The Kyalla Formation prospectivity from a mineralogical and sedimentological perspective

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Abstract

The Kyalla Formation historically has been considered a low prospectivity, secondary unconventional target in the Beetaloo Sub-basin owing to inherently high clay volume. In-depth re-evaluation of legacy data, in addition to data acquired by the Beetaloo joint venture (Beetaloo JV; Origin, Falcon Oil & Gas and Sasol) in 2015–2016, demonstrate clay volumes have been over-estimated using traditional x-ray diffraction analysis. The implications of such over-estimation are that pre-conceived assumptions of poor reservoir quality in the Kyalla Formation are potentially incorrect.

Combined sedimentological and petrographic evaluation of conventional cores from the southern Beetaloo Sub-basin east support intermittent deposition under relatively energetic settings (likely above the storm wave base) and quiescent conditions. Sedimentary structures (including cross-bedding, ripples, cross-lamination, and scour surfaces) support a depositional environment within a current dominated setting with intermittent periods of increased siliciclastic sediment input.

Fluorescence in sandstone intervals is common indicating hydrocarbon generation and local migration occurred. Limited source rock property analysis on core samples from these intervals show relatively good porosity and millidarcy-range permeability values on fluorescing intervals. Non-fluorescent samples tend to be occluded by pore-filling, authigenic siderite cement.

This study has helped re-evaluate the prospectivity of the Kyalla Formation based on compositional and sedimentological evidence from both legacy and recently acquired core and wireline data across the Beetaloo Sub-basin. A deeper understanding of mineralogy and the potential impacts of depositional and diagenetic controls on rock properties are fundamentally important to the perceived reservoir quality of shale gas reservoirs.

Introduction

The Beetaloo Sub-basin of the greater McArthur Basin in the Northern Territory hosts some of the oldest proven hydrocarbon source rocks in the world. The Mesoproterozoic Roper Group has both oil and gas potential tied in organic-rich intervals in the Velkerri and Kyalla formations. Despite numerous oil stains and gas shows, the unconventional potential of these organic-rich formations was generally overlooked during the early stages of basin exploration, which was focused on conventional oil and gas plays. The strong conventional focus is particularly evident in the limited conventional core and rock property evaluation completed across these units.

The potential of the Kyalla Formation as a possible source rock reservoir (SRR) was first recognised by the Omega Oil and Pacific Oil and Gas joint venture (JV) in 1995. The JV identified reservoir similarities between the Kyalla and the gas producing Devonian shales of the Appalachian Basin and the Bakken Formation in the Williston Basin (Clementson 1994). The concept of the Kyalla Formation as an exploration prospect was never tested as Omega Oil farmed-out of its permit commitments following unsuccessful attempts to raise capital and interest (Flavelle personal communication; in Altmann *et al* 2018). The booming shale gas industry in North America sparked a renewed interest in the unconventional potential of the Beetaloo Sub-basin with the Velkerri and Kyalla formations recognised as potential targets. Contrary to the Velkerri Formation (proven to be a technical success by Origin in 2016; in Close *et al* 2017), the Kyalla Formation was assumed to have lower prospectivity owing to the inherent large bulk clay volumes (50–70 wt% average; up to 80 wt% locally). Origin's confirmation of the quality and lateral continuity of the formation across its exploration permits (Altmann *et al* 2018), as well as in-depth re-evaluation of both legacy and data acquired in the 2015–2016 exploration campaign, have shifted pre-conceived assumptions and indicate the Kyalla Formation contains the necessary components to be a potentially viable unconventional exploration target.

The Kyalla Formation

The Mesoproterozoic Kyalla Formation (Kyalla) is part of the Roper Group in the Beetaloo Sub-basin. The formation is a medium-bedded to thinly-interbedded and interlaminated siltstone, silty claystone, claystone and very fine-grained sandstone in the subsurface, displaying an increase in resistant sandstone-rich units in outcropping areas towards the north of the basin (Munson 2016). The Kyalla conformably overlies the Moroak Sandstone in the Beetaloo Sub-basin – where it forms a transgressional and gradational, fining-upwards transition; and the oolitic, iron-rich Sherwin Formation in the Urapunga region – where it shows a sharp contact with the fine-grained, fining-upwards sequence (**Figure 1** and **2**). The top of the formation is marked by an erosional unconformity. The Bukalorkmi Sandstone overlies the formation in most of the Beetaloo Sub-basin and, where absent, sediments of the Cambrian succession, as interpreted from 2D seismic profiles in the southern margin of the basin (**Figure 3**). Wells in the western-most portion of the basin (informally known as Beetaloo Sub-basin west; NTGS 2017) confirm that sills of the 1324 ± 4 Ma Derim Derim Dolerite intrude the Kyalla in that area (Munson 2016; **Figure 2**).

The Kyalla is informally subdivided into upper, middle, and lower units. Fine sandstone to siltstone interbeds, formed by intermittent supply of relatively coarse (ie fine to medium size) siliciclastic material to the basin is common in the southern Beetaloo Sub-basin east, and becomes less frequent towards the north and north-western region,

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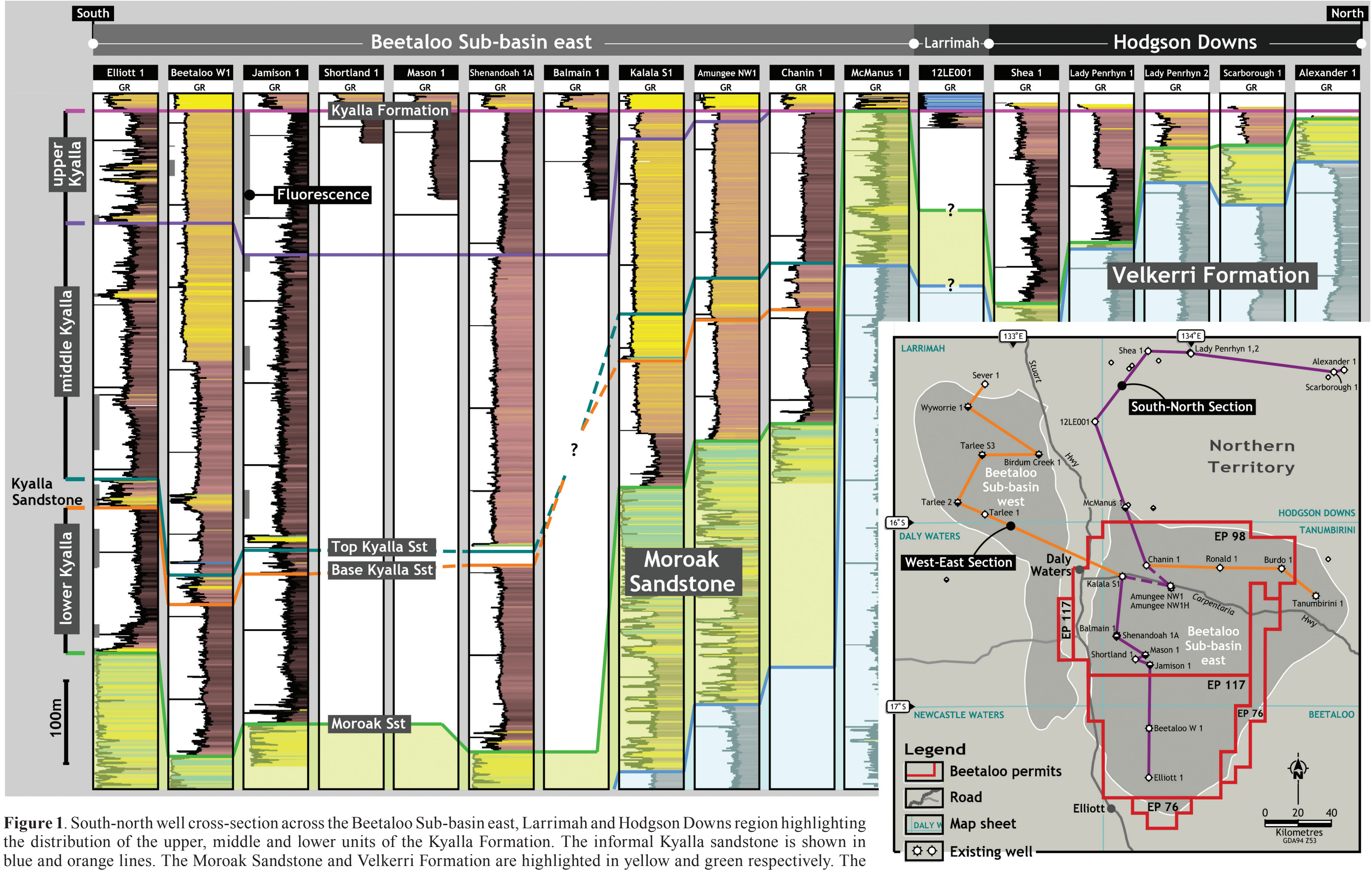

Figure 1. South-north well cross-section across the Beetaloo Sub-basin east, Larrimah and Hodgson Downs region highlighting the distribution of the upper, middle and lower units of the Kyalla Formation. The informal Kyalla sandstone is shown in blue and orange lines. The Moroak Sandstone and Velkerri Formation are highlighted in yellow and green respectively. The location of fluorescent intervals is also provided. A base map showing the Beetaloo Sub-basin extent (as per the NTGS 2017), the Beetaloo JV permit boundaries and well locations is included.

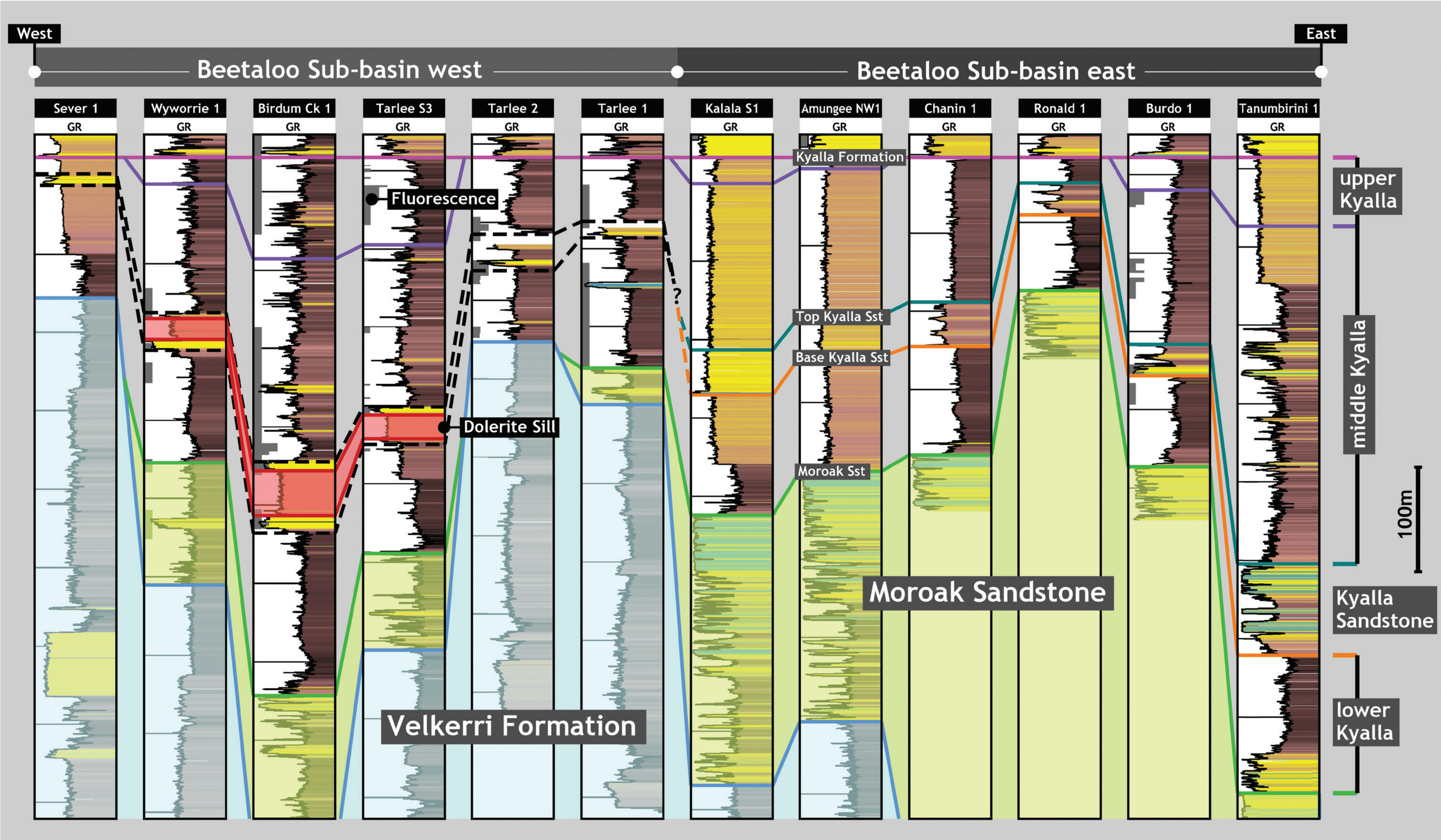

Figure 2. West-east well cross-section across the Beetaloo Sub-basin west and east highlighting the distribution of the upper, middle and lower units of the Kyalla Formation. The informal Kyalla sandstone is shown in blue and orange lines in the Beetaloo Sub-basin east wells and black dotted-lines in the Beetaloo Sub-basin west wells. The Moroak Sandstone and Velkerri Formation are highlighted in yellow and green respectively. The location of fluorescent intervals is also provided.

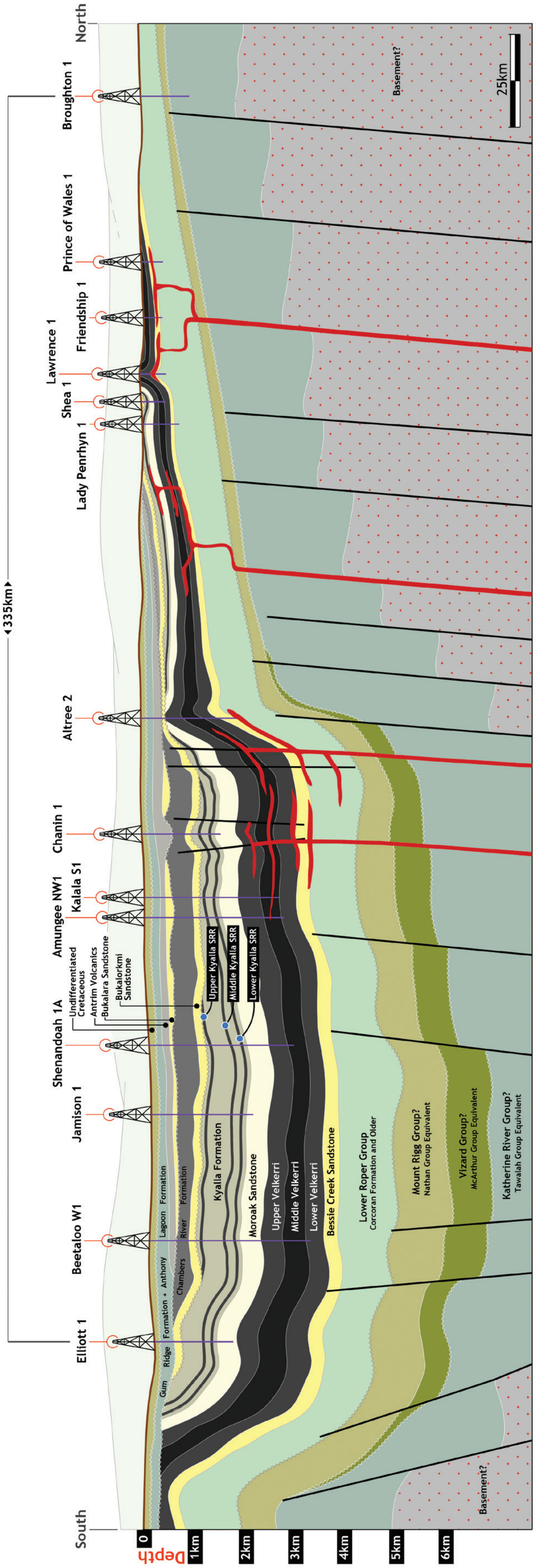

Figure 3. South-north Beetaloo Sub-basin schematic cross-section.

consistent with a more basin-ward shift in depositional setting. A prominent sandstone-rich interval, informally known as the Kyalla sandstone (or Elliott sandstone member; Gorter and Grey 2012) appears to be regionally continuous based on lithostratigraphic well correlation (**Figure 1** and **2**). The Kyalla displays remarkable lateral continuity, thinning towards the north and northeast of the basin indicating the original extent was likely considerably larger than its present distribution (Abbot and Sweet 2000). The formation reaches its greatest stratigraphic thickness in the deepest depocentres of the basin, with 784 m intersected in the center (Beetaloo W-1 well) and upwards of 980 m in the eastern margin of the Beetaloo Sub-basin east (Tanumbirini-1 well). Zircon dating analysis indicates the Moroak Sandstone and Kyalla Formation sediments were likely sourced from the Arunta Region to the south (Yang *et al* 2017).

Organic matter (kerogen) is Type I-II derived from primitive bacteria and other filamentous organisms including blue green algae (Cyanobacteria; Faiz *et al* 2016). Total organic carbon (TOC) is generally 1–4 wt%, with samples reaching up to 6–9 wt% locally. Geochemical evaluation, including methylphenanthrene index (MPI), pyrolisys T_{max}, and alginite reflectance data indicate the Kyalla is predominantly oil to wet gas mature in most parts of the Beetaloo Sub-basin east (Altmann *et al* 2018).

The unconventional potential of the unit is currently identified within three organic-rich SRR intervals informally subdivided by Origin into 'upper Kyalla SRR', 'middle Kyalla SRR' and 'lower Kyalla SRR'. The upper Kyalla SRR is restricted to the centre of the Beetaloo Sub-basin east whereas the middle and lower Kyalla SRR have a greater regional extent. The lower Kyalla SRR is typically present throughout the basin (ie Beetaloo Sub-basin east and west) before thinning north within the Hodgson Downs and Urapunga regions (**Figure 3**). The distribution of organic-rich intervals is inferred from mud gas shows observed while drilling and confirmed after rock property and petrophysical interpretation.

Mineralogy

Mineralogy is an important aspect of shale gas reservoir evaluation due to its impact on rock properties. Abundant clay minerals typically make rocks more ductile, negatively impacting the effectiveness of hydraulic fracture stimulation. Mineralogy can also affect rock properties owing to the tight packing of clay particles and realignment during burial. It also affects saturations as clay tends to adsorb and retain bound-water due to the natural affinity to water. Bulk clay content of less than 50 wt% have been described as desirable in shale gas producing plays in the United States (Lu *et al* 2012).

The average mineral composition of the Kyalla estimated from x-ray diffraction (XRD) analysis includes clays (50–70 wt% average, up to 80 wt% locally), consisting of illite, interstratified illite-smectite (I/S), mica, kaolinite and chlorite. Other components are quartz (40 wt% average) and minor to trace proportions of feldspar, pyrite, siderite, calcite and dolomite (**Figure 4**). XRD is used widely due to its fast and practical applications; however, the identification and quantification of the clay fraction can be challenging due to the fine-grained nature of the sediment. The main difficulty lies in the proper separation and identification of partially overlapped mineral peaks representative of mixed-layered I/S, illite, and mica. The overlap occurs due to similarities in the crystal structure, poor crystallinity and/or small particle size (Brindley 1952). Given the apparently large clay percentage in the Kyalla and its implications for the perceived prospectivity of shales gas reservoirs (Rezaee 2015), further evaluation was necessary to understand the impact of the mineral make-up on rock properties.

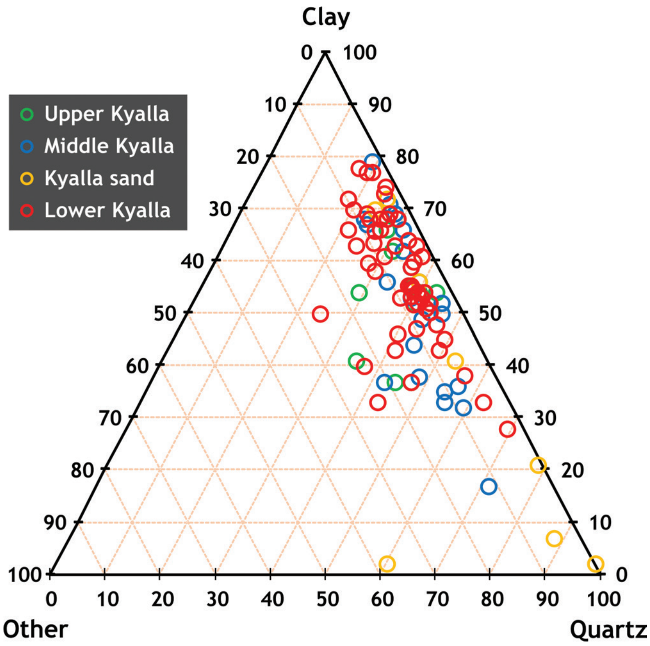

Figure 4. Ternary diagram of mineral composition in the Kyalla Formation.

Origin conducted mineralogical analysis using Fourier transform infrared spectroscopy (FTIR; a technique capable of separating the muscovite and illite spectra) on samples from its Beetaloo W-1 well. Results indicate that approximately half of what is typically classified as the unresolved illite/mica group by traditional XRD techniques is composed of mica species (ie muscovite and/or biotite). The FTIR results were subsequently confirmed through field emission scanning electron microscopy (FE–SEM) and NanoMin evaluation (ie a technique capable of sub-millimeter quantitative mineral mapping). FE–SEM images acquired in back-scattered electrons mode (BSE mode) show the mica group is dominated by muscovite and biotite. Primary clay species include kaolinite, illite, I/S, and chlorite (**Figure 5**). There is wide evidence showing diagenetic alteration of mica to clay with the most common examples being kaolinite and illite replacing detrital muscovite along the cleavage and chlorite replacing biotite. Kaolinite, illite, and chlorite aggregates also commonly occur as pore filling cements. Despite textural relationships, it is still challenging to separate the clay volume that is detrital versus authigenic in origin. The abundance of micas observed in samples is consistent with the preservation of chemically

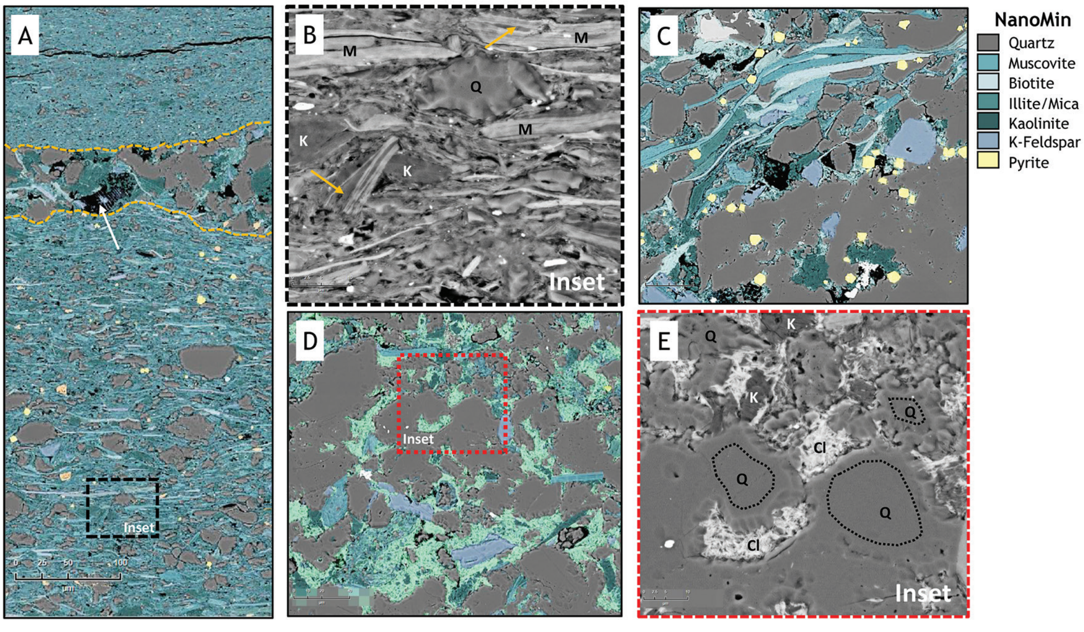

Figure 5. Field emission scanning electron microscopy (FE-SEM) in back-scattered electrons (BSE) mode and NanoMin images of the Kyalla Formation. (**a**) BSE and NanoMin composite image showing the fine-grained texture of the formation. The upper and lower portions of the image are composed primarily by illite, kaolinite and chlorite particles, quartz grains, as well as muscovite and biotite fragments. The lower section displays a relatively larger grain size overall compared to the upper section. A coarser interval made up of quartz, feldspar, mica grains, organic matter and pore filling kaolinite, and chlorite is enclosed in dashed yellow lines. Feldspar dissolution occurs within the interval (white arrow). Horizontal field of view 250 µm. (**b**) Inset of image a) in BSE mode shows diagenetic alteration of detrital muscovite to kaolinite and illite along the cleavage (yellow arrows). Horizontal field of view 60 µm. (**c**) BSE and NanoMin composite image showing pyrite crystals in anhedral to euhedral shapes. Horizontal field of view 280 µm. (**d**) BSE and NanoMin composite image showing common pore-reducing phases include diagenetic quartz overgrowths on detrital quartz and pore filling, authigenic chlorite and kaolinite. Horizontal field of view 250 µm. (**e**) Inset of image d) in BSE mode shows grain-to-grain relationships. Possible detrital quartz grain (dashed black lines) and associated quartz overgrowth is highlighted. K = kaolinite; Cl = chlorite; M = muscovite; Q = quartz. Horizontal field of view 70 µm.

immature minerals (ie micas, feldspars) characteristic of the Precambrian (Garrels and Mackenzie 1971; Weaver 1989). The absence of land biota and biotic soils at the time broadly supported a reduction in the chemical-weathering intensity resulting in preservation of chemically unstable mineral phases (Algeo and Scheckler 1998). Similar mineral preservation have also been interpreted in the Palaeoproterozoic Barney Creek Formation, a potential shale gas unit in the McArthur Group of the McArthur Basin (Baruch *et al* 2015).

XRD and FTIR data a the Beetaloo Sub-basin suggest little compositional variation with local fluctuations pertaining to the presence of fine sandstone to siltstone interbeds. HyLogger™ spectral data from the Kyalla conventional cored sections in the Elliott-1, Jamison-1, and Balmain-1 wells (south and centre of the Beetaloo Sub-basin east respectively) also support this observation (**Figure 6**). Major mineral phases detected using the HyLogger™ [dominant mineral group in the shortwave infrared spectra (SWIR)] include white micas, kaolin and chlorite. Kaolin dominates the mineral fraction in the upper Kyalla whereas white micas and chlorites increase in the middle and lower Kyalla sections. A similar pattern is observed in the lower Kyalla section penetrated by the Lady Penrhyn-1 well in the Hodgson Downs region. The paucity of data, however, makes it difficult to assert regional composition and distributions of the unit outside the core area of the Beetaloo Sub-basin east.

Depositional and diagenetic controls on rock properties

Lithological core description and associated sedimentological interpretation were conducted over 1600 m of conventional core recovered from the Kyalla. However, core degradation over clay-rich zones (ie Jamison 1 well) posed a challenge to the interpretation. The dominant lithologies recognised in the core include mudstone, siltstone and sandstone.

Mudstone intervals are typically interbedded with white, medium to light grey siltstone and fine-grained, planar to wavy bedded sandstone. Laminations display fining-upward transitions that are typically capped by erosional or sharp tops, with common evidence of cross-lamination and ripples suggesting deposition under bedload or saltation movement in a current dominated environment, likely above the storm-wave base (**Figure 7**). Presence of gutter casts and flaser bedding also support deposition under current flow or wave action conditions. Localised soft sediment deformation when present is suggestive of slope instability. Remnant microbial mats coating sand ripples, forming small domes and shrinkage cracks are also common. Associations with the mineral matrix suggest organic matter was likely formed in-situ but locally reworked during higher energy influx. Syneresis cracks commonly occur in the lower Kyalla and within intervals of relatively high silt-to-clay ratio. The preferential stratigraphic distribution and relationship with overlying, relatively coarser grained input suggest these structures are

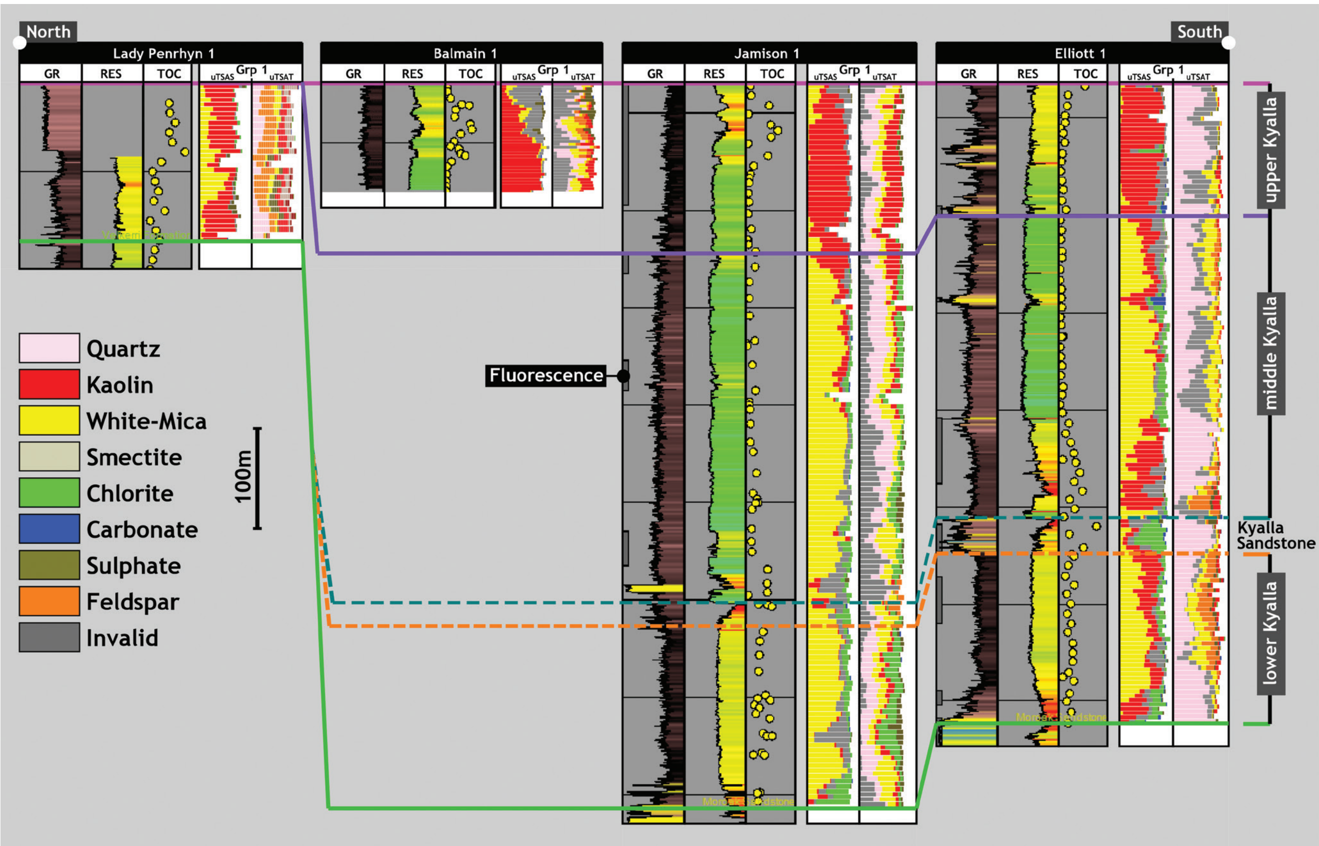

Figure 6. Well log correlation and HyLogger™ spectral data from the Kyalla conventional cored sections in the Elliott-1, Jamison-1, Balmain-1, and Lady Penrhyn-1 wells. Major mineral phases detected in the shortwave infrared spectra (uTSAS) include white micas, kaolin and chlorite. Track 1 = Gamma Ray, Track 2 = Resistivity, Track 3 = Total organic carbon (%wt), Track 4 = dominant mineral group in the HyLogger™ shortwave infrared (SWIR) spectral data, and Track 5 = dominant mineral group in the HyLogger™ thermal infrared (TIR) spectral data.

likely the result of subaqueous contraction of the clay-rich sediment driven by salinity changes, specifically dilution of the marine salinity by fresh, riverine input (Foster *et al* 1955; Donovan and Foster 1972). SEM evaluation indicates mudstones are dominated by nano- to micron-size mica and clay particles whereas siltstone/fine-grained sandstone interbeds are composed of coarser, poorly sorted, micron-size quartz and feldspar grains with minor mica and clay (**Figure 5**). Common pore size-reducing phases include diagenetic quartz overgrowths on detrital quartz and pore filling, authigenic chlorite, and kaolinite. Pyrite crystals in anhedral to euhedral shapes are also present and interpreted as a direct indicator of sediment deposition under sulfidic conditions.

Silt/sandstone-rich intervals are common throughout the Kyalla within the centre and southern Beetaloo Sub-basin east. Sandstone is generally very fine- to fine-grained, and thinly to medium bedded. The rock fabric commonly appears massive owing to cementation and recrystallization, which hinders the identification of primary sedimentary structures. Grading, cross-bedding, ripples, cross-lamination, and scoured surfaces can be identified (despite secondary alteration) and are supportive of episodic sedimentation through periods of fluctuating current intensity (**Figure 7**).

Hydrocarbon-related fluorescence has been described in cuttings within the silt/sandstone-rich intervals at various stratigraphic levels across the basin indicating hydrocarbon generation and local migration occurred within the formation. Conventional core evaluation performed on the Beetaloo W-1 well indicates fluorescence occurs as patchy, discontinuous horizons interbedded with non-fluorescing intervals (**Figure 8**). While the core was slabbed using air, the drilling fluid utilised was water-based which might have affected the distribution of the fluorescence. Petrographic examination of samples prepared from fluorescent intervals reveal the presence of disseminated organic matter consistent with microbial mat textures as well as the presence of widespread hydrocarbon coating on grains. Non-fluorescing horizons show evidence of pore-filling siderite precipitation preferentially oriented along laminations, cross-laminations and ripples. Siderite cementation is interpreted to have formed as a by-product of microbial mat degradation under relatively fresh to brackish pore water settings (Garlick 1988). Fluorescent intervals display greater porosity and permeability values overall compared with the non-fluorescent counterpart. SEM images show siderite occluding primary porosity and, depending on pervasiveness and lateral extent, is likely to have led to a reduction in pore volume connectivity within the sandstone unit. Siderite has only been observed as pore filling cement in the Kyalla sandstone; however, this assumption is likely biased by the limited core and mineralogical analysis available to the time of publication.

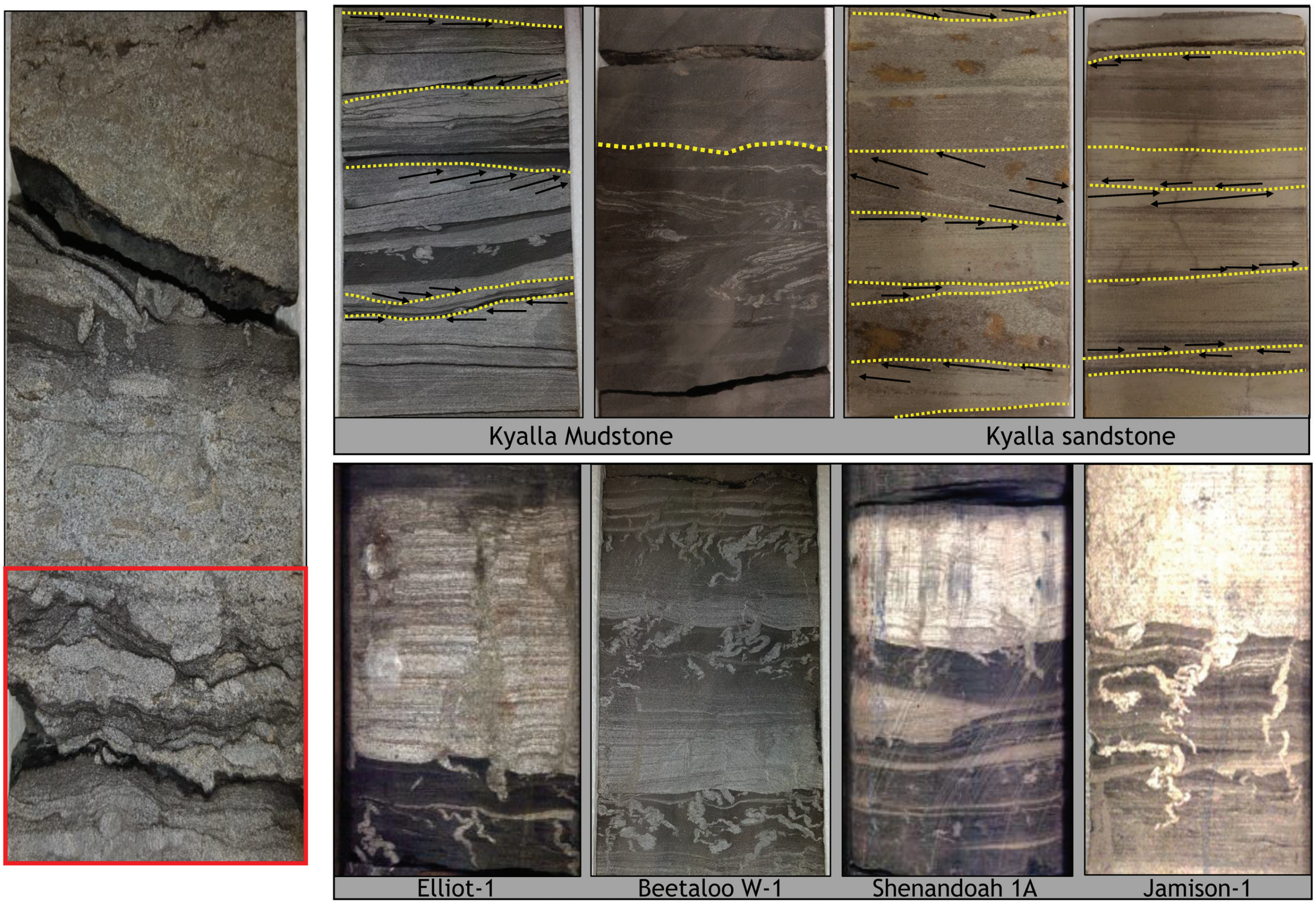

Figure 7. Sedimentological features observed in conventional core in the Kyalla Formation. (Left) Remnant microbial mats. (Upper right) Sedimentary structures including grading, cross-bedding, ripples, cross-lamination, and scoured surfaces in mudstone and sandstone facies. (Lower right) Syneresis cracks in Beetaloo Sub-basin east wells. Vertical scale approximately 15–20 cm.

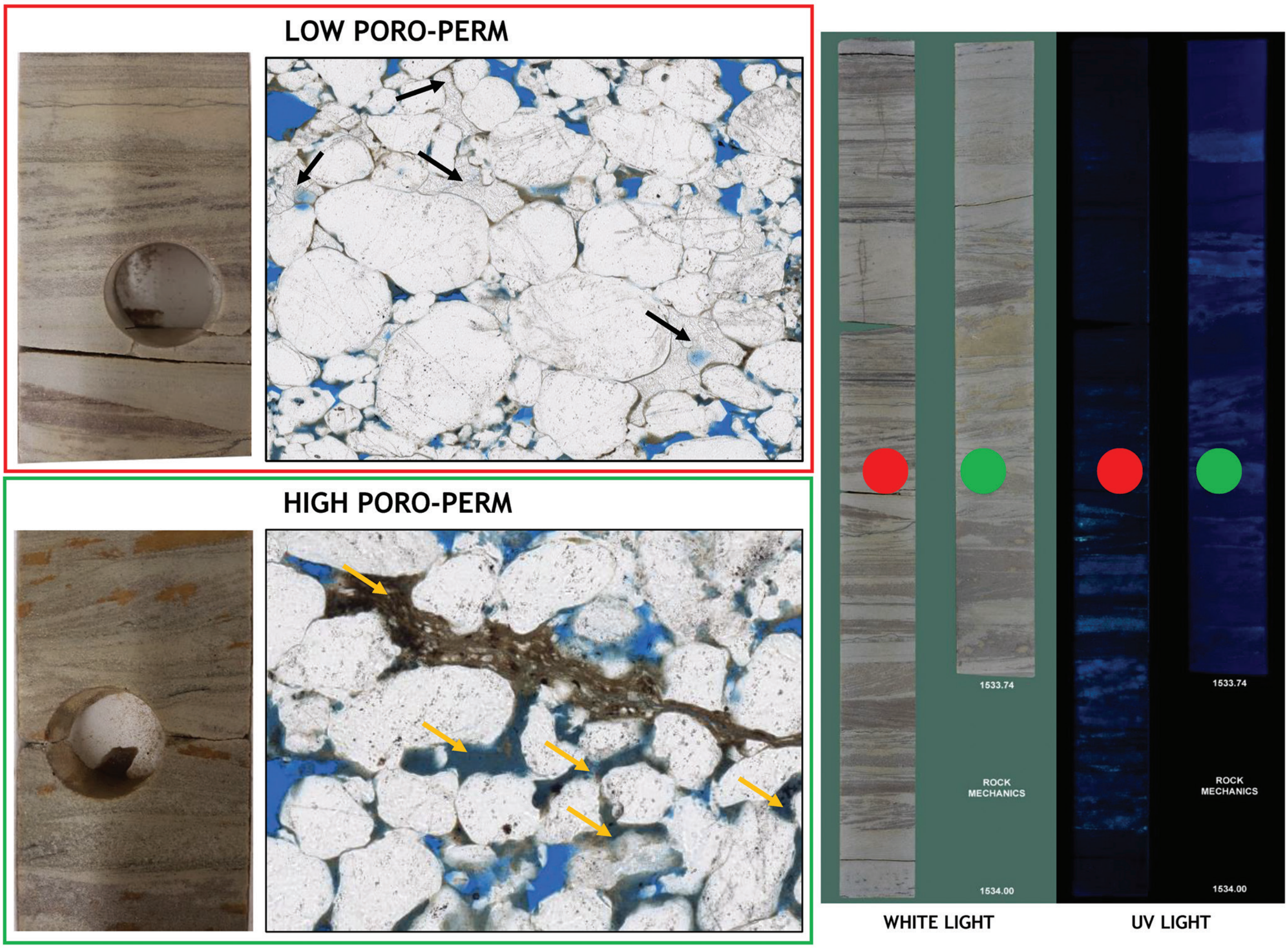

Figure 8. (Right) Conventional core imagery (Beetaloo W-1 well) shows fluorescence occurs as patchy, discontinuous horizons interbedded with non-fluorescing intervals. (Upper left) Low porosity and permeability is associated to a non-fluorescent interval. Pore-filling siderite precipitation is observed in thin sections (black arrows). (Lower left) High porosity and permeability is associated to a fluorescent interval. Remnant microbial mat and hydrocarbon coating on grains are common in thin section (yellow arrows). Vertical field of view for core pieces 15 cm; horizontal field of view for the thin section 450 µm; core length 1 m.

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