Unconventional gas potential in Proterozoic source rocks: Exploring the Beetaloo Sub-basin

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Abstract

The Proterozoic McArthur Group and Roper Group in the Northern Territory (NT) have been the focus of sporadic exploration for a number of decades with consistent oil and gas shows in exploration wells that have proven multiple working petroleum systems. Early exploration targeted conventional plays and mapped structural closures; however, since the mid- to late-2000s exploration has been primarily focused on unconventional Source Rock Reservoirs (SRR) or shale gas plays. One of the play targets of particular interest is the Mesoproterozoic Velkerri Formation of the Beetaloo Sub-basin (Beetaloo). The unique geologic history of the Beetaloo region has preserved source rocks from the Proterozoic that have been subject to relatively limited tectonic activity while still burying and maintaining them within the gas window. This play has seen relatively consistent levels of activity over a number of years, yielding encouraging results.

Even though the hydrocarbon potential of the Velkerri Formation has been known from outcrop and both petroleum and mineral exploration wells drilled since the 1970s, Origin Energy Ltd's exploration program in 2015 has provided new insights into the prospectivity of the play. Origin acquired extensive wireline data, sidewall core and full core data in addition to undertaking real-time geochemical analysis of cuttings while drilling. These results indicate reservoir intervals contain gas-saturated, quartz-rich source rocks that are mature for gas over extensive areas, providing an excellent exploration target with material volumetric upside. Additional information from acquisition of pressured sidewall cores and diagnostic fracture injectivity tests (DFIT) complemented the reservoir assessment, yielding accurate data on gas composition, saturation and an estimate of pore pressure.

This paper provides insights into and results from an active exploration program in Australia's most prospective frontier basin for unconventional gas. The Mesoproterozoic age of the target source rocks makes the exploration unique and presents a number of technical and operational challenges.

Introduction

Unconventional resources have been recognised across many Australian sedimentary basins with the Energy Information Administration (EIA) estimating a technically recoverable shale gas resource of >400 Tcf. Activity has primarily been concentrated across basins in Western Australia, South Australia and the Northern Territory. Mirroring the variable results achieved internationally, there have been successful flow tests reported in the Cooper Basin (SA), Perth Basin (WA), Fitzroy Trough/Canning Basin (WA) and McArthur Basin (NT), but disappointing results in the Kidson Sub-basin/Canning Basin (WA) and Georgina Basin (NT). Even though positive results often require more detailed analysis to determine if there has been a 'true' shale gas play tested, technical successes have encouraged interest and investment in shale gas exploration in Australia.

The greater McArthur Basin, and primarily the Beetaloo Sub-basin, has experienced the highest level of oil and gas exploration activity in the NT outside the Amadeus Basin. Initial exploration was limited to conventional leads that recognised the presence of multiple proven petroleum systems. The last decade has seen a focus shift primarily to the exploration of unconventional oil and gas resources, primarily in the Proterozoic source rocks of the Barney Creek, Velkerri and Kyalla formations.

In 2014, Origin and Sasol Ltd farmed into three exploration permits (EP98, EP117 and EP76 – the 'Permits'), that were held by Falcon Oil & Gas Ltd over the most prospective core of the Velkerri and Kyalla formation play fairways (**Figure 1**). Other operators exploring the Beetaloo region and focused on the Velkerri Formation play in particular include Santos Ltd, Pangaea (NT) Pty Ltd and INPEX Corporation. Since Falcon Oil & Gas successfully tested the Shenandoah-1A well in 2011, there have been nine exploration wells drilled into the Velkerri Formation by Santos, Origin and Pangaea.

Origin's first drilling campaign, completed in 2015, included three exploration wells in EP98, two vertical and one horizontal (**Figure 2**). Results of the wells are positive and encouraging gas-in-place metrics were observed; however, substantial further work is required to continue to assess the key risk of delivering commercial flow rates from multi-stage fracture stimulated horizontal wells.

2015 Campaign highlights

Results from two vertical wells and one horizontal well support the presence, lateral continuity and good reservoir and completion quality of the Velkerri Play. Petrophysical evaluation and core analysis indicate good reservoir properties (porosity, saturation), organic content (oil- to gas-mature Type I–II oil-prone source rocks), and a mineralogy conducive to stimulation (relatively low-clay quartz-rich mudstone to siltstone lithologies) that compares favourably with North American plays (**Table 1**).

The Kyalla Formation, a secondary target in the exploration program, was characterised by very high mud gas shows while drilling. Moreover, elastic log data suggest that despite relatively high clay contents, hydraulic fracture stimulation of the lower Kyalla Formation might

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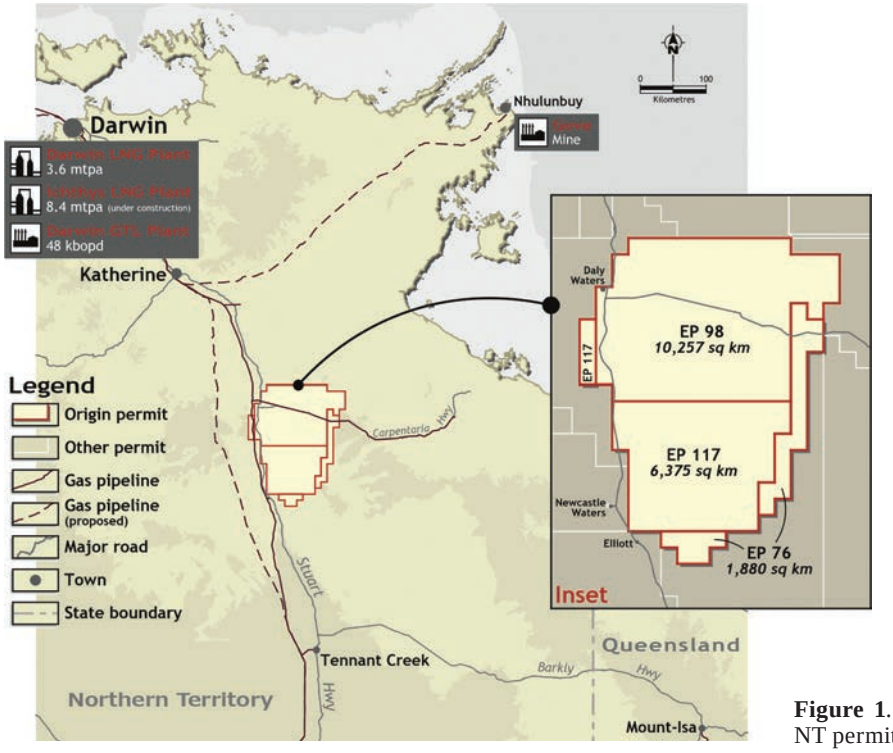

Figure 1. Extent of the Beetaloo JV's NT permits.

be effective (**Table 1**). Based on maturity indicators, the Kyalla Play is in the volatile oil to wet gas window, with fairways coincident with the current extent of the Beetaloo JV permits (**Figure 3**).

Despite potential challenges to commercialisation at shallower depths (ie challenges in the volatile oil window due to limited gas drive), the potential for a stacked play opportunity with a liquids-rich upside in the deeper parts of the basin provides the Beetaloo JV with a technically diverse opportunity.

Petrophysical data show upwards of 7% total and 4% gas-filled porosity in the middle Velkerri Formation. Average gas in place estimated from the petrophysical model aligns with the total gas content derived from direct measurements of pressurised sidewall cores. Furthermore, geomechanical proxies including Poisson's Ratio and Young's Modulus are within ranges where brittle behaviour conducive to hydraulic fracturing is expected.

Core evaluation confirms the excellent quality of the Velkerri and Kyalla formation source rocks. Rock-Eval pyrolysis indicates that both source rocks contain Type I-II kerogen material with average TOC values ranging from 1–10% in the middle Velkerri Member and 1–3.5% in the Kyalla Formation. Basin modelling and thermal maturity assessment based on alginite reflectance, associated bituminite and bitumen, suggests the Kyalla Formation is mature for oil generation, whereas the Velkerri Formation is gas mature to over-mature.

Petrographic evaluation including thin section and Ar-ion milled scanning electron microscopy (SEM) image analysis show that the middle Velkerri is dominated by siliceous mudstone to siltstone lithologies. Facies typically display massive to laminated textures and well developed, organic-hosted micron-sized porosity (**Figure 4**). Quantitative X-ray diffraction (XRD) results show that reservoir intervals typically have a mineral composition of

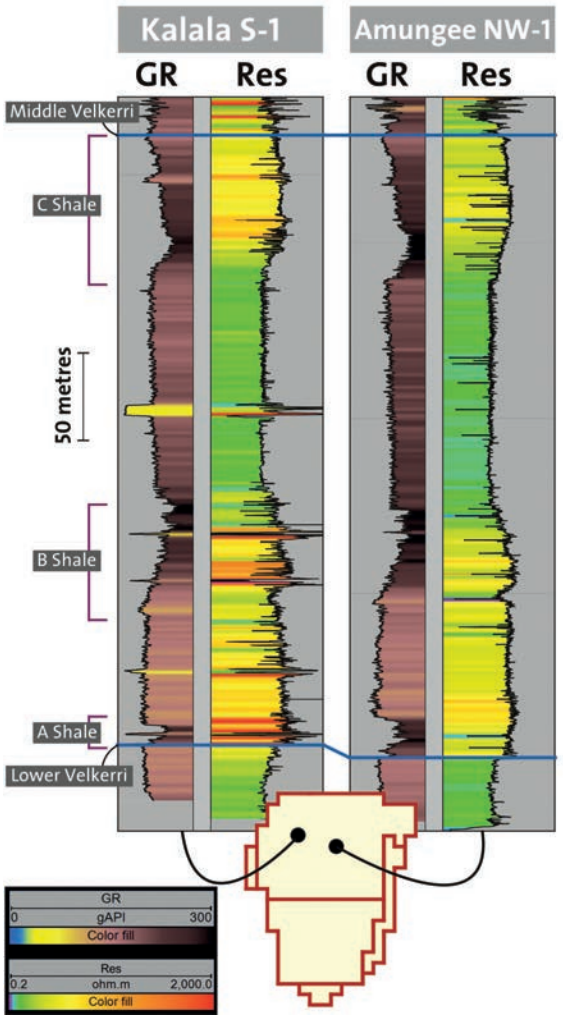

Figure 2. Kalala S-1 and Amungee NW-1 vertical exploration wells, drilled in 2015, illustrate continuity of three organic-rich intervals (A, B, and C shales) in middle Velkerri Formation across EP98 in north of Beetaloo Sub-basin.

60–80% quartz, 20–30% clays and trace to 10% carbonate and other accessory minerals (ie pyrite and feldspars). The observed mineral composition is analogous to successful North American plays (**Table 1**).

Stress and pore pressure characterisation based on Diagnostic Fracture Injection Tests (DFIT), breakout modelling and image log-based fracture evaluation provides strong evidence in support of the middle Velkerri Member being both overpressured and in a normal to strike-slip stress regime. Evidence for a normal to strike slip stress regime includes:

- closure pressure estimates from DFIT data,
- vertical fracture height growth and reactivation of conjugate fracture sets observed after an open-hole DFIT that was imaged during wireline logging,
- critically stressed fracture analysis.

The reactivation of conjugate fractures observed in image log data over the interval tested with the open-hole DFIT as well as the interpreted closure of the transverse fractures and the primary fracture from the DFIT, both support a fairly isotropic horizontal stresses. The primary direction of fracture growth observed in image log data also aligns with the average breakout orientation observed in image log data; this indicates a maximum horizontal stress orientation of northeast (north 45º east).

Understanding of the stress orientation, in addition to a detailed understanding of the reservoir and completion quality of the three primary organic-rich intervals within the middle Velkerri Formation, was critical to the planning and successful completion of the first horizontal well in the Beetaloo Sub-basin. The horizontal well was landed and geosteered within the sweetspot of the middle Velkerri B shale over a 1200 m lateral section, as indicated by consistently high gas shows and resistivity throughout the section.

Despite the overall success of the 2015 exploration campaign, drilling activities saw a number of technical and operational challenges. Drilling the top-hole section in particular was difficult due to the presence of lateritic clays at surface overlying cavernous limestone. Additional challenges through the production hole include very abrasive, sometimes water-bearing sandstones and thin dolerite sills that reduce drilling rates considerably.

Conclusions

The Proterozoic source rocks of NT basins provide a number of attractive targets for unconventional gas exploration. Origin is in the early stages of an exploration program focused on the core of the Beetaloo Sub-basin. Initial results from two vertical exploration wells and the first horizontal well in the sub-basin are positive and

Table 1. Comparison of key reservoir properties of Velkerri and Kyalla formations and a number of North American plays.

Shale	**Marcellus[1]**	**Barnett[1]**	**Fayetteville[1]**	**Middle Velkerri Member**	**B Shale**	**Kyalla Formation (Amungee NW-1)**
Basin/area	Appalachian Basin	Fort Worth Basin Texas	Arkoma Basin Arkansas	Beetaloo Sub-basin Northern Territory	Beetaloo Sub-basin Northern Territory	Beetaloo Sub-basin Northern Territory
Age	Devonian	Mississippian	Mississippian	Mesoproterozoic	Mesoproterozoic	Mesoproterozoic
Estimated basin area (km^2)	246,050	12,950	23,310	17,070[4]	17,070[4]	12,000
Typical depth for shale gas (m)	1220 - 2590	1980 - 2590	1,735	1000 - 2500	2418	1000 - 1400
Gross thickness (m)	60	60 - 305	15 - 100	45 - > 420	30	100 - 750
Net thickness (m)	15 - 105 (45)	30 - 215 (90)	5 - 60 (40)	60 - 86 (73)[2]	30	---
Reported gas contents (scf/ton)	60 - 150	300 - 350	60 - 220	100[2]	148	---
Adsorbed gas (%)	45	55	50 - 70	50[2]	45	---
Free gas (%)	55	45	30 - 50	50[2]	55	---
Porosity (%)	4.0 - 12.0 (6.2)	4.0 - 6.0 (5.0)	2.0 - 8.0 (6.0)	2.0 - 8.0	7.0 - 7.1	2.0 - 10.0
Permeability range (average) (nD)	0 - 70 (20)	0 - 100 (50)	1 - 100 (50)	10 - 100 (50)	10 - 100 (50)	---
Pressure gradient (psi/ft)	0.61	0.48	0.44	0.53[2]	0.53	---
Gas-filled porosity (%)	4.0	5.0	4.5	2.5[2]	3.6 - 4.1	---
Water saturation (%)	43	38	70	58[2]	43	---
Oil saturation (%)	1.0	10.0	< 1.0	0	0	---
Reported silica content (%)	37	45	35	49 (1.0 - 77)	54 (48 - 59)	49 (18 - 71)
Reported clay content (%)	35	25	38	35 (1.1 - 80)	29 (27 - 32)	56 (17 - 79)
Reported carbonate content (%)	25	15	12	Tr (Tr - 12.3)	1 (Tr - 4)	1 (0 - 22)
Chlorite (%)	20 (0 - 50)	2 (0 - 20)	20 (5 - 40)	3 (Tr - 40)	3 (3 - 4)	8 (3 - 14)
%Ro (average-range)	1.5 (0.9 - 5.0)	1.6 (0.85 - 2.1)	2.5 (2.0 - 4.5)	1.5 - > 2.5[3]	2.0 - 2.3[3]	1.0 - 1.6[3]
HI present-day	20	45	15	20	22	102
TOC present-day (average in wt%)	4.01 (2.0 - 13.0)	3.74 (3.0 - 12.0)	3.77 (2.0 - 10.0)	3.74 (1.0 - 10)	4.05 (3.8 - 4.1)	2.17 (1.0 - 3.5)
S1 present-day + S2 present-day (mg/g)	1.23	1.95	0.35	0.89	1.04	3.24
GIP from gas contents (average bcf/section)	130	150 - 200	55	126[2]	31	---

[1] Souce: Jarvie 2012
[2] Origin Energy Ltd estimated average values from C, B, and A shale in Kalala S-1 and Amungee NW-1
[3] Value represent Equiv. %Ro estimated from alginite reflectance
[4] Based on Beetaloo JV permit area

suggest the potential for a multi-Tcf play in the middle Velkerri Formation. Notwithstanding the positive results from Origin's 2015 exploration campaign, there remain numerous technical and non-technical challenges to commercialisation, and substantial work remains to be completed to definitively test the Velkerri Play and other plays in the sub-basin.

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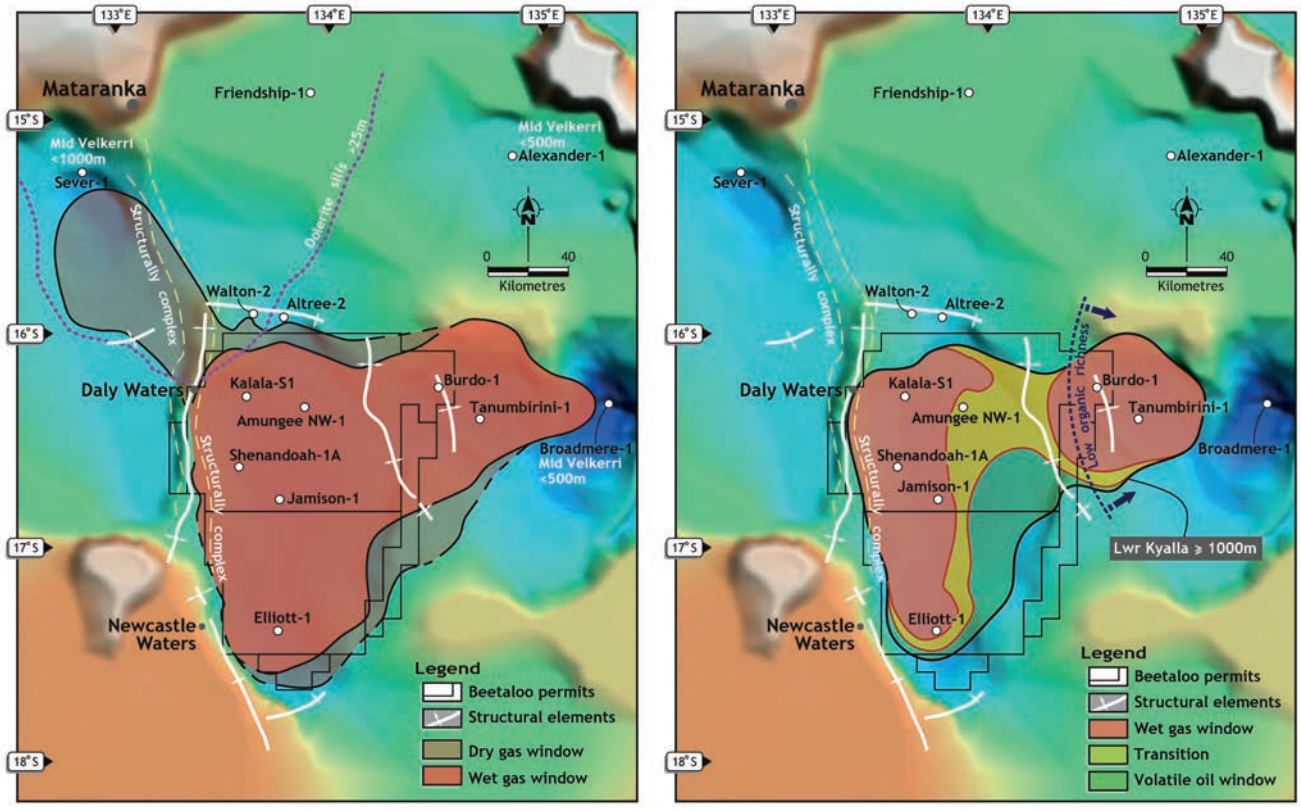


Figure 3. Extent of the Velkerri (left) and Kyalla (right) play fairways. Based on mud gas and maturity indicators, the Velkerri play is interpreted to be within the dry to wet gas window whereas the Kyalla play is in the volatile oil to wet gas window. Fairways in both plays are coincident with the current extent of the Beetaloo JV permits. Background is SEEBASE™ depth-to-basin image (after Pryor and Loutit 2005).

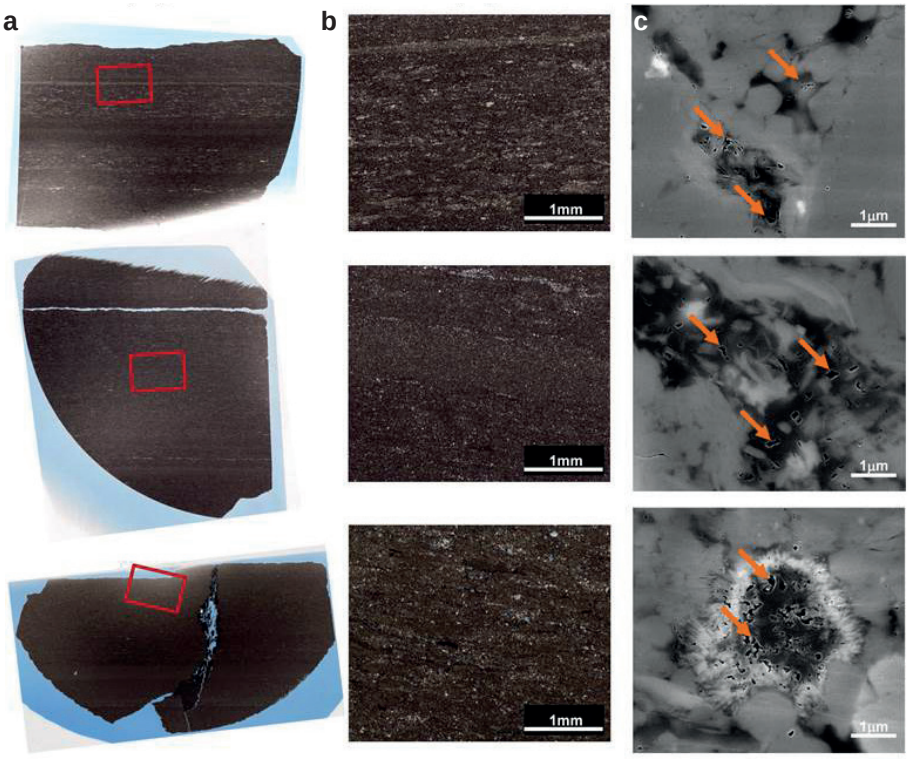
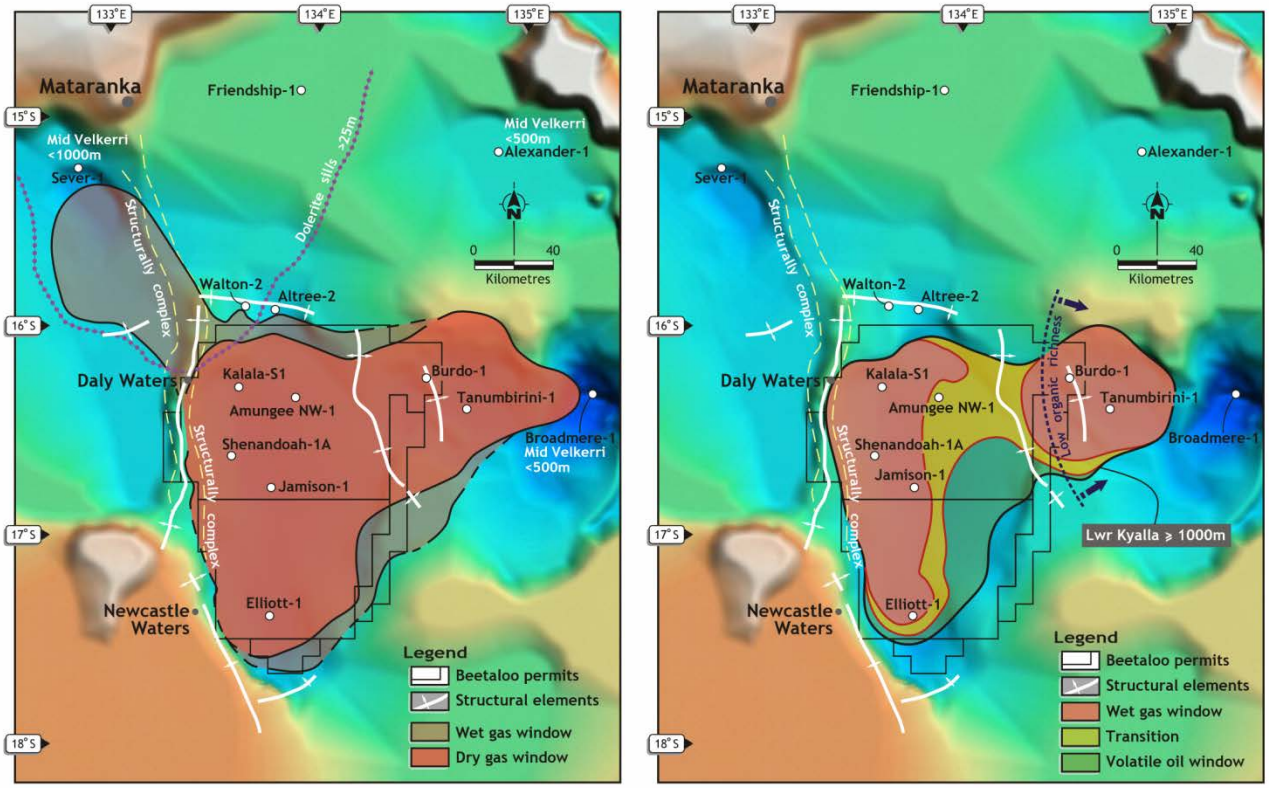


Figure 4. Petrographic analysis of samples from middle Velkerri Formation in Kalala S-1. (**a-b**) Thin sections (plane polarized light) show facies are dominated by siliceous mudstone to siltstone lithologies with common massive to laminated textures. (**b**) Close-up of red box in (**a**). (**c**) Ion-milled scanning electron microscopic (back-scatter mode) images illustrating the location of organic-hosted porosity (arrows).

Erratum

In: Close DI, Baruch ET, Altmann CM, Cote AJ, Faiz M Mohinudeen FM, Richards B and Stonier S, 2016. Unconventional gas potential in Proterozoic source rocks: Exploring the Beetaloo Sub-basin: in *'Annual Geoscience Exploration Seminar (AGES) Proceedings, Alice Springs, Northern Territory 15–16 March 2016'*. Northern Territory Geological Survey, Darwin. 91-94.

In page 94, **Figure 3** was incorrect: the legend for wet gas window and dry gas window were reversed. The correct **Figure 3** is shown below.



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