# Proterozoic shale gas plays in the Beetaloo Basin and the Amungee NW-1H discovery

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Origin Energy drilled the first horizontal well, Amungee NW-1H, in the Beetaloo Basin[3] in 2015 and completed the first multi-stage hydraulic fracture stimulation and extended production test of the middle Velkerri Formation in 2016. The successful drilling and stimulation of this horizontal well are key milestones for the Velkerri Formation Play: a Play that was first recognised in the mid-2000s by Falcon Oil & Gas Ltd, who also first targeted the play with the Shenandoah 1A well.

A total of four wells, Amungee NW-1H, and three vertical exploration wells, have been drilled in Origin's exploration campaigns over 2015 and 2016. These wells, in combination with Shenandoah 1A, have addressed many of the key technical risks of the Velkerri Formation Play. They also confirmed the presence of a material gas resource that could be competitive with other potential gas resources in onshore Australia.

The wells have provided a wealth of technical data to assist in the geologic characterisation of the Beetaloo Basin, and in particular, the Velkerri Formation Play and the Kyalla Formation Play. In this paper, we share data that confirm the presence of thick, gas saturated and over-pressured source rocks in the Velkerri Formation over a vast area. We also present a summary of the extended production test at Amungee NW-1H that demonstrates the potential of the Velkerri Formation Play.

In addition to the technical work program, Origin has undertaken preliminary environmental baseline studies and substantial stakeholder engagement activities. Ensuring environmental baseline data are available is key to demonstrating that onshore gas developments can be undertaken with social acceptance and without adverse environmental outcomes. However, data and facts alone are not sufficient to build community confidence. Origin has engaged extensively with pastoralists, local communities and Traditional Owners to build direct relationships and partnerships that encourage acceptance of the gas industry's ability to coexist and deliver mutual benefits to the businesses and communities of the Barkly region and the Northern Territory.

## Introduction

In May 2014, Origin announced a farm-in to EP98, EP117 and EP76 (the Permits) held by Falcon Oil & Gas Ltd (Falcon) in the Beetaloo Basin (Beetaloo) of the Northern Territory (NT). Through the farm-in, Origin, and fellow farminee Sasol, have the option to earn 35% equity in the Permits, which cover over 18 500 km$^2$ of prospective acreage in the core area of the Beetaloo. Origin, as operator of the 'Beetaloo JV', has been actively progressing a multi-year exploration program over the Permits that have seen four wells drilled during 2015 and 2016, including the first horizontal well in the Beetaloo. The results to date have been very positive, with effective operational execution and good technical outcomes that have confirmed Origin's technical assessment of the Mesoproterozoic Velkerri Formation in 2013–14 (Close 2015).

Despite having substantial experience in many basins and play types across Australia and internationally, this farm-in is Origin's first exploration program focused on shale gas plays and Origin's first upstream operations in the NT. Although much of the technical, commercial and stakeholder engagement expertise developed by Origin and its predecessor companies is directly relevant to operating the Beetaloo JV, Origin has been required to develop key capabilities in a number of new areas, including source rock reservoir (SRR) evaluation techniques, horizontal drilling and multi-stage hydraulic fracture stimulation.

## Exploration history

Petroleum exploration in the Beetaloo area began in 1984 when CRA Exploration Pty Limited took up acreage in exploration permits EP4 and EP5 (since lapsed), north of the core of the Beetaloo (**Figure 1**) as Pacific Oil & Gas (POG). POG was encouraged by the identification of 'live' oil in the stratigraphic well Urapunga 4, drilled by the Bureau of Mineral Resources in 1985 (Lanigan *et al* 1994). POG subsequently picked up two additional permits farther south, EP23 and EP24, over the northern margin of the Beetaloo in 1988 and then EP33, over the southern edge of the Basin. Encouraged by drilling results, POG also acquired a 90% interest and operatorship of EP19 and EP18 in the western and central Beetaloo after joint venture negotiations with permit holders Mataranka Oil NL (then known as Pardi Pty Ltd). To consolidate their dominant position across the Beetaloo, POG and partners also acquired permits EP45 and EP52 on the southern flanks of the Basin.

From 1987 to 1993, POG drilled 12 wells close to the core of the Basin, of which only four penetrated the Velkerri Formation (**Table 1**). POG also completed 2D seismic surveys over a number of areas to help target structural closures and conventional oil and gas plays. Early drilling in EP4 and EP5 met limited conventional success; however, the wells did confirm the presence and continuity of the organic-rich middle Velkerri of the Velkerri Formation (middle Velkerri) as well as bitumen and degraded oil shows within the Bessie Creek Sandstone. The confirmation of source rock continuity and hydrocarbon shows were sufficient to support the extensive acreage position built up by POG.

Despite encouraging shows, due to uncertainty over the validity of structures targeted, POG withdrew from all

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3 This geological region equates to the Beetaloo Sub-basin as published by the Northern Territory Geological Survey (Ahmad and Munson 2013).

permits in 1993 and interest in the Beetaloo waned for the remainder of the 1990s. Sweetpea Corporation (Sweetpea) recognised the potential of the Basin and applied for exploration permits over much of the area relinquished by POG in the previous decade; Sweetpea was granted EP76 in 2001, with EP98 and EP99 awarded in 2004, and finally EP117 in 2007 (**Figure 1**). Sweetpea targeted a combination of conventional oil and gas plays as well as tight gas and basin-centred gas plays.

Sweetpea completed approximately 700 km of 2D seismic before drilling Shenandoah 1 in 2007 only 120 m south of the existing Balmain 1 well. Shenandoah 1 was planned to terminate within the Bessie Creek Sandstone at a total depth of 2900 m but was suspended at 1555 m within the lower Kyalla Formation. Through a series of transactions, Falcon became operator of the four exploration permits (EP98, EP117, EP76 and EP99) in the mid to late 2000s, having recognised the potential of the Velkerri Formation as a potential shale gas play. Falcon deepened Shenandoah 1 to the Velkerri Formation (Shenandoah 1A) and then in 2011, completed one of the earliest hydraulic fracture stimulations of a shale gas play in Australia. Falcon successfully flow-tested two zones within the middle Velkerri Formation, and one zone in the Kyalla Formation. Falcon also attracted Hess Corporation (Hess) as a farminee in 2011 and proceeded to shoot over 3500 km of 2D seismic between 2011 and 2012. Falcon and Hess terminated their participation agreement in mid-2013, which ultimately led to Origin and Sasol entering a joint venture with Falcon in 2014 with Origin as operator.

### Origin's exploration strategy

Origin's exploration strategy and objectives have remained consistent through the exploration program to date, including the intent to move as rapidly as feasible and prudent to horizontal, multi-stage fracture stimulated wells (Close 2015). Despite regional well and seismic data, and permit specific data from Shenandoah 1A that were

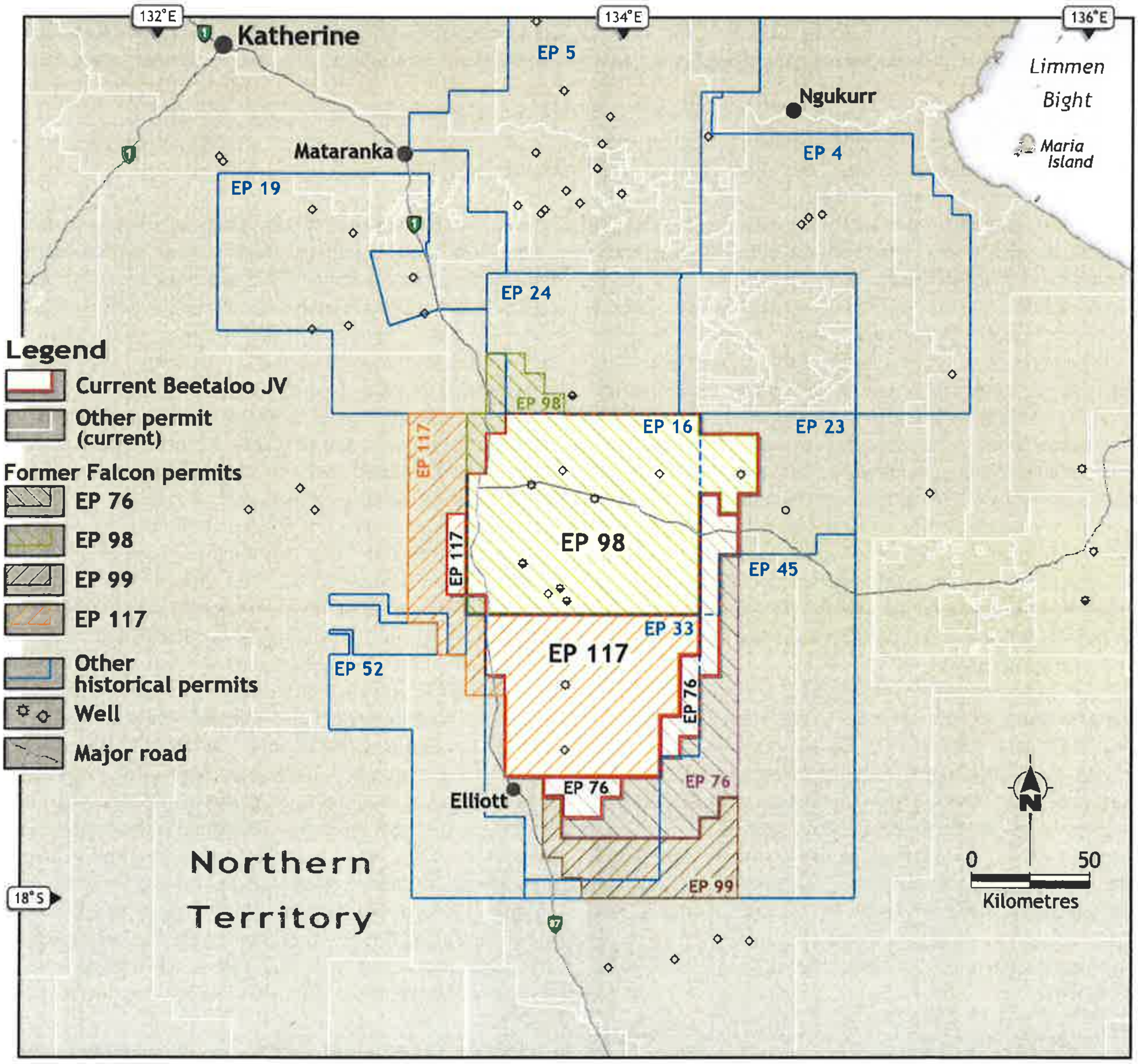



**Figure 1**. The Beetaloo JV Permits (EP98, EP117 and EP76), former Falcon Oil & Gas permits, and the outline of historic permits held by Pacific Oil & Gas and others in the 1980s and 1990s.

sufficient to de-risk the presence and approximate extent of a prospective shale gas play over the Permits (**Figure 2**), the data also confirmed the targets are of Proterozoic age. This was identified as a risk as no global producing analogues for unconventional plays in Proterozoic source rocks have been identified. Additionally, further production test data from fracture stimulated wells are required to address the two key technical risks:

1. Is there sufficient resource concentration within the source rocks (ie, gas-in-place per unit area)?
2. Can the source rocks be effectively fracture stimulated?

**Results**

In 2015, Origin drilled two vertical exploration wells (Kalala S-1 and Amungee NW-1) and one horizontal well (Amungee NW-1H). In 2016, Origin drilled one vertical exploration well (Beetaloo W-1) and fracture stimulated Amungee NW-1H (**Figure 3**). The three vertical exploration wells span a substantial fraction of the Permits and confirm the presence of organic-rich source rocks in the middle Velkerri across the core of the Beetaloo (ie A, B, and C shales from oldest to youngest; see Close 2016; **Figure 3**). Prior to the drilling of Beetaloo W-1, there were no penetrations covering the middle Velkerri in the central or southern Beetaloo; confirmation of the prospectivity of the middle Velkerri south of previous penetrations has substantially de-risked the resource potential upside. The B Shale of the middle Velkerri has been identified as the most consistently well-developed source rock interval across the Permits. Given its combination of excellent reservoir quality and geomechanical properties conducive to fracture stimulation, the B Shale was the target of the Amungee NW-1H well (**Figure 2** and **Figure 3**).

In addition to the exploration wells, a number of water monitoring bores were installed; multiple rounds of water chemistry sampling and standing-water level measurements have been completed in over 30 wells as part of Origin's comprehensive groundwater monitoring plan (GMP). The GMP is providing critical baseline data on the Cambrian Limestone Aquifer and other aquifers of importance to all stakeholders during a period when exploration activities are of insignificant impact.

**Reservoir properties and geomechanics**

Wireline log derived petrophysical interpretation, calibrated by core data, indicates a gas-filled porosity

**Table 1**. Historic drilling by Pacific Oil & Gas across the Beetaloo Basin in the late 1980s and early 1990s. Fm = Formation, Sst = Sandstone.

| Well name | Year | Summary |
|---|---|---|
| Altree 2 | 1988 | Stratigraphic test.<br>Oil and gas shows within middle Velkerri.<br>Altree 2 terminated within a dolerite sill within the Corcoran Fm. |
| Walton 2 | 1989 | Anticline test.<br>Oil and gas shows within middle Velkerri.<br>Walton 2 terminated within Bessie Creek Sst. |
| McManus 1 | 1989 | Syncline test for fracture play.<br>Oil and gas shows within middle Velkerri.<br>McManus 1 terminated within lower Velkerri. |
| Sever 1 | 1990 | Stratigraphic test.<br>Minor gas shows within middle Velkerri. Thick dolerite intrusion within middle Velkerri.<br>Sever 1 terminated within Corcoran Fm. |
| Jamison 1 | 1990 | Stratigraphic test targeting 2-way closure.<br>Drill stem test (DST) over Bukalorkmi Sst recovered 1.5–2 m of oil<br>Jamison 1 terminated within upper Moroak Sst. |
| Elliott 1 | 1991 | Stratigraphic and structural play test.<br>DST over Kyalla Sst, recovered minor oil.<br>Elliott 1 terminated within lower Moroak Sst. |
| Mason 1 | 1991 | Structural test at Bukalorkmi Sst level.<br>Minor hydrocarbons shows.<br>Mason 1 terminated within upper Kyalla Fm. |
| Balmain 1 | 1992 | Test of a lateral resistivity anomaly from CTEM survey in 1991.<br>DST over Chambers River Sst recovered minor oil.<br>Balmain 1 terminated within upper Kyalla Fm. |
| Shortland 1 | 1992 | Structural test of interpreted closure from 2D seismic lines.<br>Hydrocarbon shows were limited to weak, dull pale yellow fluorescence within Chambers River Sst and Bukalorkmi Sst.<br>Shortland 1 terminated within upper Kyalla Fm. |
| Chanin 1 | 1993 | Structural test of a 4-way dip closure mapped in 2D seismic lines.<br>Hydrocarbon shows were limited to minor mud gas while drilling and sparse fluorescence within Bukalorkmi Sst.<br>Chanin 1 terminated within upper Moroak Sst |
| Ronald 1 | 1993 | Structural test.<br>DST over top of Moroak Sst recovered minor solution gas.<br>Ronald 1 terminated within upper Moroak Sst. |
| Burdo 1 | 1993 | Crestal test of a possible fractured play within a prominent wrench structure.<br>Tight gas zone was inferred from petrophysical logs within upper Moroak Sst (1143–1151 m).<br>Burdo 1 terminated within upper to middle Moroak Sst. |

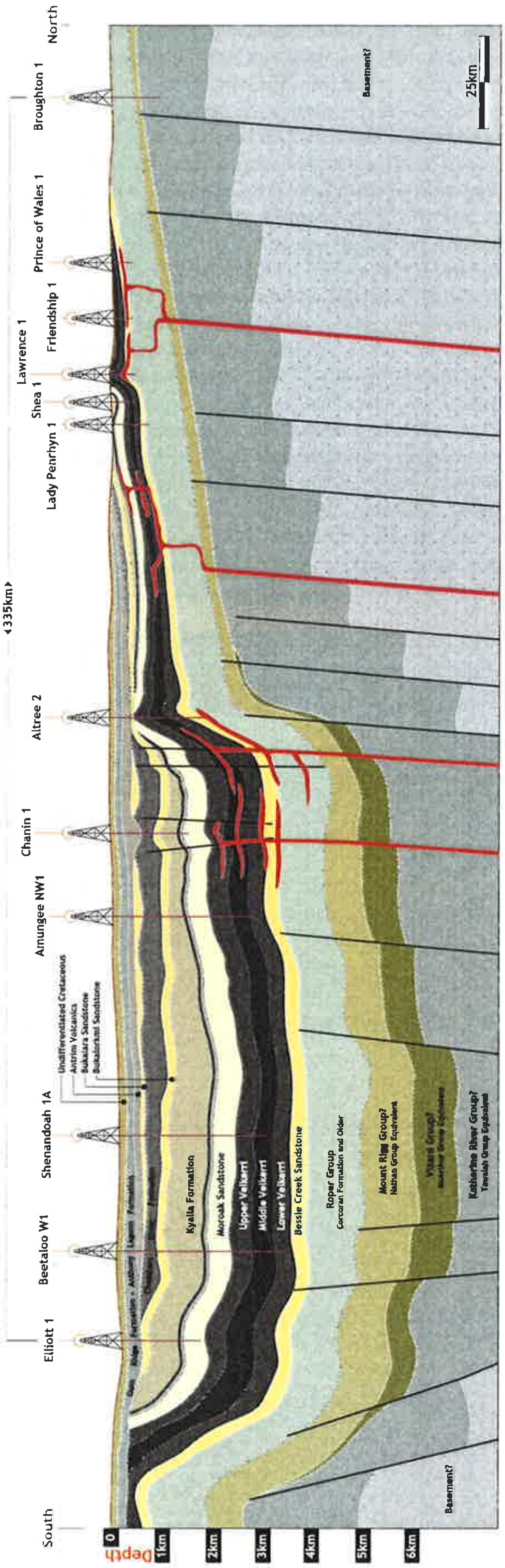



Figure 2. South–north Beetaloo Basin schematic cross-section.

range of 3–5% over the prospective intervals of the middle Velkerri (**Figure 4**). The resource concentration of the B Shale is 22–43 BCF/km$^2$ (P90–P10), which is analogous with successful North American shale plays (Jarvie 2012). In addition to the positive reservoir quality indicators, geomechanical properties inferred from sonic and density logs (i.e. dynamic measurements) and from laboratory tests on core samples (ie static measurements) indicate the organic-rich A, B and C shales are all relatively 'brittle' (ie conducive to effective fracture stimulation; **Figure 4**). Interpretation of image log data also provides valuable geomechanical data indicating that the orientation of the maximum horizontal stress direction is approximately northeast–southwest (**Figure 5**). Natural fractures, drilling induced tensile fractures and borehole breakouts interpreted in image logs also provide critical information in this frontier geological environment where there is little known about the regional stress regime; data from wells drilled by Origin indicate the middle Velkerri is in a normal to strike-slip stress regime.

Origin also acquired geomechanical data from diagnostic fluid injectivity tests (DFIT) at both Kalala S-1 and Amungee NW-1 prior to the fracture stimulation of Amungee NW-1H. The DFIT data support the geomechanical interpretation and demonstrate that closure pressure in the middle Velkerri occurs below the overburden gradient, further implying either a strike-slip or normal stress regime (critical for effective fracture stimulation operations). DFIT data from Kalala S-1 indicates the middle Velkerri is over-pressured, with a pore-pressure gradient of 0.52–0.55 psi/ft; this is also a critical success indicator of shale gas plays based on North American analogues.

### Hydraulic fracture stimulation planning and execution

The multi-stage, hydraulic fracture stimulation (HFS) of Amungee NW-1H was successfully executed in 2016. Following extensive stakeholder engagement and regulatory review, the HFS was completed safely with no environmental incidents. Stage placement across the approximately 1000 m lateral section was dictated by Origin's interpretation of reservoir and completion quality, and the location of faults interpreted from various data sources (**Figure 4**). A number of factors, including conservative buffers around faults, resulted in an effective stimulated lateral length of <700 m. Approximately 130 000 tonnes of proppant was placed over the 11 stages with a total pumped fluid volume of ~11 ML. Breakdown and treating pressures were in the range expected based on the mechanical earth model built prior to the stimulation job.

The initial flowback of Amungee NW-1H commenced on 10 September 2016 up casing with first hydrocarbons detected after 321 bbls of load fluid were recovered. The first continuous gas breakthrough occurred on 13 September; the well flowed up casing until 29 September at which time the well was shut-in to install tubing and the extended production test (EPT) commenced on 4 October. The initial production of the EPT, as measured over the first 30 days, was 1.11 MMscfd. Over the 57 day EPT, a cumulative load fluid volume of 6207 bbls was recovered, and 63 MMscf

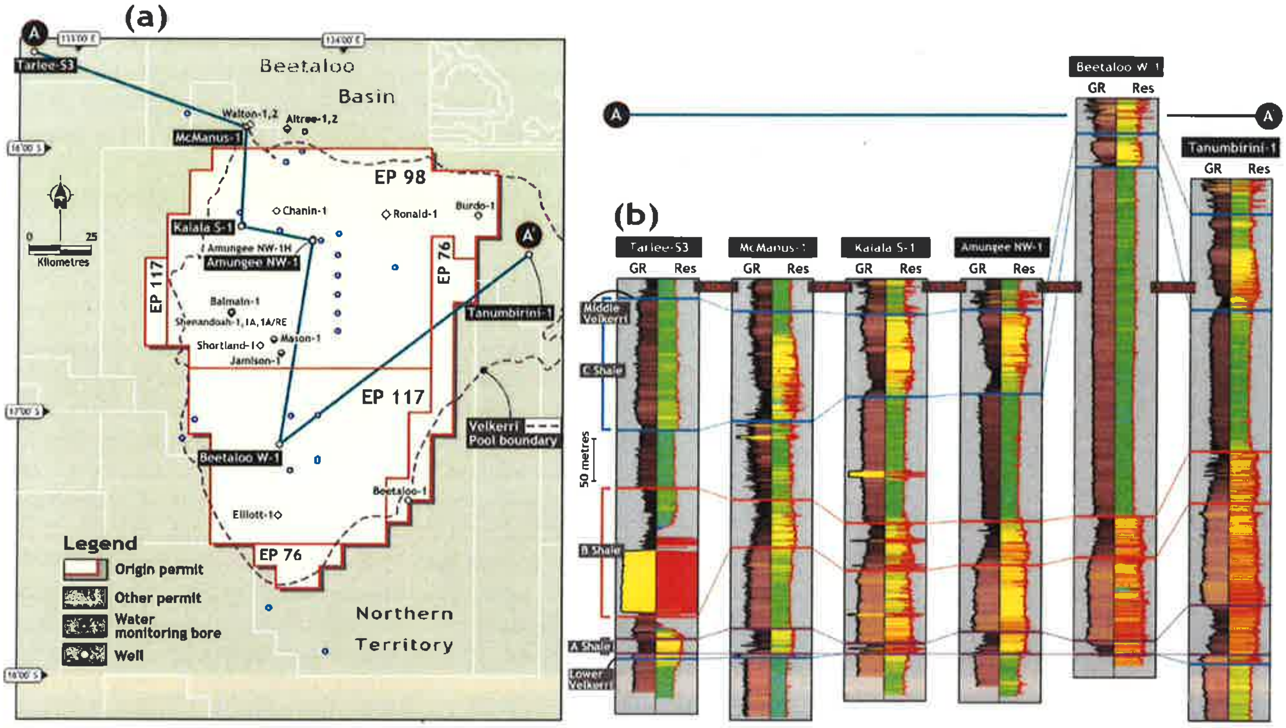
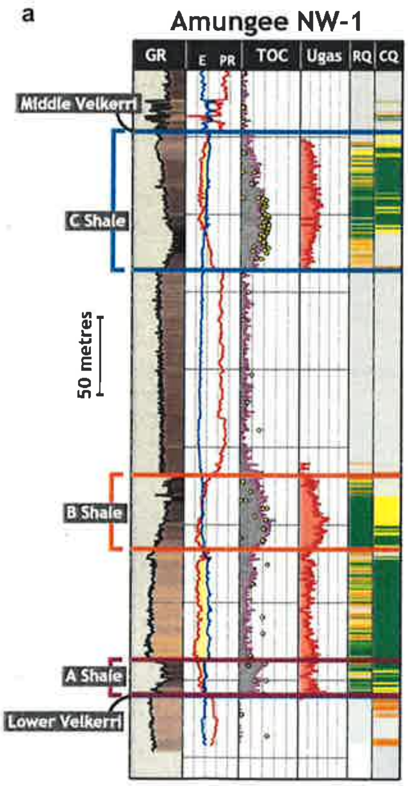



**Figure 3**. (**a**) Permit boundaries and Velkerri Formation B Shale Pool limits with exploration well and water monitoring bore locations. (**b**) Approximately east–west well cross-section over the middle Velkerri illustrating the continuity of the middle Velkerri and the B Shale in particular.




b

| Tier 1 (RQ&CQ) | B Shale |
|---|---|
| Thickness (m) | 29.5 |
| TOC (%) | 4.1 |
| Phi Gas (%) | 4-4.5 |
| Poisson's ratio | 0.2 |
| Young Modulus (GPA) | 32.8 |

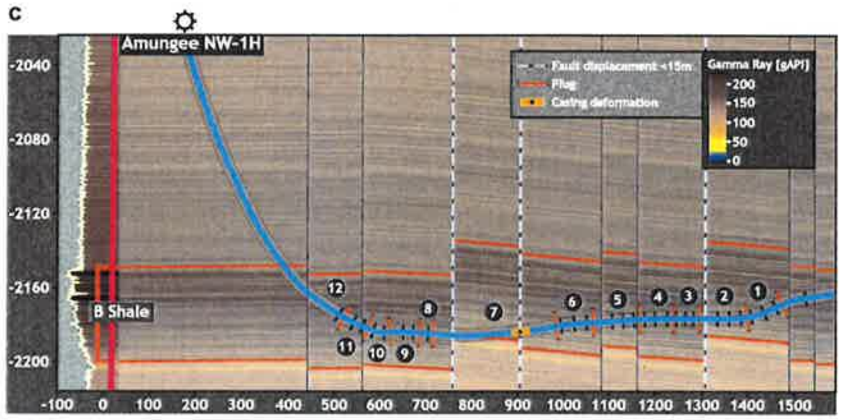



**Figure 4**. (**a**) Composite log of petrophysical data from the Amungee NW-1 well highlighting the three source rock intervals within the middle Velkerri. Tracks read from left to right: gamma ray (GR), Young Modulus (E), Poisson's ratio (PR), total organic carbon (TOC), gas-filled porosity (Ugas), reservoir quality (RQ), and completion quality (CQ). (**b**) Summary of key parameters for the B Shale interval. (**c**) Amungee NW-1H horizontal well with fracture stimulation stages and geosteering curtain section of gamma-ray values projected from the vertical pilot (Amungee NW-1).

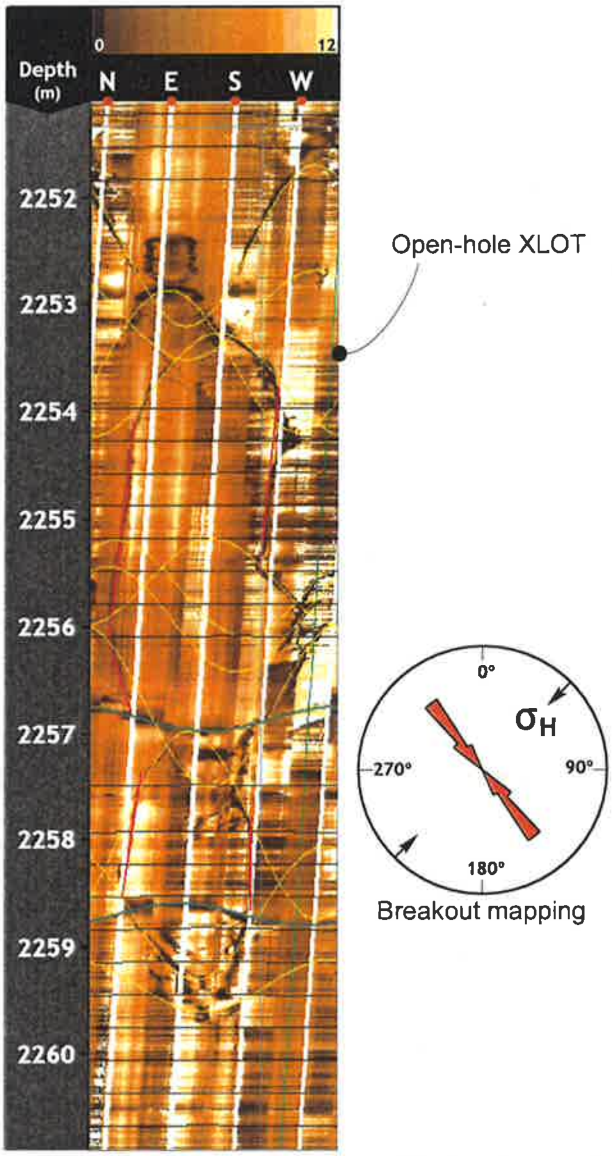



**Figure 5**. Image log interpretation provides key data on the azimuth of the maximum horizontal stress; it indicates the middle Velkerri is in either a normal or strike-slip stress regime.

of natural gas produced (**Table 2, Figure 6**). The average production rate over the EPT was 1.10 MMscfd and the final production rate of the EPT was 1.07 MMscfd: this illustrated the limited decline in gas rates over the period of the EPT. Although dry gas flowed at the Amungee NW-1H location, Origin interprets strong liquids potential to the north and east of the Permits, and also within the Kyalla Formation (a secondary Mesoproterozoic target).

## Discussion and conclusions

Origin's Permits cover the core of the most prospective fairway in the Beetaloo Basin and have the potential to provide a material new resource for Australia's domestic and export gas markets. The plays being matured by Origin provide a material growth opportunity that is an excellent fit to Origin's strategy of lowering the cost of Australia's onshore gas resources and connecting them to markets.

The drilling and HFS campaigns completed in 2015 and 2016 have technically de-risked the play. The next step for the Beetaloo JV is the determination of the appropriate combination of exploration, appraisal and pilot drilling required to prove that drilling and completion costs and well productivity can support a commercial development. There are numerous commercial opportunities for small (local to regional) and large (national and international) gas egress based on NT and east coast Australian domestic markets as well as Darwin and QLD LNG export markets; however, there will be numerous political and social challenges to any gas development as the current moratorium on HFS of unconventional reservoirs in the NT attests.

**Table 2**. Summary of the cumulative gas produced and load fluid recovered during the clean-up and extended production test (EPT) phase in Amungee NW-1H.

| Phase | Cumulative Gas Produced (MMscf) | Cumulative Load Fluid Recovered (bbl) |
|---|---|---|
| Clean-up | 5.6 | 6 100 |
| EPT | 63.0 | 6 207 |
| Total | 68.6 | 12 307 |

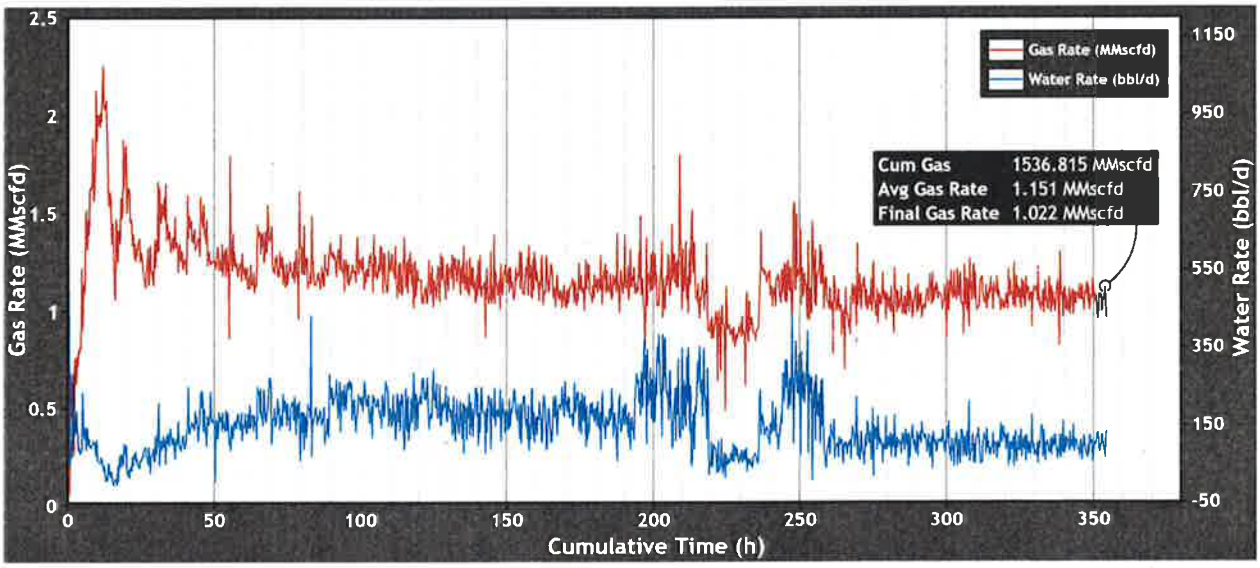



**Figure 6**. Gas and water rate data from the extended production test at Amungee NW-1H.

**Acknowledgements**

The authors wish to acknowledge Sasol and Falcon, Origin projects and operations teams, Origin management, the Northern Territory Geological Survey, and our service companies and contractors.

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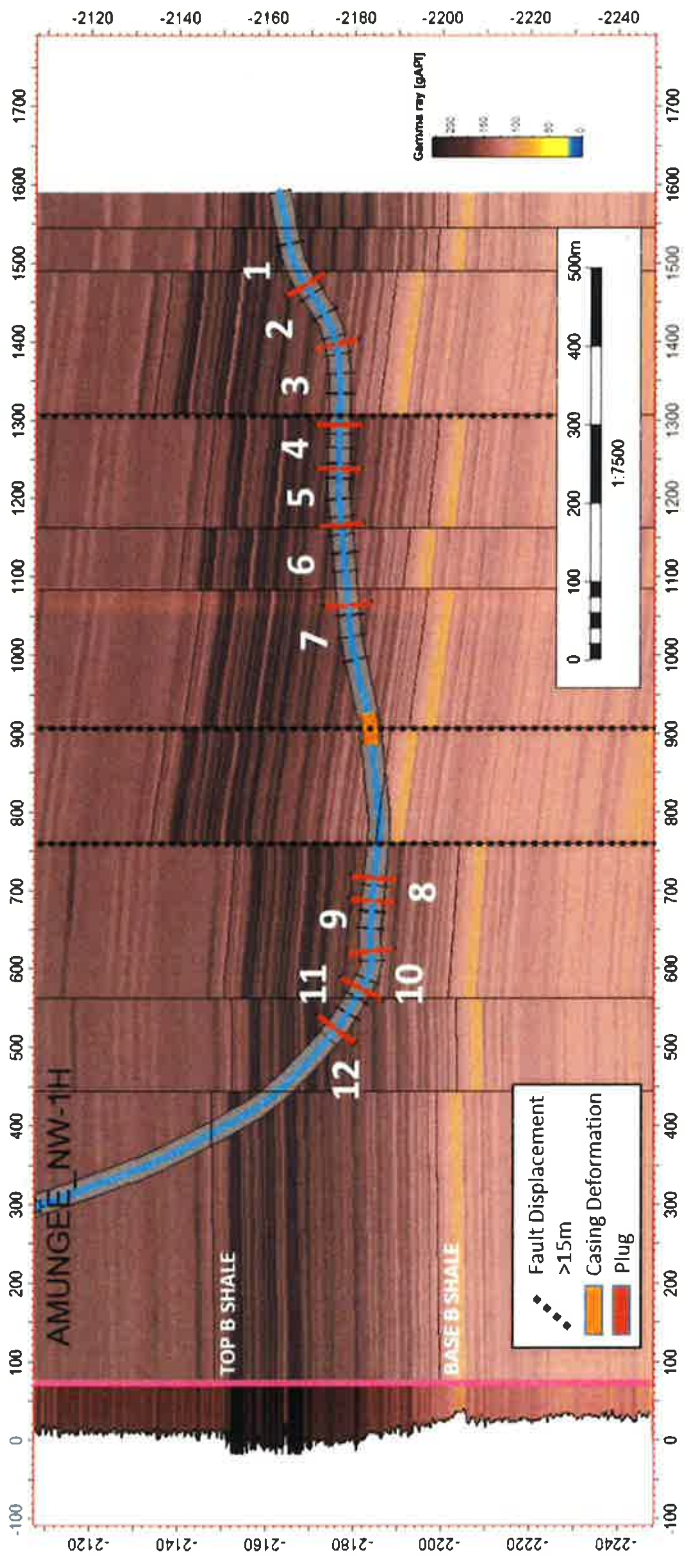


Figure 2. Location and distribution of fracture stimulation stages along Amungee NW-1H well cross-section. Background colour follows the gamma ray property values from the vertical well Amungee NW-1 as propagated across Origin's geosteering model over the B Shale interval.

## 2.2 Completion and Fracture Stimulation

Completions activities at Amungee NW-1H began in July 2016, preparing the wellbore for hydraulic stimulation operations. A Cement Bond Log (CBL) was conducted to confirm the cement integrity behind the 4.5" casing along with a 10,000 psi pressure test of the production casing to verify wellbore integrity.

An AbrasiJET perforation was performed on the toe stage, after the toe sleeve failed to shift open to gain access to the reservoir. A Diagnostic Fracture Injection Test (DFIT) was pumped on the first interval prior to the main stimulation treatments. In August 2016, a total of 11 stimulation stages were pumped, effectively placing 2.5 million lbs of proppant and 67,000 bbls of fluid (Figure 2). After the 7$^{th}$ stimulation treatment interval, a casing deformation at 3111.6 mMDRT was discovered during the pump down operation. After some diagnostics with coiled tubing, it was decided to shift the remaining 5 frac stages along the wellbore to provide a greater standoff distance between the fracture initiation point and potential bedding planes. A 12$^{th}$ stage was attempted on the well; however formation breakdown was not achieved and the frac treatment was terminated early without placing any proppant.

## 2.3 Flow-Back and Extended Production Test

The initial flowback of Amungee NW-1H commenced on 10 September 2017 up casing. The first hydrocarbons were detected after 321 bbls of load fluid were recovered. The first continuous gas breakthrough occurred on the 13 September. The well was flowed up casing until 29 September at which point it was shut-in to install tubing. The cumulative stimulation fluid recovered and gas produced to this point in time were 6,100 bbls and 5.6 MMscf respectively.

The well was completed with a tubing packer installed at 2400 mMDRT and 2 3/8" tubing. The well commenced the extended production test (EPT) after completion operations were finalized on 4 October (Figure 3). The initial production, as measured over the first 30 days was 1.11 MMscfd. The duration of the EPT was 57 days with a cumulative load fluid volume recovery and gas production volume of 6,207 bbls and 63 MMscf respectively. The average production rate over the EPT was 1.10 MMscfd and the final production rate of the EPT was 1.07 MMscfd. A summary of cumulative gas produced and load fluid recovered during the clean-up and EPT phase is provided in Table 2.

| Phase | Cumulative Gas Produced (MMscf) | Cumulative Load Fluid Recovered (bbl) |
|---|---|---|
| **Clean-up** | 5.6 | 6,100 |
| **EPT** | 63 | 6,207 |
| **Total** | 68.6 | 12,307 |

Table 2. Summary of the cumulative gas produced and load fluid recovered during the clean-up and EPT phase in Amungee NW-1H.