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Source Rocks of the Cooper Basin

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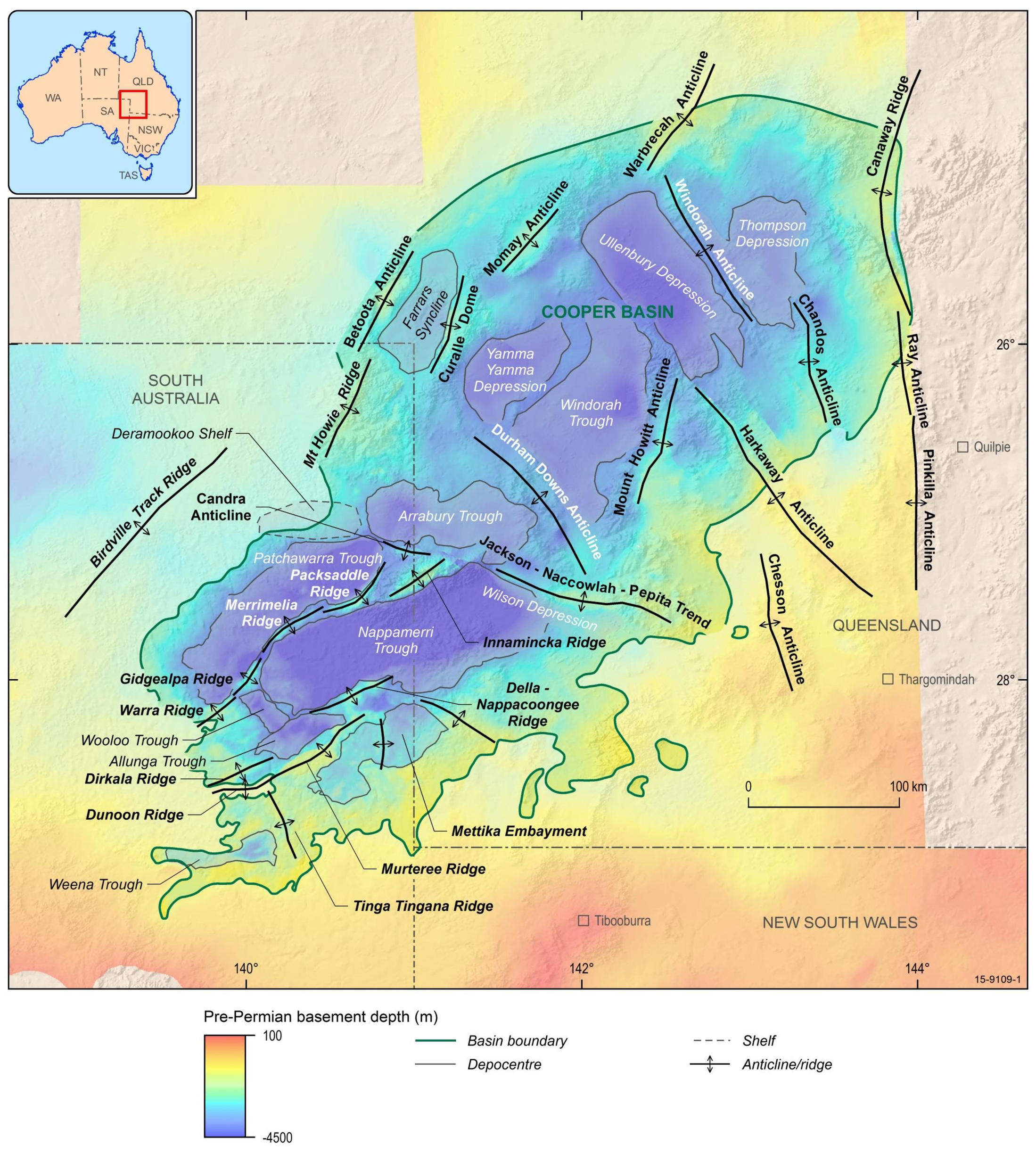

Figure 1: Structural elements of the Cooper Basin overlain on a structure contour map of the top pre-Permian basement surface. The outline of the Cooper Basin is from Stewart et al. (2013).

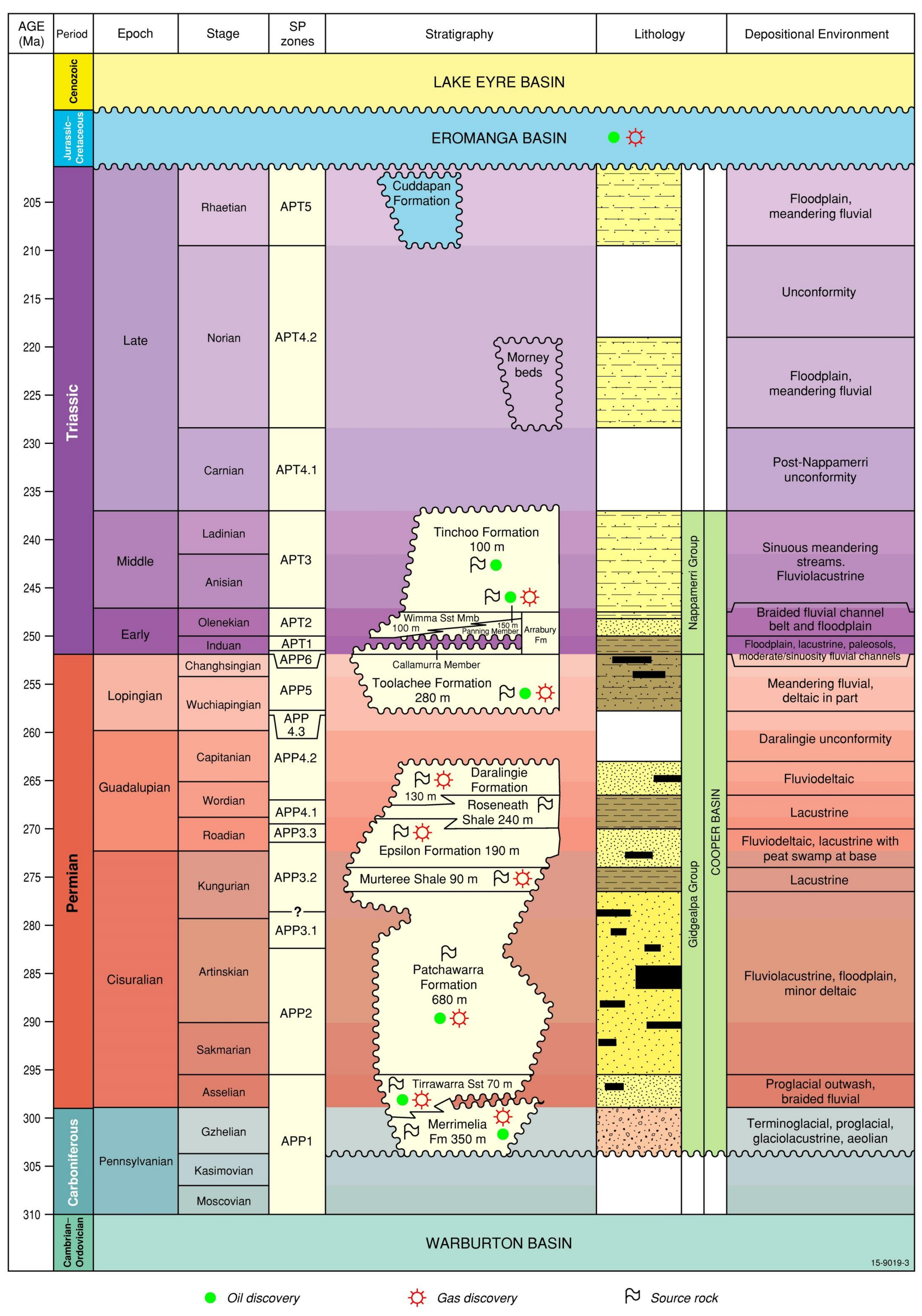

Figure 2: Stratigraphy of the Cooper Basin showing the locations of key source rocks and hydrocarbon shows in the basin (from Carr et al., 2015 and Hall et al., in prep). Stratigraphic ages have been updated for this study to ensure consistency with the 2012 Geological Time Scale (Gradstein et al., 2012) and to include new spore pollen age calibration work (e.g. Nicoll et al., 2015).

Period		Formation	Source	Reservoir	Seal
EROMANGA BASIN					
CRETACEOUS		Winton Formation	lignite		
		Mackunda Formation			
		Allaru Mudstone			
		Toolebuc Formation	Oil shale		
		Wallumbilla Formation			
		Cadna-owie Formation			
JURASSIC TO CRETACEOUS		Hooray Sandstone/upper			
		Namur Sandstone /Murta Formation			
JURASSIC		Westbourne Formation			
		Adori Sandstone			
		Birkhead Formation			
		Hutton Sandstone			
		Poolowanna Formation			
LATE TRIASSIC		Cuddapan Formation			
COOPER BASIN					
EARLY-MIDDLE TRIASSIC		Tinchoo Formation			
		Arrabury Formation			
PERMIAN	Lopingian	Toolachee Formation			
	Guadalupian	Daralingie Formation			
		Roseneath Shale			
		Epsilon Formation			
	Cisuralian	Murteree Shale			
		Patchawarra Formation			
		Tirrawarra Formation			
		Merrimelia Formation			

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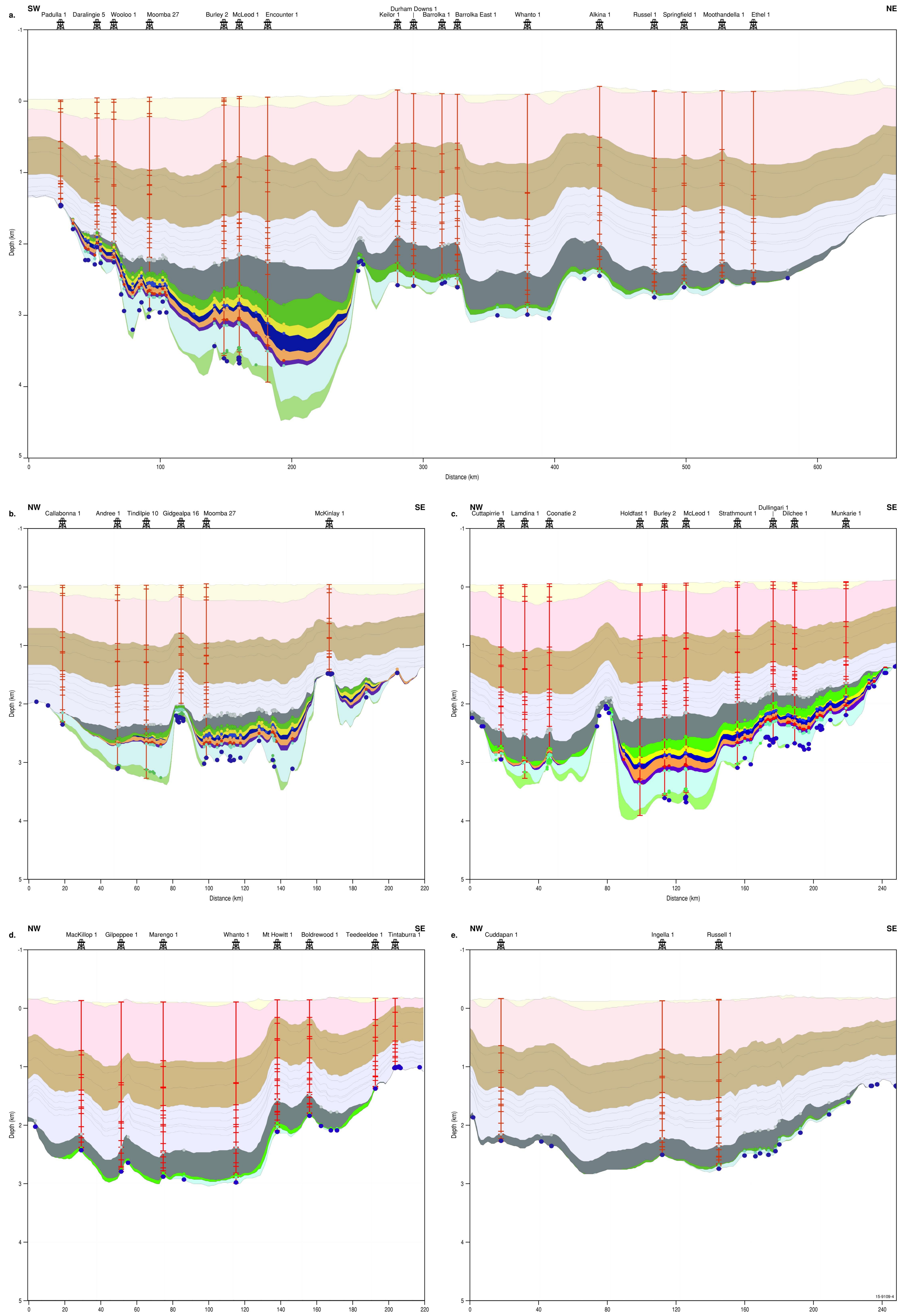
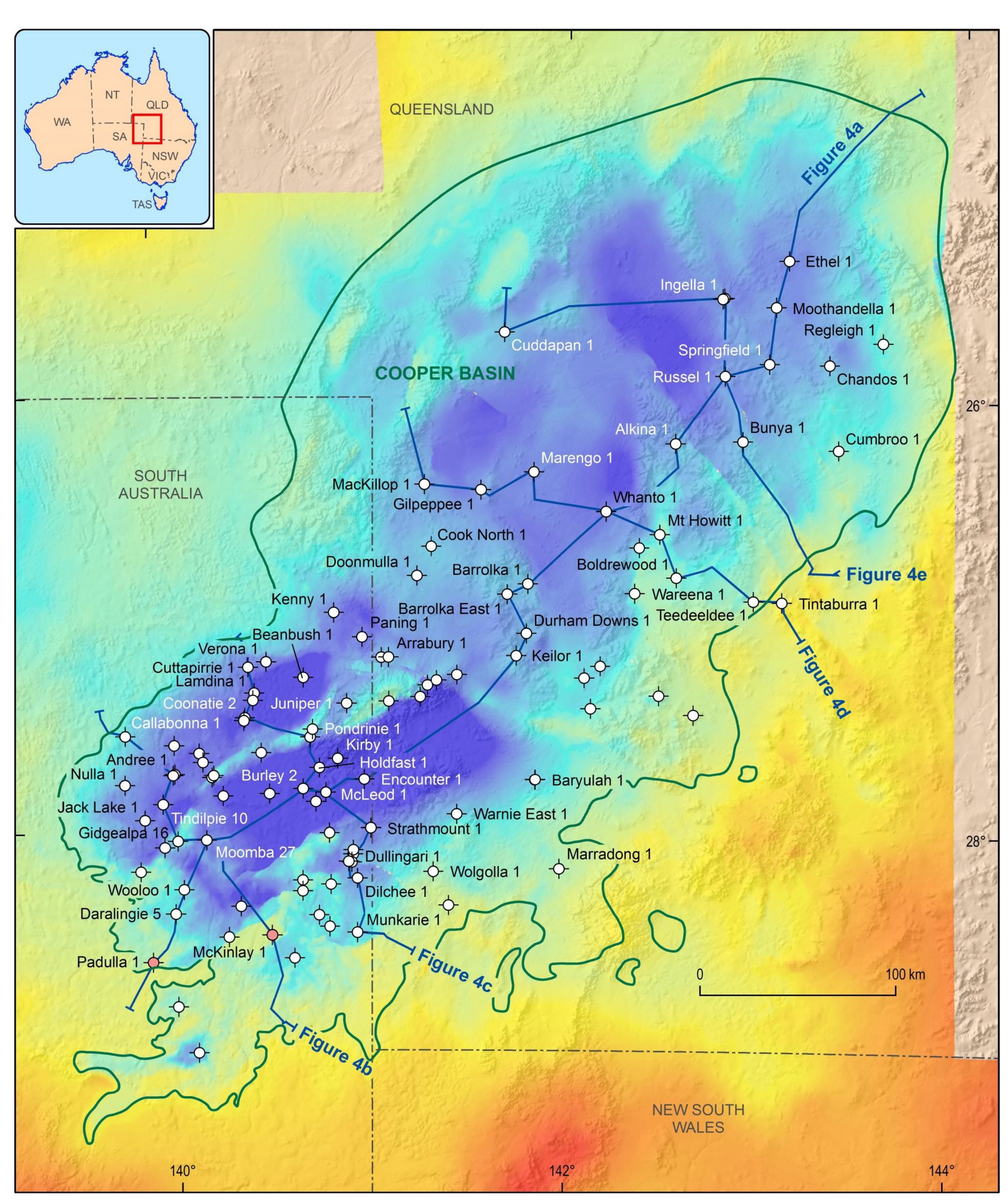
Figure 3: Stratigraphic units and presence of source, conventional reservoir and seal rocks in the Cooper and Eromanga Basins (modified from Deighton et al., 2003). The principal Permian source rocks of the basin are coals and coaly shales of the Toolachee, Daralingie, Epsilon and Patchawarra formations, along with the Roseneath and Murteree shales (Boreham and Hill, 1998).





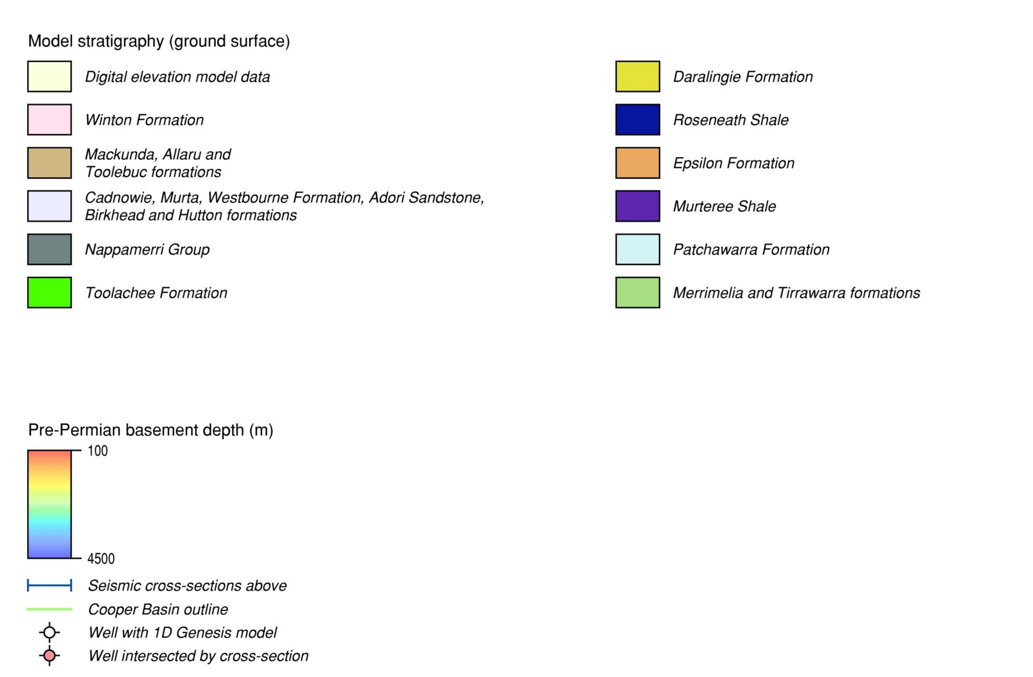


Figure 4: Regional structural cross-sections of the Cooper Basin extracted from the 3D model (from Hall et al., in prep). The regional Cooper Basin model was constructed by integrating published horizons for South Australia and Queensland (Draper, 2002; DNMR, 2015; SARIG, 2015) with new seismic and well data interpretation in selected areas. Overlying Eromanga and Lake Eyre Basin surfaces were modelled from existing seismic interpretation and well picks.

Basin Architecture

Mapping Australia’s Petroleum Source Rocks

Geoscience Australia recently commenced work on a multi-year study of Australian petroleum source rocks to improve our understanding of the petroleum resource potential of key sedimentary basins. This includes mapping source rock occurrence, thickness, quality and maturity, and the distribution and volumes of oil and gas.

The Permian source rocks of the Cooper Basin are the first to be assessed, as part of a collaborative study with the Department of State Development, South Australia and the Geological Survey of Queensland.

Cooper Basin Overview

The Cooper Basin is an upper Carboniferous—Middle Triassic intracratonic basin in northeastern South Australia and southwestern Queensland (Figure 1). The basin is Australia’s premier onshore hydrocarbon producing province and is nationally significant in providing gas to the East Coast Gas Market. The basin also hosts a range of unconventional gas play types within the Permian Gidgealpa Group, including basin-centred gas and tight gas accumulations, deep dry coal gas associated with the Patchawarra and Toolachee formations and the Murteree and Roseneath shale gas plays (e.g. Goldstein et al., 2012).

The principal source rocks for these plays are the Permian coals and coaly shales of the Gidgealpa Group (Figure 2; Figure 3). Mapping the petroleum generation potential of these source rocks, together with describing the resulting fluid composition, is critical for understanding the hydrocarbon prospectivity of the basin (Figure 4; Figure 5).

Source Rock Mapping Workflow

This study reviews the distribution, type, quality, maturity and generation potential of the Cooper Basin source rocks.

- The regional basin architecture is characterised through compilation and integration of formation tops, structural surfaces and isopach maps.
- Source rock distribution, amount and quality are reviewed through the analysis of log data and source rock geochemical data (including data acquired from new sampling), characterising source rocks across the whole basin.
- Petroleum systems modelling, incorporating new Cooper-specific kinetics, highlight the variability in burial, thermal and hydrocarbon generation histories for each source rock across the basin.

The results presented here will be released as public reports and datasets from late 2015 onwards, available from the Geoscience Australia website (www.ga.gov.au).

Petroleum systems modelling work was conducted using the Trinity-Genesis-KinEx software suite (http://www.zetaware.com).

Basin Architecture

A 3D basin model, characterising regional basin architecture, was constructed through the integration of existing horizons with formation tops and seismic interpretations (Figure 4). Isopach maps extracted from the model highlight the extent and gross thickness of each key formation containing source rocks (Figure 6).

- The Toolachee and Patchawarra formations are the thickest and most extensive formations.
- The Daralingie and Epsilon formations, along with the Roseneath and Murteree shales are restricted to the south.

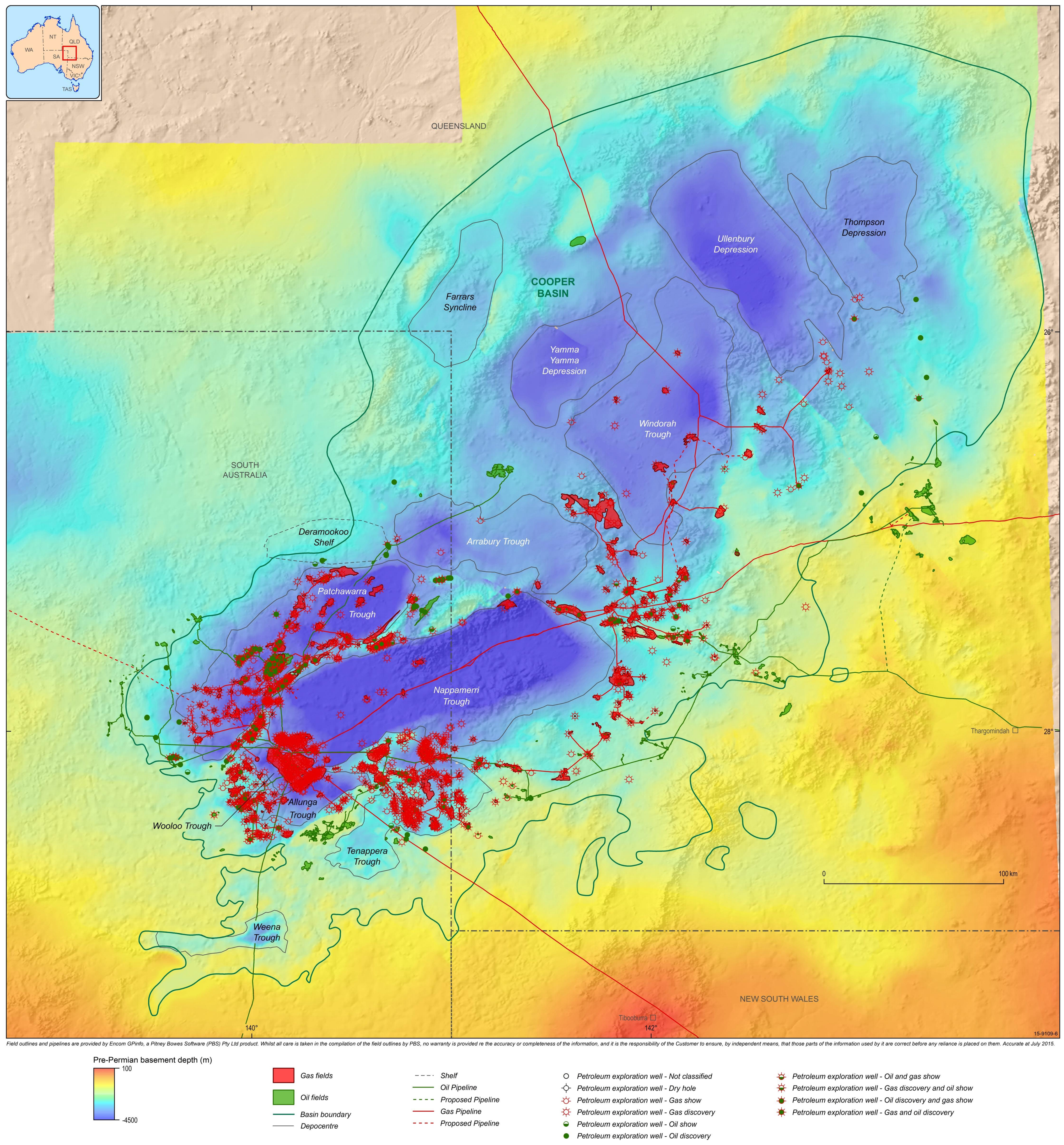


Figure 5: Strongest oil and gas shows in wells within the Cooper Basin stratigraphy.

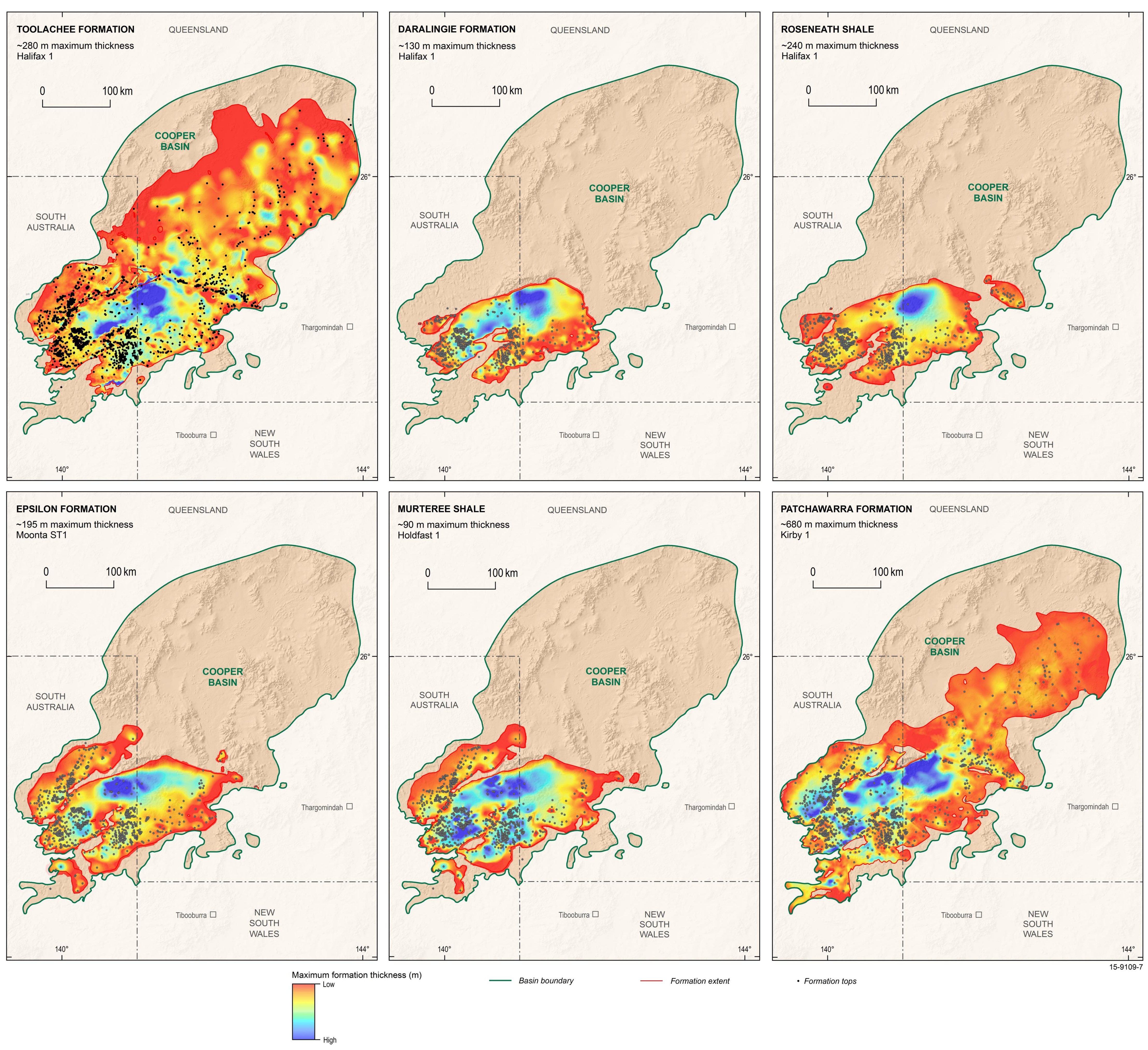


Figure 6: Gross isopachs for key formations containing Permian source rocks, generated from the regional 3D basin model (Hall et al., in prep). Well intersections are shown as black dots. Model uncertainty varies significantly according to input data distribution. The eastern Nappamerri Trough and the northern basin depocentres in Queensland are the least constrained areas and the model may need to be further refined as new data is acquired in these regions.

Source Rocks

Distribution and Thickness

The net source rock thickness of coals and coaly shales were mapped for the Toolachee, Daralingie, Epsilon and Patchawarra formations using electrofacies analysis studies (Figure 7A & B). The net Roseneath and Murteree shales source rock thickness was assumed to be the same as the gross thickness from the 3D model.

Results highlight the abundance of potential source rock facies across the basin, although source rock distribution and thickness varies spatially and by formation.

- Toolachee and Patchawarra formation coals and coaly shales are the thickest and most widespread source rock facies. Coals are thickest in the Patchawarra Formation in the Weena Trough, although coal thicknesses still exceed 10 m in the northern depocentres.
- Roseneath and Murteree shale average thickness is ~50 m, but these reach max thicknesses of 240 m and 90 m respectively in the central Nappamerri Trough.

Geochemistry

The quantity, quality, kerogen type, thermal maturity and distribution of the organic matter are investigated for each source rock using an updated compilation of all open file Total Organic Carbon (TOC), Rock Eval pyrolysis and vitrinite reflectance data (Figure 7D). Present day TOC maps are generated to show the spatial variation in the amount of source rock present within each coaly shale interval (Figure 7C). Additional Rock Eval pyrolysis analyses and vitrinite reflectance measurements were conducted to ensure a full range of source rock maturities were included in the sample set (Figure 8).

- Good to excellent organic richness (TOC > 2%) is found in all coaly shale facies source rocks. An average TOC of 70% is assumed for all coal source intervals, based on calibration with well log data.
- Toolachee and Patchawarra formations have mean HI values of ~ 200 mg HC/ g TOC typical of gas prone type III non-marine kerogens. Maximum HI values of 400-500 mg HC/ g TOC for selected coal samples suggest the influence of type II (non-marine) kerogens and good oil generation potential.
- Daralingie and Epsilon source rock characteristics are similar to the Toolachee and Patchawarra formations.
- Roseneath and Murteree shale source rocks are of low to moderate quality (mean HI ~100 mg HC/g TOC), consistent with a dry gas-prone type III-IV source. There is no evidence for higher quality source rock "sweet spots" based on available data.

Petroleum Generation Potential

Five Permian Cooper Basin source rocks were analysed for petroleum generation potential and PhaseKinetic characterisation (Mahlstedt et al., 2015). Bulk kinetics show slightly more resistant kerogen compared with typical type II-III non-marine source rocks with D/E organofacies (Pepper and Corvi, 1995) (Figure 9a) and additional potential for late primary gas generation is observed at high maturities (Mahlstedt et al., 2015). The modelled decrease in HI with increasing maturity is verified through comparison with observed data trends (Figure 9b).

A selection of absorption models were tested to determine the amount of hydrocarbons expelled versus retained, however an improved understanding of adsorption properties in coal is required before this can be modelled effectively (see Radlinski et al., 2015).

The kinetics models and observed data trends were used to estimate oil and gas windows for the basin (Table 1, Figure 10).

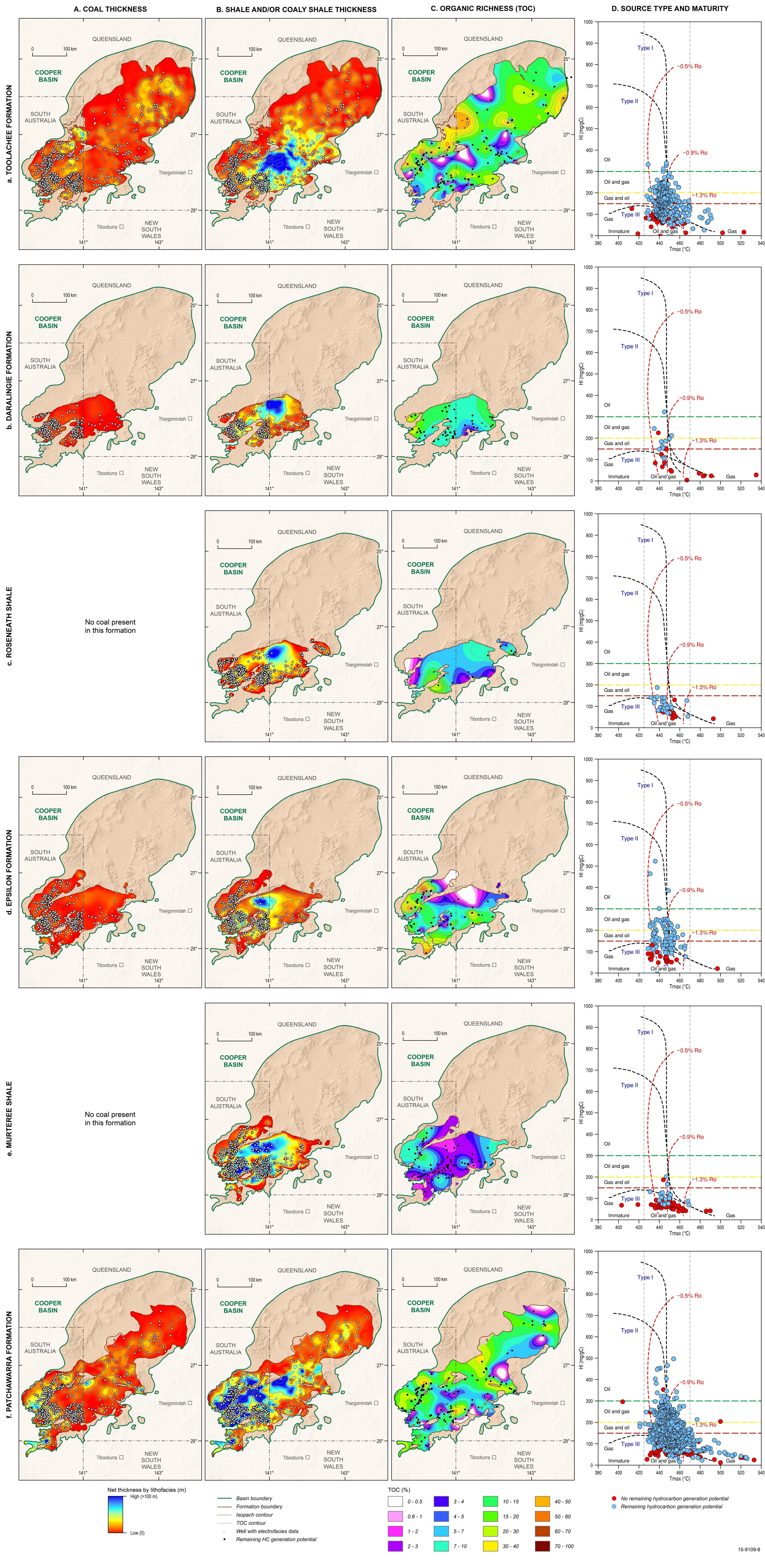


Figure 7: Cooper Basin petroleum source rock mapping results. Source rocks assessed are coals and coaly shales of the a. Toolachee Formation, b. Daralingie Formation, c. Roseneath Shale, d. Epsilon Formation, e. Murteree Shale and f. Patchawarra Formation.
Column A (coal) and B (shale and/ or coaly shale): Internally consistent, basin-wide lithofacies maps produced by integration of the following data sets: published electrofacies analysis for South Australia (Sun and Camac, 2004), new electrofacies mapping analysis in Queensland, selected well completion reports and gross isopachs from the regional 3D basin model.
Column C: Present day maps of TOC for coals and coaly shale source rock intervals. Maps of original HI and TOC prior to the onset of petroleum generation are also calculated for input into the petroleum systems models.
Column D: Plots of hydrogen Index (HI) versus maturity (Tmax) showing the variation in source rock quality and kerogen type by formation. Rock Eval pyrolysis data used in this study is sourced from a quality checked compilation of all open file TOC, Rock Eval pyrolysis and vitrinite reflectance data.

Petroleum Systems Analysis

1D Burial History and Maturity Modelling

1D burial history and maturity models were constructed for over 90 wells across the basin (Figures 11-15).

- Lithologies were calibrated using velocity, density and thermal conductivity data in key wells.
- All models were calibrated using present day corrected temperature (OZTemp database; Holgate and Gerner, 2010) and maturity indicators (Ro, Tmax).
- Thermal boundary conditions were modelled as transient heat-flow from base lithosphere. Crustal thickness and radiogenic heat production properties were used from published studies (e.g. Beardsmore, 2004; Meixner et al., 2012).
- Surface temperature and paleowater depth variation through time were included (e.g. Deighton et. al., 2003).

Key variables influencing the thermal history include: higher radiogenic heat production associated with the Big Lake suite granodiorites, Late Cretaceous uplift and erosion of the Winton Formation and the thermal blanketing effect of the thick Permian coals. Although hydrocarbon generation began in the Permian within the Nappamerri Trough, peak oil and gas expulsion across most of the basin occurred during the Cretaceous.

Integrated Charge Analysis

The 1D thermal history models were integrated with the 3D basin model and source rock property data to create a multi-1D petroleum systems model (Figure 11; see also Hall et al., 2015). Key outputs include maturity and hydrocarbon generation maps.

- Although source rock maturity varies between depocentres, large areas of the Nappamerri, Patchawarra and Windorah Troughs are gas mature (Figure 16).
- The combined theoretical volume of hydrocarbons generated from all Permian source rocks is mapped, highlighting the broad extent of the source kitchen (Figure 17).
- The total modelled volume of hydrocarbons generated from the Cooper Basin Permian source rocks is estimated to be > $2x10^6$ MMboe.

Work in progress includes addition of absorption models to map hydrocarbons expelled and retained, along with fluid composition, and use of Monte Carlo simulations to capture model uncertainty.

Conclusions

The best source rocks are the Patchawarra coals and coaly shales, followed by those of the Toolachee Formation. The broad extent of the Permian source kitchen and its large generation potential highlight the significance of the basin as a world class hydrocarbon province.

The systematic workflow applied here demonstrates the importance of integrated geochemical and petroleum systems modelling studies as a predictive tool for understanding the petroleum resource potential of Australia's sedimentary basins.

Future Work

This project is the first to contribute to the Australian Petroleum Source Rocks study. Additional work is underway in other key sedimentary provinces, including the Browse, Amadeus and Georgina basins. The new precompetitive data and analyses from these studies will help de-risk key exploration issues associated with known Australian source rocks and will aid in the identification of new prospective energy provinces across the country.

Acknowledgements

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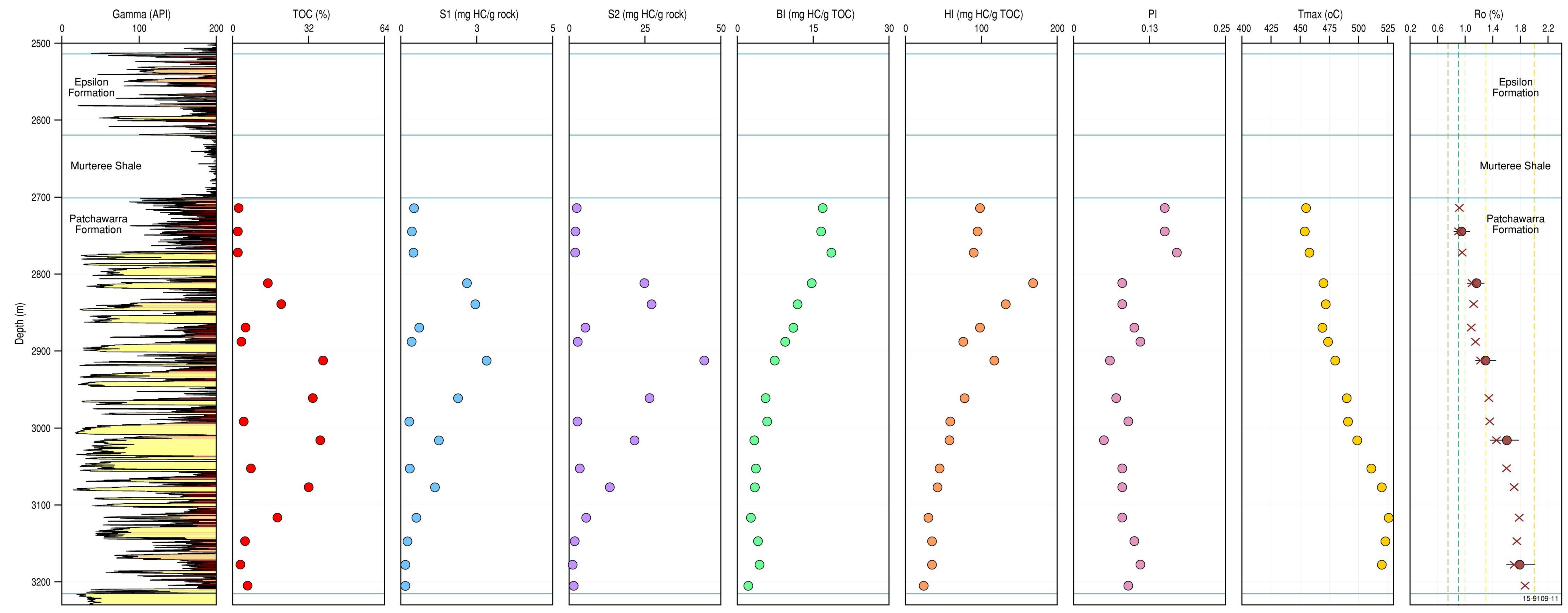

Figure 8: Source rock geochemistry and maturity data plotted by depth for the Allunga Trough-1 well in South Australia. This data is a subset of 115 additional samples analysed to capture a complete natural maturity sequence through the Permian section. Data in the Allunga Trough-1 well shows a clear reduction in HI with increasing maturity. The strong positive correlation between measured Ro and Tmax observed for the newly acquired dataset is used to calculate a Cooper Basin specific Tmax to Ro conversion equation, where $Ro_{random}(\%) = 0.0122 * Tmax - 4.6321$.

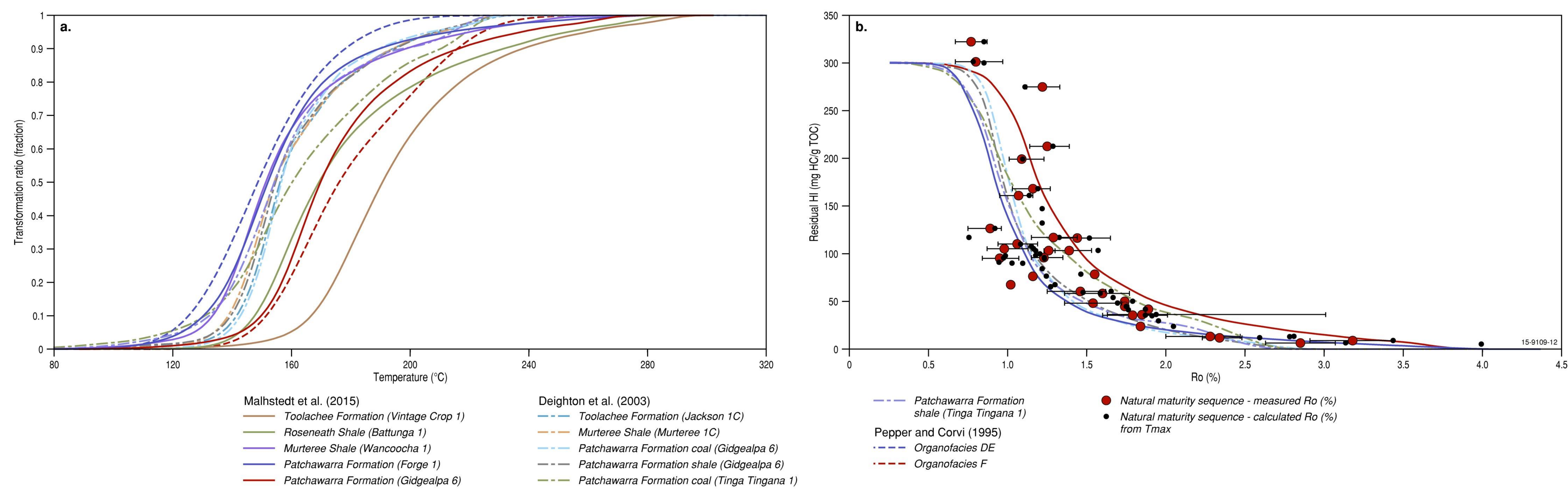

Figure 9: a. Transformation ratio (TR) vs. temperature curves for Cooper Basin bulk kinetics from Mahlstedt et al. (2015) and Deighton et al. (2003), compared with generic kinetics for organofacies D/E and F from Pepper and Corvi (1995). Geological heating rate: 3K/My.
b. Relationship between residual HI and maturity for the Patchawarra Fm. Lines: Patchawarra Fm bulk kinetics using an Original HI of 300 mg HC / g TOC. Dots: observed Patchawarra Fm Rock Eval data maturity trend. Samples with Ro < 0.7 are excluded from the plot due to HI suppression at low maturities.

	Cooper Basin	
	Ro(%)	Tmax(°C)
Early oil	0.75 - 0.9	435 - 445
Peak oil	0.9 - 1	445 - 455
Late oil	1 – 1.3	455 - 475
Wet gas	1.3 - 2	475 - 530
Dry gas	2 – 3.5	530 - 650
Over-mature	> 3.5	> 650

Table 1: Oil and gas windows estimates based on Cooper specific 2-component (gas and oil) kinetics, natural maturity sequence data and gas wetness trends from log data.

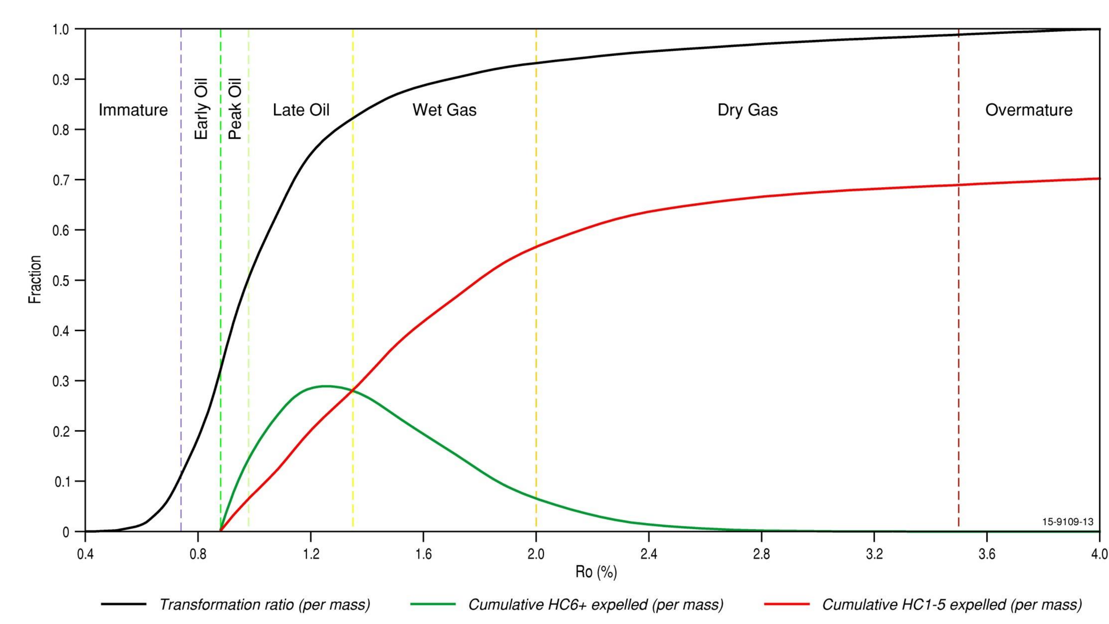

Figure 10: Cumulative oil and gas expulsion versus maturity based on Cooper Basin specific-2 component (gas and oil) kinetics and adsorption parameters.

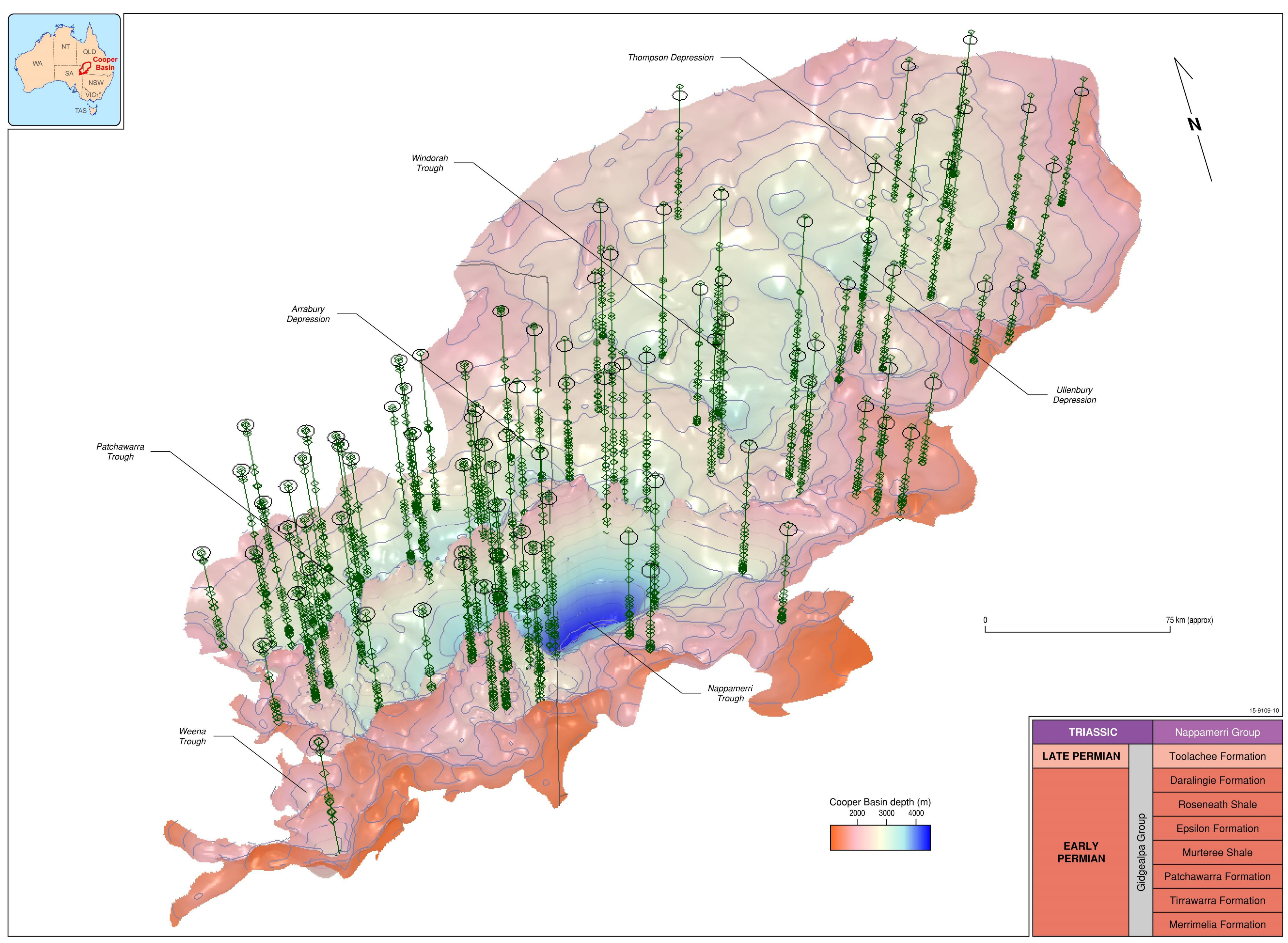

Figure 11: 3D perspective image of the regional 3D Cooper Basin model constructed using the Trinity software (see also Hall et al., 2015). 1D-genesis models used to calibrate variation in burial and thermal histories across the basin are shown as green vertical lines. The stratigraphic chart insert shows the Cooper Basin formations included in the model. Regional basin evolution through time was modelled by including updated stratigraphic ages and key unconformities, and accounted for late Cretaceous uplift and erosion of the upper Eromanga Basin (top Winton Formation).

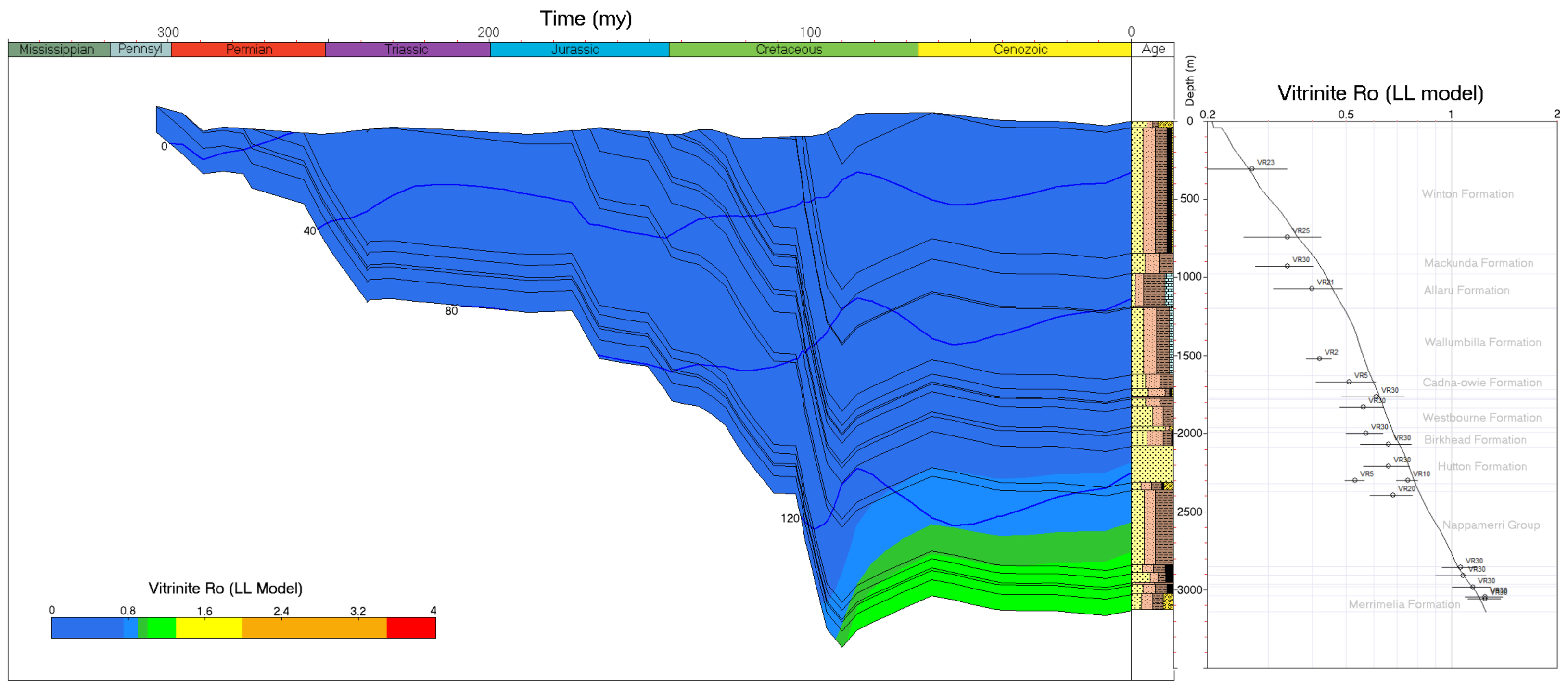

Figure 12: Petroleum systems modelling results from Paning-1 (Arrabury Trough). Left) burial history (solid blue lines indicate temperature). Right) LLNL modelled maturity-depth profile against observed maturity data (measured Ro(%): open dots with error bars, Ro(%) calculated from Tmax: black dots with error bars). Lower temperatures and maturities in the Patchawarra Trough may possibility be due to different crustal structure (e.g. Meixner et al., 2012).

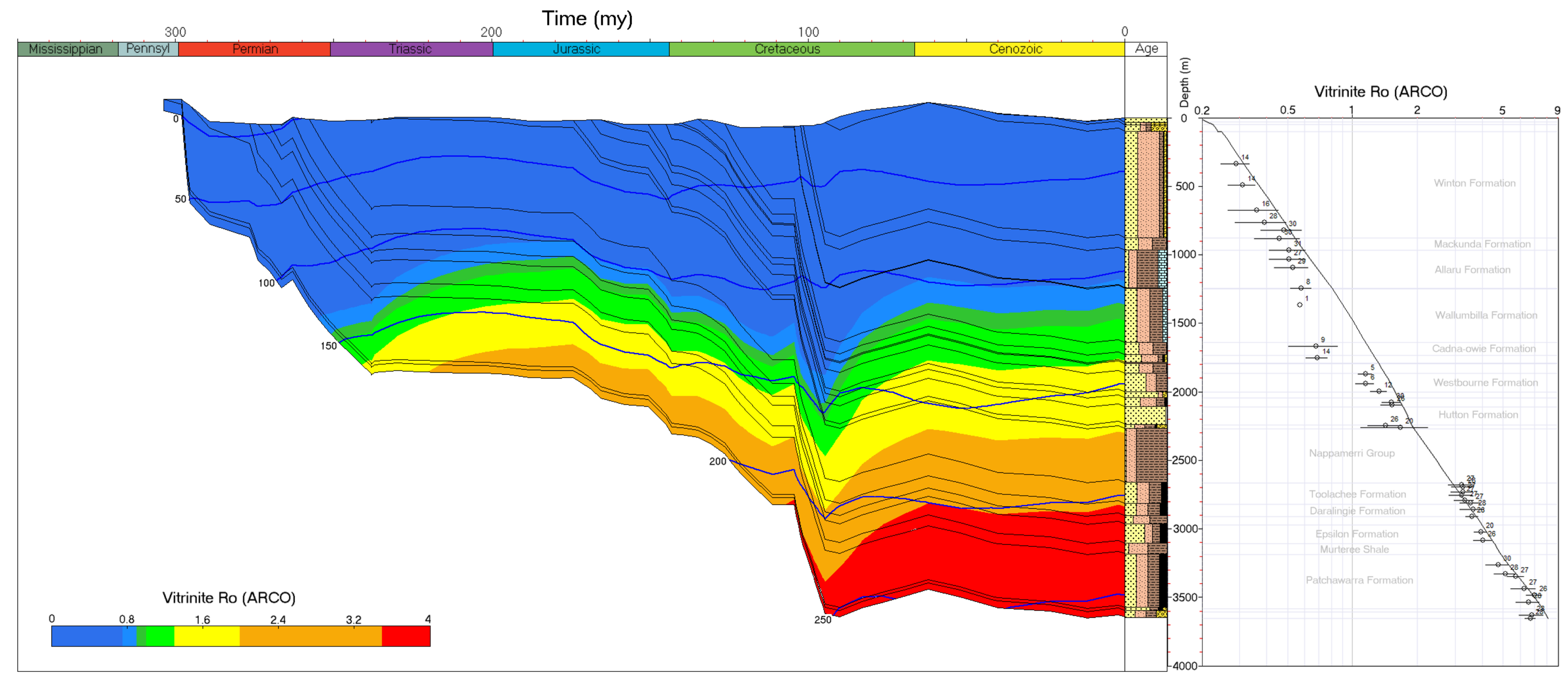

Figure 13: Petroleum systems modelling results from Burley-2 (Nappamerri Trough). Left) burial history (solid blue lines indicate temperature). Right) ARCO modelled maturity-depth profile against observed maturity data (measured Ro(%): open dots with error bars, Ro(%) calculated from Tmax: black dots with error bars). Higher temperatures and maturities reflect proximity to the Big Lake Suite granodiorite (see Meixner et al., 2012). Thermal conductivities were calibrated using Beardsmore (2004). Note the ARCO model is used due to limitations with the LLN model at higher maturities.

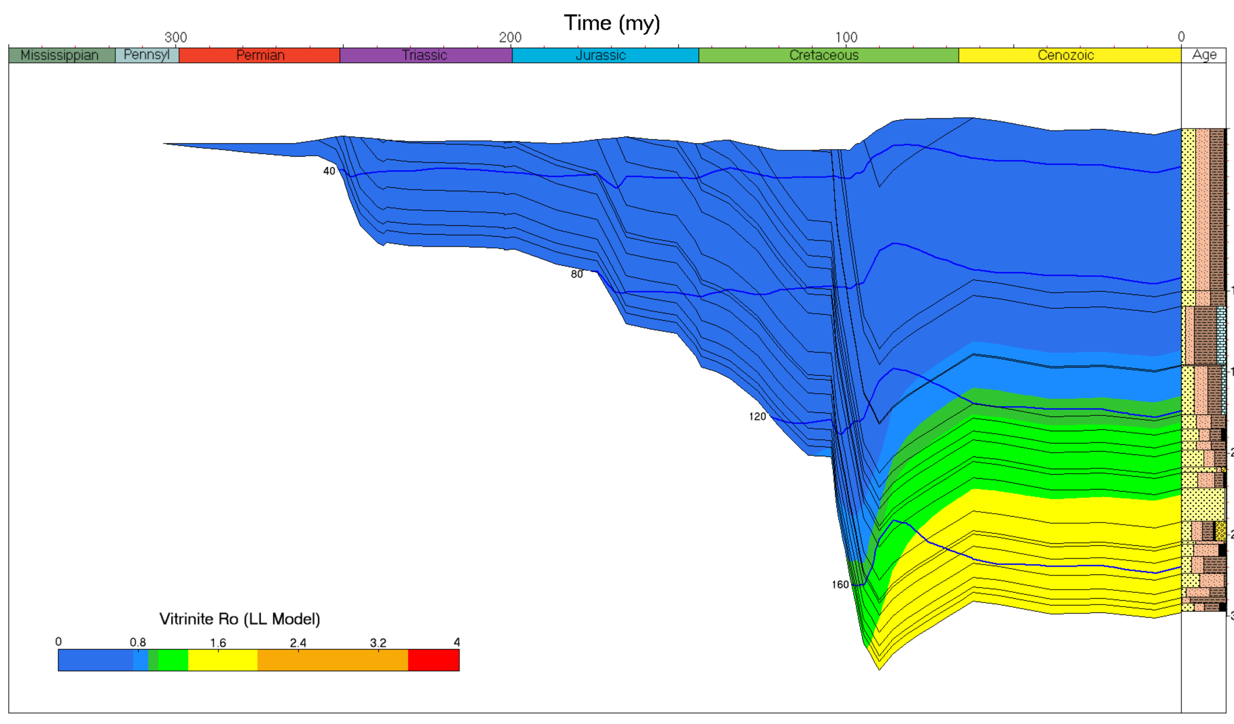

Figure 14: Petroleum systems modelling results from Marengo-1 (Windorah Trough). Left) burial history (solid blue lines indicate temperature). Right) LLNL modelled maturity-depth profile against observed maturity data (measured Ro(%): open dots with error bars, Ro(%) calculated from Tmax: black dots with error bars). The Permian section reaches the gas window. Maximum maturity is driven primarily by peak temperatures obtained during maximum depth of burial prior to late Cretaceous uplift and erosion of the Winton Formation. Note possible vitrinite suppression associated with early oil window.

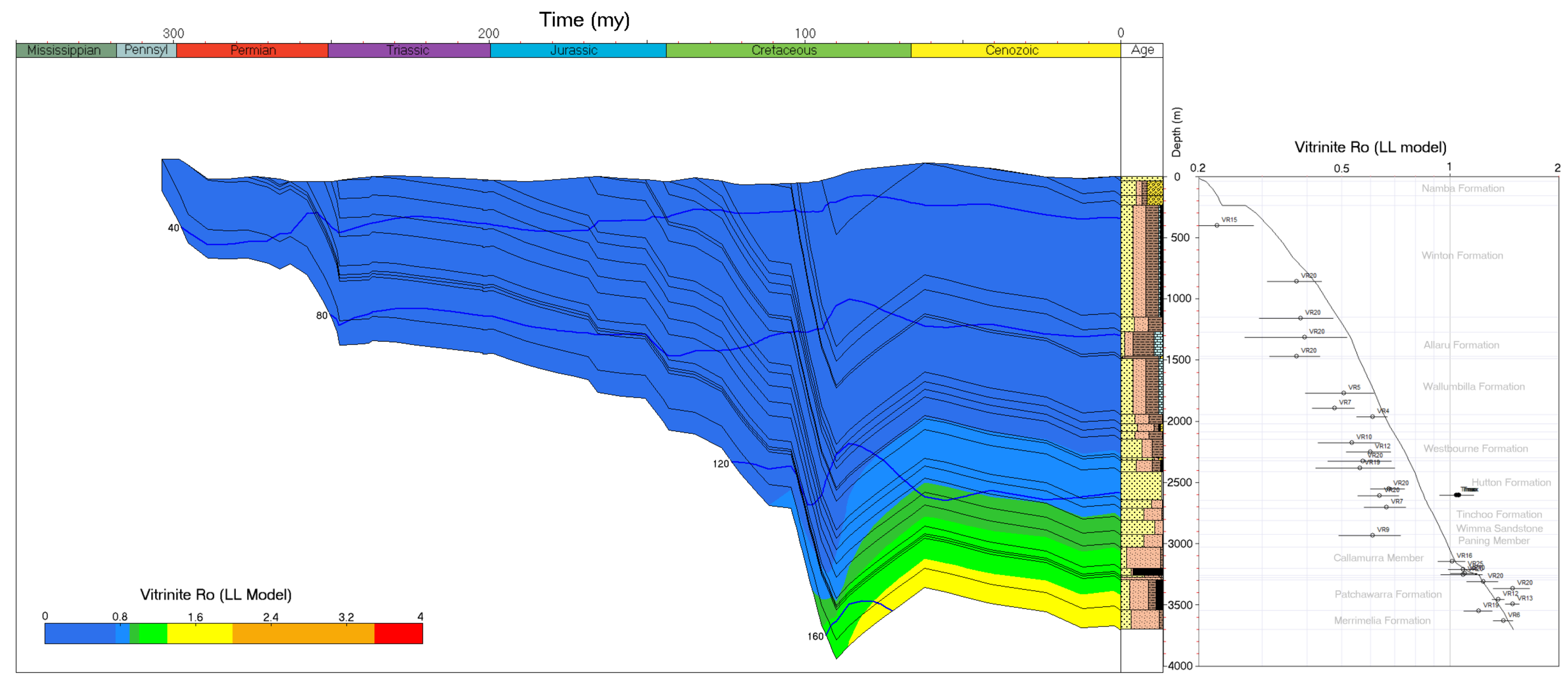

Figure 15: Petroleum systems modelling results from Beanbush-1 (Patchawarra Trough). Left) burial history (solid blue lines indicate temperature). Right) LLNL modelled maturity-depth profile against observed maturity data (measured Ro(%): open dots with error bars, Ro(%) calculated from Tmax: black dots with error bars). Lower temperatures and maturities in the Patchawarra Trough indicate a possible a difference in crustal structure (e.g. Meixner et al., 2012). The marked change in geothermal gradient between the Permian and younger successions can be successfully modelled with a thick low thermal conductivity Permian coals alone. Coal thicknesses are constrained from electrofacies analysis (Sun and Camac, 2004) and thermal conductivities are from Beardsmore (2004).

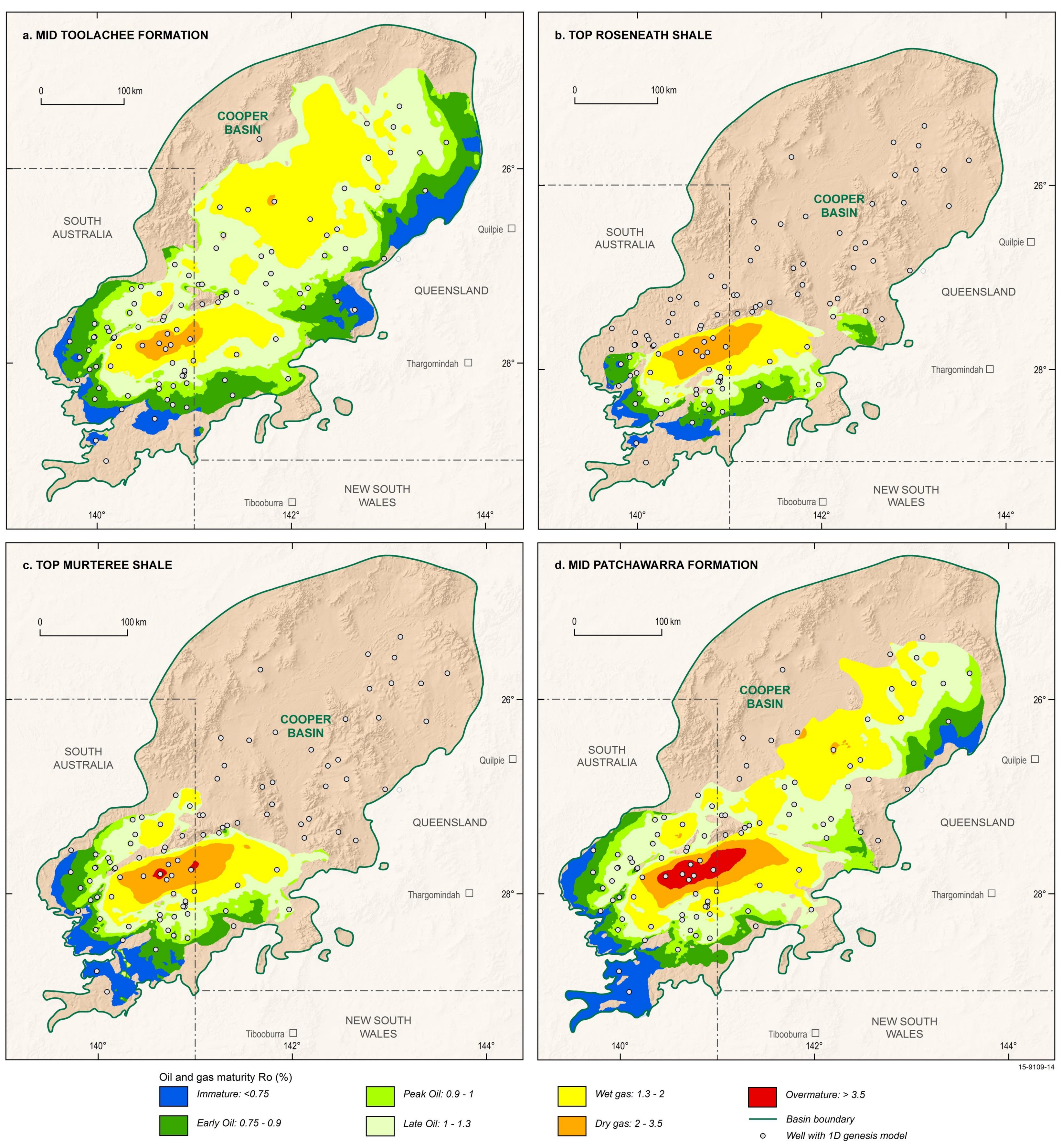

Figure 16: Maturity maps for a) mid Toolachee Formation, b) top Roseneath Shale, c) top Murteree Shale and d) mid Patchawarra Formation. The maturity colour overlay used for display represents the Cooper Basin specific relationship between thermal maturity and oil/ gas generation shown in Table 1. Locations of 1D burial history models used for calibration are marked.

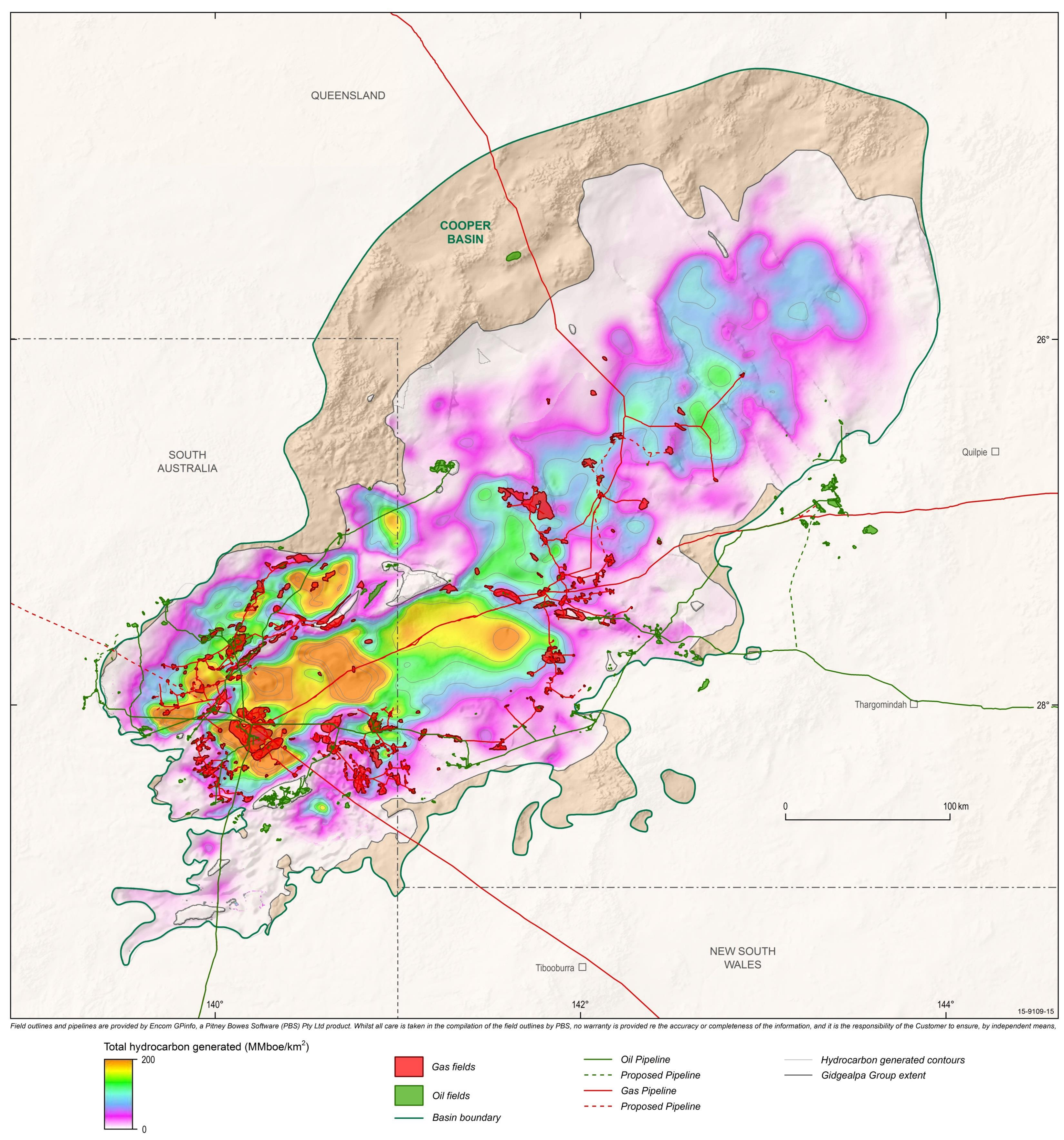

Figure 17:. Map of the combined modelled volume of hydrocarbons generated from all Permian source rocks (MMboe/km^2). Results represents the total amount of hydrocarbons generated, no distinction is made here to account for adsorption and hence hydrocarbons expelled versus retained.

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