Volumetric resource assessment of the lower Kyalla and middle Velkerri formations of the McArthur Basin

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The Proterozoic McArthur Basin of the Northern Territory hosts significant potential for self-sourced continuous petroleum systems (unconventional shale oil and gas). The Mesoproterozoic Roper Group and the Palaeoproterozoic McArthur Group have been subject to low level exploration for oil and gas for several decades; oil and gas shows have been recorded from formations in both groups. The Northern Territory Geological Survey (NTGS) has been investigating this potential for petroleum resources through a review and compilation of historical and open file literature and data, together with sampling and extensive analysis of available drill core. This work has formed the basis for a petroleum resource assessment of the key target formations of the Roper Group. Results of this work are presented herein.

The Roper Group has received the greatest interest from explorers, particularly within the Beetaloo, Gorrie, OT Downs and Broadmere sub-basins; this comprises the region of the NTGS resource assessment **(Figure 1)**. The lower Kyalla Formation and the middle Velkerri Formation lithofacies of the group are the main intervals of interest for petroleum accumulations (**Figure 1**).

The middle Velkerri Formation contains three highly prospective organic-enriched facies, the A, B and C shales, each of which holds the potential to be an individual petroleum play. Analysis of the organic matter within fine-grained siltstone from these units indicates the deposition of organic-rich Type I/II kerogen with very good to excellent generative potential (**Figure 2**). Intersections of the A, B and C shale organofacies of the middle Velkerri Formation have been encountered across multiple wells drilled within the assessment area: Shenandoah 1/1A (Falcon 2012); Walton 2, Sever 1 and Tarlee S3 (Hoffman 2015); and Kalala S-1 and Amungee NW-1 (Close *et al* 2016). Its presence is interpreted from gamma ray log in Tanumbirini 1 (Santos 2014). It has also been identified as Organic Rich Unit 3, 2 and 1 in McManus 1 and Altree 2 (Warren *et al* 1998); and it is highlighted as organic-rich intervals in the middle Velkerri in BMR Urapunga 4 stratigraphic hole (Sweet and Jackson 1986).

Gamma ray logging through the middle Velkerri Formation shows excursions through the A, B and C organofacies, clearly defined in Altree 2 **(Figure 2)** and Tanumbirini 1 **(Figure 3).** The A, B and C organofacies are

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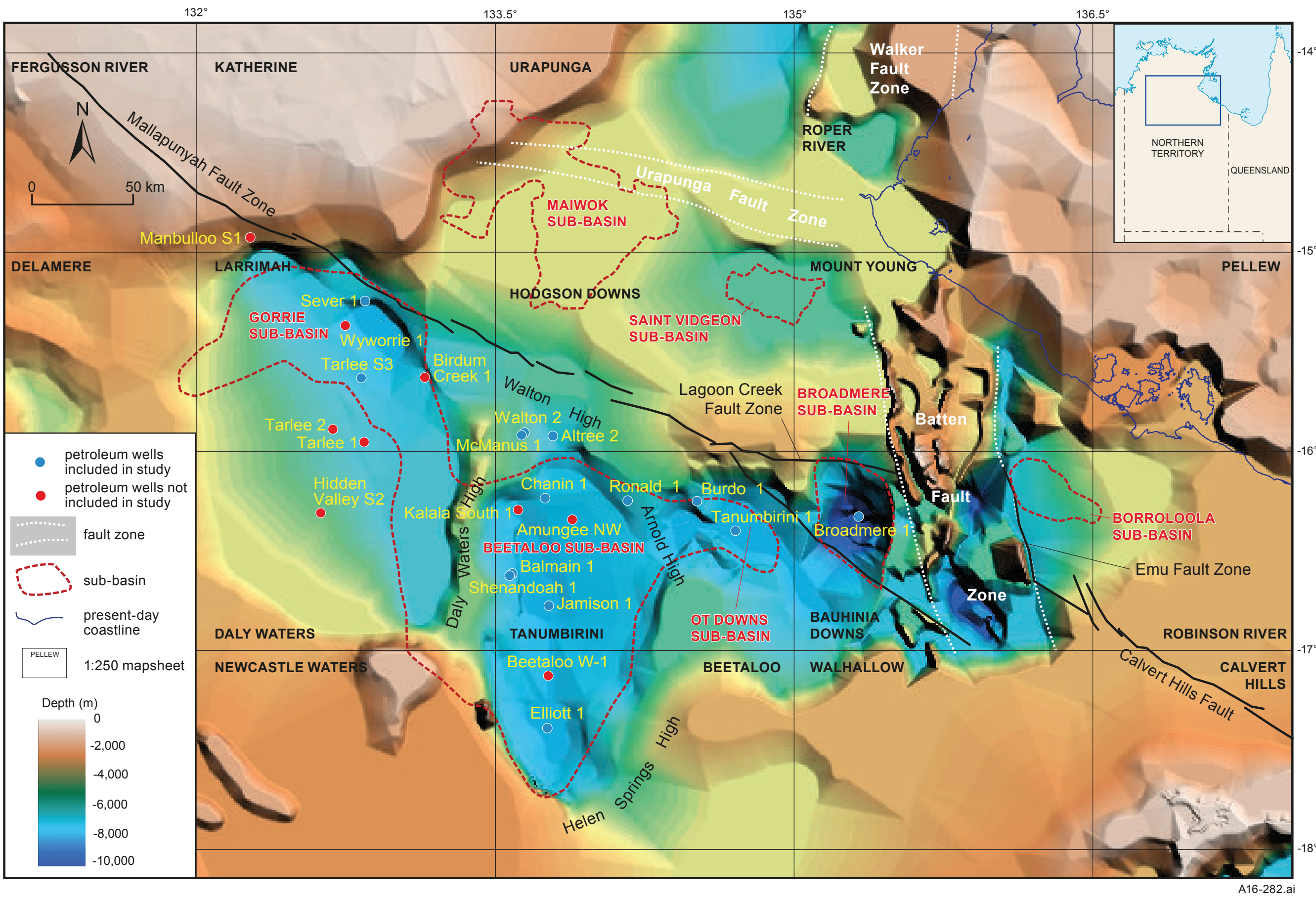


Figure 1. The greater McArthur Basin with associated sub-basins and topographic highs involving the Roper Group on the SEEBASE™ depth-to-basement image (after Pryer and Loutit 2005): yellow–brown tones depict interpreted Proterozoic basement highs; blue–green tones are interpreted depocentres. Wells not included in the study (red) were subjected to confidentiality at the time of assessment. Positions of faults after Betts *et al* (2015).

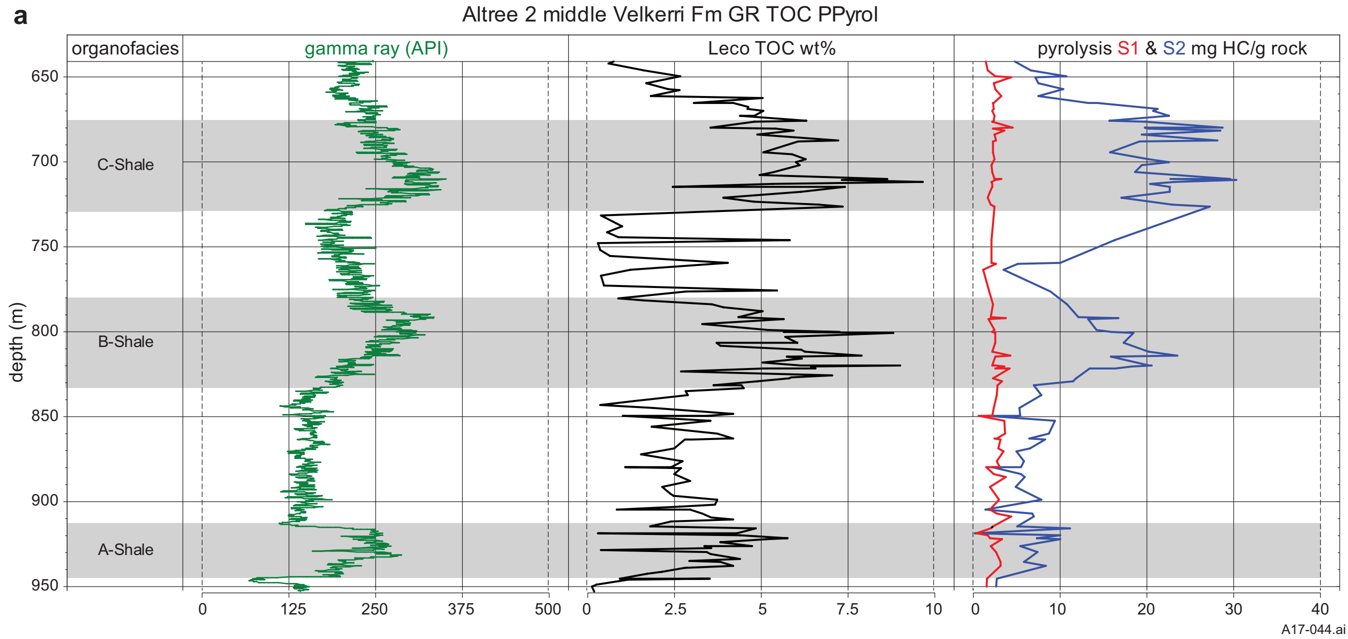
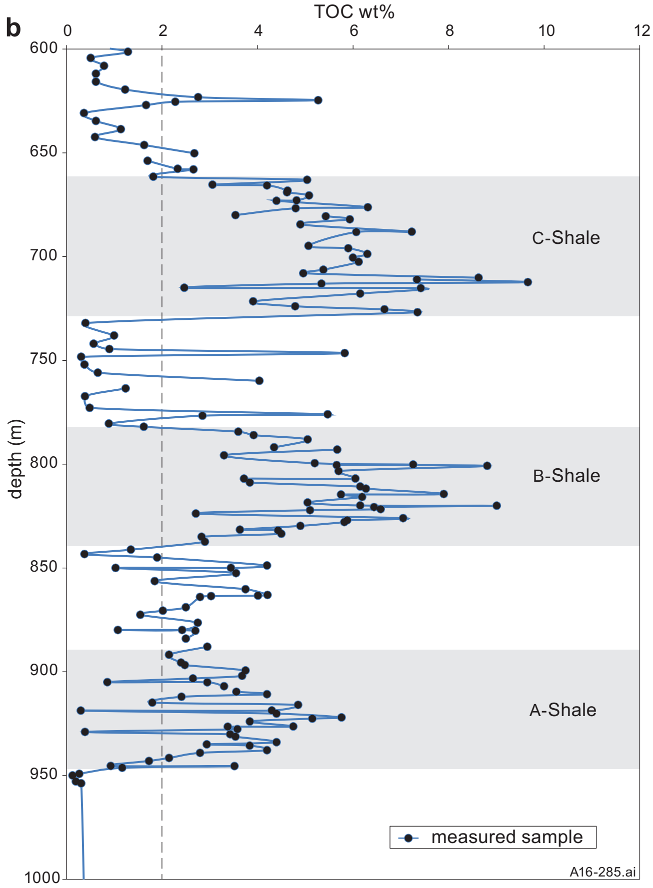


Figure 2. (**a**) Measured gamma ray (GR), total organic carbon (TOC) wt% and free-hydrocarbons in place (S1) and petroleum generative potential (S2) pyrolysis values through the middle Velkerri Formation in the Altree 2 well. Organofacies A, B and C are represented by organic-rich intervals, consistent with transgressive systems tract condensed sections. (**b**) Measured TOC values plotted through the A, B and C organofacies show a correlation with gamma ray excursions.



characterised by carbonaceous laminated mudstones; they are distinctly enriched in organic carbon content as shown in the total organic carbon (TOC) plotting of Altree 2 from 5 m, on average, downhole sampling spacing (**Figure 2**). The thickness of these organofacies varies between 30–50 m, with the A shale consistently the thinner of the three. The B shale has been the primary target of recent exploration; the first public announcement of a shale gas discovery was made from intersection and stimulation of the B shale in the Amungee NW H-1 well (Origin 2016).

The paucity of data made completing an individual resource assessment of each of the A, B and C organofacies of the middle Velkerri Formation a task outside of the scope of the NTGS program, so the middle Velkerri lithofacies was assessed as one unit. To quantify this unit, the average thickness of the combined A, B and C organofacies was considered as a percentage of the total thickness of the middle Velkerri Formation. Together these organofacies comprise on average 33% of the total thickness of the middle Velkerri Formation lithofacies. This percentage was used as the thickness quotient for the middle Velkerri Formation volumetric assessment.

The Kyalla Formation was informally divided into an upper and lower lithofacies for the purposes of the assessment. The lower lithofacies is relatively organic-enriched, and formed the basis of the Kyalla Formation resource assessment. Using the method above, a total volume of 50% was applied for the Kyalla Formation volumetric assessment.

3D modelling of the greater McArthur Basin from NTGS Digital Information Package 012 (Bruna *et al* 2016) was utilised for the volumetric assessment. This provided a stratigraphic and structural base for the construction of new surfaces for this assessment. Weatherford Laboratories were engaged to undertake the basin and petroleum system modelling, incorporating the delineated extents of the formations from the 3D model with the geochemical data from the sampling program utilising Petrel™ software.

Analytical results used for this assessment were restricted to open file data and drill cores; data from 2015–2016 closed file exploration wells could not be included. These closed file wells will have a significant impact on any future assessment on the petroleum prospectivity of the region as they specifically targeted the Kyalla and middle

Velkerri formations as unconventional petroleum plays; this unavailable data includes the shale gas discovery well Amungee NW H-1.

The volumetric analysis required the generation of multiple assessments from a variety of data sources in order to calculate all of the volume in place numbers. The workflow followed these procedures:

1. Map-based volumetric assessment:
   - Generated top and base surfaces for both the Kyalla and middle Velkerri formations using well tops and available open file seismic data.
   - Generated maps (P10, P50 and P90) for hydrocarbon saturation (S_w-1), and porosity (phi, ϕ) using shale rock properties calculated from core analysis.
   - Generated thermal maturity map for Kyalla Formation; this shows Kyalla Formation to be in the oil window. Only oil in place (OIP) to be calculated.
   - Generated thermal maturity map for middle Velkerri Formation; this shows middle Velkerri Formation is in both oil and gas windows. OIP and gas in place (GIP) to be calculated.
2. Calculated basin-based OIP and GIP values using shale rock property (SRP) data and free-hydrocarbons in place values (S1) generated from core data.
3. Compare map-based volumetric analysis with the SRP and S1-based volumetric analysis.

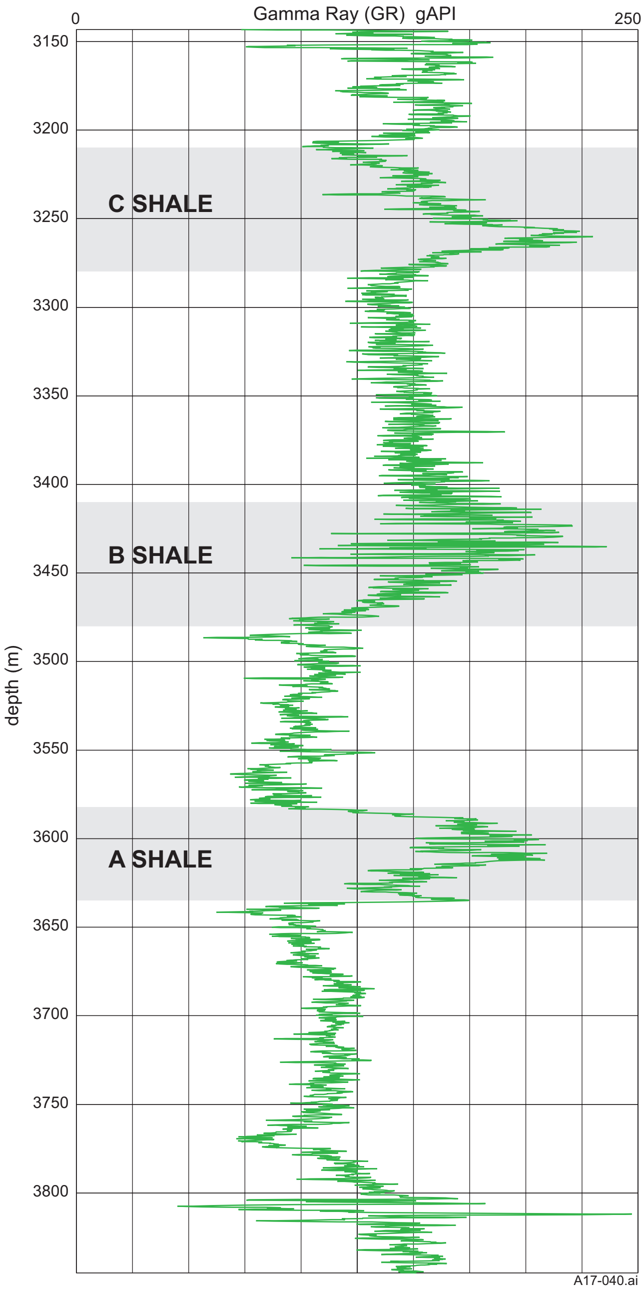


Figure 3. Tanumbirini 1 measured gamma ray (GR) log through the middle Velkerri Formation interpretation highlighting the excursions of the ray trace through the A, B and C organofacies. The excursions of the ray trace in the dry gas mature section are less pronounced than those shown in the early oil mature Altree 2. Figure adapted from Tanumbirini 1 basic well completion report (Santos 2014) and interpreted from NTGS core observations.

The results of the lower Kyalla Formation thermal maturity mapping estimation are shown in **Figure 4**. The Beetaloo Sub-basin has a range of maturity from immature through to late oil maturity mapped. The late oil window thermal maturity region extends through the central region of the sub-basin and corresponds with the deepest, thickest intersections analysed. These central regions are also the most prolific for oil generation modelled (**Figure 5**).

The middle Velkerri Formation modelled thermal maturity (**Figure 6**) shows increasing thermal maturity from the oil mature-northern flanks through to the overmature (dry gas-mature) southern regions of the Beetaloo Sub-basin. The OT Downs Sub-basin is immature for oil generation in the east, toward the well Broadmere 1, and increases in thermal maturity through to the dry gas window towards the west, where maturity is contiguous with that of the Beetaloo Sub-basin. Modelling GIP P50 values is heavily constrained by the presence of well intersections of the middle Velkerri Formation (**Figure 7**). The northern flanks of the Beetaloo, OT Downs and Gorrie sub-basins have the highest modelled GIP values,

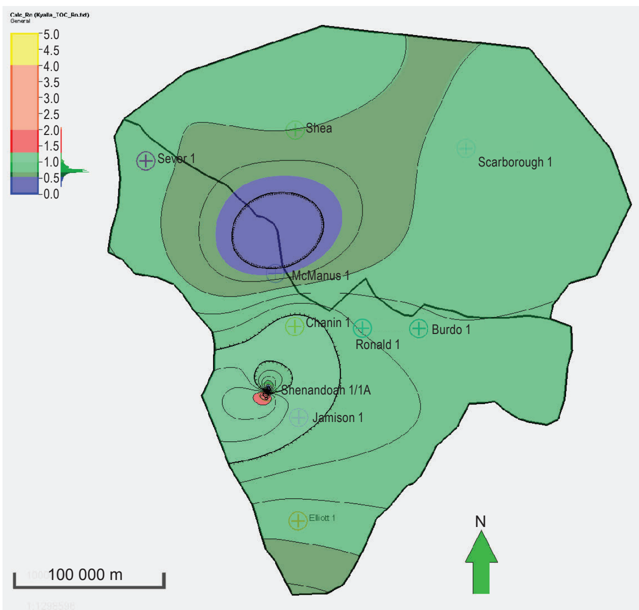


Figure 4. Kyalla Formation interpreted thermal maturity. Blue represents immature regions; green represents regions that are mature for oil generation; red represents regions that are potentially condensate/wet gas-mature.

with decreasing volumes through to the south of the sub-basins. The forecasting of GIP volumetric estimations in the southern regions of the Beetaloo Sub-basin is restricted due to paucity of available geochemical data; however, thermal maturity estimations modelled on structural and geochemical data indicate the middle Velkerri Formation is dry gas mature in this region. Volumetric assessment of the GIP values have calculated a diminishing volume of gas moving south through the sub-basin. Incorporation of generative modelling techniques from a complete reservoir modelling, and the inclusion of data from the recently drilled Beetaloo W-1 well (closed file at the time of this resource assessment) may change the volume of gas estimated in the region.

Comparative volumetric assessment figures for the GIP and OIP of the lower Kyalla and middle Velkerri formations (**Table 1**) for P10, P50 and P90 indicate a wide range of values.

It is useful to compare the estimation with producing shale plays from the USA. GIP estimates from the Marcellus Shale play range between 40–150+ billion cubic feet per square mile (bcf/mi^2), the Barnett Shale between 50–200 bcf/mi^2, and the Fayetteville Shale between 40–100 bcf/mi^2 (Breyer 2012). These values compare favourably with the GIP estimated for middle Velkerri Formation: Gorrie Sub-basin, 62–300 bcf/mi^2; Beetaloo Sub-basin, 100–350 bcf/mi^2; and OT Downs Sub-basin, 450–1575 bcf/mi^2. The GIP values of the middle Velkerri Formation across these sub-basins are greater than the minimum current development GIP for the Marcellus Shale [50 bcf/mi^2 (Breyer 2012)]; although of course there

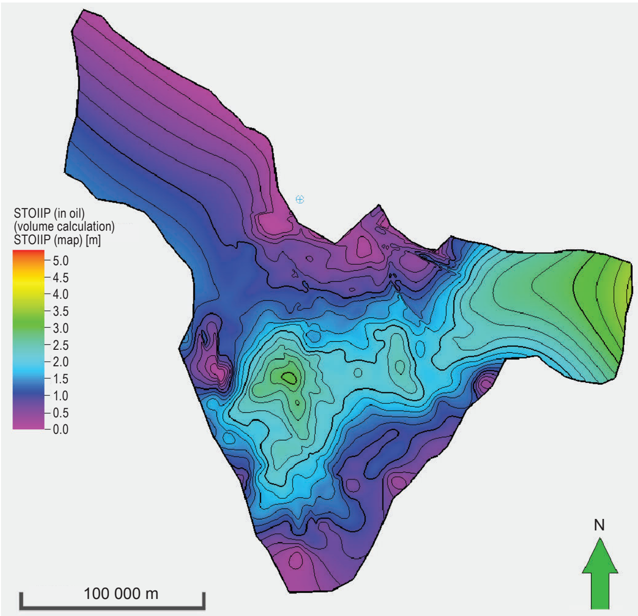


Figure 5. Kyalla Formation stock-tank original oil in place (STOIP) P50 oil in place estimation from volumetric analysis. Increasing warmth of colour represents increasing volumes of oil calculated to be present in the formation.

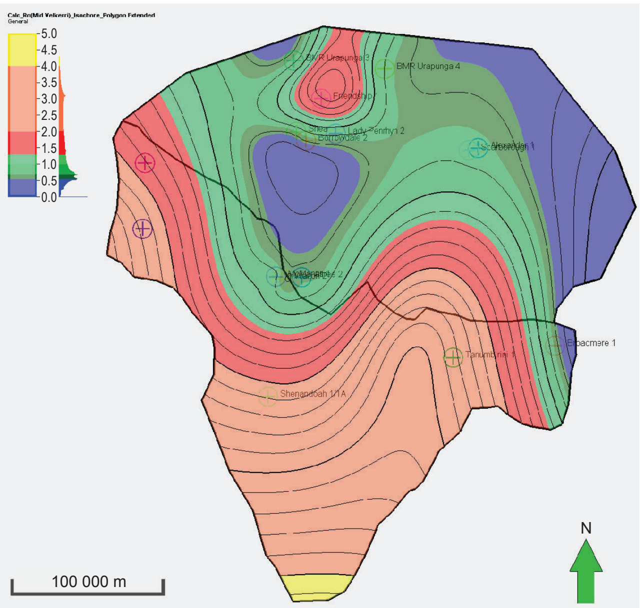


Figure 6. Middle Velkerri Formation estimated thermal maturity. Wells with vitrinite reflectance (R_o) data for the middle Velkerri Formation shown. The thermal maturity is shown to be increasing from immature (green) on the northern flanks of the Beetaloo Sub-basin, through to overmature (yellow) in the southern regions of the sub-basin.

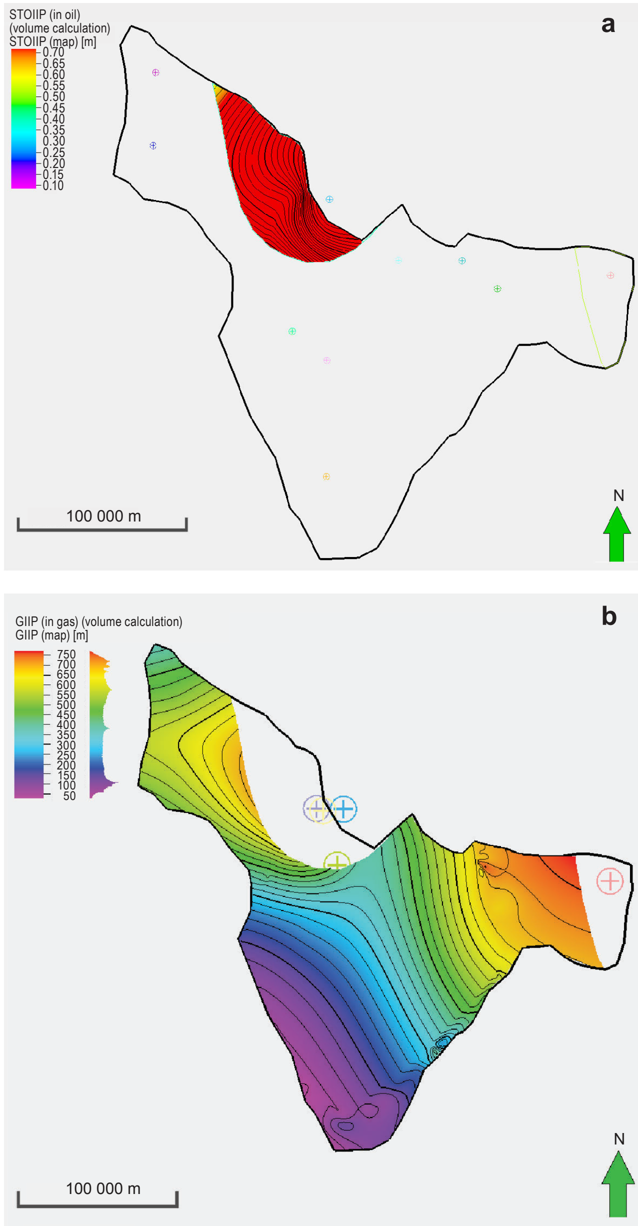


Figure 7. Middle Velkerri Formation. (**a**) Oil in place P10 from volumetric analysis. (**b**) Gas in place P10 estimation.

Kyalla Formation (36 600 km²)	Oil (Bbbl)		
	P10	P50	P90
Map-based volumetric	1333	899	487
SRP-based volumetric		143	
S1-based volumetric		94	
HC yield-based volumetric		293	
middle Velkerri Formation (4000 km²)	**Oil (Bbbl)**		
Map-based volumetric	115	85	63
SRP-based volumetric		9	
S1-based volumetric		13	
HC yield-based volumetric		24	
middle Velkerri Formation (31 100 km²)	**Gas (TCF)**		
Map-based volumetric	308	208	124
S1-based volumetric		752	

Table 1. Oil in place (OIP) and gas in place (GIP) figures for the Kyalla and middle Velkerri formations. Map-based volumetric analysis figures are in comparison to shale rock property (SRP), *in situ* hydrocarbons (S1) and potential hydrocarbon yield (HC) volumetric assessments. Bbbl = billions of barrels, TCF = trillions of cubic feet.

are many other factors that come into play for successful production.

There are several sources of uncertainty associated with the modelling of this data. Most of the samples taken were from drill core that have been exposed to atmospheric conditions for prolonged periods of time. Fluids in the core, both hydrocarbons and water, may have changed composition as a result of this exposure. Estimated hydrocarbons could be higher or lower depending on how the core was affected. SRP data was sparse considering the size of the basin (analysis was on 36 600 km^2): there was a total of 14 Kyalla Formation samples from three wells, and a total of 36 middle Velkerri Formation samples from seven wells. The SRP values measured/calculated from the core have been assumed to be representative of the whole area modelled. The siltstones of the formations do display some heterogeneity in rock properties, and assumptions of homogeneity in SRP values will also greatly affect the final outcome.

Core data may also have been high-graded in some instances where sampling targeted the intervals with the best potential for hydrocarbons. Any hydrocarbon in place estimates therefore could have been overestimated and may not be representative of the overall reservoir characteristics for the volume of reservoir used in the calculations. The geochemistry-based hydrocarbon yield volumetric calculations had an arbitrary retention factor applied to all of the data. If this assumed retention factor was too high compared with present-day conditions, the hydrocarbon yields would be overestimated. Core sample data alone may not capture the true variability needed to accurately estimate hydrocarbons in place on a basin scale. A complete reservoir model, rather than a core-based approach, would better serve this purpose.

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