Unlocking the eastern extension of the Beetaloo Sub-basin middle Velkerri shales

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In 2006, Sydney-based Empire Energy Group Limited (Empire), which has been listed on the ASX since 1984, made its initial entry into the USA oil and gas industry via a natural gas joint venture development in the Appalachian Basin. Although the joint venture initially targeted conventional hydrocarbons, the focus soon shifted to the unconventional Marcellus Shale. From that point on, unconventional hydrocarbons have a remained a core component of the company's growth strategy.

In early 2010, Empire identified the McArthur Basin as having attractive potential for hydrocarbon-bearing marine shales and was successful in securing seven licence applications in the Northern Territory (**Figure 1**). Although the Palaeoproterozoic Barney Creek and Wollogorang shales of the McArthur Basin were the original sphere of interest, and remain an area of ongoing activity, it is the younger Beetaloo Sub-basin Mesoproterozoic shales within the Velkerri and Kyalla formations that became the stratigraphic intervals of focus. The Beetaloo Sub-basin lies within the youngest sedimentary package of the McArthur Basin. Empire's southernmost permit, EP187, is located over an eastern extension of the Beetaloo Sub-basin. It is within this permit that Empire has focused its operational activities in the last few years.

The unmetamorphosed, intracratonic McArthur Basin is a Palaeoproterozoic to Mesoproterozoic superbasin containing multiple marine shale petroleum systems with a preserved thickness of up to 10 km (Plumb and Wellman 1987). The basin is marked by periods of extension and orogeny, with the basin-wide successions described as packages. The five major continuous or contiguous packages of the McArthur Basin are the Redbank, Goyder, Glyde, Favenc and Wilton, listed from oldest to youngest (Ahmad *et al* 2013, Rawlings 1999; **Figure 2**). Each package consists of groups that may be laterally equivalent, although this is an area of ongoing basin research. The Roper Group within the Wilton Package contains the Beetaloo Sub-basin shale target intervals. Nearly all the Beetaloo Sub-basin is unconformably overlain by the Neoproterozoic to Devonian Georgina Basin and the Jurassic-Cretaceous Carpentaria Basin, with outcrop only observed toward the basin margins. The Roper Group has an aerial extent of more than 145 000 km^2; thickness preservation can be more than 6000 m in the relatively flat lying Beetaloo Sub-basin. The primary shale targets of the Beetaloo Sub-basin are the Amungee Member of the Velkerri Formation (ca 1400 Ma; Kendall *et al* 2009), also termed the middle Velkerri Formation in some texts, and the Kyalla Formation, which was deposited prior to the Derim Derim Dolerite intrusion (ca 1313 Ma, Collins *et al* 2019).

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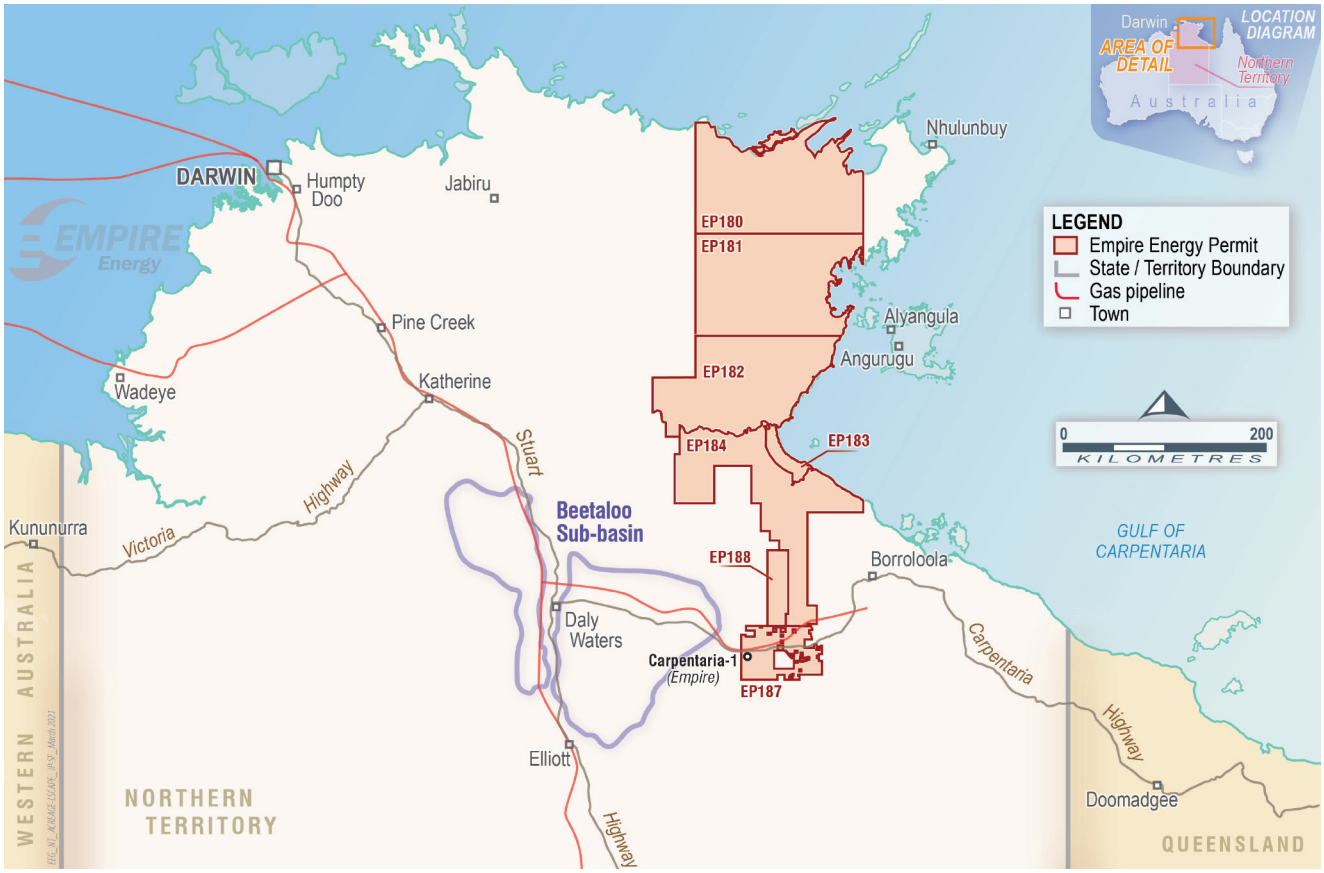

Figure 1. Empire Energy Permits, Carpentaria-1 location and NTGS Beetaloo Sub-basin outline from Williams (2019).

Over the last few years, the Beetaloo Sub-basin has become a focus area for unconventional hydrocarbon exploration and appraisal. Unconventional hydrocarbons differ from conventional hydrocarbons in the way that the hydrocarbons are trapped in the formation. Conventional hydrocarbons are trapped by buoyancy pressure, whereas the pressure in unconventional systems is through hydrocarbon generation and retention. For this reason, the unconventional reservoirs are generally also the source rock for hydrocarbon generation, or are stratigraphically proximal. The two major subgroups of unconventional reservoirs are shales and coal seams; only shales will be discussed in this paper. Shales are organic rich, fined-grained, clastic sedimentary rocks deposited in a marine or lacustrine setting. Through burial and heating, the shales become more thermally mature and initially generate oil; with rising burial pressure and temperature, gas will be generated with increasing dryness. Much of the hydrocarbons will escape to surface or to a conventional trap but a large proportion will be retained in the source rock system. These retained hydrocarbons are the target of shale gas development.

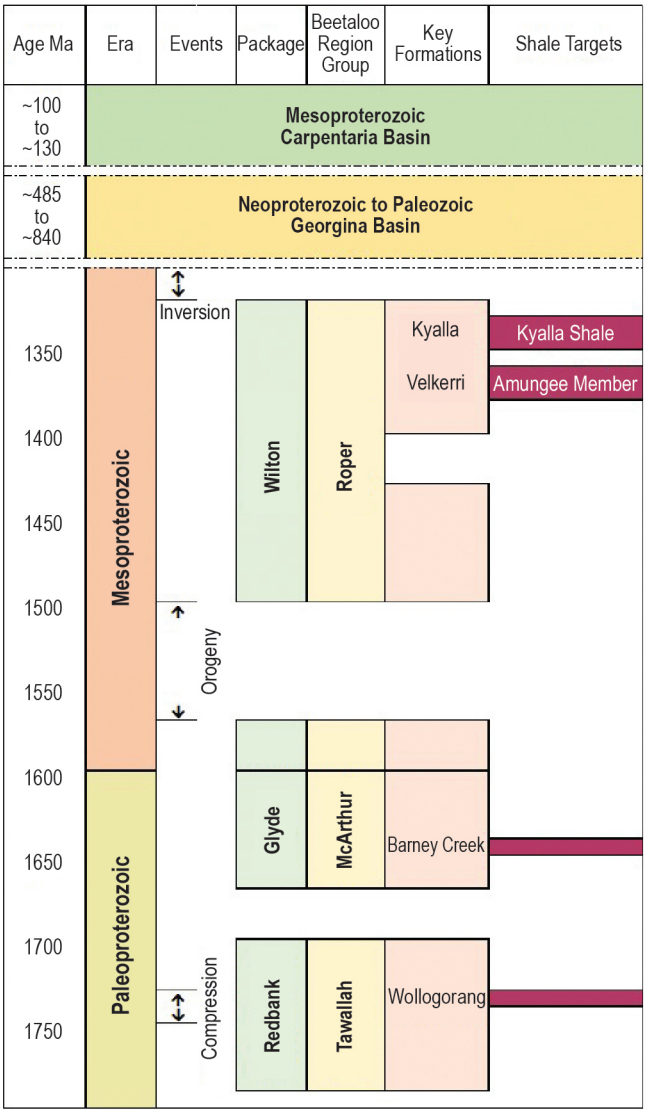

Figure 2. Simplified stratigraphic section of the Beetaloo Sub-basin area of the McArthur Basin.

Due to the fine-grained matrix of the shales, porosity and permeability is diminished compared to conventional reservoirs. In the context of petroleum reservoirs, porosity is the space between rock grains that is available to hold hydrocarbons, whereas permeability is a measure of the ability of hydrocarbons to flow through the rock. To produce commercial gas flows, the permeability of the shales may be enhanced through hydraulic stimulation. Hydraulic stimulation is the injection of sand (proppant) and liquid at high rates and pressure to fracture the rock and create an interconnected permeability network propped open by sand through which gas may flow. The generated fracture networks may reach several hundred metres away from the producing wellbore. To maximise the surface area of the generated fracture network, standard practice has become to drill lateral wells that follow the shale unit stratigraphy. Lateral sections of the wells may reach several kilometres in length. Multiple fracture stimulations, called stages, are undertaken through the length of the lateral wells.

Shale gas produced by these methods currently accounts for up to 78% of United States gas production. Since the first gas well came onto production in the early 2000s, the lateral length and number of fracture stimulation stages per well has continued to increase. The Marcellus Shale within the Appalachian Basin now accounts for a quarter of that nation's dry gas production.

In 2019, through its 100% owned subsidiary Imperial Oil and Gas, Empire acquired six onshore 2D seismic lines totalling 223 km. The seismic survey was the first to be undertaken in the EP187 permit and demonstrated the eastern extent of the Beetaloo Sub-basin in an area termed the Eastern OT Downs (Northern Territory Geological Survey and Geognostics Australia Pty Ltd 2021). In late September and October 2020, Empire drilled the vertical Carpentaria-1 well in EP187 on the basis of the newly acquired seismic data. Carpentaria-1 is located ~85 km southwest of Borroloola within the Beetaloo Sub-basin and McArthur Basin in the Northern Territory. The well was designed to evaluate the hydrocarbon potential of the stacked Velkerri Formation shale sequences (Velkerri A, B and C) as the primary target, and the shales of the Kyalla Formation as the secondary target. A full formation evaluation suite was undertaken, including standard wireline logs and specialised logs such as lithology scanner, dipole sonic, nuclear magnetic resonance and fullbore resistivity imaging, as well as extra-large rotary sidewall cores. Following a suite of diagnostic fracture injection testing, a further fullbore resistivity imaging run was undertaken.

The target formations were intersected shallower than pre-drill prognosis and the rate of penetration achieved whilst drilling exceeded pre-drill expectation; this result, coupled with the shallow outcome, resulted in time to drill being significantly faster than forecast. Empire considers the results successful because reservoir properties are better than prognosed, there is liquids-rich gas potential in the primary target shales of the Amungee Member of the Velkerri Formation, and the drilling conditions are better than expected. Moreover, a gas-bearing Intra A/B unit was identified additional to the Velkerri A, B and C targets. The shales of the Kyalla Formation were present in the well but

at too shallow a depth and are no longer considered a target in EP187. Nonetheless, future drilling targeting the Velkerri Formation will intersect the Kyalla Formation (**Figure 3**).

In Williams (2019), the Beetaloo Sub-basin boundary was defined where the top of the Kyalla Formation is more than 400 m below the surface. The Kyalla Formation was selected as it was defined as the top of the Roper Group (Munson 2016) and is the most constrained unit based on multiple drillhole intersections across the basin. The boundary was delimited by 26 wells tied to 96 2D seismic lines. The 400 m cut-off was chosen because of the difficulty of mapping the unit above 400 m because of the poor quality of the shallow (0.2 to 0.26 seconds) seismic data and the consequent difficulty of defining the subcrop position below the regionally extensive unconformable cover of the Georgina and Carpentaria Basins. Therefore, the boundary is not only based on stratigraphy but also on the quality of the tool (seismic) used to define it. This definition of the basin extent excludes areas where Roper Group sediments older than Kyalla Formation are preserved in their entirety. Williams (2019) acknowledges this and recognises that Roper Group hydrocarbon-bearing formations extend beyond their defined boundary.

Well intersections do not have the same resolution constraints as seismic data, and in the strictest sense of the Williams (2019) boundary definition, the Carpentaria-1 well, in which the Kyalla Formations is ~300 m below surface, is located outside the Beetaloo Sub-basin. It is worth highlighting, however, that a full section of the Velkerri Formation was intersected in the Carpentaria-1 well. The authors assert that the Carpentaria-1 well intersection should be included in the Beetaloo Sub-basin boundary on this basis. Regardless of whether or not Carpentaria-1 is considered to be within the Beetaloo Sub-basin as defined by Williams (2019), seismic data indicate that strata in the Eastern OT Downs area dip northwards from the well location and that the top of the Kyalla Formation is deeper than 400 m below surface within much of the EP187 resource area (**Figure 4**, **Figure 5**). For this reason, the previously defined area of the Beetaloo Sub-basin has increased based on Empire's 2019 seismic acquisition and the drilling of Carpentaria-1 (**Figure 6**).

An outcome of the shallower than predicted Velkerri Formation Amungee Member in Carpentaria-1 is that the mudgas observed whilst drilling indicated a more liquids-rich gas than pre-drill expectation. In multiple United States shale plays, similar liquids-rich gas is targeted for the economic upside of the liquid hydrocarbon stream. Although there is some debate, within the reservoir the longer carbon chain liquid hydrocarbons are surmised to be in a gas phase when mobilised, along with the shorter chain gases, methane and ethane. The low viscosity gas stream can flow through the smaller pores of the shale matrix, whereas a more viscous, pure liquid hydrocarbon stream would not achieve commercial flow rates in such low permeability rocks. Planned production testing of the vertical Carpentaria-1 well will calibrate mudlog response to actual produced hydrocarbons and establish hydrocarbon liquid and gas ratios (**Figure 7**).

The Carpentaria-1 mudgas observed whilst drilling the Amungee Member becomes drier and less liquids-rich with increasing depth; this is in line with increasing thermal maturity. Source rocks contain insoluble carbon-rich organic matter called kerogen. As a source rock is buried and heated, the kerogen becomes more thermally mature and commences generating hydrocarbons. The Beetaloo Sub-basin Velkerri Formation source rocks contain mainly marine kerogens with some evidence of lacustrine input,

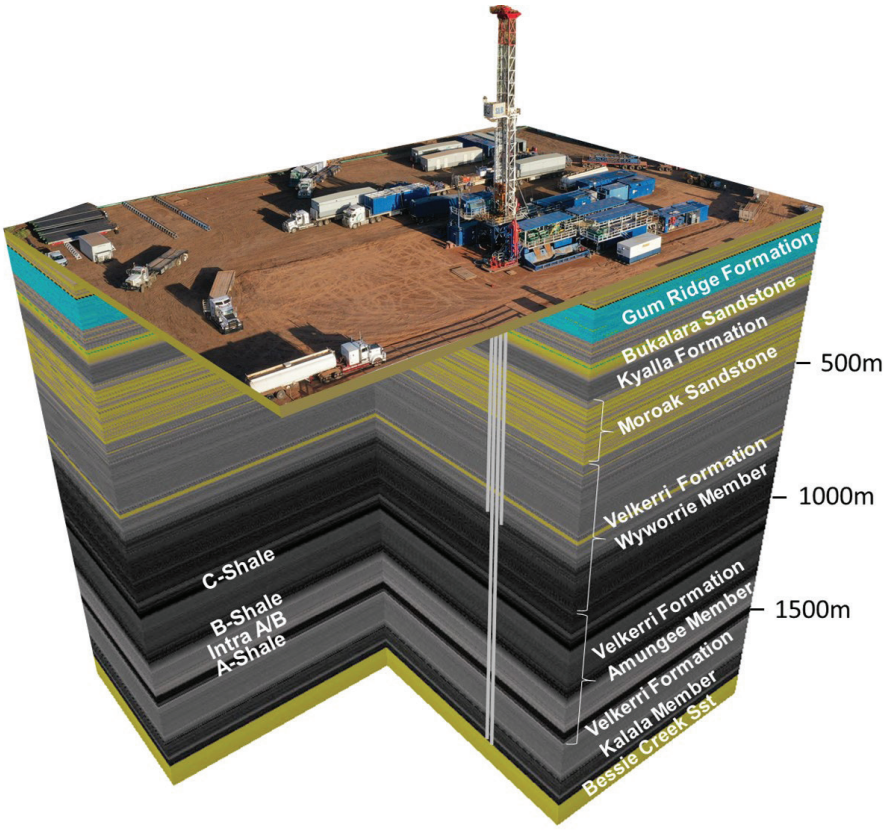

Figure 3. Carpentaria-1 3D schematic.

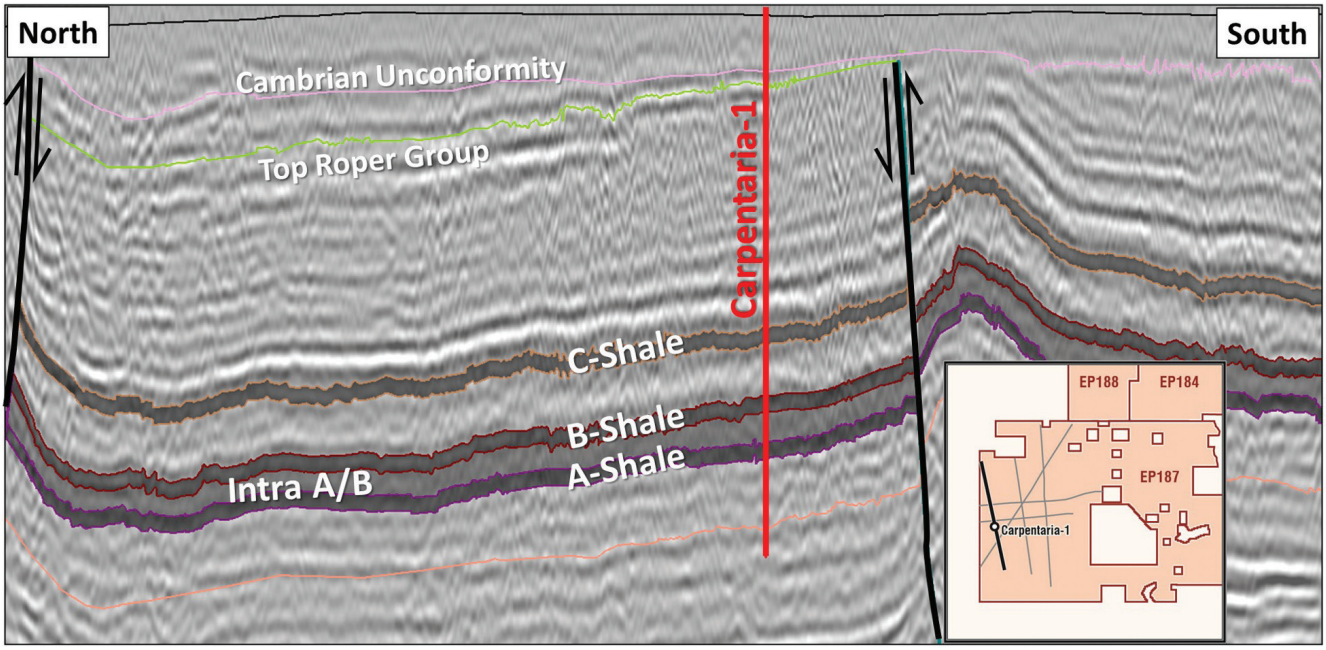

Figure 4. Seismic Line 2019-04 illustrating northward structural dip in the Eastern OT Downs area.

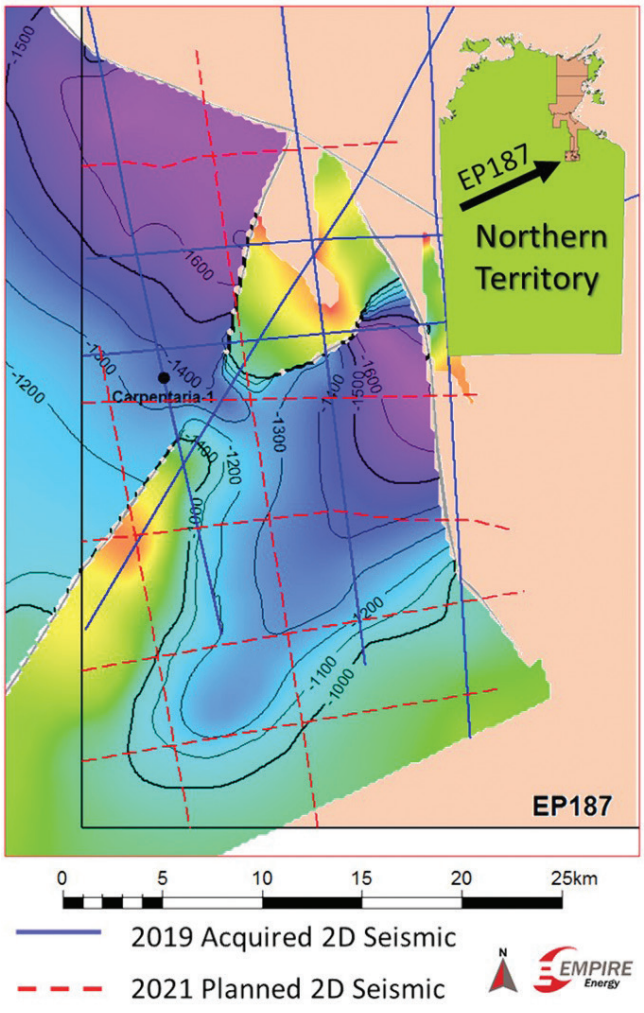

Figure 5. Depth to base Velkerri Formation, Amungee Member B-Shale.

making them more prone to generating oil than gas. Like all source rocks with increasing thermal maturity, they become more gas prone.

Typically, thermal maturity is estimated by vitrinite reflectance (R_0), which is measured under a microscope as a change in colour due to heating. Vitrinite is a component of coal and is found in most source rocks. However, due to the age of the Velkerri Formation shales, vitrinite is absent thus making this standard method of measurement problematic but not without application. It is worth noting that the life forms during the deposition of the Velkerri Formation were more basic than global hydrocarbon analogues as this age period marked the commencement of multicellular life on earth. Other thermal maturity estimation methods, such as pyrolysis (Tmax), thermal alteration index and solid-bitumen reflectance, have useful but limited application due to similar issues of calibration to ancient source rocks. There are standard conversions of these methods to a vitrinite reflectance equivalent; however, the calibration to ancient source rocks is across a limited dataset.

Another widely used method for thermal maturity estimation is carbon isotope analysis of gas, sampled either during drilling or produced at the well head, as opposed to analysis of the source rocks. Like the other methods, the standard procedure for isotope analysis were developed with a dataset from younger source rocks, mainly mid-Palaeozoic and younger (Carvajal-Ortiz 2021). The procedure does not encompass hydrocarbon gases generated from the cracking of Precambrian and Proterozoic kerogens of the Beetaloo Sub-basin, which are over 1 billion years older than the sample set and sourced from much simpler organisms. A different set of assumptions and considerations are needed when evaluating the thermal maturity of gases generated from such source rocks, and currently a procedure has not been fully established. However, an initial investigation of Carpentaria-1 isotope samples suggests that EP187 gas might have been generated from cracking of oil or gas.

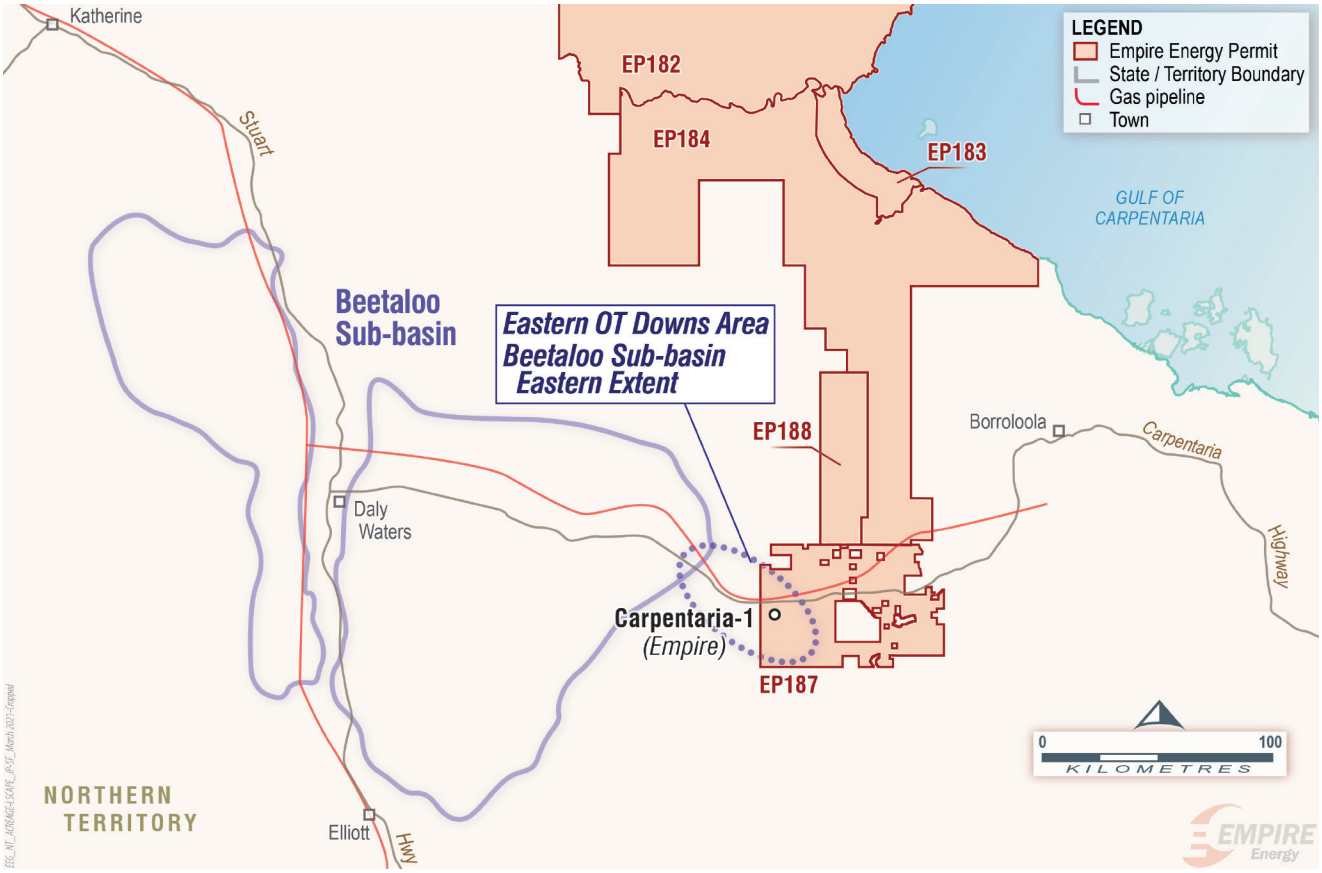

Figure 6. NTGS Beetaloo Sub-basin outline from Williams (2019) with Eastern OT Downs Area.

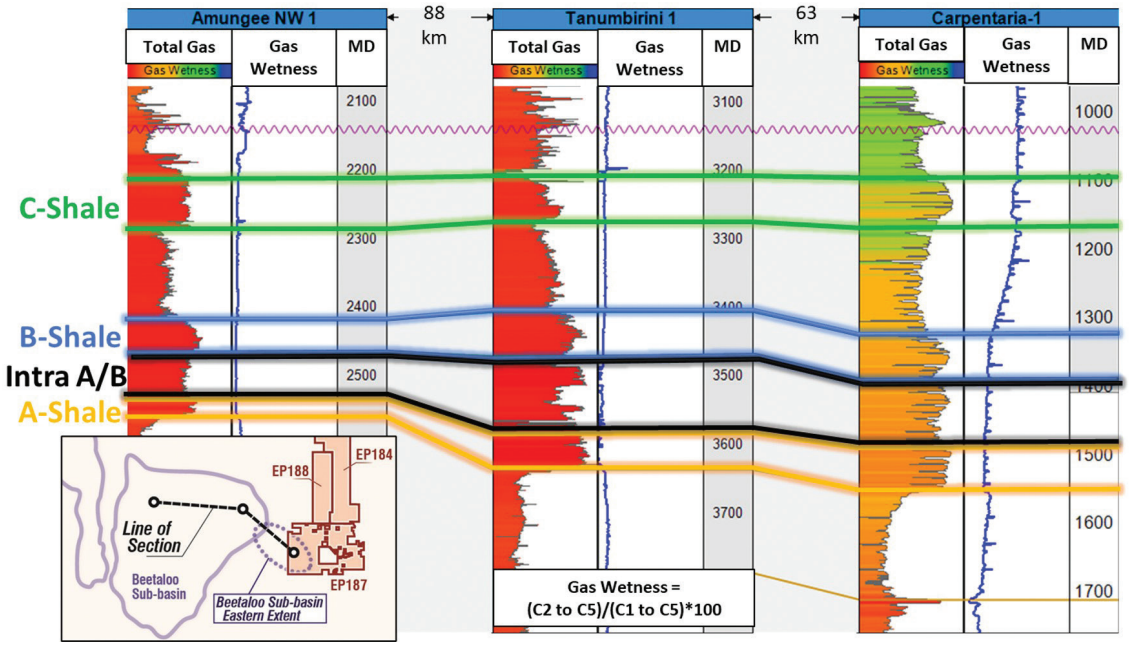

Figure 7. Well correlation between Beetaloo Sub-basin wells. Datum: Velkerri Formation top Amungee Member.

A comparison of Carpentaria-1 R_0 thermal maturity indicators and gas isotope data indicates that the Amungee Member source rocks become more dry gas prone at a lower R_0 than shale plays in the US due to thermal cracking of kerogen or generated hydrocarbon. This may be a result of the above-mentioned limited calibration of thermal maturity estimation methods to ancient source rocks, the source rock geochemistry, or the history of uplift and burial of the Velkerri Formation. This will remain an area of ongoing investigation for Empire as it plans future vertical and lateral wells in the stacked pay sequence of the Amungee Member of the Velkerri Formation shales and seeks to determine the optimal liquids-rich gas ratio for commercial outcomes. The ranking of the shales within the stacked sequence and identifying the optimal depth for development will be areas of continued research. On this note, the Beetaloo Sub-basin

has the potential to hold multiple distinct sweet spots analogous to the Marcellus Shale in the USA, which has both dry and liquids rich gas sweet spots separated laterally by several hundred kilometres.

The Carpentaria-1 Amungee Member target shale thickness is nearly identical to the nearest Beetaloo Sub-basin offset well, Tanumbirini-1 (**Figure 7**), drilled by Santos in 2014, which is also in the deepest part of the basin. The lateral consistency of the target shales between the wells is indicative that the locations share proximity to the shoreline at the time of deposition; however, there is major divergence in the post depositional burial and uplift history of the two locations. The tectonic evolution of Empire's EP187 will be an area of ongoing investigation. The liquids-rich mudgas and indications of clay mineralogy unaltered by temperature suggest that maximum burial at this location is less than other parts of the basin.

The formation evaluation results for Empire's Carpentaria-1 well compare favourably with working US shales; however, further on-ground activity is required to de-risk the play. The next phase of the work program is to fracture stimulate and production test the vertical Carpentaria-1 well. Additional seismic acquisition is planned to further delineate the EP187 permit and the resource area, which spans several hundred km^2. During the next drilling phase, a horizontal well is anticipated with the target interval and depth to be selected based on production testing and synthesis of the formation evaluation.

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