Unconventional Gas Potential in the Northern Territory, Australia: Exploring the Beetaloo Sub-Basin*

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Abstract

The Proterozoic McArthur Group and Roper Group have been the focus of sporadic exploration in the Northern Territory, Australia, 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, 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 including 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 but not without 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 frontier and producing basins in Western Australia, South Australia, and the Northern Territory (Figure 1). Over the last five years almost every sedimentary basin across these states has been gazetted. 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) in addition to disappointing results in the Kidson Sub-Basin/Canning Basin (WA) and the Georgina Basin (NT). Exploration across these basins has focused on multiple play types, including buoyancy trapped tight gas, basin centred gas (BCG) and shale gas – with a general recognition that the largest resource upside is in the latter two play types. 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 the interest and investment on shale gas exploration in Australia.

The greater McArthur Basin, and primarily the Beetaloo, has seen the highest level of oil and gas exploration activity in the Northern Territory (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.

Origin and Sasol Ltd farmed into three exploration permits (EP98, EP117, and EP76 – the "Permits") over the most prospective core of the Velkerri and Kyalla play fairways (Figure 2) that were held by Falcon Oil & Gas Ltd in 2014. 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 are 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.

Regional Geologic Setting of the McArthur Basin and Beetaloo Sub-Basin

The Palaeo- to Mesoproterozoic McArthur Basin is a poorly outcropping unit with subsurface coverage extending over a known area of 180,000 km^2 (69,500 mi^2) (Figure 3) (Bull, 1998). The basin comprises, from oldest to youngest the McArthur, Nathan, and Roper Groups and it is generally capped by the overlying Georgina, Wiso, Daly, and Carpentaria basins (Powell et al., 1987; Dunster and Ahmad, 2010; and Ahmad and Scrimgeour, 2013). The sequence is primarily an unmetamorphosed succession of sedimentary and minor volcanic rocks that accumulated within a multiphase intra-cratonic basin setting (Munson, 2014). The sequence reaches maximum thickness of up to 15,000 m (49,210 ft) in the deepest parts of the basin (Munson, 2014) and thins over major structural features and away from major depocenters. Despite covering a great portion of the NT, the total subsurface extent of the McArthur Basin remains poorly constrained. There has been considerable

improvement in understanding sediment distribution within the Walker Fault Zone and Batten Fault Zone regions due to the relative abundance of outcrop and mining exploration in the area, however, regional understanding is still lacking.
A remarkable aspect of the McArthur Basin is that it preserves some of the oldest, organic-rich source rock intervals in the world within the Barney Creek (1640 ± 3 Ma), Velkerri and Kyalla (1429 ± 31 Ma) formations. Environmental conditions during the Proterozoic, a restricted marine environment and high organic productivity, resulted in a prolific, long-lived, source sink system where high quality organic-rich sediments accumulated and were preserved over vast areas. Despite their antiquity, these source rocks have not been exposed to extreme alteration, rather remaining within depths and temperature ranges consistent with thermogenic generation of gas.

One of the largest structural depocenters within the McArthur Basin and current focus of considerable petroleum exploration activity is the Beetaloo Sub-Basin (Beetaloo) (Figure 3). Located in the southern part of the Greater McArthur Basin, the Beetaloo is structurally subdivided into three geographical areas and two major structural highs. The north-south trending, structurally complex Daly Waters Arch (west) and structurally benign Arnold Arch (east) divide the area in three major depocenters, referenced here as the Sever Sub-Basin, the Core area, and the OT Downs Sub-Basin from west to east respectively (Figure 4). The northern boundary of the Beetaloo is largely defined by the regional Mallapunya Fault where seismic and well penetrations indicate that the strata shallow significantly to the north. Typically the Kyalla Formation is eroded outside of the Beetaloo area and the Velkerri Formation is often found at depths of <1000 m or is also eroded. Despite an enigmatic tectonic genesis, the Beetaloo is interpreted to result from multiple basin reconfigurations including periods of intra-cratonic sag (Plumb and Wellman, 1987), crustal extension (i.e. Batten and Walker Fault zones) and foreland development (as suggested by a possible ancient arc or orogenic belt to the south) (Jackson et al., 1990 and Jackson et al., 1999). Seismic and well coverage across the Beetaloo confirm the core area was a major depocenter at the time of accumulation of the Roper Group retaining the thickest and most complete section known in the Northern Territory.

The Mesoproterozoic Roper Group comprises cyclical repetition of mudstone and sandstone units reaching thickness greater than 3,000 m (9,840 ft) and averages of 1,500 m (4,920 ft) away from major depocenters (Figure 5) (Abbott and Sweet, 2000). The succession has yet to be fully penetrated in the deepest depocenters; however, individual formations can be traced over most of the McArthur Basin in seismic profiles and especially across the Beetaloo, where they show remarkable thickness consistency and lateral continuity (Munson, 2014). The sequence is unconformably overlain by the Chambers River Formation which may be as young as Neoproterozoic (Lanigan et al., 1994), and successively overlain by the Bukalara Sandstone and volcanic rocks of the late early Cambrian Kalkarindji Large Igneous Province (Kalkarindji Province), and by Neoproterozoic–Palaeozoic Georgina Basin and Mesozoic Carpentaria Basin strata (Munson, 2014). The Roper Group succession was deposited in a variety of shallow-marine, and nearshore to shelf environments (Powell et al., 1987; Jackson et al., 1988; and Abbott and Sweet, 2000) with organic enrichment confined to the Velkerri and Kyalla formations. The sequence has been recognized as having excellent exploration potential (Falcon, 2015).

The Velkerri Formation, comprising green, grey and black shale, and siltstone sits conformable on the Bessie Creek Sandstone, often showing a gradational contact with the Moroak Sandstone (Figure 5). The formation is subdivided into three informal units – lower, middle, and upper Velkerri members. The unconventional potential of this unit is greatest in the organic-rich mudstones of its middle Member – informally subdivided by Origin and other operators in the area as A, B, and C Shale (from oldest to youngest). These organic-rich mudstones are typically separated by organic-lean siltstones. A ~1320 Ma dolerite sill known as the Derim Derim dolerite typically separates the Bessie Creek

Sandstone and the Velkerri Formation to the north and west of the Beetaloo reaching maximum thickness of 120 m (390 ft) before thinning and fingering to less than 10 m (33 ft) (average) within the Core area.

The Kyalla Formation, dominated by grey and black siltstone and shale sits conformably on the Moroak Sandstone but displays a sharp, erosional and disconformable contact with the overlying Cambrian succession. The Formation is subdivided into an upper and lower unit. Organic richness is generally confined to the lower Kyalla Formation. Historic drilling has seen multiple oil shows and gas bleeds in the lower Kyalla Formation supporting its potential as an unconventional play.

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 (Figure 6).

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 the lower Kyalla Formation may be effectively hydraulically fracture stimulated (Figure 6). 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 7). Despite potential challenges to commercialisation at shallower depths (i.e. challenges in the volatile oil window due to limited gas drive), the potential for a stacked play opportunity with a liquids-rich upside within 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 petrophysical models align with the total gas content derived from direct measurements of pressurised side wall cores recovered at Kalala S-1. 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 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 the middle Velkerri is dominated by siliceous mudstone to siltstone lithologies. Facies typically display massive to laminated textures and well-developed, organic-hosted micron-size porosity. Quantitative X-Ray Diffraction (XRD) results show reservoir intervals typically have a mineral make up of 60-80% quartz, 20-30% clays with trace to 10% carbonate and other accessory minerals (i.e. pyrite and feldspars). The observed mineral composition is analogous to successful North American plays (Figure 6).

Stress and pore pressure characterisation based on Diagnostic Fracture Injection Tests (DFIT), breakout modelling, and image log-based fracture evaluation provides strong evidence supporting that the middle Velkerri Member is both overpressured and in a normal to strike-slip stress regime. Evidence supporting 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, and 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 align with the average breakout orientation observed in image log data and indicate a maximum horizontal stress orientation of north-east (north 45 degrees 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. The horizontal was landed and geosteered within the sweetspot of the middle Velkerri B Shale for over 1200 m with 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 challenging 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 dolerites sills that reduce drilling rates considerably.

Conclusions

The Proterozoic source rocks of Northern Territory 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 Basin, are positive and 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 Basin.

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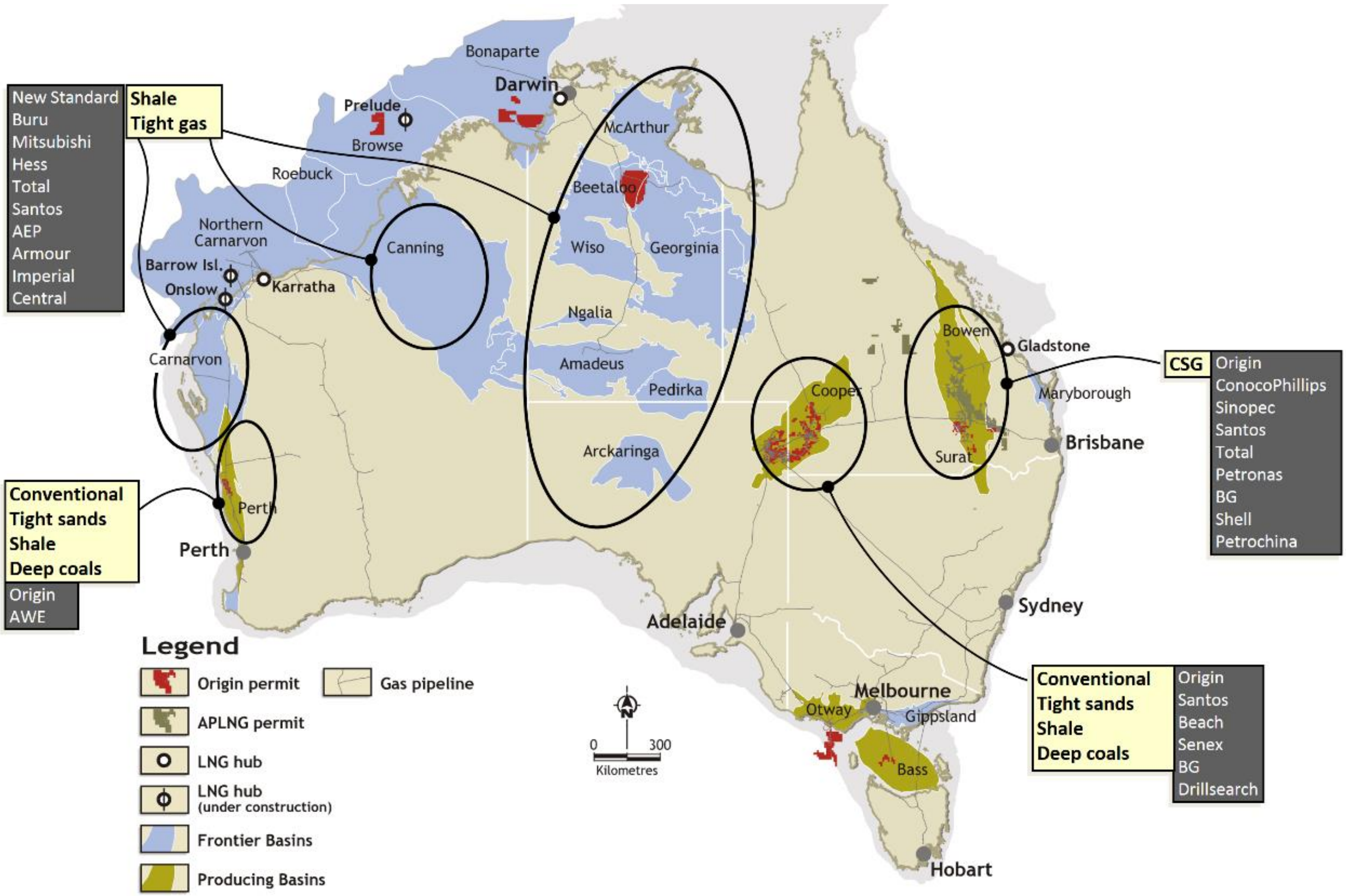

Figure 1. Unconventional shale gas exploration in Australia has primarily been concentrated across frontier basins in Western Australia, South Australia, and the Northern Territory as well as in the mature Perth and Cooper basins (after Close, 2015).

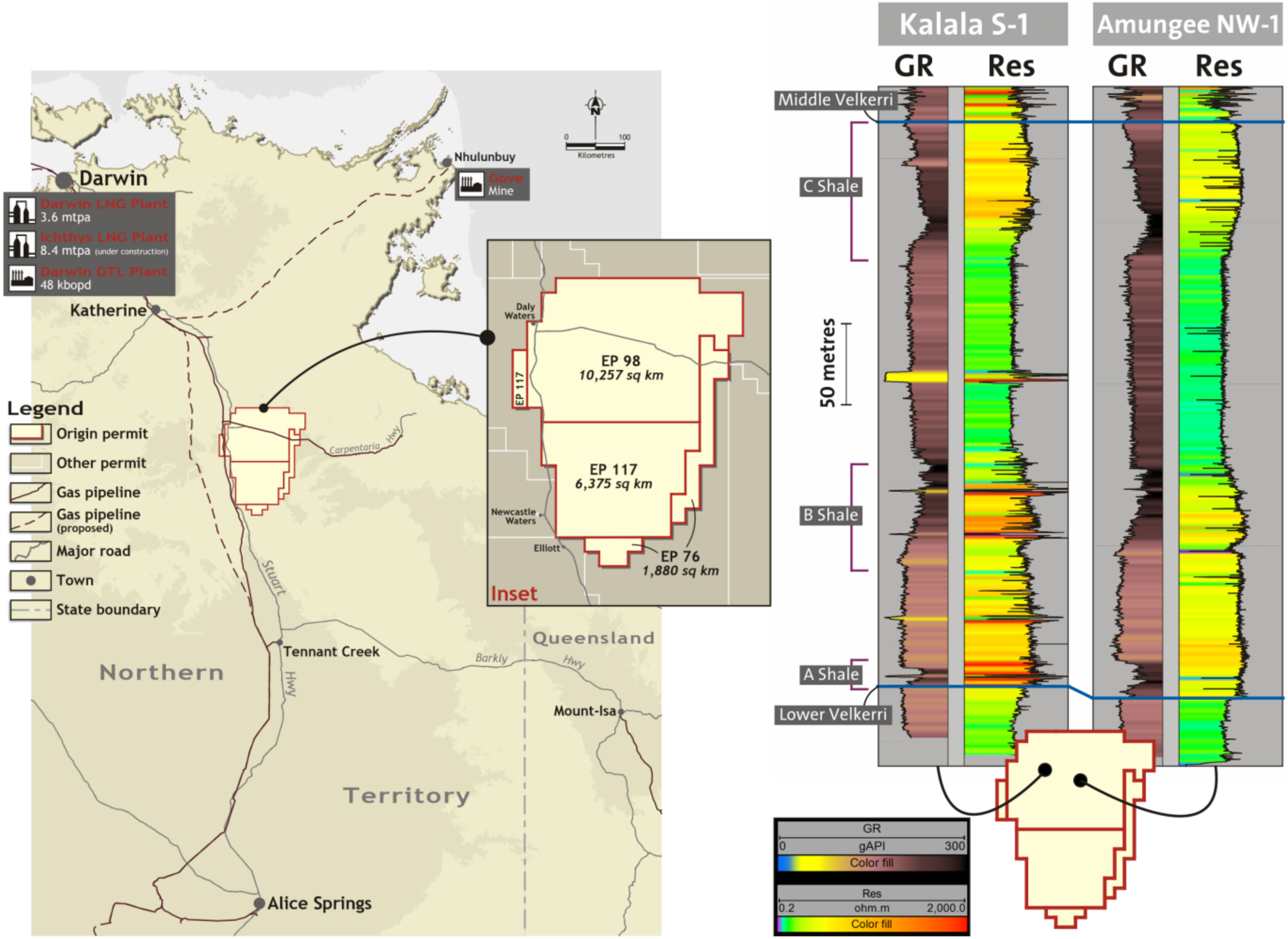

Figure 2. The extent of Origin permits in the McArthur Basin (left). The Kalala S-1 and Amungee NW-1 exploration wells, drilled in 2015, illustrate the continuity of three organic-rich intervals (A, B, and C Shales) within the middle Velkerri Formation across EP98 in the north of Beetaloo Sub-Basin (right).

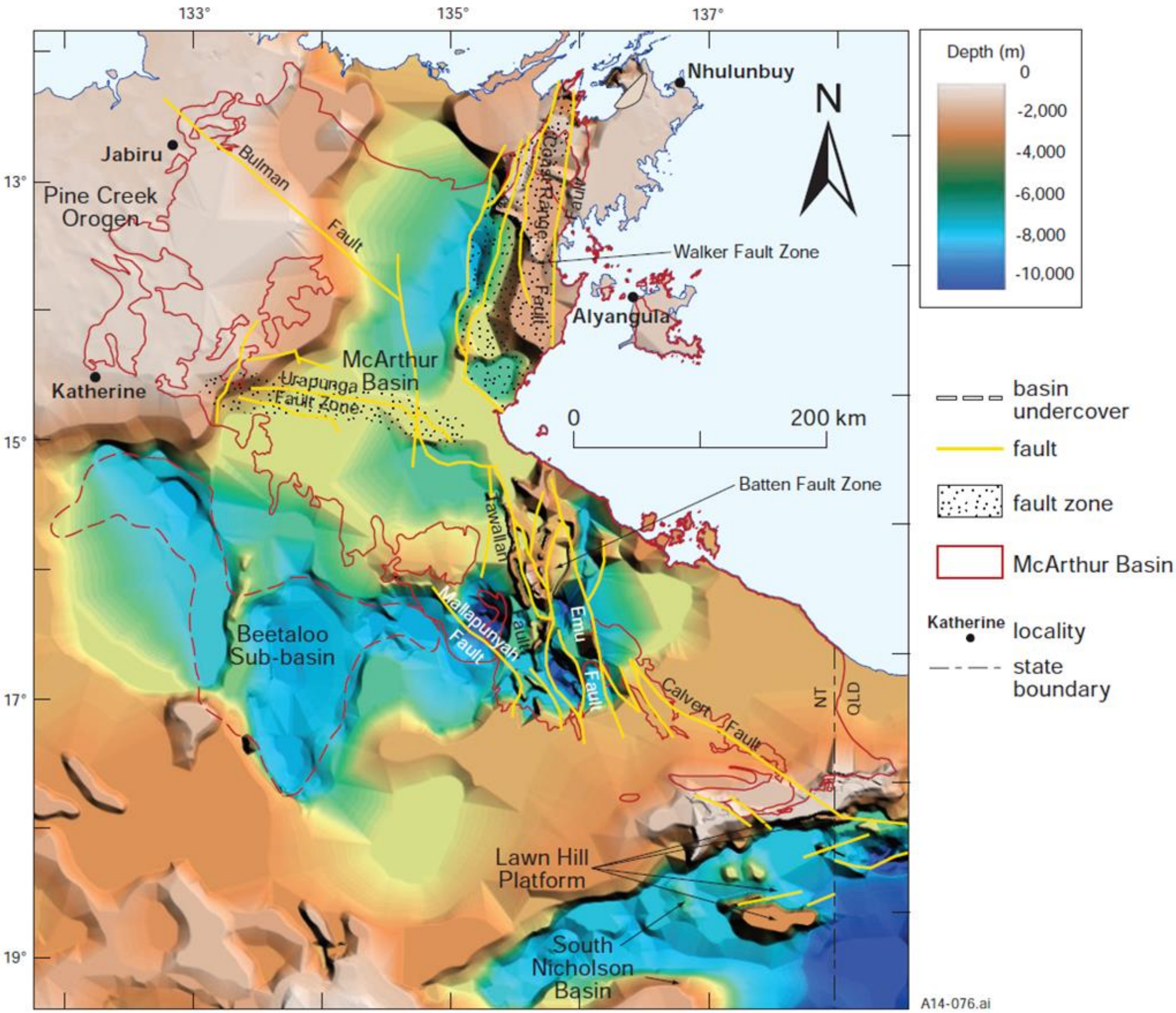

Figure 3. SEEBASE^{TM} depth-to-basin image (Pryer and Loutit, 2005) showing interpreted location of the McArthur basin and other associated basins in the Northern Territory. The Beetaloo sub-basin is outline in red (after Munson, 2014).

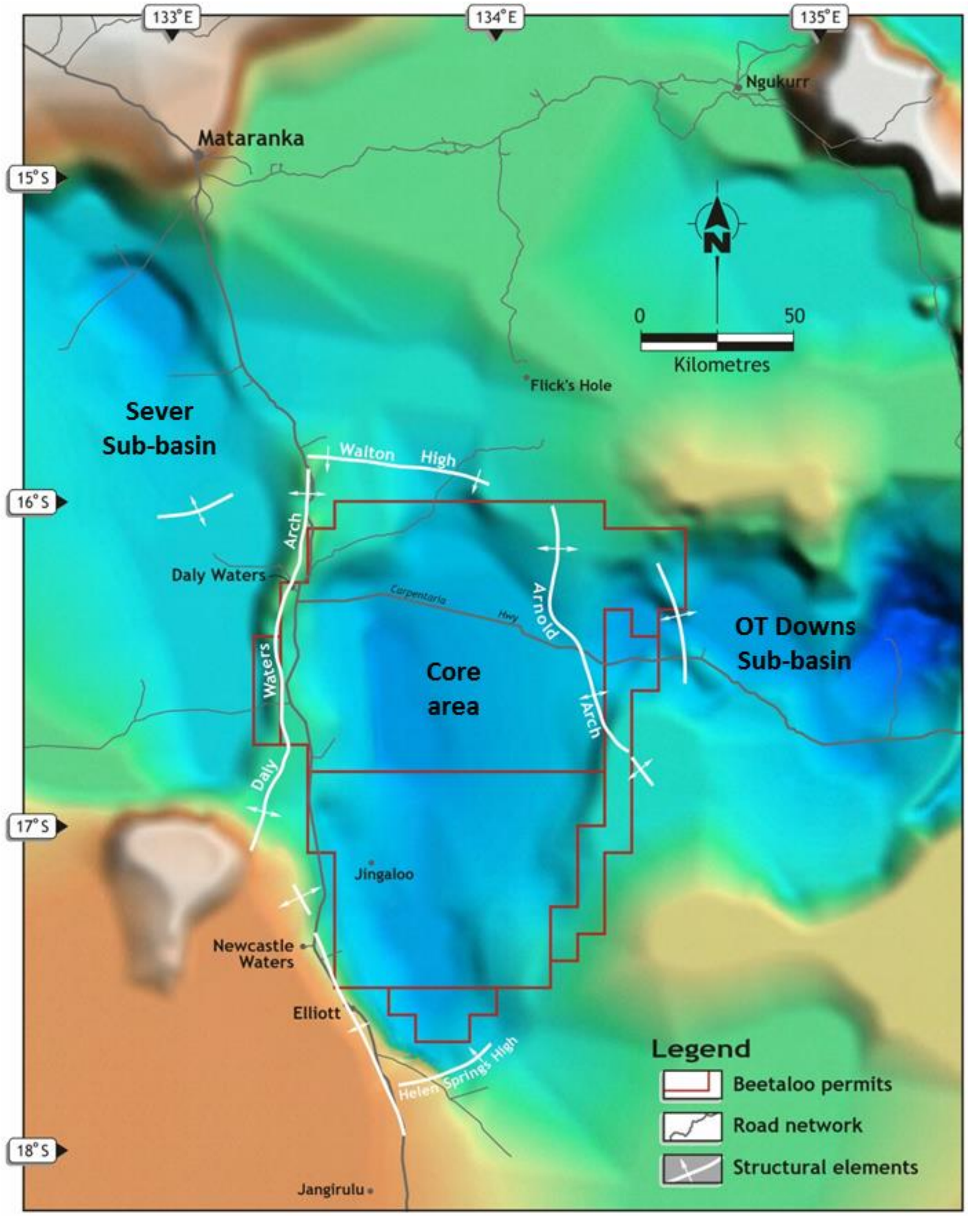

Figure 4. The Beetaloo Sub-basin is structurally subdivided into three geographical areas and two major structural highs. The north-south trending Daly Waters Arch (west) and Arnold Arch (east) divide the area in three major depocenters: the Sever Sub-Basin, the Core area, and the OT Downs Sub-Basin. The sub-basin is bounded to the north by the Walton High and south by the Helen Spring High. Background is SEEBASE™ depth-to-basin image (Pryer and Loutit, 2005).

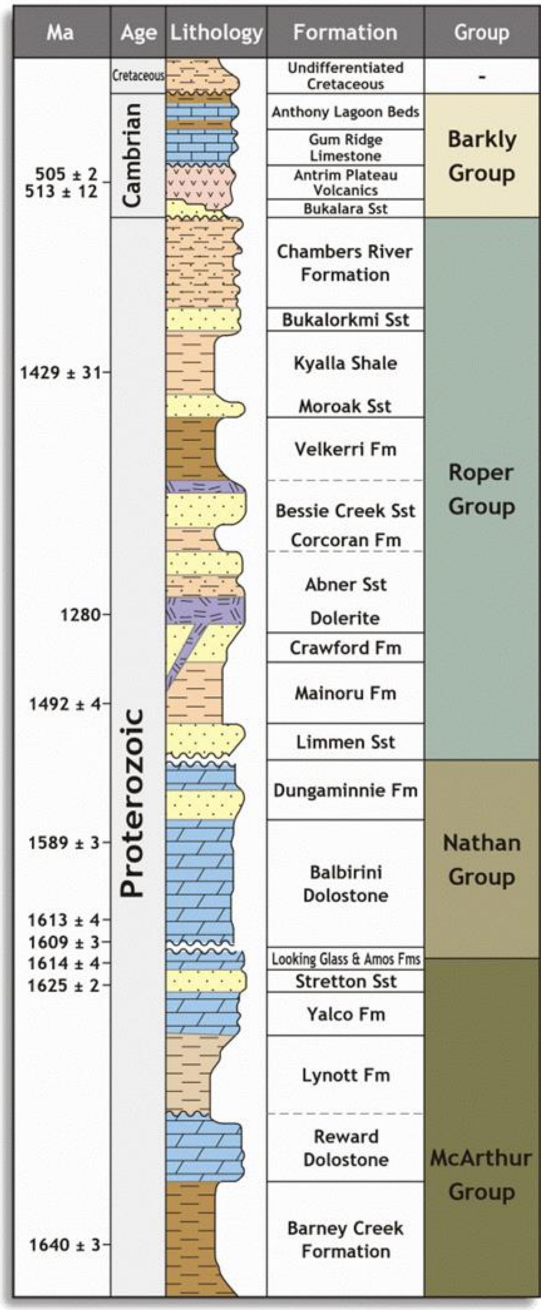

Figure 5. Stratigraphic column showing distribution of the McArthur, Nathan, Roper, and Barkly groups and overlaying units.

Shale	Marcellus[1]	Barnett[1]	Fayetteville[1]	Middle Velkerri Member	B Shale (Amungee NW-1)	Kyalla Formation
Basin/area	Appalachian Basin	Fort Worth Basin Texas	Arkoma Basin Arkansas	Beetaloo Basin Northern Territory	Beetaloo Basin Northern Territory	Beetaloo 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, D.M., 2012, AAPG Memoir 97, p. 69-87

[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

Figure 6. Comparison of key reservoir properties among the Velkerri and Kyalla formations and a number of North American plays.

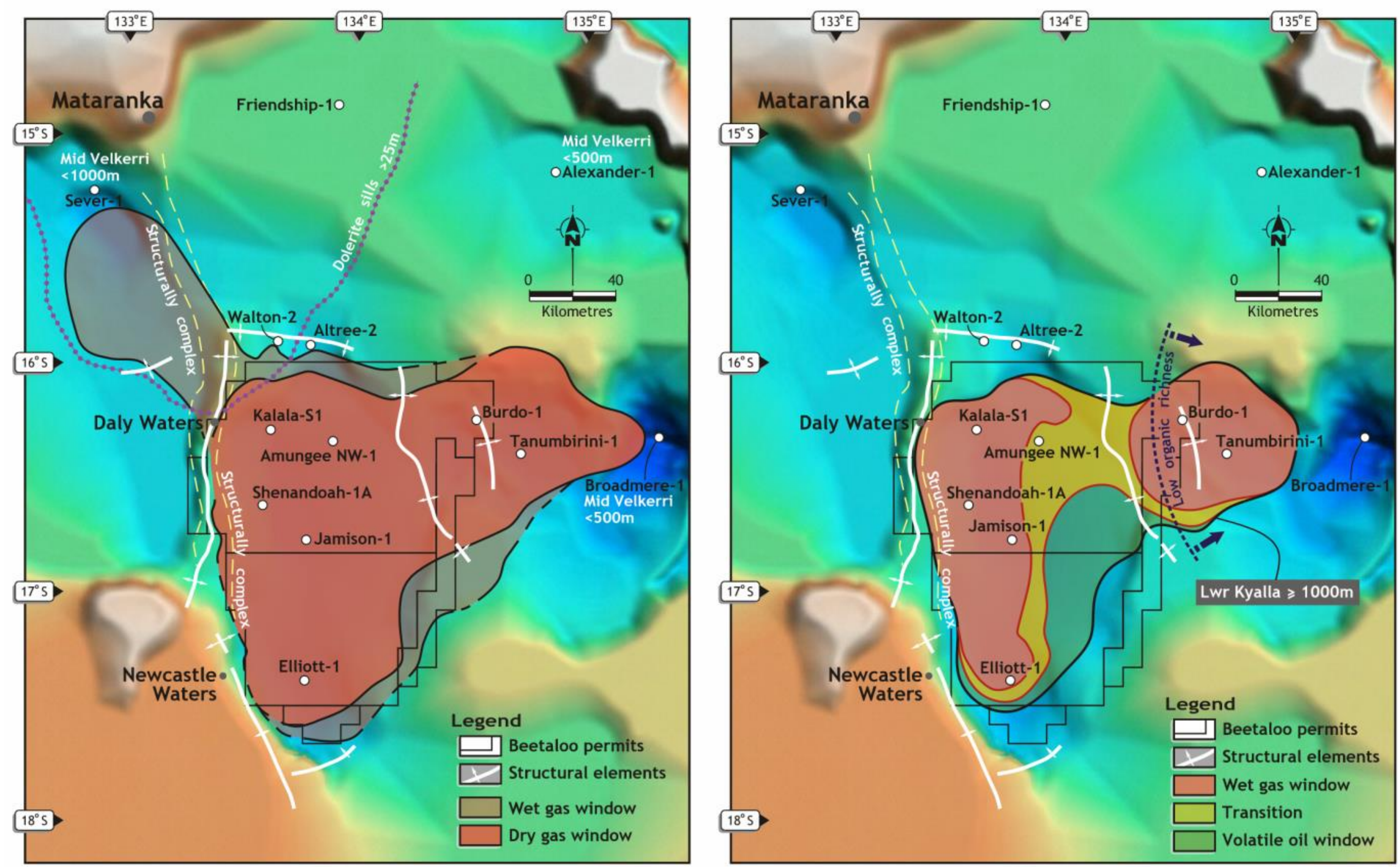

Figure 7. Extent of the Velkerri (left) and Kyalla (right) play fairways. Based on mud gas and maturity indicators, the Velkerri play is interpreted to be within the dry to wet gas window whereas the Kyalla play is in the volatile oil to wet gas window. Fairways in both plays are coincident with the current extent of the Beetaloo JV permits. Background is SEEBASE™ depth-to-basin image (Pryer and Loutit, 2005).