From the back of the shed to the forefront of exploration: What the NTGS core store is revealing about the Roper Group shales of the greater McArthur Basin

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Significant potential for unconventional hydrocarbon resources exists in the underexplored Proterozoic source rocks of the large and poorly exposed greater McArthur Basin of the Northern Territory, Australia (**Figure 1**).

Advances in hydrocarbon extraction technologies for shale gas has encouraged exploration in remote frontier basins such as the greater McArthur Basin. As a consequence of favourable economic conditions, there was a significant increase in onshore exploration for unconventional resources in the Northern Territory from 2012 to 2015, particularly in the Beetaloo Sub-basin, the depocentre of the highly prospective Mesoproterozoic Roper Group (**Figure 2**).

The Northern Territory Geological Survey (NTGS) is currently assessing the Palaeo-Mesoproterozoic shales of the greater McArthur Basin for the potential to host self-sourced, continuous, shale hydrocarbon plays. This assessment process consisted of compilation of data from drill and core sample reports together with the analysis of core from previous exploration activity in the region. Historical petroleum and mineral exploration drill cores from the greater McArthur Basin have been re-examined and extensively sampled. Direct measurements from this sampling has provided determinations for total organic carbon (TOC), brittle and clay mineral content, shale maturity, kerogen types, fluid and gas contents, permeability and porosity, and mechanical rock properties.

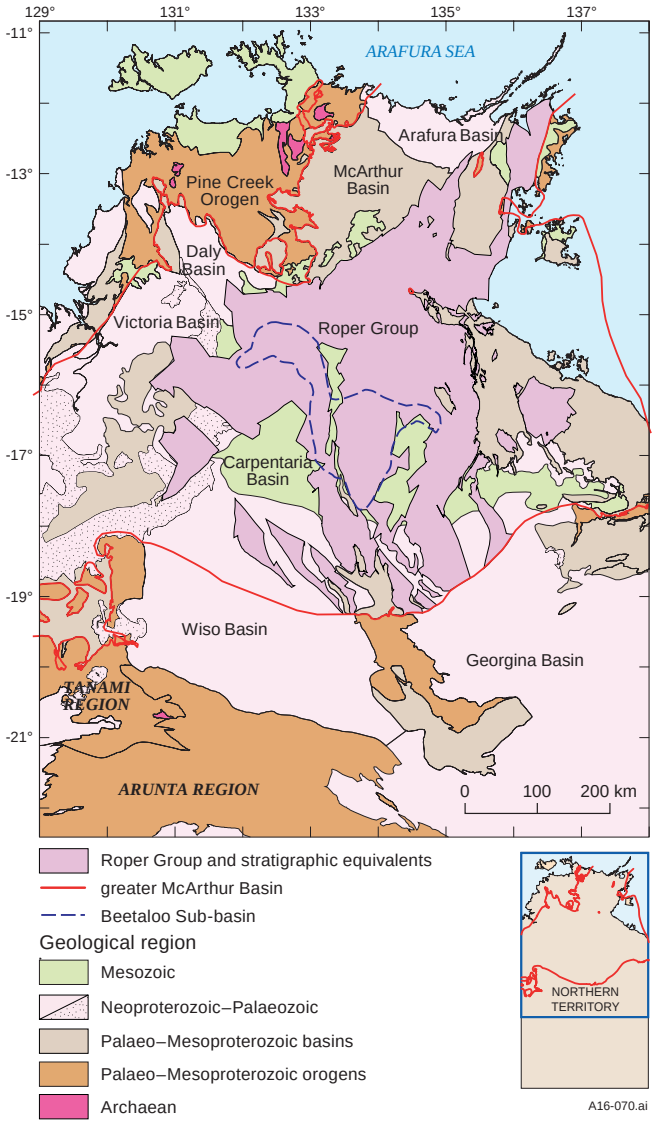

Figure 1. Location of the greater McArthur Basin, NT, Australia.

The newly acquired data has been combined with historical data and complied in the NTGS product DIP014 (Revie 2015). This combined dataset has been used to compare measurements and data from the shales of the greater McArthur Basin to that of productive shale gas systems present in North America and elsewhere worldwide. The comparable characteristics considered as indicators for productive shale gas systems, as outlined by Jarvie (2012), are:

i. marine shales commonly described as type II organic matter (Hydrogen Index original value (HI_o): 250–800 mg hydrocarbon/g TOC)
ii. organic rich source rock [>2 wt.% present-day TOC (TOC_{pd})]
iii. within the gas window [>1.4% equivalent vitrinite reflectance (R_{oe})]
iv. low oil saturations (<5% S_o)
v. significant silica content (>30%) with some carbonate presence
vi. non-swelling clays
vii. low permeability (<1000-ηd)
viii. less than 15% porosity, more typically about 4–7%
ix. gas-in-place (GIP) values more than 100 bcf/section
x. 45+ m of organic rich mudstone
xi. slightly to highly overpressured
xii. very high first-year decline rates (>60%)
xiii. consistent or known principle stress fields
xiv. drilled away from structures or faulting
xv. continuous mappable systems.

Several of these characteristics have been identified in historical reporting and from the recent sampling of cores held in the NTGS and Geoscience Australia core facilities. This has yielded information that can be modelled to gain insight into the potential for the shale and siltstone formations of the greater McArthur Basin to host shale gas resources.

Using this methodology, early analysis of shale formations within the Mesoproterozoic Roper Group have emphasised the potential of the Velkerri and Kyalla formations. Thick endowments of effective mudstone/siltstone/shale with TOC >2 wt % and with favourable

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mineralogy, permeability and porosity, have been identified within the Velkerri Formation. These endowments have been informally divided into the *upper, middle and lower* organofacies. Thick organic-rich deposits of the Kyalla and Velkerri formations have been intersected over interval greater than 750 m thickness (eg 843 m Kyalla Formation in drillhole Shenandoah-1, 753 m Velkerri Formation in drillhole Sever-1) (**Figure 3**).

Reconstruction of original source-rock generative potential for the Roper Group shales was conducted using the DIP014 dataset. The original quantity of organic carbon (TOC_o) and quality (HI_o) of the organic matter prior to thermal maturity was estimated using the mass-balance equations of Peters *et al* (2005). The results of the reconstruction indicate that the Roper Group contains formations with HI_o value ranging between 300–900 mg HC/g TOC, representative of Type II and Type I/II kerogens. This is supported by the present-day HI and OI values obtained from Rock-Eval pyrolysis for the Velkerri Formation of the Roper Group (**Figure 4a**). The Proterozoic age of the sediments predate the appearance of terrestrial plants thus restricting the organic matter to Type I and II sapropelic kerogen.

Pyrolysis results are complemented by elemental analysis of kerogen (for elements C, H, N, O, S) to further constrain kerogen type and thermal maturity. Elemental kerogen analysis of selected samples taken from the Kyalla and Velkerri formations indicate a range of maturities are present within the formations. Results range between thermally immature to overmature with the middle and lower units of Kyalla Formation and Velkerri Formation returning results >1.4% R_{oe} (**Figure 4b**).

The TOC_{pd} values of formations of the Roper Group other than the Velkerri and Kyalla, namely the Chambers River,

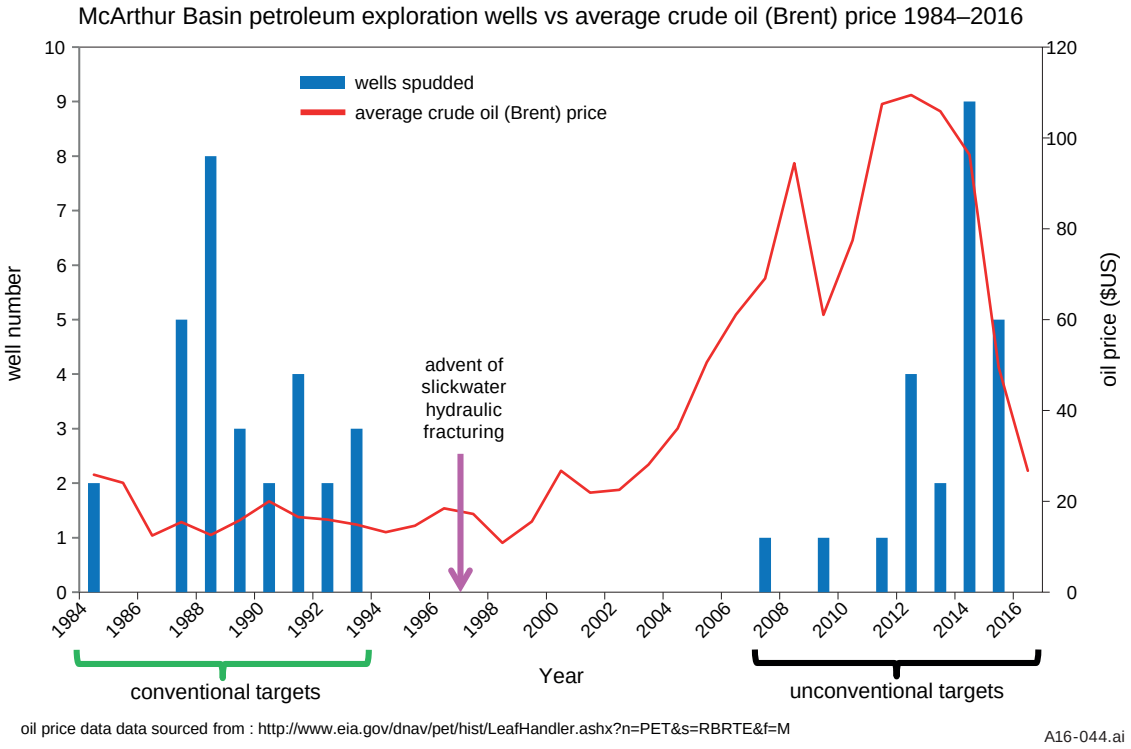

Figure 2. Historical chart of McArthur Basin petroleum wells spudded versus average crude oil price (Brent) from 1984 to 2016. The introduction of slickwater hydraulic fracturing in 1997, combined with favourable oil prices contributed to the increased global exploration for hydrocarbons within shale formations.

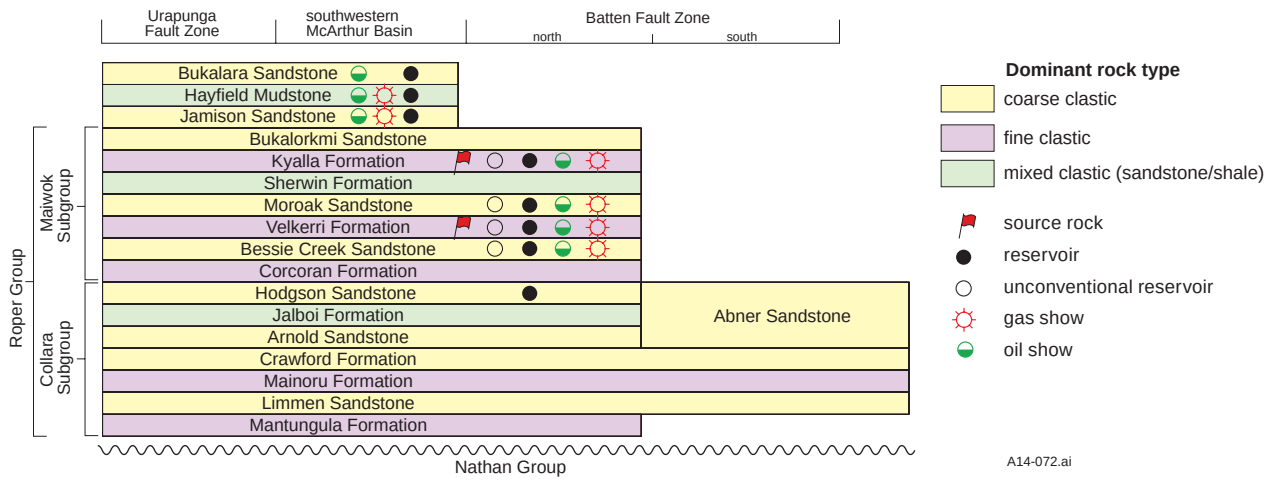

Figure 3. Stratigraphic column of the Roper Group of the McArthur Basin, adapted from Munson (2014).

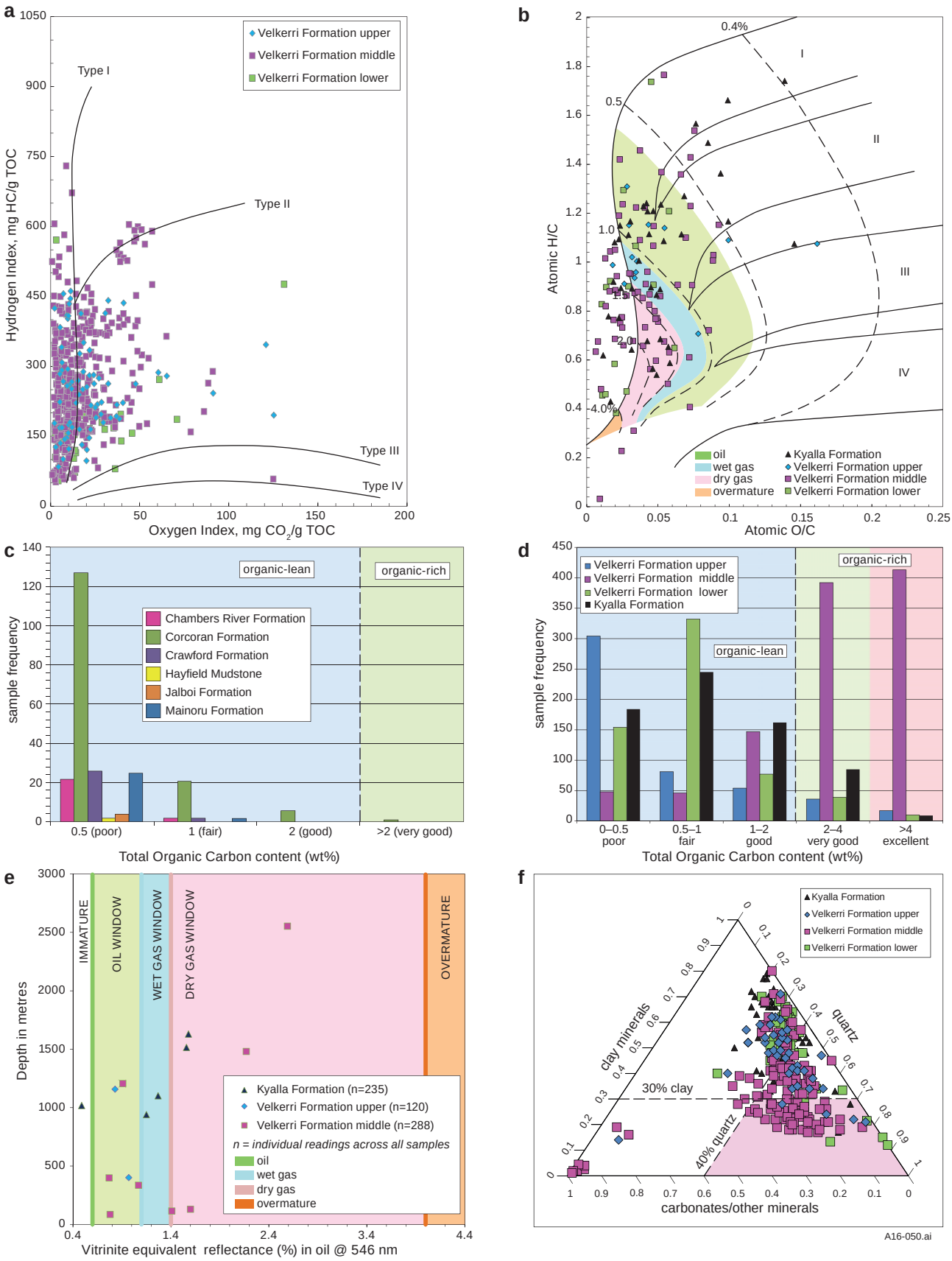

Figure 4. (**a**) HI versus OI of the Velkerri Formation of the Roper Group. Present-day HI and OI values are shown. Kerogen type II and I/II are present indicating oil- and oil/ gas- prone source rocks. (**b**) Van Krevelen diagram of the Kyalla and Velkerri formations indicating kerogen type and thermal maturity from selected samples. Dashed lines are isorank lines based on vitrinite reflectance %R_o. Thermal maturity migration pathways increase toward the bottom left-hand corner of the diagram. (**c**) Present-day TOC content for other formations of the Roper Group indicate insufficient organic matter to be a significant source for petroleum. (**d**) Present-day TOC content of sampled Velkerri and Kyalla formations of the Roper Group. (**e**) Depth versus organic reflectance data of bituminite and alginites (shown in vitrinite reflectance equivalence value) for the Kyalla and Velkerri formations of the Roper Group. (**f**) Ternary plot of quartz/carbonate/clay mineral content of the Velkerri and Kyalla formations. The pink quadrant represents favourable mineralogy for hosting shale gas plays.

Corcoran, Crawford, Jalboi, Mainoru formations and the Hayfield Mudstone, are dominated by values within the poor (0–0.5 wt.%) to fair (0.5–1 wt.%) range (**Figure 4c**). Original TOC (TOC_o) values of these formations can be up to 50% higher than present day values depending on maturation and expulsion of hydrocarbons. The TOC_o values are mostly within the fair to good range when applying a maximum HI_o value of 600 mg HC/g TOC in mass-balance equations to calculate original TOC_o values for these other formations. This indicates that the formations did not have sufficient organic matter to be significant petroleum source rocks. In contrast, the Velkerri and Kyalla formations of the Roper Group have TOC_{pd} values in the very good (3–4 wt. %) to excellent (>4 wt. %) range (**Figure 4d**). These two formations satisfy the minimum TOC requirements to be considered as potential petroleum source rocks for shale gas plays; they are currently the primary focus for exploration in the Beetaloo Sub-basin.

Bituminite and lamalginite/alginite maceral reflectance values from organic petrography of samples taken from the Roper Group indicate a range of maturities; the reflectance values also confirm the presence of kerogen type I/II in the sediments. Several samples from the Kyalla and Velkerri formations have reflectance values greater than the 1.4% R_o gas-window; the highest values are from samples taken from depths greater than 1400 m (**Figure 4e**).

Recovery of hydrocarbons from a shale gas play requires engineering solutions such as hydraulic fracturing to liberate gas from tight geology. Current usage of hydraulic fracturing is successful in specific mineral conditions where a highly brittle tenacity allows the procedures to propagate fracturing rather than plastically deform the rock. Rock brittleness is a function of clay and silica content. X-ray diffraction (XRD) was used to determine the bulk and clay mineral content of core samples. XRD analysis of samples from the Kyalla and Velkerri formations indicate that the Velkerri Formation middle unit has favourable mineralogy for hosting potential shale gas plays, including high quartz (>30%)/low clay mineral content (<30%) (**Figure 4f**). The

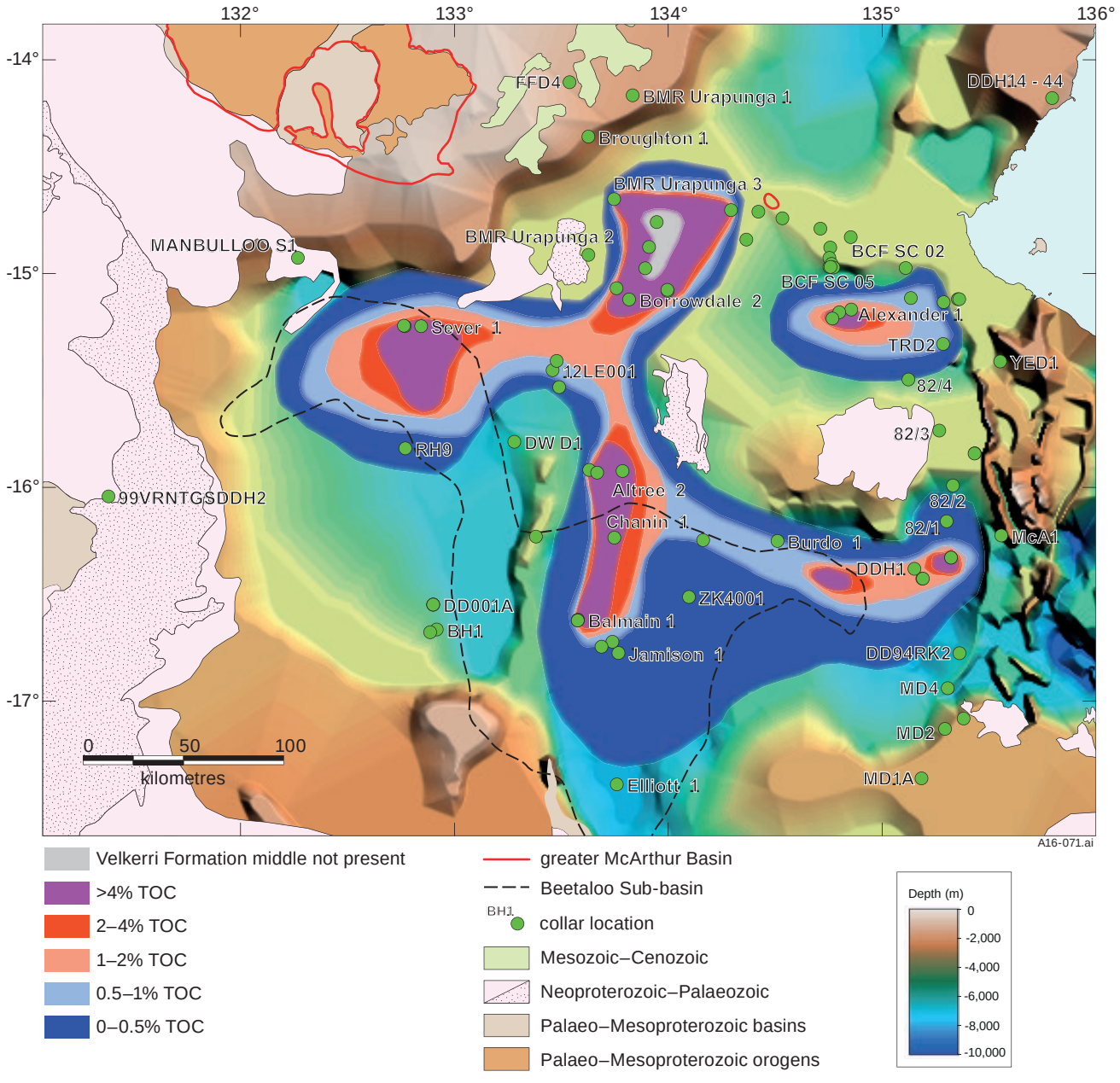

Figure 5. TOC_{pd} 2D sub-surface map of the Velkerri Formation middle unit in the McArthur Basin.

Kyalla Formation returned XRD results indicating >30% clay mineral content; however the bulk of the clay fraction is composed mainly of non-swelling clays and therefore technological advancements in extraction of hydrocarbons in the future may see an increase in the formation's potential.

A combination of seismic data, historical and new well sample data together with modern sedimentary basin analogues have been used for mapping interpretations of 2D sub-surface maps of TOC_{pd} in the Velkerri Formation middle unit (**Figure 5)**. The seismic data indicates that the stratigraphy in the Roper Group is continuously mappable, largely flat-lying and relatively undisturbed away from major fault systems. The newly acquired data is useful for defining the depositional environment of the sediments. The Velkerri Formation mudstones were deposited in an enclosed marine basin with a positive water balance where the outflow of fresh water exceeds the relatively small inflow of deeper saline water forming a stratified water column and anoxic conditions. Modern day analogues of this depositional environment include the Black Sea and Lake Maracaibo (Venezuela) where the enclosed marine basin maintains a physically restricted connection to the open sea with limited water exchange (Allen and Allen 2013, **Figure 6**).

Current exploration programs underway in the greater McArthur Basin will eventually yield new information regarding the formation pressure, GIP values and well decline rates of the areas targeted in drilling programs. This valuable information cannot be readily discerned from sampling existing core that has been stored for up to five decades in the tropical atmospheric conditions in Darwin.

This ongoing study of the Palaeo-Mesoproterozoic shales of the greater McArthur Basin has combined new and existing data with the application of new analytical techniques, approaches and ideas to improve the understanding of the regional-scale geology and basin architecture with the aim of identifying previously unrecognised unconventional gas plays.

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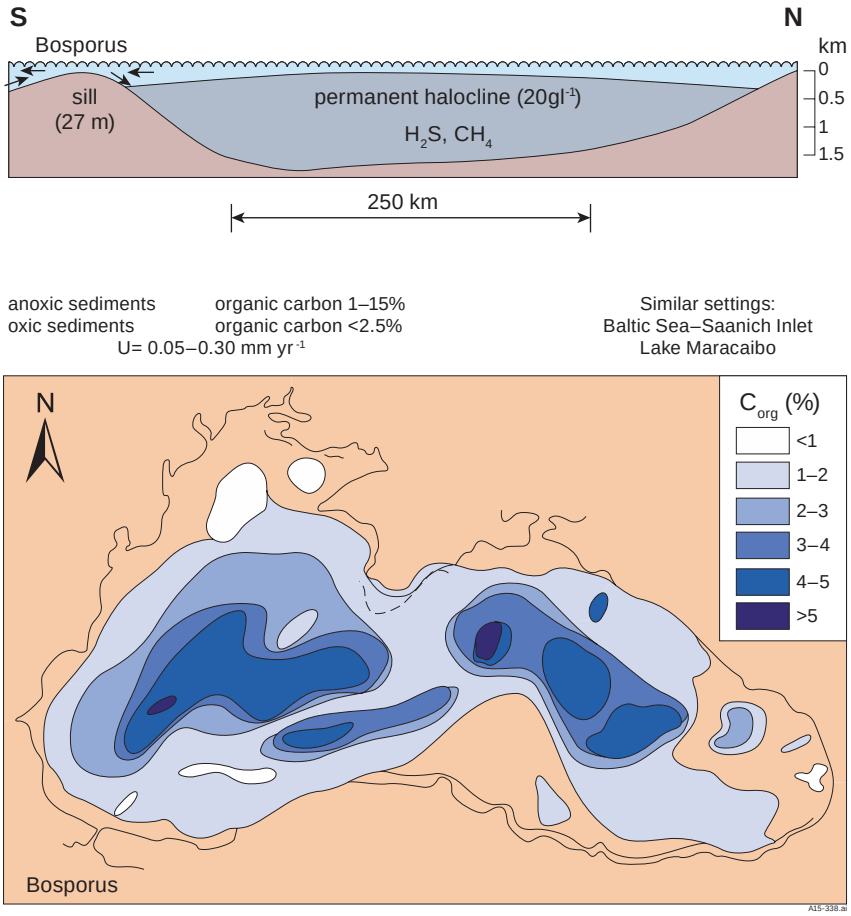

Figure 6. TOC concentrations in the Black Sea, a modern-day analogue of the McArthur Basin. TOC concentrations are highest in the deepest regions of the basin at water depths up to >1 km below a stratified water body (Allen and Allen 2013).