A multidisciplinary evaluation of the Velkerri Formation in the Beetaloo Sub-basin: Implications for geological history and reservoir quality

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Introduction

The Proterozoic (ca 1.43 Ga) Velkerri Formation of the Roper Group (McArthur Basin, Northern Territory) is believed to host one of the world's oldest petroleum systems (Jackson *et al* 1986). Due to its excellent source rock characteristics, the formation is currently the target of exploration activities in the Beetaloo Sub-basin within the greater McArthur Basin, Northern Territory. This unconventional resource hosts vast quantities of liquid and gas hydrocarbons and spans an aerial extent of nearly 80 000 km^2 with thicknesses reaching up to 800 m (Abbott and Sweet 2000, Munson 2016).

The preservation of this 'live' petroleum system is a geological wonder and implies that the Velkerri Formation has not been dramatically affected by major tectonic or metamorphic events. It has remained at relatively shallow depths since its deposition approximately 1.4 billion years ago, and has been exposed to maximum temperatures consistent with hydrocarbon generation. Moreover, the composition of the oil found in the Velkerri Formation is consistent with derivation from organic matter composed of bacteria and primitive algae deposited in a marine environment (eg Munson 2016). The Velkerri Formation has been divided into three members, the Kalala (lower), Amungee (middle) and Wyworrie (upper) members (Munson and Revie 2018). The Amungee Member, previously referred to as the middle Velkerri, shows the highest organic richness and thermal maturation of the same, which has resulted in large quantities of potentially recoverable resources estimated as 118–293 trillion cubic feet in volume (Revie 2017). Of prime importance among the sources of uncertainty associated with this wide range of estimated resources are: i) reservoir characterisation, and ii) age dating of burial and tectonic events controlling the thermal evolution, hydrocarbon generation and expulsion history of the sedimentary rocks hosting the resource. Moreover, sills of the Derim Derim Dolerite emplaced at ca 1.32 Ga intrude the Velkerri Formation, as seen in a number of wells in the Beetaloo Sub-basin, providing a thermal perturbation likely affecting the maturity of the hydrocarbon source rock, at least locally.

The scope of this work, therefore, was to complement the existing knowledge on the characteristics of the Velkerri Formation summarised in data released by the Northern Territory Geological Survey (eg Revie and Normington 2018). In particular, our study focuses on samples at various levels of thermal maturation collected from the cored sections of the Amungee Member of the Velkerri Formation intersected in six wells (Altree 2, Borrowdale 2, Walton 2, Lady Penrhyn 2, Shenandoah 1A and Tarlee S3) in order to characterise the following parameters:

- whole rock and clay mineralogy and crystallinity [via x-ray diffraction (XRD)]
- maceral types and maturity assessment (via light reflectance, pyrolysis and Raman spectroscopy)
- porosity and pores size distribution (via mercury intrusion porosimetry)
- methane adsorption capacity (via laboratory measurements at reservoir conditions)
- permeability and its anisotropy (via multidirectional laboratory measurements)
- diagenetic events affecting the shales microstructure (via optical and electron microscopy)
- geochronology of diagenetic events (via K–Ar dating of diagenetic illite and U–Pb dating of diagenetic calcite).

Thermal maturity cannot be determined by conventional vitrinite reflectance analysis because deposition of these ancient sedimentary rocks predate the evolution of land plants; therefore, we used different organic and mineral thermal maturation indices including: i) illite crystallinity, ii) other maceral reflectances, and iii) Raman spectroscopy of organic material.

Results

XRD results indicate that the mineralogy of the whole rock samples is dominated by quartz and clay minerals. Analysis of the clay fraction shows that these are mainly mixed layer smectite/illite with illite content between 70 and 90%. Detailed analysis of the 0.2–2 µm fraction show that the 10Å illite peak is best fitted by two almost overlapping peaks interpreted as two generations of diagenetic illite. For this limited dataset, illite crystallinity increases almost linearly with depth and is highest in samples located in proximity to documented doleritic intrusions (ie Tarlee S3 samples).

Organic richness of the shale samples, as quantified by the total organic carbon (TOC) content, ranges between 1.2% (Shenandoah 1A sample, 2517.28 m) to 10.7% (Walton 2 sample, 397.85 m). For all samples studied, the organic components identified by optical microscopy are mainly composed of bitumen with lesser amount of alginite, with one exception (Walton 2 sample: 397.85 m) having major alginite instead. The bitumens have mean reflectance values ranging between 0.28% (Walton 2: 397.85 m) to 4.03% (Tarlee S3: 1438.61 m).

Maximum palaeo-temperatures were estimated from the analysis of the Raman spectra obtained from organic

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particles using the geothermometer proposed by Kouketsu *et al* (2014). The data set returns palaeo-temperatures ranging between 67°C (Lady Penrhyn 2: 376.66 m) and 233°C (Tarlee S3: 1438.61 m). The data recorded a positive correlation between estimated palaeo-temperatures and mean bitumen reflectance, with anomalously high values recorded in the sample from the Tarlee S3 well closest to the top of the dolerite intrusion.

Microstructural analysis reveals the presence of common features in samples, irrespective of their thermal maturity and geographical position. These are illustrated in **Figure 1** and include:

- a bedded appearance defined by the alignment of elongate detrital particles and stringers of organic matter (**Figure 1a**)
- diagenetic phases like blocky pyrite (**Figure 1a**) and apatite spherules of possible bacterial origin (**Figure 1b**)
- a microcrystalline matrix composed of interspersed clays and quartz (**Figure 1c**)
- micron to sub-micron scale pores hosted in what is interpreted to be migrated bitumen (**Figure 1d**).

Bitumen porosity is interpreted to be the dominant contribution to the total porosity of the samples as shown by a positive correlation between TOC and the volume of mesopores (10 nm < size < 50 nm), measured by mercury intrusion porosimetry. Indeed, methane adsorption curves measured on this data set at temperatures up to 80°C also show that TOC is one of the main factors controlling the amount of adsorbed gas in the Velkerri Formation. The laminated nature of the sediment imparts a significant anisotropy to the permeability experimentally measured in the laboratory on cubic samples. At an effective pressure of 6.7 MPa, permeability along the bedding can be up to 0.2 mD and around 3 orders of magnitude higher than across the bedding.

K–Ar dating of diagenetic illite extracted from samples of the Altree 2, Borrowdale 2, Shenandoah 1A and Tarlee S3 wells consistently show a well-defined thermal maximum at 1030 ± 25 Ma. Considering that hydrocarbon generation and smectite illitisation occur within the same range of temperature, these dates can help improve the understanding of the timing of hydrocarbon generation within the Velkerri Formation. Furthermore, analysis of selected samples under ultraviolet light reveal strong fluorescence from oil trapped

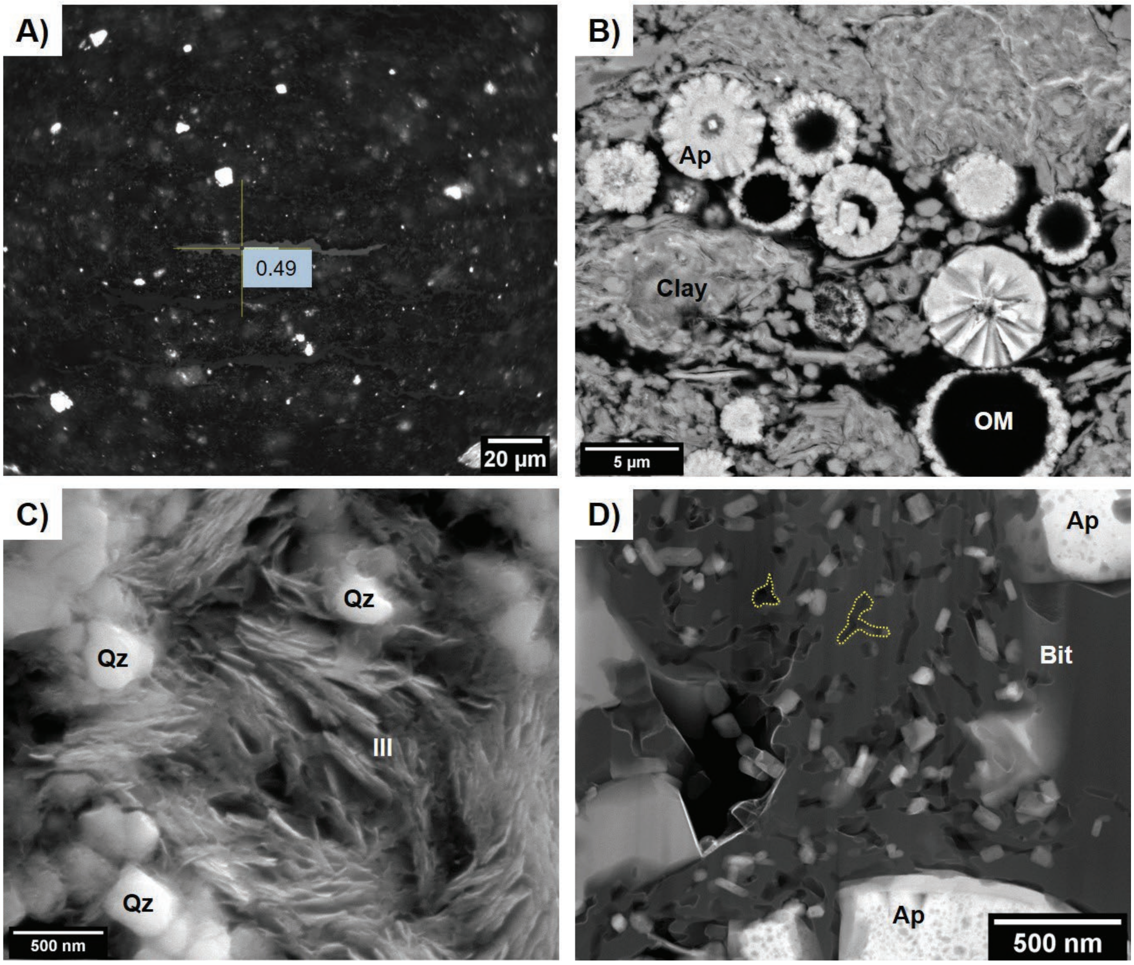

Figure 1. Microstructural characteristics of the Amungee Member of the Velkerri Formation. (**a**) Reflected light image of an elongate alginate particle with reflectance of 0.49%, sedimentary bedding is horizontal. White euhedral crystals are pyrite (Walton 2: 397.85 m). (**b**) Scanning electron microscope (SEM) image of apatite spherules (Ap), spatially associated with organic matter (OM) and surrounded by clay matrix (Clay). (Walton 2: 397.85 m) (**c**) SEM image of interspersed sub-micron sized quartz (Qz) and illite (Ill) (Lady Penrhyn 2: 399.7 m). (**d**) Transmission electron microscope image of bitumen (Bit) with irregularly shaped pores (examples highlighted by dashed yellow contours). Bright particles are apatite (Ap) (Tarlee S3: 1438.61 m).

in fluid inclusions within carbonate cements in samples from wells Tarlee S3 and Lady Penrhyn 2, and in carbonate-filled fractures in well Borrowdale 2. These observations suggest that oil migration possibly occurred through fluid-assisted brittle deformation within a well-compacted and lithified mudstone. Ongoing dating of the oil inclusion-bearing calcite-filled fractures will provide further constraints on the timing of hydrocarbon migration.

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