Sever 1 Interpretive Summary

Kyalla – Corcoran Interval

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PETROLEUM GEOCHEMISTRY

INTRODUCTORY NOTE

A geochemical investigation has been conducted to assess hydrocarbon prospectivity of the Kyalla, Upper, Middle and Lower Velkerri, and Corcoran Formations in the Sever 1 well located in the Beetaloo Sub-Basin, Northern Territories, Australia. Forty (40) core chip samples from this well were analyzed by a variety of geochemical techniques, including total organic carbon (TOC, LECO®), programmed pyrolysis (SRA) and organic petrology with measured maceral reflectance (R_o). In addition, client supplied published geochemical data for 97 samples were also incorporated into the interpretive evaluation. The complete results of these analyses are documented in this report along with an integrated geochemical interpretation that is summarized in the following table.

Well Name	Formation	Main Product	Thermal Maturity	Source Rock Richness	Organic Matter Type	Shale Oil/Gas Risk
Sever 1	Kyalla	***Estimated Original →***		*Fair (0.93% TOC)*	*Oil-prone Type II*	**High** *(Oil)*
Measured Currently →		Oil	Peak Oil Window	Fair (0.72% TOC)	Gas-prone Type III	
Sever 1	Upper Velkerri	***Estimated Original →***		*Very Good (2.88% TOC)*	*Oil-prone Type II*	**Moderate** *(Oil)*
Measured Currently →		Oil	Peak Oil Window	Very Good (2.15% TOC)	Inert Type IV	
Sever 1	Middle Velkerri	***Estimated Original →***		*Excellent (4.93% TOC)*	*Oil-prone Type II*	**Low** *(Gas)*
Measured Currently →		Dry Gas	Dry Gas Window	Very Good (3.79% TOC)	Inert Type IV	
Sever 1	Lower Velkerri	***Estimated Original →***		*Good (1.74% TOC)*	*Oil-prone Type II*	**High** *(Gas)*
Measured Currently →		Dry Gas	Dry Gas Window	Fair (0.80% TOC)	Gas-prone Type III	
Sever 1	Corcoran	***Estimated Original →***		*Good (1.03% TOC)*	*Oil-prone Type II*	**High** *(Gas)*
Measured Currently →		Dry Gas	Dry Gas Window	Fair (0.58% TOC)	Inert Type IV	

Current TOC averages represent all data available; Original TOC averages are only high graded samples that have PPy data

Table 1. Geochemical Summary

KYALLA

Six (6) samples from the Kyalla Formation were analyzed for LECO TOC content and programmed pyrolysis, with the remaining data set (4 samples) composed of client supplied public data (Fig. 1). TOC contents ranged from 0.47 to 1.13 wt.% and averaged 0.72 wt.% (fair). Two (2) samples have TOC content above the minimum requirement of 1 wt.% for *effective* petroleum source rocks, while none of the samples have TOC content above the minimum requirement of 2 wt.% for *economic* petroleum source rocks. Highest TOC content was found in the basal portion of the designated Kyalla interval (326.1 m depth) (Fig. 1) and there is a general trend of decreasing TOC toward the middle of this interval, reaching

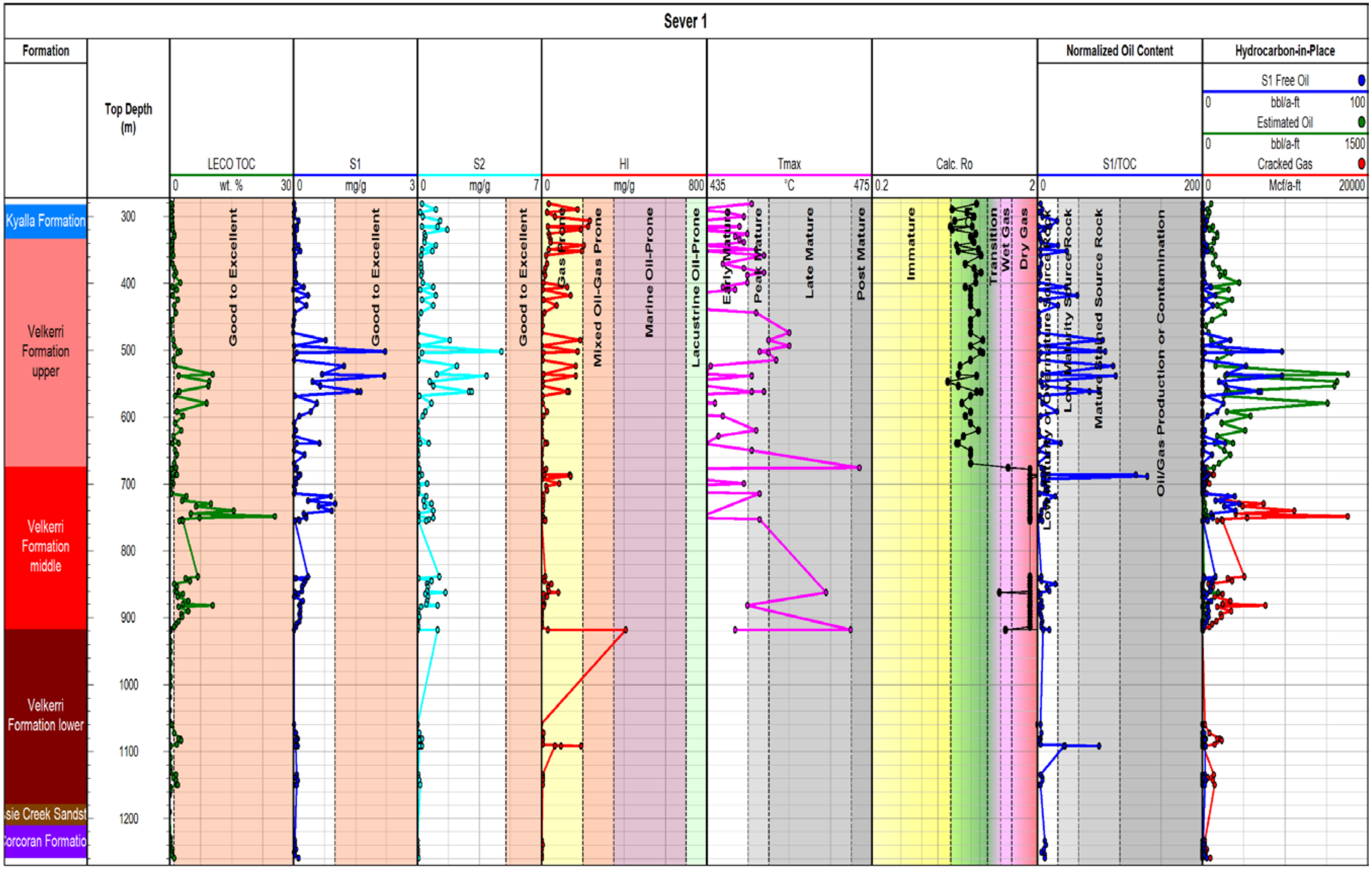

Figure 1. Geochemical depth plots for the Sever 1 well.

a minimum at a depth of 301.97 m, then increasing upward again. This is likely related to a depositional cycle within this interval and could be indicative of a parasequence boundary.

The S1 values of the Kyalla source rock samples average 0.05 mg HC/g rock (1 bbl oil/acre-ft) and the S2 values average 0.70 mg HC/g rock (15 bbl oil/acre-ft). The S1 and S2 values indicate very low in-situ hydrocarbon saturation and poor remaining generative potential (Fig. 1). The normalized oil contents (NOC) in the Kyalla samples, (S1/TOC) x 100, average 7 (Fig. 1). NOC values of 20 to 50 are typical of low maturity source rocks, whereas values of 50 to 100 indicate possible oil staining or shows in thermally mature, tight petroleum source rocks. NOC > 100 are often associated with conventional oil reservoirs and indicate good prospectivity in unconventional shale oil plays. Very low NOC values < 20 are common in post-mature source rocks that have generated and expelled most of their in-situ hydrocarbon saturation, but can also be found in source rocks with poor original hydrocarbon generation capacity. Jarvie (2012) has utilized a depth comparison of TOC versus programmed pyrolysis S1 yields as a potential indicator of producible hydrocarbon saturation in unconventional source rocks. When the S1 yields (reported as mg HC/g rock) exceed or "cross-over" the measured TOC content (reported as wt.%), this would be interpreted to represent zones with good potential for containing producible hydrocarbon saturation (or zones of possible contamination). In the present study, there is no S1 cross over TOC in any of the Kyalla samples analyzed (Fig. 1).

The measured Hydrogen Index (HI) values in the Kyalla average 108 mg HC/g TOC, indicating gas-prone Type III kerogen quality in these source rocks at present day. Original HI_o of these samples are estimated to average 450 mg HC/g rock, which indicate oil-prone Type II kerogen. Transformation ratios (TR) based upon HI are 82%, which is consistent with late oil to early wet gas window thermal maturity. High variability in HI values mean that this parameter should be interpreted with caution since there is no actual measured kerogen data to constrain the estimation. The T_{max} values in the Kyalla samples average 439°C. T_{max} between 435 and 445°C typically indicate peak oil window, while values between 445 and 450°C indicate late oil window (Type II kerogen). On the basis of these guidelines, the Kyalla T_{max} values in this well would be interpreted to be in the peak oil widow. Using the formula published by Jarvie et al. (2007) for Type II kerogen (Calculated $R_o = (0.0180)(T_{max}) - 7.16$), the measured T_{max} value of 439°C is equivalent to a Calc. %R_o value of 0.74%. It is important to note that T_{max} is only a crude measure of thermal maturation (Peters, 1986) and it can be compromised by a variety of pyrolysis artifacts and caveats.

The Production Index (PI) value in the Kyalla samples average 0.07. These low PI values are more typical of immature source rocks, which usually have PI values < 0.10. However, they could also indicate source rocks in which in-situ hydrocarbon saturation has been expelled, possibly because of a migrating gas charge from underlying source rock intervals.

UPPER VELKERRI FORMATION

Twenty-nine (29) samples from the Upper Velkerri Formation were analyzed for LECO TOC content and programmed pyrolysis, with the remaining data set (16 samples) composed of client supplied public data (Fig. 1). The Upper Velkerri Formation in the Sever 1 well exhibits very good generative potential for petroleum source rocks based on TOC content values (Fig. 1). TOC content ranges from 0.28 to 10.60 wt.% and averages 2.15 wt.% (very good). Fourteen (14) samples analyzed exceed the minimum value of 2.0 wt.% for *economic* petroleum source rocks (Lewan, 1987). High TOC samples occur in the lower portion of the sampled interval between depths of ~500 to 600 m (Fig. 1).

The S1 values in the Upper Velkerri average 0.36 mg HC/g rock (8 bbl oil/acre-ft), indicating poor in-situ hydrocarbon saturation (Fig. 1) and are consistent with an elevated thermal maturity in the condensate/wet gas window. These values should be considered a minimum for in-situ oil saturation since they do not account for potential loss of volatile components during sample collection and analysis. NOC values in the Upper Velkerri interval are slightly higher in comparison to the Kyalla Formation and average 16. Oil cross over (NOC > 100) was not observed in any of these samples, but several samples did have elevated NOC values in the 75-95 range (Fig. 1), which could suggest possible producible hydrocarbons at these depths. The S2 values in the Upper Velkerri average 0.75 mg HC/g rock (16 bbl oil/acre-ft), indicating poor remaining hydrocarbon generation potential.

Measured HI values in these samples average 50 mg HC/g TOC, which indicate inert Type IV kerogen quality in these source rocks at present day. This is generally consistent with elemental analyses of select kerogen samples from the Upper Velkerri that have average H/C ratios of 0.71, which is typical for Type IV kerogen. These values have been reduced due to thermal maturity. Estimated original HI_o values in these samples average 450 mg HC/g TOC, which indicate oil-prone Type II kerogen quality. Transformation ratios (TR) based upon HI average 92%, which is consistent with a gas window thermal maturity.

The organic-matter in the Upper Velkerri interval in the Sever 1 well is thermally mature and is interpreted to be in the peak oil window. Programmed pyrolysis T_{max} values are highly variable and average 442°C on the basis of select samples evaluated by examination of pyrogram data (Fig. 1). Using the formula published by Jarvie et al. (2007) for Type II kerogen (Calculated $R_o = (0.0180)(T_{max}) - 7.16$), the average measured T_{max} value of 442°C is equivalent to a Calc. $\%R_o$ value of 0.79%. It is important to note that T_{max} is only a crude measure of thermal maturation (Peters, 1986) and it can be compromised by a variety of pyrolysis artifacts and caveats.

Production Index (PI) values in these Upper Velkerri samples average 0.30. These elevated PI values are more consistent with source rocks in the late oil window, which tend to have PI values between ~0.25 and 0.35. The PI values tend to be more elevated in the basal portion of the Upper Velkerri interval, which could suggest possible producible in-situ oil saturation within this horizon.

Organic petrology was performed on one sample from the Upper Velkerri interval (400.00−400.03 m). The results from this analysis show a distribution that consists of macerals identified as either fluorescing Alginite, low reflecting solid bitumen or high reflectance solid bitumens (Fig. 2). The single reading taken on fluorescing Alginite has a reflectance value of 0.64% R_o and exhibits orange/brown to dark brown fluorescence. These observations would suggest a thermal maturity within the late oil window. The low reflectance solid bitumen population is dominant and has relatively higher reflectance values that average 0.98% R_o and are considered the most representative indigenous kerogen population for thermal maturity assessment. This higher reflecting group of organic macerals is thought to possibly represent fine grained migrabitumen, although they could also represent preserved original cyanobacterial kerogen that has subsequently undergone thermal conversion to form a dispersed solid bitumen network within these Velkerri Formation source rocks. The mean measured reflectance value for the single sample of high reflectance solid bitumen is 1.28% R_o. Published solid bitumen conversions were applied to these reflectance values. The conversion formula published by Landis and Castaño (1995) for bitumen in lenses/layers (Eq. R_o = (Bitumen R_o +0.41)/1.09) was applied to the low reflectance bitumens and resulted in a 1.27% Eq. R_o. The conversion formula published by Jacob (1985) (Eq. R_o = (Bitumen $R_o \times$ 0.618) + 0.4) for 'angular-like' pyrobitumen trapped in mineral pore spaces was applied to the high reflectance bitumen and resulted in a 1.19% Eq. R_o. The Landis and Castaño (1995) conversion suggest a condensate/wet gas window thermal maturity, which is much higher than predicted by T_{max} for these samples. The Jacob (1985) conversion also suggests a thermal maturity that is within the early condensate/wet gas window. Comparison with other samples examined in the current study suggest that the high reflectance solid bitumen reflectance readings can be corrected using the Jacob (1985) formula and often these “corrected” values compare favorably to “uncorrected” readings from the population of low reflectance solid bitumen within the same sample. In this well that does not appear to be entirely valid since the calculated 1.19% Eq. R_o value and the measured 0.98% R_o values would suggest the Lower Velkerri samples in this well are within the early wet gas/condensate and late oil windows respectively.

The thermal maturity of the Upper Velkerri source rocks was also evaluated by measured Kübler Index values from XRD, which are based upon illite crystallinity. These values can be used as maturity indicator when samples contain sufficient high quality clays (Abad, 2008). Three (3) samples from the Upper Velkerri (avg. 41% clays) have an average measured Kübler Index of 0.238, which is equivalent to a measured vitrinite reflectance of >4% (late stage metagenesis). This interpretation is inconsistent and suggests a much higher thermal maturity in comparison with the organic petrology data reported in this study. This observation suggests the Kübler Index should be used with caution to evaluate thermal maturity in Mesoproterozoic aged source rocks.

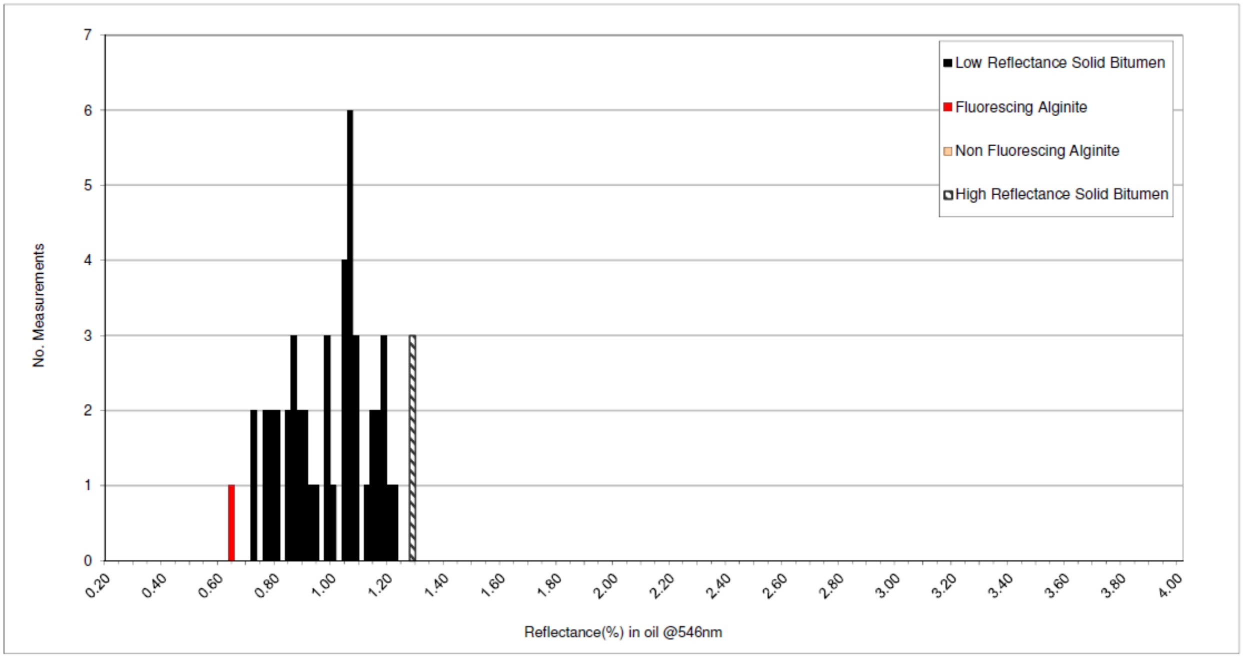

Figure 2. Organic petrology of the Upper Velkerri (400 m) in the Sever 1 well. Mean maceral reflectance of low reflecting solid bitumen is 0.98% R_o. The high reflecting solid bitumen has mean reflectance of 1.28% R_o, which equates to calculated Eq. R_o of 1.19% R_o using the conversion of Jacob (1985).

MIDDLE VELKERRI FORMATION

Three (3) samples from the Middle Velkerri Formation were analyzed for LECO TOC content and programmed pyrolysis, with the remaining data set (39 samples) composed of client supplied public data (Fig. 1). TOC contents ranged from 0.09 to 25.60 wt.% and averaged 3.79 wt.% (very good). Twenty-four (24) of these samples exceed the minimum requirement of 2 wt.% for *economic* petroleum source rocks. There appears to be three distinct cycles of TOC within this interval with maxima occurring at depths of 749, 840 and 882 m (Fig. 1), although the zone between 758-840 m was not sampled due to the presence of a volcanic intrusive sill within this interval. These three organic rich intervals have been previously recognized within the Middle Velkerri (Lanigan et al, 1994) and could be associated with the base of transgressive systems tracts (TST) in a series of platform/ramp parasequences (Bohacs et al., 2013). These stepwise changes in TOC and corresponding minimal change in Hydrogen Index values (HI) suggests that production was the major control on organic richness along with auto-dilution by pelagic carbonate (Bohacs et al., 2013).

The S1 values in the Middle Velkerri source rock samples average 0.22 mg HC/g rock (5 bbl oil/acre-ft) and S2 values are low with an average 0.38 mg HC/g rock (8 bbl oil/acre-ft). The S1 and S2 values imply generally poor in-situ hydrocarbon saturation and poor remaining generative potential (Fig. 1). The normalized oil content (NOC) in the Middle Velkerri samples average 7 (Fig. 1) and there are only two samples exhibiting oil "cross-over", both of which are very low TOC (<0.10 wt. %) and thus do not necessarily represent zones containing producible hydrocarbon saturation.

Measured Hydrogen Index (HI) values in the Middle Velkerri average 22 mg HC/g TOC, indicating inert Type IV kerogen quality in these source rocks at present day (Fig. 1). This is generally consistent with elemental analyses of select kerogen samples from the Middle Velkerri that have average H/C ratios of

0.67, which is typical for Type IV kerogen. These values have been reduced due to thermal maturity. Original HI_o of these samples are estimated to average 450 mg HC/g rock, which indicate oil-prone Type II kerogen. Transformation ratios (TR) based upon HI average 97%, which is consistent with a dry gas window thermal maturity. T_{max} values in the Middle Velkerri samples average 499°C on the basis of a few select samples which were considered valid. T_{max} values > 470°C typically indicate post-mature dry gas window (Type II kerogen). Using these guidelines, the average Middle Velkerri T_{max} values in this well would be interpreted to be in the dry gas window. Using the formula published by Jarvie et al. (2007) for Type II kerogen (Calculated $R_o = (0.0180)(T_{max}) - 7.16$), the average measured T_{max} value of 499°C is equivalent to a Calc. %R_o value of 1.82%. It is important to note that T_{max} is only a crude measure of thermal maturation (Peters, 1986) and it can be compromised by a variety of pyrolysis artifacts and caveats.

Production Index (PI) values in the Middle Velkerri samples average 0.46. These elevated PI values are more consistent with source rocks in the late oil to condensate window, which typically have PI values between ~0.25 and 0.40, whereas samples in the dry gas window tend to have much lower PI values due to extensive oil cracking to gas.

The high thermal maturity of the Middle Velkerri source rocks is also supported by measured Kübler Index values from XRD, which are based upon illite crystallinity. These values can be used as maturity indicators when samples contain sufficient high quality clays (Abad, 2008). Two (2) samples from the Middle Velkerri (avg. 30% clays) have an average measured Kübler Index of 0.210, which is equivalent to a measured vitrinite reflectance of >4% (late stage metagenesis). This interpretation is inconsistent with the other geochemical data reported in this study and suggests the Kübler Index should be used with caution to evaluate thermal maturity in Mesoproterozoic aged source rocks.

LOWER VELKERRI FORMATION

Two (2) samples from the Lower Velkerri Formation were analyzed for LECO TOC content and programmed pyrolysis, with the remaining data set (29 samples) composed of client supplied public data (Fig. 1). TOC contents ranged from 0.12 to 2.93 wt.% and averaged 0.80 wt.% (fair). Only three (3) of these samples exceed the minimum requirement of 2 wt.% for *economic* petroleum source rocks. Highest TOC was found in the basal portion of the sampled interval with two distinct maxima occurring at depths of 1085 and 1150 m (Fig. 1).

The S1 values in the Lower Velkerri source rock samples average only 0.07 mg HC/g rock (2 bbl oil/acre-ft) and S2 values are low with an average 0.21 mg HC/g rock (5 bbl oil/acre-ft). The S1 and S2 values imply poor in-situ hydrocarbon saturation and poor remaining generative potential (Fig. 1). The normalized oil content (NOC) in the Lower Velkerri samples average 5 (Fig. 1) and there no samples exhibiting oil “cross-over”.

Measured Hydrogen Index (HI) values in the Lower Velkerri average 55 mg HC/g TOC, indicating gas-prone Type III kerogen quality in these source rocks at present day (Fig. 1). Original HI_o of these samples are estimated to average 450 mg HC/g rock, which indicate oil-prone Type II kerogen. Transformation ratios (TR) based upon HI average 90%, which is consistent with dry gas window thermal maturity. T_{max} values in the Lower Velkerri samples average 556°C on the basis of select samples. T_{max} values > 470°C typically indicate post-mature dry gas window (Type II kerogen). Using these guidelines, the average Lower Velkerri T_{max} values in this well would be interpreted to be in the dry gas window. Using the formula published by Jarvie et al. (2007) for Type II kerogen (Calculated $R_o = (0.0180)(T_{max}) - 7.16$), the average measured T_{max} value of 556°C is equivalent to a Calc. %R_o value of 2.85%. It is important to note that T_{max} is only a crude measure of thermal maturation (Peters, 1986) and it can be compromised by a variety of pyrolysis artifacts and caveats.

Production Index (PI) values in the Lower Velkerri samples average 0.33. These elevated PI values are more consistent with source rocks in the late oil window, which typically have PI values between ~0.25 and 0.35, whereas samples in the dry gas window tend to have much lower PI values due to extensive oil cracking to gas. This could indicate the presence of minor amounts of contamination (in the S1) in these samples and thus PI values should be interpreted with caution.

Corcoran Formation

No samples from the Corcoran Formation were analyzed for LECO TOC content or programmed pyrolysis and all data evaluated (8 samples) is composed of client supplied public data (Fig. 1). TOC contents ranged from 0.39 to 1.19 wt.% and averaged 0.58 wt.% (fair). Only one (1) of these samples exceeds the minimum requirement of 1 wt.% for *effective* petroleum source rocks and none exceed the 2 wt. % requirement for *economic* petroleum source rocks. Highest TOC was found in lower most sample collected from this interval at a depth of 1259.85 m (Fig. 1).

The S1 values in the Corcoran source rock samples average only 0.07 mg HC/g rock (1 bbl oil/acre-ft) and S2 values are very low with an average 0.03 mg HC/g rock (1 bbl oil/acre-ft). The S1 and S2 values imply poor in-situ hydrocarbon saturation and poor remaining generative potential (Fig. 1). The normalized oil content (NOC) in the Corcoran samples average 9 (Fig. 1) and there no samples exhibiting oil “cross-over”.

Measured Hydrogen Index (HI) values in the Corcoran Formation average only 3 mg HC/g TOC, indicating inert Type IV kerogen quality in these source rocks at present day (Fig. 1). Original HI_o of these samples are estimated to average 450 mg HC/g rock, which indicate oil-prone Type II kerogen. Transformation ratios (TR) based upon HI average 100%, which is consistent with dry gas window thermal maturity. No reliable T_{max} values were found in the Corcoran samples and interpretation of thermal maturity is based upon extrapolation of data from the overlying source rock intervals, which would suggest an average R_o value of ~3.2% within the late dry gas window.

Production Index (PI) values in the Corcoran samples average 0.79. These very elevated PI values are not considered reliable and are more a consequence of data scatter due to very low S1 and S2 values.

Original Generative Potential and Hydrocarbon Yield Calculations

Petroleum generative capacity depends on the original quantity of organic matter (TOC_o) and the original type of organic matter (HI_o) (Peters et al., 2005, p. 97). The petroleum generation process has likely decreased the remaining generative potential as measured by TOC_{pd} and HI_{pd} in the Kyalla, Velkerri and Corcoran source rocks examined in this study. We can estimate the extent of the petroleum generation process, the volume of expelled oil and the expulsion efficiency by making some reasonable assumptions based on the core geochemical data and published regional information (Jarvie et al., 2007; Peters et al., 2005).

HI_o values can be computed from visual kerogen assessments and assigned kerogen-type HI_o average values using the following equation (Jarvie et al., 2007):

$$HI_o = \left(\frac{\%\text{Type I}}{100}\times 750\right) + \left(\frac{\%\text{Type II}}{100}\times 450\right) + \left(\frac{\%\text{ Type III}}{100}\times 125\right) + \left(\frac{\%\text{Type IV}}{100}\times 50\right) \quad (1)$$

This equation requires the input of maceral percentages from visual kerogen assessment of a source rock. For the present study, only limited kerogen data were available. Where available, these kerogen data sets were used. In the absence of other measured kerogen data original kerogen type were interpreted in the context of measured present day TOC, HI and OI values to arrive at an appropriate kerogen mix for each sample examined in this investigation. All samples were modeled using appropriate kerogen mix to maintain an appropriate transformation ratio consistent with the interpreted thermal maturity. The average maceral percentage in the various formations evaluated in the current study are shown in Table 2, along with the resultant average original HI_o values calculated using equation (1) above. The kerogen estimations used in this study are generally in agreement with other published values that suggest Type II to a mixed Type I/II kerogen assemblage (Law et al., 2010; Crick et al., 1988; Taylor et al., 1994).

Formation	%Type I 750 HI_o	%Type II 450 HI_o	%Type III 125 HI_o	%Type IV 50 HI_o	HI_o
Kyalla	0	100	0	0	450
Upper Velkerri	0	100	0	0	450
Middle Velkerri	0	100	0	0	450
Lower Velkerri	0	100	0	0	450
Corcoran	0	100	0	0	450

Table 2. Average Kerogen Estimations for Sever 1 well.

The extent of the petroleum-generation process, or transformation ratio (TR) which is also called fractional conversion, is calculated as follows (Jarvie et al., 2007, p. 497):

$$TR_{HI} = 1 - \frac{HI_{pd}\left[1200 - HI_o\left(1 - PI_o\right)\right]}{HI_o\left[1200 - HI_{pd}\left(1 - PI_{pd}\right)\right]} \tag{2}$$

HI_{pd} and PI_{pd} are the measured HI and PI values for the various source rock samples in this well. The average HI_{pd} and PI_{pd} for the formations evaluated in the current study are shown in Table 3. HI_o and PI_o are the original HI and PI values for immature organic matter in the rocks. For this calculation using the assumptions described previously results in an average HI_o values of 450 mg HC/g TOC (Table 2). We assume a PI_o of 0.02 (see Peters et al., 2005). Using these values in equation 2, the extent of fractional conversion of HI_o to petroleum is 0.82 to 1.00 (Table 3), i.e., on average an estimated 82 to 100% of the petroleum generation process has been completed.

The original TOC_o in the source rocks before burial and thermal maturation is constrained by mass balance considerations as follows (corrected from Jarvie et al., 2007):

$$TOC_o = \frac{HI_{pd}\left(\frac{TOC_{pd}}{1+k}\right)(83.33)}{\left[HI_o\left(1 - TR_{HI}\right)\left(83.33 - \left(\frac{TOC_{pd}}{1+k}\right)\right)\right] + \left[HI_{pd}\left(\frac{TOC_{pd}}{1+k}\right)\right]} \tag{3}$$

In this equation k is a correction factor based on residual organic carbon being enriched in carbon over original values at high maturity (Jarvie et al., 2007, p. 497). For Type II kerogen the increase in residual carbon C_R at high maturity is assigned a value of 15% (whereas for Type I, it is 50%, and for Type III, it is 0%) and the correction factor k is then $TR_{HI} \times C_R$. The kerogen mix for each individual sample was used in this calculation.

Using equation 3, the average estimated original TOC_o for the source rock samples in this well before petroleum generation varies from 0.93 to 4.93 wt.% (Table 3).

The original generation potential $S2_o$ can be calculated using the following equation:

$$S2_o = \left(\frac{HI_o \times TOC_o}{100}\right) \tag{4}$$

For the source rocks examined in the Sever 1 well, the average $S2_o$ values vary from 4.2 to 22.2 mg HC/g rock or approximately 92 to 485 bbl/acre-ft (multiply $S2_o$ by 21.89 to calculate barrels/acre-ft, Jarvie and Tobey, 1999) (Table 3).

Knowing the measured remaining generation potential S2 from programmed pyrolysis and using the calculated original generation potential $S2_o$ enables a determination of the amounts of hydrocarbons generated. A VR_o algorithm can then be applied to estimate fractional oil cracking thereby converting yields to estimated oil and cracked gas (reported as Mcf/acre-ft or thousand cubic feet/acre-ft).

$$\text{Original } (S2_o) - \text{Remaining } (S2) = \text{Generated HCs} \quad (5)$$

Using this methodology for the Kyalla samples analyzed in the current study, the generated oil yields average 76 bbl/acre-ft (Table 3). For the Upper Velkerri samples analyzed in the current study, the generated oil yields average 267 bbl/acre-ft along with 4 Mcf/acre-ft of secondary cracked gas. Thermal maturity is estimated to have dramatically increased in the underlying Middle Velkerri due to the presence of an igneous intrusive and the generated cracked gas yield is 2771 Mcf/acre-ft and 15 bbl/acre-ft of residual oil/condensate. The Lower Velkerri generated 995 Mcf/acre-ft of cracked gas and had 1 bbl/acre-ft of residual oil, while the underlying Corcoran Formation generated 605 Mcf/acre-ft of cracked gas (due to elevated maturity all residual oil in this interval was estimated to have cracked to secondary gas) (Table 3).

Formation	TOC_{pd}	HI_{pd}	$S2_{pd}$ bbl/a-ft	HI_o	TR	TOC_o	$S2_o$ bbl/a-ft	S1 Free Oil bbl/a-ft	Est. Oil bbl/a-ft	Cracked Gas Mcf/a-ft
Kyalla	0.72	108	15	450	0.82	0.93	92	1	76	0
Upper Velkerri	2.19	50	16	450	0.92	2.88	284	8	267	4
Middle Velkerri	3.79	22	8	450	0.97	4.93	485	5	15	2771
Lower Velkerri	1.29	55	5	450	0.90	1.74	171	2	1	995
Corcoran	0.75	3	1	450	1.00	1.03	101	1	0	605

Table 3. Hydrocarbon Yields average data for Sever 1 well.

For shale oil systems, the amount of hydrocarbons (oil + gas) expelled from the rocks can be estimated as the difference between the amount of residual oil measured via programmed pyrolysis (S1) and the amount of estimated generated hydrocarbon yields determined above (equation 5). The expulsion efficiency (ExEf) can then be calculated as a direct proportion of the measured retained oil saturations and the average generated hydrocarbon yields. Thus, the resulting expulsion efficiency for the Kyalla, Velkerri and Corcoran intervals is 97 to 99%, which may be a consequence of increased thermal maturity resulting in more volatile in-situ oil compositions and higher gas/oil ratios, both of which would tend to enhance expulsion in these rock intervals. It could also suggest flushing of the Kyalla and Upper Velkerri intervals with gas generated in the underlying Middle Velkerri during igneous intrusion emplacement.

The Kyalla, Velkerri and Corcoran source rock intervals in the Sever 1 well are interpreted to be in the peak oil to dry gas windows and hydrocarbon yield calculations suggest moderate to significant amounts of generation have occurred (both oil and thermogenic cracked gas). From an exploration risk perspective, this is generally favorable. However, it is useful to relate these hydrocarbon yields to other productive unconventional US Shale plays (Table 5). In doing so, the potential critical value is not necessarily the generated oil and gas yields, but also the original ($S2_o$) generation potential of the source rocks. These values related to the ultimate volumes of hydrocarbon that could be generated at depth in the basin. For the Kyalla original generation potential ($S2_o$) averages only 92 bbl oil/acre-ft, this is below all of the other formations on the list of unconventional US Shale plays shown below. Likewise, the 171 bbl oil/acre-ft for the Lower Velkeri and 101 bbl oil/acre-ft for the Corcoran are also well below US Shale plays (Table 5). For the Upper and Middle Velkerri intervals, original generation potential is much higher from 284 to 485 bbl oil/acre-ft and both of these units do compare favorably with other unconventional US Shale plays.

Sample Database Averages TOC >1%	HI° mg/g TOC	TR	TOC° wt%	S2° mg/g Rock	Remaining Potential bbl/a-ft	Original Potential bbl/a-ft	Oil Cracked %	S1 Free Oil bbl/a-ft	Estimated Oil bbl/a-ft	Cracked Gas Mcf/a-ft
Barnett Shale Ft. Worth Basin	435	0.84	5.38	23.40	94	513	0.40	33	251	1005
Barnett Shale Delaware Basin	435	0.91	5.25	22.84	52	500	0.80	32	90	2149
Woodford Shale Delaware Basin	480	0.89	6.41	30.79	139	674	0.89	46	60	2854
Haynesville Shale E. Texas Basin	400	0.98	3.93	15.73	7	344	1.00	3	0	2022
Fayetteville Shale Arkoma Basin	435	0.95	3.34	14.53	15	318	1.00	10	0	1820
Woodford Shale Arkoma Basin	520	0.87	5.15	26.80	12	587	0.70	87	170	2431
Eagle Ford Shale Gulf Coast Basin	520	0.85	3.19	16.61	61	364	0.47	22	161	848
Marcellus Shale Appalachian Basin	600	0.97	6.44	38.66	34	847	1.00	24	0	4875
Utica Shale Appalachian Basin	450	0.98	2.74	12.32	6	270	1.00	12	0	1585
Barnett Shale Oil	450	0.47	5.47	24.64	326	540	0.00	79	213	0
Barnett Shale Gas	450	0.96	5.58	25.13	23	550	0.87	7	68	2751
Kyalla	450	0.82	0.93	4.18	15	92	0.00	1	76	0
Upper Velkerri	450	0.92	2.88	12.97	16	284	0.00	8	267	4
Middle Velkerri	450	0.97	4.93	22.17	8	485	0.95	5	15	2771
Lower Velkerri	450	0.90	1.74	7.81	5	171	0.96	2	1	995
Corcoran	450	1.00	1.03	4.63	1	101	1.00	1	0	605

Table 4. Geochemical Properties and Generation Potential for US Shale plays and current study.

HYDROCARBON SATURATIONS

A comparison was made between oil saturations based upon shale rock properties (SRP) analyses and those determined via programmed pyrolysis for a single sample from the Middle Velkerri Formation (756.56 m depth). The measured SRP oil saturations are exactly the same as those determined by SRA methods using the S1 yields. The saturation determined by SRP was 0.15 mg oil/g AR Rock (3 bbl oil/acre-ft), while that determined from S1 yields on a nearby sample (756.54 m depth) is also 0.15 mg oil/g AR Rock (3 bbl oil/acre-ft). This suggests that the S1 is reliably estimating the total hydrocarbons extracted using Dean-Stark methods (toluene).

UNCONVENTIONAL OIL & GAS RISK ASSESSMENT

The Mesoproterozoic Kyalla, Velkerri and Corcoran Formation source rocks in the Sever 1 well have been evaluated for unconventional oil and gas potential. These source rock samples are presented in a modified geochemical risk assessment diagram (Fig. 3) based upon published results from the Barnett Shale in the Fort Worth Basin. The data illustrated in the star plot represents average values for all four diagnostic ratios where available. Also shown are the recommended areas for unconventional oil (in green) and gas (in red). Data that lies above the minimum threshold and within the shaded areas indicates samples with low geochemical risk for either thermogenic oil or gas production. Data that lie below the minimum threshold and fall in the immature region (in gray) indicate a high risk for commercial shale oil or gas production. Transformation Ratios (TR) were calculated based upon HI_o estimates using measured and interpreted fractional composition of kerogen macerals.

The Kyalla source rock interval in the Sever 1 well is interpreted to represent a high geochemical risk for in-situ shale oil production. The average measured TOC content of 0.72 wt.% is below the generally accepted minimum value of 1% TOC to be considered an *effective* source rock for hydrocarbon generation/expulsion (Fig. 3). It is also well below the minimum requirements of 2 wt.% for *economic* petroleum source rocks, which is also the minimum threshold for prospective shale gas. Original organic matter type is interpreted to be predominantly oil-prone Type II marine algal kerogen. Thermal maturity parameters from programmed pyrolysis place the Kyalla source interval in the peak oil window. The average T_{max} value of 439°C is above recommended minimum value of 435°C for shale oil and below the minimum of 455°C for shale gas (Fig. 3). This amount of conversion would likely be sufficient to generate/expel minor amounts of hydrocarbons from this oil prone source facies. Transformation ratios (TR), the least constrained risk parameter, average 82% and fall above the recommended minimum of 50% for shale oil and 80% for shale gas systems (Fig. 3). On the basis of all of these measured geochemical risk parameters, the Kyalla source interval would be considered a high risk for shale oil because despite having sufficient thermal maturity it has insufficient organic richness (Fig. 3). The measured in-situ oil saturation from S1 yields in this interval is also very low (avg. 1 bbl/acre-ft) and this further enhances the high risk for shale oil production.

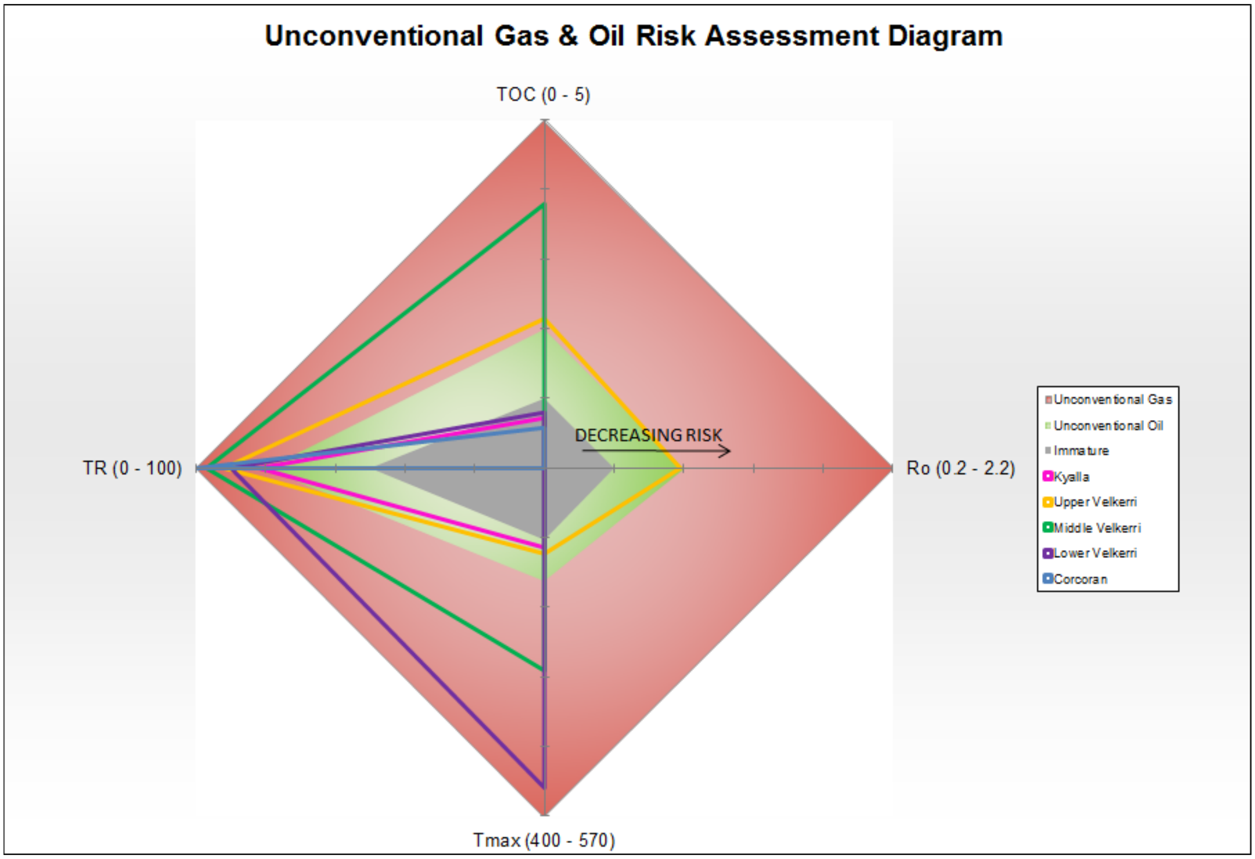

Figure 3. Geochemical Risk Assessment diagram for Mesoproterozoic Kyalla, Velkerri and Corcoran Formation source rocks in the Sever 1 well.

Two other formations examined in the current study are also considered to represent high risk for in-situ shale gas production on the basis of insufficient organic richness. The Lower Velkerri interval examined has an average TOC value of 0.80 wt.% and the Corcoran Formation averages only 0.58 wt.%, which are both below the recommended minimum threshold of 2 wt. % TOC for shale gas. Thermal maturity indicators suggest dry gas window maturity. On the risk assessment diagram, the Transformation Ratios of 90 and 100% are both above the recommended minimum of 80% for shale gas (Fig. 3). The average T_{max} value of 556°C in the Lower Velkerri is also just above the recommended minimum value of 455°C for shale gas (Fig. 3).

In contrast, both the Upper Velkerri and Middle Velkerri intervals in the Sever 1 well are interpreted to have moderate and low geochemical risk for potential shale oil and shale gas development, respectively. The Upper Velkerri interval examined has an average TOC value of 2.15 wt.% and the Middle Velkerri is even higher with an average 3.79 wt.%, which are both above the recommended minimum threshold of 2 wt. % TOC for shale gas. Thermal maturity indicators suggest peak oil to dry gas window maturity. On the risk assessment diagram, the Transformation Ratios of 92 and 97% are above the recommended minimum of 80% for shale gas (Fig. 3). The average T_{max} values of 442 and 499°C are also both above the recommended minimum values of 435°C for shale oil and 455°C for shale gas (Fig. 3). Measured maceral reflectance values in the Upper Velkerri give a mean for low reflectance bitumen of 0.98% R_o, which is well above the recommended minimum value of 0.5% for shale oil and just below the recommended minimum of 1.0% for shale gas (Fig. 3). On the basis of all of these measured parameters, the Upper Velkerri source interval would be considered a low risk for shale oil since all risk parameters fall above recommended minimum thresholds (Fig. 3). However, measured in-situ oil saturation from S1 yields in this interval is very low (avg. 8 bbl/acre-ft) and for this reason the Upper Velkerri is considered a moderate risk for shale oil production.

Hydrocarbon yield calculations on as-received samples show estimates of average generated oil from the Upper Velkerri at 267 bbl oil/acre-ft along with a minor amount of secondary cracked gas (4 Mcf gas/acre-ft)(Fig. 4). In the Kyalla estimated oil generation averages 76 bbl oil/acre-ft (Fig. 4). As a comparison, a representative example from the core area of Barnett Shale oil production in the Fort Worth Basin has an estimated generated oil yield of 213 bbl/a-ft with a measured in-situ oil saturation of 79 bbl/a-ft (Fig. 4). While the generated oil yield of the Upper Velkerri exceeds the Barnett, the in-situ oil saturation is significantly lower and this is the reason the Upper Velkerri is considered a moderate risk for commercial shale oil development. Further investigation is needed to assess the reasons why measured in-situ hydrocarbon saturation is so low within the both the Upper Velkerri and overlying Kyalla intervals. One possible explanation is that the in-situ oil saturation was expelled/flushed from these source rock intervals as a consequence of gas generation in the underlying units possibly enhanced during the emplacement of the 82 m thick igneous intrusion within the Middle Velkerri Formation.

In the prospective Middle Velkerri source interval, measured in-situ oil saturation determined by programmed pyrolysis S1 yields is low (5 bbl oil/acre-ft), which consistent with samples that are presently within the main gas window (Fig. 4). This is also supported by the low in-situ hydrocarbon saturations determined from SRP analysis (3 bbl oil/acre-ft). Hydrocarbon yield calculations on the as-received sample shows estimates of average generated cracked gas from the Middle Velkerri at 2771 Mcf gas/acre-ft and oil cracking is estimated to have been 95%, resulting in a residual oil/condensate yield of 15 bbl oil/acre-ft (Fig. 4). As a comparison, a representative example from the core area of Barnett Shale gas production in the Fort Worth Basin has an estimated cracked gas yield of 2751 Mcf/acre-ft, with 68 bbl/acre-ft of residual oil/condensate and a measured in-situ oil saturation of 7 bbl/a-ft. These values are comparable to the Middle Velkerri despite slight differences in organic richness between these two intervals (Barnett Shale gas example has average of 4.21 wt. % TOC).

In the Lower Velkerri and Corcoran source intervals measured in-situ oil saturation from S1 yields and estimated generated oil yields are generally low (avg. < 2 bbl oil/acre-ft), but there is minor to moderate amounts of secondary cracked gas (avg. 605−995 Mcf/acre-ft) due to elevated thermal maturity and estimated ~96 to 100% oil cracking (Fig. 4). These values are considered high risk for shale gas development and the estimated cracked gas yields are significantly lower than the Barnett Shale gas in the Fort Worth Basin.

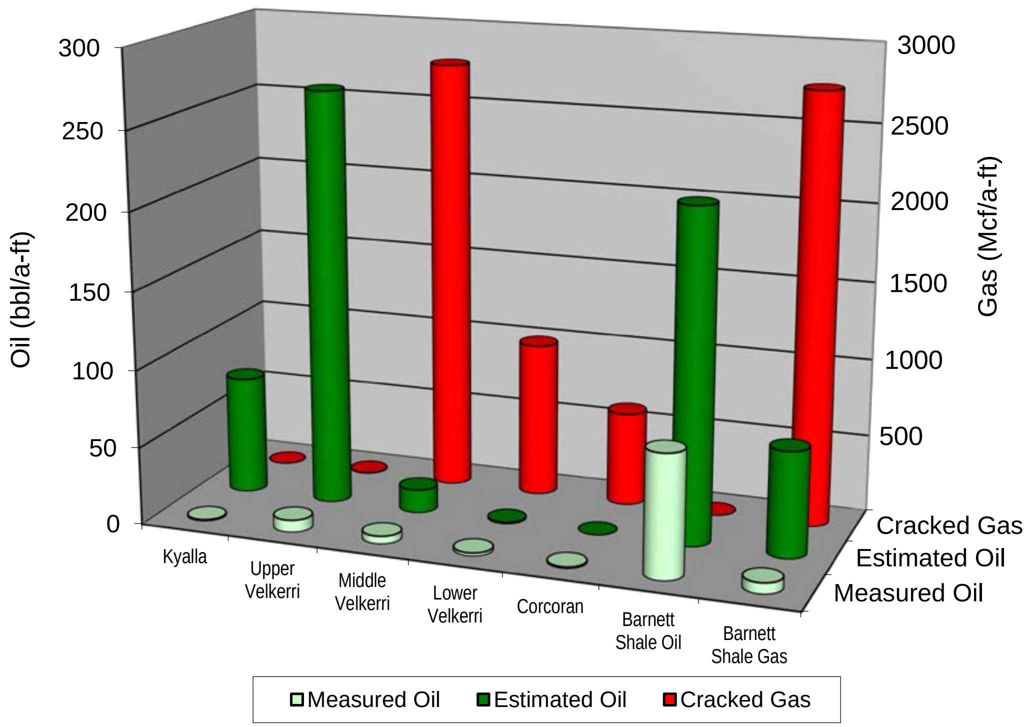

Figure 4. Hydrocarbon yield estimates for the Mesoproterozoic source rocks in the Sever 1 well compared to Barnett Shale in the gas window.

GEOCHEMICAL SUMMARY

The Middle Velkerri source interval in the Sever 1 well is interpreted to represent low geochemical risk for unconventional shale gas development. This formation clearly has elevated organic richness (avg. 3.79 wt.% TOC) and is considered a very good source rock with dominantly oil-prone Type II kerogen. Thermal maturity parameters indicate that this source interval is in the dry gas window, 1.82% Calc. R_o and key risk ratios are above recommended minimum thresholds for shale gas systems. This interval has likely generated high amounts of secondary cracked gas (avg. 2771 Mcf/acre-ft), which generally compare will to proven shale gas systems like the Barnett Shale.

The Upper Velkerri source interval in the Sever 1 well is interpreted to represent moderate geochemical risk for unconventional shale oil development. It has elevated organic richness (avg. 2.15 wt.% TOC) and oil-prone Type II kerogen. Thermal maturity parameters indicate that this interval is in the peak to late oil window, 0.79% Calc. R_o and 0.98% measured R_o. Although all key risk ratios are above recommended minimum thresholds for shale oil systems, the measured in-situ oil saturations are low (avg. 8 bbl oil/acre-ft). The Upper Velkerri has likely generated high amounts of oil (267 bbl/acre-ft), but it appears likely that most of this oil has been expelled/flushed from the source rock interval.

The Kyalla, Lower Velkerri and Corcoran source rock interval evaluated in the Sever 1 well are all considered high risk for unconventional shale oil/gas development. These horizons have organic richness values that average between 0.58 and 0.80 wt% TOC, which are well below the recommended minimum thresholds. Thermal maturity parameters are all above minimum thresholds and indicate peak oil in the Kyalla and dry gas in the Lower Velkerri and Corcoran. These intervals have likely generated a fair amount of oil (76 bbl/acre-ft) and secondary cracked gas (605−995 Mcf/acre-ft), but in comparison to proven shale gas systems like the Barnett Shale the generated volumes are significantly lower.

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