[PS]Emerging Continuous Gas Plays in the Cooper Basin, South Australia*

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Abstract

The Late Carboniferous-Late Triassic Cooper Basin is an intracratonic, non-marine basin consisting of a basal glaciogenic succession overlain by fluvio-deltaic, floodplain and lacustrine deposits with extensive and thick coal measures.

The presence of a basin centered gas accumulation (BCGA) in the Nappamerri Trough, Cooper Basin has been suspected for over two decades. Resistivity of the Permian succession exceeds 20Ωm over large intervals, tests have recovered gas with no water, and gas is located within overpressured compartments indicative of hydraulic isolation. The Permian succession in the Nappamerri Trough is up to 1,000 m thick, comprising very thermally mature, gas-prone source rocks with interbedded sands, ideal for the creation of a BCGA. Excluding the Murteree and Roseneath shales, the succession comprises up to 45% carbonaceous and silty shales and thin coals deposited in flood plain, lacustrine and coal swamp environments.

The Early Permian Murteree and Roseneath shales are thick, generally flat lying, and laterally extensive, comprising siltstones and mudstones deposited in large and relatively deep freshwater lakes. Total organic carbon values average 3.9% in the Roseneath Shale and 2.4% in the Murteree Shale. The shales lie in the wet gas window (0.95 - 1.7% Ro) or dry gas window (>1.7% Ro) over much of the Cooper Basin.

Thick Permian coals in the deepest parts of the Patchawarra Trough and over the Moomba high on the margin of the Nappamerri Trough are targets for deep coal seam gas. Gas desorption analysis of a thick (18 metre) Patchawarra coal seam returned excellent total raw gas results ranging 15.3 - 27.8 scc/g and averaging 21.2 scc/g (680 scf/ton) over 10 metres. This equates to 15 Bcf gas in place in a 15 m seam in a one square kilometre area. Scanning electron microscopy has shown that the coals contain significant microporosity in variably preserved cell lumen within telinite and semifusinite bands.

Recent off-structure drilling in the Nappamerri Trough has confirmed the presence of gas saturation through most of the Permian succession, including the Roseneath and Murteree shales. Basin centered gas, shale gas and deep coal seam gas plays in the Cooper Basin are now the focus of an escalating drilling and evaluation campaign.

Emerging continuous gas plays in the Cooper Basin, South Australia: Cooper Basin introduction

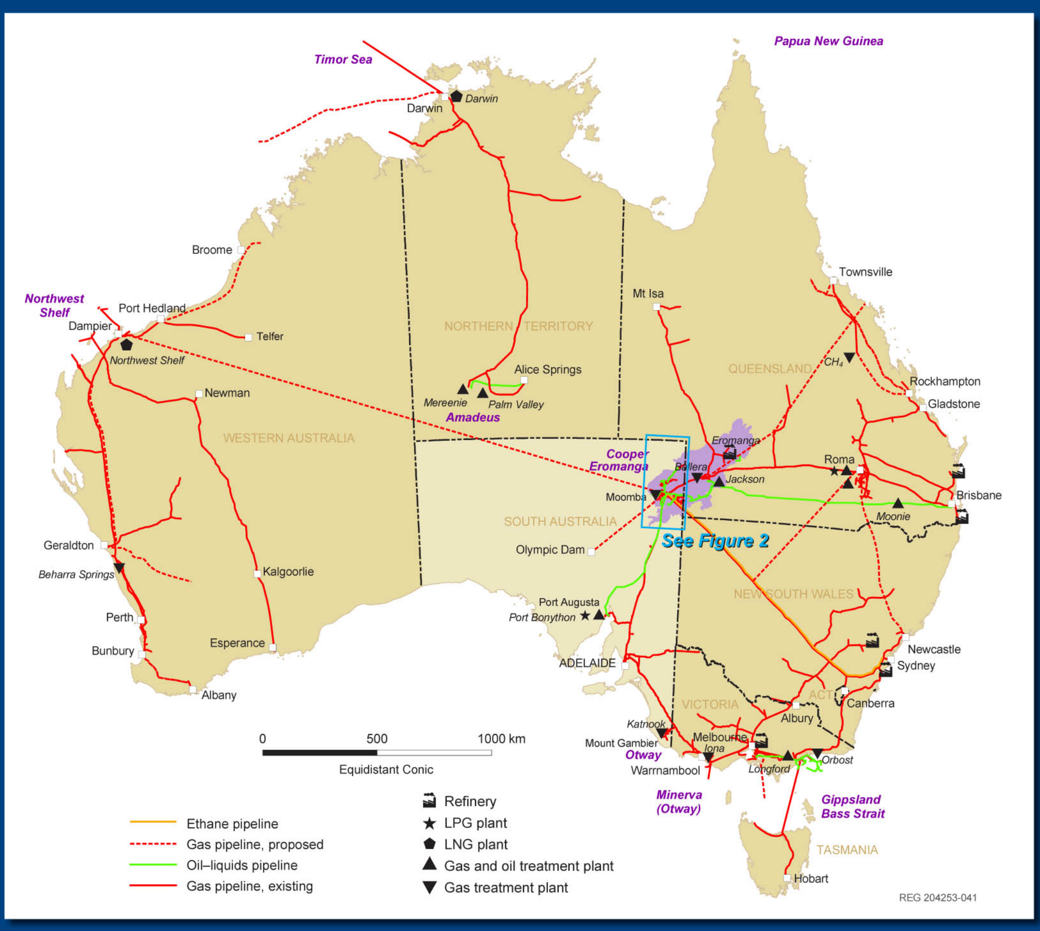

Figure 1 Map of Australia showing oil and gas infrastructure and the Cooper Basin.

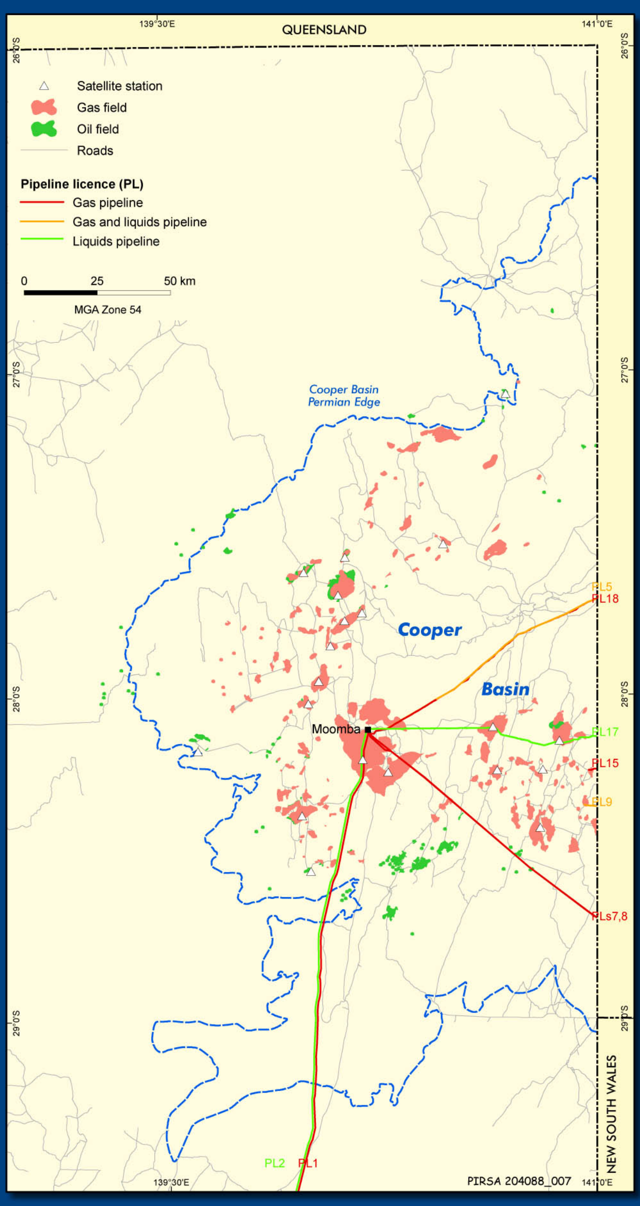

Figure 2 Oil and gas fields and infrastructure, Cooper Basin, South Australia.

The Cooper Basin is a Permo-Carboniferous to Triassic intracratonic basin located 800 km north of Adelaide, extending into southwest Queensland (Fig. 1). The total area of the Basin exceeds 130 000 km^2, of which approximately 35 000 km^2 are in north-eastern South Australia.

The first wells specifically targeting continuous gas plays in the Cooper Basin were drilled only recently (Forge1 – CSG – 2010, Encounter 1 – Shale Gas – 2010, Holdfast 1 – Shale Gas – 2011). However the basin has a long history of exploration with the first commercial gas discovery made at Gidgealpa 2 in 1963. Since then a number of conventional oil and gas fields have been discovered in the Basin (Fig. 2). To end June 2011 the South Australian parts of the Cooper Basin and overlying Eromanga Basin have produced around 5 tcf of gas, 76 mmboe of condensate, 154 mmbbl of oil and 77 mmboe of LPG.

The Cooper Basin comprises three major troughs (Patchawarra, Nappamerri and Tenappera) separated by structural ridges (Gidgealpa-Merrimelia-Innamincka and Murteree) associated with reactivation of thrust faults in the underlying Warburton Basin (Fig. 3). The Cooper Basin succession infills an erosional land surface shaped by the Late Carboniferous-Early Permian Gondwana glaciation.

The Australian Plate lay at high latitudes throughout the Early Permian to Early Triassic and peat swamp and floodplain facies were deposited during the waning stage of the Gondwana glaciation [1]. Post-glacial deposition included two lacustrine units (Roseneath and Murteree shales) with intervening peat swamp and floodplain deposits (Fig. 4). Uplift late in the Early Permian led to erosion of the Daralingie Formation and underlying units from basement ridges. Peat swamp and floodplain deposits were again deposited above the unconformity during the Late Permian (Toolachee Formation) and passed conformably into Early Triassic organically lean, oxidised lacustrine and fluvial deposits (Nappamerri Group).

The Permian succession of the Cooper Basin is now being actively explored for continuous gas accumulations and early results are very encouraging. Continuous gas plays being pursued in the Cooper Basin include shale gas, basin-centred gas (pervasive tight gas) and both deep and shallow coal seam gas. The second dedicated shale gas exploration well in the Cooper Basin was drilled in 2011, with outstanding results. Beach Energy's Holdfast 1 well in the Nappamerri Trough flowed gas at up to 2 mmscf/d after a seven stage fracture stimulation of the gas saturated Early Permian succession. Other explorers targeting shale gas in the Cooper Basin reported encouraging results from shale core analyses in 2011.

At this early stage the Cooper Basin JV (operated by Santos) and Beach Energy already have contingent unconventional gas resources totalling more than 5 tcf in the South Australian Cooper Basin, equivalent to the total sales gas production from the South Australian Cooper Basin to date. Beach has stated that there is potential for at least 15–20 tcf gas in terms of probable contingent (2C) resources in PEL 218 [2]. The US Energy Information Administration has estimated that the entire Cooper Basin (South Australia and Queensland) has a risked recoverable shale gas resource of 85 tcf [3].

Currently there are 15 vertical wells and three horizontal wells planned to test continuous gas plays in the Cooper Basin in 2012.

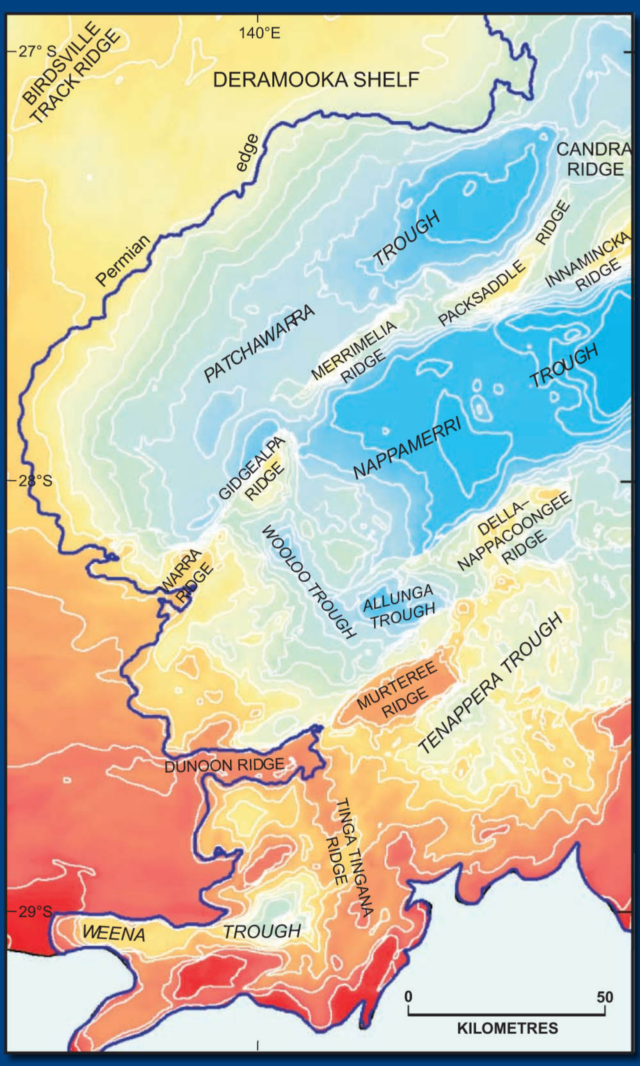

Figure 3 Basement (Z horizon) depth structure contour map highlighting structural features of the Cooper Basin.

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[2] *"A new shift in the global energy scene: Australian shale". Article in Gas Today, Australia*, Issue 18, November 2011, 50-53.

[3] *World Shale Gas Resources: An Initial Assessment of 14 Regions Outside the United States. US Energy Information Administration*, April 2011, Chapter 14, Australia.

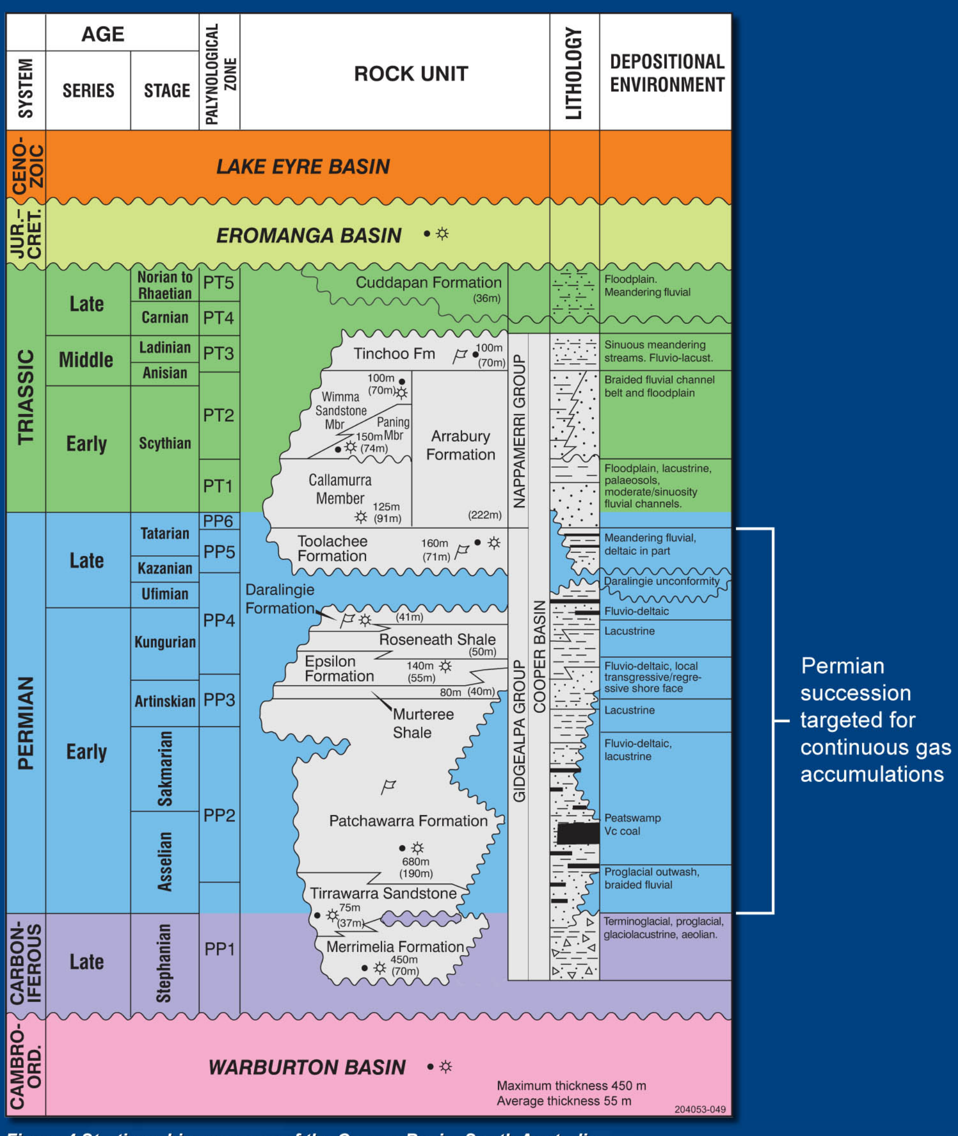

Figure 4 Stratigraphic summary of the Cooper Basin, South Australia.

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Emerging continuous gas plays in the Cooper Basin, South Australia: Shale gas play

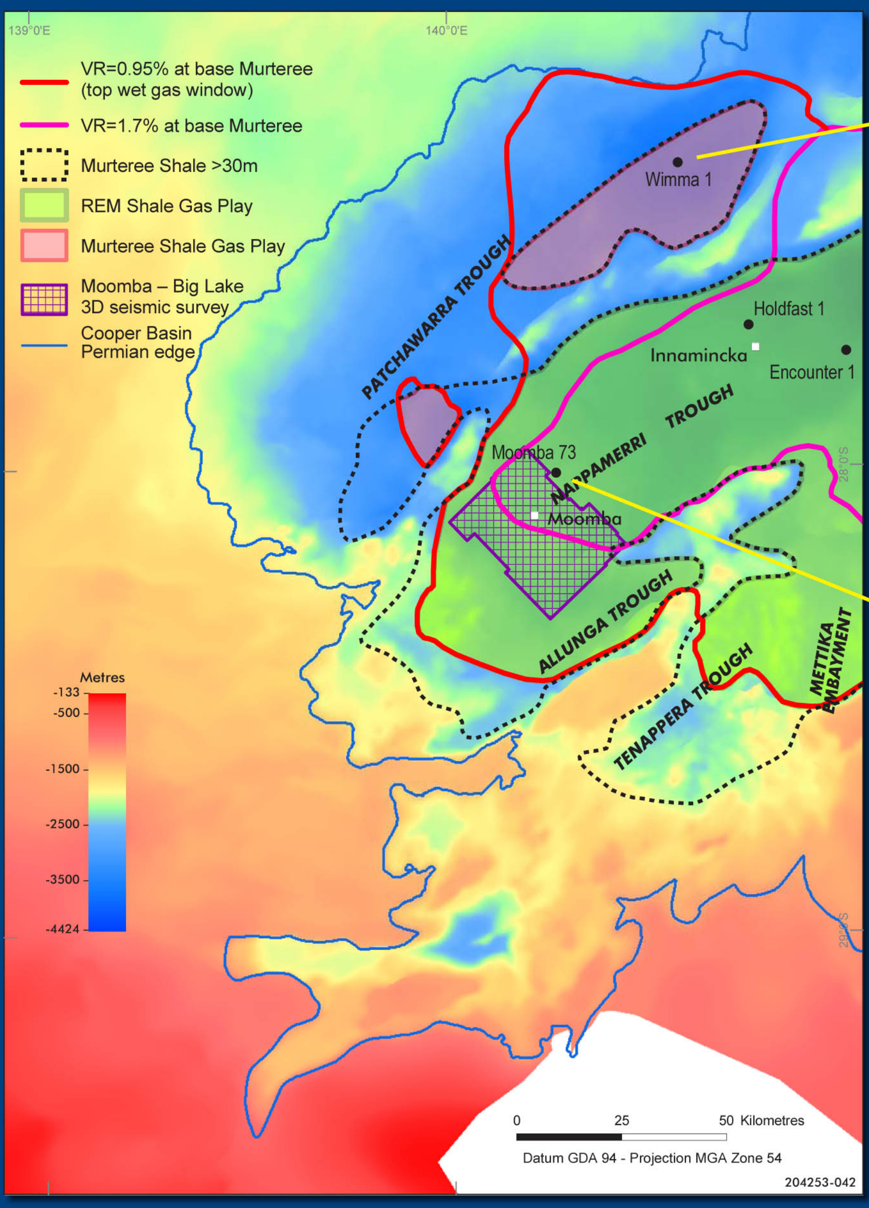

Figure 5 Basement (Z horizon) depth structure map showing shale gas play fairways in the Cooper Basin, South Australia.

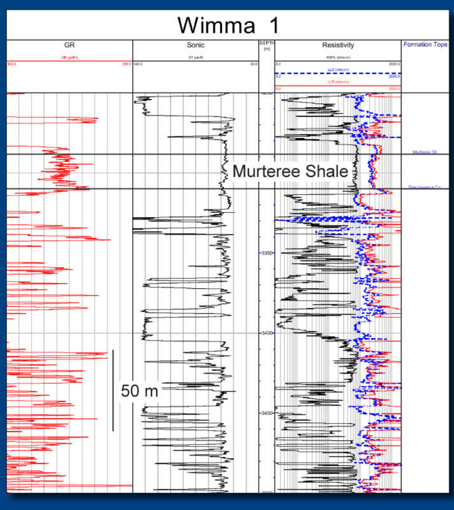

Figure 7 Wireline logs through the Murteree Shale, Wimma 1, Patchawarra Trough. The Roseneath Shale is absent over most of the Patchawarra Trough.

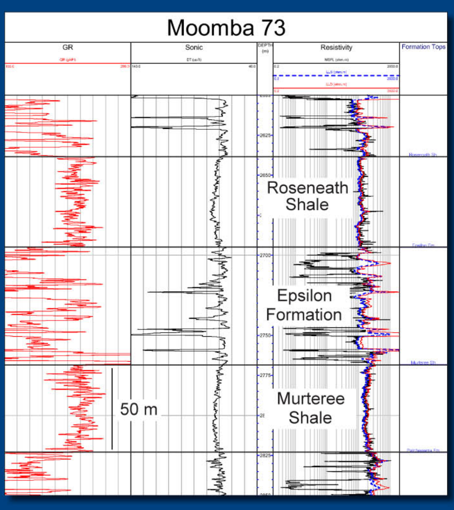

Figure 6 Wireline logs through the REM (Roseneath-Epsilon-Murteree) package, Moomba 73.

The Early Permian Roseneath and Murteree shales are the primary shale gas exploration focus in the Cooper Basin. Figure 5 shows the Cooper Basin shale gas play fairways defined by the Murteree Shale exceeding 30 m thickness, with a minimum maturity at the base of the Murteree Shale of 0.95 Ro (top of the wet gas window). The shales are actually almost exclusively siltstones that were deposited in a large freshwater lake, with occasional dropstones in the Murteree Shale indicating seasonal ice flows [4]. The shales are separated by fluvio-deltaic sandstones, siltstones and coals of the Epsilon Formation, representing a regression-transgression cycle (Figs 6 and 7).

The Murteree Shale is present over most of the Cooper Basin, reaching a maximum thickness of 86 m in the Nappamerri Trough. The younger Roseneath Shale is not as extensive as the Murteree Shale and is mostly restricted to the Nappamerri and Tenappera troughs, reaching a maximum thickness of 105 m in the Tenappera Trough [5]. Large ridges that separate the troughs typically have no Roseneath-Epsilon-Murteree (REM) package as the result of a combination of onlap of palaeohighs and erosion during periods of contraction and uplift.

Rock Eval analyses of samples from the Roseneath Shale indicate that the shale is dominated by Type III, humic-rich gas prone kerogen with some Type II algal rich kerogen present that is capable of generating liquids (Fig. 10). TOC values range 0.84 to 10.3% and average 3.76% (18 wells, 50 samples). Rock Eval analyses of samples from the Murteree Shale indicate that the shale is dominated by Type III, humic-rich gas prone kerogen with some Type II algal rich kerogen present (Fig. 11). TOC values range 0.86 to 4.7% and average 2.4% (27 wells, 86 samples).

The Murteree Shale is mature for wet gas generation (VR >0.95%) in only the deepest part of the Patchawarra Trough (Fig. 5). However the Nappamerri Trough is underlain by high heat producing granites [6] resulting in an elevated geothermal gradient and higher organic maturity. As a result the REM package is mature for wet gas generation in the northern Tenappera Trough, Mettika Embayment and the south-western margin of the Nappamerri Trough, and is mature for dry gas generation (VR >1.7%) in the Nappamerri Trough.

Seismic data in the core Nappamerri Trough area is variable with reasonable 2D seismic grid coverage in some parts and very little seismic data in other parts. However seismic coverage over the Moomba high on the south-western margin of the Nappamerri Trough is very good and this area was selected in 2010 as the starting point of a fault and fracture systems study for application to unconventional gas plays in the Basin. Seismic attribute analysis of the Moomba – Big Lake 3D seismic cube identified an orthogonal natural fracture system oriented N-S and E-W [7] (Fig. 12).

Beach has stated that gas desorption results from the shales cored in the Holdfast 1 (2011) and Encounter 1 (2010) wells indicate almost 100 tcf of shale gas in place in PEL 218 (Figs 8 and 9). Other explorers targeting shale gas in the Cooper Basin reported encouraging results from shale core analyses in 2011. Senex stated that the coals and shales cored in the 2011 Vintage Crop 1 conventional oil discovery well are gas charged, the gas is liquids rich, and mineralogy is favourable for fracture stimulation. Santos stated that results from the Moomba 185 shale core analyses are commensurate with US producing shale gas basins.

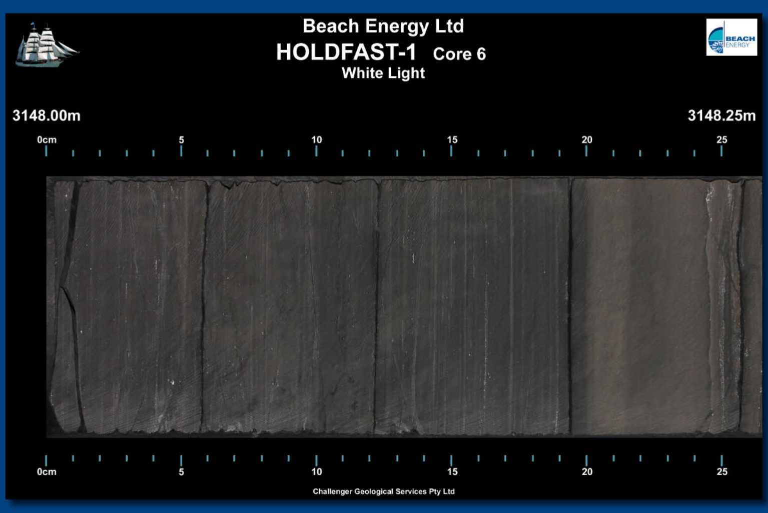

Figure 8 Roseneath Shale core from Holdfast 1, Nappamerri Trough (photo kindly provided by Beach Energy Limited).

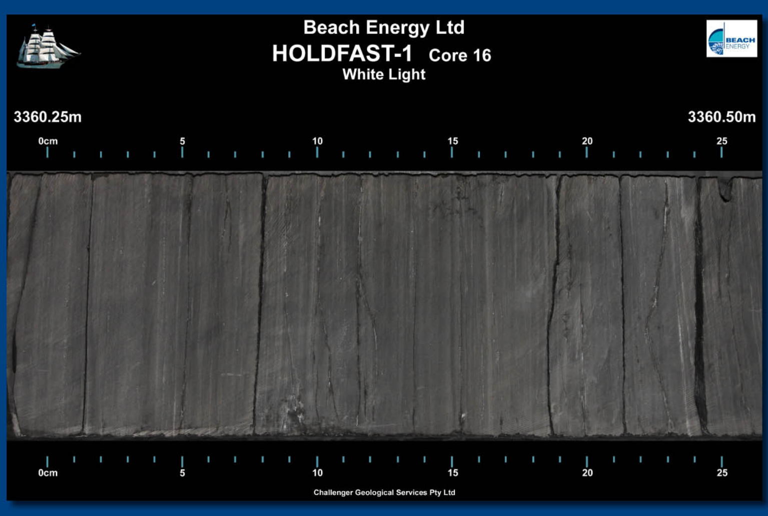

Figure 9 Murteree Shale core from Holdfast 1, Nappamerri Trough (photo kindly provided by Beach Energy Limited).

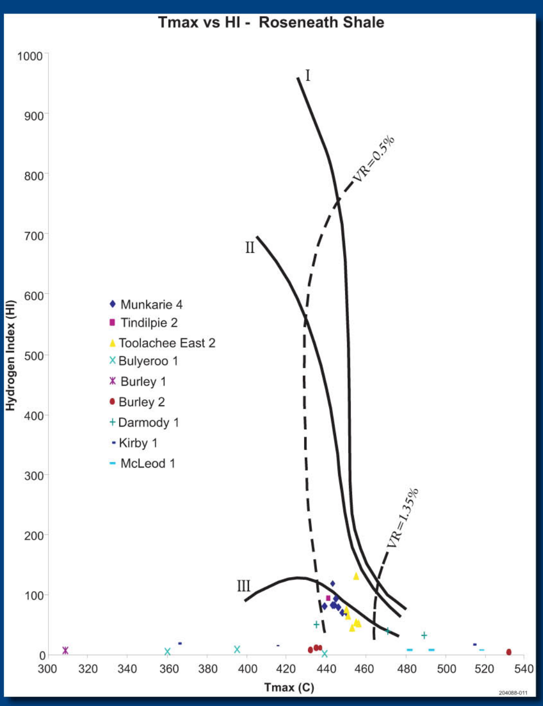

Figure 10 Rock Eval analyses of samples from the Roseneath Shale.

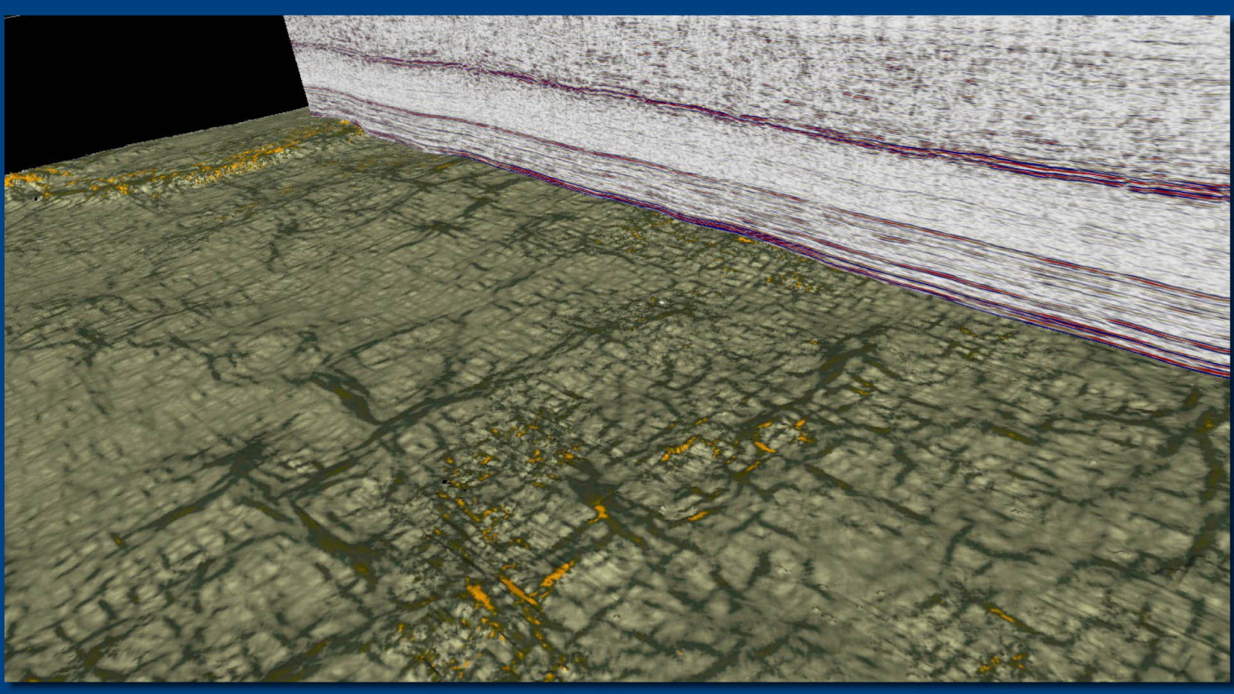

Figure 12 Most positive curvature on Roseneath Shale horizon, Moomba-Big Lake 3D seismic cube (mapping and attribute analysis by Hani Abul Khair, supervisor Guillaume Backé) showing features interpreted as an orthogonal set of natural fractures oriented N-S and E-W (3D seismic survey location shown on Figure 5).

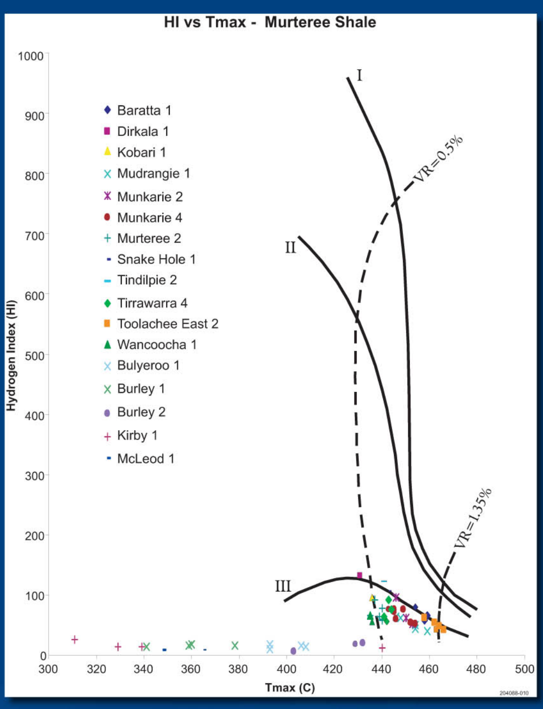

Figure 11 Rock Eval analyses of samples from the Murteree Shale.

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Emerging continuous gas plays in the Cooper Basin, South Australia: Tight gas play

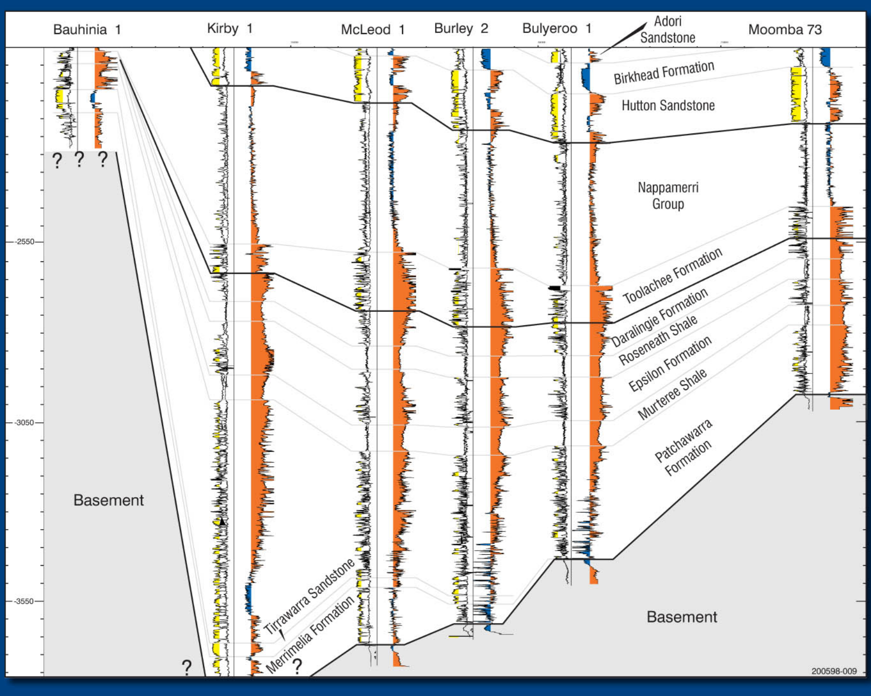

Figure 13 Regional log correlation through the Nappamerri Trough. Resistivity logs are illustrated with shading to a 20 Ωm cut-off on the laterolog deep or equivalent (red >20 Ωm, blue <20 Ωm). Note thick sections with high resistivities that appear to be entirely gas saturated. Left track shows gamma ray and sonic logs, gamma ray shaded yellow <80 API (sands) and sonic shaded black >90 ms/ft (coals). Vertical scale exaggerated relative to horizontal scale (from Hillis et al, 2001). See Figure 17 for well locations.

The presence of a basin-centred gas accumulation (BCGA) in the Nappamerri Trough, Cooper Basin has been suspected for over two decades. Resistivity of the Permian succession exceeds 20 Ωm over large intervals (Fig. 13), tests have recovered gas with no water, and gas is located within overpressured compartments indicative of hydraulic isolation (Fig. 16) [8]. The Permian succession in the Nappamerri Trough easily exceeds 1000 m in the deeper parts (Fig. 17), comprising very thermally mature, gas-prone source rocks with interbedded sands, ideal for the creation of a BCGA.

The Early Permian succession in the Patchawarra Trough also has the necessary elements for a BCGA – gas-prone coal beds, sufficient maturity for thermal gas generation, low porosity and permeability reservoirs interbedded with the source rocks and gas shows [9]. At Wimma 1, in the deepest, most mature part of the Patchawarra Trough, overpressured gas sandstones with poor reservoir properties were encountered in the Early Permian succession (Fig. 17).

Thick coals and organic rich shales in the Early Permian succession are capable of generating enormous hydrocarbon volumes. The total gas generative potential of the Cooper Basin source rocks has been estimated to be between 4027 tcf (minimum estimate) to 8055 tcf (maximum estimate) [10]. Coal and carbonaceous shale of the Patchawarra Formation represent the principal source rocks of the Cooper Basin, both in source richness and quality, and overall thickness [11]. Rock-Eval data (Fig. 14) indicates that Patchawarra Formation source rocks contain a mix of both Type II and Type III kerogen. Toolachee Formation coal and carbonaceous shale represent the second most important source rock unit of the Cooper Basin in terms of richness, quality and thickness. Rock-Eval data (Fig. 15) indicates that Toolachee Formation source rocks also contain a mix of both Type II and Type III kerogen.

The interpreted BCGA in the Nappamerri Trough is considered analogous to the regionally extensive tight-gas accumulation in the Mesaverde Group of the Piceance Basin (Fig. 18). The Piceance Basin accumulation is the product of several important geological circumstances [12]:

- Large volumes of gas were generated from thick Mesaverde coals as they achieved high thermal maturity.
- Gas migration was inhibited by the very low permeability and discontinuous nature of the fluvial sandstone reservoirs.
- The gas generated rate exceeded the rate at which gas could escape, resulting in overpressure.
- Eventually, the pressure of the gas phase in the pore system exceeded the capillary pressure of the water-wet pores, and water was expelled from the pore system, resulting in the development of an overpressured, gas-saturated reservoir with little movable water. Gas generation has been negligible since ~25 Ma [13], but overpressure has been retained.

Early Permian Patchawarra Formation sands in the Nappamerri Trough are similarly discontinuous fluvial sands (Fig. 19), interbedded with highly mature carbonaceous shale and coal source rocks. Thick siltstones of the Nappamerri Group may have been a regional top seal for the pervasive gas accumulation. Generation and expulsion of hydrocarbons from the Cooper Basin source rocks occurred in the mid Cretaceous [14], but overpressure has been retained in the Nappamerri Trough (Fig. 16).

Beach has stated that the Encounter and Holdfast wells confirm the presence of gas in sands outside of structural closure in the Nappamerri Trough and estimate that gas in place potentially exceeds 200 tcf in sands across PEL 218.

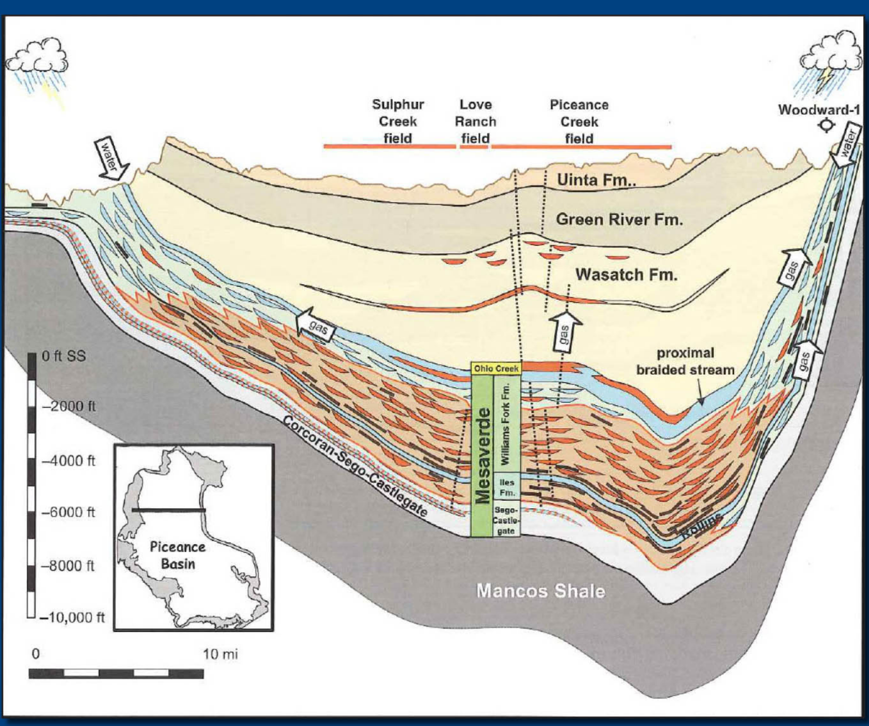

Figure 18 Regional east-west cross section through the northern Piceance Basin depicting the regional distribution of gas and water within the Mesaverde (from Yurewicz et al, 2008. AAPG © 2008. Reprinted by permission of the AAPG whose permission is required for further use).

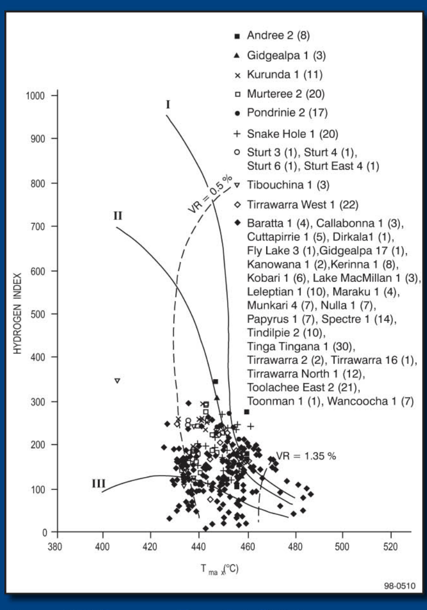

Figure 14 HI versus T_{max} plot, Patchawarra Formation.

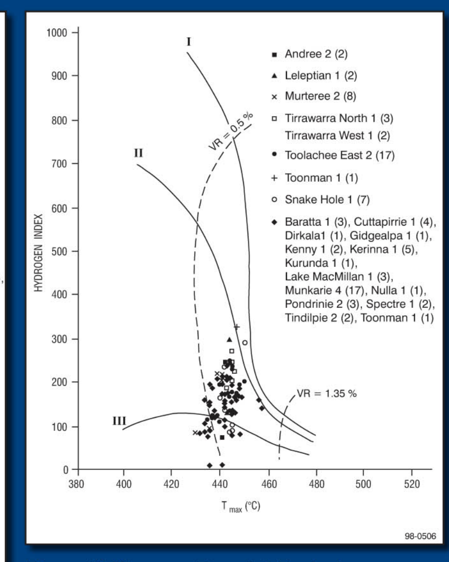

Figure 15 HI versus T_{max} plot, Toolachee Formation.

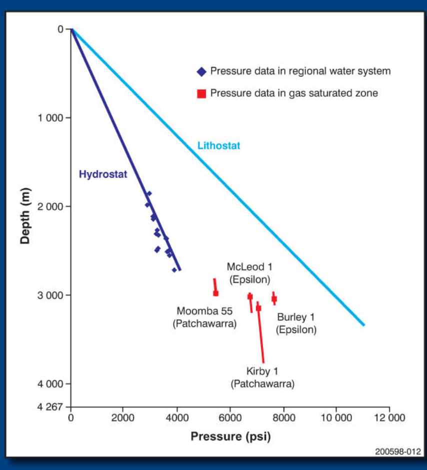

Figure 16 Pressure plot for gas columns in the Nappamerri Trough. Plots are anchored on one reliable DST-derived pressure (squares) with an assumed gas gradient extrapolated for thickness of the unit in which the test was undertaken. The gas columns exist in separate, overpressured cells within an overall overpressured system. A normally pressured free water level for these columns would be located in basement to the Nappamerri Trough (from Hillis et al, 2001).

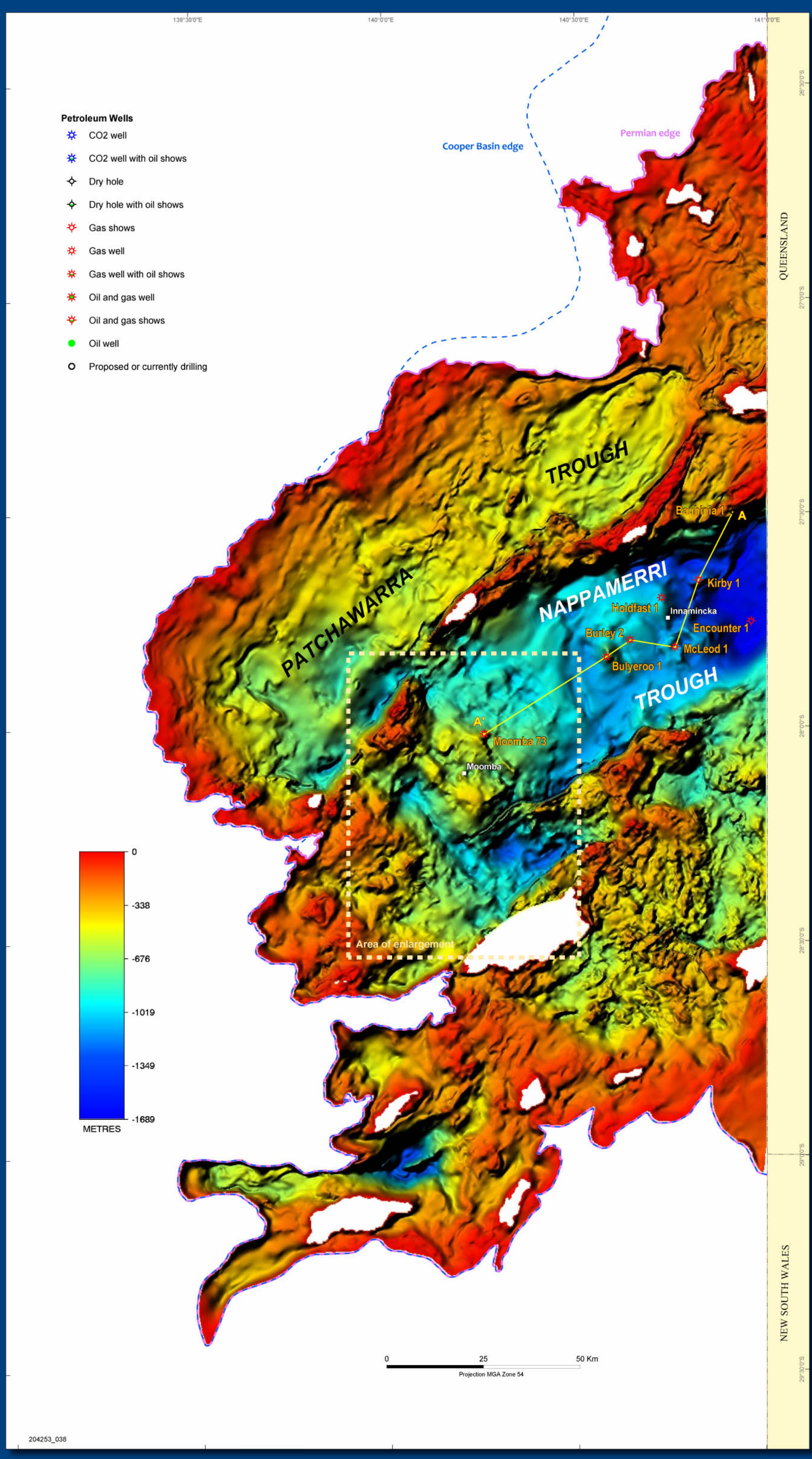

Figure 17 Top Permian (P) –Basement (Z) isopach map.

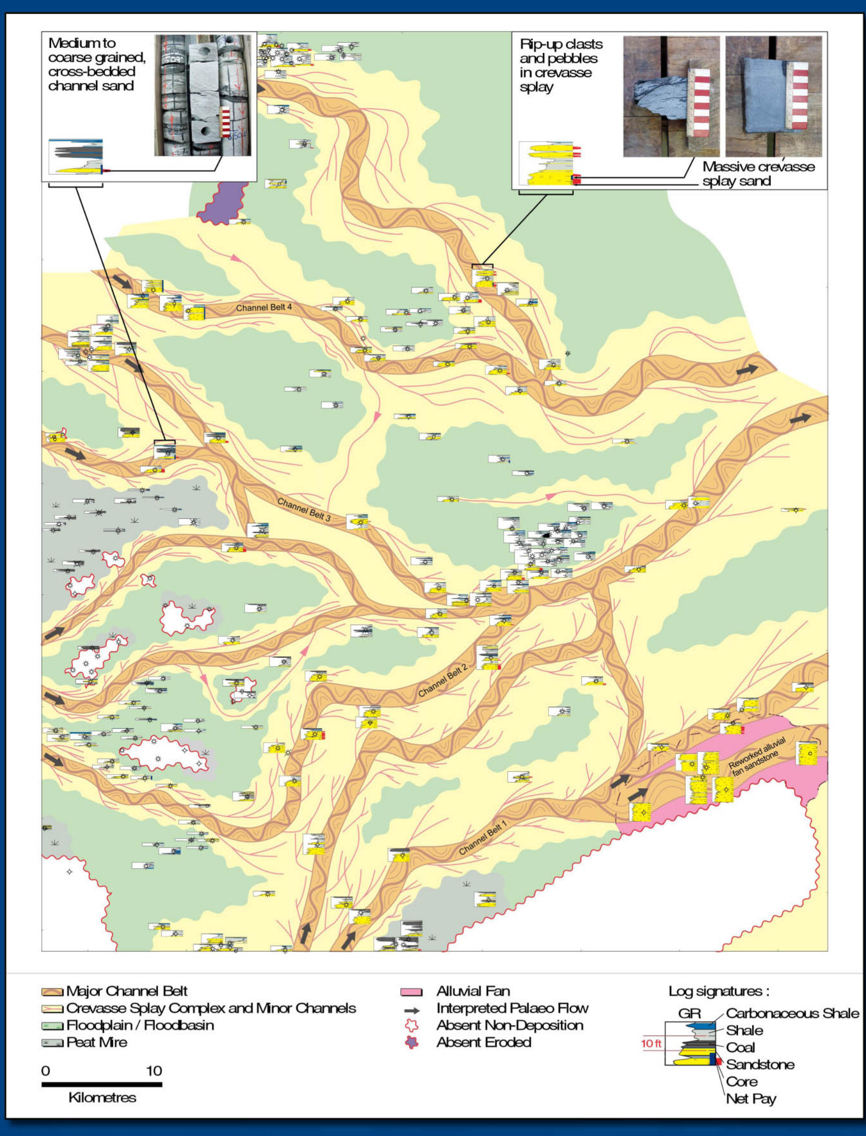

Figure 19 Palaeogeography for the VL32 to VU34 interval, Patchawarra Formation (from Strong et al, 2002). See Figure 17 for map location.

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Emerging continuous gas plays in the Cooper Basin, South Australia: Coal seam gas play

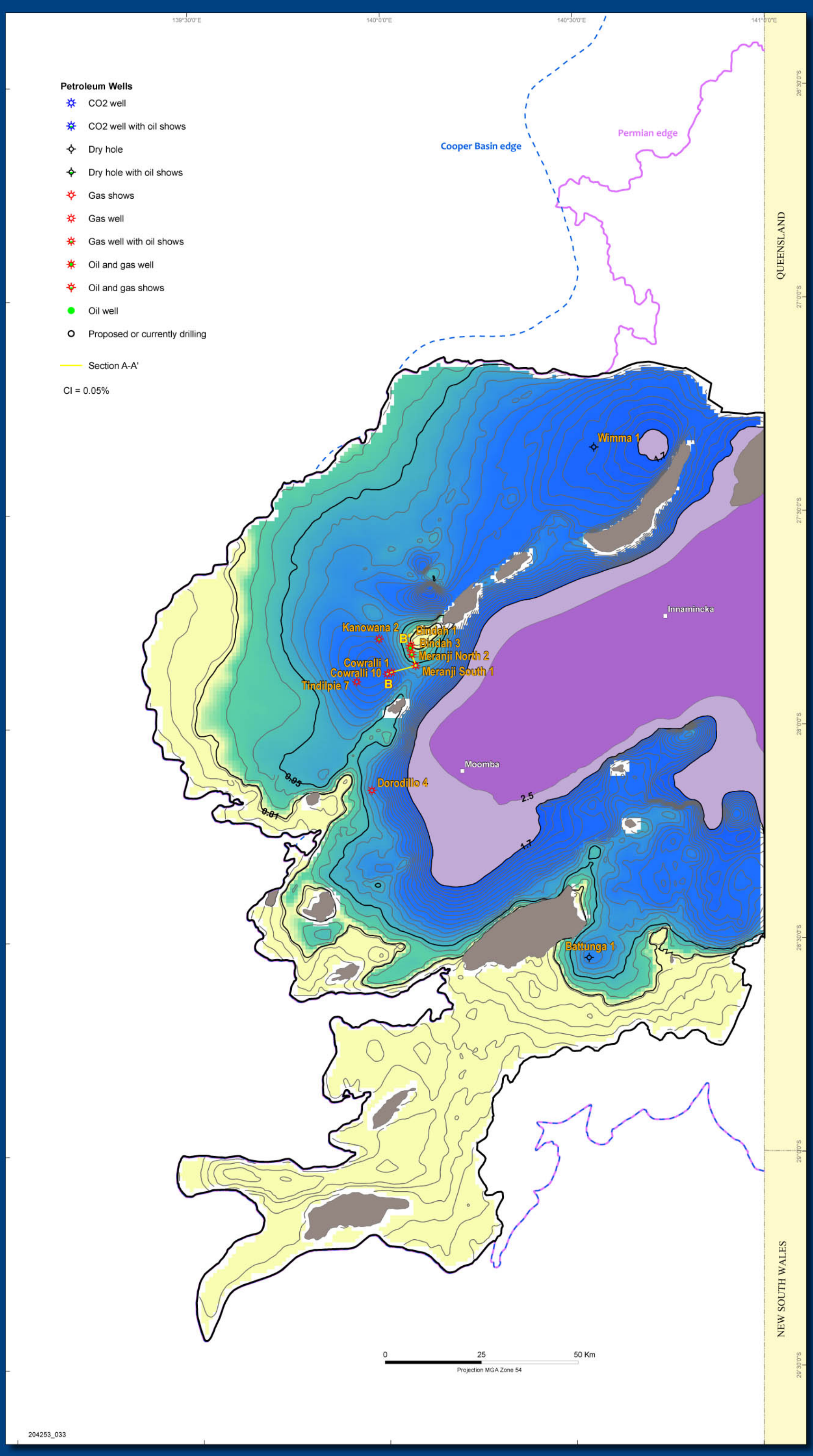

Figure 20 Vitrinite reflectance contours for the base Patchawarra Formation (NGMA Cooper Eromanga Project) indicate that coals in the Patchawarra Formation are sufficiently mature for thermogenic gas generation over much of the basin.

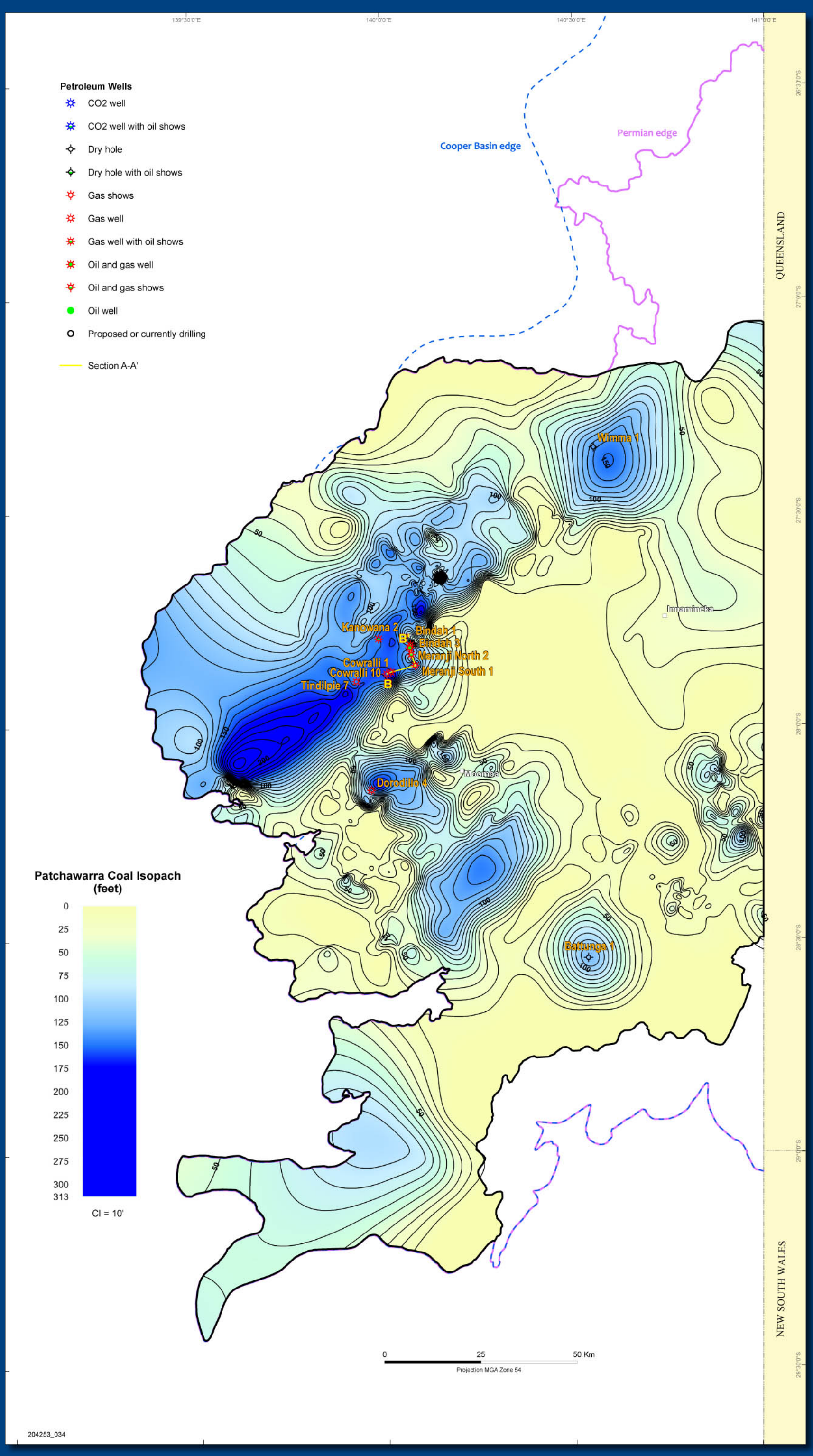

Figure 21 Total coal thickness map for the Patchawarra Formation.

The Permian Gidgealpa Group is characterised by coal measures, especially in the Patchawarra, Epsilon and Toolachee formations. Thick, laterally extensive coal seams have been intersected in both the Early Permian Patchawarra Formation and the Late Permian Toolachee Formation.

The Patchawarra Formation was deposited in a coal-dominated fluvial/lacustrine depositional environment, with fluvial channel and point bar sandstones the principal conventional reservoirs, characterised by relatively low porosity and permeability [16]. A robust sub-formational chronostratigraphic framework developed by geoscientists at Santos identifies key surfaces constrained by high resolution palynology. These key surfaces are either widespread lacustrine flooding events represented by high gamma ray shales, or climatically or tectonically controlled periods of clastic shutdown represented by regionally extensive coal seams (Fig. 22).

The VC50 chronostratigraphic unit corresponds to the thickest laterally extensive coal seam in the Patchawarra Formation [16], and to the Vc seismic horizon [17]. Comparison of the Patchawarra Formation isopach map and the Patchawarra Formation total coal isopach map show there is some correlation between total Patchawarra Formation thickness, cumulative Patchawarra coal thickness, and the presence of a thick VC50 coal seam (Figs 21 and 23). Examples of a thick VC50 coal seam, ranging 13 to 23 m, are given in Table 1.

Assessment of the deep coal seam gas potential of the basin commenced with desorption analysis of a 4 m Patchawarra coal seam cored in the Dorodillo 2 gas appraisal well in1998. Further assessment of deep coal seam gas was suspended until 2007, when Santos flowed gas to surface at 100 000 scf/day from a fracced Patchawarra Formation coal in the Moomba 77 gas development well. Since then additional deep coal seam gas assessment work, including coring the VC50 coal seam for analysis, has been carried out in several gas development wells. Gas desorption analysis of the VC50 coal seam cored in Bindah 3 returned excellent total raw gas results averaging 21.2 scc/g (680 scf/ton) over 10 metres [18]. Whilst the CO_2 content of the desorbed gas was high, CO_2 contents around the Basin are highly variable and lower CO_2 contents are expected in other parts of the Basin.

The base Patchawarra Formation maturity map shows that the Patchawarra Formation is sufficiently mature for the generation of gas from coal seams over much of the basin (Fig. 20). High mud gas readings are generally recorded when mature Patchawarra Formation coals are intersected in wells (Table 1).

Well name	VC50 coal seam thickness (m)	Total gas (units)
Bindah 3	19	80–500
Meranji South 1	16	1000
Cowralli 1	18	1000–2000
Cowralli 10	16	2065–3550
Kanowana 2	18	600–900
Tindilpie 7	16	1000
Dorodillo 4	13	100–1000
Battunga 1	23	1835
Wimma 1	14	2800

Table 1 VC50 coal seam thickness and mud gas recorded whilst drilling for selected wells.

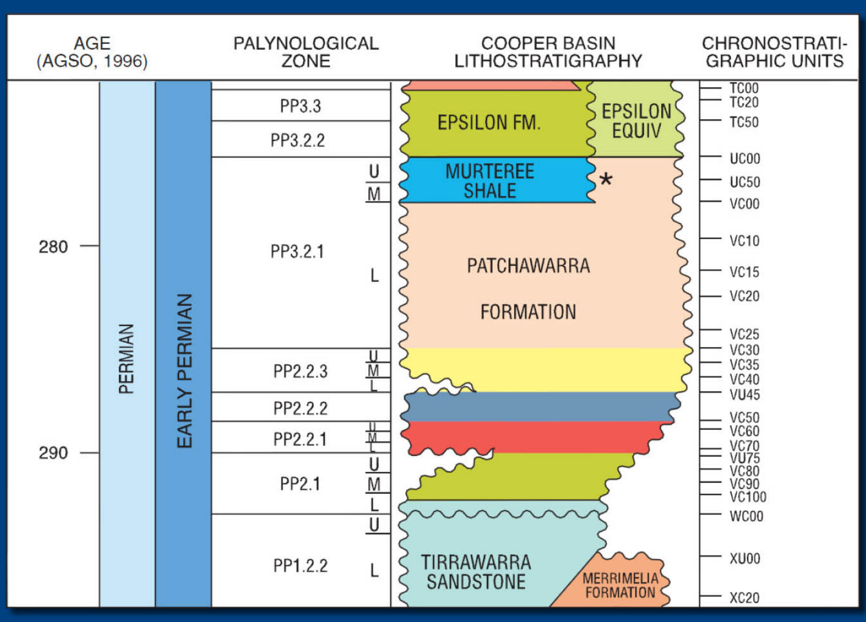

Figure 22 Permian chronostratigraphic framework developed by Strong et al (2002).

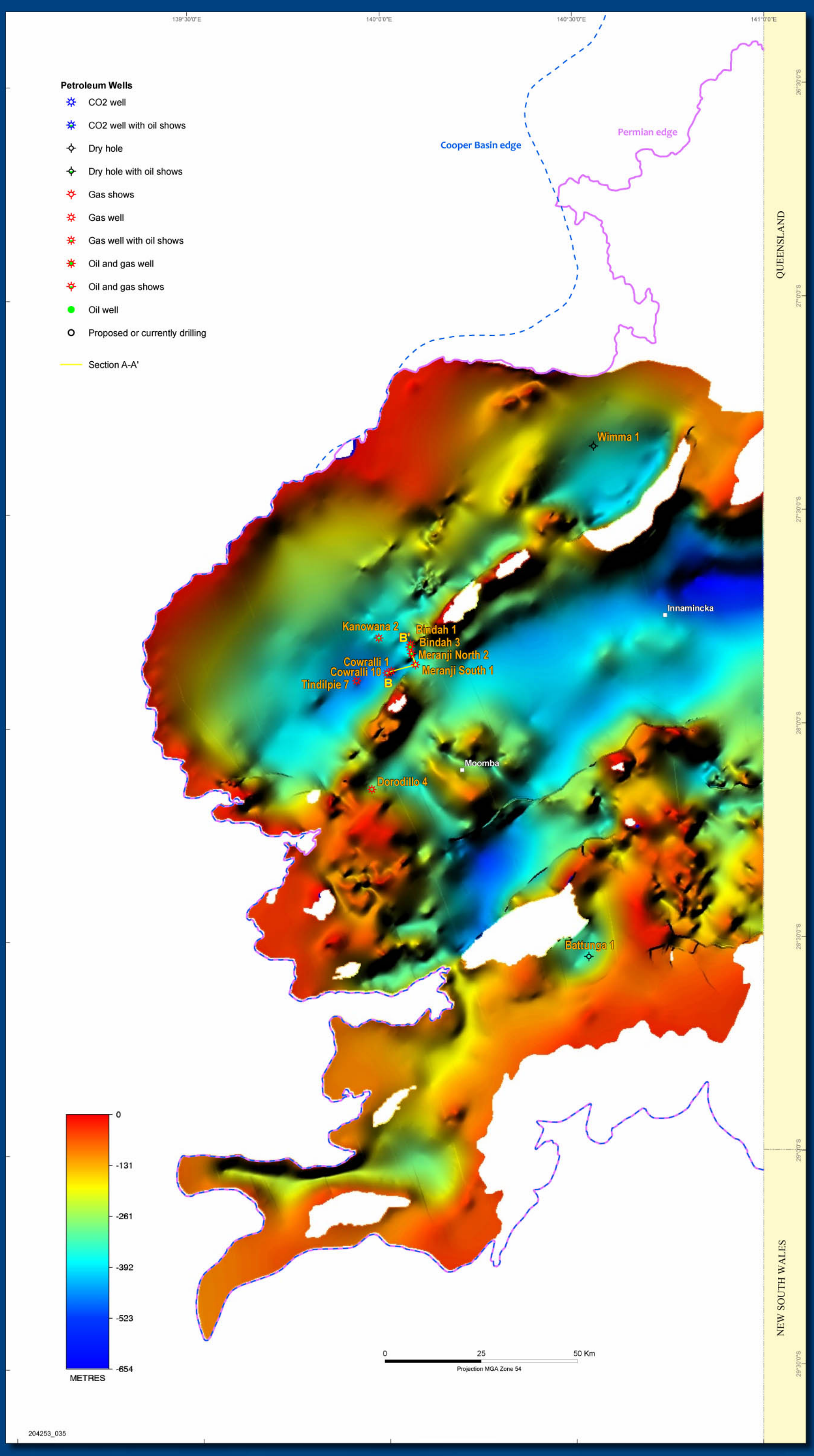

Figure 23 Patchawarra Formation isopach with selected wells that intersect the VC50 coal seam.

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[16] Strong, P.C., Wood, G.R., Lang, S.C., Jollands, A., Karalaus, E., and Kassan, J., 2002. *High resolution palaeogeographic mapping of the fluvial-lacustrine Patchawarra Formation in the Cooper Basin, South Australia.* APPEA Journal 42(1), 65-81.

[17] Alexander, E.M., Gravestock, D.I., Cubitt, C. and Chaney, A., 1998. *Lithostratigraphy and Environments of Deposition.* In: Gravestock, D.I., Hibburt, J.E. and Drexel, J.F. (eds) The *Petroleum Geology of South Australia, Volume 4: Cooper Basin.* South Australian Department of Primary Industries and Resources. Report Book 203-09.

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Emerging continuous gas plays in the Cooper Basin, South Australia: Coal seam gas play

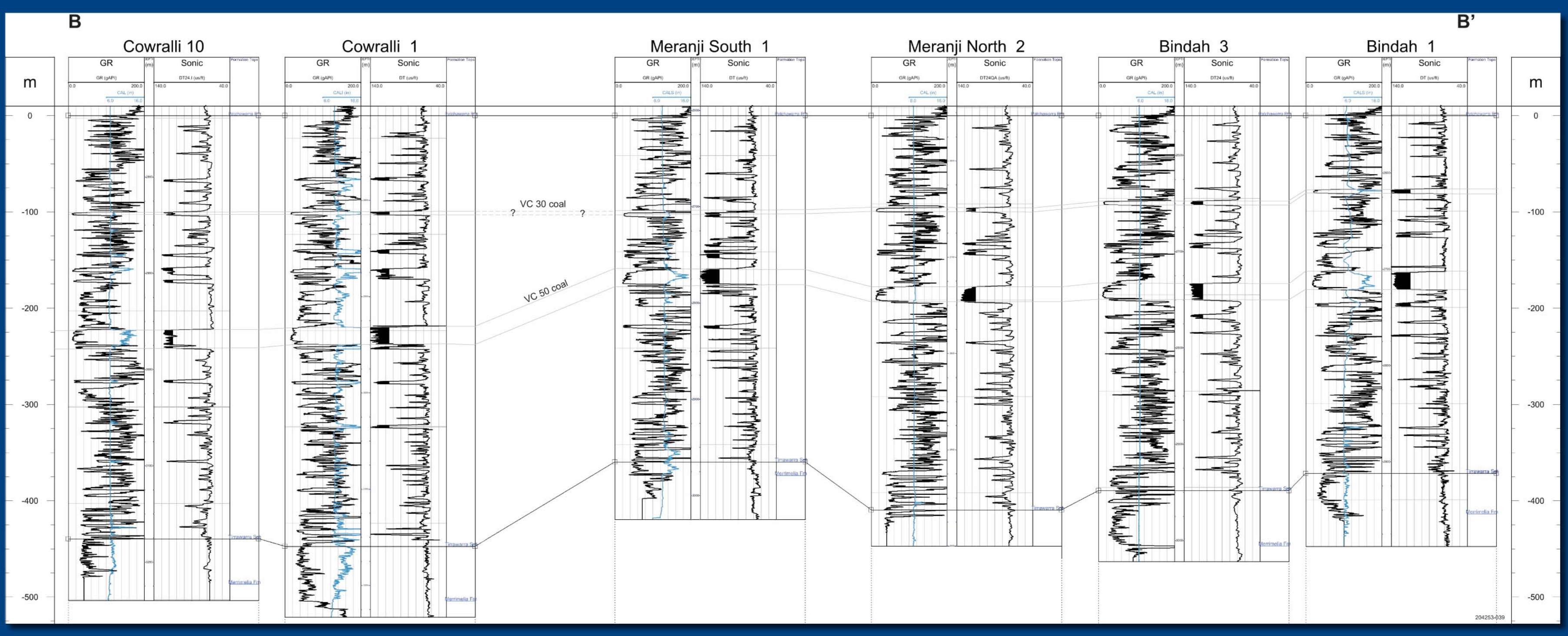

Figure 24 Wireline log correlation B-B' for the Patchawarra Formation highlighting the lateral continuity of the VC50 coal seam over 8 km at this location (sonic >115 microsecs/ft shaded black to highlight coals). See Figure 23 for well locations.

The Patchawarra coal seams are deeper than 2000 m over most of the Cooper Basin. 2000 m is generally considered the floor for CSG production due to cleat closure and permeability reduction at these depths. However scanning electron microscopy of VC50 coal core samples from Bindah 3 has shown that the coals contain significant microporosity, most of which is accounted for by variably preserved cell lumen along telinite and semifusinite bands [19] (Figs 25 and 26). The VC50 coal is thick and laterally continuous (Fig. 24) in parts of the Basin and may be suited to gas extraction using horizontal drilling and hydraulic stimulation techniques. Targeting natural fracture systems is likely to enhance production rates and optimise drainage. The coals are expected to be gas saturated, so de-watering would not be necessary. However the higher pressures at these depths means that free gas will be produced, but little adsorbed gas is likely to be accessed.

Thick, laterally extensive coal seams are also characteristic of the Late Permian Toolachee Formation (Figs 27 and 29). The Toolachee coals are sufficiently mature for thermogenic gas generation in the Nappamerri and Arrabury troughs, and parts of the Patchawarra Trough (Fig. 28), and high mud gas readings have been recorded whilst drilling through mature Toolachee coals (e.g. Paning 1).

Several operators are currently targeting the Patchawarra and Toolachee coals for CSG and a number of coal cores are expected to be acquired in 2012 drilling programs.

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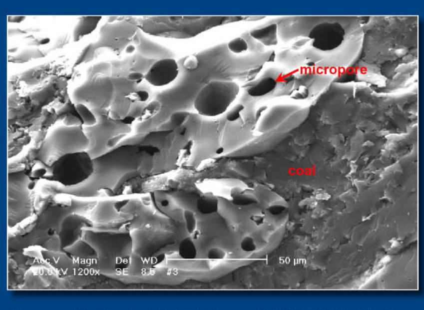

Figure 25 Bindah 3 VC50 coal (8971' 5"), SEM micrograph showing microporosity (from Weatherford Laboratories petrology report in Bindah 3 Well Completion Report).

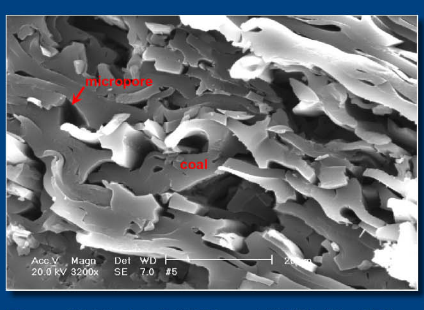

Figure 26 Bindah 3 VC50 coal (8977' 5"), SEM micrograph showing microporosity (from Weatherford Laboratories petrology report in Bindah 3 Well Completion Report).

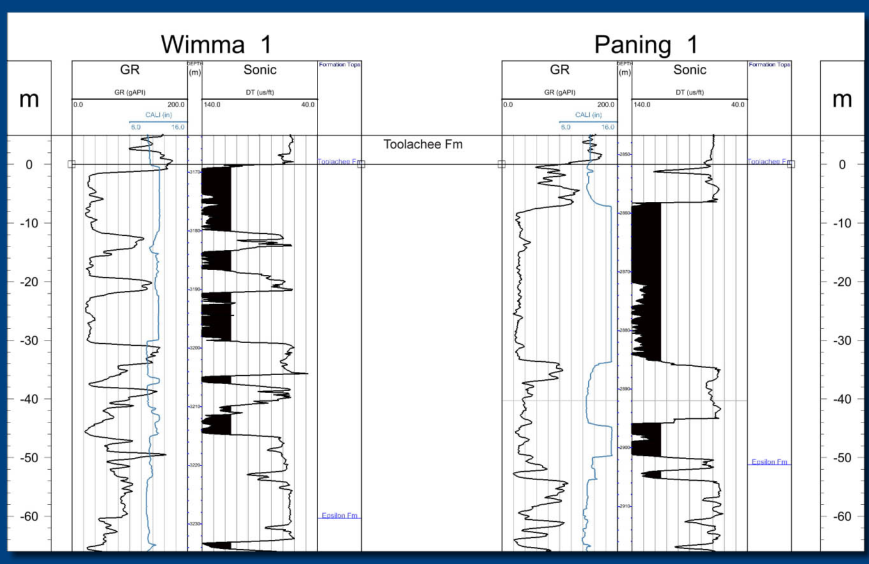

Figure 27 Wireline logs through the Toolachee Formation highlighting the thick coal seam(s) present at the Wimma 1 and Paning 1 well locations (sonic >115 microsecs/ft shaded black to highlight coals). See Figure 29 for well locations.

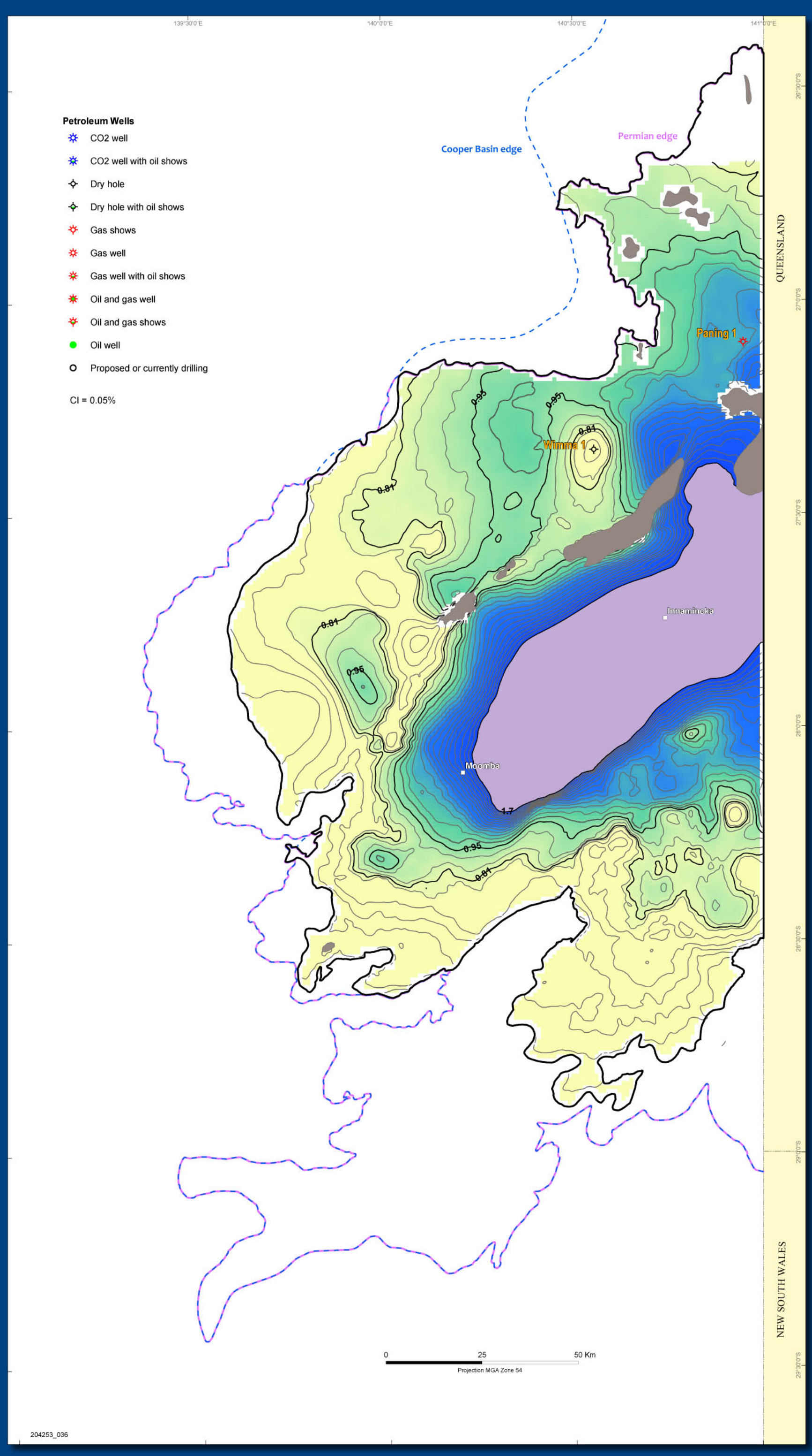

Figure 28 Vitrinite reflectance contours for the top Toolachee Formation (NGMA Cooper Eromanga Project) indicate that coals in the Toolachee Formation are sufficiently mature for thermogenic gas generation in the Nappamerri Trough, and parts of the Patchawarra and Arrabury troughs.

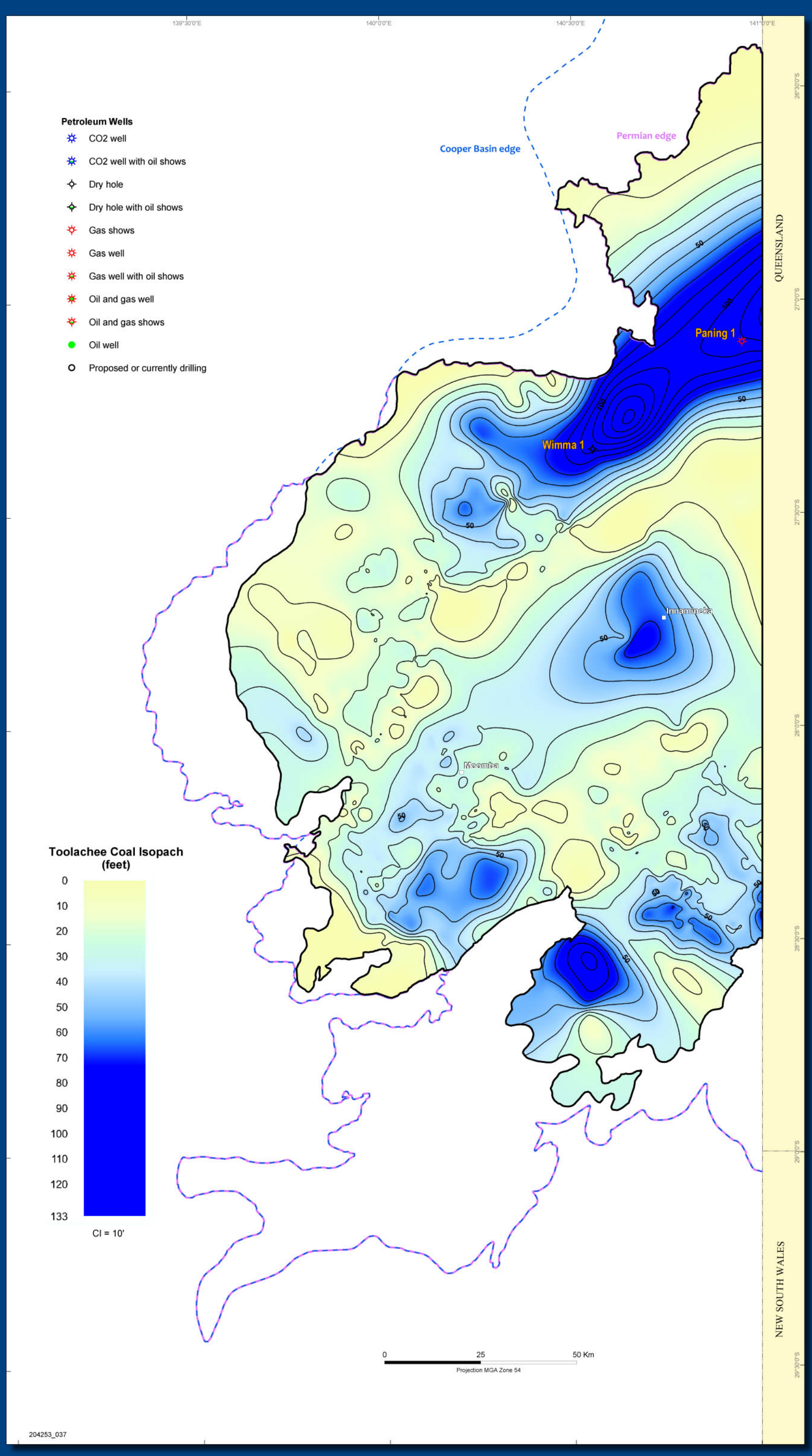

Figure 29 Total coal thickness map for the Toolachee Formation.