthur Basin.
1 Introduction

The McArthur Basin is a Paleoproterozoic–Neoproterozoic basin that is mainly exposed over approximately 180 000 km² in the Northern Territory (Plumb, 1987; Jackson et al., 1987), with a smaller component present in Queensland (Figure 1). The basin fill consists of a 10–12 km thick succession of relatively undeformed siliciclastic and carbonate rocks, along with minor mafic and felsic volcanic and shallow intrusive rocks (see recent summaries by Ahmad et al., 2013; Munson, 2014).

The McArthur Basin is part of a larger region, referred to informally as the greater McArthur Basin (Close, 2014). Stratigraphic correlations between the McArthur Basin, the Birrindudu Basin to the west and the Tomkinson Province have been supported by seismic data (Hoffman, 2014) and recent drilling (Hoffman, 2015) demonstrating undercover continuity of stratigraphic packages.

The McArthur Basin has the potential to host conventional oil and gas, in addition to unconventional shale gas and oil plays (Muir et al., 1980; Munson, 2014; Revie, 2016; Revie, 2017). The first gas discovery was reported in the mineral exploration drillhole GRNT79-9, which flowed substantial volumes of gas (Thomas, 1981). The first discovery of live-oil in the basin was made during stratigraphic drilling of the Urapunga 4 well by Geoscience Australia, with volatile hydrocarbons bleeding from shales of the Velkerri Formation (Jackson et al., 1986). Since initial exploration began in the McArthur Basin, numerous small hydrocarbon shows have been found within the Paleoproterozoic and Mesoproterozoic sedimentary rocks, the overlying Paleozoic sedimentary rocks, as well as within breccia pipes in the Redbank area within the Calvert Hills 1 : 250 000 Map sheet area (e.g. Knutson et al., 1979; Muir et al., 1980). These include live-oil, gas, and extensive oil staining and bitumen/pyrobitumen in drillcore and mine sites. An extensive summary of the petroleum potential of the McArthur Basin and Beetaloo Sub-basin has been undertaken (Munson, 2014; Revie, 2017).

Three petroleum supersystems have been identified in the basin. The petroleum systems in the McArthur Group are included within the McArthur Supersystem and those of the Roper Group are within the Urapungan Supersystem (Bradshaw, 1993; Bradshaw et al. 1994; Laurie, 2012). An older petroleum system is present within the Tawallah Group, since hydrocarbon shows are known in the McDermott and Wollogorang formations (Munson, 2014). To date, work on the prospective petroleum systems has focused principally on source rocks within the McArthur and Roper groups in the southern parts of the basin. However due to limited data availability, the spatial variability in source rock quality, type and thermal maturity remains poorly constrained across the region.

This study aims to improve our understanding of the petroleum resource potential of the McArthur Basin, through collection of new source rock geochemistry data. This report contains the total organic carbon (TOC) content and Rock-Eval pyrolysis data of seventy-eight samples selected from eight petroleum wells in the McArthur Basin (Alexander 1, Bing Bong 5, Bing Bong 6, Borrowdale 2, DD91DC1, DD91RC18, Friendship 1 and Prince of Wales 1; Figure 1). These samples covered four formations: the Mesoproterozoic Velkerri Formation and the Paleoproterozoic Barney Creek, Wollogorang and McDermott formations (Figure 2). These samples were selected to complement previous work undertaken by Geoscience Australia and the Northern Territory Geological Survey (NTGS) (Crick et al., 1988; Chen et al., 2003; Revie, 2016). Table 1 lists a summary of the rocks analysed in this study and Appendix A contains the full dataset.

All analyses were carried out in the Isotope and Organic Geochemistry and Inorganic Geochemical Laboratories at Geoscience Australia.
This work has been conducted in collaboration with the NTGS, as part of the Exploring for the Future Programme, an Australian Government initiative dedicated to boosting investment in resource exploration in Australia. The new pre-competitive data and information presented here is publicly available to support and de-risk resource decision making and investment.

Figure 1 Location of the McArthur Basin including the Beetaloo Sub-basin on a base map of surface geology (Raymond et al., 2012) with locations of drillcores analysed in this study. The McArthur Basin outline is sourced from Raymond et al. (2018). The Beetaloo Sub-basin was provided by the NTGS (Northern Territory Geological Survey, 2017) and the greater McArthur Basin outline is from Close (2014).
Table 1. Summary of samples analysed in this study. See Figure 1 for well location

<table>
<thead>
<tr>
<th>Formation</th>
<th>Well</th>
<th>Number of samples analysed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velkerri Formation</td>
<td>Alexander 1</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Borrowdale 2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Friendship 1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Prince of Wales 1</td>
<td>3</td>
</tr>
<tr>
<td>Barney Creek Formation</td>
<td>Bing Bong 5</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Bing Bong 6</td>
<td>9</td>
</tr>
<tr>
<td>Wollogorang Formation</td>
<td>DD91RC18</td>
<td>4</td>
</tr>
<tr>
<td>McDermott Formation</td>
<td>DD91DC1</td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 2 Stratigraphy of the McArthur Basin with source rock, reservoir units and petroleum shows (after Munson, 2014). Correlations of stratigraphic units are based on Rawlings (1999) and Munson (2014).
2 Experimental procedure

2.1 Introduction to Rock-Eval Pyrolysis

Programmed pyrolysis, or Rock-Eval pyrolysis (as has been most often used in Australia), provides further information about the source rock quality, including organic matter type and hydrocarbon generation potential, and the extent of thermal maturity of the source rock (Peters, 1986; Peters & Casa, 1994; Hart & Steen, 2015).

The Rock-Eval pyrolysis methodology involves heating a powdered, homogenised sample under an inert atmosphere (e.g. helium or nitrogen) over a pre-determined temperature rate to obtain four initial parameters; the total amount of hydrocarbons generated from the rock (S1 and S2 peaks), the CO$_2$ content (S3 peak) and $T_{\text{max}}$, the temperature corresponding to the maximum rate of hydrocarbons generated from the cracking of kerogen (Figure 3; Tissot & Welte, 1984; Peters et al., 2005). Typically, the samples are placed in a pre-oxidised crucible, heated to 300°C and held isothermal for several minutes, in order to thermally distil free and adsorbed hydrocarbons (S1 peak), which are then measured by a flame ionisation detector (FID). The oven temperature is then ramped from 300°C to either 600°C or 650°C at 25°C/min (depending on the laboratory and instrument model) and held isothermal for about a minute, in order to crack the kerogen and generate hydrocarbons (S2 peak). These hydrocarbons are measured by the FID. The CO$_2$ released during the kerogen cracking process (S3) is trapped and subsequently measured by a thermal conductivity detector (TCD). The temperature at which the maximum amount of S2 hydrocarbons is generated is denoted as $T_{\text{max}}$ (Tissot & Welte, 1984). Conversion of kerogen to liquid and gaseous hydrocarbons occurs at different temperatures depending on the kerogen present in the source rock. Definitions and calculations of Rock-Eval pyrolysis parameters are provided in Table 2.

![Figure 3 Rock-Eval pyrolysis measurement parameters](image)

*Figure 3 Rock-Eval pyrolysis measurement parameters (based on original experimental set up, e.g. Rock Eval II). The green curve shows the variation in oven temperature with time (redrafted from Hart & Steen, 2015). Red areas represent hydrocarbons liberated (S1) pyrolysis generated (S2) and CO$_2$ generated (S3) during the course of the analysis. Note: $T_{\text{max}} = T_{\text{peak}} - 40^\circ\text{C}$, where exact $T_{\text{max}}$ value is based upon calibrated standards.*
2.2 Experimental set-up

All analyses were carried out in the Isotope and Organic Geochemistry, and Inorganic Geochemical Laboratories at Geoscience Australia. TOC content and hydrocarbon potential were measured using a Rock-Eval 6 Turbo™ (Vinci Technologies, France). Approximately 60 mg of powdered whole rock (shale and carbonate lithologies) samples were loaded into pre-combusted crucibles (600°C; 9 hours) which were loaded into the carousel and heated under inert nitrogen in both the pyrolysis (to obtain S1, S2, T_{max} and S3 peaks) and oxidation (to obtain the S4 peak) ovens. The pyrolysis oven was first held at 300°C for 5 minutes and then increased at 25°C per minute to 650°C. The oxidation oven was held at 400°C for 3 minutes, and then increased at 20°C per minute to 850°C and held isothermal at 850°C for 5 minutes.

The flame ionisation detector (FID) was calibrated by running the Institut Francais du Petrole standard ‘IFP 160000’. The infra-red (IR) analyser was calibrated against a standard gas with a known concentration of CO2 and CO. Analysis blanks were run with the sample batch and the blank data was automatically subtracted from all analyses.

The results were processed with Optkin 3.0.0 software (Beicip, France) providing peak heights (S1, S2, T_{max}, S3, S4) and the following calculated geochemical indices: Total Organic Carbon (TOC) content, Oxygen Index (OI), Hydrogen Index (HI) and Production Index (PI).

Table 2. Definitions of Rock-Eval pyrolysis parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name (units)</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>mg extractable hydrocarbons (HCs) / g rock</td>
<td>Measure of the amount of free hydrocarbons (HCs) present in the rock. The free HCs are those thermally desorbed at 300°C for 3 mins.</td>
</tr>
<tr>
<td>S2</td>
<td>mg HCs (kerogen pyrolysate) / g rock</td>
<td>Measure of HCs formed by cracking of kerogen, resins and asphaltenes. The pyrolysate is measured from 300°C to 650°C at 25°C/min</td>
</tr>
<tr>
<td>S3</td>
<td>mg CO2 (organic) / g rock</td>
<td>Measure of CO2 generated from oxygenated functional groups in kerogen. The CO2 is collected from 300°C to 390°C at 25°C/min</td>
</tr>
<tr>
<td>T_{max}</td>
<td>Maximum height of the S2 peak in the temperature program (°C)</td>
<td>The temperature corresponding to the maximum rate of HC generation from the cracking of kerogen (S2)</td>
</tr>
<tr>
<td>TOC</td>
<td>Total Organic Carbon (wt %)</td>
<td>Measure of the rock’s organic richness. TOC = PC (pyrolysable carbon, wt %) + RC (Residual carbon, wt %)</td>
</tr>
<tr>
<td>PC</td>
<td>Pyrolysable carbon (wt %)</td>
<td>The amount of TOC represented by S1 and S2. PC = 0.83 * (S1 + S2)</td>
</tr>
<tr>
<td>RC (S4)</td>
<td>mg C / g rock</td>
<td>Measure of the residual carbon (RC) in a rock. Also termed S4.</td>
</tr>
<tr>
<td>PI</td>
<td>Production Index</td>
<td>The extent to which kerogen has been transformed into oil and gas. PI = [S1 / (S1 + S2)]</td>
</tr>
<tr>
<td>HI</td>
<td>Hydrogen Index [mg hydrocarbons (S2) / g TOC]</td>
<td>Amount of HCs released on pyrolysis (S2) normalised to TOC. HI = 100 * S2 / TOC</td>
</tr>
<tr>
<td>OI</td>
<td>Oxygen Index [mg CO2 (S3) / g TOC]</td>
<td>Amount of carbon dioxide released on pyrolysis (S3) normalised to TOC. OI = 100 * S3 / TOC</td>
</tr>
<tr>
<td>MINC</td>
<td>Mineral Carbon (wt %)</td>
<td>The amount of carbon (C) contained in mineral phases e.g. carbonates. Also termed total inorganic carbon (TIC)</td>
</tr>
</tbody>
</table>
3 Source rock analysis

3.1 TOC and Rock-Eval data quality control

All data have to be checked for quality before starting interpretation. Some data can be unreliable for a number of reasons such as contamination of cuttings with drilling fluid or low TOC content (Carvajal-Ortiz & Gentzis, 2015; Dembicki, 2009; Peters, 1986).

To ensure the integrity of the Rock-Eval pyrolysis data, the following data were excluded from analysis (Hall et al., 2016 and references therein):

- Internally inconsistent Rock-Eval pyrolysis data, with indices entered into the database not relating correctly to the measured parameters (e.g. HI does not equal S2/TOC *100)
- Rock-Eval pyrolysis data where S2 < 0.1 mg HC/g rock: Rock-Eval pyrolysis results may be unreliable for organically lean samples as they yield low and poorly defined S2 peaks resulting in unreliable T_max and HI values
- Rock-Eval pyrolysis data where T_max < 380°C: low values may imply an incorrect programmatical selection of the S2 peak, or the S1 peak is broad due to the presence of non-indigenous free hydrocarbons, either migrated hydrocarbons or drilling fluid contaminants
- Rock-Eval pyrolysis data where OI > 350 mg CO2/g TOC: high OI values may be unreliable due to either thermal breakdown of carbonates, the presence of oxidised organic matter or the presence of drilling fluid contaminants.

Both oil staining due to migration and contamination from mud additives and oil-based drilling fluids affect the Rock-Eval pyrolysis data. Cuttings samples and side-wall cores are typically more prone to drilling fluid contamination than whole-core samples. Contamination or hydrocarbon migration may result in high PI and low T_max values (Peters, 1986; Peters & Cassa, 1994). The primary focus of this study are in-situ source rocks, therefore Rock-Eval pyrolysis data meeting the following criteria were flagged as possibly being affected by either migrated hydrocarbons or drilling fluid contaminants, and were removed from the analysis:

- PI > 0.2 with T_max < 435°C
- PI > 0.3 with T_max between 435–445°C.

3.2 Source rock classification

There are a range of classification schemes used to assess source potential in terms of organic richness and quality (Baskin, 1997; Bordenave et al., 1993; Hall et al., 2016; Peters & Cassa, 1994).

The criteria listed in Table 3 and Table 4 was applied to describe the organic richness, hydrocarbon potential and kerogen type of the source rocks. These are based on interpretive guidelines provided by Peters & Cassa (1994) and Hall et al. (2016).

The classification scheme published by Peters & Casa (1994) categorized rocks with TOC 1–2 % as good source rocks and those with TOC 0.5–1 wt % as fair source rocks. However, from a practical perspective, expulsion efficiencies for rocks containing less than 2 wt % TOC will be low and as a result, rocks classed as having TOC < 2% are unlikely to be effective source rocks (Peters et al.,
The classification scheme used in this study (Table 3) was slightly modified to reflect this: rocks with TOC 0.5–2 wt % are classed as fair source rocks, whereas rocks with TOC 2–4 wt % are classed as good source rocks.

**Table 3. Source rock classification scheme.**

<table>
<thead>
<tr>
<th>Source rock potential (Quality)</th>
<th>Organic richness TOC (wt %)</th>
<th>S1 (mg HC/g rock)</th>
<th>S2 (mg HC/g rock)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>&lt; 0.5</td>
<td>&lt; 0.5</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>Fair</td>
<td>0.5–2.0</td>
<td>0.5–1</td>
<td>2.5–5</td>
</tr>
<tr>
<td>Good</td>
<td>2.0–4.0</td>
<td>1–4</td>
<td>5–20</td>
</tr>
<tr>
<td>Excellent</td>
<td>&gt; 4</td>
<td>&gt; 4</td>
<td>&gt; 20</td>
</tr>
</tbody>
</table>

**Table 4. Kerogen type, Hydrogen Index and expelled product at peak maturity.**

<table>
<thead>
<tr>
<th>Kerogen type (quality)</th>
<th>HI (mg HC/g rock)</th>
<th>Main product at peak maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&gt; 600</td>
<td>Oil</td>
</tr>
<tr>
<td>II</td>
<td>300–600</td>
<td>Oil</td>
</tr>
<tr>
<td>II/III</td>
<td>200–300</td>
<td>Oil and gas</td>
</tr>
<tr>
<td>III</td>
<td>50–200</td>
<td>Gas</td>
</tr>
<tr>
<td>IV</td>
<td>&lt; 50</td>
<td>None</td>
</tr>
</tbody>
</table>

Kerogen type is related to the original type of organic matter, which has evolved over time, and the preservation of the organic matter which is linked to depositional environment and climate (Figure 1). Several different classification schemes have been proposed.

Tissot & Welte (1984) and Peters *et al.* (2005) describe four principal kerogen types, as described below:

- Type I (very oil-prone) kerogen is mostly derived from lacustrine algal and bacterial matter, although some petroleum source rocks deposited in marine settings are also dominated by type I kerogen, such as those found in Proterozoic and early Paleozoic sedimentary rocks.
- Type II (oil-prone) kerogen is globally the most common type that has sourced conventional hydrocarbon accumulations. It is common in marine sediments, indicating deposition of autochthonous algal and bacterial material in a reducing environment. Type II is kerogen enriched in sulphur that is more labile than type II kerogen and is commonly associated with carbonates and carbonaceous or dolomitic shales (Orr, 1986; Tissot & Welte, 1984).
- Type III (gas-prone) kerogen is typically derived from plant matter and indicates an origin in terrigenous environments, such as swamps, lagoons and deltas, and generally has a higher oxygen content relative to type I and II kerogen.
Type IV (inert) kerogen has low HI values, being typical of oxidised organic matter, charcoal and reworked organic matter.

An alternative organofacies scheme by Pepper & Corvi (1995) relates lithology and kerogen type to depositional environment and includes the five organofacies:

- A: aquatic, marine siliceous or carbonate/evaporate (equivalent to type IIS)
- B: aquatic marine, siliciclastic (equivalent to type II)
- C: aquatic, non-marine, lacustrine (equivalent to type I)
- D/E: terrigenous, non-marine, waxy (equivalent to type III)
- F: terrigenous, non-marine, wax-poor (equivalent to type III to type IV).

*Figure 4 Schematic model illustrating different source rock forming depositional environments.*
Table 5. Relationship between kerogen type and depositional environment, modified from Tissot & Welte (1984) and Pepper & Corvi (1995).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater lacustrine</td>
<td>Rift basin/intra-cratonic sag/tropics</td>
<td>Siliciclastics</td>
<td>Algae</td>
<td>I</td>
<td>C</td>
</tr>
<tr>
<td>Fluvio-deltaic</td>
<td>Upper delta plain</td>
<td>Coal</td>
<td>Higher plants, algae</td>
<td>III, IIIa</td>
<td>F, D/E</td>
</tr>
<tr>
<td>Fluvio-deltaic</td>
<td>Lower delta plain</td>
<td>Coal, siliciclastics</td>
<td>Higher plants, algae</td>
<td>III, IIIa</td>
<td>F, D/E</td>
</tr>
<tr>
<td>Deltaic</td>
<td>Pro-delta</td>
<td>Siliciclastics</td>
<td>Higher plants, marine algae</td>
<td>II, III</td>
<td></td>
</tr>
<tr>
<td>Saline lacustrine and lagoonal</td>
<td>Rift basin/arid/back barrier</td>
<td>Evaporites, carbonates, siliciclastics</td>
<td>Algae, cyanobacteria</td>
<td>II, IIS</td>
<td>B, A</td>
</tr>
<tr>
<td>Marine</td>
<td>Active/passive margin</td>
<td>Carbonates, siliciclastics</td>
<td>Algae, phytoplankton, zooplankton</td>
<td>II, IIS</td>
<td>B, A</td>
</tr>
</tbody>
</table>

3.3 Thermal maturity

$T_{max}$ is the temperature of maximum S2 generation during Rock-Eval pyrolysis (Tissot & Welte, 1984). Conversion of kerogen to liquid and gaseous hydrocarbons occurs at different temperatures depending on the kerogen present in the source rock. In this study we have adopted the general ranges of thermal maturity described by Peters & Casa (1994) (Table 6).

Table 6. Level of thermal maturity assessed from $T_{max}$ (Peters & Casa, 1994).

<table>
<thead>
<tr>
<th>Thermal Maturity Window</th>
<th>$T_{max}$ (°C) range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immature</td>
<td>$\leq 435$</td>
</tr>
<tr>
<td>Early oil</td>
<td>435 – 445</td>
</tr>
<tr>
<td>Peak oil</td>
<td>445 – 450</td>
</tr>
<tr>
<td>Late oil</td>
<td>450 – 470</td>
</tr>
<tr>
<td>Overmature</td>
<td>$&gt; 470$</td>
</tr>
</tbody>
</table>
Source rock quality, type and thermal maturity

Source rock organic richness, hydrocarbon-generating potential, kerogen type and level of thermal maturity are discussed in the following paragraphs in order of increasing age for the Velkerri, Barney Creek, Wollogorang and McDermott Formations.

Present-day statistics for TOC and Rock-Eval pyrolysis data ($T_{\text{max}}$, HI and OI) from McArthur Basin wells are provided for each Formation in Velkerri Formation.

The Velkerri Formation comprises grey and black mudstone, claystone and siltstone. It also contains minor fine grained glauconitic sandstone, calcite nodules, and pyrite (Lanigan et al., 1994; Abbott et al., 2001; Munson, 2014). Lanigan et al. (1994) recognised three informal divisions of the Velkerri Formation based on drillcore. The lower Velkerri is a grey to blue claystone with silty mudstone and interbedded sandstones; the middle Velkerri Formation is an organic rich dark grey to black claystone, mudstone and siltstone; and the upper Velkerri Formation is a grey mudstone and siltstone with increasing fine sandstone towards the top of the unit (Lanigan et al., 1994; Munson, 2014). The Velkerri Formation was likely deposited in either a low energy marine environment (Jackson et al., 1988), or a restricted lacustrine, barred basin environment (Donnelly & Crick, 1988). This corresponds to a type B to C organofacies (Pepper & Corvi, 1994). The middle Velkerri Formation is the organic and most prospective interval in the Beetaloo Sub-basin (Munson, 2014).

Four wells analysed in this study intersect the Velkerri Formation (Alexander 1, Borrowdale 2, Friendship 1 and Prince of Wales 1). These wells are located to the north of the Beetaloo Sub-basin (Figure 1). The samples range in depth from 9m to 599m (Appendix 1).

The Velkerri Formation samples have a variable TOC content, averaging 2.8 wt %, reaching a maximum TOC of 7.5 wt % in the organic rich middle member demonstrating good to excellent organic richness. The Velkerri Formation kerogens have the potential to generate both oil and gas based on hydrogen indices ranging from 13 mg HC/g TOC to 256 mg HC/g TOC. The HI average value is 149 mg HC/g TOC, suggestive of the Velkerri Formation samples in this study are mostly dominated by type III kerogen. Type I to type III kerogens are reported for the Velkerri Formation (Revie, 2017).

$T_{\text{max}}$ values for the Velkerri Formation samples range from 387°C to 465°C (Table 7). This corresponds to an immature to late oil window (Peters & Cassa, 1994). The Velkerri Formation samples in drillcores Alexander 1 and Borrowdale 2 are immature to mature for oil and gas generation ($T_{\text{max}} < 435°C$), while the Velkerri Formation in Friendship 1 and Prince of Wales 1 are slightly more mature and have values that range from immature to within the early to late oil window ($T_{\text{max}} 398–465°C$).
Table 7.

Statistical analysis was carried out on quality-controlled data based on the criteria described above. All Rock-Eval pyrolysis data are available in Appendix A and the associated pyrograms in Appendix B.

4.1 Velkerri Formation

The Velkerri Formation comprises grey and black mudstone, claystone and siltstone. It also contains minor fine grained glauconitic sandstone, calcite nodules, and pyrite (Lanigan et al., 1994; Abbott et al., 2001; Munson, 2014). Lanigan et al. (1994) recognised three informal divisions of the Velkerri Formation based on drillcore. The lower Velkerri is a grey to blue claystone with silty mudstone and interbedded sandstones; the middle Velkerri Formation is an organic rich dark grey to black claystone, mudstone and siltstone; and the upper Velkerri Formation is a grey mudstone and siltstone with increasing fine sandstone towards the top of the unit (Lanigan et al., 1994; Munson, 2014). The Velkerri Formation was likely deposited in either a low energy marine environment (Jackson et al., 1988), or a restricted lacustrine, barred basin environment (Donnelly & Crick, 1988). This corresponds to a type B to C organofacies (Pepper & Corvi, 1994). The middle Velkerri Formation is the organic and most prospective interval in the Beetaloo Sub-basin (Munson, 2014).

Four wells analysed in this study intersect the Velkerri Formation (Alexander 1, Borrowdale 2, Friendship 1 and Prince of Wales 1). These wells are located to the north of the Beetaloo Sub-basin (Figure 1). The samples range in depth from 9m to 599m (Appendix 1).

The Velkerri Formation samples have a variable TOC content, averaging 2.8 wt %, reaching a maximum TOC of 7.5 wt % in the organic rich middle member demonstrating good to excellent organic richness. The Velkerri Formation kerogens have the potential to generate both oil and gas based on hydrogen indices ranging from 13 mg HC/g TOC to 256 mg HC/g TOC. The HI average value is 149 mg HC/g TOC, suggestive of the Velkerri Formation samples in this study are mostly dominated by type III kerogen. Type I to type III kerogens are reported for the Velkerri Formation (Revie, 2017).

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T_max values for the Velkerri Formation samples range from 387°C to 465°C (Table 7). This corresponds to an immature to late oil window (Peters & Cassa, 1994). The Velkerri Formation samples in drillcores Alexander 1 and Borrowdale 2 are immature to mature for oil and gas generation (T_max < 435°C), while the Velkerri Formation in Friendship 1 and Prince of Wales 1 are slightly more mature and have values that range from immature to within the early to late oil window (T_max 398–465°C).
Table 7 Statistical summary of Rock-Eval data by formation, n.d. refers to statistics not determined due to low sample number.

<table>
<thead>
<tr>
<th></th>
<th>Velkerri Formation</th>
<th>Barney Creek Formation</th>
<th>Wollogorang Formation</th>
<th>McDermott Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC Min</td>
<td>0.1</td>
<td>0.5</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>TOC Max</td>
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<td>4.4</td>
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<td>0.7</td>
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<tr>
<td>TOC Average</td>
<td>2.8</td>
<td>1.6</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>TOC stdev</td>
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<td>1.0</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>n =</td>
<td>28</td>
<td>31</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Tmax Min</td>
<td>387</td>
<td>418</td>
<td>420</td>
<td>438</td>
</tr>
<tr>
<td>Tmax Max</td>
<td>465</td>
<td>449</td>
<td>446</td>
<td>439</td>
</tr>
<tr>
<td>Tmax Average</td>
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<td>437</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Tmax stdev</td>
<td>20</td>
<td>7</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>HI Min</td>
<td>13</td>
<td>16</td>
<td>74</td>
<td>49</td>
</tr>
<tr>
<td>HI Max</td>
<td>256</td>
<td>65</td>
<td>118</td>
<td>160</td>
</tr>
<tr>
<td>HI Average</td>
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<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>HI Stdev</td>
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<td>11</td>
<td>n.d.</td>
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</tr>
<tr>
<td>OI Min</td>
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<td>8</td>
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<tr>
<td>OI Max</td>
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<td>34</td>
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<td>27</td>
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<tr>
<td>OI Average</td>
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<td>15.4</td>
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<td>n.d.</td>
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<tr>
<td>OI Stdev</td>
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<td>n.d.</td>
<td>n.d.</td>
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<tr>
<td>n =</td>
<td>24</td>
<td>19</td>
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<td>3</td>
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</tbody>
</table>
Figure 5 Rock-Eval pyrolysis data plots for the Velkerri Formation in drillcores Alexander 1 (green triangles), Borrowdale 2 (black squares), Friendship 1 (blue circles) and Prince of Wales 1 (purple diamonds): a) Tmax (°C) vs HI (mg/g TOC), b) Production Index (PI = S1/(S1+S2)) vs Tmax (°C), c) TOC (wt %) vs HI (mg/g TOC), d) OI (mg/g CO₂) vs HI (mg/g TOC).
4.2 Barney Creek Formation

The Barney Creek Formation is a dolomitic, carbonaceous and pyritic shale and siltstone unit that contains occasional gypsum casts, locally abundant tuffs and breccias (Jackson et al., 1987; Munson, 2014). The Barney Creek Formation was deposited during a marine transgression representing a maximum flooding environment.

The two wells analysed in this study (Bing Bong 5 and Bong Bing 6) are located in the Bing Bong area within the southeast of the Mount Young 1: 250 000 Map Sheet area (Figure 1; Dashlooty, 1983). The samples range in depth from 108.4m to 335.8m (Appendix A).

The Barney Creek Formation samples have variable TOC contents ranging from 0.5 wt % to 4.4 wt % (average 1.6 ±1.0 wt %), indicating fair to excellent organic richness. The kerogen contains HI values < 200 mg/g TOC, demonstrating their potential to expel gas only at peak maturation (Figure 6).

$T_{\text{max}}$ ranges from 418°C to 449°C, representing a range of thermal maturity from immature to peak oil maturity (Figure 6). This demonstrates that the low HI values are a reflection of poor source quality in these samples.

4.3 Wollogorang Formation

The Wollogorang Formation is composed of dolomitic siltstone, oolitic and stromatolitic dolostone in addition to minor dolomitic and quartz sandstone (Jackson, 1982; Ahmad & Wygralak, 1989; Pietsch et al., 1994; Munson, 2014). The lower Wollogorang Formation was deposited in either a lacustrine (Jackson, 1982) or shallow marine environment (Rawlings, 2002) and the upper Wollogorang was deposited in a shallow marine to shelf environment (Rawlings, 2002). This corresponds to a type B to C organofacies (Pepper & Corvi, 1994).

In this study, samples from the Wollogorang Formation were analysed from drillcore DD91RC18 located in the Running Creek prospect in the Robinson River 1:250 000 Map Sheet area (Figure 1; Palmer, 1992). This drillcore was analysed due to its black shale facies, reported bituminous nodules (Palmer, 1992) and oil staining visible in HyLogger imagery (Smith, 2015a). The samples range in depth from 249.6m to 280.8m (Appendix A).

TOC varies between 0.1 wt % and 2.5 wt % suggesting the Wollogorang Formation samples have poor to good organic richness. This variation is likely due to the four different facies within the Wollogorang Formation that range from dolostone, dolomitic siltstone, organic rich siltstone, and dolomitic and quartz sandstone (Palmer, 1992). The kerogen contains HI values comprised between 50 and 150 mg HC/g TOC, demonstrating their potential to expel gas.

$T_{\text{max}}$ for DD91RC18 samples ranges from 420°C to 446°C, showing that the sampled section is immature to peak oil mature.
Figure 6 Rock-Eval pyrolysis data plots for the Barney Creek Formation in drillcores Bing Bong 5 (black squares) and Bing Bong 6 (green diamonds): a) Tmax (°C) vs HI (mg/g TOC), b) Production Index (PI = S1/[S1+S2]) vs Tmax (°C), c) TOC (wt %) vs HI (mg/g TOC), d) OI (mg/g CO2) vs HI (mg/g TOC).
Figure 7 Rock-Eval pyrolysis data plots for the Wollogorang Formation in drillcore DD91RC18 (blue triangle): a) \(T_{\text{max}}\) (°C) vs HI (mg/g TOC), b) Production Index \((P_I = S1/[S1+S2])\) vs \(T_{\text{max}}\) (°C), c) TOC (wt %) vs HI (mg/g TOC), d) OI (mg/g CO2) vs HI (mg/g TOC).
4.4 McDermott Formation

The McDermott Formation is composed of stromatolitic and oolitic dolomite, dolarenite, glauconitic sandstone, shale and siltstone with chert interbeds deposited in shallow marine, subtidal to supratidal environments (Jackson et al., 1987; Ahmad & Wygralak, 1989).

The drillcore analysed in this study (DD91DC1) is located in the Dingo Creek prospect in the Calvert Hills 1:250 000 Map Sheet area (Figure 1; Palmer & Stegman, 1992). The core contains shale and algal laminated dolostones in addition to vuggy intervals with what appears to be solid bitumen in veinlets (Palmer & Stegman, 1992; Smith, 2015b). The samples range in depth from 24.1m to 34.1m (Appendix A).

TOC is low, ranging from 0.2 wt % to 0.7 wt % and the HI ranges from 49 mg HC/g TOC to 160 mg HC/g TOC, demonstrating that the samples have only a poor potential to generate gas. $T_{\text{max}}$ for DD91DC1 is constrained to 438°C to 439°C, corresponding to the early oil window; Table 7). This demonstrates that the low HI values are a reflection of poor source quality in these samples.
Figure 8 Rock-Eval pyrolysis data plots for the McDermott Formation in drillcore DD91DC1 (grey circles): a) Tmax (°C) vs HI (mg/g TOC), b) Production Index ($PI = S1/(S1+S2)$) vs Tmax (°C), c) TOC (wt %) vs HI (mg/g TOC), d) OI (mg/g CO2) vs HI (mg/g TOC).
5 Conclusions

This study appraised the hydrocarbon-generating potential and thermal maturity of source rocks in the McArthur Basin based on new Rock-Eval pyrolysis data from the Velkerri, Barney Creek, Wollogorang and McDermott Formations. This work has been conducted as part of the Exploring for the Future Programme, an Australian Government initiative aimed at improving our understanding of the petroleum resource potential of Northern Australia.

The Velkerri Formation has poor to excellent potential to generate both oil and gas based on TOC in the range 0.1-7.5 wt % and associated HI values in the range 13–256 mg HC/g TOC. Thermal maturity for the samples range from immature to the late oil window (Tmax 387°C-465°C, depth 9m-599m).

The Barney Creek Formation samples have only a fair potential to generate gas, in spite of good organic richness (TOC average = 1.6 ± 1.0 wt %; HI average = 29 ± 11 mg HC/g TOC). Thermal maturity for the samples range from immature to peak oil mature (Tmax = 418°C-449°C, depth 108.4m-335.8m).

The Wollogorang Formation samples analysed in this study have poor to good source potential to generate gas (TOC = 0.1-2.5 wt %; 50 <HI < 150 mg/g TOC). Thermal maturity for the samples range from immature to mature (Tmax = 420°C-446°C, depth 249.6m-280.8m).

The McDermott Formation samples analysed in this study have a poor potential to generate gas (TOC = 0.2-0.7 wt%; HI = 49-160 mg HC/g TOC). Thermal maturity is within the early oil window (Tmax = 438°C-439°C, depth 24.1m-34.1m).

Future work will consist of collating this data with existing data from the Northern Territory Geological Survey and Geoscience Australia’s ORGCHEM databases to generate statistics quantifying the spatial distribution, quantity and quality of McArthur Basin source rocks in addition to mapping the distribution of source rocks. This will provide important insights into the hydrocarbon prospectivity of the greater McArthur Basin.

Acknowledgments

Access to the wells was provided to Geoscience Australia (GA) by the Northern Territory Geological Survey (NTGS). We would like to thank Darryl Stacey (NTGS) for assistance with access to the Darwin Core Library, Northern Territory Geological Survey, Junhong Chen (GA) and Dianne Edwards (GA) for management through the laboratories. We would like to thank Emmanuelle Grosjean (GA), Lisa Hall (GA) and Dorothy Close (NTGS) for peer review.

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Appendix A- Rock-Eval pyrolysis data

This table reports TOC and Rock-Eval pyrolysis data from the McArthur Basin. The table is provided as a separate digital spreadsheet.

Header definitions in the table are as follows:

TOC: Total Organic Carbon (wt%). Measure of the whole rock’s organic richness (traditionally using a LECO instrument; now a calculated value from Rock-Eval 6 etc).

S1: mg HC (extractable)/g rock. Measure of the amount of free hydrocarbons and volatile non-hydrocarbons present in the rock. This includes free hydrocarbons initially present prior to maturation and those that have been released during early maturation and remain after sample recovery. The free hydrocarbons are those thermally desorbed at 300°C for several minutes.

S2: mg HC (kerogen pyrolysate)/g rock. Measure of hydrocarbons formed by cracking of kerogen, resins, asphaltenes and (pyro)-bitumen. This is the potential hydrocarbon yield of the sample at complete kerogen conversion. The pyrolysate is measured from 300°C to 550°C (or 650°C in Rock-Eval 6) at 25°C/min.

S3: mg CO₂ (organic)/g rock. Measure of CO₂ generated from oxygenated functional groups in the kerogen. The CO₂ is collected from 300°C to 390°C at 25°C/min.

T<sub>max</sub> °C: Based on maximum height of the S2 peak in temperature program. Temperature corresponding to the maximum amount of hydrocarbons generated from the cracking of kerogen (S2). Temperature measured outside of the furnace in earlier instruments e.g. Rock Eval II.

HI: Hydrogen Index, mg hydrocarbons (S2)/g TOC. Amount of hydrocarbons released on pyrolysis (S2) normalised to TOC. HI = 100 * S2/TOC

OI: Oxygen Index, mg CO₂ (S3)/g TOC. Amount of carbon dioxide released on pyrolysis normalised to TOC content. OI = 100 * S3/TOC

PI: Production Index, S1/S1+S2. Extent to which the kerogen has been transformed into oil and gas.

BI: Bitumen Index, mg HC (S1)/g TOC. Amount of free hydrocarbons (S1) normalised to TOC content. BI = 100 * S1/TOC
Appendix B- Rock-Eval pyrograms

Rock-Eval pyrograms for all samples analysed in this study are included in a separate digital PDF. Note that the ‘Sample No’ in Appendix A correlates to the ‘sample number’ field on the pyrograms.