COULD THE MESOPROTEROZOIC KYALLA FORMATION EMERGE AS A VIABLE GAS CONDENSATE SOURCE ROCK RESERVOR PLAY IN THE BEETALOO SUB-BASIN?

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SUMMARY

Reservoir and geomechanical analysis of Kyalla Formation core and wireline logs acquired at Beetaloo W-1 indicate the presence of two potential Source Rock Reservoir (SRR) intervals; the middle Kyalla SRR and the lower Kyalla SRR. The key properties of the SRRs include TOC 1-3%wt, PHIT 5-10%BV, SWT 30-60%PV, free gas porosity 2-5%BV, and 20-40scf/ton adsorbed gas content. A Poissons Ratio of 0.15-0.2 and Young's Modulus of 30-35GPa suggest favourable geomechanical properties for effective hydraulic fracture stimulation. The lower Kyalla SRR has the greatest potential as it displays consistently positive geomechanical properties over the entire SRR interval as well as consistently high free gas porosity (>2-3%BV). Mudgas and core analysis indicate that the reservoir hydrocarbon phase is likely to be a wet gas. Potential retrograde condensation may yield significant condensate and LPG fractions from the produced gas stream.

The positive reservoir and geomechanical properties within the Kyalla Formation SRR intervals at Beetaloo W-1 suggest further appraisal work is warranted to determine the deliverability of the SRRs and to determine what LPG and Condensate yields can be recovered at the well head.

Key words: Kyalla Formation, Beetaloo Sub-Basin, Australian Shale Gas, Proterozoic Hydrocarbons, Australian Frontier Exploration

INTRODUCTION

The shale gas and oil industry, born in the United States in the mid-1990s with the discovery of the Barnett and Bakken Shale Plays, invigorated and re-shaped forever the future of the onshore hydrocarbon industry in North America. With the unlocking of vast reserves of oil and gas within shale source rocks, the industry changed focus from improving recovery from depleting conventional reserves to exploring and appraising unconventional targets. The commercial unlocking of source rock hydrocarbons became viable with a well-developed and mature pipeline and rail infrastructure system, a large and skilled workforce with significant volumes of readily available equipment, ongoing capital injection and above all continual development and refinement of horizontal drilling and fracture stimulation technologies.

In 2016 the U.S. EIA estimated 43.3 Bcf/day of dry natural gas production was coming from shale (EIA 2017a) and 4.25 million bbl/day oil/lease condensate (EIA 2017b) along with significant volumes of LPG were produced from tight oil resources (including shale). The prolific production of shale resources is almost exclusively confined to North America, with limited success outside of core North American Plays. The failure of many international shale plays can be attributed in part to the absence of the factors previously stated. In addition to these economic factors, unfavourable geology of some proposed shale plays muted the effectiveness of the key technology, hydraulic fracture stimulation, to access the reservoir surface area needed to counteract the incredibly low permeabilities of the shale reservoirs.

Within Australia numerous shale plays have been publicized by many operators over the last 10 years. Many of these plays have been subsequently proven through reconnaissance reservoir analysis, geomechanical testing, or horizontal drilling and fracture stimulation testing to be either technical failures or technically feasible but economically challenged. The global resources downturn which began in late 2014 resulted in many petroleum companies retracting capital from exploration and appraisal investments, especially in immature shale plays and frontier areas. Companies instead invested the limited capital available into core assets where returns were more certain. This left many frontier shale exploration plays orphaned in a capital restricted environment or abandoned altogether.

The Kyalla Formation

The Mesoproterozoic Kyalla Formation (Kyalla) in the Beetaloo Sub-Basin has historically yielded consistent high mud gas shows, and multiple oil shows and gas bleeds, which empirically support its potential as a SRR.

Deposition of the Kyalla is interpreted to have occurred in the transition from shelf to a deep marine dominated environment with intermittent periods of increased coarse siliciclastic sediment input. The transition between the underlying Moroak Formation and the Kyalla represents a transgressional contact evidenced by the abrupt finning upwards sequence. The top of the Kyalla is bounded by a regional erosional unconformity of poorly constrained timing. This event resulted in a regionally variable erosional profile of the Kyalla Formation and underlying Roper Group Sediments, with the greatest denudation occurring towards the basin margins (Figure 1). The Bukalorkmi Sandstone was subsequently deposited on this erosional surface.

Three primary SSRs exist within the Kyalla Formation, informally subdivided by Origin into 'upper Kyalla', 'middle Kyalla' and 'lower Kyalla'. The upper Kyalla SRR extent is restricted to the centre of the combined EP98 and EP117 exploration permits, where less erosion has occurred. The middle Kyalla SRR and lower Kyalla SRR display a greater regional extent, and are present throughout much of EP98 and EP117 (Figure 1).

Kerogen within the Kyalla SRRs is primarily Type I-II derived from bacteria and filamentous organisms such as blue green algae (Cyanobacteria) (Faiz et al, 2016). Total organic carbon (TOC) content is generally 1-4 wt%, but sporadic samples throughout the sub-basin have yielded 6-9%wt. Analyses of maturity parameters including Methylphenanthrene Index (MPI) and alginite reflectance indicate a thermal maturity equivalent to a vitrinite reflectance of ~1.3-1.6% for the middle to lower Kyalla source rocks at Beetaloo W-1. Offset MPI core data from Jamison-1 suggests the upper Kyalla source rocks at Beetaloo W-1 are within late, early oil generation, with a thermal maturity equivalent to a vitrinite reflectance of ~0.66%.

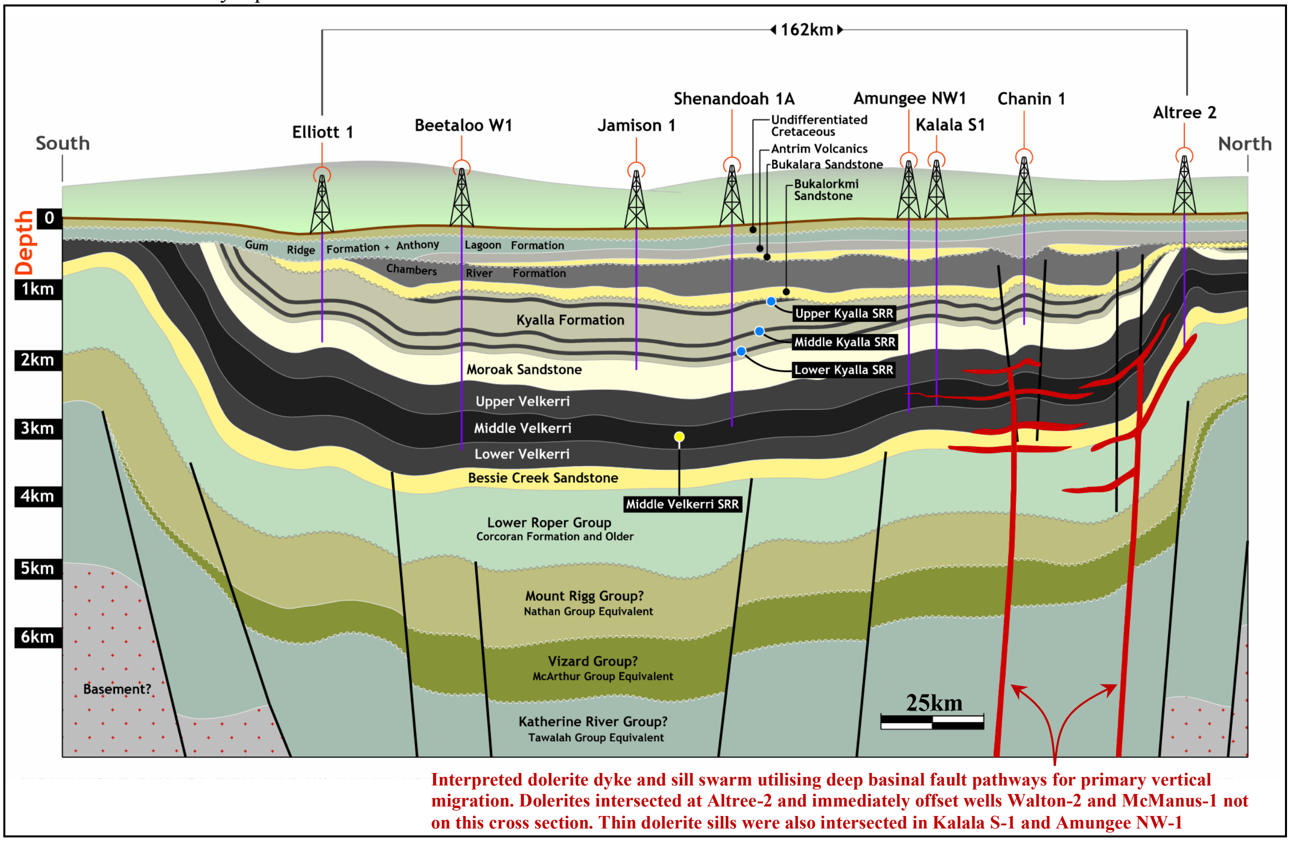

Figure 1 - Regional South to North schematic cross-section across the central portion of EP76, EP117 and EP98 based on a combination of 2D seismic and well penetrations. The presence and distribution of formations below the Bessie Creek Sandstone are interpretive based on general seismic reflector trends. Identified Kyalla SRRs are notated in blue.

Exploration History of the Kyalla Formation Source Rock Reservoirs

The Kyalla Formation was first identified as a SRR by the Omega Oil and Pacific Oil and Gas joint venture (JV) in 1995. The exploration concept employed by the Omega and Pacific JV, identified similarities between the Kyalla and the gas producing Devonian shales of the Appalachian Basin as well as the oil and gas producing Bakken Formation of the Williston Basin (Clementson 1994) and led to a comprehensive study into the 'Viability of horizontal drilling into fractured self-sourcing black shales, Kyalla Formation, Northern Territory' (Karajas and Flavelle 1995). Karajas and Flavelle (1995) documented and detailed the SRR potential of the Kyalla, in particular the SRR intervals within the light oil maturity window at the top of the Formation (upper Kyalla SRR), as per the company's oil exploration goals at the time. The report drew comparisons between the development of the Bakken Shale from horizontal wells drilled into naturally fractured zones and a proposed appraisal and development plan for the Kyalla SRRs (Karajas and Flavelle 1995). Interest in the Kyalla Formation SRR play waned when Omega Oil ceased operations in the Beetaloo Sub-Basin in 1995 (Flavelle 2017), following unsuccessful attempts to raise capital and interest.

Interest in the SRR potential of the Beetaloo Sub-Basin was re-invigorated in 2009 when Falcon Oil and Gas (Falcon) deepened the Shenandoah-1 well (suspended in 2007 – re-named Shenandoah-1A), following an unsuccessful attempt by Sweetpea Petroleum to test the deep basin centre gas play within the Moroak and Bessie Creek Sandstones in 2007 (Silverman et al, 2007). The primary targets of Shenandoah-1A included the evaluation of the original deep basin centre gas exploration model as well as an assessment of the Kyalla and Velkerri SRR potential.

During the drilling of Shenandoah-1A encouraging wet mudgas shows in the lower Kyalla SRR section warranted further evaluation. A Drill Stem Test (DST #1) was conducted over the lower Kyalla SRR section to assess its pressure and productivity, however, the test was aborted after the packing seat failed five minutes after the tool was opened (Falcon 2007). Promising post-drilling petrophysical evaluation led to Falcon's decision to hydraulically fracture stimulate and test the lower Kyalla SRR to assess the viability of the play. A single stage was placed within the middle section of the lower Kyalla SRR (1631-1649 mMDRT) with the fracture stimulation treatment consisting of 7834 bbls of slick water placing 69,447 lbs of 100 mesh and 158,736 lbs 40/70 mesh silica sand (Falcon 2011). The treatment was pumped through 4 ½" casing at an average rate of 50.4 bpm with an average pressure of 5630 psi. Breakdown occurred at a pressure of 6660 psi (1.238 psi/ft). The bottom hole initial shut-in pressure (ISIP) was 5643 psi (1.049 psi/ft). A total of 2419 bbls of flowback (30.9% of total pumped volume) was recovered with the assistance of intermittent nitrogen as the formation energy was unable to lift the stimulation fluid out of the wellbore likely due to the small single stage size, well configuration and pumped fluid density. No stable gas flow rates were recorded, however, small, intermittent gas flows were measured at surface, including a very small unassisted flare (Figure 2) (Falcon 2011).

Figure 2 - Brief unassisted gas flare from hydraulic fracture stimulation stage 5 at Shenandoah-1A within the lower Kyalla SRR.

The fracture stimulation job at Shenandoah-1A proved that 1) the lower Kyalla SRR interval can be broken down at pressures well within operational capabilities, 2) significant volumes of proppant (228,000 lbs) can be placed effectively at high pump rates (near constant 50 bpm) and 3) gas can flow to surface, although at very low rates (gas was noted to have broken through after one wellbore volume was recovered).

In 2016 Origin Energy (Origin) and JV partners conducted the first multi-stage hydraulic fracture stimulation and production test of a SRR in a horizontal well in the Beetaloo Sub-Basin targeting the middle Velkerri 'B' Shale in the Amungee NW-1H well (Figure 3). A successful 57day production test recovered a total of 66 mmscf of dry gas with low inerts at an average rate of 1.15 mmscf/day with a final rate of 1.12 mmscf/day (Close et al, 2017). (average production test gas composition: C1 - 92.5%mol, C2 - 2.87%mol, CO_2 - 3.84%mol, 0.64%mol N_2, C3 - 0.13%mol, C4+ - 0.02%mol – air-free calculated). Subsequent reservoir evaluation and favourable production test results resulted in Origin reporting a 2C resource for the middle Velkerri 'B' shale of 6.6 TCF (gross) over a 1,968km^2 area (Origin ASX 2017).

As part of the 2016 exploration campaign, Origin drilled the Beetaloo W-1 exploration well within the central portion of exploration permit EP117 (Figure 2, Figure 3). The well confirmed the presence and quality of the middle Velkerri and Kyalla SRRs in the southern portion of the sub-basin. Despite being designed primarily to assess the southern extent and facies variation of the middle Velkerri Formation in the southern Beetaloo Sub-basin, the Beetaloo W-1 well was deemed close to optimally placed to test the regional SRR potential of the Kyalla SRR plays based on the formation depth and thermal maturity.

METHOD AND RESULTS

The Kyalla SRR potential was assessed at Beetaloo W-1 by a combination of a comprehensive wireline logging suite (including elemental spectroscopy, nuclear magnetic resonance, dipole sonic, micro-resistivity borehole imaging) with rotary side wall core and conventional core lab analysis to provide calibration for the petrophysical and geomechanical analyses (Table 1). Estimates of the composition of the reservoir hydrocarbons was determined from mudgas data, Isotube™ and Isojar™ gas samples, in combination with extracted liquid volumes from modified GRI and Retort shale property measurements.

Core Analysis	Major Parameters Obtained
X-Ray Diffraction (XRD) and Fourier Infra-Red Spectroscopy (FTIR)	• Minerals present in lithology and formation / Quantitative volume of minerals within the formation to compare with mineral volumes calculated from petrophysically derived multimin model.
Modified GRI and Retort	• Total Helium Porosity • Bulk and Grain Density (as received / clean and dry) • Total Water, Gas and 'Oil' Saturation • Matrix Air Pressure Decay Permeability (as received / clean and dry)
Pyrolysis and Total Organic Carbon (TOC)	• Core measured TOC to compare to petrophysically calculated TOC from log measured TC for a reality check. Pyrolysis data used to determine production indices as a pseudo-maturity indicator.
Soxhlet Extraction / Medium Pressure Liquid Chromatography / Gas Chromatography of Aromatic and Saturate Fraction	• Bulk composition (Saturates, Aromatics NSO's, Asphaltenes) of solvent extracted oils and/or bitumen's • Aromatic hydrocarbon ratios as an indicator of maturity – in particular the MPI ratio • Distribution of the hydrocarbon chain length of both Saturate and Aromatic extracts
Adsorption Isotherms – Methane and Ethane	• Langmuir Isotherm Parameters for adsorbed gas determinations and Ambrose corrections
Rock Mechanics	• Static geomechanical properties to calibrate a well 1D geomechanical model along with dynamic geomechanical data
Capillary Suction Time / Cation Exchange Capacity	• Formation reactivity to fluids
Organic Petrology	• Alginite and bitumen reflectance values – Converted to equivalent vitrinite reflectance values to approximate maximum source rock maturity
Thin Sections	• Qualitative assessment of the macro matrix structure of the source rock reservoir as well as qualitative macro distribution of kerogen and bitumen's
Argon-ion Milled SEM / with EDS Mapping	• Qualitative assessment of micro matrix structure. Micro porosity identification and distribution. Semi quantitative determination of mineral elemental compositions.
Isolated Kerogen CHNOSFe Elemental Analysis	• Kerogen elemental composition for qualitative maturity determination and TOC to Kerogen calculation from log derived TOC
Isotube™ and Isojar™ Bulk Gas Chromatography with selected Carbon and Deuterium Isotopes	• Reservoir gas composition estimates • Qualitative maturity based on Carbon and deuterium isotopes of gas species

Table 1 - Geological sample analysis preformed on recovered core and gas samples from Beetaloo W-1

Results from petrophysical modelling confirms the presence of two prospective SRRs (Figure 4), informally referred by Origin as the 'middle Kyalla SRR' and the 'lower Kyalla SRR' (Early oil mature 'upper Kyalla SRR' behind intermediate casing). Origin additionally generated a 1D geomechanical model using dynamic log data, calibrated with static core geomechanical test results. The resulting 1D model indicates the lower Kyalla and middle Kyalla SRR's have geomechanical properties which traditionally have been conducive to successful fracture stimulation (Figure 4). Mudgas (Figure 4) and core analysis indicates reservoir hydrocarbon phase is a wet gas and potentially within a wet to retrograde condensate window. This observation suggests the Kyalla has the potential to yield significant condensate and LPG fractions from the produced gas stream (Normalised air-free Isotube™ gas sample calculated **in-place** yields - 96.63bbl/mmscf LPG_{C3+C4}, 23.81bbl/mmscf $Condensate_{C5+}$).

Both the middle Kyalla and lower Kyalla SRR are considered valid exploration and appraisal targets given the petrophysical and geomechanical modelled properties. However, the lower Kyalla SRR, due to its lower variability in reservoir and geomechanical properties over the entire SRR interval is considered to have the greatest chance of success at Beetaloo W-1 and therefore is the preferred target for future appraisal work in the immediate area.

Petrophysical analysis also indicates some tight gas potential for the thinly bedded Kyalla sandstones (Figure 4) in addition to the identified SRR potential. With no core available over these Kyalla sandstones at Beetaloo W-1, difficultly arises in reconciling the petrophysical interpretation, particularly the calculated total water saturation. Future Kyalla penetrations near Beetaloo W-1 should aim to constrain this saturation uncertainty with the collection and analysis of conventional core.

A key learning that occurred during the Kyalla SRR study at Beetaloo W-1 was the confirmation that high total clay content (>65%wt) from historic Kyalla Formation XRD was misleading due to the inability of the XRD analyses to separate muscovite/biotite and illite. FTIR (Fourier-transform infrared spectroscopy) data indicated that as much as half the traditional XRD Illite/mica peak is composed of muscovite/biotite. Modelled geomechanical properties suggest that the lower Kyalla SRR is potentially conducive to hydraulic fracture stimulation. It is plausible that the significant muscovite/biotite volume, may have a positive impact on grain to grain contact packing pattern of the source rock matrix. Clearly this is a unique situation whereby the traditionally negative high clay/mica rock from XRD analysis masks a prospective SRR with favourable geomechanical properties conductive to hydraulic fracture stimulation

Lower Kyalla SRR Play Technical Risks

Technical Risk	Comments on Risk
Low System Permeability	No DFIT data to measure system permeability available at Beetaloo W-1. Core data suggests low matrix permeability, 34-108nD for the lower Kyalla SRR. FMI logs show no notable natural fracture systems contacted by the Beetaloo W-1 vertical wellbore.
Fracture Height Growth and Lateral Propagation	While geomechanical data suggests that the lower Kyalla SRR has properties traditionally favourable to hydraulic fracture stimulation, the exact nature of the fracture development and growth away from the wellbore, encompassing fracture height growth and ease of lateral propagation is relatively unknown. Observed and measured high detrital muscovite and/or biotite and mica that is oriented perpendicular to mudstone laminae (Figure 6) could retard achievable fracture height growth.
Gas Condensate PVT Sensitivities	The PVT sensitives of the reservoired gas condensate is relatively unknown. If the gas condensate is particularly sensitive to changes from reservoir pressure and temperature to fracture or wellbore pressure and temperature, or in a worse case migrating formation pressure transient gradient from production drawdown, the gas condensate could move past the dew point, causing liquid condensate to drop out of the gas stream before reaching the surface separator. This could potentially drastically inhibit matrix or fracture permeability.
Formation Pressure Gradient	No formation pressure gradient measurements have been measured from DFIT's at Beetaloo W-1. **Formation pressure currently appears to be the greatest current technical risk pertaining to the Kyalla SRR play**.

Table 2 – Lower Kyalla SRR key identified technical risks to play success

Lower Kyalla SRR De-Risking Opportunities for Technical Risks

Technical Risk	De-Risking Opportunities
Low System Permeability	Extended monitoring of DFIT/s within the Kyalla SRR's to constrain reservoir system permeability
Fracture Height Growth and Lateral Propagation	Desktop fracture modelling using available 1D geomechanical model and Micro-seismic data acquisition and the employment of tracers during appraisal well completion activities. Pending cost and perceived technical value vs cost so early in the play appraisal.
Gas Condensate PVT Sensitivities	• Pressure core (ideally whole core or at a minimum RSWC CoreVault™ pressure cores) over lower Kyalla SRR. • Accurate temperature profiling • Conduct full PVT suite on collected and recombined gas and condensate liquids. • Combine calculated PVT diagrams from measured PVT analyses with reservoir pressure determinations or constrained ranges to determine modelled, expected sensitivities of the gas condensate from reservoir conditions to surface conditions.
Formation Pressure Gradient	Extended monitored DFIT/s within Kyalla SRR's to converge on a likely formation pressure gradient window.

Table 3 – Lower Kyalla SRR de-risking options and opportunities for key identified technical risks to play success.

Kyalla SRR vs middle Velkerri SRR Potential Development Advantages

Advantage	Expected Result	Comments of Expected Results of Advantage
Shallower Depth	Lower Drilling Time Costs	The Kyalla SRR's, within a plausible appraisal and development depth range, are 950-1350mTVD shallower than the middle Velkerri SRR's (A, B and C shales – Beetaloo W-1 and Amungee NW-1). This represents a significant cost reduction in drilling expenses from a faster drilling time per well. In particular the drilling time decrease for Kyalla SRR wells is somewhat amplified by the nature of the rocks between the Kyalla SRR and the middle Velkerri SRR's, being the highly cemented and slow to drill Moroak Sandstone (~450m – ave. 3.83m/hr).
	Smaller Capacity Drilling Rig Required to Drill Equivalent Length Laterals	With a shorter overall wellbore (~950-1350m within areas where both plays are in plausible appraisal windows) a smaller capacity drilling rig may be able to be utilised which will cut daily cost spread of the drilling capital cost.
	Reduced Horse-Power Capacity Required for Equivalent Sized Hydraulic Fracture Stimulation Stages	This possible cost reduction assumes a similar fracture gradient for both the middle Velkerri SRR's and the Kyalla SRR's. In reality there are likely to be differences, but in the absence of data suggesting what the absolute fracture gradient of the lower Kyalla SRR is, this advantage is carried as a possible cost reduction on stimulation horse-power given the large reduction in overburden stress.
	Reduction in Casing Strings Required to Safely Case the Wellbore	950-1350mTVD vertical reduction in depth from the middle Velkerri SRR targets to the lower Kyalla SRR could provide the potential for the reduction in the number of drill strings needed for the safe completion of development wells.
Higher LPG and Condensate Yields from Gas Stream	Higher Heating Value of Sales Gas Fraction and/or Additional Revenue from LPG and Condensate Fractions Extracted from the Produced Gas Stream	Compared to the average dry gas composition of the Amungee NW-1H production test gas the lower Kyalla SRR gas from bulk analysis of mudgas Isotube™ samples, following air free normalisation, indicates a calculated **in-place** LPG yield of 96.6 bbl/mmscf and an **in-place** condensate yield of 23.81 bbl/mmscf. This could suggest that in a successful completion and production test case of the lower Kyalla SRR, the recovered gas may yield significant volumes of LPG and/or condensate which would improve economics of such a well. **Depending on the matrix pore / pore-throat size distribution, PVT phase sensitivities and system permeability of the Kyalla SRR, only a portion of the in-place LPG and condensate may be recovered at surface. Only a successful appraisal well with stable surface flowback will be able to constrain or determine expected LPG and condensate yields, as well as calorific heating value of sales gas.**

Table 4 – Potential advantages of a Kyalla SRR development compared to a middle Velkerri SRR development

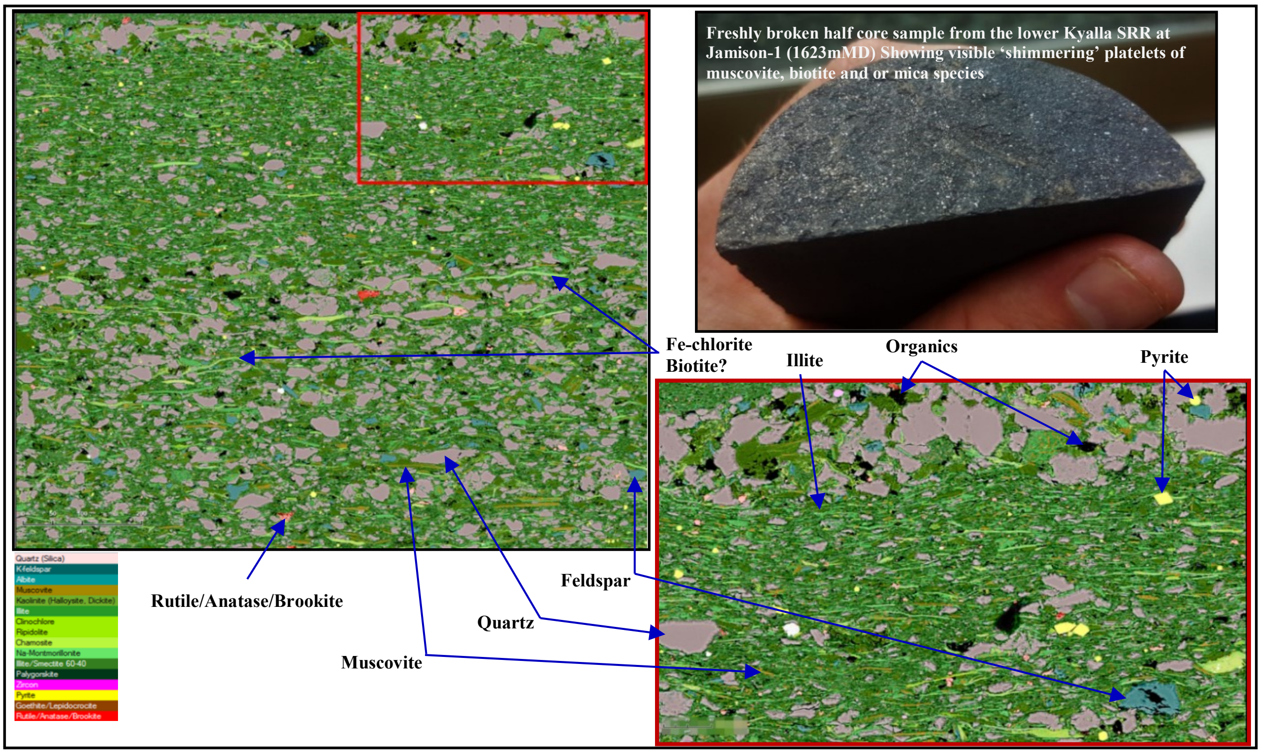

Figure 6 - Middle Kyalla SRR sample showing the highly laminated micro-texture of mudstone matrix from alignment of muscovite and/or biotite and mica platelets. As well as possibly inhibiting perpendicular fracture height growth, this micro-texture will likely have strong implications on directional matrix permeability preferences, with the horizontal permeability expected to be many times the vertical permeability due to oriented muscovite, biotite and mica.

CONCLUSIONS

- The lower Kyalla SRR has reservoir storage capacity properties making it a highly prospective SRR play.
- Geomechanical properties indicate the lower Kyalla SRR should be conducive to successful hydraulic fracture stimulation.
- Due to lower expected drilling costs, a lower Kyalla SRR development could have significant cost advantages over a middle Velkerri SRR development case.
- Calculated LPG and condensate yields of the reservoir gas phase within the Kyalla SRRs, has the potential to considerably improve the economics if a liquids stream can be effectively produced at surface,
- In the event of a successful lower Kyalla SRR test, the possibility of a 'stacked' play development along with the underlying middle Velkerri SRR is possible with infrastructure sharing synergies, reduced regional footprint and allowing a greater portion of infrastructure to be centralised at a lower cost.
- Total clay content from historic XRD is misleading due to the inability of the XRD analyses to separate muscovite and illite. New FTIR results indicate that up to half the traditional illite/mica content from XRD over the lower Kyalla SRR is composed of muscovite or biotite.

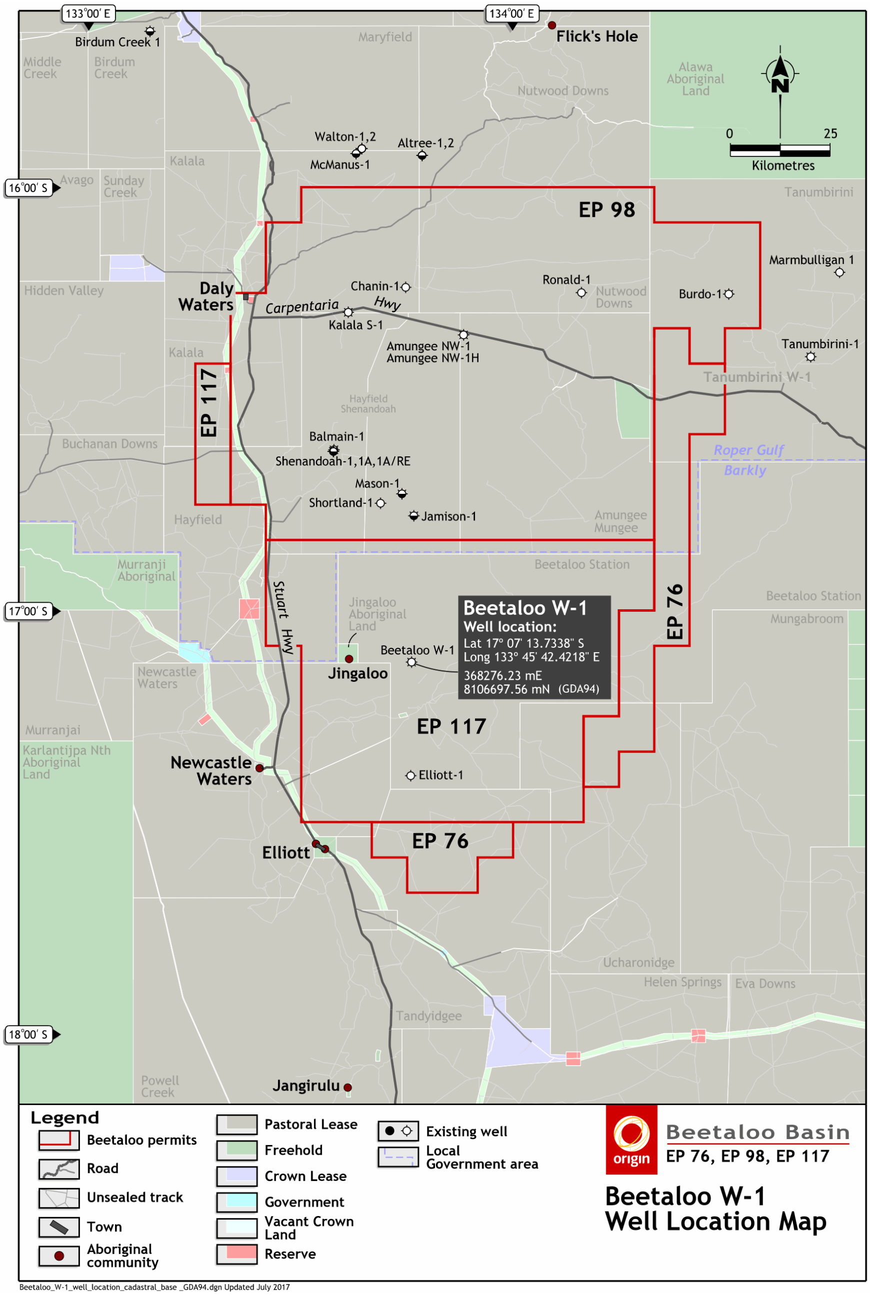

Figure 3 – Location of exploration permits EP 98, 117 and 76, along with exploration wells and major regional infrastructure and land use. The location of Beetaloo W-1, the highlight of the Kyalla SRR study, is highlighted in the centre of EP 117.

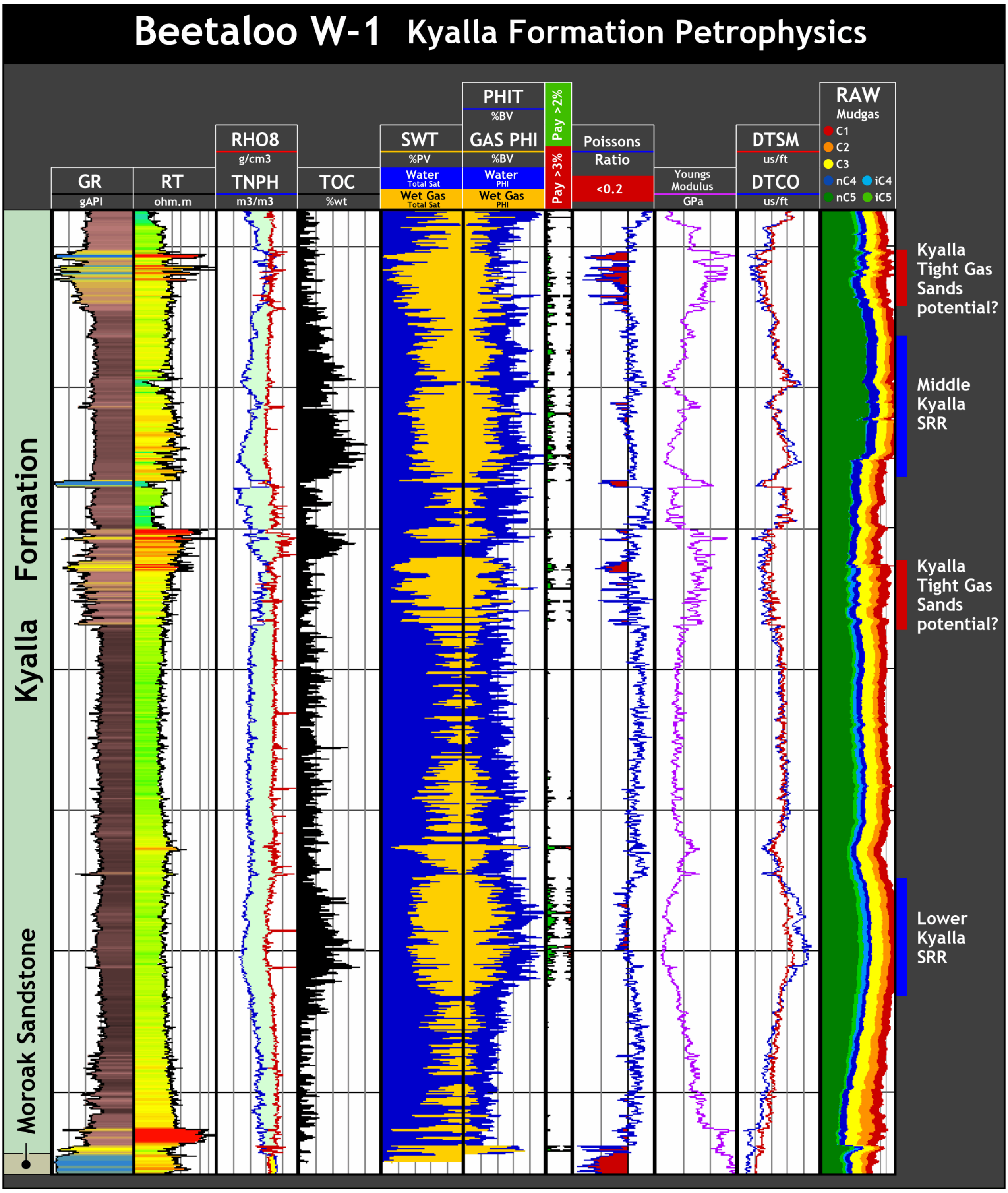

Figure 4 – Beetaloo W-1 Kyalla petrophysical model outputs. The middle Kyalla and lower Kyalla SRR intervals are notated on the right.

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