# Future exploration opportunities targeting Permian reservoirs on the western side of the Southern Bowen Basin

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## SUMMARY

The south-western flank of the Bowen Basin hosts several small to medium sized gas/condensate fields with late Permian Tinowon and Muggleton Formation sandstone reservoirs. Recent exploration has highlighted the potential for larger gas/condensate discoveries in mildly over pressured tight sandstones and stratigraphic traps deeper on the western flank of the Taroom Trough.

We present a model of a continuous Tinowon and Muggleton Formation (including the Lorelle Sandstone Member) play fairway on the western flank of the Taroom Trough. This fairway can be divided into three play segments, including (1) conventional structural, (2) structural/stratigraphic, and (3) tight gas/condensate sandstones with over pressured/stratigraphic traps. Tinowon and Muggleton Formation reservoirs were deposited in a complex mosaic of cold climate fluvial, flood plain, coastal plain, braided-fan delta, barrier/shoreface, and nearshore marine environments. Fluvial and coastal plains contain extensive peats. Sediments were primarily sourced from valleys draining western cratonic uplands composed of granite, low grade metasediments and siliceous volcanics, tuffs and andesite. Better quality reservoirs were sourced from the quartz rich Carboniferous Roma Granite. The extensive fluvial flood plain and coastal plain peats of the Wallabella Coal Member act as both a source and seal.

Little exploration potential remains in the volumetrically smaller conventional structural traps in the shallower part of the play fairway. Greater potential exists in the deeper mildly over pressured play segment. The juxtaposition of source, reservoir, seal, and rapid vertical and lateral facies changes in this zone provides for stratigraphic trapping of reservoir sandstones. Thicker sandstone reservoirs and stratigraphic trapping within coals in the optimum over pressure zone offer the greatest potential for large volumes of gas/condensate. Future exploration will require densely spaced 3D seismic to map stratigraphic traps and differentiate between rapid vertical and lateral facies changes. Appropriate permeability enhancement through fracture stimulation/horizontal techniques will need to be cost effective and able to recover sufficient volumes of gas/condensate.

**Key words:** Bowen Basin, Permian hydrocarbon reservoirs, Tinowon Formation, Muggleton Formation.

## EXPLORATION HISTORY

The south-western part of the Bowen-Surat basin has been explored for hydrocarbons since 1900, primarily targeting fluvial Jurassic and Triassic reservoirs in structural closures. See Figure 1.
The advent of seismic in the late 1950s and 1960s led to the recognition of a thick Permian section on the flank of the Roma Shelf - a major basement high block underpinned by the Carboniferous Roma Granite. Swindon (1968) also recognised several deep basement valleys, the largest of which he named the Coonardoo Valley. Several wells were drilled off structure as stratigraphic tests to evaluate the potential of Permian reservoirs. Meeleebee 1 (1962) and Lorelle 1 (1963) encountered a thick Lorelle Sandstone Member which was tested and deemed to be of low permeability. Further to the south, Myall Creek 1 (1964) was drilled on the Balonne Nose, located between the Roma Shelf and Wunger Ridge, and was also considered to have poor quality Permian reservoirs. Further drilling in the 1960-70s in the Coonardoo Valley resulted in five wells flowing gas in the Lorelle Sandstone Member at rates < 0.15 MMscf/d. Sub-optimal perforations in Lorelle 2 (1981) did not result in commercial gas flows.
The discovery of gas in the Tinowon Formation in Wallumbilla South 1 in 1967 confirmed a viable and commercial petroleum system in the Tinowon Formation. Further south in Noorindoo 1 (1970), fracture stimulation of a permeable Tinowon Formation resulted in a good gas flow rate on test but was not produced commercially. Much of the drilling up to the early 2000s focussed on small faulted structural closures within and on the flanks of the paleo valleys, with many small commercial gas accumulations discovered primarily in the Tinowon Formation.
The first evidence of stratigraphically trapped Tinowon Formation reservoirs was in Churchie 3 (2002) on the Balonne Nose. During the late 1990s and early 2000s, the use of 3D seismic, underbalanced, and lateral drilling led to the discovery and development of two large gas/condensate fields: Churchie/Myall Creek and Waggamba. Both fields

contain a stratigraphic trapping component, in combination with a structural closure in Waggamba 1, and several sub-culminations in Churchie/Myall Creek (Willink et al, 2004). Myall Creek-Churchie has produced substantial volumes of gas/condensate and Waggamba > 300,000 barrels of condensate primarily from the Tinowon Formation.

In 2011, QGC (Shell) conducted a major exploration programme targeting Permian and Triassic tight gas/condensate sandstones in the southern Taroom Trough. Three wells: Daydream 1, Fantome 1 and Tasmania 1 targeted the deeper parts of the trough and were fracture-stimulated with limited success in Fantome 1. This initial campaign was successful in establishing a basin-centred gas/condensate system, presence of a material in place resource across the southern Taroom Trough and the ability to fracture-stimulate over pressured clay rich Permian sandstones. In 2014-2015, two further wells, Dunk 1 and Magnetic 1, were drilled further up dip on the flank of the trough. The Tinowon Formation and Lorelle Sandstone Member were successfully fracture-stimulated in Dunk 1, with encouraging flow rates. Reservoir quality was poorly developed in Magnetic 1 and was not tested.

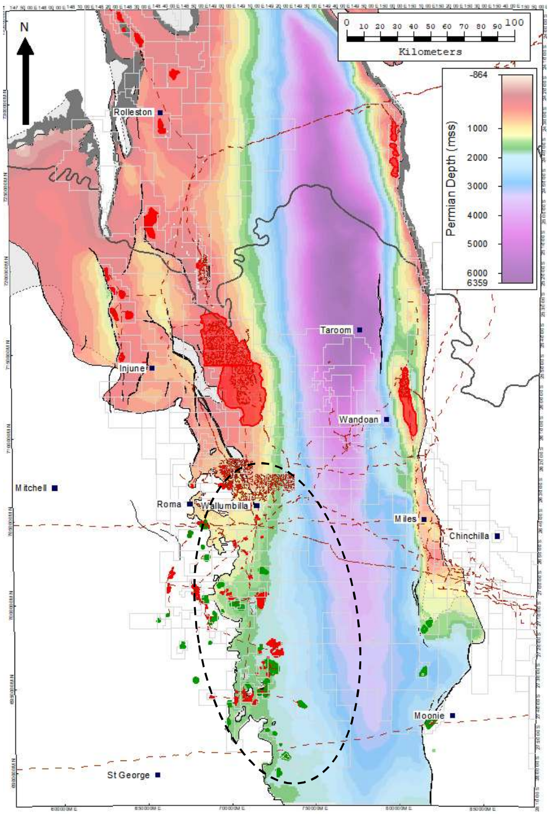


**Figure 1. Bowen Basin top Permian depth map with gas and oil fields shown in red and green. Black dashed ellipse shows the western flank of the Southern Bowen Basin.**

## STRATIGRAPHY

Paten and Groves (1974) recognised the Permian stratigraphy on the Roma Shelf as sufficiently different to the adopted Denison Trough nomenclature and proposed a new nomenclature based on Bengalla 1 (Table 1). This included the Tinowon Formation and Lorelle Sandstone Member of the Muggleton Formation - the primary reservoir targets. However, since that time, a multitude of informal names have been adopted largely because of the multiple facies changes (often beyond seismic resolution) that exist away from the Bengalla 1 well. Figure 2 shows an interpreted correlation from Bengalla 1 to Lorelle 2 and Dunk 1.

Willink et al, 2004 proposed a sequence stratigraphy to address the uncertainties associated with the lithostratigraphic schemes (Figure 3). They proposed the section as a third order transgressive systems tract with the lower Muggleton Formation as a high stand and the Lorelle Sandstone Member, upper Muggleton Formation and Tinowon Formation as late low stand to early transgressive and the Mantuan Productus Beds as late transgressive. Willink et al, 2004 shows a progressive onlap of the section to the west due to base level rise caused by flexural subsidence in the east.

Despite this framework, rapid facies change still hinder stratigraphic control, and correlations of reservoir units remain uncertain.

| Previous usage: Swindon 1968 | Previous usage: Traves 1971 | Proposed Usage (Paten and Groves, 1974) |
|---|---|---|
| BANDANNA FORMATION | BANDANNA FORMATION | BANDANNA FORMATION |
| | BLACK ALLEY SHALE | BLACK ALLEY SHALE<br>Winnathoola Coal Mbr |
| Mantuan Productus Bed | Mantuan Productus Bed | Mantuan Productus Bed |
| "DRY CREEK SHALE" | PEAWADDY FORMATION | TINOWON FORMATION<br>Wallabella Coal Mbr. |
| "EARLY STORMS SANDSTONE" | INGELARA FORMATION | MUGGLETON FORMATION<br>Lorelle Sst. Mbr. |

**Table 1. Roma Shelf Permian stratigraphy (Paten and Groves 1974).**

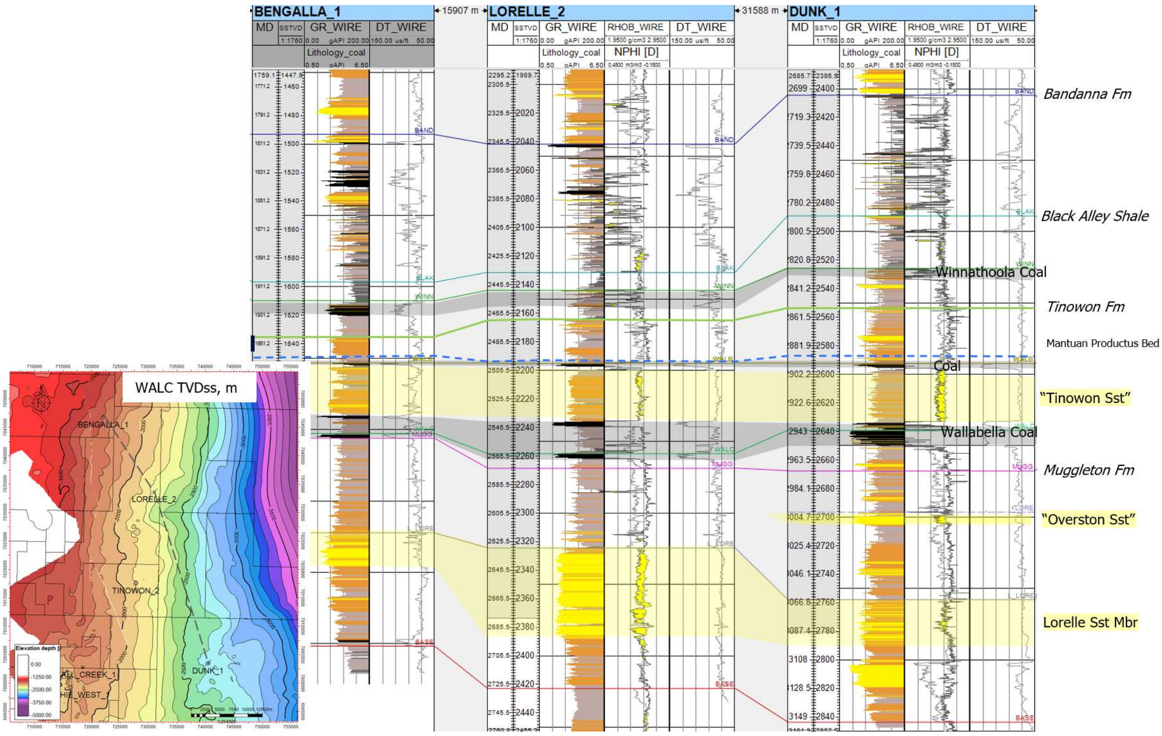


**Figure 2. Well cross-section with Lorelle 2 and Dunk 1 tied to the Bengalla 1 reference well of Paten and Groves (1974).**

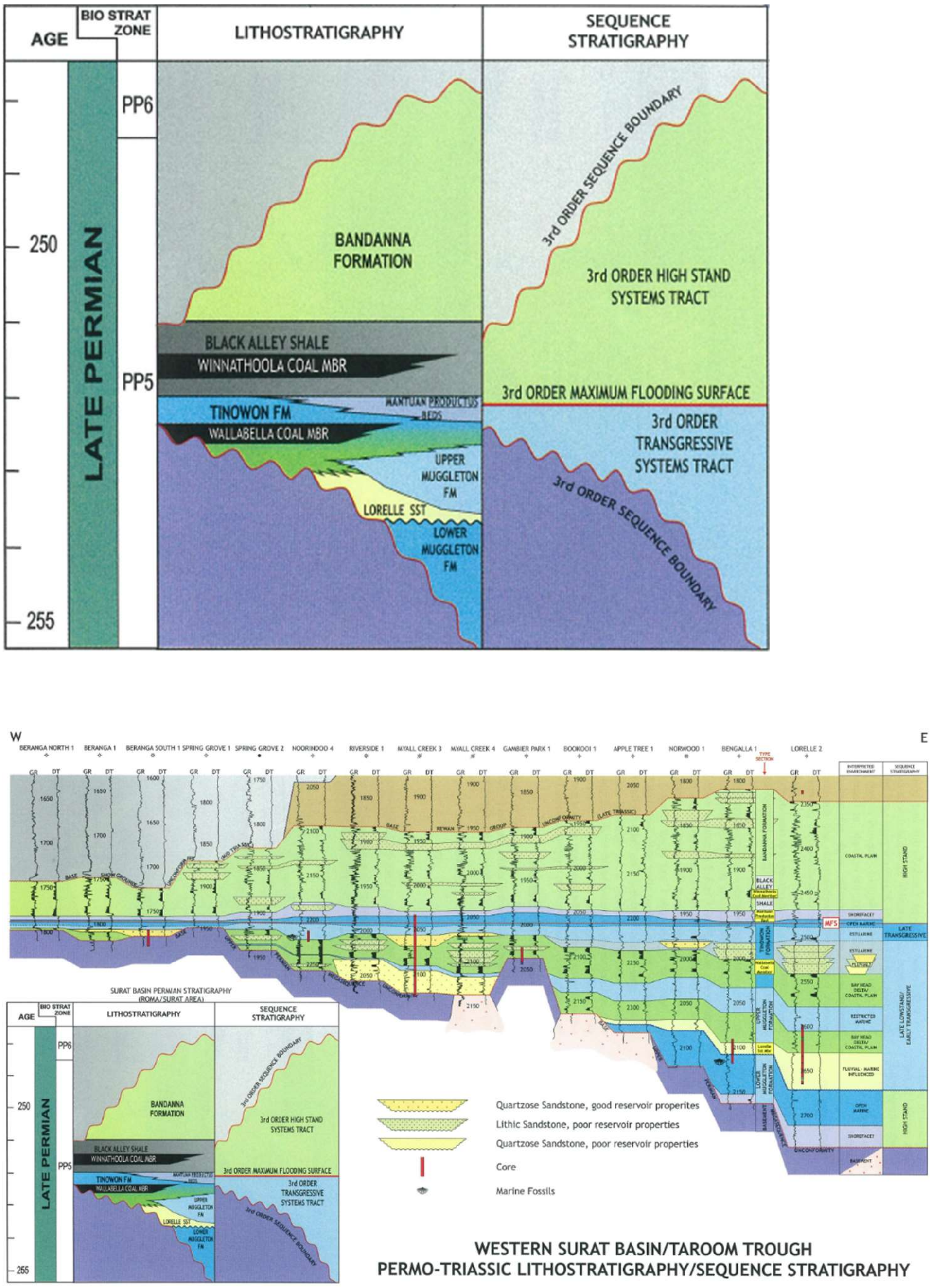


**Figure 3 Late Permian lithostratigraphy/sequence stratigraphy as defined by Willink, et al, 2004.**

## TINOWON FORMATION AND MUGGLETON FORMAITON DEPOSITIONAL SYSTEMS

Depositional environments within the Muggleton and Tinowon Formations include a complex mosaic of cold climate fluvial, flood plain, coastal plain and nearshore marine environments (with evidence of drop stones). Contemporaneous easterly derived tuffs are also present in-situ and as reworked sediments. Marine incursions are more recognisable to the east and progressively onlap basement to the west over time. The open marine lower Muggleton Formation is thicker and more widespread basin ward to the east than the succeeding more restricted marine upper Muggleton Formation incursion. This latter incursion onlaps basement further westwards. The marine incursion associated with the fossiliferous Mantuan Productus Beds is the most aerially extensive, onlapping basement further westwards, as well as being present over the Taroom Trough to the east. This suggests a regional transgressive event across the basin related to foreland flexural loading to the east.

Sediments were derived from valleys draining western cratonic uplands composed of granite, low grade metasediments and siliceous volcanics, tuffs and andesite. Several prominent paleo valleys and coastal embayments with rocky headlands were present within and between the basement highs of the Roma Shelf and Wunger Ridge. These include the Coonardoo and Noorindoo Valleys and other unnamed valleys and embayments. These valleys were progressively infilled westwards with younger sediments. See Figures 4 and 5.

We present a depositional model of the Lorelle Sandstone Member as an initial progradation of cold climate braided fluvial-fan delta complexes and associated barriers/shorefaces into nearshore marine environments to the east. Cold water marine limestones are present in Tasmania 1. Landward are valleys and coastal plains containing braided fluvial channels and peat swamps. The Lorelle Sandstone Member is restricted to the western flank of the Taroom Trough with onlap to the west and progradation into nearshore marine environments to the east. Sediment input for the Lorelle Sandstone Member is derived from the west.

The depositional model for the Tinowon Formation is one of fluvial valley flood plains and extensive coastal plains with peat swamps traversed by laterally constrained channel belts. The Tinowon Formation is much more aerially extensive than the Lorelle Sandstone Member and appears to also be present in the eastern part of the Taroom Trough. This suggests there may have been coeval fluvial valleys and coastal plains with sediments derived from the west and east. Sediments derived from the east in the evolving foreland are much more volcano-lithic in nature and are of poorer reservoir quality. Marine equivalents to the Tinowon Formation in the southern Denison Trough suggest progradation to the north.

Reservoirs are developed in fluvial, coastal plain, fluvio-deltaic to fan delta and nearshore barrier sandstones. Thicker reservoirs are developed outboard of the valleys within braided fan-delta/barrier sandstones in the Lorelle Sandstone Member and stacked fluvial to coastal plain channel sandstones in the Tinowon Formation. Sediment input from different basement terrains results in reservoir sandstones of varying quality. Better quality reservoirs are sourced from the quartz rich Roma granite.
The fluvial paleo valleys and coastal plains contain thick and extensive coals which act as both a hydrocarbon source and seal. Thick coal seams with combined thickness of up to 20 metres are present within the Wallabella Coal Member. This allows for stratigraphic trapping of fluvial and coastal plain sandstones within coal seams which act as a seal.

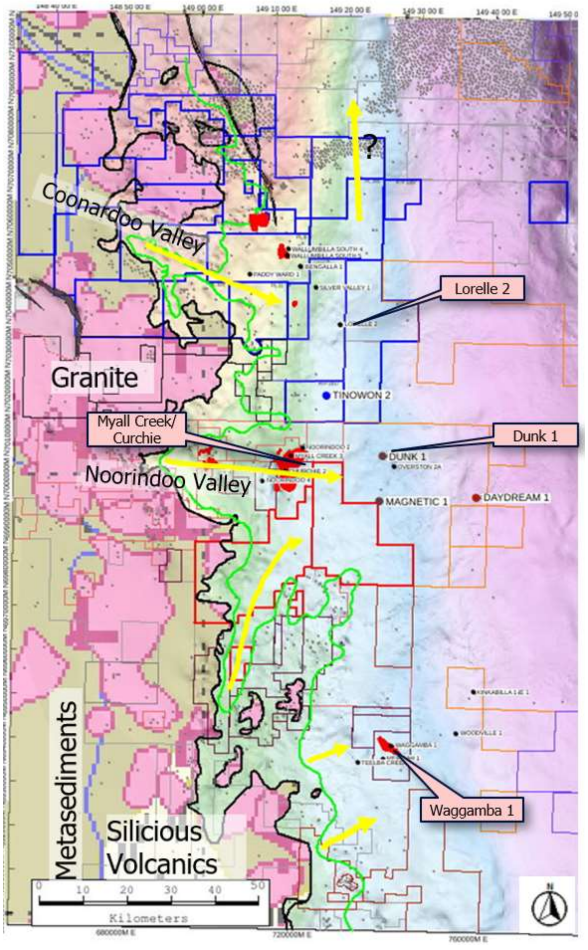


**Figure 4. Basement provenance map showing western sediment input corridors into fluvial valleys and coastal plains of the Tinowon-Muggleton Formation. Black – Permian edge, green Muggleton/Tinowon Fm edge . Yellow arrows - possible directions of sediment transport.**

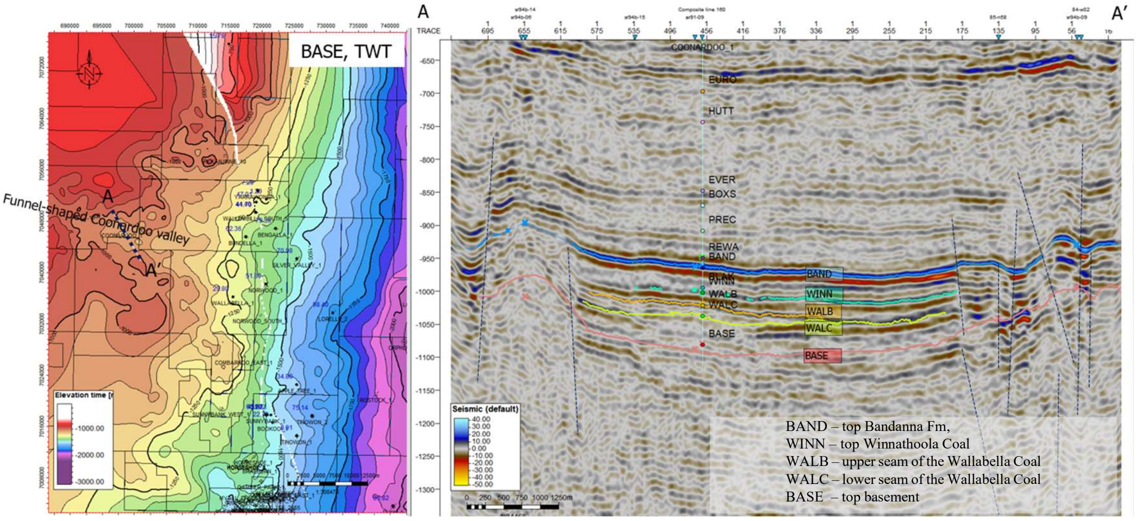


**Figure 5. Left – Basement TWT (Two Way Time) map showing the funnel-shaped Coonardoo valley. Right – Seismic section showing the Coonardoo valley and surrounding basement high blocks.**

## TINOWON AND MUGGLETON FORMATION PLAY FAIRWAY

Drilling and well testing results indicate that the western flank of the south-western Bowen Basin contains a continuous Tinowon and Muggleton Formation play fairway which can be divided into several play segments. These include hydrostatically pressured conventional structural traps, combination structural/stratigraphic traps and tight gas/condensate plays with elements of over pressure and stratigraphic trapping. Broadly, there is a W-E distribution with hydrostatic structural traps in shallower areas to the west and tight gas/condensate and stratigraphic plays in deeper areas to the east. See Figure 6.

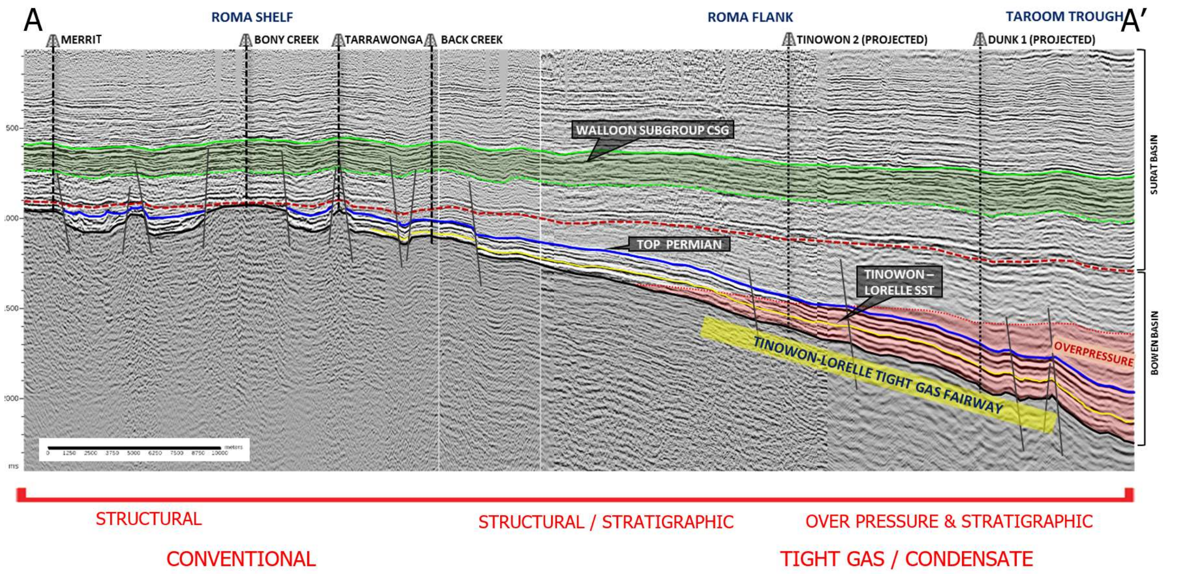


**Figure 6. Composite seismic section showing the different play segments on the western flank of the Taroom Trough and Roma Shelf.** Note, the location of the section is shown in Figure 7.

The conventional structural traps contain small accumulations (primarily Tinowon Formation), located in shallower (< 2000 m G. L.) fault bounded basement-linked structures. Most of these are water drive reservoirs with thinner fluvial channel sandstones within modest structural closures. The fluvial sandstones are quartzose with good primary permeability. Structural closure and reservoir presence and quality are the key risks. Most of these structures have been identified and drilled and there is little further exploration potential left in this play segment.

Combined structural/stratigraphic traps such as Churchie/Myall Creek and Waggamba are located further down dip, below 2000 m G.L. These fields contain larger gas/condensate accumulations in multiple reservoir sandstones, primarily the Tinowon Formation, but also the Lorelle Sandstone Member or equivalents. Pressure depth plots in the Churchie-Myall Creek field indicate not only slight overpressure but also separately pressured reservoirs between the Tinowon Formation and Lorelle Sandstone Member or equivalents (Willink et al, 2004). Reservoir quality is variable across the field and is related to variations in the composition of sediment supply from different basement terrains and diagenesis. Reduction of permeability is due to compaction, authigenic clay mineralisation and quartz overgrowths. This play segment was unlocked using 3D and reprocessed 2D seismic data to help understand the distribution of Tinowon Formation channels (see Suto and Doyle, 2001), and the use of under balanced and horizontal drilling to minimize formation damage and to access thicker channel sandstones.

Further down dip to the east, results of wells drilled below 2400 m subsea indicated a mildly over pressured tight gas/condensate fairway independent of structural closure. This zone contains juxtaposed source, reservoir, and seal. The Triassic Rewan Formation and Snake Creek Mudstone Member form a regional seal to the Permian section, with the Permian Black Alley Shale and Mantuan Productus Beds forming a semi-regional seal and coals providing local seals. Based on drilling and testing results, we have interpretated an over pressure zone below ~2400 m subsea. The major Permian structural/stratigraphic traps are located immediately to the west of the over pressure zone. See Figures 7 and 8.

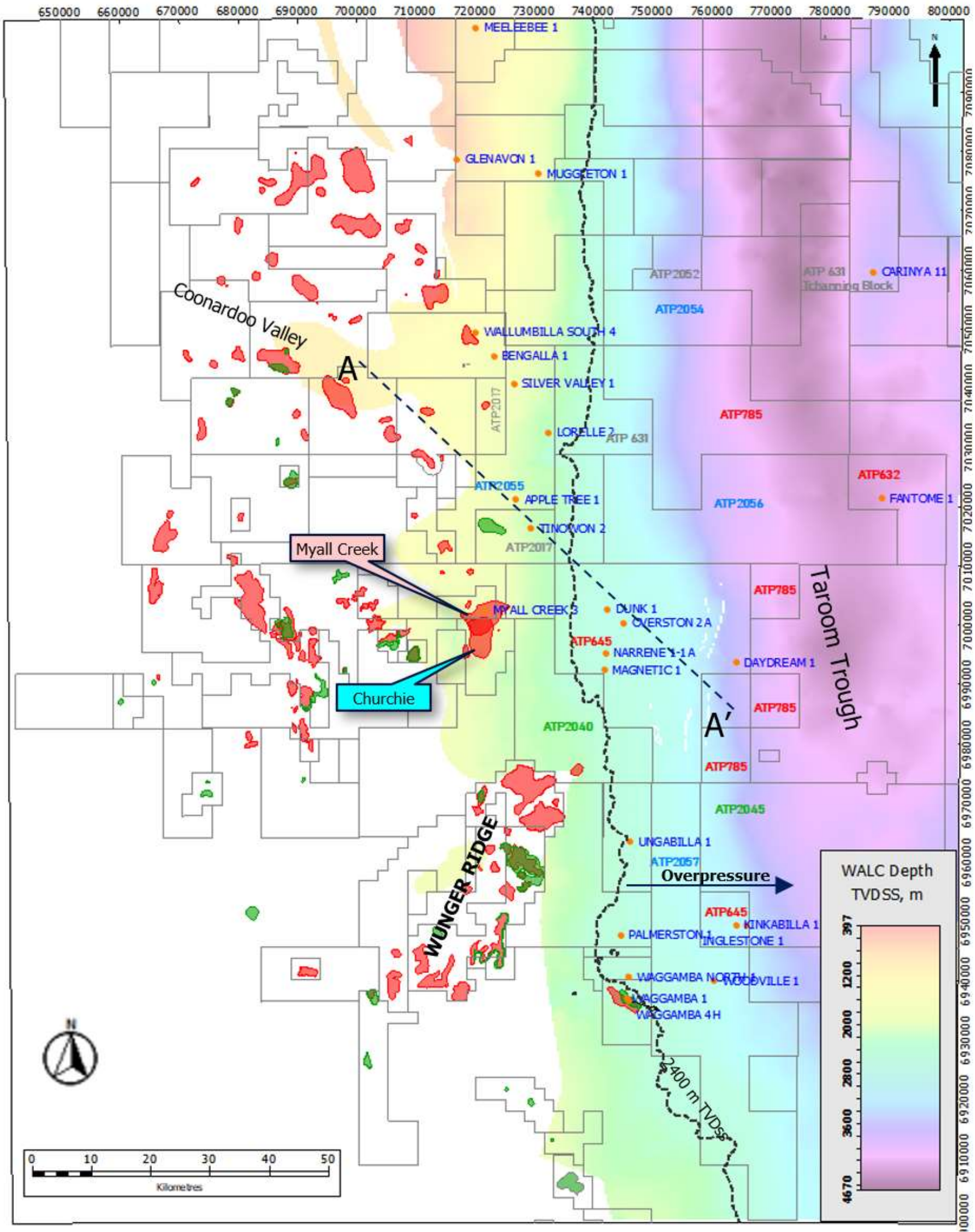


**Figure 7. Wallabella Coal Member depth map showing interpreted overpressure onset at 2400 m subsea.**

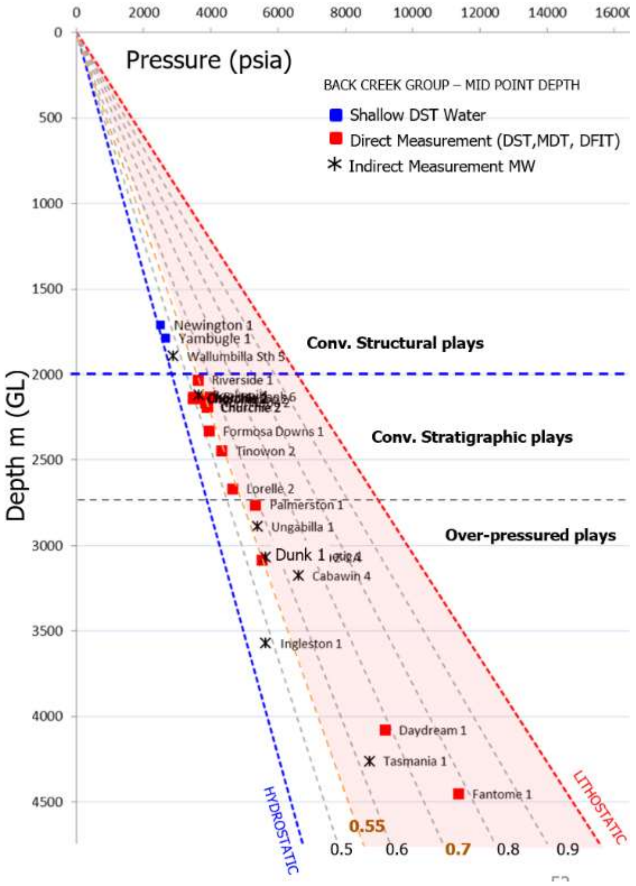


**Figure 8. Pressure depth plot for key wells in the Tinowon-Muggleton Formation play fairway.**

In the deeper areas of the Taroom Trough, the Triassic Rewan Formation and all the Permian sediments lie within the over pressure zone and present an exploration opportunity, given reservoir development. Some success has been achieved in fracture stimulation of the uppermost Tinowon Formation and Black Alley Shale in Fantome 1. Intermittent gas rates of 0.3 MMscf/d and 2-15 bbl./d of condensate were recorded at depths of 4100-4200 m subsea. Unfortunately, poor reservoir development of the Tinowon and Muggleton Formation in Daydream 1 resulted in poor fracture stimulation results at depths of 3500-3770 m subsea with 0.7 psi/ft over pressure.

More positive results have been achieved in Dunk 1 (0.55psi/ft) located near the edge of the over pressure zone. The Tinowon and Muggleton Formations were fracture stimulated between 2600-2780 m subsea. Initial combined gas rates of ~2 MMscf/d declined to ~0.7 MMscf/d with 6-10 bbl./d of condensate. Approximately 30 m of net pay and 8% porosity is present in stacked channels in the Tinowon Formation. Secondary porosity has resulted from dissolution of potassium feldspar grains derived from granitic sources. 3D seismic mapping has indicated that the thick Tinowon Formation channel sandstones in Dunk 1 may also be stratigraphically trapped between coals.

Reservoir presence and quality and cost-effective stimulation strategies are the key risks within this play segment. Due to the high costs of drilling (>2600 m depth) and productivity enhancement (fracture stimulation/lateral drilling), laterally continuous reservoirs with 20-30 m net pay are required. 3D seismic is required to identify any thick and laterally continuous sandstone bodies and stratigraphic traps.

## UNLOCKING THE TIGHT GAS/CONDENSATE SANDSTONE PLAY

Exploration in the tight gas/condensate portion of the Tinowon-Muggleton Formation play fairway offers the greatest potential to discover substantial volumes of gas/condensate. However, any appraisal and development will require appropriate and cost-effective fracture stimulation and/or lateral drilling of gas/condensate reservoirs. This will require discovering thick (20-30 m) good quality Tinowon Formation and Lorelle Sandstone Member reservoirs in an optimum position within the over pressure window. Stratigraphic trapping of these sandstones, either by up dip or lateral pinch out and/or by coalescing of underlying and overlying coal seams provides a further opportunity not only within, but up dip of the over pressured zone. Stratigraphic trapping of sandstone reservoirs between coal seams offers the most favourable juxtaposition of source, reservoir, and seal.

One such opportunity is downdip of Lorelle 1 and Lorelle 2 which has thick Lorelle Sandstone Member and Tinowon Formation sandstones which are located just outside the over pressure zone. The Tinowon Formation was not tested but appears similar to Dunk 1 and may also be stratigraphically trapped between coals. Unfortunately, the sparse 2D data is insufficient to map the stratigraphic trap. The Lorelle Sandstone Member was perforated in Lorelle 2 with inconclusive results. Fracture stimulation of these sandstones down dip in the over pressure zone with lower water saturation may result in a successful gas/condensate flow. Opportunities also exist near Dunk 1, which demonstrated gas/condensate flows from the Tinowon and Muggleton Formations with potential stratigraphic trapping of thick stacked Tinowon Formation channel sandstones between coals. One of the key questions to resolve is: can we determine the lateral extent and quality of the reservoirs outside of well control, and can we use 2D/3D seismic to achieve this?

## APPLICATION OF SEISMIC DATA AND CHALLENGES

Identification of stratigraphic traps and thicker Tinowon and Muggleton Formation reservoirs away from well control will require a densely sampled 3D seismic dataset and the use of seismic attribute analysis and inversion techniques. Currently, mapping and interpretation of seismic data within the Tinowon – Muggleton Formation play fairway is challenging due to sparse seismic coverage, and seismic quality and resolution issues. Despite the availability of several small 3D seismic data sets, most of the area is covered by 2D seismic acquired since the 1960s. Much of this seismic is concentrated on the shallower western Roma Shelf and Wunger Ridge targeting small structural closures. There is only sparse coverage over the deeper tight gas/condensate play fairway. Furthermore, multiple coal seams overlying, within, and underlying the target reservoirs contribute to multiple energy, mode conversions and signal attenuation. In many cases the thickness of the reservoir sandstones is below seismic resolution especially if surrounded by thick coals. Where the reservoir thickness is sufficient (20 m+) to be seismically resolvable, seismic amplitude alone is often not able to resolve reservoir quality.

Despite the data coverage and imaging difficulties, some success has been achieved in 3D mapping a seismically resolvable interval between two coals within the Tinowon Formation. This coal split coalesces to the west and up dip of the Dunk 1, Overston 1 and 2A wells. This split can also be mapped based on seismic attributes such as the number of zero crossings. There is also a strong correlation with a thickening of the Winnathoola Coal Member and Wallabella Coal Member isochron, which is a useful indicator in areas of sparse or poorer quality 2D seismic data. The mapped interval between the coal split corresponds to the thick stacked channel sandstones of the Tinowon Formation in Dunk 1, Overston 1 and 2A. The results indicate that the thick Tinowon Formation sandstones seen in Dunk 1 may be stratigraphically trapped between two coals that coalesce to the west. Unfortunately, seismic amplitude analysis has not been able to resolve reservoir quality differences seen in this interval between Dunk 1 and Overston 1 and 2A. See Figure 9.

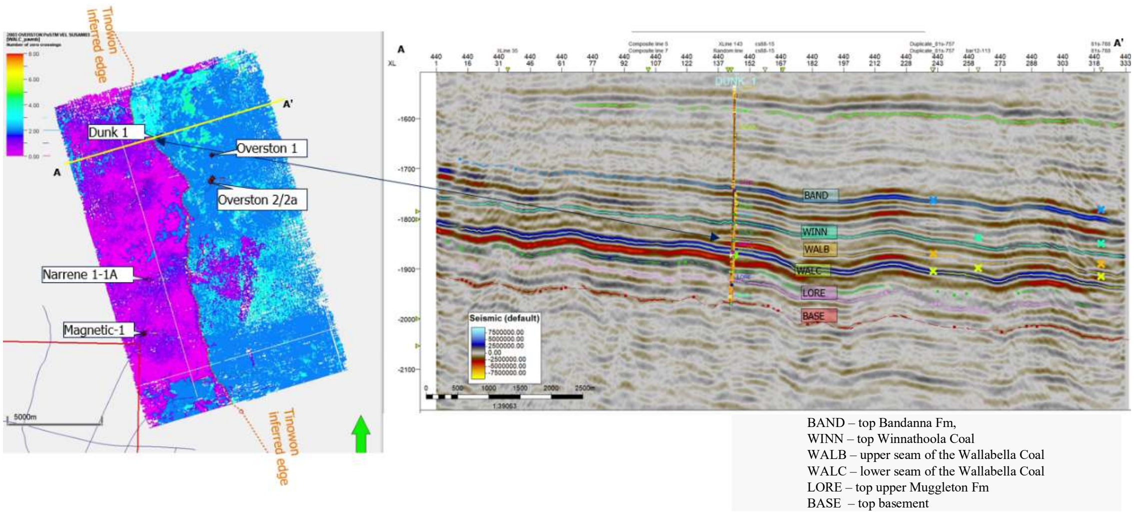


**Figure 9. Stratigraphic trapping of Tinowon Formation sandstones within Wallabella Coal Member coals displayed as number of zero crossings seismic attribute map and Overston 3D seismic line through Dunk 1. N.B. Dunk 1 has 30 metres of stacked channel sandstones between the coal split.**

Seismic interpretation of the Muggleton Formation, which includes the Lorelle Sandstone Member, is more challenging. An accurate interpretation of the basement is needed, as the Muggleton Formation onlaps basement westward. There is often not a strong reflectivity contrast between basement and the overlying strata, particularly over the low-grade metasediments of the Devonian Timbury Hills Formation. This makes it difficult to identify a thick Lorelle Sandstone Member interval, especially in the over pressured play segment. Some success has been achieved in identifying Muggleton Formation facies changes that onlap basement up dip. This is more apparent where there is a transition to upper Muggleton Formation coals in coastal plains close to basement highs. Granite basement and coal within the Muggleton Fm are characterised by brightening of both basement and Muggleton Formation seismic events (Figure 10). Seismic amplitude can be extracted along the Lorelle seismic event from 3D and 2D datasets to understand where coal was developed close to and on the paleo highs. Similar to the Tinowon Formation, the isochron from the top Lorelle to top basement seismic event has a good correlation with the gross thickness identified from wells.

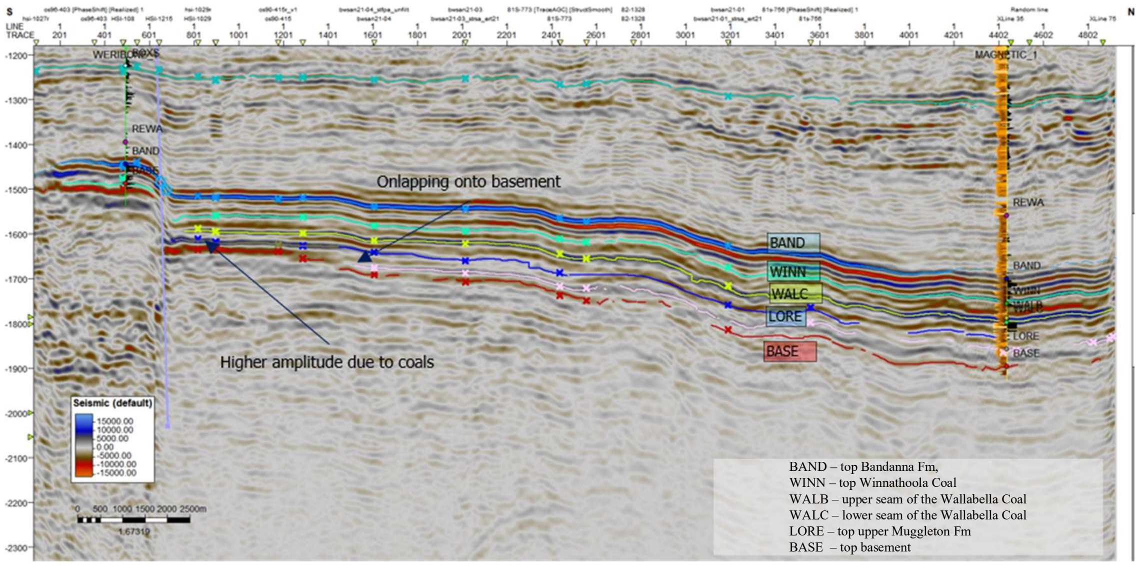


**Figure 10. A cross-section from Weribone 1 to Magnetic 1. The lower Muggleton Fm package (pink horizon) appears to onlap onto the Basement, while the upper Muggleton Fm package (blue horizon) brightens westward towards the Basement high as the facies change from sandstone.**

## CONCLUSIONS

This paper has demonstrated there is a continuous Tinowon – Muggleton Formation play fairway on the western flank of the southern Bowen Basin. There is limited potential left in the conventional structural plays. Future exploration will need to focus on the structural/stratigraphic and over pressured tight gas/condensate play segment. Thicker sandstone reservoirs and stratigraphic trapping within coals in the optimum over pressure zone offer the greatest potential for large volumes of gas/condensate. To unlock these complex plays, densely spaced 3D seismic is needed to map stratigraphic traps and differentiate between rapid vertical and lateral facies changes. Appropriate permeability enhancement through fracture stimulation/horizontal techniques will need to be cost effective and able to recover sufficient volumes of gas/condensate. It is also paramount to progress our understanding of the controls on reservoir quality including sediment supply provenance and burial diagenesis which can result in both reservoir degradation and enhancement through secondary porosity.

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