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APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

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by

L.K. Carr[1], R.J. Korsch[1], H. Struckmeyer[1], L.E.A. Jones[2], J. Holzschuh[2], R.D. Costelloe[2] and A.J. Meixner[2].

Australian Government
Geoscience Australia

1. Energy Division, Geoscience Australia GPO Box 378 Canberra ACT 2601
2. Minerals and Natural Hazards Division, Geoscience Australia GPO Box 378 Canberra ACT 2601

Department of Resources, Energy and Tourism
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Geoscience Australia
Chief Executive Officer: Dr Chris Pigram

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Executive Summary

Many of the onshore sedimentary basins in Australia are underexplored with respect to hydrocarbons. The Onshore Energy Security Program was funded by the Australian Government over five years (2006–2011) for Geoscience Australia to provide precompetitive geoscience data and assessments of the potential of some frontier onshore sedimentary basins for energy resources, including hydrocarbons, uranium, thorium and geothermal energy. The basins studied in this project include the Burke River Structural Zone of the Georgina Basin (northwest Queensland), the Yathong Trough in the eastern Darling Basin (western New South Wales), and the Arrowie Basin (South Australia). The interpretation of deep seismic reflection profiles and petroleum systems maturation modelling was undertaken in these basins to increase the understanding of their petroleum potential.

The Arrowie Basin seismic data shows an asymmetrical basin architecture, with the basin fill being ~3800 m at its thickest. Several sequence boundaries are mapped in this seismic section, and are correlated with the sequence boundaries between the major Neoproterozoic stratigraphic groups in the Adelaide Rift System. In the easternmost part of the seismic section, a series of east-dipping thrust faults disrupt the stratigraphic section. The petroleum systems maturation modelling shows that potential Cambrian source rocks are likely immature to mature for oil generation. In contrast, potential Neoproterozoic source rocks are likely to be mature to overmature for oil generation, and immature to mature for gas generation. With hydrocarbon systems clearly present in the Arrowie Basin as shown by bitumen in shallow exploration wells drilled in the 1950's, future work, possibly with a focus on unconventional hydrocarbons, would be warranted.

The Burke River Structural Zone of the Georgina Basin seismic data shows the basin is ~65 km wide, with a half-graben geometry, being bounded in the west by a rift border fault. The succession in the basin has a maximum thickness of ~2800 m, with the stratigraphy being relatively flat lying, and thickening towards the west. The petroleum systems maturation modelling shows potential Cambrian source rocks are likely to be oil mature. Significant generation and expulsion probably occurred early in the burial history, in response to Cambrian-Ordovician loading. Expulsion occurred after trap formation in the Neoproterozoic-Cambrian, but before later trap formation in the Devonian. The required long preservation time and unroofing are the major risk factors within the basin.

The Yathong Trough of the Darling Basin seismic data interpretation shows that the basin fill consists of a thick succession characterised by alternating high and low amplitude seismic reflections, interpreted to represent the expected Devonian succession mudstones and sandstones. The basement units below the Yathong Trough are interpreted to be Ordovician turbidites and Ordovician-Silurian granites, considered to be part of the Lachlan Orogen. The petroleum systems maturation modelling shows that potential Lower and Middle Devonian source rocks are likely to be overmature for oil generation and mature for gas generation. Generation and expulsion from Lower and Middle Devonian potential marine source rocks occurred early during their burial history, prior to Carboniferous uplift and erosion, and thus, major trap formation. Later burial during the Permian and/or Cretaceous may have resulted in minor gas generation and expulsion from a Middle Devonian potential source rock.

Introduction

Many of the onshore sedimentary basins in Australia are underexplored with respect to hydrocarbons. Only the Cooper-Eromanga basin system has been a major commercial oil and natural gas producer but, recently, this has been complemented by commercialisation of coal seam gas resources in the Bowen and Surat Basins in Queensland. With domestic oil production in steady decline, and increasing offshore exploration costs, the Onshore Energy Security Program was funded by the Australian Government over five years (2006–2011) for Geoscience Australia to provide precompetitive geoscience data and assessments of the potential for onshore energy resources, including hydrocarbons, uranium, thorium and geothermal energy.

As part of the Onshore Energy Security Program, deep seismic reflection data have been acquired across several frontier sedimentary basins to stimulate petroleum exploration in onshore Australia. The basins studied in this project include the Burke River Structural Zone of the Georgina Basin (northwest Queensland), the Yathong Trough in the eastern Darling Basin (western New South Wales), and the Arrowie Basin (South Australia) (Figure 1). The interpretation of deep seismic reflection profiles from these onshore sedimentary basins focussed on the overall stratigraphic and structural architecture of the basins. Petroleum systems maturation modelling was also undertaken to increase the understanding of the petroleum potential of these basins.

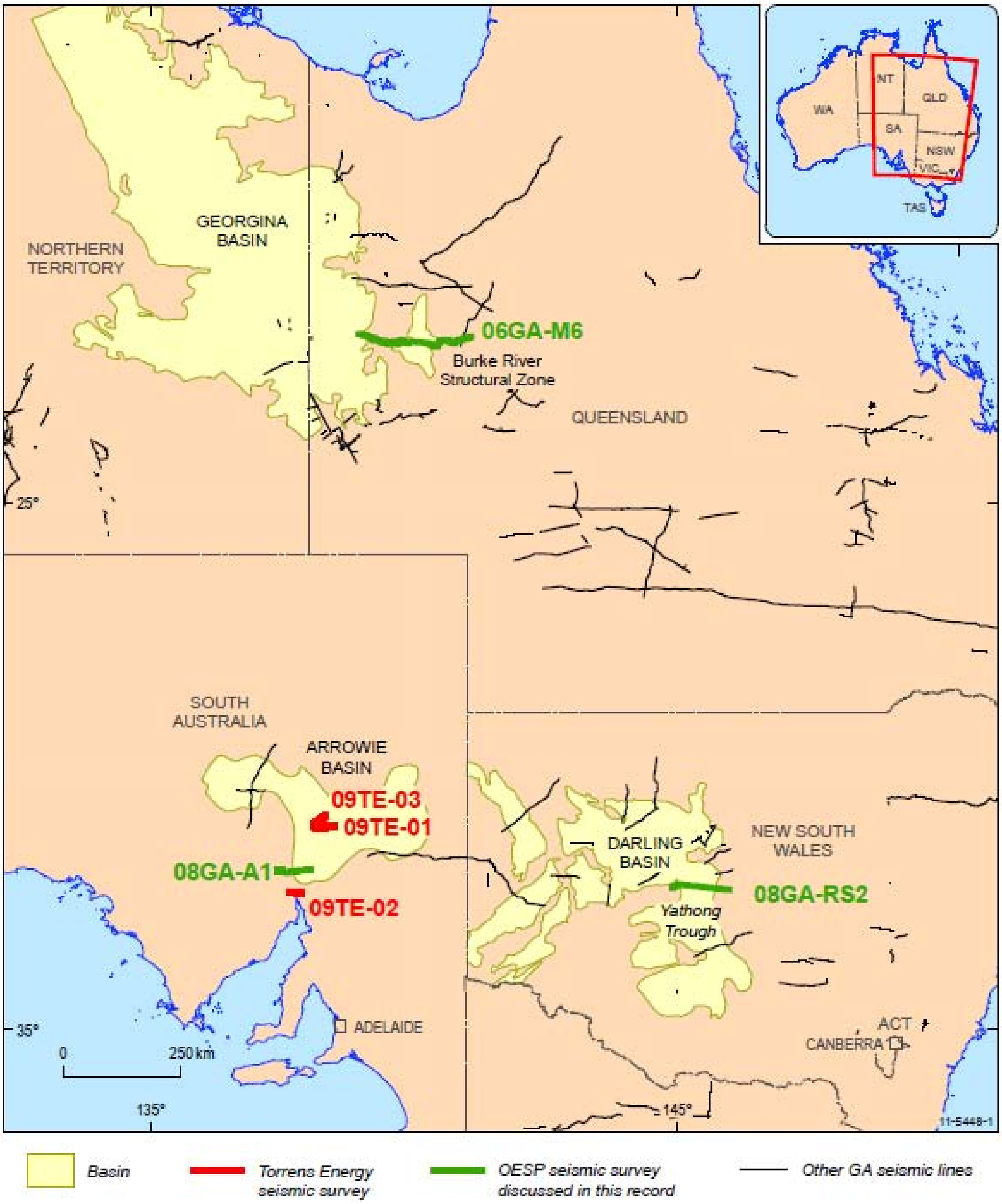


Figure 1 *Map showing the locations of seismic lines 06GA-M6 across the Burke River Structural Zone (QLD), 08GA-A1, 09TE-01, 09TE-02 and 09TE-03 in the Arrowie Basin (SA), and 08GA-RS2 across the Yathong Trough (NSW).*

Arrowie Basin, South Australia

AIM OF THE SEISMIC SURVEYS

In 2008, Geoscience Australia, in conjunction with Primary Industries and Resources South Australia (PIRSA, now Department of Manufacturing, Innovation, Trade, Resources and Energy, DMITRE*)*, acquired a 60 km long deep seismic line (08GA-A1) across the western part of the Arrowie Basin, immediately to the west of the central Flinders Ranges (Figures 2 to 4). The survey acquired new data over the southern margin of the Arrowie Basin, with the aim of better understanding the preserved structures in the basin, the likely distribution of source rock intervals and their thermal maturity levels, as well as information on the likely effects of the Delamerian Orogeny on the Cambrian succession.

This part of the basin has received almost no attention for hydrocarbon exploration since the shallow Wilkatana wells were drilled in the 1950s, to a maximum depth of ~670 m. Some of these wells, located about 15 km to the south of the seismic line, encountered non-commercial bituminous hydrocarbons in the Cambrian succession (SANTOS, 1957). The Cambrian source rocks are considered to have generated oil and, in some places, are still within the oil generation and preservation window (McKirdy, 1994). In 2009, as part of their geothermal exploration program, Torrens Energy Limited acquired a 41 km long seismic line (09TE-01) at Parachilna and a 28 km long seismic line at Nilpena (09TE-03), both located to the north of seismic line 08GA-A1. An additional seismic line, about 25 km long, was acquired near Port Augusta (09TE-02), south of seismic line 08GA-A1 (Figures 2-4). Seismic line 09GA-CG1 is shown in Figures 2 to 4 because of its proximity to the lines discussed here, and a full description of it is given by Korsch and Kositcin (2010).

Project management for the acquisition of seismic line 08GA-A1 was undertaken by the Seismic Acquisition and Processing Project from Geoscience Australia, and a summary of acquisition parameters is given by Fomin et al. (2010). For this seismic line, 75-fold seismic reflection data were acquired to 20 s two-way travel time (TWT), using three Hemi-60 (60,000 lb) peak force vibrators. A Sercel 388SN recording system was used to record and correlate the seismic data. Three sweeps, 6-64 Hz, 12-96 Hz, 8-72 Hz, each 12 s long, with an 80 m vibration point interval, were selected as source acquisition parameters for this survey. Data were processed in the DISCO/FOCUS seismic processing package. The final processing flow for seismic line 08GA-A1 is summarised by Fomin et al. (2010). Seismic lines 09TE-01, 09TE-02 and 09TE-03 were acquired for Torrens Energy Limited and originally the data were processed commercially. Subsequently, R.D. Costelloe from Geoscience Australia reprocessed the data, focussing in particular on the deep data below the Arrowie Basin and the Adelaide Rift System.

GEOLOGY OF THE ARROWIE BASIN

The Arrowie Basin in South Australia represents the last phase of sedimentation in the Neoproterozoic to Cambrian Adelaide Rift System which, in the vicinity of the seismic lines described here, consists of five major structural components: (from west to east) the Stuart Shelf, the Torrens Hinge Zone, the central Flinders Ranges, and the Moorowie and Yalkalpo Sub-basins to the east of the Flinders Ranges and extending into westernmost New South Wales (PIRSA, undated). Initially, extension in the Rodinian supercontinent resulted in the Neoproterozoic succession being deposited in a predominantly shallow marine environment, in the active Adelaide Rift System. A series of transgressive and regressive cycles, due to continued rifting, followed initial sedimentation. Later, increasing accommodation space during the post-rift thermal subsidence phase resulted in the accumulation of carbonate and clastic sediments. Sedimentation continued into the Cambrian, with the term Arrowie Basin being given to this part of an essentially continuous succession. Deposition ceased at the onset of contractional deformation at the start of the Delamerian Orogeny in the late Cambrian.

In the vicinity of the seismic lines, the western part of the Arrowie Basin forms part of the essentially undeformed Stuart Shelf, with the Torrens Hinge Zone being a zone of faulting and folding to the east. The Torrens Hinge Zone occurs immediately to the west of the highly folded component of the Adelaide Rift System in the Flinders Ranges. In the seismic sections from the Arrowie Basin, a nearly complete Neoproterozoic succession has been interpreted, but the Cambrian succession appears to vary in thickness, due to localised deformation, uplift and erosion, in part caused by the Delamerian Orogeny. Depositional successions on the Stuart Shelf overlie the northeasternmost part of the Gawler Craton. The Neoproterozoic sediments deposited on the shelf are thin, flat-lying and largely undeformed. The Torrens Hinge Zone, described by Preiss (1987) as the locus of rifting, is characterised by an area of sediment thickening and some deformation, and is the transition zone from the thinner, undeformed Neoproterozoic and Cambrian successions on the Stuart Shelf, to the markedly thicker successions in the now uplifted Flinders Ranges.

Gravity and magnetic images have been used to aid the interpretation of the seismic sections. The gravity image (Figure 3) shows the relative density of the crust in the region near the seismic lines. The less dense region, shown as dark blue, is along the western part of the Flinders Ranges. This gravity image aids the understanding of the thickness and extent of the basin away from the seismic line. Some features of the basin, such as faults, can be seen in the gravity image; for example, the fault on seismic line 09TE-03. The magnetic intensity image (Figure 4) is useful in understanding the geological structure of the basin, and the locations of faults, such as those on seismic lines 08GA-A1 and 09TE-01, can be constrained.

The stratigraphy of the Arrowie Basin is described by Jago et al. (2002), Zang (2002) and Preiss (2010), and is part of a continuous depositional system in the Adelaide Rift System that began with Neoproterozoic deposition of the Callanna and Burra Groups. Overlying this are later Neoproterozoic formations including the Umberatana and Wilpena Groups. The overlying Cambrian succession is referred to as the Arrowie Basin; it includes the Hawker Group at its base overlain by the Billy Creek Formation and Wirrealpa Limestone. The Lake Frome Group is the uppermost unit of the Arrowie Basin, and is not present on all seismic lines discussed herein.

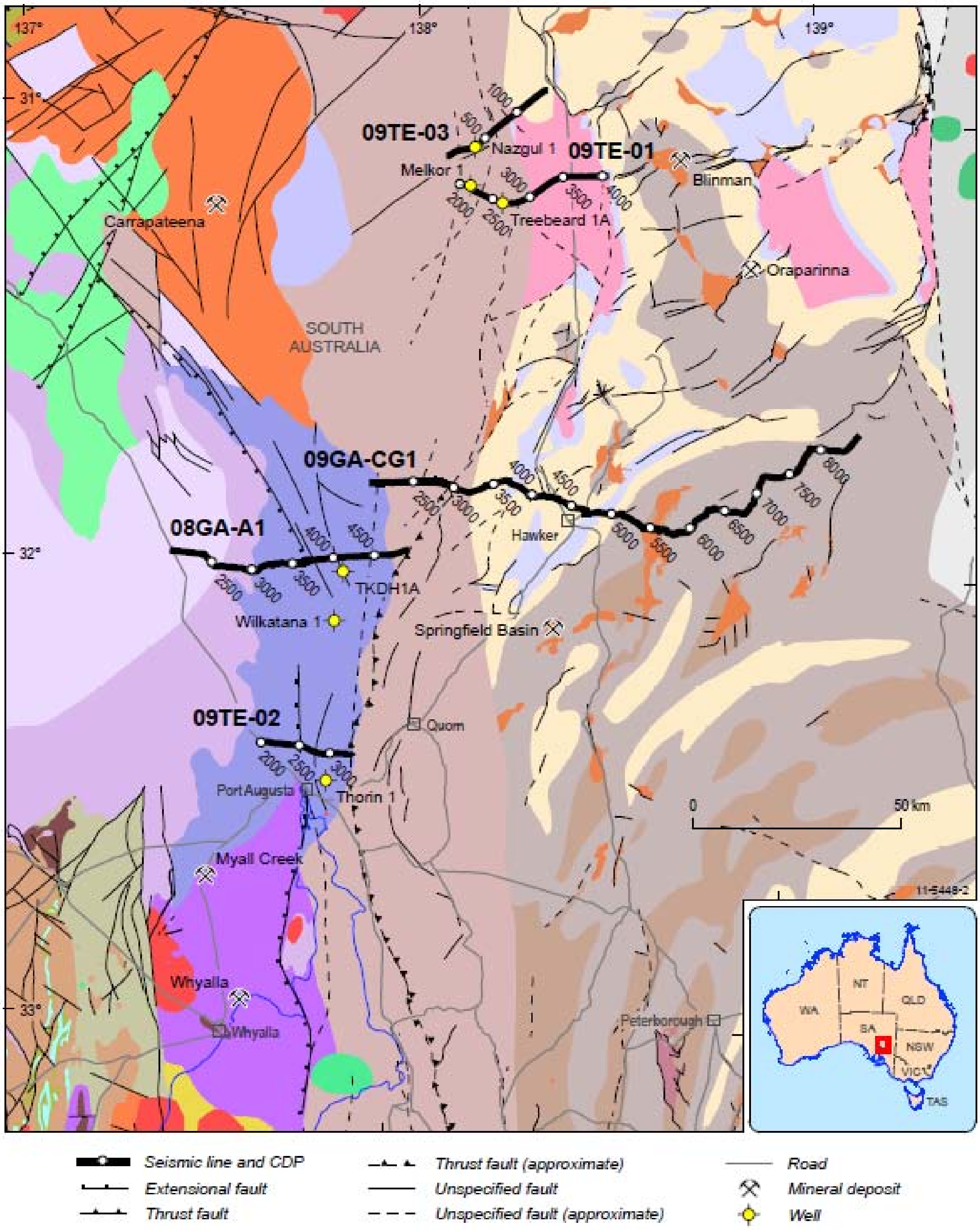


Figure 2 *Solid geology map (after Cowley, 2006a, 2006b, which also contains the legend) showing the locations of seismic lines 08GA-A1, 09TE-01, 09TE-02 and 09TE-03 in the western Arrowie Basin, South Australia. Numbers on the lines represent CDP locations. Seismic line 09GA-CG1 is shown because of its proximity to the lines described here. Full description of this line is in Korsch and Kositcin (2010).*

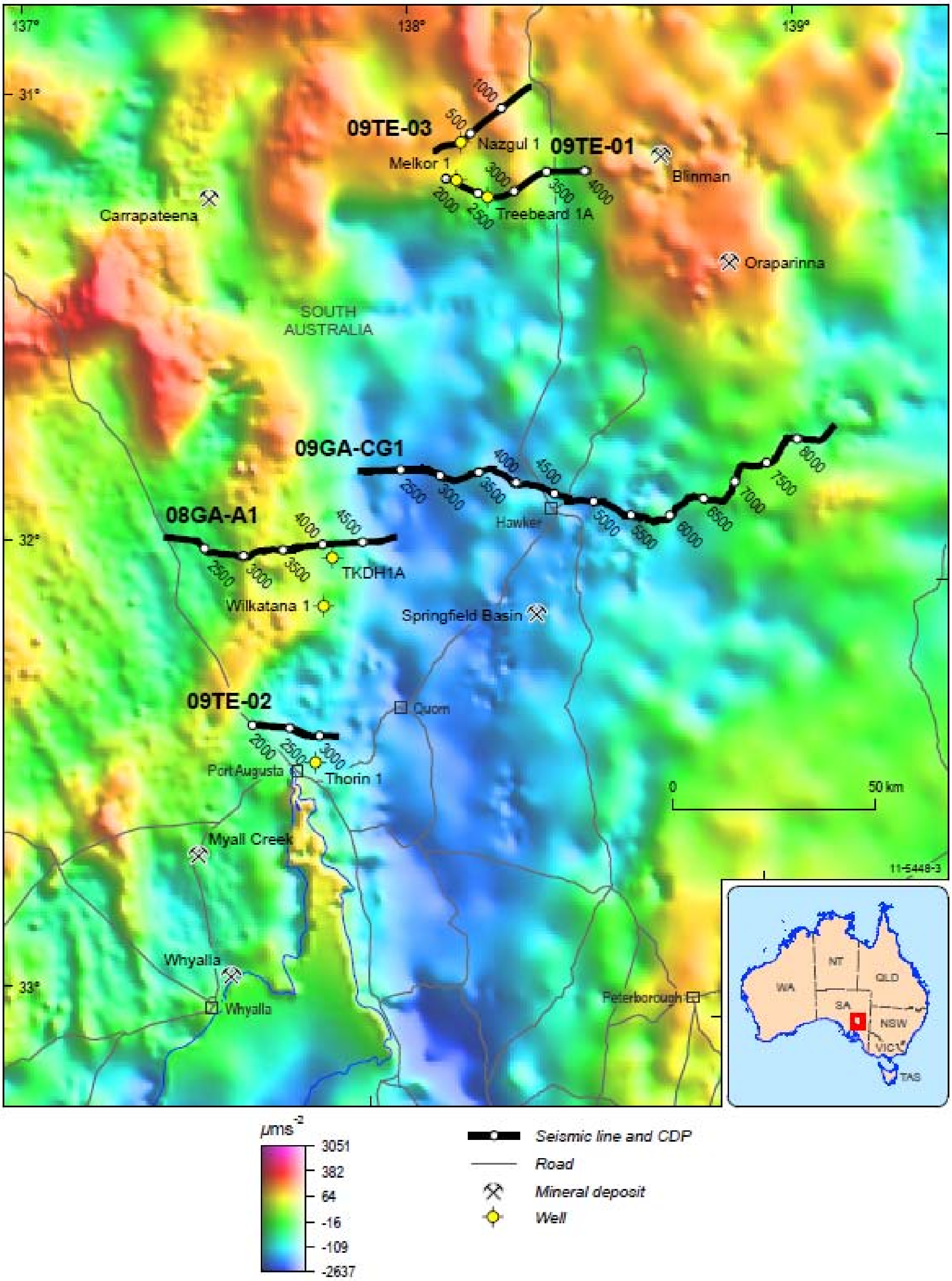


Figure 3 *Gravity image showing the locations of seismic lines 08GA-A1, 09TE-01, 09TE-02 and 09TE-03 in the western Arrowie Basin, South Australia. Seismic line 09GA-CG1 is shown because of its proximity to the lines described here. Full description of this line is in Korsch and Kositcin (2010).*

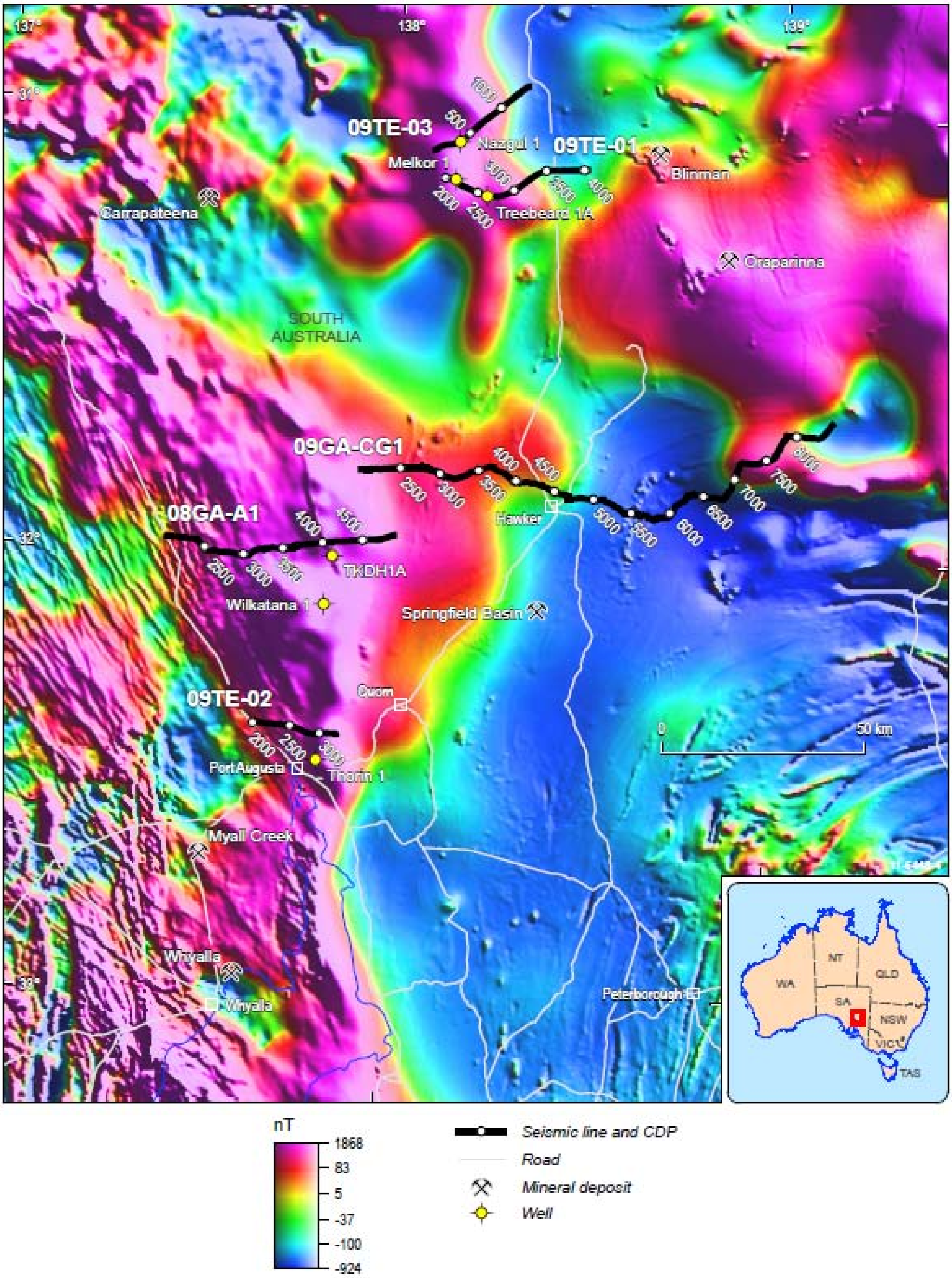


__Figure 4__ Total magnetic intensity image showing the locations of seismic lines 08GA-A1, 09TE-01, 09TE-02 and 09TE-03 in the western Arrowie Basin, South Australia. Seismic line 09GA-CG1 is shown because of its proximity to the lines described here. Full description of this line is in Korsch and Kositcin (2010).

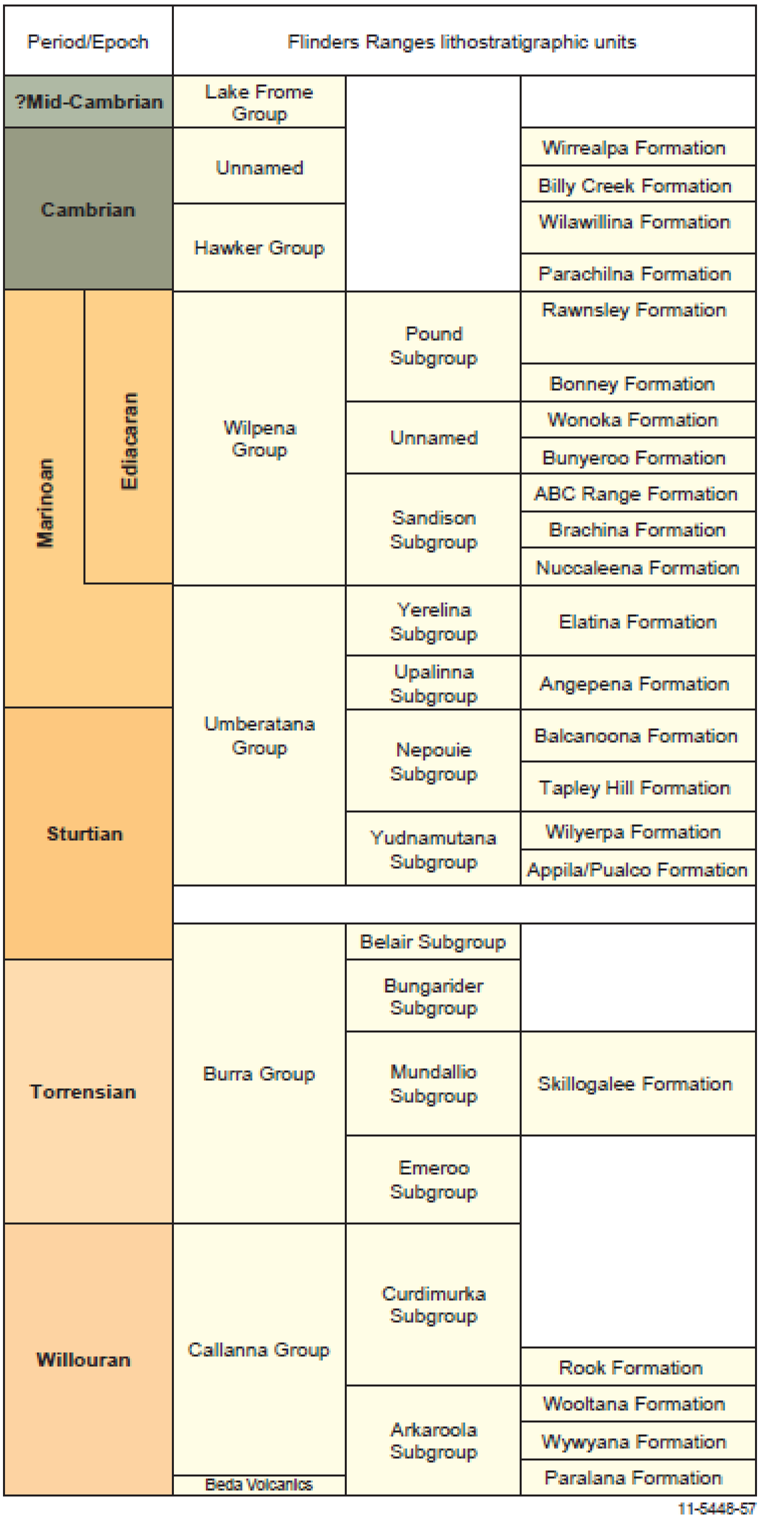


Figure 5 *Stratigraphic column showing the chronostratigraphy and lithostratigraphy of the Arrowie Basin and underlying Adelaide Rift System (after Preiss, 2010).*

INTERPRETATION OF THE SEISMIC DATA

Seismic line 08GA-A1

Seismic line 08GA-A1 crosses the southwestern portion of the Cambrian Arrowie Basin, which is underlain by the Neoproterozoic succession of the Adelaide Rift System (Figure 2). The basin is seen to be asymmetrical, varying in thickness from about 0.5 s TWT (~700 m) in the west, up to about 2 s TWT (~3800 m) in the east, calculated from stacking velocities (Figures 6 and 7). There is limited stratigraphic control in this region, and the Wilkatana wells, located about 15 km to the south of the seismic section, mostly reach total depth in the Cambrian succession. Recent industry drilling of mineral exploration hole TDKH1A, by Lincoln Minerals Limited to a total depth of 1002 m (Lyons, 2009) to the south of the seismic line, intersected part of the Neoproterozoic succession. Several sequence boundaries mapped in this seismic section, are correlated with the sequence boundaries between the major Neoproterozoic stratigraphic groups in the Adelaide Rift System, which crop out in the Flinders Ranges to the east.

The east-dipping Yadlamalka Fault (CDP 4000, Figures 6 and 7) is a post-depositional thrust fault, defining the eastern limit of the Stuart Shelf, to the east of which is the Torrens Hinge Zone. The drill hole TDKH1A intersected the Beda Volcanics (part of the basal Neoproterozoic Callanna Group) in the hangingwall of the thrust, and our interpretation suggests that there has been at least 1200 m of pre-Cenozoic throw on the fault. A narrow linear magnetic high on the aeromagnetic image (Figure 4) is interpreted to represent the upthrust Beda Volcanics on the eastern side of the Yadlamalka Fault (CDP ~4000).

In the seismic section, the Callanna Group forms a highly reflective lowermost package in the basin; much of the reflectivity is due to the presence of the mafic Beda Volcanics. This Group has been interpreted across the entire seismic line and has a relatively constant thickness, varying from 200 ms TWT (~500 m) in the west to 300 ms TWT (~750 m) in the east. Above the Callanna Group, the Burra Group varies in thickness along the section, and its upper part has been removed by erosion to the west of CDP 2300 (Figure 7), below the Cenozoic unconformity. It is a reflective package in the west, but is less reflective to the east of the Yadlamalka Fault. It also has an erosional upper surface beneath the unconformably overlying Umberatana Group. The Umberatana Group thickens towards the east, where its upper surface terminates below the Cenozoic unconformity at CDP 2600. To the west of the Yadlamalka Fault, the uppermost unit in the Neoproterozoic, the Wilpena Group, has had its upper part removed by erosion below the Cenozoic unconformity (Figure 7).

In this seismic section, only a thin remnant of the Cambrian succession is preserved, occurring to the east of the Yadlamalka Fault. It is into this succession that the Wilkatana wells were drilled to the south of the seismic line. The presence of bituminous hydrocarbons (consistent with a considerable thickness of sediment overburden required to thermally mature the hydrocarbons) at depths of less than 670 m in these wells, indicates that a considerable amount of erosion has occurred in this area. McKirdy (1994) considers that the source of these hydrocarbons to be the Hawker Group, Mernmerna Formation and Wilkawillina Limestone, from where the bitumen was recovered, indicating that these hydrocarbons are *in situ*.

In the easternmost part of the seismic section, a series of east-dipping thrust faults disrupt the stratigraphic succession. These faults might be related, in part, to the currently active, east-dipping Wilkatana Fault, which occurs immediately to the east of the seismic line, and is associated with the recent uplift of the Flinders Ranges (Quigley et al., 2006). Further to the east, the Neoproterozoic succession thickens dramatically (e.g., Preiss et al., 2010).

Below the Neoproterozoic succession, strong, subhorizontal to gently-dipping reflections are interpreted to represent the Mesoproterozoic (ca. 1585 Ma) Gawler Range Volcanics (Figure 7). These volcanic rocks have been disrupted by faulting, and then in part eroded, prior to initiation of sedimentation in the Adelaide Rift System at about 830 Ma.

Below the Gawler Range Volcanics, there is a zone of low reflectivity about 3 s TWT (~9 km) thick. We interpret this to be equivalent to the folded and metamorphosed Wallaroo Group and equivalent units described in seismic line 08GA-G1 by Fraser et al. (2010). The base of this package is defined by the top of a package of strong reflections forming the middle crust. A significant fault (Nob Hill Fault), occurs at about CDP 2800, and shows an extensional displacement of both the Gawler Range Volcanics and the top of the middle crust reflective package below the equivalents of the Wallaroo Group (Figure 7). The intensity of the reflectivity decreases downwards in the crust, so that the lowermost part of the crust is only weakly reflective. Here, the middle to lower crust, which has not been traced to the surface in the seismic lines, is referred to as the Warrakimbo Seismic Province (Korsch et al., 2010). The Moho is poorly defined, and we infer it to occur at about 14 s TWT (~42 km) depth.

Forward modelling of the potential field data along seismic line 08GA-A1 shows a good match with the geological interpretation of the seismic line (Figure 8). There is a broad gravity high in the middle of the seismic section, from CDP 2800 to 3800 (Figures 3 and 8). By assuming that the wedge of reflective material immediately below the Gawler Range Volcanics (Figures 7 and 8) consists of mafic volcanic rocks (density 2.84 gcm^{-3}), it was possible to reproduce the observed gravity data (Figure 8).

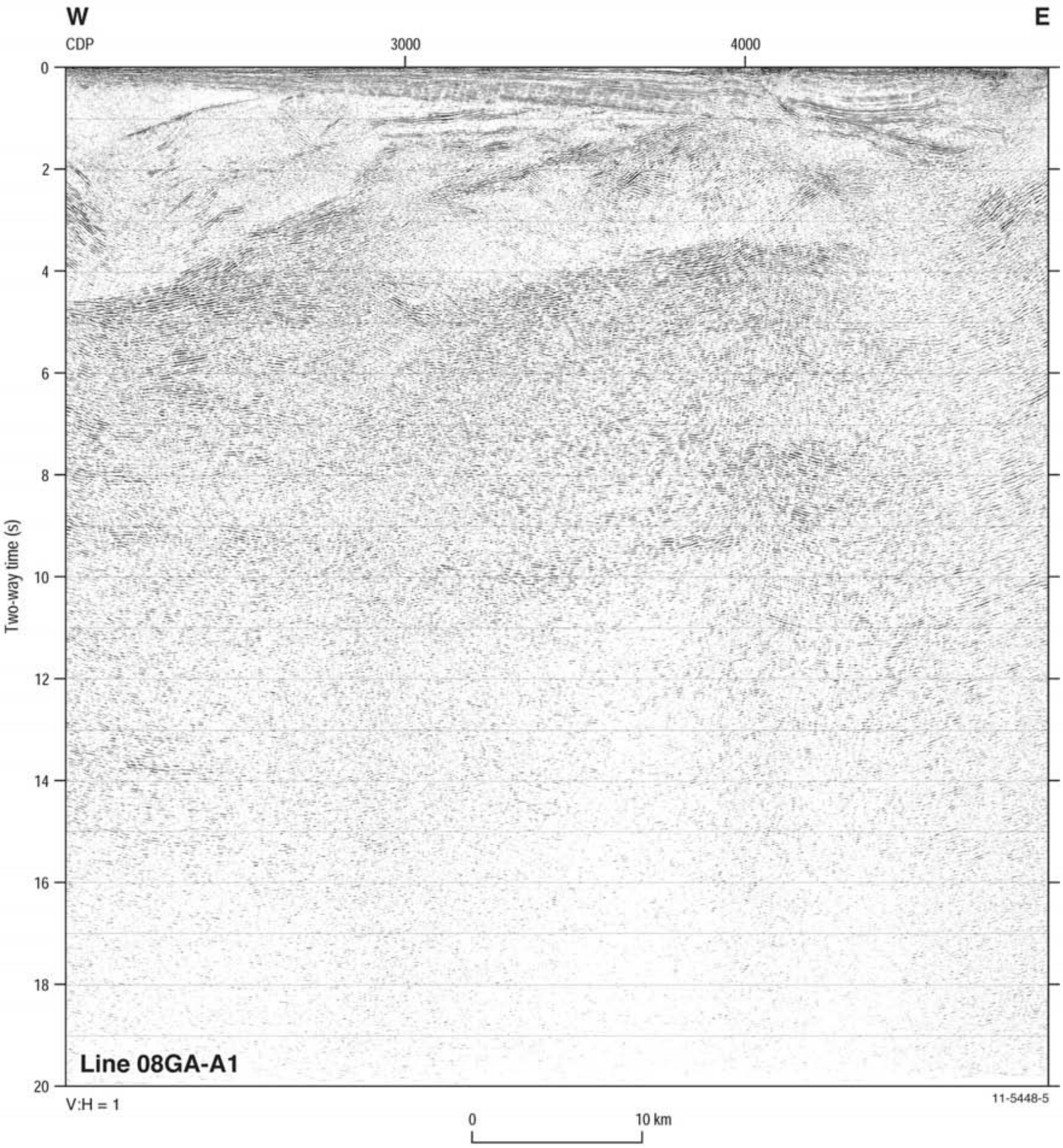


Figure 6 *Uninterpreted migrated seismic line 08GA-01, across the western Arrowie Basin, displayed at vertical: horizontal = 1:1, assuming average crustal velocity of 6000 ms^{-1}.*

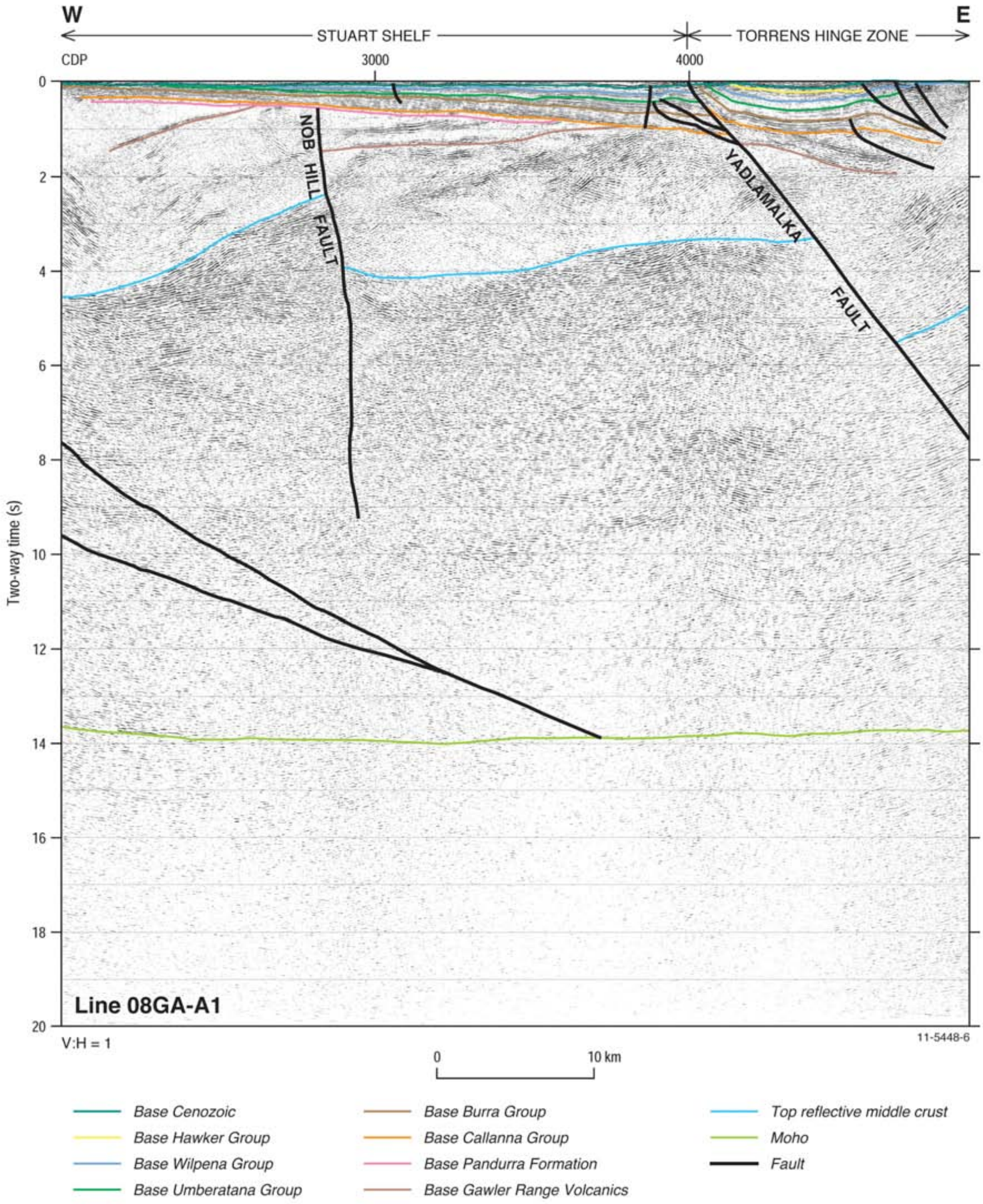


***Figure** 7 Interpretation of migrated seismic line 08GA-01, across the western Arrowie Basin, displayed at vertical: horizontal = 1:1, assuming average crustal velocity of 6000 ms^{-1}.*

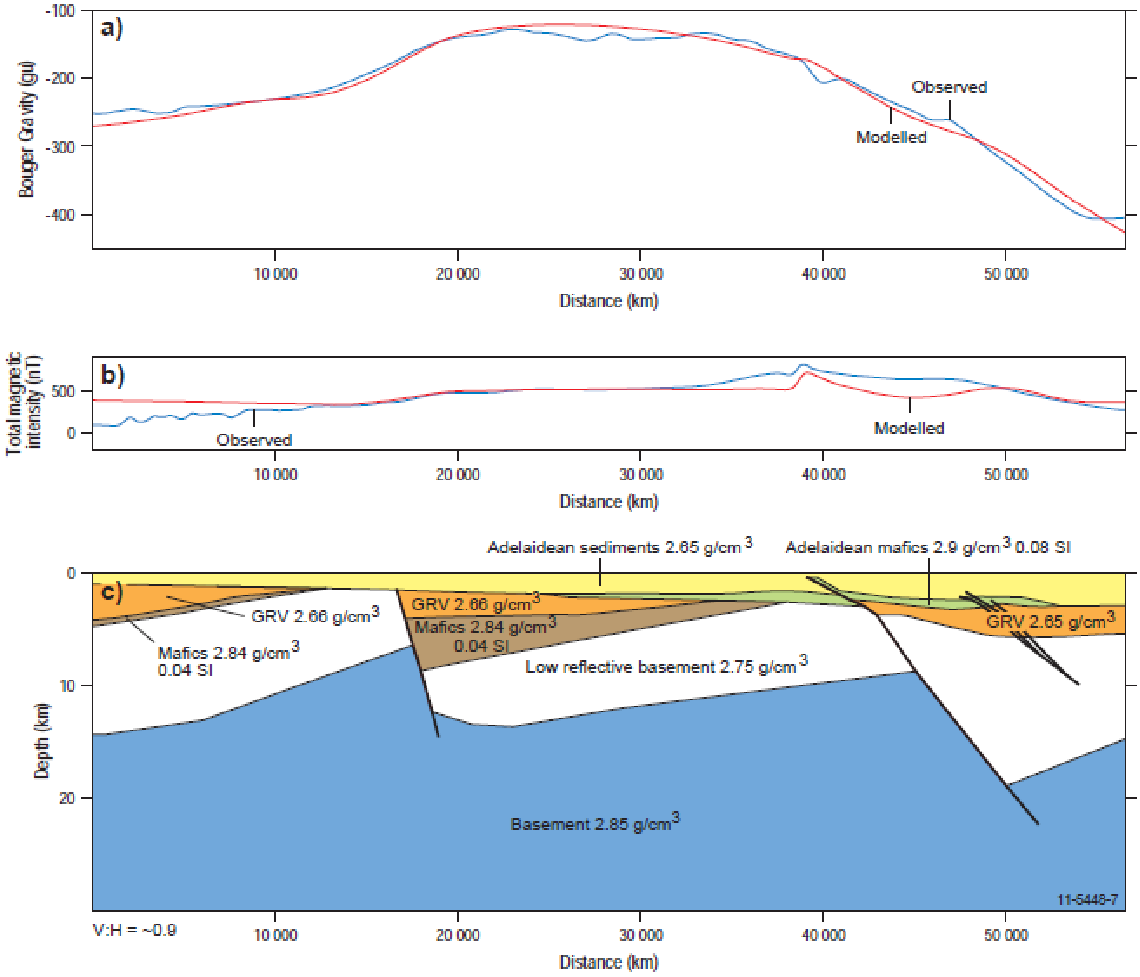


Figure 8 *Forward model of the gravity and magnetic profile along the seismic line 08GA-A1, shown to a depth of 30 km. The upper panel shows the observed gravity signal in blue, and the modelled signal in red. The middle panel shows the observed magnetic signal in blue, and the modelled signal in red. The lower panel shows the density and magnetic values assigned to the model, with the geometry used being based on the interpretation of the seismic line 08GA-A1 (Figure 7).*

Seismic line 09TE-01

In contrast to seismic line 08GA-A1, described above, the Parachilna seismic line 09TE-01 collected for Torrens Energy Limited, imaged a much thicker (up to 1500 m) Cambrian succession above the Neoproterozoic (Figures 9 and 10). In this section, the Neoproterozoic-Cambrian succession is over 3500 m thick at the western end of the line and about 5800 m thick at the eastern end of the line. In this area, Cenozoic sediments are relatively thick, up to 430 m in places, and there is a significant angular unconformity at their base (Figure 10). The Callanna Group is interpreted to occur in the western part of this section, but it possibly terminates at about CDP 2500, and its strongly reflective character is not recognised to the east of this position.

The stratigraphy of seismic line 09TE-01 was constrained by Treebeard 1A well, which intersected 420 m of Cenozoic sediment, overlying 1387 m of the Cambrian succession in the Arrowie Basin before terminating in the Wilkawillina Limestone of the Cambrian Hawker Group at a depth of 1807 m.

In the western part of the seismic line, the relatively coherent sedimentary package is terminated by the east-dipping Ediacara Fault at CDP ~2800 (Figure 10). To the east of the fault, the seismic reflectivity is low, although weak reflections define a relatively low-amplitude, long-wavelength anticline. It is possible that the low seismic reflectivity could be caused by a Neoproterozoic diapir, similar to those which are common in the Flinders Ranges to the east. This is supported by the presence of a thin (17 m thick), bedding parallel, diapiric breccia unit, which has been observed near the base of the Treebeard 1A well, to the west of the Ediacara Fault.

The seismic section indicates that the Ediacara Fault is a major structure, and that it has been reactivated in the Quaternary. Cenozoic sediments are uplifted in the hangingwall to the east of the fault; movement on the fault is also responsible for the Quaternary uplift of the Ediacara Range to the north of the seismic section. Thus, the Ediacara Fault can be considered the western range-front fault in this area. Other faults in the section, to the east of the Ediacara Fault, also show minor displacement of the Cenozoic sediments. There is good seismic reflectivity near the eastern end of the line, where a steep-sided syncline is interpreted to preserve Cambrian Lake Frome Group in its core. This syncline is interpreted to be a possible footwall syncline to a west-dipping thrust fault; it has a classic concentric geometry, with the fold amplitude increasing with increasing depth. An alternative possibility is that this syncline could be part of a series of concentric folds above a decollement located near the base of the sedimentary succession, which was then cut by younger thrust faults.

Data for seismic line 09TE-01 were recorded to 10 s TWT (~30 km depth) and hence do not provide an image of the whole crust. Nevertheless, the geometry of the crust below the Neoproterozoic succession is very similar to that seen in seismic line 08GA-A1, about 90 km to the south (Figure 7). Immediately below the basin is a zone of relatively weak reflections, which we correlate with the inferred Wallaroo Group in the southern section. We see no evidence for the Gawler Range Volcanics in this section. The base of this zone of weak reflectivity is again defined by the top of a package of strong reflections forming the middle crust, which we infer to be the Warrakimbo Seismic Province. Both this reflective package and the inferred Wallaroo Group are cut by east-dipping thrusts, one of which appears to be unconformably overlain by the Neoproterozoic succession.

High heat flow values have been recorded from sediments in wells drilled on the seismic line: Melkor 1 (115 mWm^{-2}) and Treebeard 1A (91 mWm^{-2}; Torrens Energy Limited, 2010). This makes this area attractive for geothermal energy exploration. Also, the nonreflective basement beneath the Arrowie Basin and Adelaide Rift System, interpreted to be the equivalent of the Wallaroo Group, would be expected to have a relatively low heat flow; hence the high heat flow values could be derived from high heat-producing granites of the Hiltaba Suite, which could be present in the nonreflective package, but are not imaged seismically.

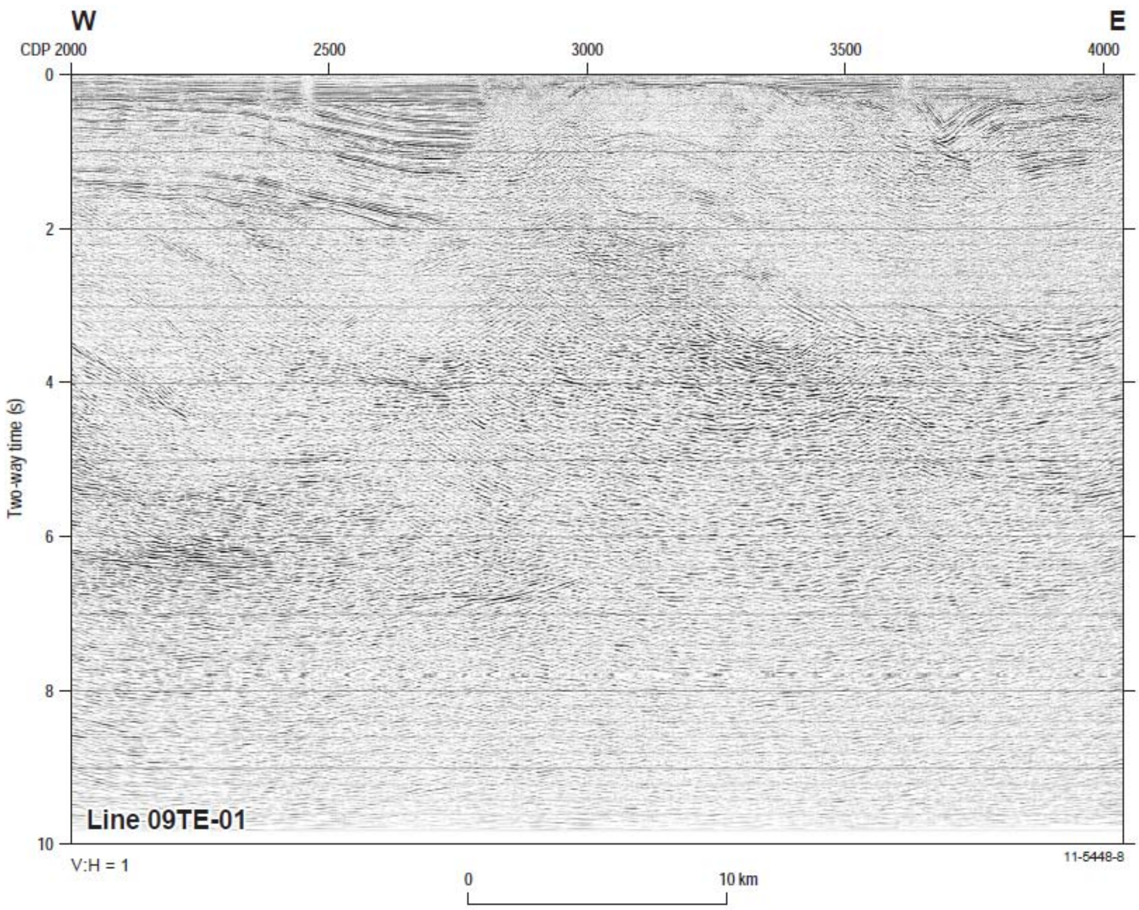


Figure 9 *Uninterpreted migrated seismic line 09TE-01, across the Arrowie Basin displayed at vertical: horizontal = 1:1, assuming average crustal velocity of 6000 ms^{-1}.*

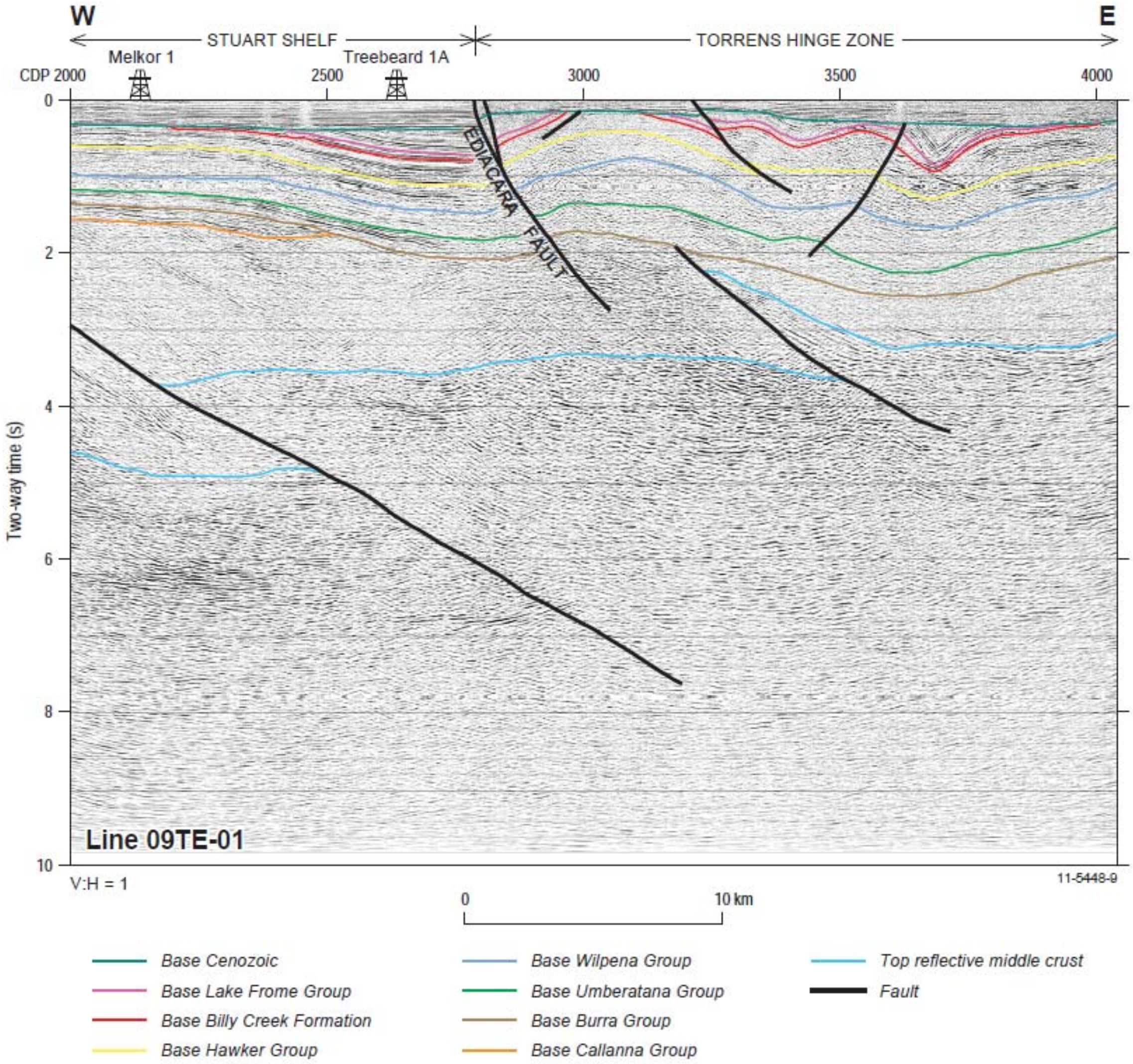


Figure 10 *Interpretation of migrated seismic line 09TE-01, across the Arrowie Basin displayed at vertical: horizontal = 1:1, assuming average crustal velocity of 6000 ms*$^{-1}$.

Seismic line 09TE-02

The Port Augusta seismic line 09TE-02, was obtained for Torrens Energy Limited to the south of seismic line 08GA-A1, and shows a similar asymmetrical geometry (Figures 11 and 12). The sedimentary rock packages are about 0.8 s TWT (~2 km) deep in the west and 1.4 s TWT (~3.5 km) deep in the east. The east-dipping Yadlamalka Fault, again defining the eastern limit of the Stuart Shelf, occurs just to the east of the eastern end of this section.

Some surface constraints for the geology are provided by the PORT AUGUSTA 1:250 000 geological map (Dalgarno et al., 1968), where the Corraberra Sandstone Member of the Tent Hill Formation is mapped between CDPs 2400 and 2500. This unit is equivalent to the ABC Quartzite and Brachina Formation of the Neoproterozoic Wilpena Group. The Torrens Energy drill hole, Thorin 1, was projected northwards onto the seismic section at about CDP 2900. This hole is used to constrain the upper part of the Neoproterozoic-Cambrian stratigraphy beneath the Cenozoic deposits in the east.

Key sequence boundaries have been picked, with the most obvious sequence boundary being base of the Umberatana Group, which is a major erosion surface. In the seismic section, there are several terminations and truncated reflections below this horizon. The series of strong parallel reflections at 0.5 s TWT at CDP 2550 (and becoming deeper to the east) are interpreted as probable mafic volcanic rocks within the Callanna Group. This is consistent with our interpretation of seismic line 08GA-A1 to the north, where the volcanic rocks were intersected by the drill hole TDKH1A (Lyons, 2009). The strong reflections at CDPs 2400-2500 just above 1 s TWT are interpreted as being the Gawler Range Volcanics (GRV) and have been tracked from the surface outcrop, away from the seismic line. We interpret the less reflective package between the Callanna Group and Gawler Range Volcanics to be the Pandurra Formation.

Although there are relatively minor faults present, no evidence for major faults are observed in this seismic section. The lack of clarity at the eastern end of the section, where the good reflections disappear, may be due to either a lower fold at the end of the section, or geology adjacent to the end of the section (in this case a fault to the east of the section), or it may be even a processing artefact. The seismic section shows a remarkable similarity to the cross section C-D by Dalgarno et al. (1968), drawn on the PORT AUGUSTA 1:250 000 geological map (See section from point C to about the location of No. 1 bore).

Cambrian units are interpreted to occur beneath the Cenozoic deposits at the eastern end of the seismic section. Just over 2 km further east, the Callanna Group is mapped at the surface (Dalgarno et al., 1968). This implies that a major east-dipping thrust fault, the Yadlamalka Fault just to the east of the seismic line, has brought the Callanna Group from a depth of over 3500 m in the seismic section to the surface.

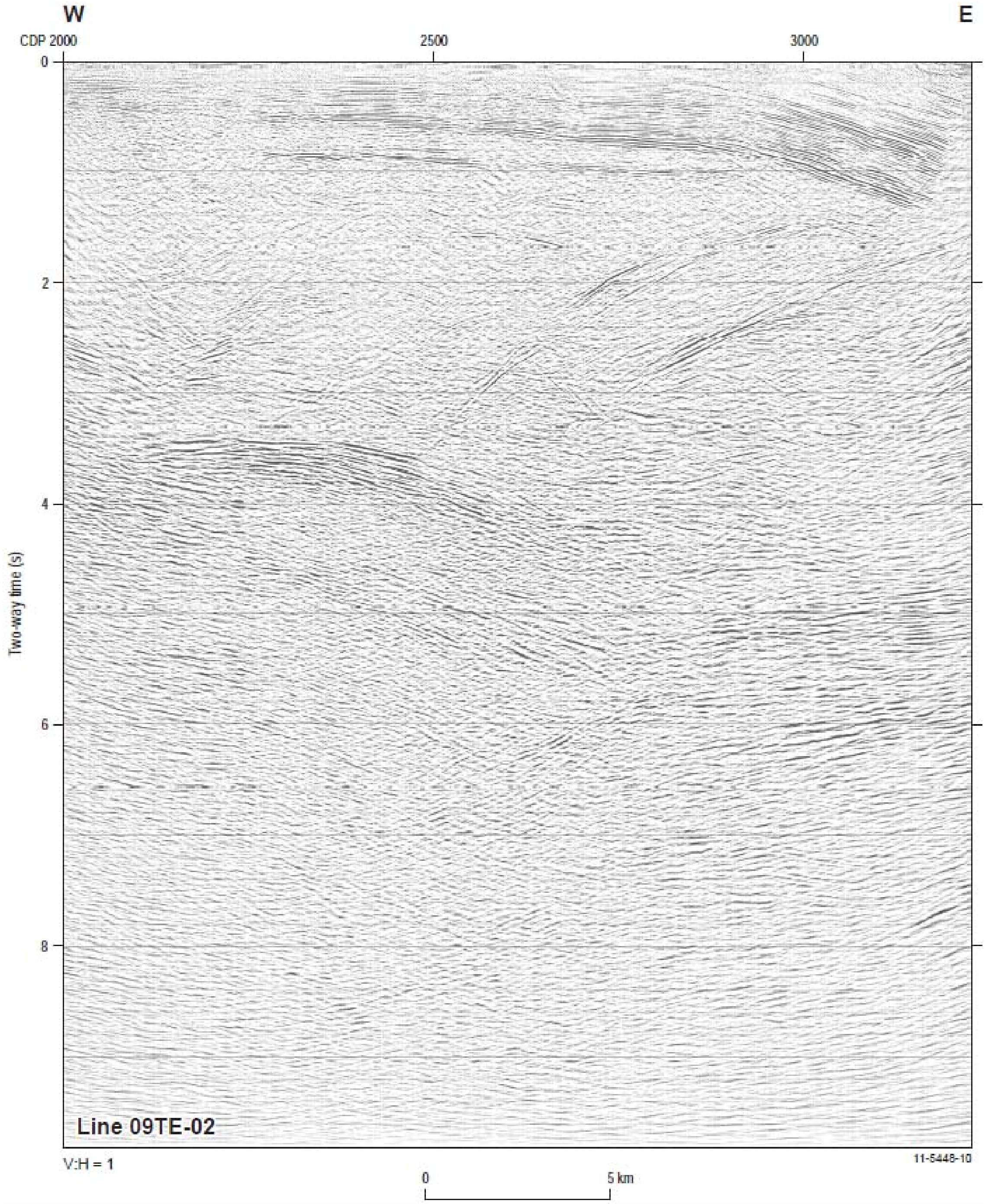


***Figure 11** Uninterpreted migrated seismic line 09TE-02, across the Arrowie Basin displayed at vertical: horizontal = 1:1, assuming average crustal velocity of 6000 ms^{-1}.*

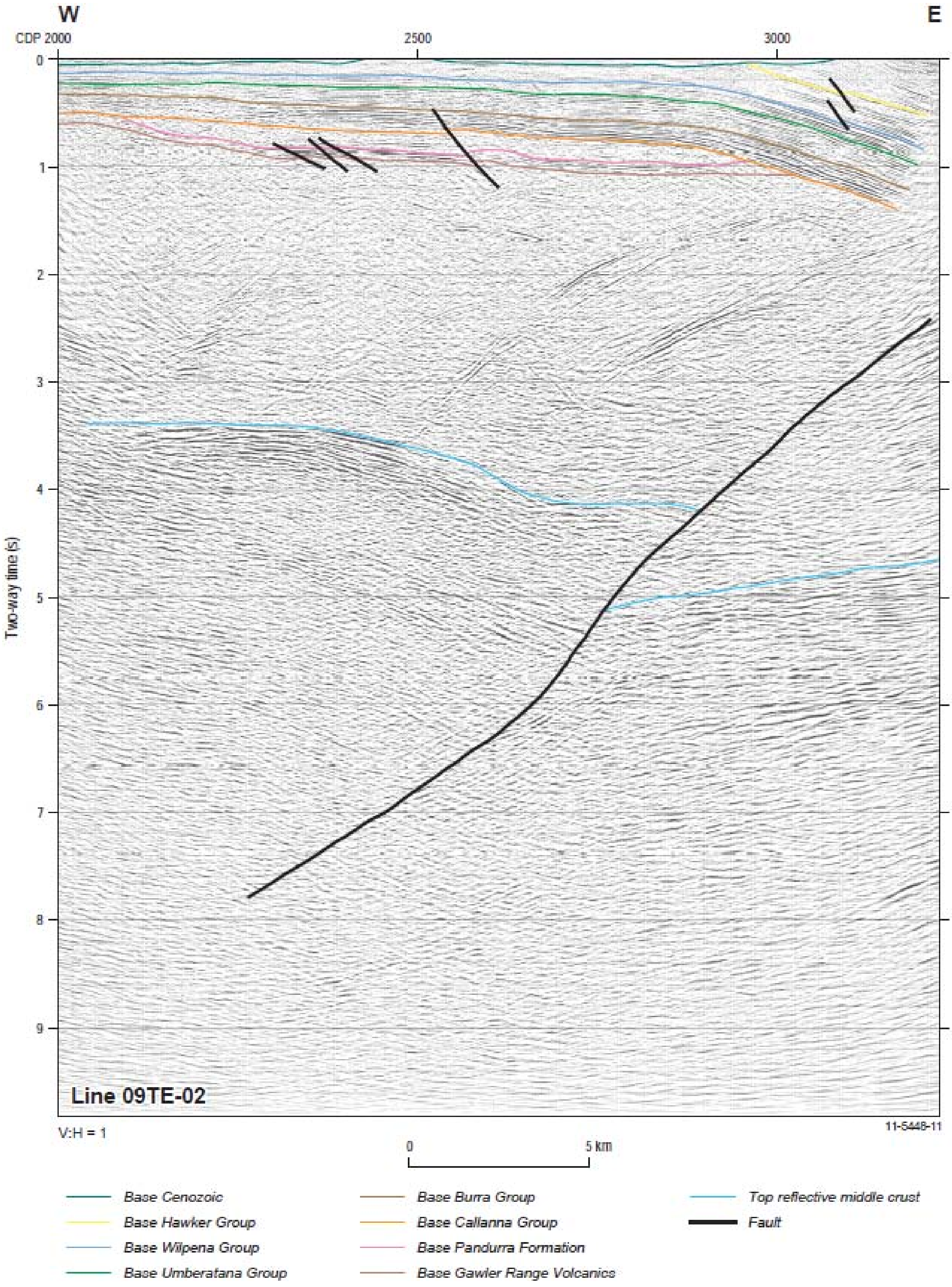


Figure 12 *Interpretation of migrated seismic line 09TE-02, across Arrowie Basin displayed at vertical: horizontal = 1:1, assuming average crustal velocity of 6000 ms^{-1}.*

Seismic line 09TE-03

The Nilpena seismic line (09TE-03), obtained for Torrens Energy Limited, imaged a 28 km long section to the north of the Parachilna seismic line 09TE-01, discussed above. Like seismic line 09TE-01, this line also images a thick Cambrian succession above the Neoproterozoic units, in contrast to the thinner successions on seismic lines 08GA-A1 and 09TE-02 to the south. The Neoproterozoic-Cambrian succession on seismic line 09TE-03 is between 1.5 s TWT (~3.75 km) and 3 s TWT (~7.5 km) thick (Figures 13 and 14).

The Ediacara Fault is projected from the north to cross the line of the section at about CDP 740. It is the western bounding fault to the Flinders Ranges and is currently active, with a thrust sense of movement. It has displaced the base of the Cenozoic succession from about 400 ms TWT (~1000 m) depth in the west to about 100 ms TWT (~250 m) in the east. We have interpreted it as a steeply east-dipping thrust fault; its geometry is constrained by truncations of the Neoproterozoic succession at depth to the east of the fault.

To the west of the Ediacara Fault, units of the Adelaide Rift System are interpreted to occur as a relatively flat-lying succession. The Callanna Group is variably reflective, over which sedimentary rocks of the Burra Group occur as a series of high amplitude, continuous, subparallel reflections. The Umberatana and Wilpena Groups are interpreted to overlie these units, as indistinct sets of low amplitude and discontinuous reflections. Minor contractional faults occur throughout the units in the Adelaide Rift System. A thick succession of Cambrian sedimentary rocks overlies the Neoproterozoic succession, and is interpreted to include Hawker Group and Billy Creek Formation.

A surface constraint is provided by the PARACHILNA 1:250 000 geological map (Reid and Preiss, 1999), where the Cambrian Wirrapowie Limestone is mapped between CDPs 750 and 900. The Torrens Energy Limited drill hole Nazgul 1 was drilled on the seismic section at about CDP 330 (Figure 14), and is used to constrain the Cambrian stratigraphy on the seismic section beneath the Cenozoic deposits. Within the Cenozoic succession, it is possible to map both the base of the Quaternary and the base of the Oligocene to Miocene Neuroodla Formation. The Nazgul 1 well was drilled to a depth of 600 m, penetrating the Cambrian Billy Creek Formation over the interval 384-592 m, with the Wilkawillina Formation below it.

East of the Ediacara Fault, the most obvious sequence boundary is the base of Umberatana Group, which overlies a major erosion surface. In the seismic section, there are several terminations and truncated reflections below this horizon. The Ediacara Fault has a complicated history, with evidence for initial extension, as seen by displacement of the sequence boundaries marking the bases of the Callanna and Burra Groups. This was followed by inversion, because units shallower than 1 s TWT, in the hangingwall on the eastern side, have been uplifted, showing a thrust sense of displacement. At least some of the thrust displacement is Quaternary in age, as the base of the Quaternary has been uplifted on the eastern side of the fault, relative to the western side.

The seismic line has imaged a half graben geometry to the east of the Ediacara Fault, indicating a significantly thicker Neoproterozoic to Cambrian succession in the east. The main thickening is in the Callanna and Burra Groups (from about 3.0 to 1.8 s TWT). The geometry indicates that the bounding fault to the half graben is west-dipping, but it has not been imaged in the seismic section. It is probably located close to the end of the section, but the edge effects due to the migration processing possibly mask any reflections in this area. The half-graben geometry is consistent with the geology to the east, in the Flinders Ranges, and the geology imaged in seismic lines such as 09GA-CG1.

Overall, the Neoproterozoic to Cambrian sedimentary package thins gradually to the west. Correlation of stratigraphic units across the Ediacara Fault is difficult, due to poor imaging in the vicinity of the fault and of the succession immediately west of the fault.

There are minor faults present in the section, although we have only interpreted a few of these. East of the Ediacara Fault there appear to be several thrusts with only minor displacement. West of the Ediacara Fault, we have interpreted a flower structure, possibly related to strike-slip faulting. Fault displacement decreases upwards and is transformed into an anticline, which is truncated at the unconformity at the base of the Cenozoic.

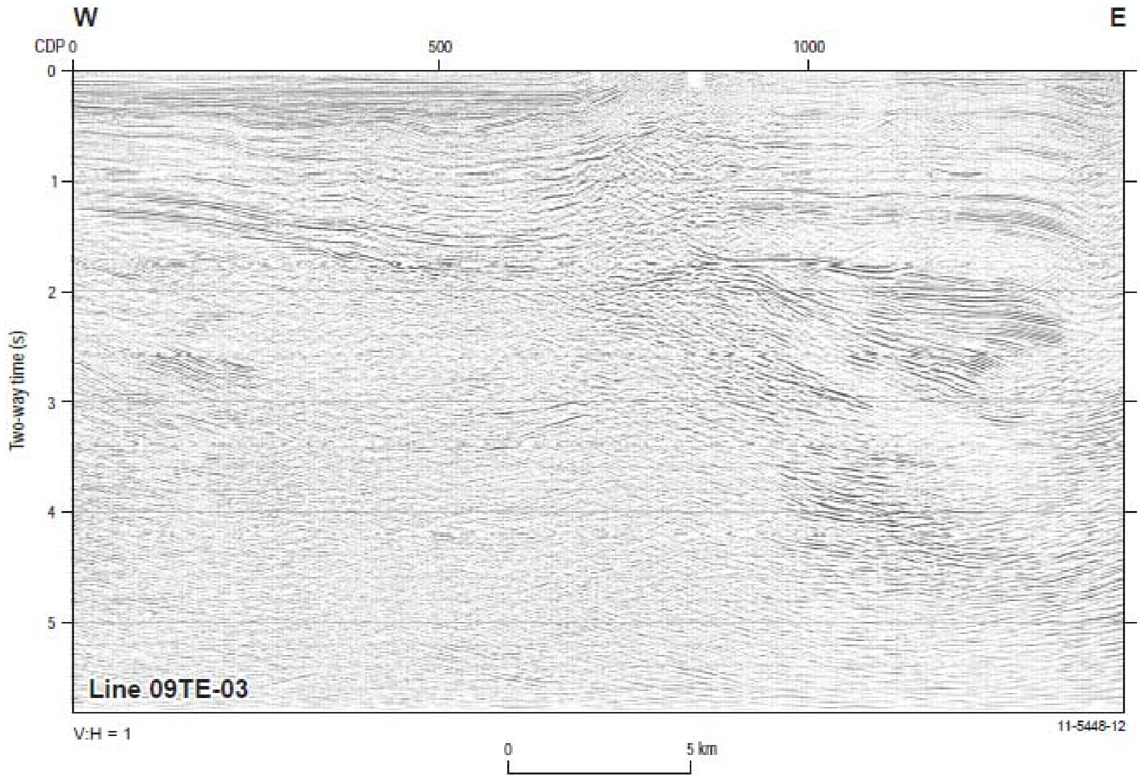


Figure 13 *Uninterpreted migrated seismic line 09TE-03, across the Arrowie Basin displayed at vertical: horizontal = 1:1, assuming average crustal velocity of 6000 ms^{-1}.*

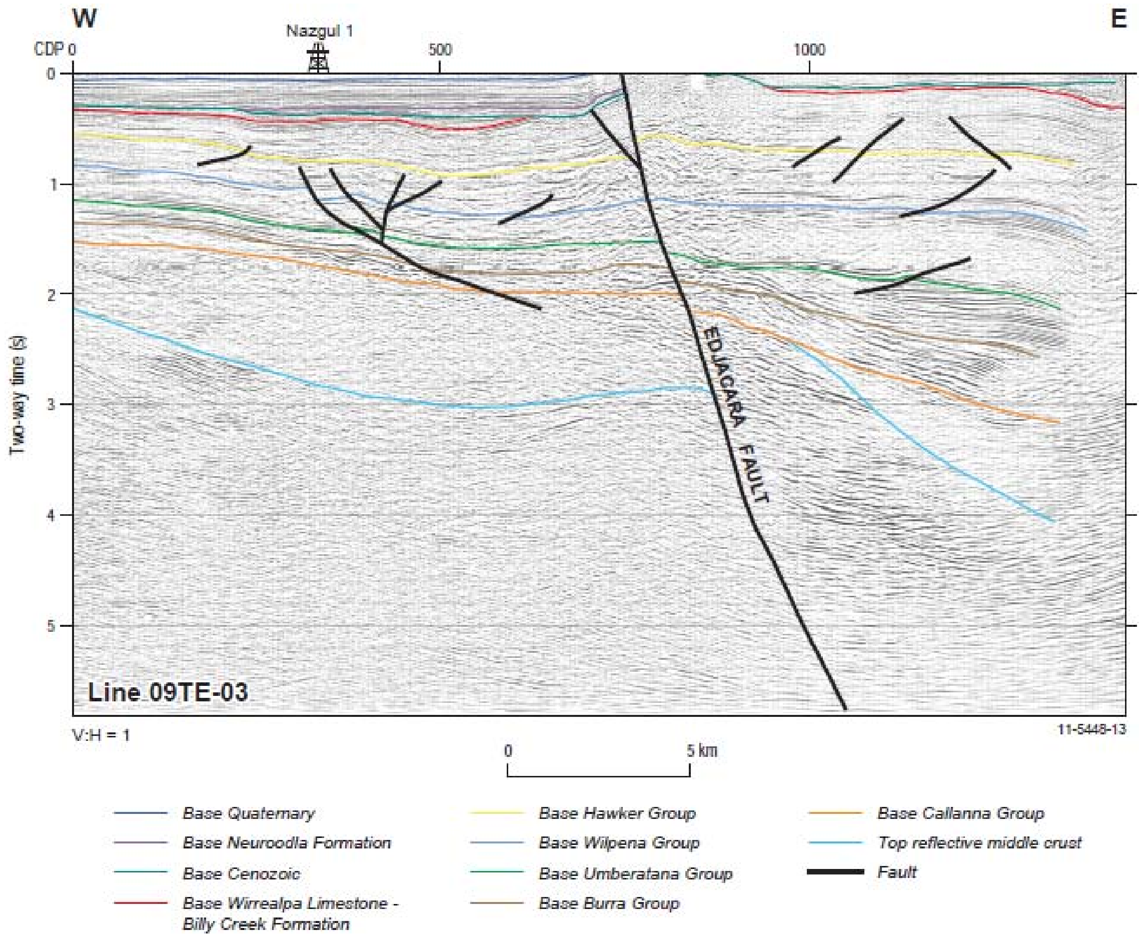


Figure 14 *Interpretation of migrated seismic line 09TE-03, across the Arrowie Basin displayed at vertical: horizontal = 1:1, assuming average crustal velocity of 6000 ms^{-1}.*

PETROLEUM SYSTEMS MATURATION MODELLING

Petroleum systems maturation modelling in the Arrowie Basin was carried out using the interpretation of stratigraphy and architecture of seismic line 08GA-A1, as discussed above, along with published geological information (Gravestock and Hibburt, 1991; McKirdy, 1994; Teasdale et al., 2001; Zang, 2002; Jago et al., 2002; Torrens Energy Limited, 2009). The greater part of the fill consists of Neoproterozoic sedimentary rocks of the Adelaide Rift System. These are overlain by very thin Cambrian units (Hawker and Lake Frome Groups) of the Arrowie Basin and a Cenozoic cover. The pseudo-well (see location in Figure 15) chosen for modelling, is located in the eastern part of the seismic line (08GA-A1), where the sedimentary section is thickest. Interpreted horizon picks were depth converted using stacking velocities for the nearest CDP, indicating that the section is about 4500 m thick.

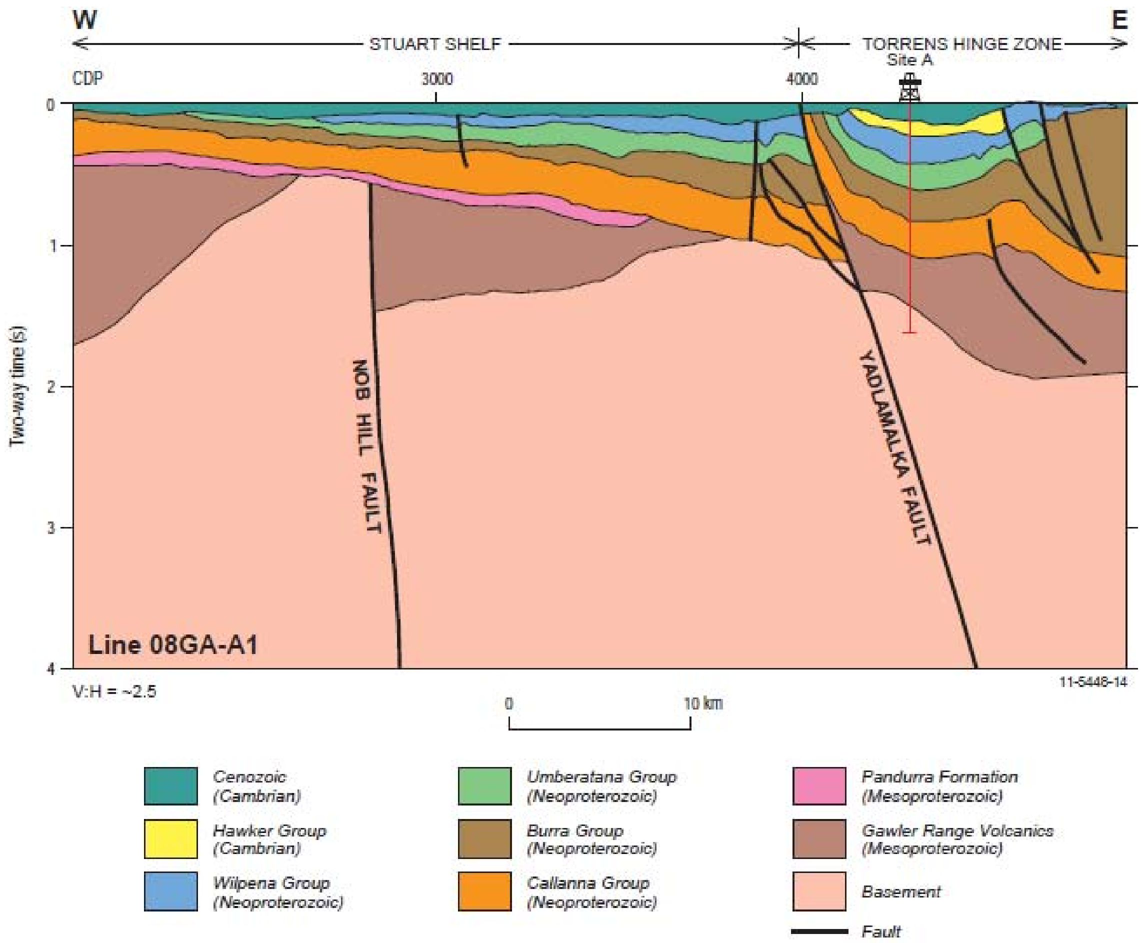


Figure 15 *Geological model of the Arrowie Basin, showing the location of the one dimensional model used for petroleum systems modelling.*

Input data

Input data for the modelling is shown in Table 1, and includes estimates of total organic carbon (TOC) content, reaction kinetics and initial hydrocarbon index (HI) for each source rock unit. The stratigraphic units and age interpretations are based on those of Gravestock and Hibburt (1991), Zang (2002), and Jago et al. (2002). The model also considers other aspects of the geological history, such as overburden and timing of erosion. The amount of erosion modelled includes 100 m of Neoproterozoic eroded during the late Neoproterozoic. It is also assumed, for the purpose of the model, that an additional 1000 m of Cambrian Hawker, Wirrealpa and Lake Frome Groups, were eroded during the late Cambrian (Delamerian Orogeny) and 300 m of Cenozoic was eroded during the Pliocene to Holocene. The Neoproterozoic Tindelpina Shale Member and the Cambrian Oraparinna Shale are considered to be the main potential source rocks (McKirdy, 1994), and were included as nominal source units for the modelling. The position of these units within the succession is estimated from the architecture described above. The choice of Type II, sulfur-rich kerogen kinetics is based on the high proportion of carbonate and probable algal-bacterial organic matter likely to have been deposited in the restricted shallow marine depositional environments.

Table 1 Main Input data for petroleum systems modelling at site A on seismic line 08GA-A1 in the Arrowie Basin.

Stratigraphic Unit	Top (m)	Base (m)	Thick (m)	Eroded (m)	Deposited from (Ma)	Deposited to (Ma)	Eroded from (Ma)	Eroded To (Ma)	Lithology[1]	PSE	TOC %	Kinetic	HI
Cenozoic	-60	15	75	300	23	12	12	0	Sst 60, Cgl 10, Slst 20, Sh 10	Seal rock			
Wirrealpa-Lake Frome Group	15	15	0	600	517	505	500	495	Lst 40, Sst 30, Slst 30	Overburden			
Hawker Group	15	15	0	400	522	517	495	490	Sst 40, Slst 25, Lst 25, Dol 10	Overburden			
Hawker Group	15	100	85		526	522			Sst 40, Slst 25, Lst 25, Dol 10	Reservoir			
Oraparinna Shale	100	160	60		530	526			Slst (org-rich 2-3 %) 60, Lst (Org-rich 1-2%) 40	Source rock	3	Pepper and Corvi (1995)	450
Hawker Group	160	280	120		535	530			Sst 40, Slst 25, Lst 25, Dol 10	Overburden			
Wilpena Group	280	280	0	100	570	560	560	550	Sst 55, Dol 25, Slst 15, Sh 5	Overburden			
Wilpena Group	280	700	420		635	570			Sst 55, Dol 25, Slst 15, Sh 5	Reservoir			
Upper Umberatana Group	700	900	200		655	635			Sst 70, Cgl 5, Slst 10, Dol 10, Sh 5.	Overburden			
Tindelpina Shale Member	900	1050	150		660	655			Sh (org-rich) 50, Lst (org-rich 1-2%) 50	Source rock	2	Pepper and Corvi (1995)	450
Lower Umberatana Group	1050	1190	140		700	660			Sst 60, Cgl 10, Sst (quartzite) 10, Sh 18, hematite 2	Underburden			
Burra Group	1190	1820	630		790	760			Sst 40, Sst (arkose) 10, Dol 40, Slst 10	Underburden			
Callanna Group	1820	2670	850		820	810			Sst 40, Sh 30, Slst 20, Salt 10	Underburden			

Stratigraphic Unit	Top (m)	Base (m)	Thick (m)	Eroded (m)	Deposited from (Ma)	Deposited to (Ma)	Eroded from (Ma)	Eroded To (Ma)	Lithology[1]	PSE	TOC %	Kinetic	HI
Callanna Group-salt	2670	3300	630		830	820			Anhydrite 15, halite 20, gypsum 30, Sh 35	Underburden			
Callanna Group - volcanics	3300	4400	1100		850	830			Basalt 50, rhyolite 30, tuff 20	Underburden			
Mesoproterozoic Basement	4400	5000	600		1050	1000			Granite	Underburden			
						1050							

[1]Sst = Sandstone, Cgl = Conglomerate, Slst = Siltstone, Sh = Shale, Lst = Limestone, Dol = Dolomite.

Boundary conditions, burial history and maturity

Boundary conditions for the geohistory modelling include palaeowater depths, temperatures at the sediment-water interface (SWIT), and heat flow through time. The palaeowater depths are based on regional geology, with most deposition likely to have occurred in shallow to very shallow marine and terrestrial environments. The Cambrian deformational period was modelled as uplift. Sediment-water interface (SWIT) temperatures are based on calculations provided by the software (PetroMod v11 SP2) for a present-day latitude of 32ºS.

The site of the model is located near the eastern edge of the South Australian heat flow anomaly (Neumann et al., 2000), with anomalously high surface heat flow of 92 mWm^{-2} due to Proterozoic granites at depth. Measured temperatures from geothermal wells located to the north of the modelled site indicate heat flows ranging between 74 and 120 mWm^{-2} (Torrens Energy Limited, 2009) A present day heat flow of 80 mWm^{-2} was used as input for the modelling (Table 2, Figure 16).

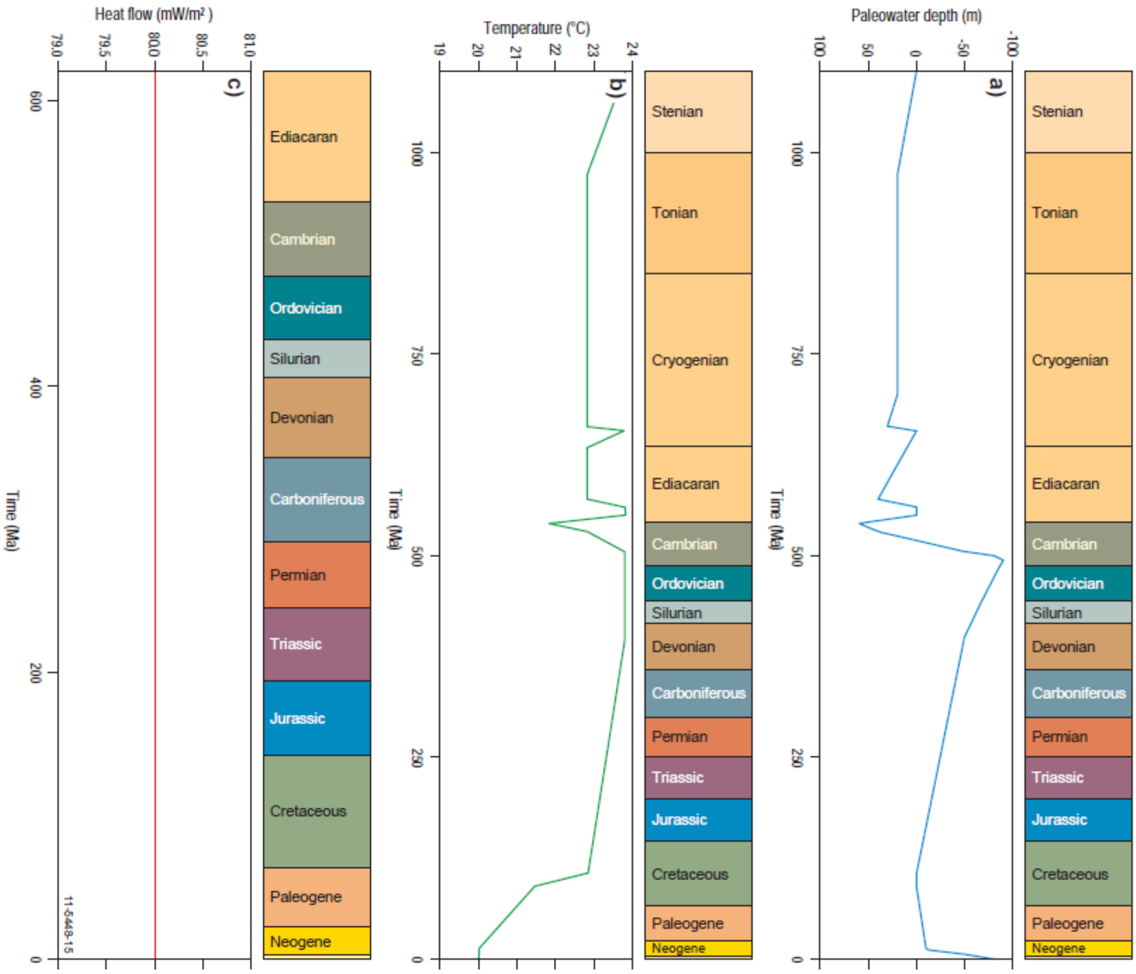


Figure 16 *Boundary conditions modelled for the Arrowie Basin, including* ***a)*** *paleowater depth,* ***b)*** *sediment water interface (SWIT), and* ***c)*** *heat flow through time.*

Table 2 Boundary conditions for palaeowater depth (PWD), temperature of sediment-water interface (SWIT), and heat flow (HF).

Age (Ma)	PWD (m)	Age (Ma)	SWIT (°C)	Age (Ma)	HF (mWm^{-2})
0	-60	0	20	0	80
12	-10	12	20	200	80
90	0	90	21.44	540	80
106	0	106	22.65	620	80
400	-50	400	23.81		
450	-70	450	23.81		
495	-90	495	23.81		
500	-80	500	23.81		
505	-50	505	23.81		
530	40	530	22.81		
540	60	540	21.81		
550	0	550	23.81		
560	0	560	23.81		
570	40	570	22.81		
635	10	635	22.81		
655	0	655	23.81		
660	30	660	22.81		
700	20	700	22.81		
800	20	800	22.81		
920	20	920	22.81		
970	20	970	22.81		
1100	0	1100	23.81		

The resulting burial history, (Figure 17), shows rapid burial during the Late Proterozoic (Cryogenian) and Cambrian, followed by uplift and erosion in the late Cambrian (Delamerian Orogeny). In this model, the remainder of the Phanerozoic is assumed to represent a long hiatus until deposition recommenced in the Cenozoic. Relatively minor uplift and erosion is implied for the last 5 Ma until the present. Tingate et al. (2007) proposed several kilometre-scale uplift events for the late Cambrian, Carboniferous, Cretaceous and Neogene, based on AFTA® data from the Blinman 2 drillhole, located more than 50 km to the north of the modelled site, in the central Flinders Ranges. Blinman 2 drillhole, however, is located adjacent to the Blinman Diapir, and the maturity and uplift history for this well, therefore, are not considered necessarily representative of other areas in the Flinders Ranges.

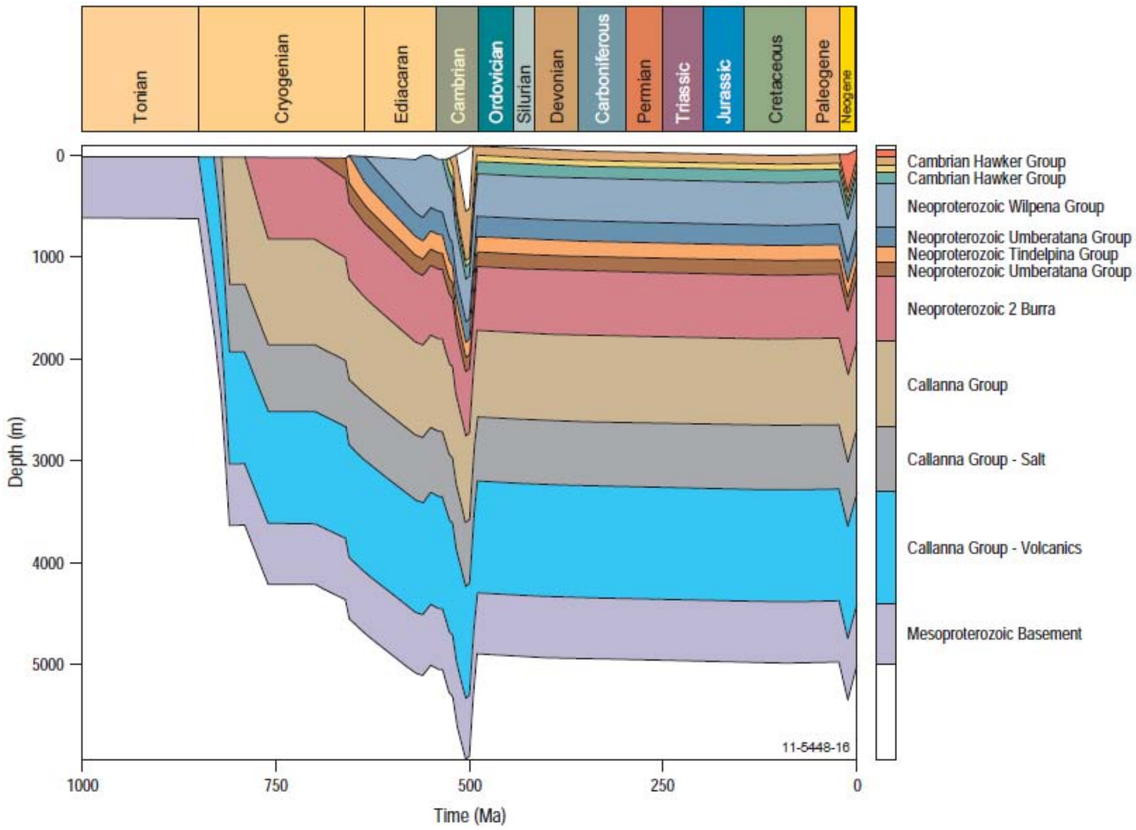
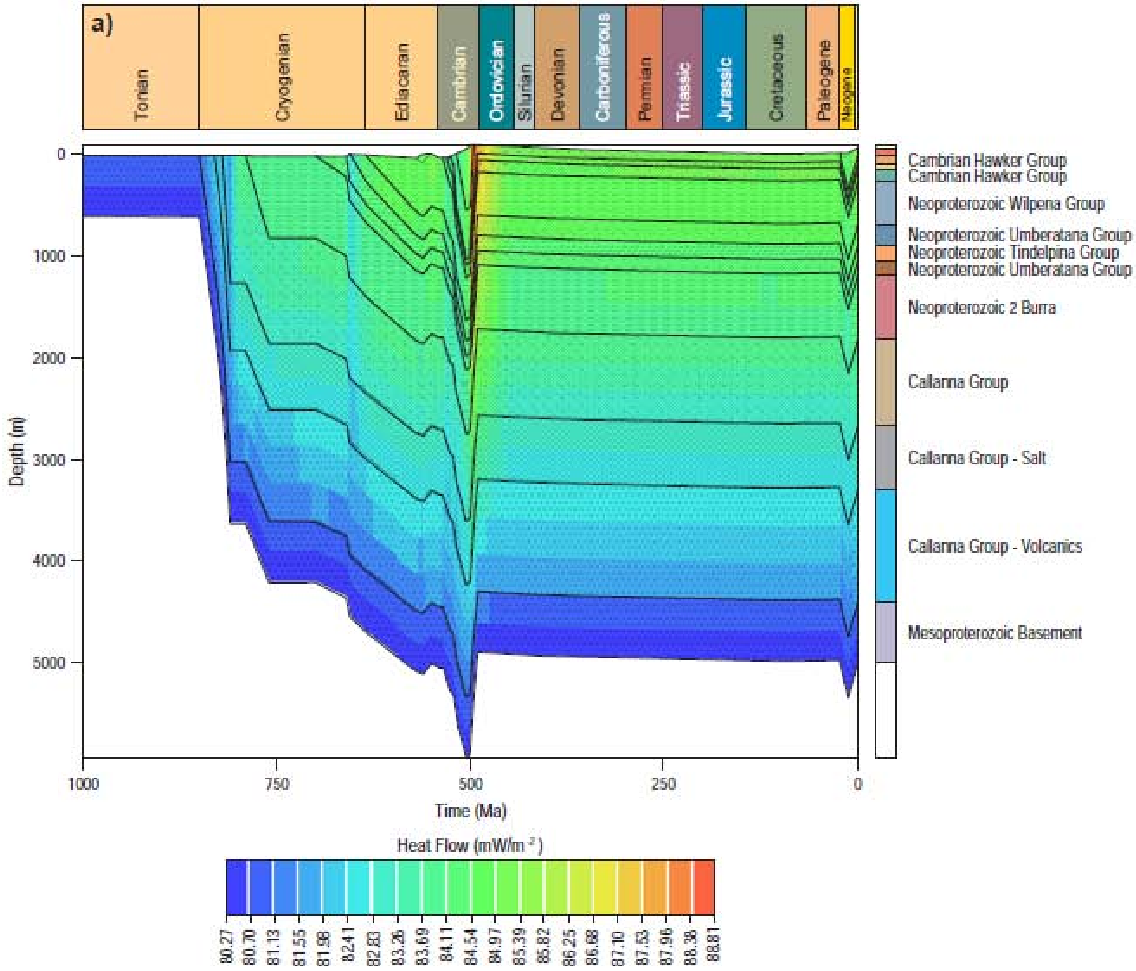
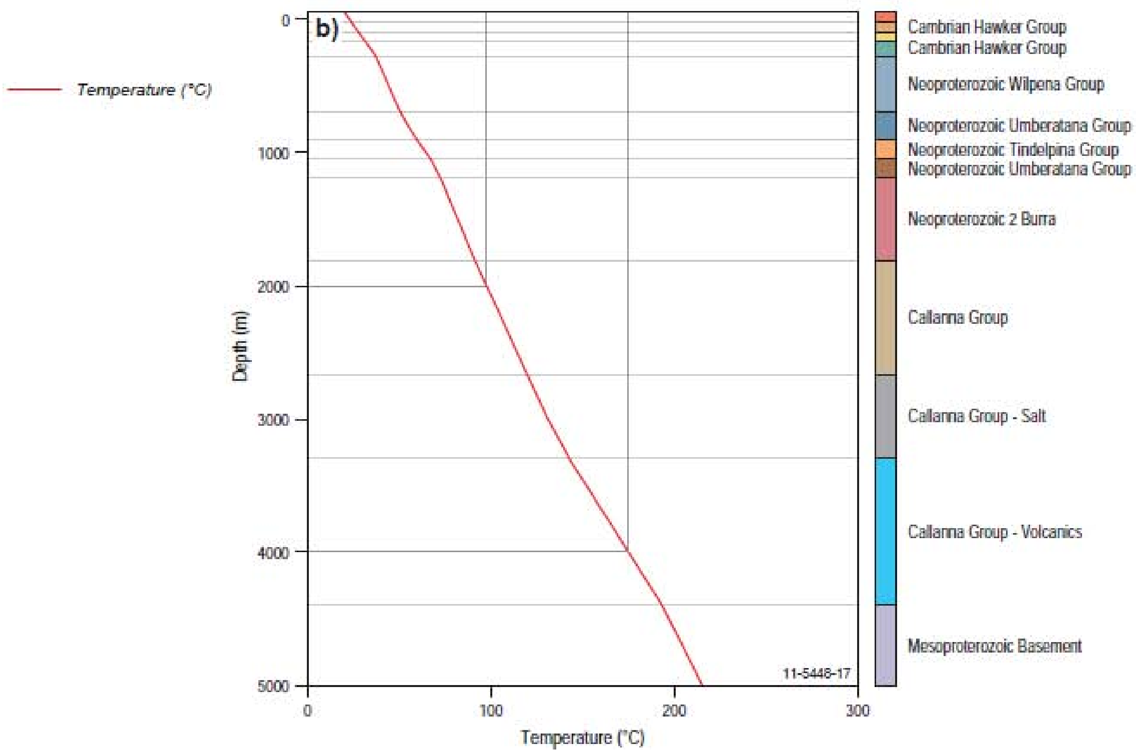


Figure 17 *Results from petroleum systems maturation modelling at site A in the Arrowie Basin: burial history plot modelled with rapid late Proterozoic and Cambrian burial, and minor uplift in the last 5 Ma.*

The assumed surface heat flow and lithologies suggest a present-day temperature of about 70ºC at a depth of 1 km, 100ºC at 2 km, and 180ºC at 4 km. This is slightly lower than the temperature of 98.4ºC recorded in Treebeard 1A at a depth of 1807m, but broadly consistent with regionally measured heat flows and measured temperatures (Torrens Energy Limited, 2009, 2010)

Figure 18 (next page) *Results from petroleum systems maturation modelling at site A in the Arrowie Basin.* ***a)*** *Modelled heatflow superimposed on the burial history plot.* ***b)*** *Plot of temperature versus depth for site A in the Arrowie Basin.*


a)
Tonian
Cryogenian
Ediacaran
Cambrian
Ordovician
Silurian
Devonian
Carboniferous
Permian
Triassic
Jurassic
Cretaceous
Paleogene
Neogene
Depth (m)
Time (Ma)
Heat Flow (mW/m 2)
80.27
80.70
81.13
81.55
81.98
82.41
82.83
83.26
83.69
84.11
84.54
84.97
85.39
85.82
86.25
86.68
87.10
87.53
87.96
88.38
88.81
Cambrian Hawker Group
Cambrian Hawker Group
Neoproterozoic Wilpena Group
Neoproterozoic Umberatana Group
Neoproterozoic Tindelpina Group
Neoproterozoic Umberatana Group
Neoproterozoic 2 Burra
Callanna Group
Callanna Group - Salt
Callanna Group - Volcanics
Mesoproterozoic Basement


b)
Temperature (°C)
Depth (m)
Temperature (°C)
11-5448-17
Cambrian Hawker Group
Cambrian Hawker Group
Neoproterozoic Wilpena Group
Neoproterozoic Umberatana Group
Neoproterozoic Tindelpina Group
Neoproterozoic Umberatana Group
Neoproterozoic 2 Burra
Callanna Group
Callanna Group - Salt
Callanna Group - Volcanics
Mesoproterozoic Basement

The modelled maturity profile suggests that potential Neoproterozoic source rocks, such as the Tindelpina Shale Member of the Tapley Hill Formation (Umberatana Group), are currently in the oil window (Figure 19a). In contrast, the Cambrian units at this location are likely to be immature for oil generation. In comparison, modelled maturity values for a site to the north of the Arrowie seismic line (at approximate location of Treebeard 1A well), where erosion of the Cambrian section during the Delamerian Orogeny was less severe, suggests that potential Cambrian source rocks are mature for oil and gas generation. To the north, the Neoproterozoic source rocks are probably late gas mature to overmature. Thus, the maturity levels of potential Cambrian source rocks are likely to vary considerably, depending on the depth of burial and amount of erosion of the Cambrian succession across the basin.

The predicted porosity versus depth for the model shows that porosities of 20% or higher are predicted to about 800 m depth and of 15% or higher down to about 1800 m depth (Figure 19b). The maturity overlay on the burial history plot clearly shows that rapid burial during the Cambrian brought potential Neoproterozoic source rocks of the Tindelpina Shale Member into the oil window (Figure 20). Subsequent uplift and erosion resulted in these rocks staying at the same maturity level throughout their remaining burial history. Late Cenozoic burial is considered unlikely to have been sufficient to increase maturity levels. The modelling predicts that only Cenozoic deposition and erosion in excess of 1 km will result in very minor increases in the kerogen transformation ratio.

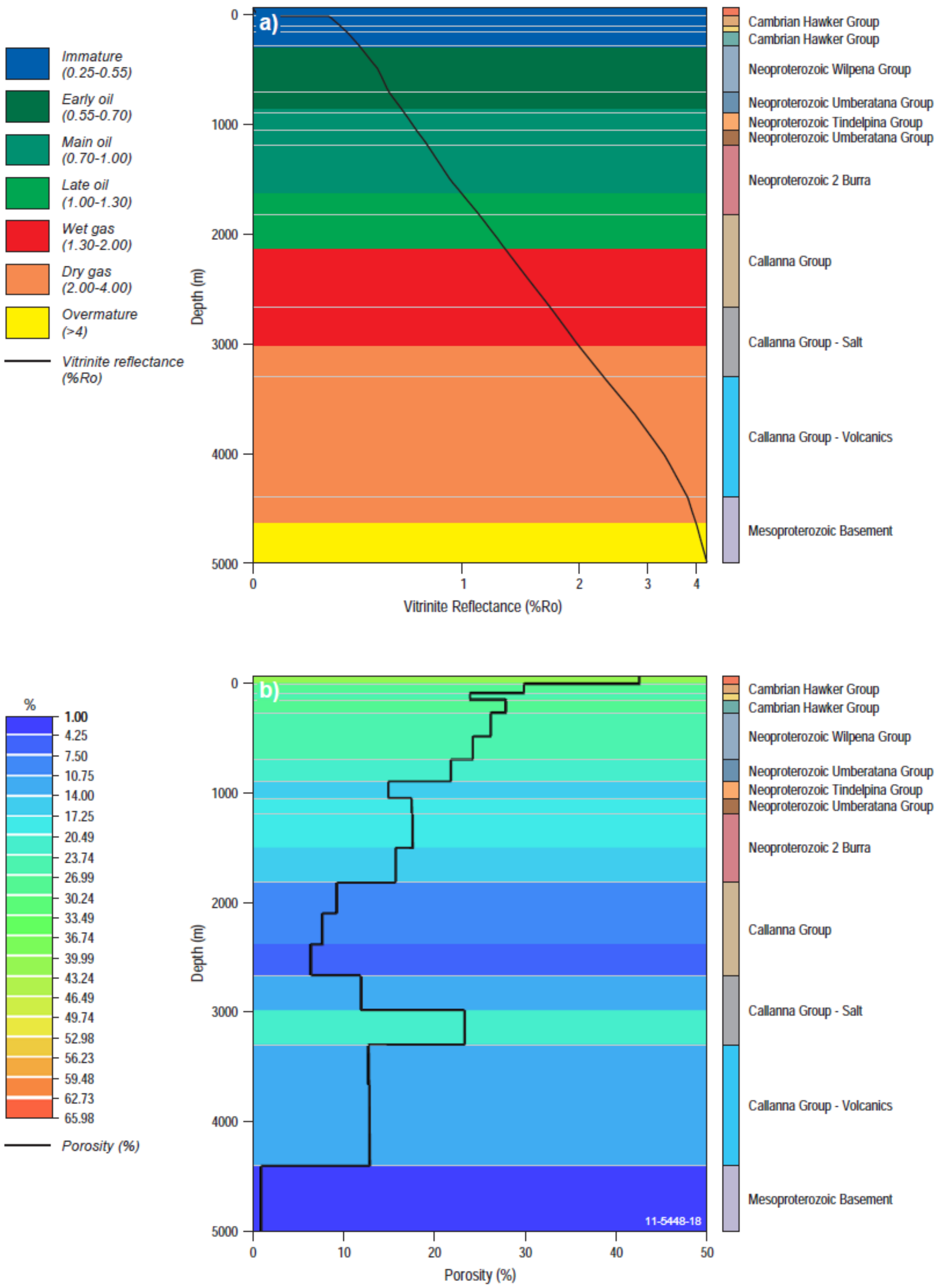


Figure 19 *Results from petroleum systems maturation modelling at site A in the Arrowie Basin.* ***a)*** *Modelled maturity profile showing depth versus vitrinite reflectance.* ***b)*** *Plot of predicted porosity versus depth.*

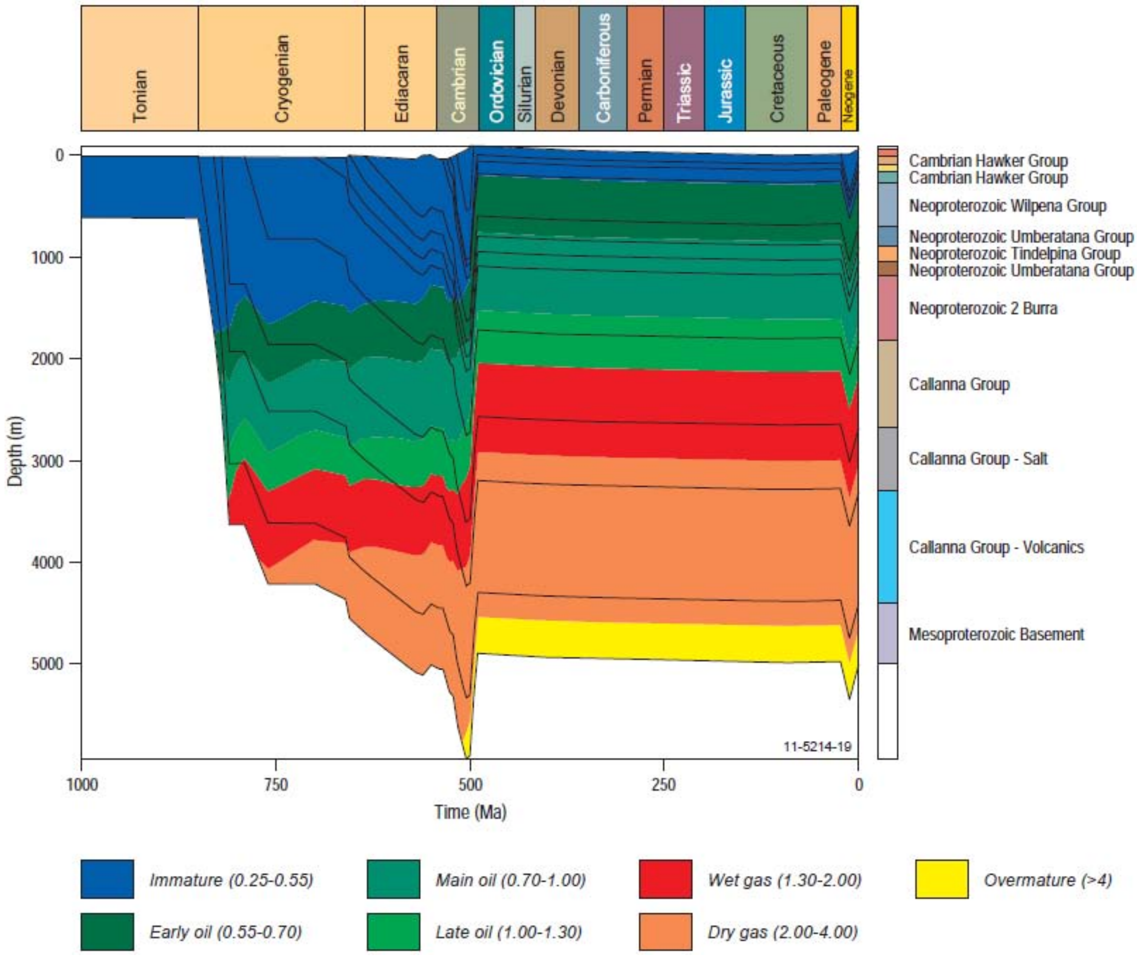


Figure 20 *Results from petroleum systems maturation modelling at site A in the Arrowie Basin, showing modelled maturity superimposed on the burial history plot.*

The temperature overlay on the burial history plot shows that the present-day temperature at 5 km is about 220ºC (Figure 21). The implied gradient is consistent with a predicted temperature of 180ºC at about 5 km depth. For the Neoproterozoic source, the Tindelpina Shale Member, about 60% of the available kerogen was transformed by the late Cambrian, resulting in the early expulsion of oil and minor gas (Figure 22). This means that close to 60% of available kerogen is likely to have been transformed by the late Cambrian, with later events (e.g. Cenozoic) having no noticeable effect. Expulsion of oil and minor gas is likely to have occurred during the middle to late Cambrian, prior to uplift and erosion during the late Cambrian (Figure 24). The kerogen transformation ratio plot for the modelled Cambrian source layer, the Oraparinna Shale, shows that only about 4% of available kerogen was transformed by the late Cambrian, with later events (for example, the Cenozoic) having no noticeable effect. As a result, the model predicts no expulsion of oil and gas for this particular site (Figure 23).

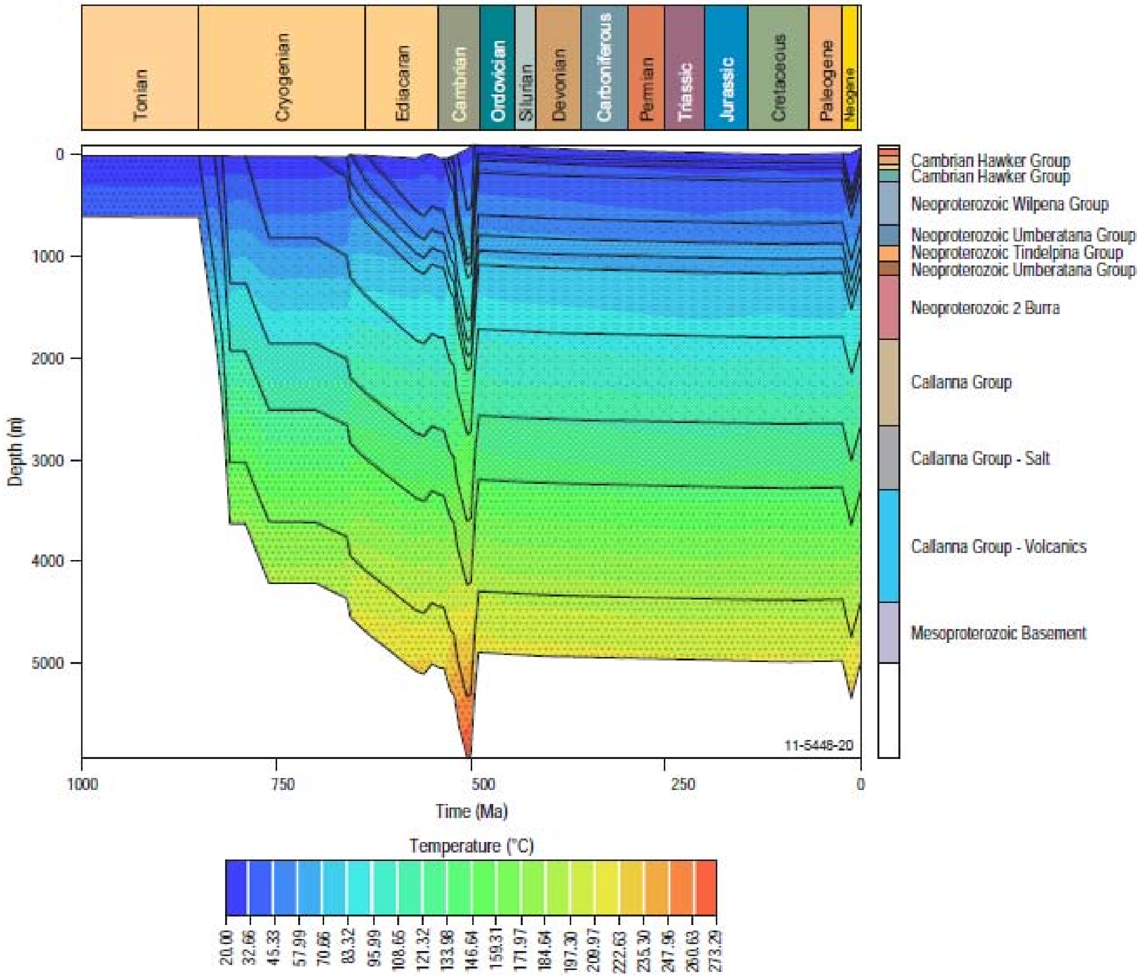


Figure 21 *Results from petroleum systems maturation modelling at site A in the Arrowie Basin, showing modelled temperature overlain on burial history curves.*

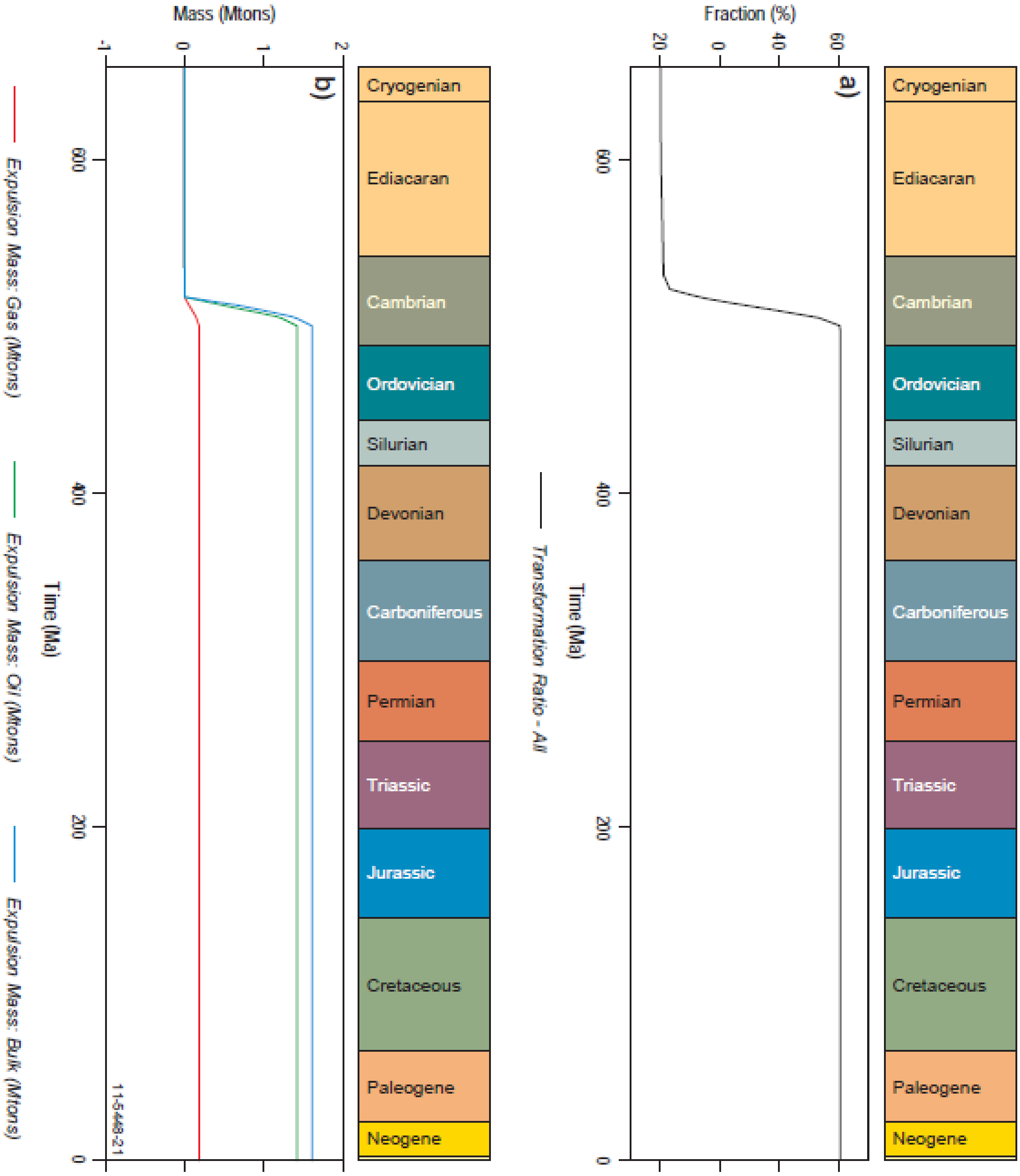


Figure 22 *Modelled Neoproterozoic source rock - Tindelpina Shale Member - showing* ***a****) the fraction of kerogen transformed, and,* ***b)*** *early oil and gas expulsion.*

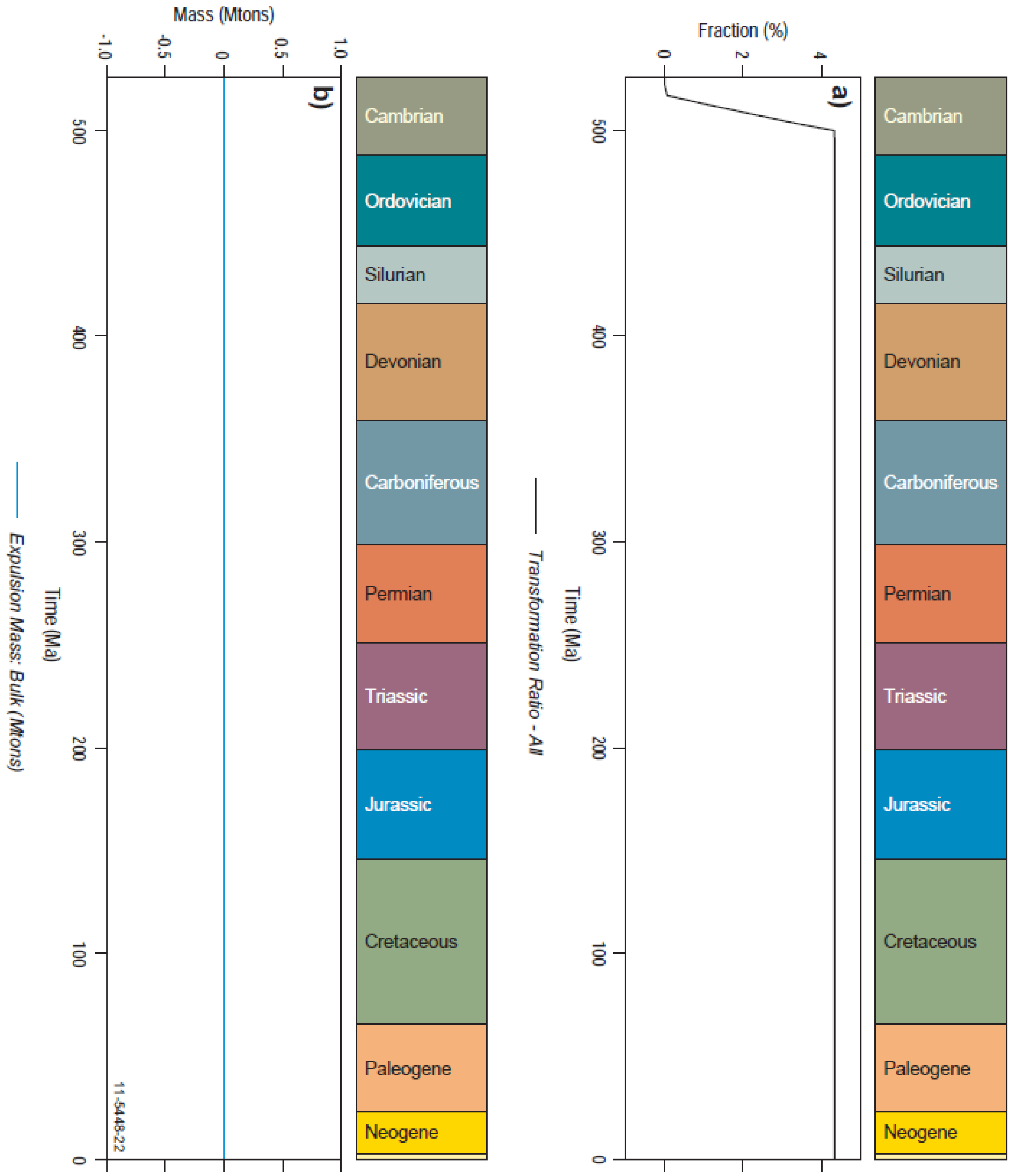


Figure 23 *Modelled Cambrian source rock - Oraparinna Shale - showing* ***a)*** *the fraction of kerogen transformed and,* ***b)*** *expulsion (nil).*

Proposed petroleum systems events chart, Arrowie Basin

In summary, the modelling at site A in the Arrowie Basin shows that the generation and expulsion of hydrocarbons from mature source rocks occurred early during the burial history, and mostly prior to the late Cambrian, and this is consistent with previous findings (McKirdy, 1994). Potential Cambrian source rocks are probably immature to mature for oil generation at the modelled site in the Arrowie Basin. In contrast, potential Neoproterozoic source rocks are likely to be mature to overmature for oil generation, and immature to mature for gas generation. In a more regional context, the maturity level of potential source units is dependent on the thickness of the Cambrian overburden, and the amount of uplift and erosion associated with the Delamerian Orogeny. Cenozoic burial appears to have had little effect on generation and expulsion. With hydrocarbon systems clearly present in the Arrowie Basin, future work, possibly with a focus on unconventional hydrocarbons, would be warranted.

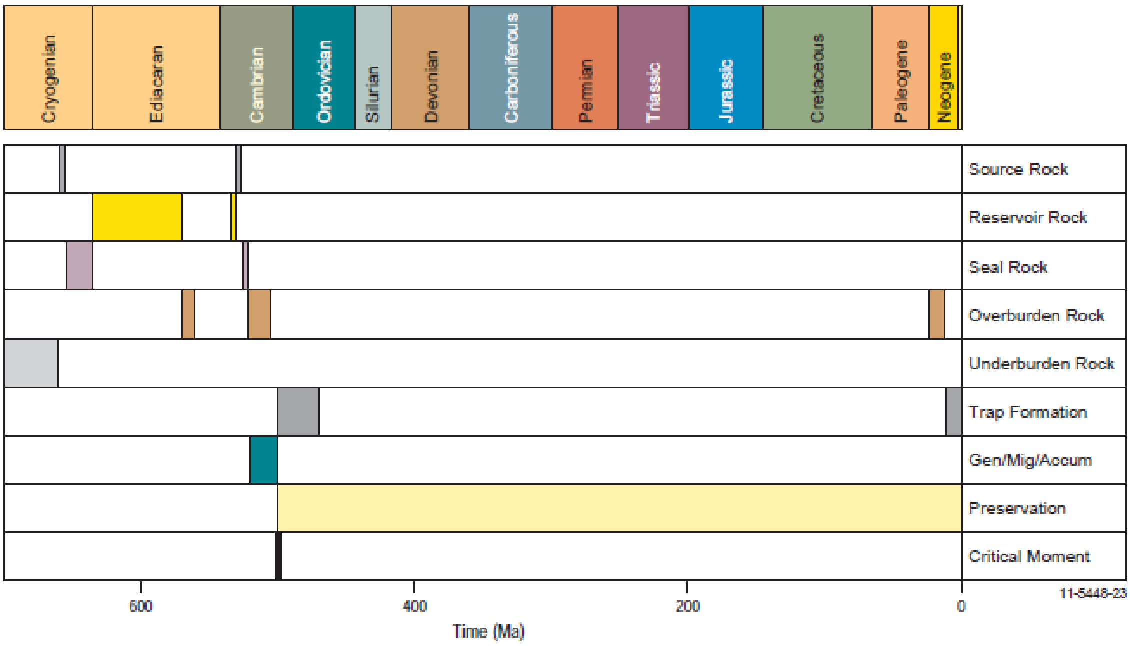


__Figure 24__ Proposed petroleum systems events chart, for the Arrowie Basin.

Georgina Basin, Northwest Queensland: Burke River Structural Zone

AIM OF SEISMIC SURVEY

In 2006, Geoscience Australia, in conjunction with the Geological Survey of Queensland, the Predictive Mineral Discovery Cooperative Research Centre and Zinifex Limited, acquired a 283 line km deep seismic reflection transect (06GA-M6) across the Burke River Structural Zone of the Georgina Basin in Queensland (Figures 25-27), as part of a larger, ~900 km line survey focussing on the Mount Isa Province (Hutton and Korsch, 2008).

Seismic line 06GA-M6 was designed to investigate the possibility of structural and stratigraphic hydrocarbon traps formed during the Late Ordovician to Carboniferous (450–300 Ma) Alice Springs Orogeny, to evaluate the depth of burial of known Cambrian source rocks in the Georgina Basin, and to image the rocks forming the basement Mount Isa Province in this region. Although the southern Georgina Basin is considered a significant potential hydrocarbon source, and includes a largely unexplored middle Cambrian petroleum system (Ambrose et al., 2001), only limited exploration has occurred, most of it in the Northern Territory. Following the discovery of hydrocarbon indicators in water bores drilled into the Cambrian succession, exploration included several petroleum exploration wells, which were unsuccessful (Ambrose et al., 2001). In recent times, the Georgina Basin has again been the subject of exploration, for both unconventional and conventional hydrocarbons, including the drilling of Macintyre 2 within the basin (Baraka Energy and Resources, 2011), and the publication of a report on the shale gas potential of the Georgina Basin (Tiem et al., 2011).

GEOLOGY OF THE GEORGINA BASIN

The Georgina Basin is a northwest-southeast trending extensional basin, which covers up to 325,000 km^2 in both Queensland and the Northern Territory. The Georgina Basin is a component of the largely Neoproterozoic Centralian Superbasin (Walter et al., 1995). Other components of this superbasin include the Amadeus, Officer and Ngalia basins, and resulted from the breakup and erosion of the Rodinia Supercontinent (de Vries et al., 2008). It is bounded by Proterozoic rocks of the Mount Isa Province and Lawn Hill Platform to the north, the Tennant Creek Region to the west, and Arunta Region to the south (Southgate and Shergold, 1991). The basin contains thick successions of Neoproterzoic through to Lower Devonian sedimentary rocks and potential Cambrian hydrocarbon systems, with some parts of the Northern Territory portion of the basin considered to be within the oil window, with prospective Cambrian and Ordovician carbonate and clastic sedimentary rocks (Questa, 1994).

Neoproterozoic extension in the Georgina Basin was followed by thermal subsidence, resulting in lower Cambrian sediments being deposited mainly in the south. It was not until the mid Cambrian that marine conditions became widespread and deposition of marine facies occurred throughout the basin. Units deposited at this time included the sandstone, conglomerate, shale and mudstone of the Mount Birnie beds. These are overlain by carbonate and potential source rocks of the Thorntonia Limestone, which includes sections of chert. The overlying Beetle Creek Formation contains siltstone, chert and shale, which is also an important source of phosphate, with phosphorite and phosphatic siltstone both occurring in the region (Southgate and Shergold, 1991).

The Georgina Basin in Queensland has had limited exploration for hydrocarbons, with few seismic surveys conducted, with the exception of a grid around the Ethabuka 1 well in the Toko Syncline. In the vicinity of 06GA-M6 seismic line, the region (Blake et al., 1983; Casey et al., 1967) has been explored for phosphates, and subject to shallow stratigraphic drilling in 1986-7 (Southgate et al, 1988), with the only nearby stratigraphic well control for the seismic line being the Duchess 18 drillhole. There are also several petroleum wells in the region, including Black Mountain 1, Canary 1, Bean Tree 1 and Elizabeth Springs 1, but none are helpful for stratigraphic control, due to their distance from the seismic line. Although exploration drilling has been limited, there are several known middle to late Cambrian prospective petroleum systems in the Northern Territory component of the Georgina Basin (Boreham and Ambrose, 2007), with numerous oil and gas shows and solid bitumen recovered from drillcore (Volk et al., 2007). Recently, Draper (2007) has suggested the presence of an lower Paleozoic carbonate petroleum system in the Georgina Basin in Queensland, and he considers that although the Toko Syncline is more prospective, the Burke River Structural Belt is still worthy of further exploration.

The stratigraphy discussed by Draper (2007) describes the sedimentary rocks of the Burke River Structure Belt sitting on the basement of the Mount Isa Province, in contrast to the Toko Syncline to the west, which overlies the Arunta Province. The orientation of major structures in the basin has been inherited predominantly from the underlying basement. This is evident on the magnetics image (Figure 27), which shows a complex, north-south trend for structures in the area, in contrast to the northwest-southeast trends in the Toko Syncline to the west (Draper, 2007). The gravity image also shows the same north–south trending features (Figure 26).

Both the Mount Birnie beds and Thorntonia Limestone are interpreted to occur on seismic line 06GA-M6, and are collectively overlain by a series of carbonate and siliciclastic formations, which include the Cambrian O'Hara Shale, Pomegranate Limestone and Chatsworth Limestone, and the Cambro-Ordovician Ninmaroo Formation (Blake et al., 1983) (Figure 28). The Arthur Creek Formation, which occurs in the western Georgina Basin is equivalent to the Devoncourt Limestone in the east, and is used as an equivalent in the petroleum systems maturation modelling discussed below.

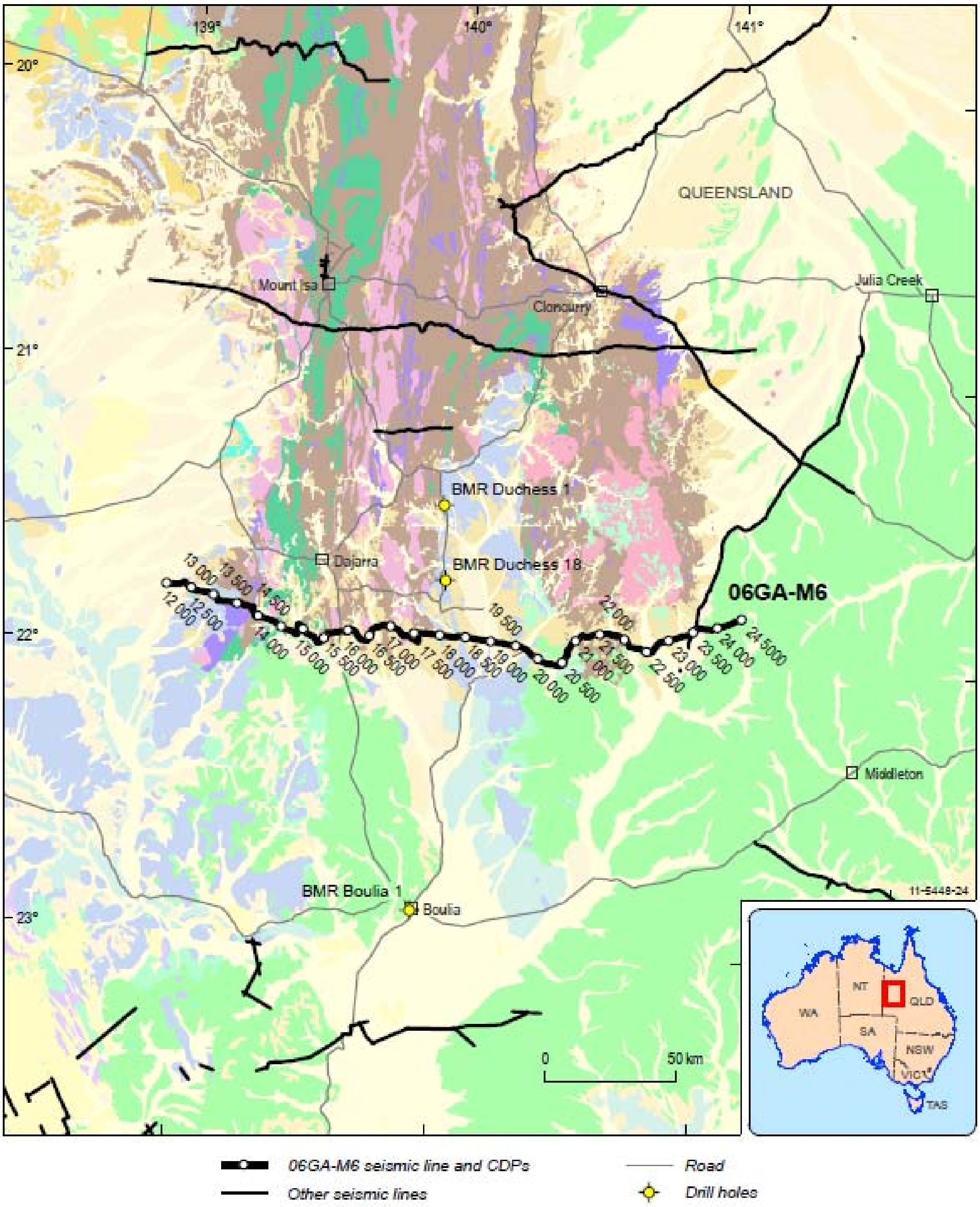


***Figure 25** Map of the surface geology showing the location of seismic line 06GA-M6 across the Burke River Structural Zone, Queensland. Numbers on the seismic line represent CDP locations.*

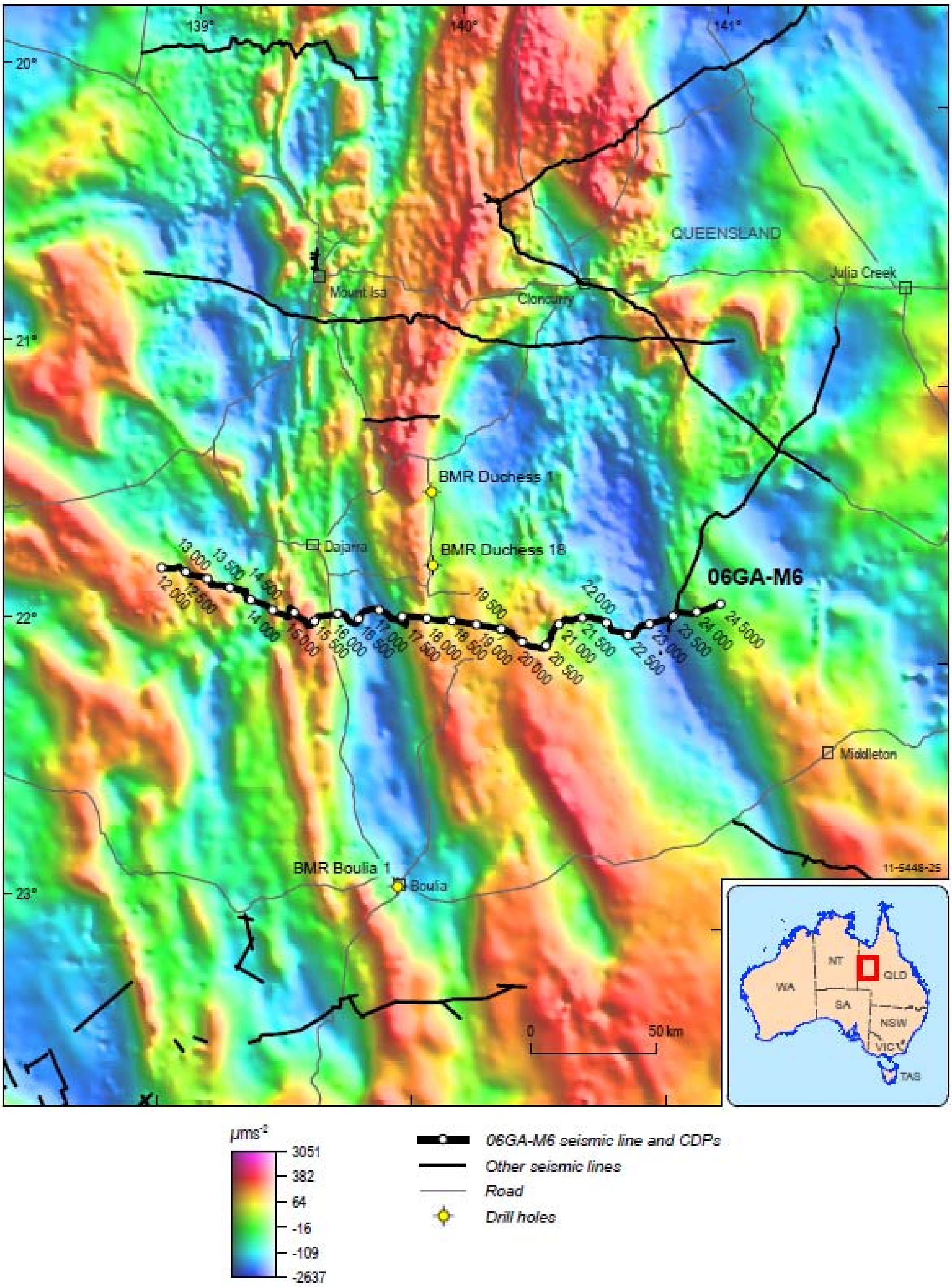


Figure 26 *Gravity image showing the location of seismic line 06GA-M6 across the Burke River Structural Zone, Queensland.*

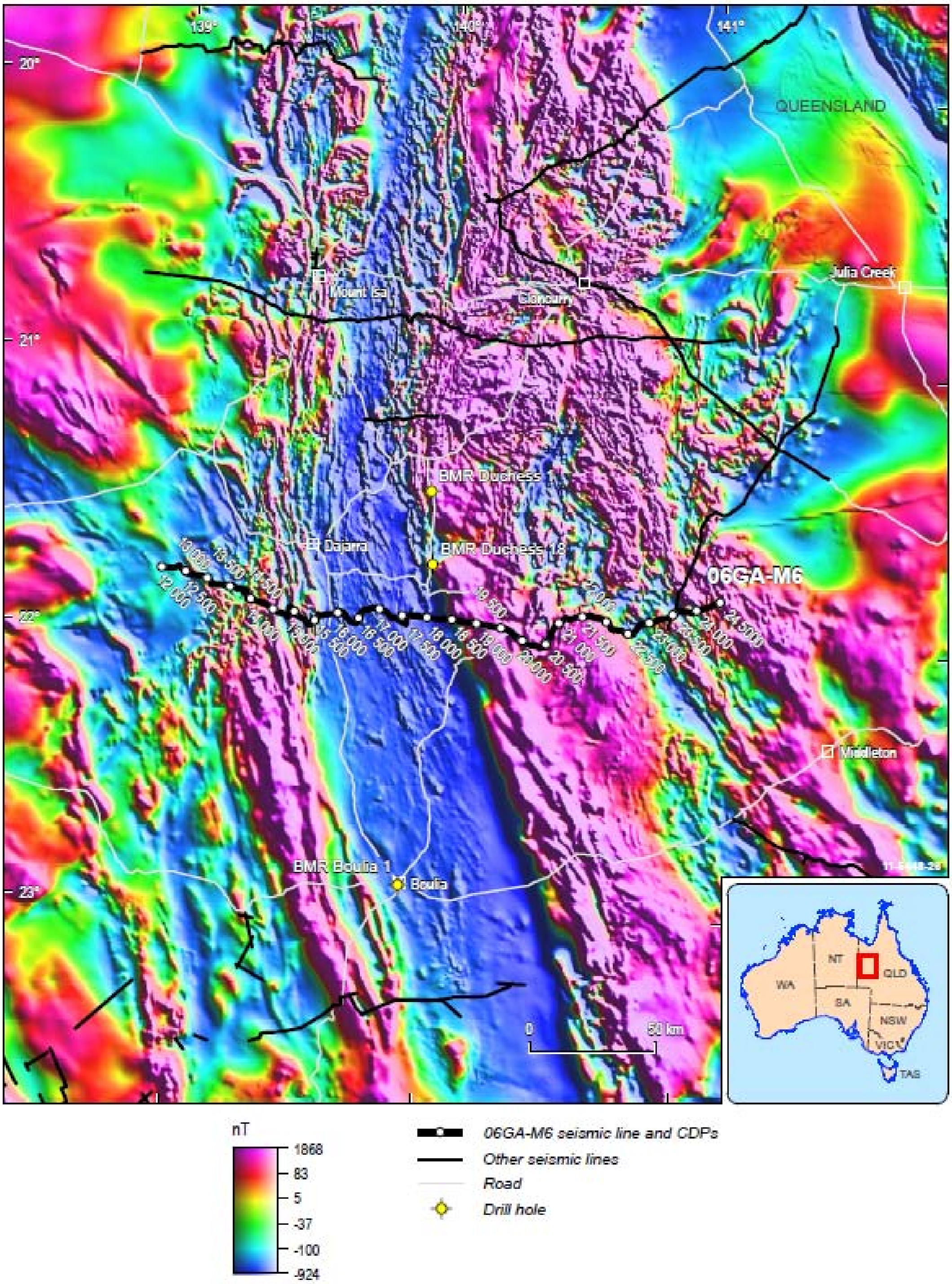


Figure 27 *Total magnetic intensity image showing the location of seismic line 06GA-M6 across the Burke River Structural Zone, Queensland.*

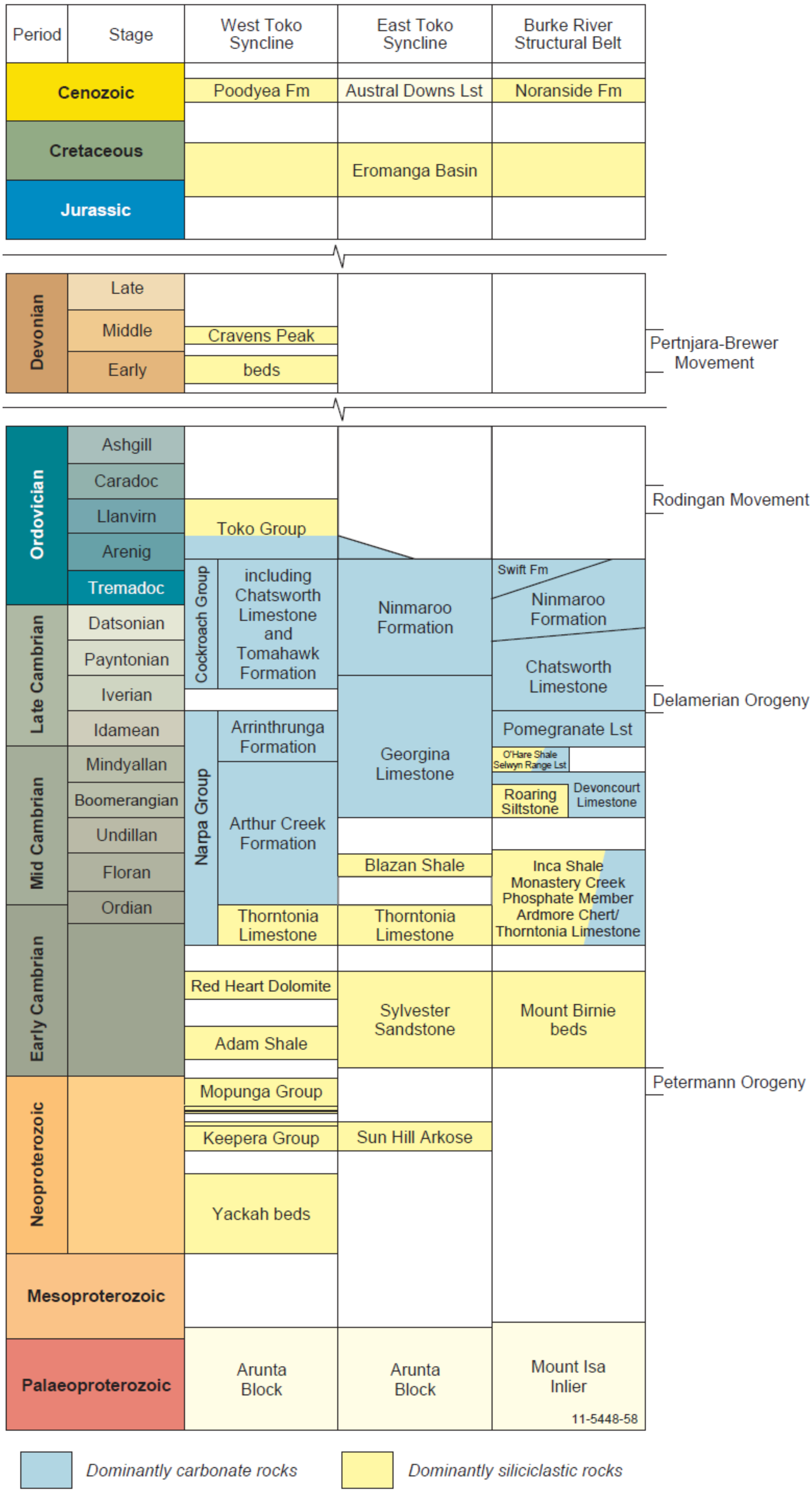


Figure 28 *Stratigraphic column showing the chronostratigraphic and lithostratigraphic break down of the Georgina Basin, Queensland (after Draper, 2007, Grey et al 2011 and the Australian Stratigraphic Units Database, Geoscience Australia).*

INTERPRETATION OF THE SEISMIC DATA

Seismic line 06GA-M6

At the southern end of the exposed part of the Mount Isa Province, northwest Queensland, the deep seismic reflection line, 06GA-M6 crossed the Burke River Structural Zone of the Neoproterozoic to early Paleozoic Georgina Basin (Figures 25-27). This seismic line provides the first seismic image across the Burke River Structural Zone. Here, this part of the basin is ~65 km wide, with a half-graben geometry, being bounded in the west by a rift border fault (Figures 29, 30). The succession in the basin has a maximum thickness of ~2800 m (calculated from stacking velocities), with the strata being relatively flat lying, and thickening towards the west. Interpretation of the stratigraphy is constrained by scattered outcrops in the vicinity of the seismic line (Blake et al., 1983; Casey et al., 1967). The lowermost sequence is interpreted to be the lower Cambrian Mount Birnie beds, which overlie a major angular unconformity above Proterozoic basement. Truncations below this unconformity can be observed on the seismic section (Figures 29-30). The sequence has mixed amplitude reflections with a discontinuous seismic character.

Control provided from the nearby BMR Duchess 18 drillhole suggests that unconformably overlying the Mount Birnie beds is the Cambrian Thorntonia Limestone. It is identified as a pair of strong continuous seismic reflections which can be traced over the seismic image. Stratigraphic units adjacent to the basin-bounding fault do not occur farther to the east, suggesting that they were either not deposited or have been eroded, with a second unconformity occurring above the Thorntonia Limestone (Southgate and Shergold, 1991).

Overlying the Thorntonia Limestone is a package of low amplitude continuous reflections which are interpreted to represent the Inca Shale or the Beetle Creek Formation, the package being up to 0.3 s TWT (~900 m) thick. Above the sequence boundary which occurs at the top of this package, another package is interpreted to include the mid-upper Cambrian Chatsworth Limestone, Pomegranate Limestone and O'Hara Shale. These are interpreted as a high amplitude package of discontinuous reflections below the Cenozoic sediments at the top of the section. At its thickest, this package is up to 0.2 s TWT (~600 m) thick. There are no sedimentary rocks of Ordovician age interpreted to occur on this seismic line.

There has been intense inversion on the basin-bounding fault at CDP 17950, presumably during the Alice Springs Orogeny, with the strata between the basin bounding fault and another fault at CDP 18050 being rotated to steep dips, with angles of up to 75º measured at the surface (Figure 30). To the east of the fault at CDP 18050, the basin is essentially undeformed and preserves the original half graben geometry. At about CDP 18300, there are a series of minor extensional faults, which appear to site above a major basement fault, the Pilgrim Fault.

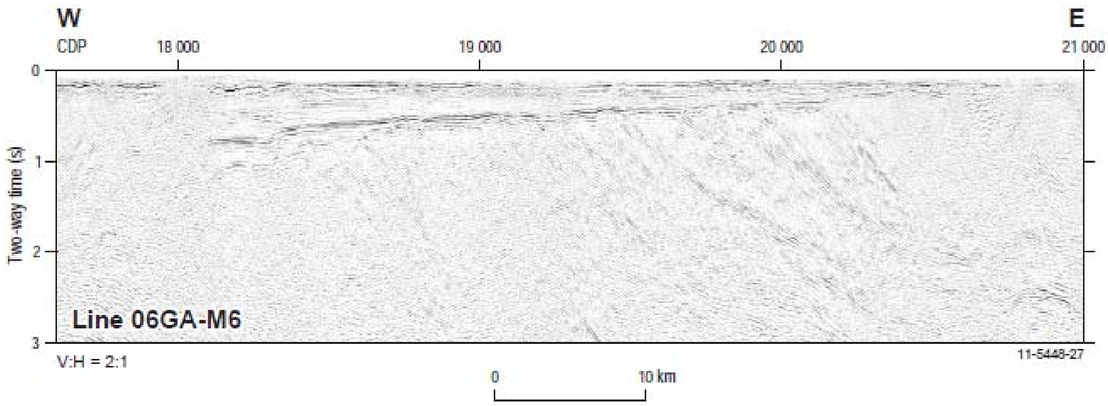


Figure 29 *Uninterpreted migrated seismic line 06GA-M6, across the Burke River Structural Zone in the Georgina Basin, Queensland, displayed at vertical:horizontal = 2:1, assuming average crustal velocity of 6000 ms^{-1}.*

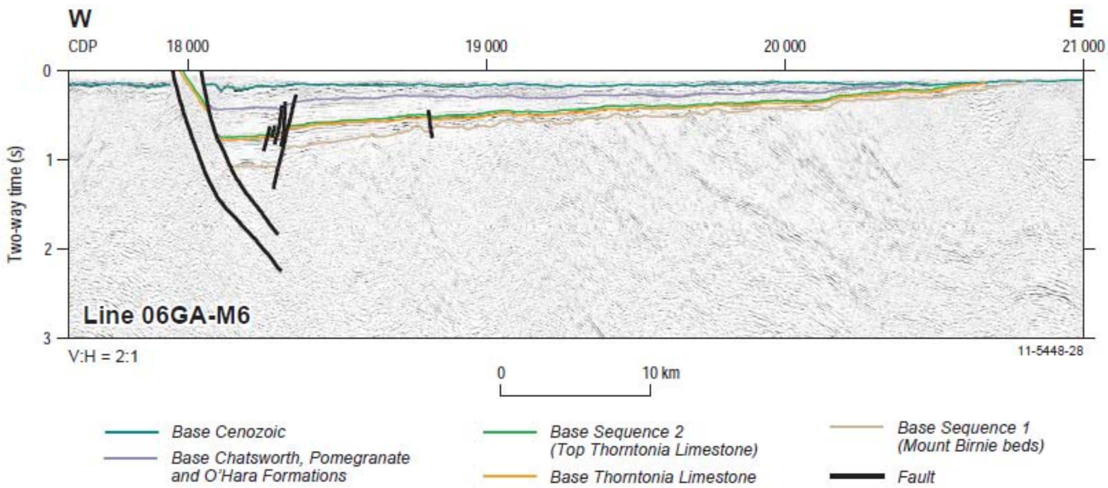


Figure 30 *Interpretation of migrated seismic line 06GA-M6, across the Burke River Structural Zone in the Georgina Basin, Queensland, displayed at vertical:horizontal = 2:1, assuming average crustal velocity of 6000 ms^{-1}.*

PETROLEUM SYSTEMS MATURATION MODELLING

Petroleum systems maturation modelling in the Georgina Basin was conducted utilising information from the interpretation of stratigraphy and architecture of seismic line 06GA-M6, described above for site A in the modelled basin (CDP 18200). This modelling also considered published data from the Toko Syncline and the Burke River Structural Zone in the southeast Georgina Basin (Jackson, 1982; Southgate and Shergold, 1991; Karajas, 1994; Ambrose et al., 2001; Draper, 2007; Ambrose and Putnam, 2007; Boreham and Ambrose, 2007; Radke 2009). A site for the model was chosen over the deepest section imaged by seismic line (Figure 29).

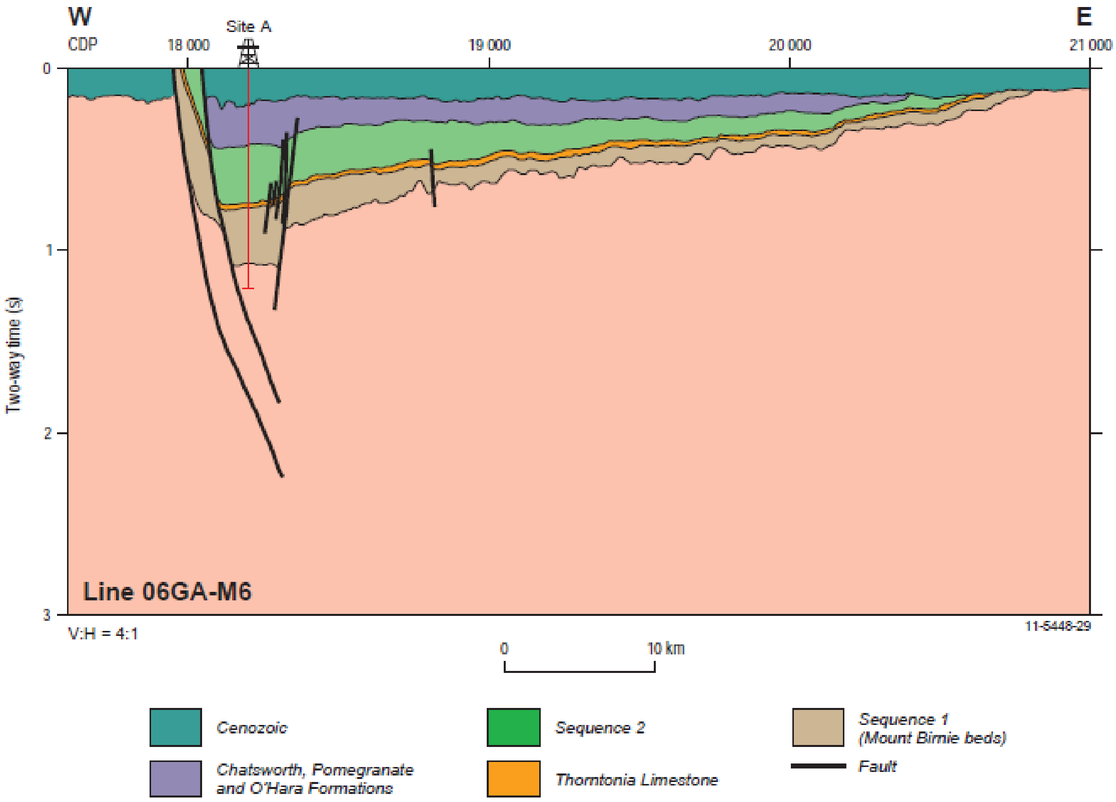


Figure 31 *Geological model of the Burke River Structural Zone, showing the location of the one dimensional model (site A) used for petroleum systems modelling.*

Input data

Input data for the modelling include estimates of total organic carbon (TOC) content, reaction kinetics, and the initial hydrocarbon index (HI) for each source rock unit (Table 3). The stratigraphic units and age interpretations are based on those of Southgate and Shergold (1991), Ambrose et al. (2001) and Draper (2007). The model also considers erosional aspects of the geological history, such as the amount of overburden and timing of erosion. The amount of erosion modelled includes an additional 500 m for the Ordovician Toko Group, which was assumed to be eroded during the late Devonian to Carboniferous (Alice Springs Orogeny), and an additional 300 m of Cretaceous sedimentary rocks (Gilbert River Formation, Toolebuc Formation and Allaru Mudstone), assumed to be eroded during the Late Cretaceous (Figure 31). The organic-rich unit in the Arthur Creek Formation is included as a nominal source rock in this model. Both this unit and the Thorntonia Limestone-Inca Shale are considered to be the main potential source rocks in this part of the basin. The choice of Type II kerogen kinetics is based on the probable restricted shallow marine depositional environment.

Table 3: Main input data for modeling Georgina Basin on seismic line 06GA-M6

Stratigraphic Unit	Top (m)	Base (m)	Thick (m)	Eroded (m)	Deposited From (Ma)	Deposited to (Ma)	Eroded from (Ma)	Eroded To (Ma)	Lithology %[1]	PSE	TOC %	Kinetic	HI
Alluvium	-25	80	105		3	0			Sst 60, Cgl 10 Slst 20, Sh 10	Overburden			
Cenozoic	80	265	185		15	5			Lst (chalk) 100	Overburden			
Toolebuc Formation-Allaru Mudstone	265	265	0	100	106	90	75	65	Lst (shaly) 50, Marl 20, Lst (org-rich 10% TOC) 20, Sst 10	Seal			
Gilbert River Formation	265	265	0	200	167	106	83	75	Sst (quartzite) 60, Cgl 10, Slst (org-rich) 20, Sh 10	Reservoir			
Toko Group	265	265	0	500	476	461	370	310	Sst 70, Glauconite 2, Sh 13, Lst (chalk) 5, Slst 10	Reservoir			
Cockroach Group	265	939	674		498	476			Lst (org-rich 1-2% TOC) 20, Lst (ooid) 40, Lst (shaly) 20, Slst (org rich) 18, Sst 2	Reservoir			
Devoncourt Limestone-Arthur Creek Formation	939	1770	831		504	499			Lst 80, Slst 20	None			
Arthur Creek Formation equivalent	1770	1800	30		505	504			Sh (org-rich 8% TOC) 90, Marl 10	Source rock	4	Tissot et al. (1987)	700
Thorntonia Limestone–Inca Formation	1800	1920	120		508	506			Dol (org-rich) 50, Chert 1, Sst 5, Slst (org-rich) 14, Sh (org-rich) 30	Source rock	2	Tissot et al. (1987)	600

Stratigraphic Unit	Top (m)	Base (m)	Thick (m)	Eroded (m)	Deposited From (Ma)	Deposited to (Ma)	Eroded from (Ma)	Eroded To (Ma)	Lithology %[1]	PSE	TOC %	Kinetic	HI
Thorntonia Limestone - basal reservoir	1920	1952	32		511	508			Sst 60, Dol 30 Sh (org-rich 3% TOC) 10	Reservoir			
Mount Birnie beds	1952	2790	838		530	515			Sst 50, Dol 30, Slst (org-rich) 20, Sh 15	Underburden			
Proterozoic basement	2790	3320	530		640	630			Granite (1000ma) 70, schist 15, quartzite 15	Underburden			
						640							

[1]Sst = Sandstone, Cgl = Conglomerate, Slst = Siltstone, Sh = Shale, Lst = Limestone, Dol = Dolomite.

Boundary conditions, burial history and maturity

The main boundary conditions for geohistory modelling include palaeowater depths, temperatures at the sediment-water interface, and heat flow through time (Table 4, Figure 32). Palaeowater depths are based on regional geology, with most deposition likely to have occurred in shallow to very shallow marine environments. The erosion during the Paleozoic Alice Springs Orogeny was modelled as significant uplift. The Sediment-Water Interface Temperatures (SWIT) are based on calculations provided by the software (Petromod v11 SP2) for a present-day latitude of 22ºS. Present-day heat flow in the region is approximately 80 mWm^{-2} and has probably been higher in the past, assuming basement granites are also present in the Burke River Structural Belt, as they are in the other areas of the Georgina Basin (Ambrose et al., 2001). For reasons of simplicity, and lack of other information, the thermal history of the basin was modelled (Figure 33) using a present day heat flow of 80 mWm^{-2} based on Geoscience Australia's geothermal surface heat flow points (Geoscience Australia, 2011).

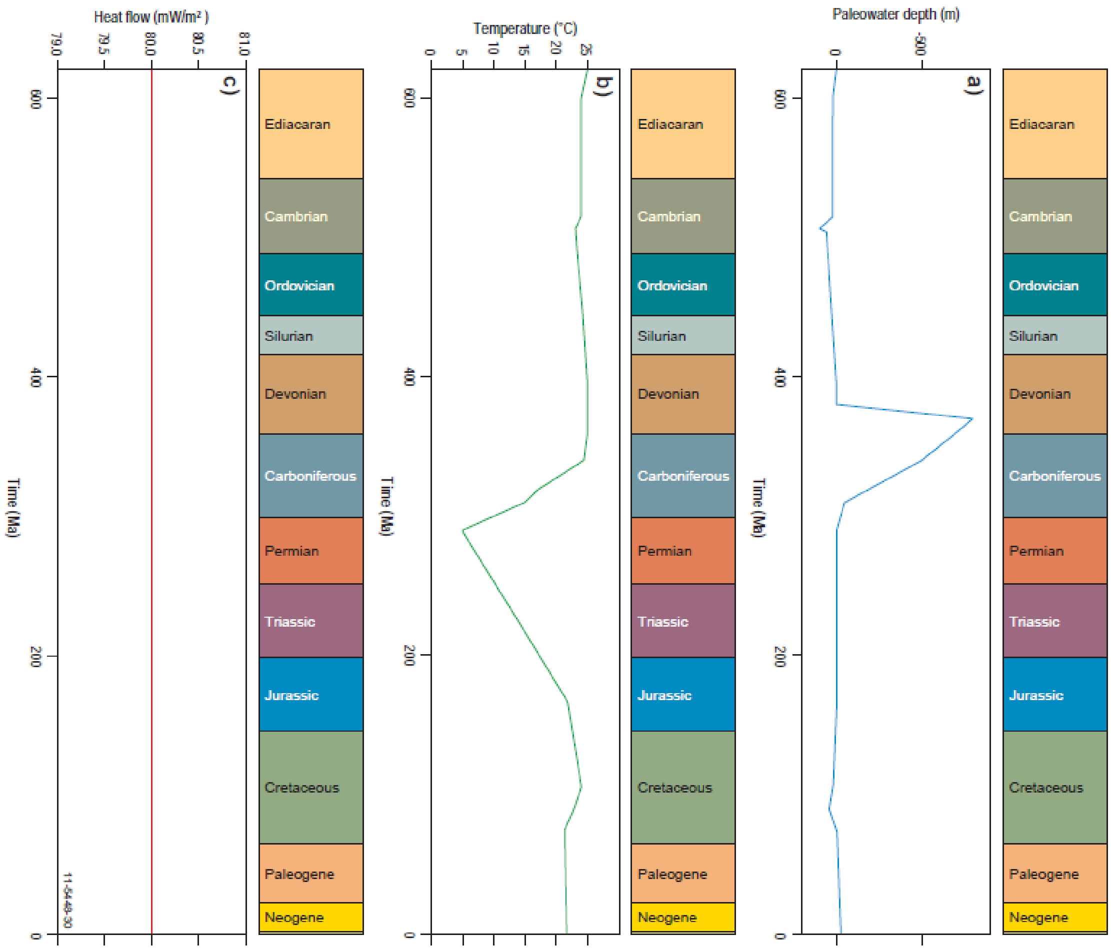


***Figure 32** Boundary conditions modelled for the Georgina Basin, including **a)** paleowater depth, **b)** sediment-water interface (SWIT), and **c)** heat flow through time.*

Table 4 Boundary conditions for paleowater depth (PWD), sediment-water interface temperatures (SWIT), and heat flow (HF).

Age (Ma)	PWD (m)	Age (Ma)	SWIT (°C)	Age (Ma)	HF (mW/m^{-2})
0	-25	0	21.62	0	80
75	0	75	21.33	200	80
90	40	90	22.82	540	80
106	20	106	24.00	620	80
167	0	167	21.83		
290	0	290	5.00		
310	-50	310	15.00		
320	-200	320	17.30		
340	-500	340	24.44		
360	-700	360	25.00		
370	-800	370	25.00		
380	0	380	25.00		
390	0	390	25.00		
394	0	394	25.00		
460	40	460	24.00		
504	60	504	23.00		
506	100	506	23.00		
515	20	515	24.00		
600	20	600	24.00		
620	0	620	25.00		

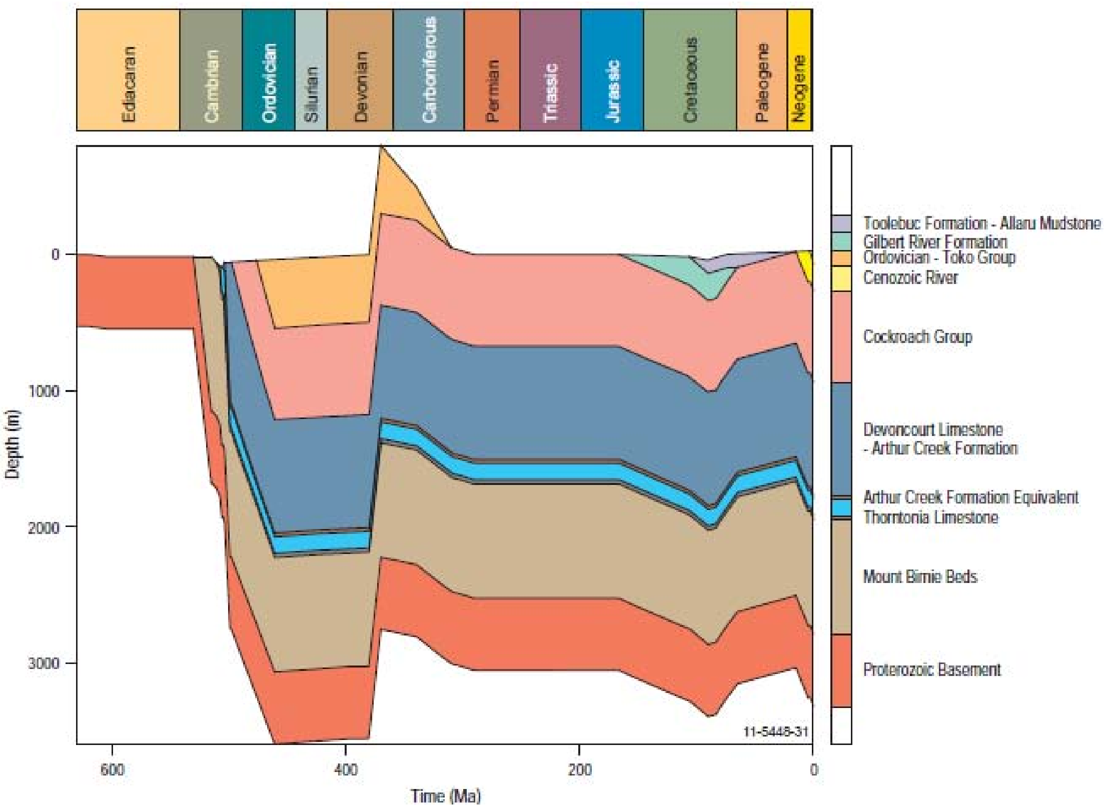


Figure 33 *Results from petroleum systems maturation modelling at site A in the Burke River Structural Zone of the Georgina Basin, showing the burial history plot modelled with 500 m of erosion of Ordovician sediments during the Devonian-Carboniferous Alice Springs Orogeny.*

The burial history was modelled with 500 m deposition of Ordovician sediment (Toko Group) and subsequent erosion of it, assumed from the regional geological history. Increasing the amount of erosion modelled results in earlier and more rapid kerogen transformation. Further deposition of approximately 300 m of Cretaceous sedimentary rocks, also subsequently eroded, was assumed for this location, although the thickness of this eroded section could be too great, considering only minor remnants of the Gilbert River Formation crop out in the area.

A temperature overlay on the burial history for Site A shows that the present-day temperature at 3 km is about 150ºC (Figure 34). The implied gradient is consistent with a predicted temperature of 180-200ºC at about 5 km crustal depth (Geoscience Australia, 2011).

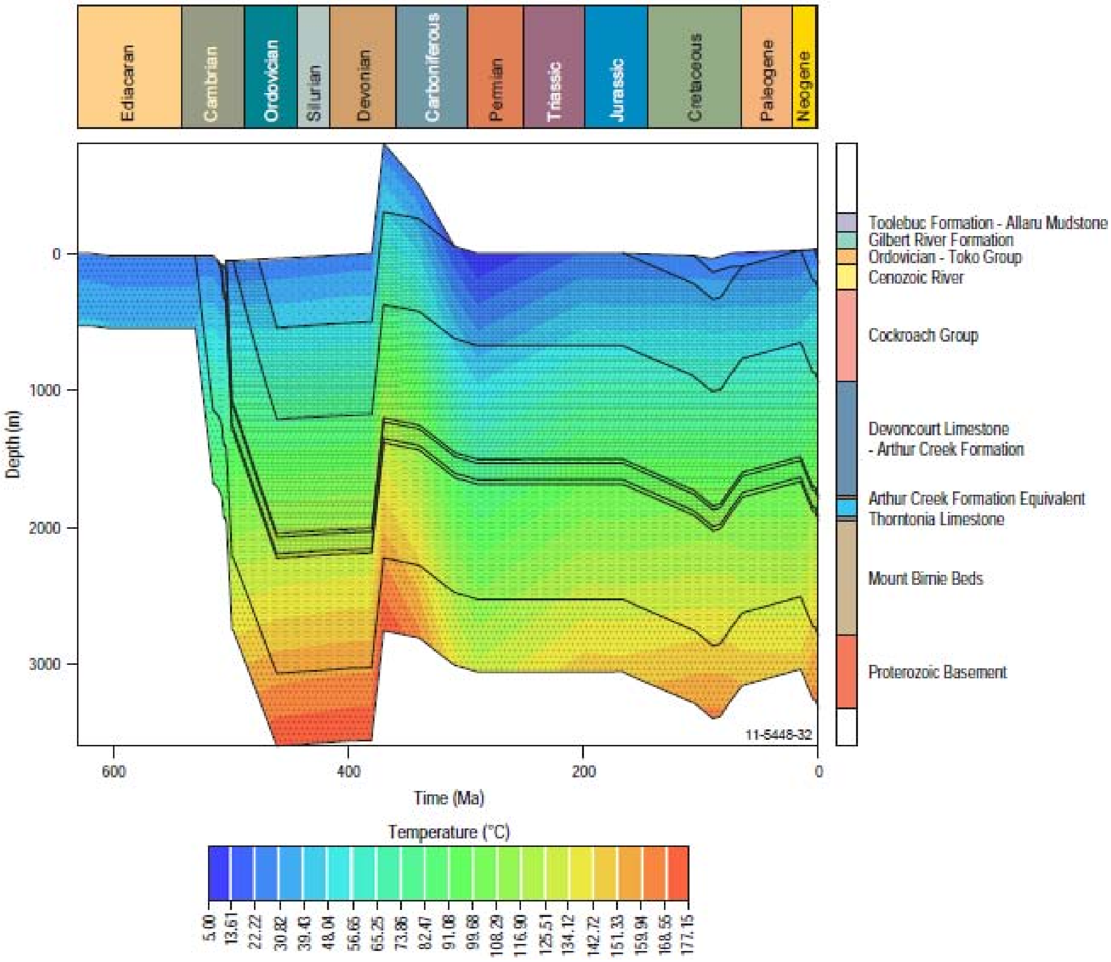


Figure 34 *Results from petroleum systems maturation modelling at site A in the Burke River Structural Zone of the Georgina Basin showing temperature modelled with a constant heat flow of 80 mWm*$^{-2}$ *overlain on the burial history plot.*

The modelled maturity shows that rapid burial during the late Cambrian to Early Ordovician brought potential middle Cambrian source rocks into the peak oil window early in their burial history, where they have probably remained; with the later Cretaceous burial appearing to have had little effect (Figures 35, 36a). The maturity profile for Georgina Basin model illustrates that potential source rocks are presently in the main to late oil window.

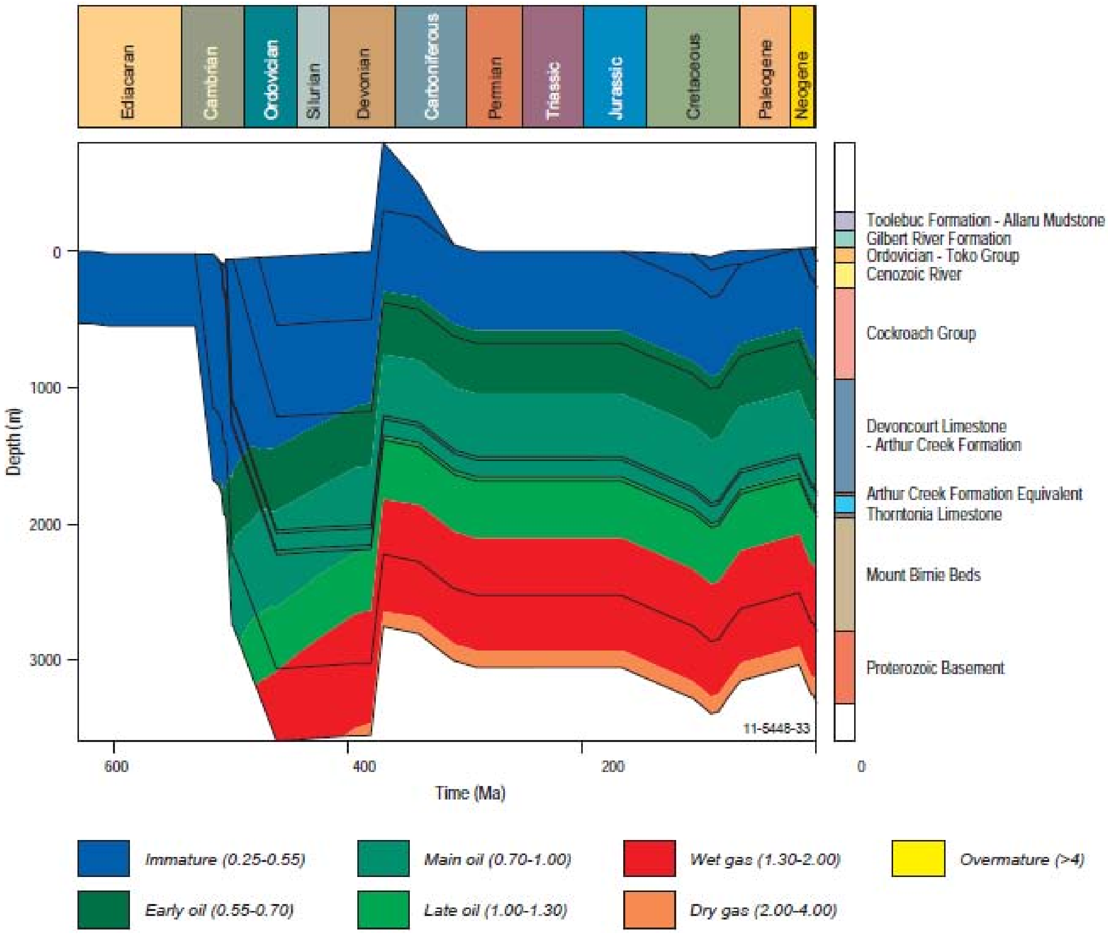


Figure 35 *Results from petroleum systems maturation modelling at site A in the Burke River Structural Zone of the Georgina Basin, showing modelled maturity overlain on burial history plot.*

A plot of predicted porosity versus depth for this site shows that porosities of 20% or higher are predicted to a depth of about 1500 m and of 15% or higher down to a depth of about 2500 m (Figure 36b), although carbonate reservoirs could behave differently.

The timing of generation and expulsion for the Thorntonia Limestone source rock are shown in Figure 37. Close to 80% of available kerogen was transformed by the Middle-Late Devonian. The expulsion rate rose steadily from the Late Ordovician to the Early-Middle Devonian in response to increased burial, but ceased due to Late Devonian uplift. Subsequent Cretaceous burial did not cause a second phase of generation, probably because these sediments were eroded soon after deposition. Modelling a higher amount of assumed Cretaceous deposition and or later erosion does not change this result.

The modelled timing and expulsion for the source rocks in the Arthur Creek Formation show that the timing of generation and expulsion are similar to that of the underlying Thorntonia Limestone source (Figures 38). Overall, the modelling results are consistent with previous findings for the western Toko Syncline by Ambrose et al. (2001), who postulated early maturation from these source rocks.

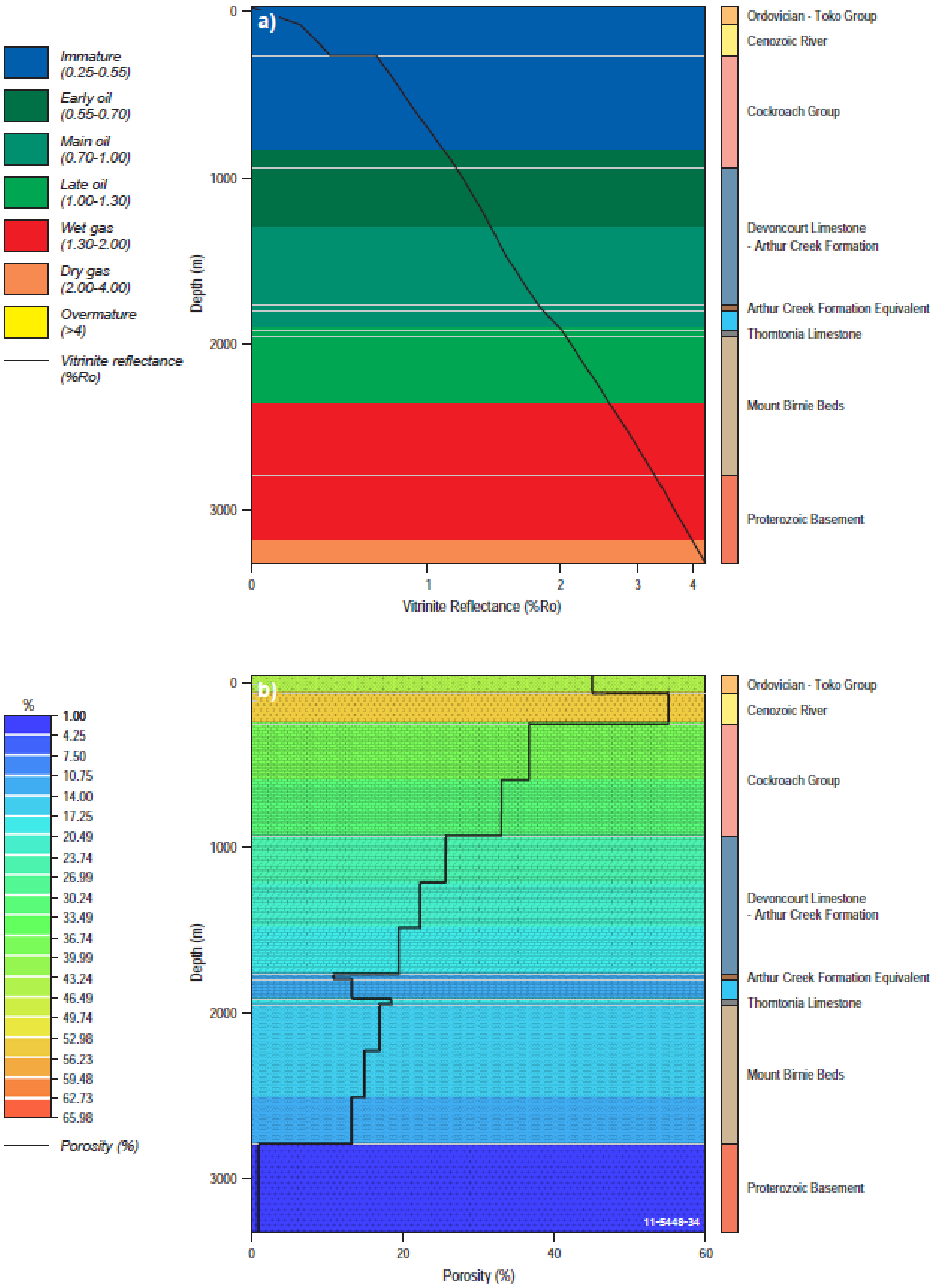


Figure 36 *Results from petroleum systems maturation modelling at site A in the Burke River Structural Zone of the Georgina Basin, showing* ***a)****, plot of the predicted vitrinite reflectance and maturity with depth, and* ***b)*** *plot of predicted porosities versus depth.*

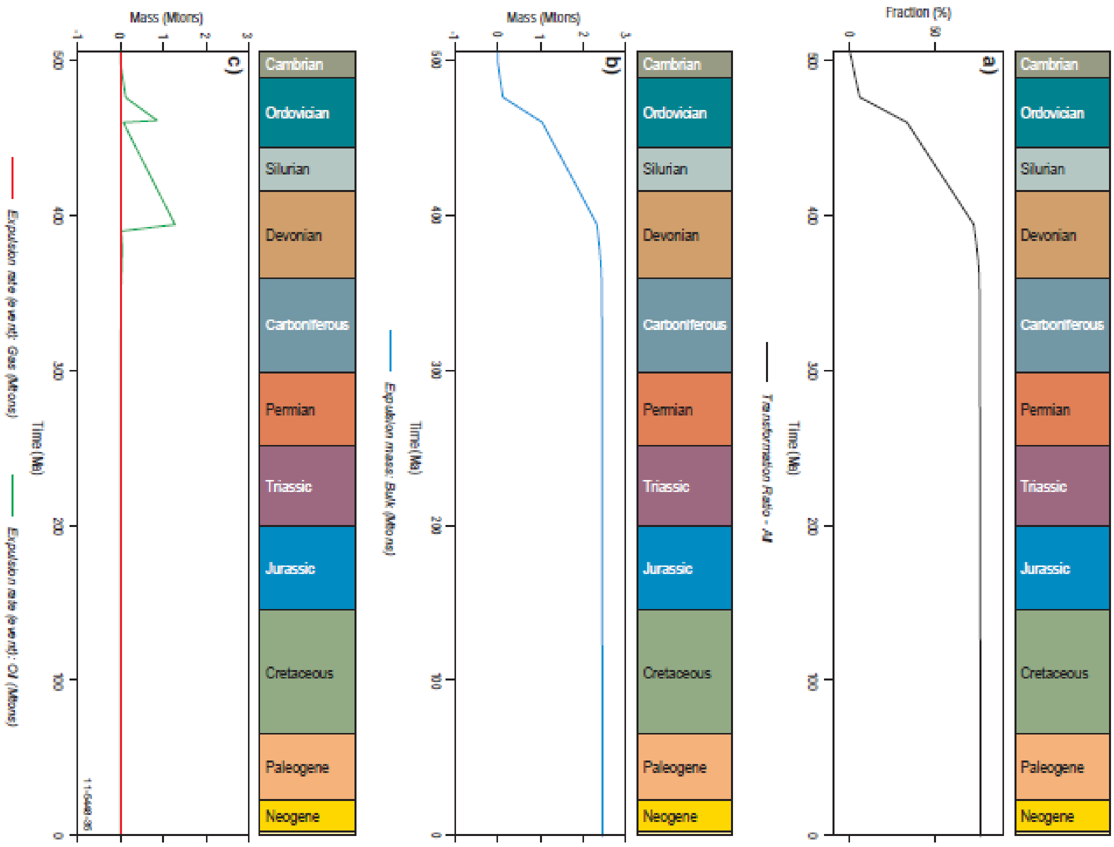


Figure 37 *Modelled timing and expulsion for the source rock interval in the Thorntonia Limestone showing* ***a)*** *transformation ratios,* ***b)*** *expulsion mass (bulk), and,* ***c)*** *expulsions mass for oil and gas.*

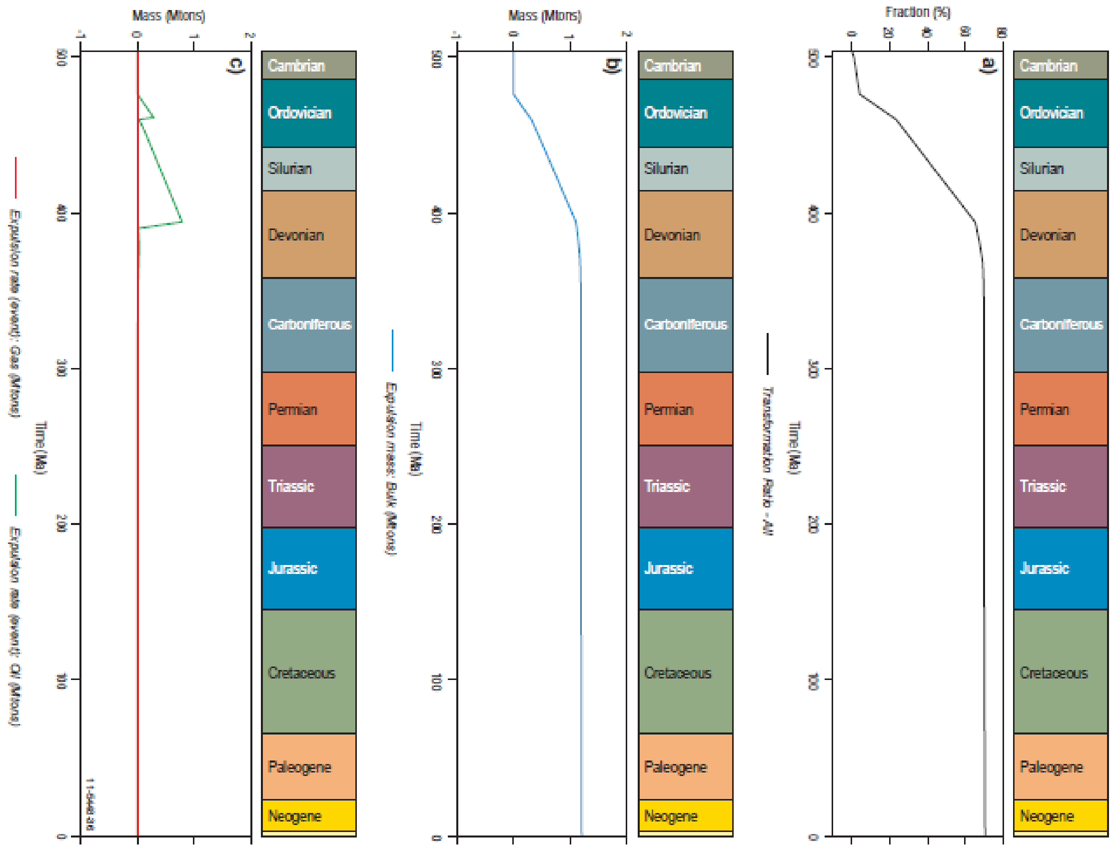


Figure 38 *Modelled timing and expulsion for the source rock interval in the Arthur Creek Formation showing **a)** transformation ratios, **b)** expulsion mass (bulk), and, **c)** expulsions mass for oil and gas.*

Proposed petroleum systems events chart, Burke River Structural Zone

In summary, the modelling suggests that the potential Cambrian source rocks in the Burke River Structural Zone are likely to be oil mature. Significant generation and expulsion probably occurred early in the burial history, in response to Cambrian-Ordovician loading. Expulsion occurred after Neoproterozoic-Cambrian trap formation, but before Devonian trap formation. The long preservation time and unroofing, therefore, are the major risk factors within the basin (Figure 39). The deposition of the sediments of the Jurassic–Cretaceous Eromanga Basin had no effect on the maturation and expulsion history of the Cambrian source rocks. The above results are based on an assumed constant heat flow of 80 mWm^{-2}. Modelling this site with a reduced heat flow of 60 mWm^{-2} resulted in reduced volumes of oil expelled, but the timing of generation and expulsion remained substantially the same. Nevertheless, the model predicts a second, albeit minor phase of expulsion from the Arthur Creek Formation during the Late Cretaceous to Holocene.

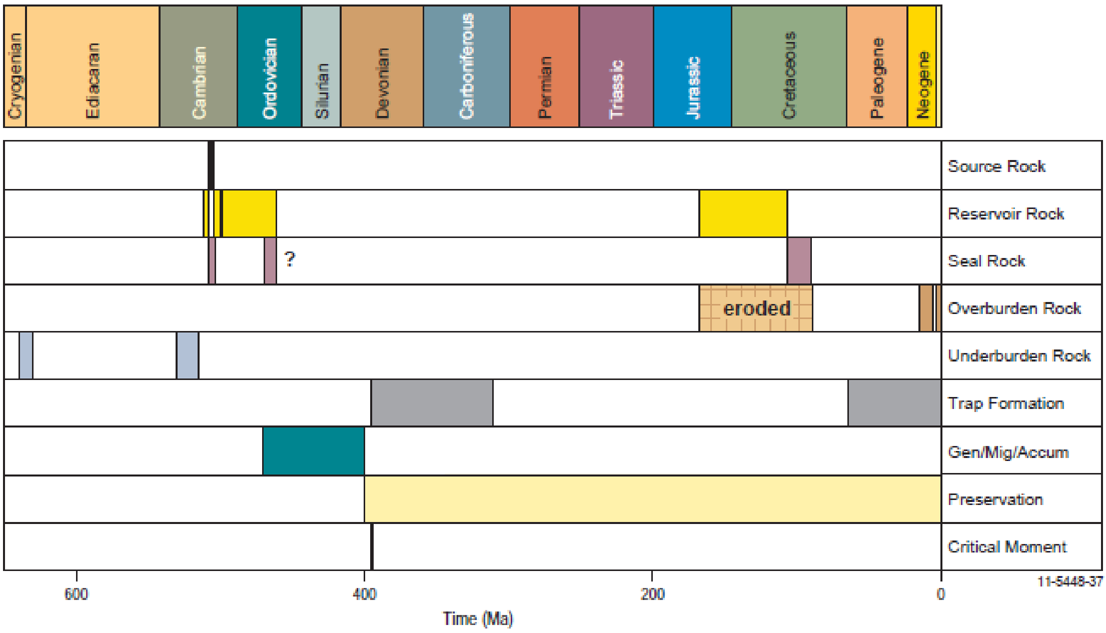


Figure 39 *Proposed petroleum systems event chart for the Burke River Structural Zone, Georgina Basin.*

Yathong Trough, Darling Basin, New South Wales

AIM OF SEISMIC SURVEY

In 2008, Geoscience Australia, in conjunction with New South Wales Department of Primary Industries and Resources, (NSW-DPI), acquired two east-west deep seismic reflection lines, one each across the Rankins Springs and Yathong Troughs in the southeastern Darling Basin in western New South Wales, to investigate the hydrocarbon prospectivity of the basin. The survey acquired a total of 234 km of seismic data in March 2008, with a further, eastern extension of one line in 2009.

The specific aims of the survey included determining the nature of the sedimentary fill in the Rankins Springs and Yathong Troughs, and the structure of the underlying basement, in order to ascertain the northward extent of the suspected Devonian-Permian sedimentary succession identified in the 2006 NSW Department of Primary Industries (NSWDPI) Griffith-Murrumbidgee seismic survey. This would provide an indication of the nature of the overlap between the Devonian-dominated Darling Basin and the Permo-Triassic Oaklands Basin to the south. Another aim was to identify potential source rocks within the Rankins Springs and Yathong Troughs, determine structures and stratigraphy of significance to hydrocarbon migration and trapping, and to assess the petroleum potential of the area.

The Rankins Springs seismic survey was the first survey in the underexplored southeastern part of the Darling Basin (Figure 40-42). The 107 km long deep seismic line 08GA-RS2, which is the subject of this interpretation, crossed a thick Devonian section in the Yathong Trough, whereas seismic line 08GA-RS1 showed the absence of Devonian sedimentary rocks in the Rankins Springs Trough. In February 2009, the northernmost line across the Yathong Trough was extended 32 km to the east over the Central Lachlan Orogen. The 2008 seismic data 08GA-RS2 was reprocessed together with the 2009 data to produce the Rankins Springs Extension line (09GA-RS2).

GEOLOGY OF THE DARLING BASIN

The Darling Basin in New South Wales covers an area of up to 100,000 km^2 consisting of at least seven sub-basins containing a thick succession of sedimentary rocks. The basin is bounded to the west by the Curnamona Province, to the north by the Thomson Orogen, and to the east by the Cobar Basin (Cooney and Mantaring, 2007). It is known to contain more than 8000 m of upper Silurian to lower Carboniferous sedimentary rocks, which range from alluvial to marine facies, but dominated by Middle-Upper Devonian red beds, with potential source rocks at depth. The succession in the east contains continental to shallow marine units, in contrast to the west where deep open marine facies occur. Although the basin is underexplored, previous studies indicate the existence of at least one active Paleozoic petroleum system (Alder et al., 1998).

The Darling Basin was last deformed during the Carboniferous Kanimblan Orogeny, with thrust faults and related hangingwall anticlines having the potential to act as traps for hydrocarbons (Stewart and Alder, 1995). Cooney and Mantaring (2007) suggest that the Darling Basin has many similarities to the Adavale Basin to the north, whereas others have compared the lower successions to those in the Amadeus Basin (Bembrick, 1997). Within the basin, there are differing structural styles, making the subsidence mechanism which formed the basin unclear. Cooney and Mantaring (2007) suggest that gravity and seismic imaging of the basin show extensional sub-basins, which are fault bound, forming half graben structures, indicative of an intra-continental extensional setting.

The Yathong Trough occurs in the southeast part of the Darling Basin, and prior to this work has not been explored through seismic acquisition or drilling. Hydrocarbon-focused exploration in the Darling Basin began in 1963, when Mid Eastern Oil drilled the Mount Jack 1 well. In the 1980s BHP, Comserve and Esso also acquired seismic and drillhole data in the Darling Basin. Despite this work, the Darling Basin is underexplored with 28 wells, only 12 of which have been over 1000 m deep. About 2400 km of multifold seismic data (Cooney and Mantaring, 2007) have been acquired prior to the new surveys (08GA-RS1 and 08GA-RS2), but none had been recorded in the vicinity of the Yathong Trough. There is, however, gravity and magnetics coverage of much of the basin (Figures 41 and 42). Earlier exploration work concentrated on the structural highs, which have proved to be very complex, resulting in poor data (Cooney and Mantaring, 2007).

Much of the Darling Basin is covered by a veneer of Cenozoic alluvium and, thus, the stratigraphy of the basin has been difficult to establish. Many of the Devonian successions are very thick and uniform in distribution, and any potential source rocks in the basin would occur deep in the succession.

The stratigraphy of the basin consists of two Groups and several Formations. The lowermost succession forms the Lower Devonian Winduck and Amphitheatre Groups. In the east and centre of the basin, the Winduck Group consists of sedimentary rocks deposited in a fluvial environment and, in the west, the Amphitheatre Group consists of marine shelf and basin deposits. Overlying this is a thick succession of the Middle to Upper Devonian Mulga Downs Group, which includes red beds deposited in a dominantly fluvial environment, although some minor marine incursions occur in the middle of the succession.

As well as the formal lithostratigraphic subdivision, Bembrick (1997) and Willcox et al. (2003) proposed subdivisions for the basin based on sedimentary "intervals" and stratigraphic "sequences", respectively.

Willcox et al. (2003) developed a detailed seismic stratigraphic framework, based on seismic characteristics, particularly the recognition of sequence boundaries. We have also followed a sequence stratigraphic approach, through mapping recognisable sequence boundaries in the seismic section. Nevertheless, the framework of Willcox et al. (2003) was developed for an area well to the north of our study area, and, hence their sequence boundaries do not necessarily equate to those interpreted by us in the Yathong Trough

An alternative subdivision was proposed by Bembrick (1997; see also Cooney and Mantaring, 2007), who subdivided the entire succession into the Winduck Interval, Snake Cave Interval and Ravendale Interval, although these intervals do not coincide with the sequences defined by Willcox et al. (2003). The lower sequences in the Mulga Downs Group mapped by us (Sequences A to C) are approximately equivalent to the Snake Cave Interval, whereas the upper sequences (D to H) are considered to be part of the Ravendale Interval (Figure 43, after Bembrick 1997).

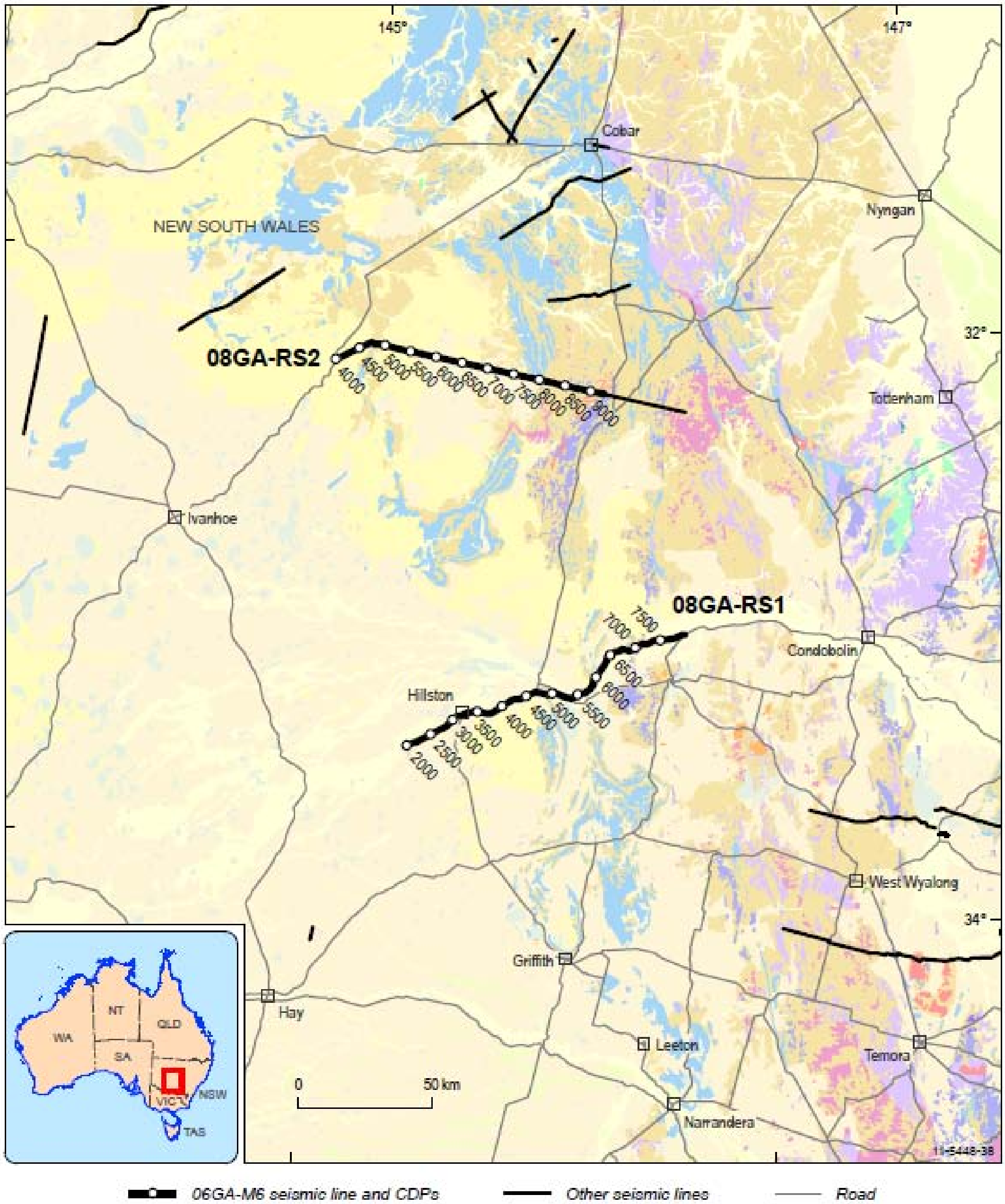


Figure 40 *Map of the surface geology showing the location of seismic lines 08GA-RS1 (Rankins Springs Trough) and 08GA-RS2 (Yathong Trough) in the Darling Basin, New South Wales. Numbers on the seismic lines represent CDP locations.*

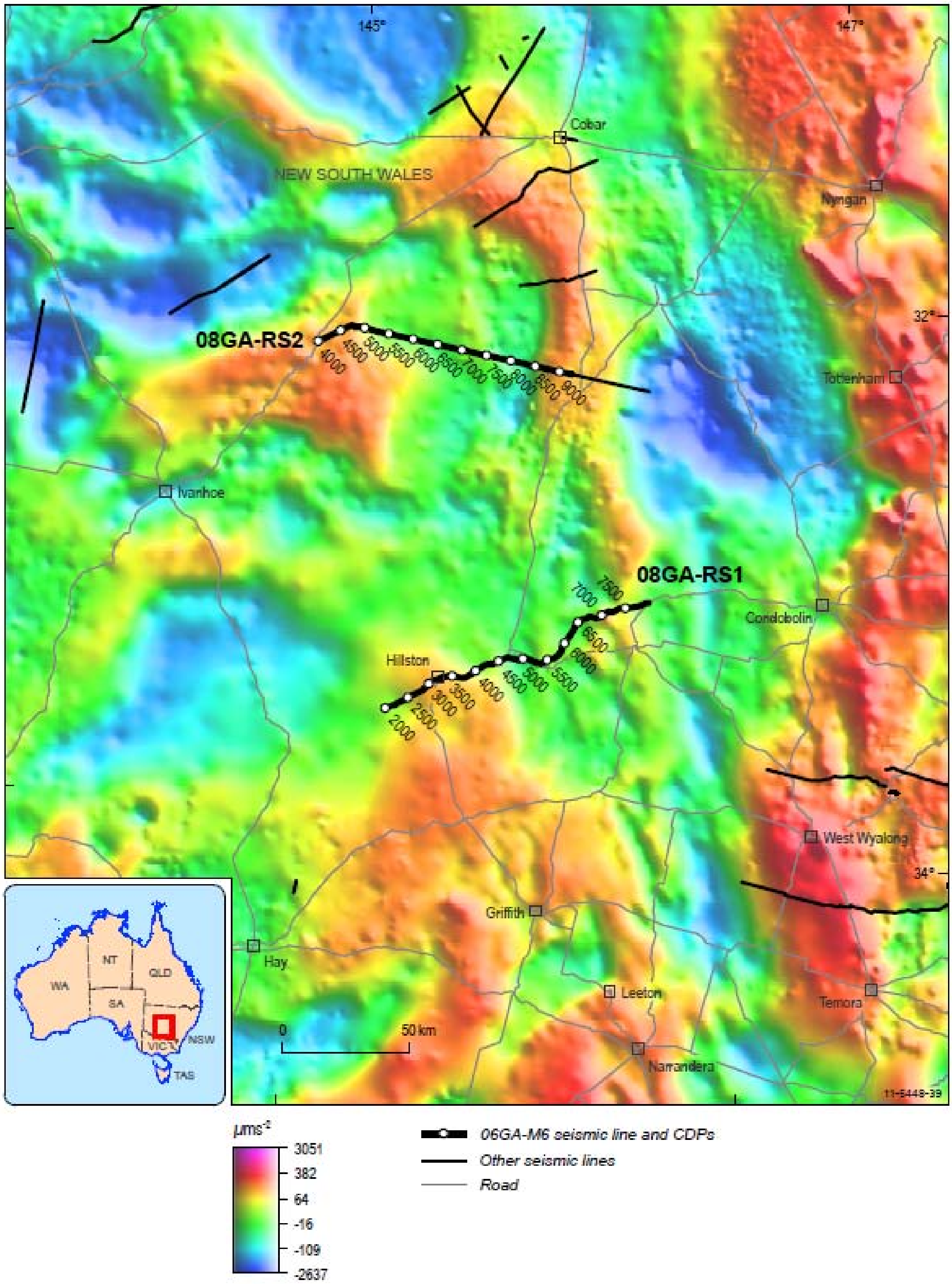


Figure 41 *Gravity image showing the location of seismic lines 08GA-RS1 (Rankins Springs Trough) and 08GA-RS2 (Yathong Trough) in Darling Basin, New South Wales. Numbers on the seismic lines represent CDP locations.*

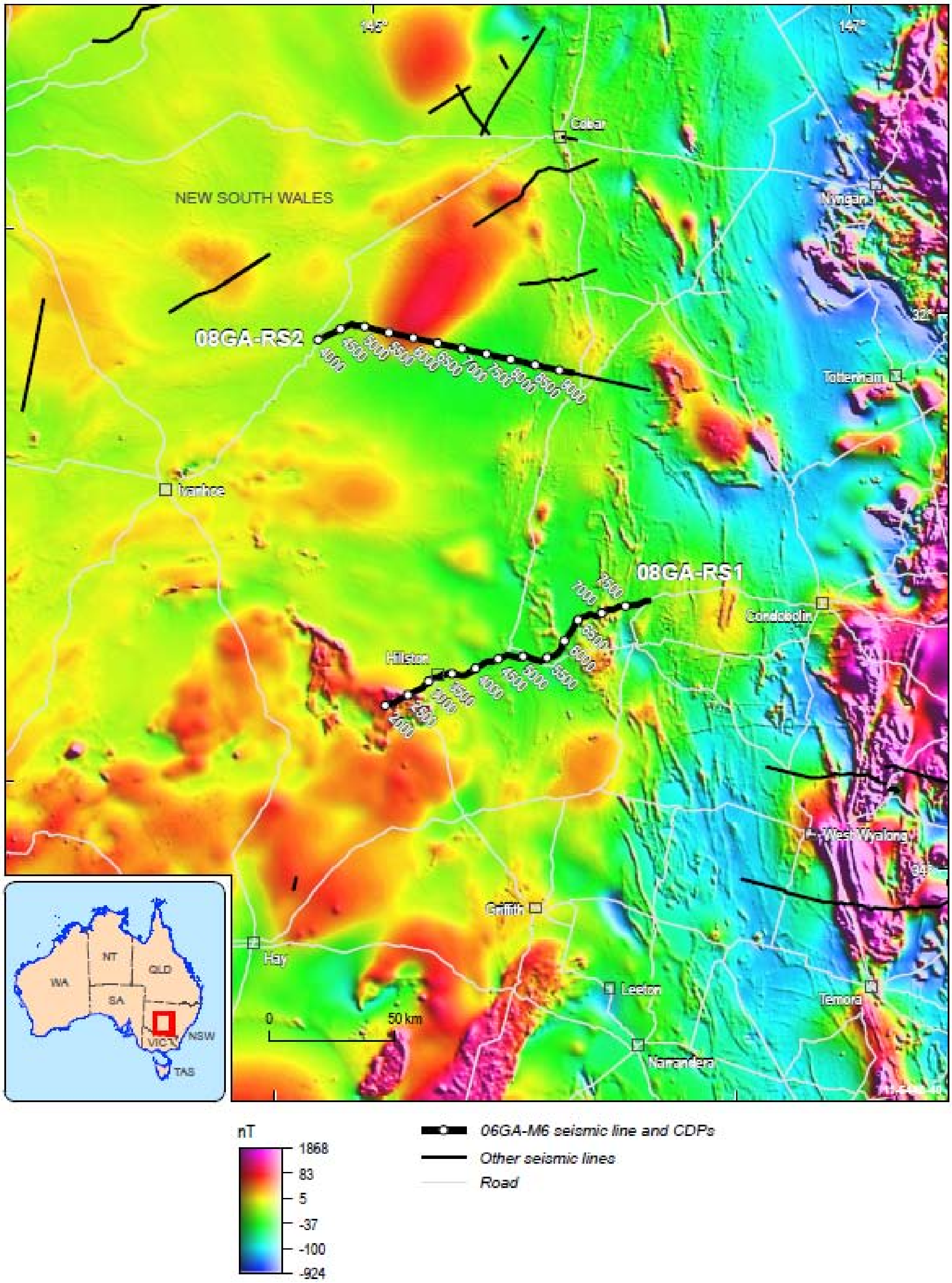


Figure 42 Total magnetic intensity image showing the location of seismic lines 08GA-RS1 (Rankins Springs Trough) and 08GA-RS2 (Yathong Trough) in the Darling Basin, New South Wales. Numbers on the seismic lines represent CDP locations.

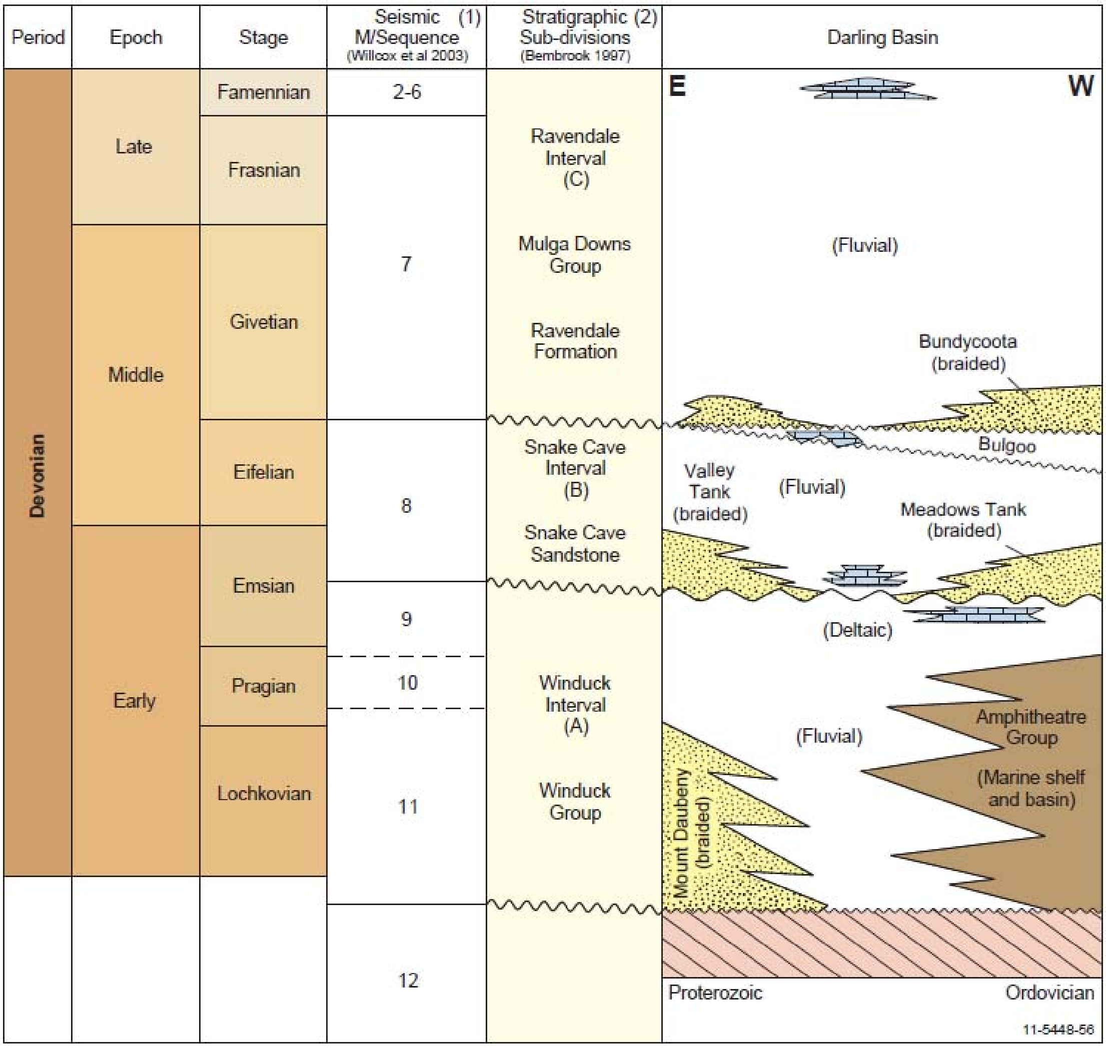


Figure 43 *Stratigraphic column showing the lithostratigraphy and sequence stratigraphy of the Darling Basin, after Bembrick (1997) and Willcox et al. (2003)*

INTERPRETATION OF THE SEISMIC DATA

Seismic line 08GA-RS2

The Yathong Trough was imaged in seismic line 08GA-RS2, which shows that the basin fill consists of a thick succession characterised by alternating high and low amplitude seismic reflections, interpreted to represent the expected Devonian succession mudstones and sandstones (Figures 44 and 45).

The basement units below the Yathong Trough are interpreted to be Ordovician turbidites and Ordovician-Silurian granites, considered to be part of the Lachlan Orogen. The units appear as a high amplitude package over which the continuous stratigraphic layers of the basin are deposited.

For our interpretation of the Yathong Trough, we have followed the methodology of Willcox et al. (2003), who, in a study further to the north, developed a seismic stratigraphic framework for the

Darling Basin. Overlying the basement, the lowermost unit in the basin is a thin extensional package, consisting of shallow marine shelf deposits of the Lower Devonian Winduck Group. These are interpreted as a thin package which thickens into the faults. This unit is much less continuous and lower in amplitude than the overlying units. Two sequence boundaries have been identified in the seismic section for the Winduck Group; one of these is at the base while the other is in the middle(Figure 45).

A very thick succession of Middle-Upper Devonian red beds form the overlying Mulga Downs Group, with several sequence boundaries being identified within the Group (Figure 45). The lower Mulga Downs Group sequences A-C, represent the Snake Cave Interval of early interpretations (Bembrick, 1997) and include the Snake Cave Sandstone, which probably contains red beds deposited in alluvial fan or braided stream environments (Willcox et al., 2003).

Overlying the Mulga Downs Group sequences A-C and still within the Mulga Downs Group, are the Mulga Downs Group sequences D-H, previously interpreted as the Ravendale Interval. This was interpreted by Willcox et al. (2003) to include a minor marine incursion, overlain by further red beds deposited in braided stream and lacustrine environments. Many of these units are of high amplitude seismically and have strong, continuous reflections. They are interspersed with a few discontinuous reflections, particularly lower in the section. The Winduck and Mulga Downs Groups form a very thick succession of about 3 s TWT (~6500 m). A thin Cenozoic cover is interpreted to overlie the uppermost Darling Basin sedimentary rocks.

The sequence boundary at the base of the Mulga Downs Group is a marked erosion surface, denoting the change from shelf to continental sedimentation. The trough is fault bounded in the west by a positive flower structure associated with a north-south trending strike-slip fault. Within the trough, near its eastern margin (CDP ~7800), a west-dipping thrust fault has a hangingwall anticline on its western side. The eastern margin of the trough is terminated by a major, east-dipping thrust fault. Possible traps include anticlinal and fault closures near the eastern margin of the trough.

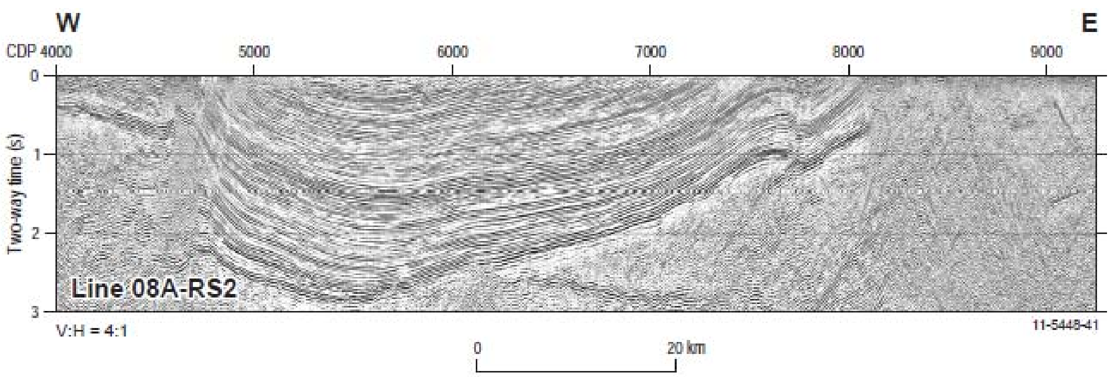


***Figure 44** Uninterpreted migrated seismic line 08GA-RS2, across the Yathong Trough in the Darling Basin, New South Wales, displayed at vertical:horizontal = 4:1, assuming an average crustal velocity of 4000 ms^{-1}.*

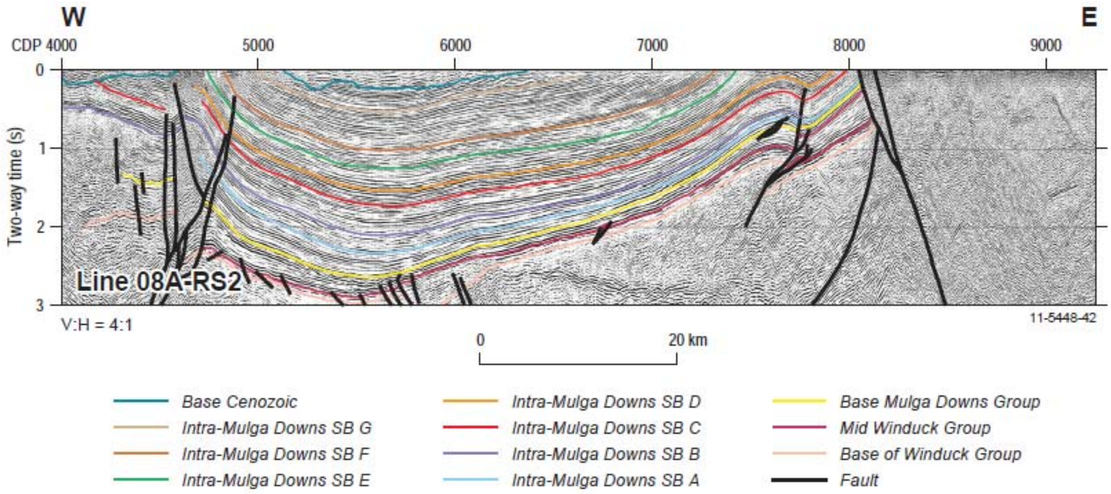


Figure 45 *Interpreted migrated seismic line 08GA-RS2, across the Yathong Trough in the Darling Basin, New South Wales, displayed at vertical:horizontal = 4:1, assuming an average crustal velocity of 4000 ms^{-1}.*

PETROLEUM SYSTEMS MATURATION MODELLING

Input data

Petroleum systems maturation modelling for the Darling Basin was conducted using input data from the interpretation of stratigraphy and architecture imaged by seismic line 08GA-RS2. 1D petroleum systems modelling for the Yathong Trough was conducted using a pseudo-well located at CDP 5600 (site A), on seismic line 08GA-RS2 (Figure 46). The stratigraphy, interpreted above, suggests extension during the deposition of the upper Silurian-Lower Devonian Winduck Group, followed by a Middle-Late Devonian phase of thermal subsidence and possible foreland basin deposition. The basement to the Yathong Trough is likely to consist of Ordovician turbidites and Ordovician to Silurian granites of the Wagga-Omeo Zone of the Lachlan Orogen (Champion et al., 2009).

The main input data for petroleum systems modelling for the Yathong Trough includes depth to top and base of each unit, depositional age of each unit, amount and timing of erosion, lithology (mix of summary lithologies for each unit, based on published data), assignment of petroleum systems elements, estimated total organic carbon (%), reaction kinetics and initial Hydrocarbon Index for each source rock unit (Table 5).

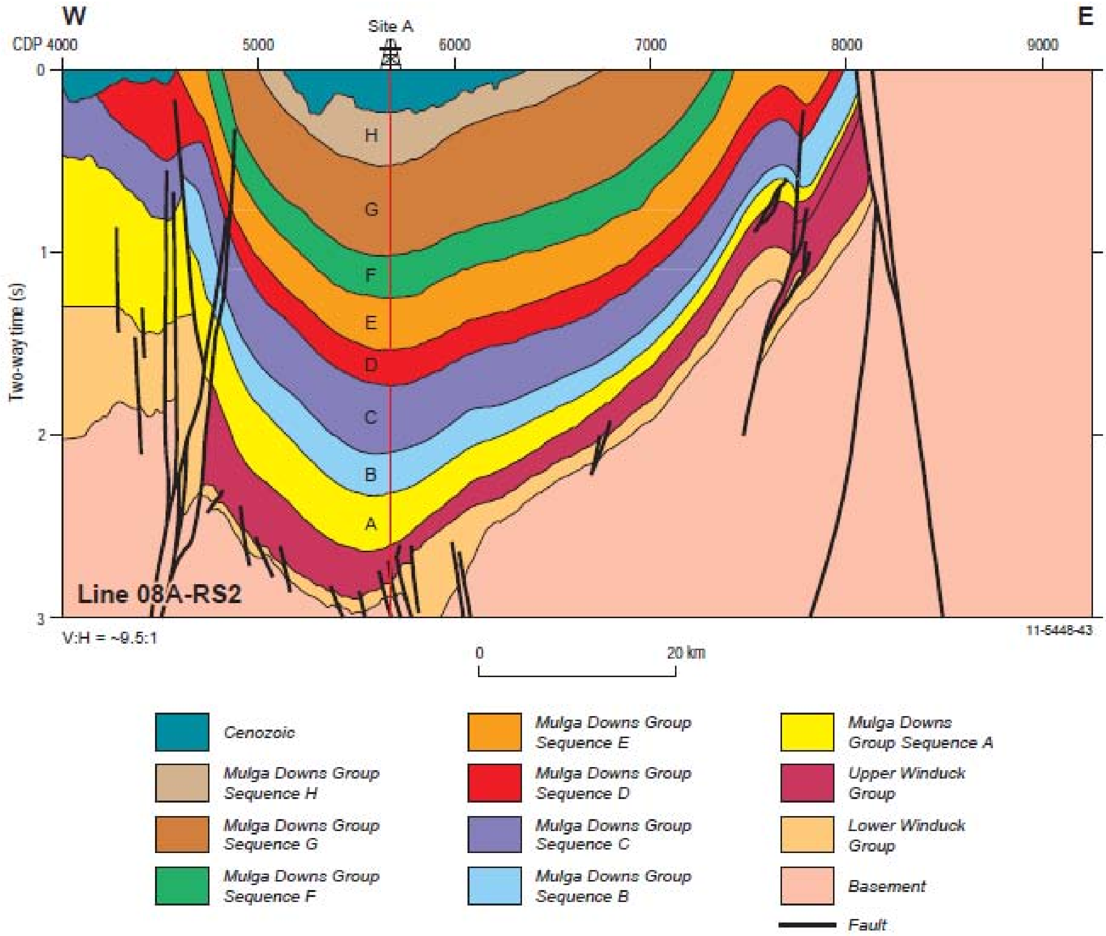


Figure 46 *Geological model of the Yathong Trough in the Darling Basin, showing the location of the one dimensional model (site A) used for petroleum systems modelling.*

The model initially assumed that extension occurred during the deposition of the upper Silurian-Lower Devonian Winduck Group and subsequent thermal subsidence during the deposition of the Mulga Downs Group sequences A –C (Snake Cave Interval) to Mulga Downs Group sequences D - H (Ravendale Interval) The model uses a McKenzie (1978)-style crustal stretching during the Middle to Late Devonian, with a suggested beta factor of about 2.7 for the extension event, although this model did not achieve a very good fit for the thermal subsidence phase within the basin. If the units mapped as Mulga Downs Group sequence A are included with the Winduck Group in the mechanical extension phase, then a better match between the modelled and estimated (from seismic) subsidence is achieved (Figure 47).

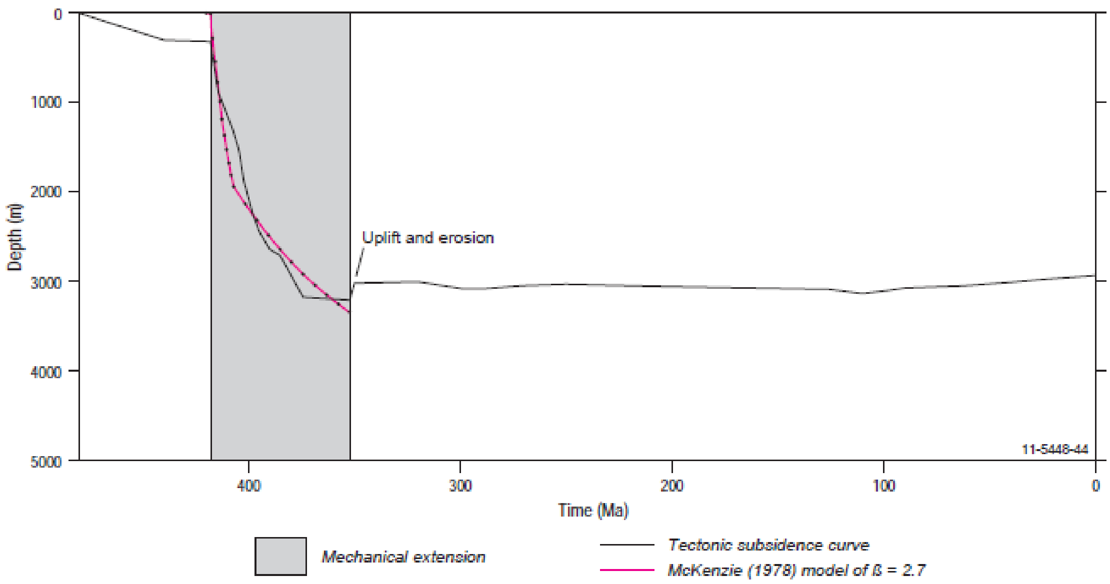


Figure 47 *Results from petroleum systems maturation modelling at site A in the Yathong Trough, Darling Basin, showing the estimated tectonic subsidence based on the seismic interpretation and the modelled tectonic subsidence.*

The amount of erosion modelled for the Yathong Trough includes a nominal 1000 m of additional Upper Devonian-lower Carboniferous sedimentary rocks, eroded during the late Carboniferous Kanimblan Orogeny. A further 200 m each of Cisuralian (eroded during the late Permian) and Lower Cretaceous (eroded during the Late Cretaceous) was also included (Figure 48). The Lower Devonian upper Winduck Group and the Upper Devonian Mulga Downs Group sequence D (lower Ravendale Interval) are considered to include potential source rocks (e.g. Alder et al., 1998). The choice of Type II kerogen kinetics is based on the likely presence of carbonate and probable algal-bacterial organic matter deposited in restricted shallow marine depositional environments. The potential source units were modelled with a bulk TOC of 2% and an initial HI value of 500 mgHC/gTOC.

Table 5: Yathong Trough main input data

Stratigraphic Unit	Top (m)	Base (m)	Thick (m)	Eroded (m)	Deposited From (Ma)	Deposited to (Ma)	Eroded from (Ma)	Eroded To (Ma)	Lithology %[1]	PSE	TOC %	Kinetic	HI
Cenozoic	-150	-50	100		10	0			Sst 60, Cgl 10, Slst 20 Sh 10	Overburden			
Cretaceous	-50	50	100	200	125	110	90	60	Sst 50, Slst (org-rich 2-3%) 30, Sh 20	Overburden			
Permian	50	50	0	200	300	292	270	250	Cgl 10, Sh 40, Sst 40, Granite (500 Ma) 10	Overburden			
Mulga Downs Group Unit H	50	290	240	1000	374	352	350	320	Cgl 5, Sst 65, Slst 20, Sh 10	Reservoir			
Mulga Downs Group Unit G	290	1850	1560		385	374			Cgl 5, Sst 65, Slst 20, Sh 10	Reservoir			
Mulga Downs Group Unit F	1850	2250	400		390	385			Cgl 5, Sst 65, Slst 20, Sh 10	Reservoir			
Mulga Downs Group Unit E	2250	2950	700		395	390			Cgl 10, Sst (quartzite) 50, Slst 20, Sh 10	Reservoir			
Mulga Downs Group Unit D	2950	3450	500		398	395			Cgl 10. Sst (quartzite) 40, Slst 20, Sh (org-rich 3%), Lst 10	Source Rock	2	Pepper and Corvi (1995)	500
Mulga Downs Group Unit C	3450	4310	860		402	398			Sst 80, Cgl 5 Lst (org-rich) 5, Slst 10	Overburden			
Mulga Downs Group Unit B	4310	5150	840		405	402			Sst 70, Cgl 15, Lst (ooid) 5, Slst 10	Overburden			
Mulga Downs Group Unit A	5150	6000	850		407	405			Sst 70, Cgl 15, Lst (ooid) 5, Slst 10	Overburden			

Stratigraphic Unit	Top (m)	Base (m)	Thick (m)	Eroded (m)	Deposited From (Ma)	Deposited to (Ma)	Eroded from (Ma)	Eroded To (Ma)	Lithology %[1]	PSE	TOC %	Kinetic	HI
Upper Winduck Group	6000	6650	650		414	407			Slst 30, Sh (org-rich 3%) 35, Marl 5 Lst (micrite) 30	Source rock	2	Pepper and Corvi (1995)	500
Lower Winduck Group	6650	7250	600		418	414			Sst 75, Sh 20 Lst 5	Underburden			
Basement	7250	8300	1050		480	440			Quartzite 50, schist 10, granite (500 Ma)	Underburden			
						480							

[1]Sst = Sandstone, Cgl = Conglomerate, Slst = Siltstone, Sh = Shale, Lst = Limestone, Dol = Dolomite.

BOUNDARY CONDITIONS, BURIAL HISTORY AND MATURITY

Boundary conditions for the geohistory modelling include palaeowater depths, temperatures at the sediment-water interface (SWIT), and heat flow through time. Palaeowater depths are based on regional geology (Alder et al., 1998; Willcox et al., 2003; Blevin et al., 2007) with most deposition likely to have been in terrestrial environments, with the exception of the modelled source intervals, which were deposited in shallow marine environments (Table 6). Temperatures at the sediment-water interface are based on calculations provided by the software (PetroMod v11 SP2) for present-day latitude of 32ºS.

Regional heat flow maps (Geoscience Australia, 2011) suggest a high surface heat flow of about 80 mWm^{-2} for the study area. Considering the thickness and type of sediment in the Yathong Trough, this would imply a basal heat flow of about 70 to 75 mWm^{-2}. A beta factor of 2.7 suggests a basal heat flow of about 115 mWm^{-2} at the end of the extensional phase, decreasing to the pre-extension heat flow during the thermal subsidence phase. The assumed basal heat flow of 70 mWm^{-2} has been modelled as constant since that time (Table 6, Figure 49).

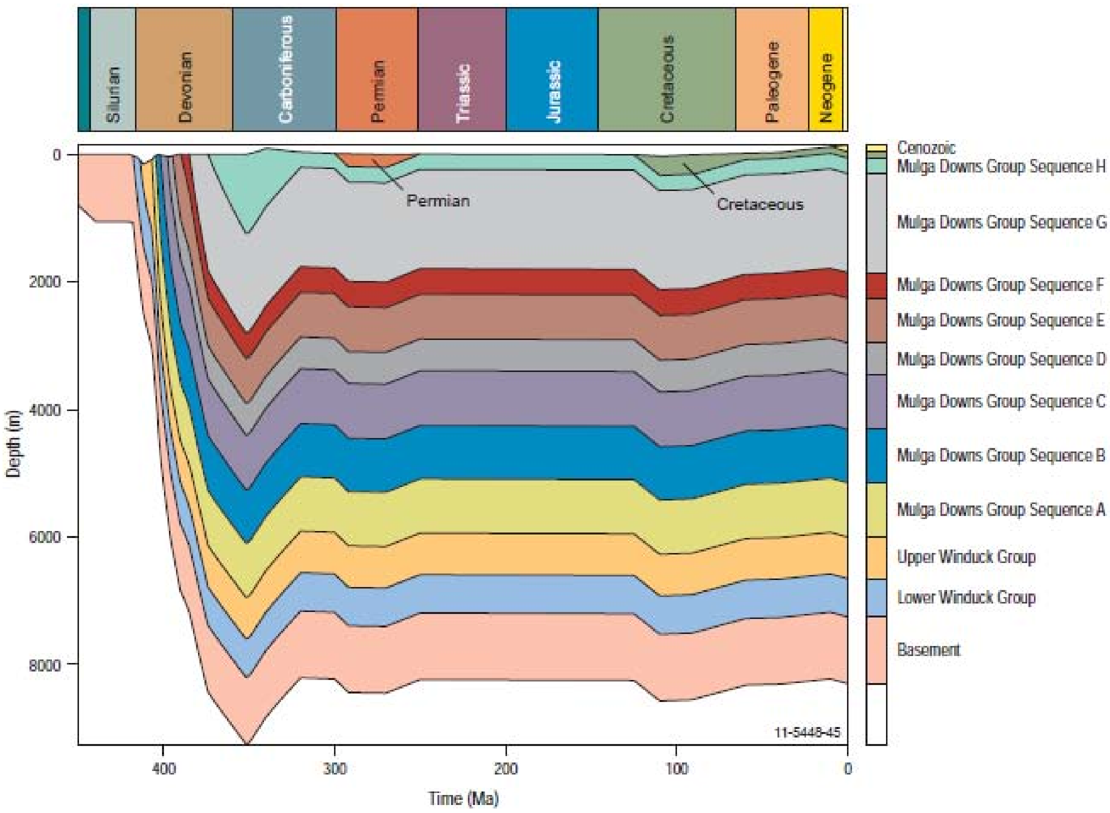


Figure 48 *Results from petroleum systems maturation modelling at site A in the Yathong Trough, Darling Basin, showing the modelled burial history plot.*

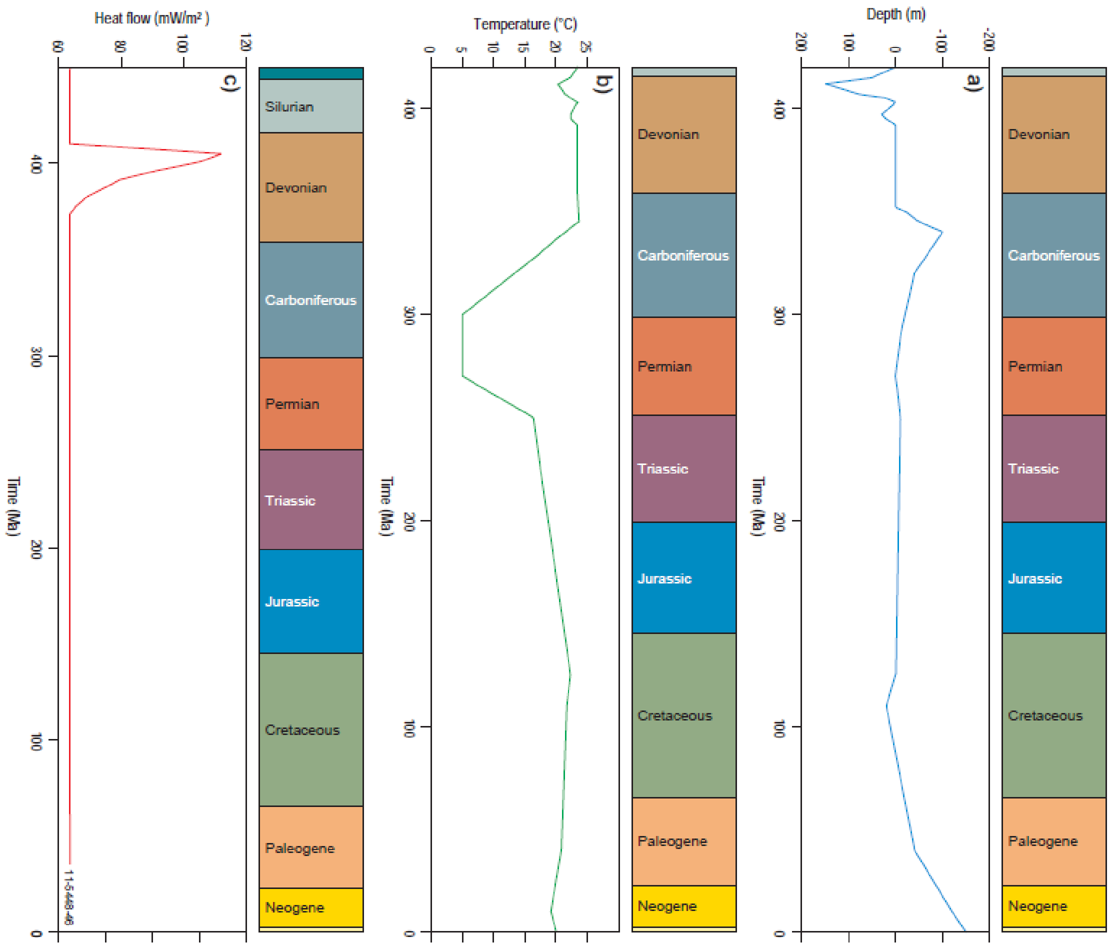


Figure 49 *Boundary conditions modelled for the Yathong Trough, Darling Basin, including* ***a)*** *paleowater depth,* ***b)*** *sediment-water interface temperature (SWIT), and* ***c)*** *heat flow through time.*

Table 6 Boundary conditions for paleowater depth (PWD), temperatures at the sediment-water interface (SWIT) and heat flow (HF).

Age (Ma)	PWD (m)	Age (Ma)	SWIT (°C)	Age (Ma)	HF(mW/m^{-2})
0	-150	0	20.00	450.00	70.00
10	-120	10	19.14	418.00	70.00
40	-40	40	20.76	416.70	70.00
110	20	110	21.65	415.40	70.00
125	0	125	22.30	414.10	70.00
250	-10	250	16.31	412.80	70.00
270	0	270	5.00	411.50	70.00
290	-10	290	5.00	410.20	70.00
300	-20	300	5.00	408.90	80.00
320	-40	320	13.40	407.60	91.42
330	-70	330	17.51	406.30	105.06
340	-100	340	21.35	405.00	115.00
345	-50	345	23.57	400.50	108.00
350	-20	350	23.47	396.00	95.00
352	0	352	23.43	391.50	85.00
360	0	360	23.32	387.00	80.00
375	0	375	23.32	382.50	75.00
377	0	377	23.32	378.00	72.00
385	0	385	23.32	373.50	70.00
387	0	387	23.32	369.00	70.00
392	0	392	23.32	364.50	70.00
395	20	395	22.32	360.00	70.00
397	30	397	22.32	360.00	70.00
403	0	403	23.32	320.00	70.00
405	20	405	22.32	0.00	70.00
407	80	407	21.32		
412	150	412	20.32		
415	50	415	22.32		
420	0	420	23.32		

A predicted temperature of 165ºC at 5 km depth was used for modelling and is broadly consistent with published estimates (Geoscience Australia, 2011). Predicted temperatures at 1 km depth of 63ºC and at 2 km depth of 96ºC (Figures 50 and 51) are higher by 10-20ºC than available downhole temperatures for the Blantyre 1 and Pondie Range 1 drillholes, located to the northwest of the Yathong Trough. If, however, downhole temperatures are corrected (+10ºC) for temperature losses due to circulation, the difference is reduced to about 5-10ºC. Considering the overall lack of data for the Yathong Trough, this is considered to be a reasonable assumption.

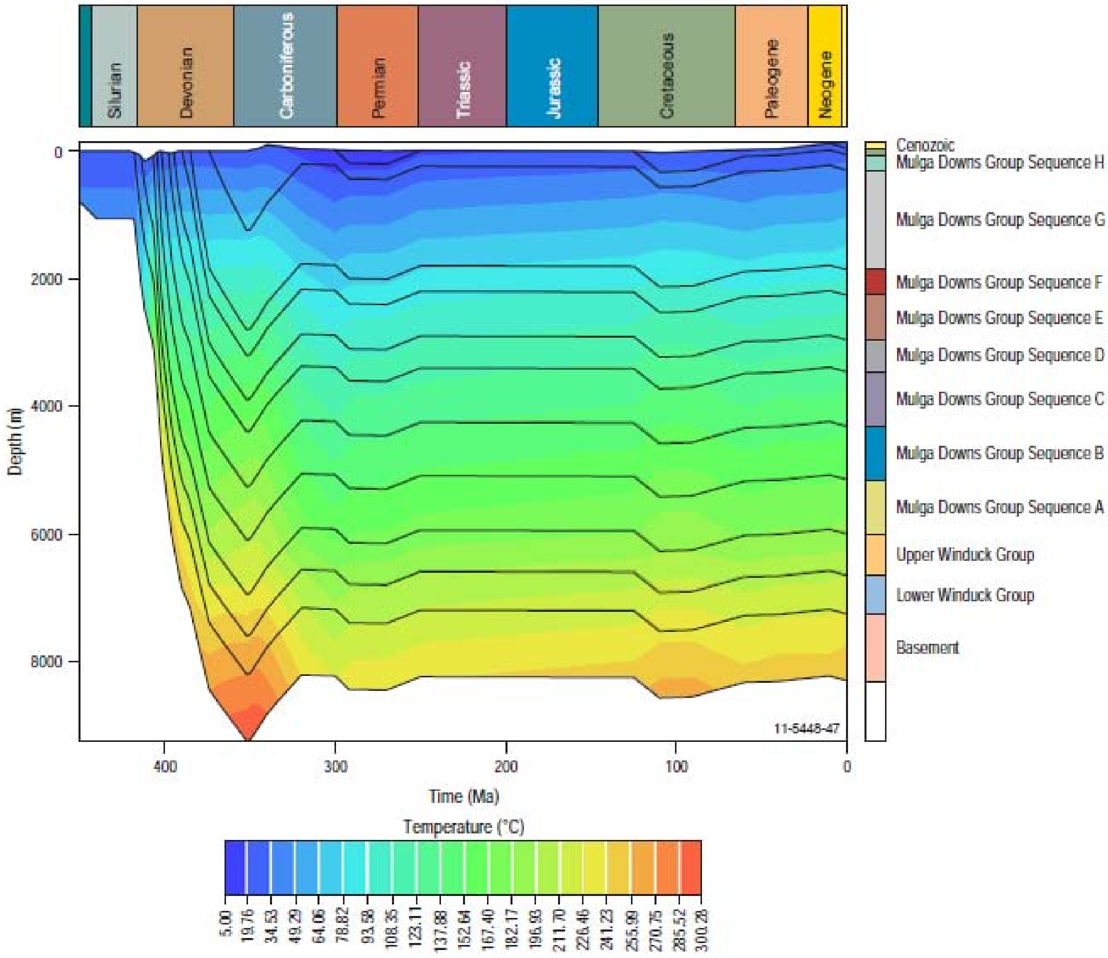


Figure 50 *Results from petroleum systems maturation modelling at site A in the Yathong Trough, Darling Basin, showing the modelled temperature overlain on the burial history plot.*

The modelled maturity profile in Figure 52a suggests that potential Lower Devonian source rocks (Winduck Group) are currently in the dry gas window, whereas the Middle Devonian Mulga Downs Group Sequence D (lower Ravendale Interval) at this location is currently mature for wet gas generation. This result is based on the assumption of 1 km of additional Late Devonian-early Carboniferous deposition and subsequent erosion during the late Carboniferous. The modelled profile in Figure 52b assumes only 200 m of deposition and erosion, resulting in a similar maturity level for the Winduck Group, but the Mulga Downs Group Sequence D is late oil mature in this model (Figure 52).

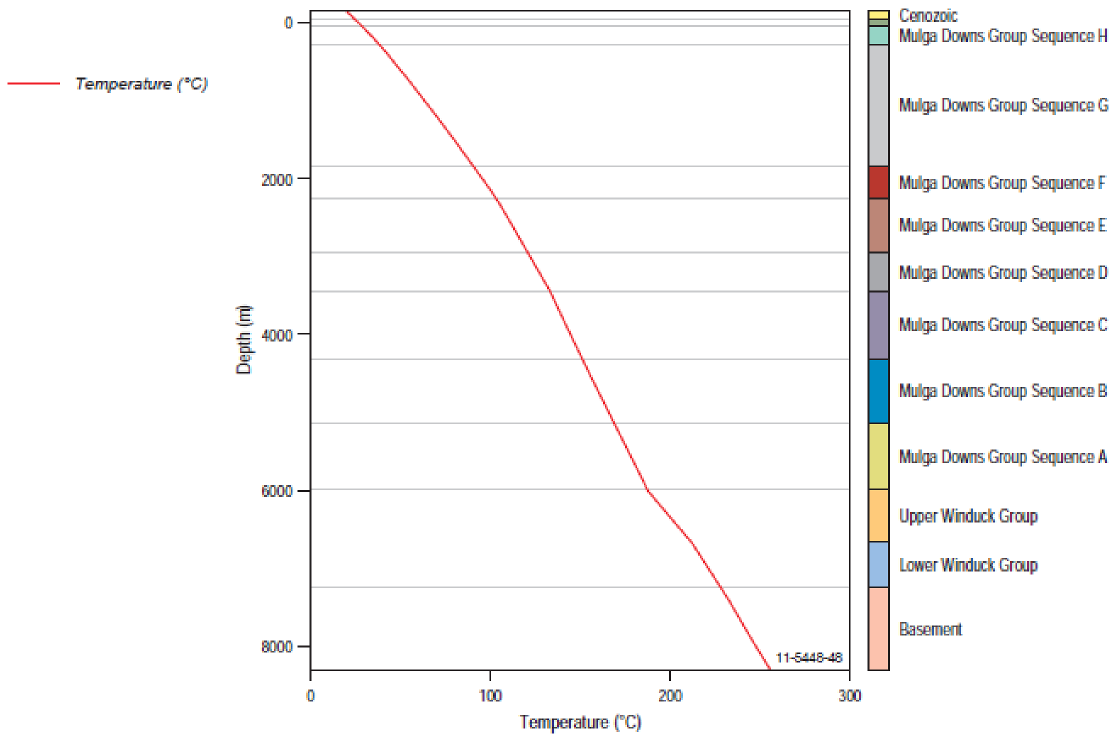


***Figure 51** Results from petroleum systems maturation modelling at site A in the Yathong Trough showing predicted temperature of 165 ºC at 5 km depth is broadly consistent with published estimates (Geoscience Australia, 2011).*

Vitrinite reflectance values for the Blantyre 1 and Pondie Range 1 drillholes, to the northwest of the Yathong Trough, are ambiguous in that they show two populations at depths greater than 1 km, with the lower values possibly representing downhole contamination (Alder et al., 1998). Measured values for the lower values from the wells range from around 0.7% Ro for depths between 260 and 690 m to around 0.9% for depths greater than 1500 m. The second population ranges from 1.5 to 1.6% Ro. In our current modelling, for the two scenarios shown in Figure 52, the lower vitrinite reflectance (VR) values may be representative of the true maturity, with VR values of 0.9% occurring within a depth range of 2000 to 2500 m. To achieve VR values of 1.5% at this depth range, 3 km of Devonian-Carboniferous deposition and erosion would be required.

The maturity overlay on the burial history plot shows that rapid burial during the Devonian brought potential Lower-Middle Devonian source rocks (upper Winduck Group and Mulga Downs Group Sequence D) into the gas and oil window (Figure 53). The upper Winduck Group passed through the oil window in the Early Devonian and the wet gas window in the Middle to Late Devonian. The Mulga Downs Group Sequence D passed through the oil window in the Late Devonian, prior to uplift and erosion in the Carboniferous, and has been in the wet gas window since then. Subsequent uplift and erosion and minor Permian and Cretaceous deposition have had no effect on the maturity levels. Although the maturity level of the younger potential source unit is lower in the scenario with less erosion, the end result of early maturation is not changed.

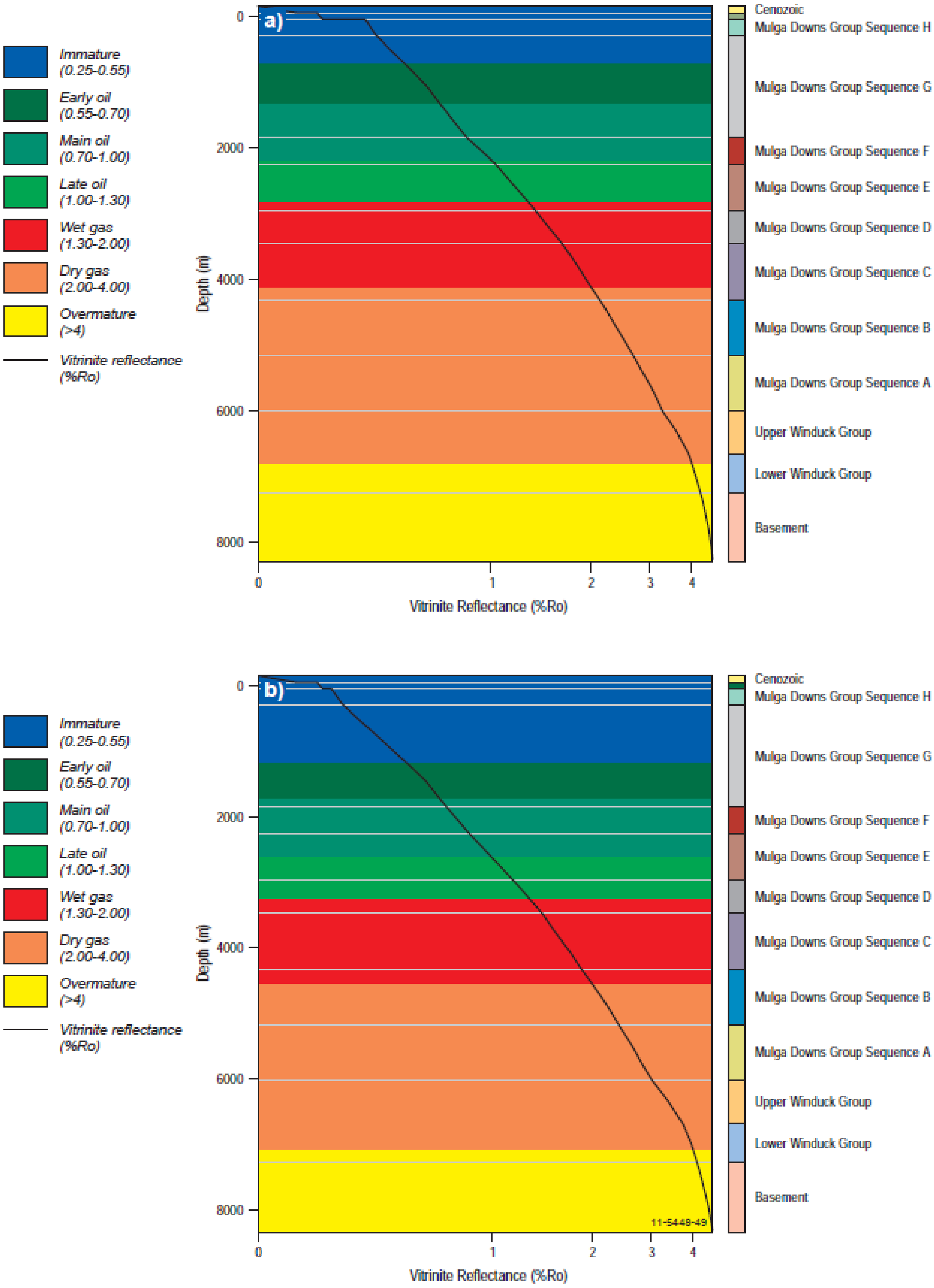


Figure 52 *Modelled vitrinite reflectance and maturity profile showing* ***a)*** *1000 m additional deposition and erosion and* ***b)*** *200 m additional deposition and erosion.*

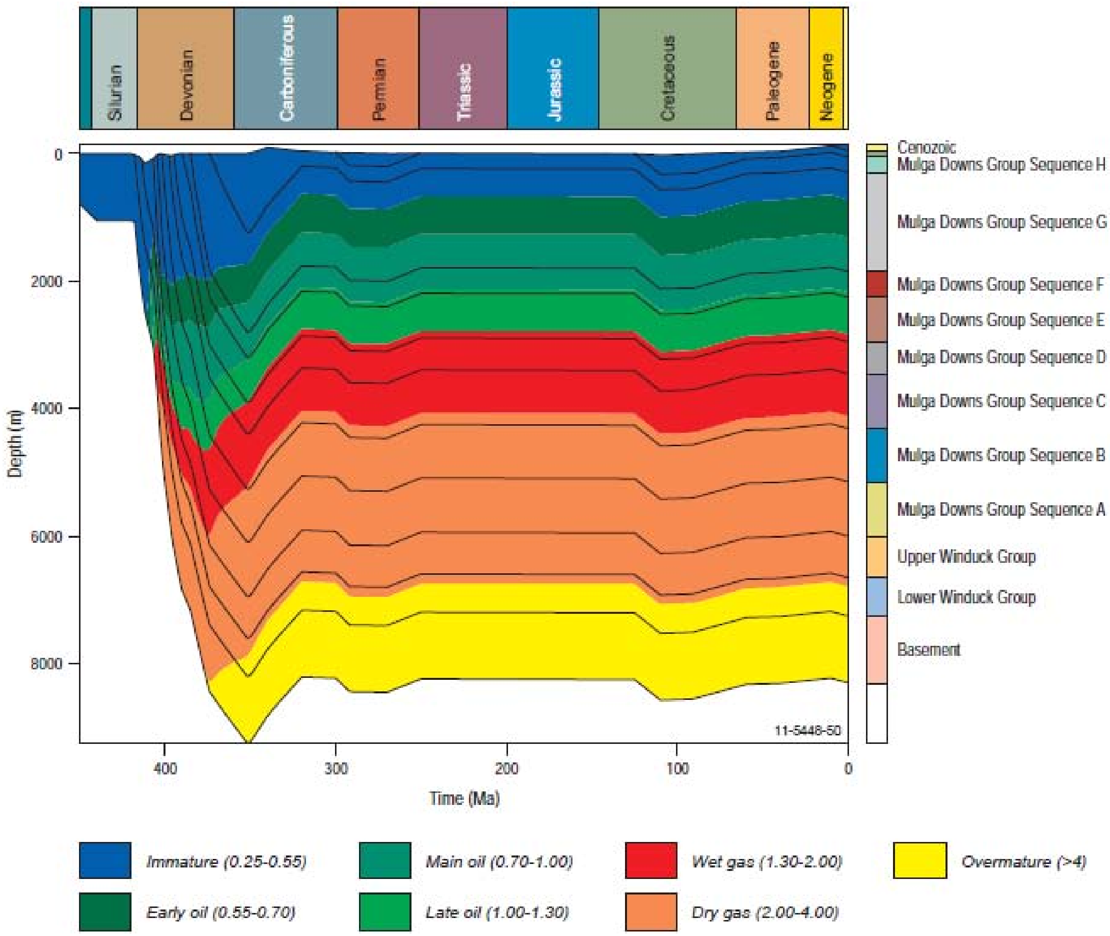


Figure 53 *Results from petroleum systems maturation modelling at site A in the Yathong Trough, showing modelled maturity overlain on the burial history plot.*

Using a scenario of Lower Devonian source rock (Winduck Group) with 1000 m deposition and erosion, Figure 54 shows the kerogen transformation ratio and expulsion mass for the modelled Lower Devonian source rock. Close to 100% of available kerogen is likely to have been transformed by the Carboniferous, with later events (e.g. Cretaceous) having no notable effect. Expulsion of oil and minor gas is likely to have occurred in the Devonian, prior to uplift and erosion during the Carboniferous.

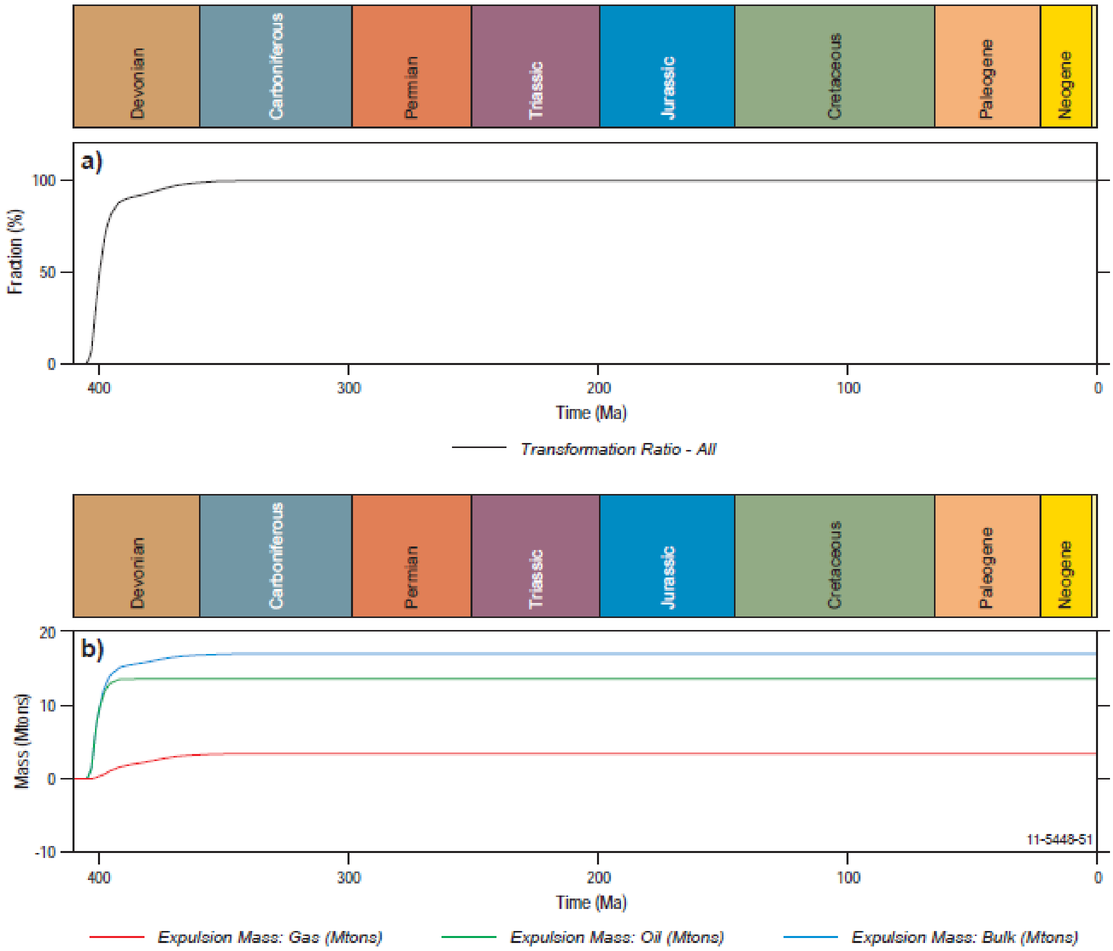


Figure 54 *Lower Devonian source rock (lower Winduck Group) with 1000 m deposition and erosion, showing* ***a)*** *100 % of kerogen transformed and* ***b)*** *early expulsion of oil and minor gas.*

A second scenario for the Lower Devonian source with 200 m deposition and erosion shows the kerogen transformation ratio and expulsion mass for the same potential source layer, but for less deposition and erosion (Figure 55). It is evident that, for the oldest potential source rock, the modelled transformation ratio and expelled hydrocarbons are extremely similar to the previous scenario with 1000 m of erosion. Thus, the amount of erosion modelled for this source unit is not necessarily a critical factor. Modelling with a lower heat flow will only reduce the transformation ratio by minor percentage points, but not the timing of generation and expulsion.

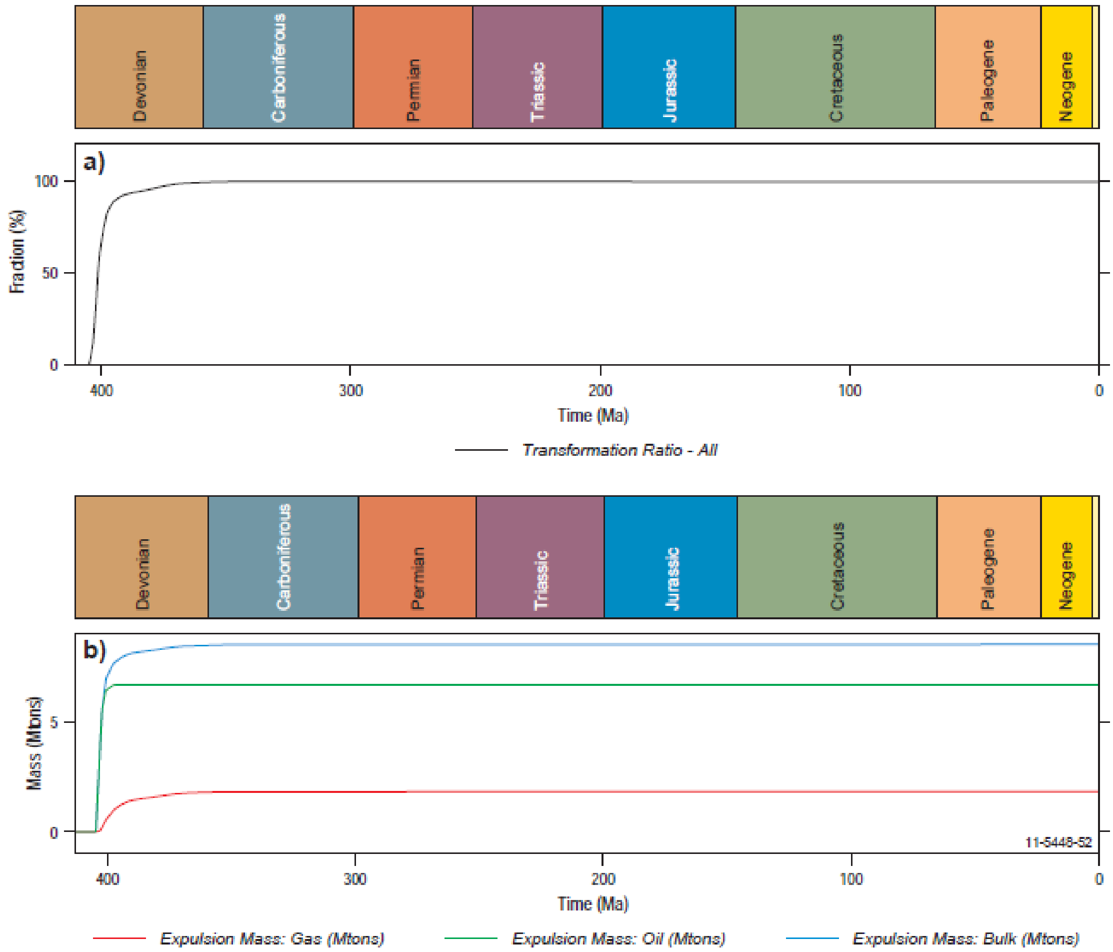


Figure 55 *Lower Devonian source rock (lower Winduck Group) with 200 m deposition and erosion showing **a)** 100 % of kerogen transformed, and **b)** early expulsion of oil and minor gas.*

In the scenario modelled for the Middle Devonian (Mulga Downs Group Sequence D) source rock, the kerogen transformation ratio plot shows that about 93% of available kerogen was transformed by the early Carboniferous. Similar to the Upper Devonian potential source rocks, and this has probably resulted in early expulsion of oil and minor gas (Figure 56).

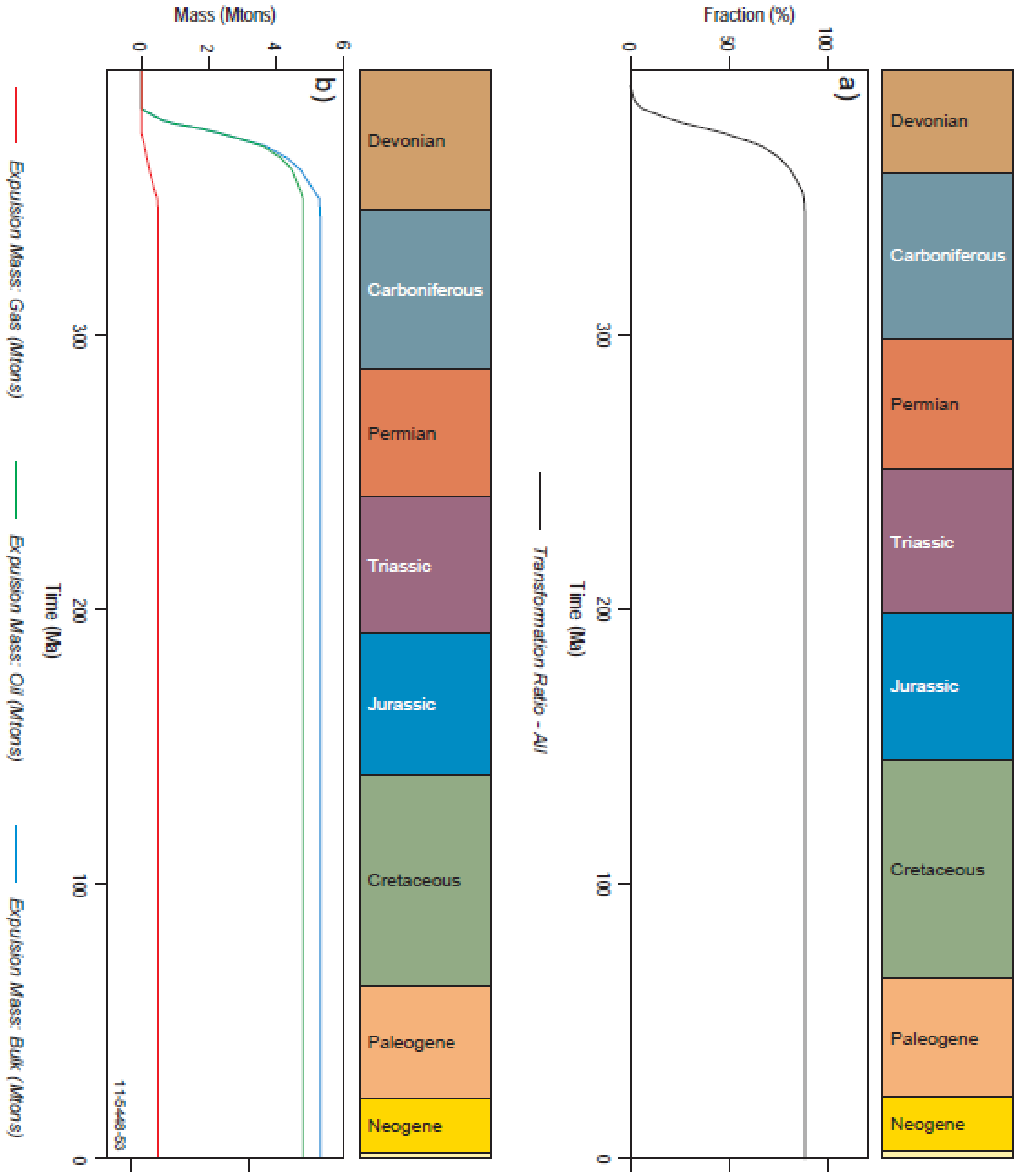


Figure 56 *Middle Devonian source rock (Mulga Downs Group Unit 4) with 1000 m deposition and erosion scenario showing* ***a)*** *~93% of kerogen transformed by early Carboniferous, and* ***b)*** *early expulsion of oil and minor gas.*

For the scenario with only 200 m of deposition and erosion during the Carboniferous, the results are similar, with a slightly lower kerogen transformation ratio (Figure 57). A very small fraction (2%) has been transformed since the Cretaceous and Figure 57 suggests that this resulted in the expulsion of very minor amounts of gas.

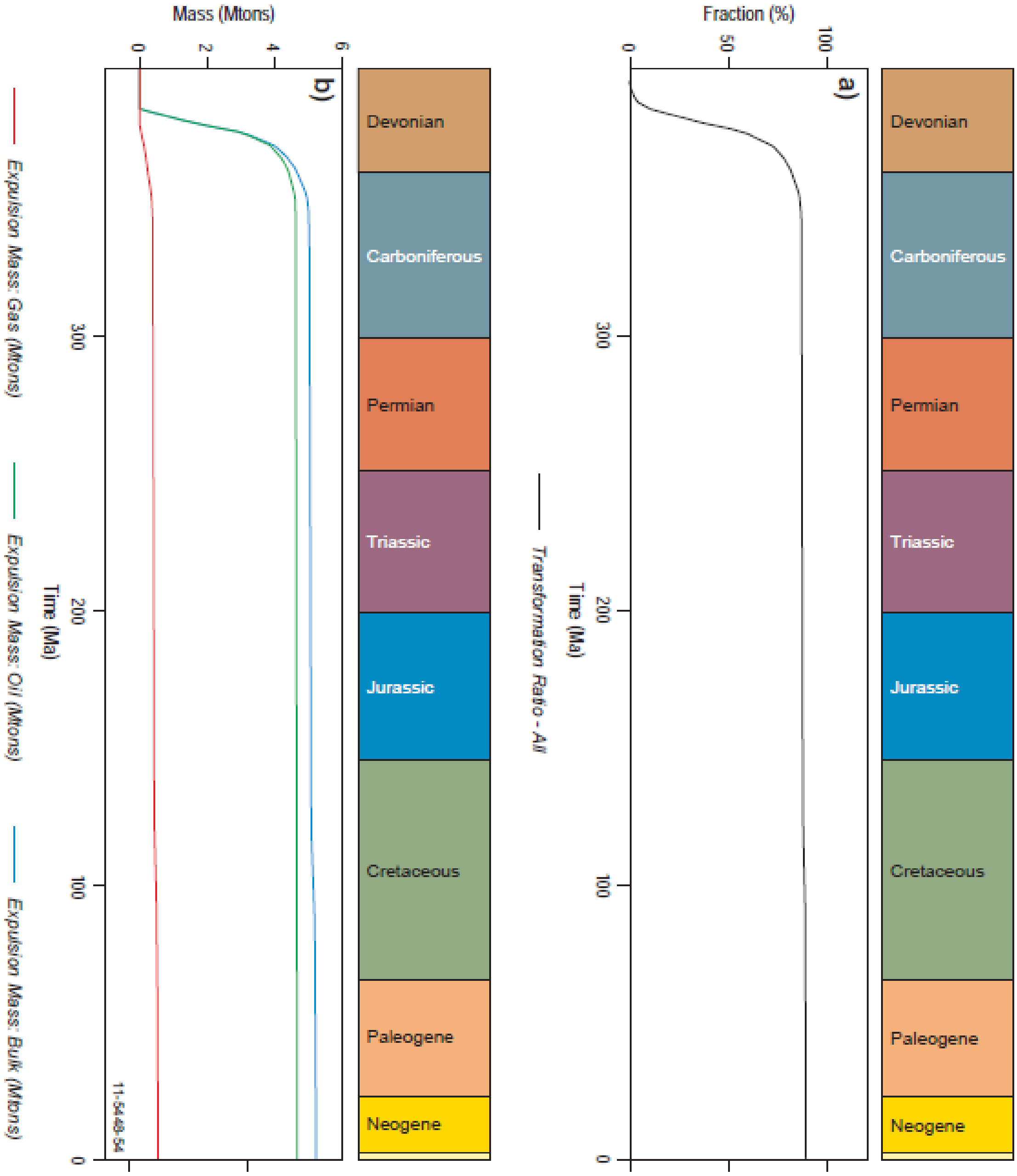


Figure 57 *Middle Devonian source rock (Mulga Downs Group Unit D) with 200 m deposition and erosion scenario, showing* ***a)*** *~87% of kerogen transformed by early Carboniferous, and 2% since Cretaceous and* ***b)*** *early expulsion of oil, with very minor expulsion of gas since Cretaceous.*

Proposed petroleum systems events chart, Yathong Trough

In summary the potential Lower and Middle Devonian source rocks in the Yathong Trough are likely to be overmature for oil generation and mature for gas generation. Generation and expulsion from Lower and Middle Devonian potential marine source rocks occurred early during their burial history, prior to Carboniferous uplift and erosion and thus, major trap formation (Figure 58). This is consistent with previous findings (Alder et al., 1998). Later burial during the Permian and or Cretaceous may have resulted in minor gas generation and expulsion from a Middle Devonian potential source rock. Varying the amount of Carboniferous erosion and or the basal heat flow does not substantially change these findings, although lower deposition and erosion during the Paleozoic and lower heat flow (-10%) will result in more substantial gas expulsion in the Cretaceous to Holocene.

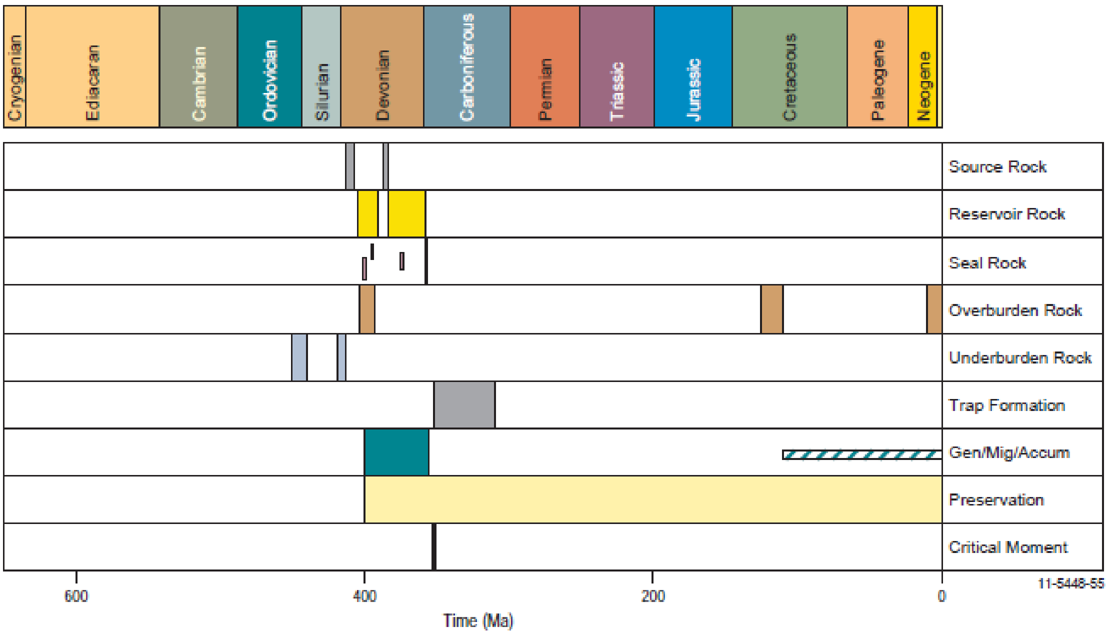


Figure 58 *Proposed Petroleum Systems Events Chart, Yathong Trough, Darling Basin.*

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