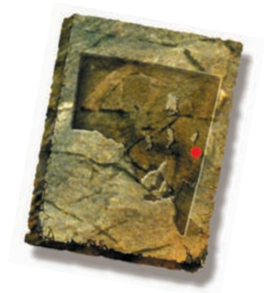
The new 3D sedimentary basin model of the Curnamona Province: geological overview and exploration implications



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Introduction

A 3D model has been constructed of cover to the Curnamona Province, enabling the base surface of sedimentary basins and their modelled depth to be visualised in an interactive platform (Fabris and Gouthas 2009). The model was generated to improve the understanding of thickness and extent of the sub-surface geology, highlight gaps in our knowledge for the region and provide a 3D interrogation of existing data.

The Curnamona model includes an update of the previous depth to basement surface for the region (Burtt et al. 2005), as well as the distribution and depth to base of Cambrian (Arrowie Basin), Mesozoic (Eromanga Basin) and Cenozoic (Callabonna Sub-basin) sediments. The 3D model provides an aid to exploration in a number of ways. These include:

- improved depth prediction to key surfaces (e.g. base Cenozoic)
- use in exploring for sediment-hosted mineralising systems (e.g. sedimentary uranium, Portia-style eluvial–alluvial gold)
- improved understanding of the distribution of regolith materials
- improved understanding of basin extents and their 3D geometries
- better delineation of areas with enhanced prospectivity for geothermal energy, enabling improved modelling of thermal gradients
- potential use in dispersion modelling through an improved understanding of the 3D geometry of mineral systems
- generation of pseudosections for subsequent drill-testing.

Creating the model

The workflow for creating surfaces for the Curnamona 3D model is outlined in Figure 1. One of the main tasks involved in the modelling of stratigraphic surfaces is bringing together varied interpretations of what has been encountered in drillholes. Within the province there is considerable inconsistency in the stratigraphic interpretation of sediments and recognition of weathered basement from holes drilled by various exploration companies. This is largely due to difficulties distinguishing similar lithologies of different ages. Therefore, at the initial stage of creating surfaces, significant reinterpretation of drillholes was required. Reinterpretation has been based on descriptions in drill logs, surrounding drillhole interpretations, palynology and correlation between seismic lines. Remaining conflicts were readily visible in 3D space and these data points omitted if found to be unreliable.

Each surface was created using point-source depth estimations derived from interpolation between known depths from drillholes and interpretations from seismic sections. In areas of sparse drilling, which is a large portion of the province, depth information relied heavily on seismic interpretation (Fig. 2). Thirty-five seismic lines were utilised.

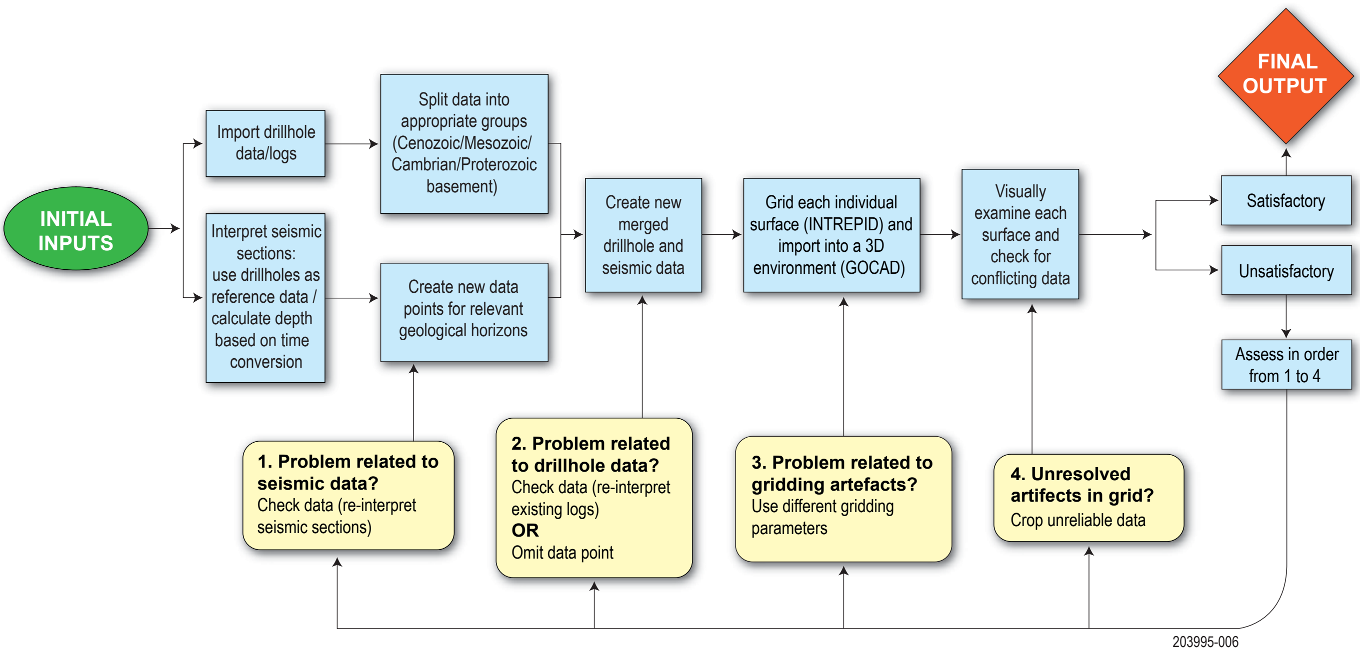


Figure 1 *Workflow for creating surfaces for the Curnamona 3D model.*

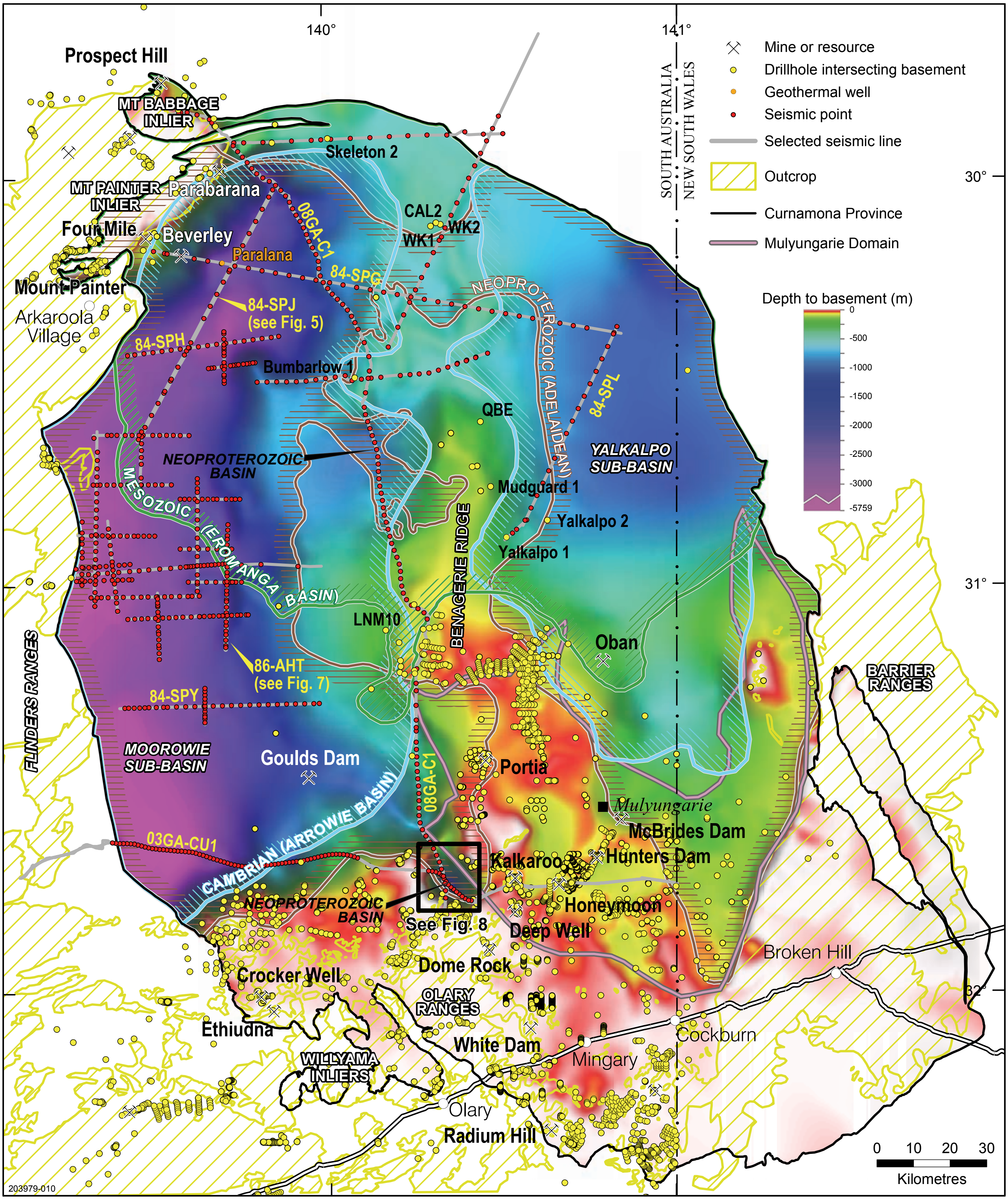


Figure 2 Pseudocolour image of depth-to-basement surface for the Curnamona Province derived from gridding point source depth estimations using drillholes and interpretations from seismic sections. Respective extents of each overlying basin are shown. Modelled depth to basement can be used to identify areas within exploratory depth with limited basement intersecting drillholes.

These were from surveys acquired either during the 1970s and 1980s to assess the petroleum potential of the Moorowie Sub-basin (Arrowie Basin), or from more recent surveys aimed at outlining the crustal architecture of the Curnamona Province (03GA-CU1 and 08GA-C1; Korsch et al. 2009). The process involved delineating reflectors that correlated to specific sedimentary boundaries as defined from drillholes and, in combination with drillhole data, using these to identify the boundaries between sedimentary basins and estimate their depth. Specifically, surfaces that have been defined for the Curnamona region include the base of the Callabonna Sub-basin (Cenozoic), Eromanga Basin (Mesozoic), Arrowie Basin (Cambrian) and top of Palaeo-Mesoproterozoic basement.

Depths were determined from seismic lines by using average velocities for major chronostratigraphic packages, as determined by deep drillholes in the Curnamona region. Velocities used included: 2063 ms^{-1} for Cenozoic sediments; 2100 ms^{-1} for Mesozoic sediments; and 4282 ms^{-1} for Cambrian and Neoproterozoic sediments. Therefore, depth to basement was the sum of the distances to the respective base of all these overlying sedimentary packages. This method was found to give similar, although slightly shallower estimates of the depth of basement, as a formula based on a time-depth curve previously used by Burtt et al. (2005). The method used in this study was found to provide a more accurate depth for the shallower horizons (e.g. base Mesozoic).

Depth points were gridded in Intrepid software (Intrepid Geophysics) using either a nearest-neighbour or variable density method, depending on the distribution of data points. Surfaces were then created in GOCAD software (Paradigm). A 3D Adobe PDF format has also been created that allows the user to fully interact with the model using the free Adobe Reader application. Within the interactive PDF model, objects can be rotated, layers selected and identified, and vertical exaggeration and dynamic cross-sectioning can be applied (Fig. 3).

Geology and basin history

The Curnamona 3D model combines a significant volume of data that enables improved quantification of sediment thickness and helps us understand the extent of sedimentary basins that overlie the Curnamona Province.

The following section describes the region's basin history and outlines the geology of sediments modelled by the Curnamona 3D model. A stratigraphic chart for the Curnamona Province and the overlying Phanerozoic basins is provided in Figure 4.

Basement

For the purpose of the Curnamona 3D model, basement is taken to be the shallowest intersection of Palaeo-Mesoproterozoic rocks, including their in situ weathered products. This encompasses the Palaeoproterozoic Willyama Supergroup and Mesoproterozoic sediments, intrusives and volcanics, which are regarded as the most shallow 'crystalline' rock units. Strictly speaking, Mesoproterozoic deposition was the first of numerous phases of basin development in the region; however, rocks of this age may well be the oldest of the NW Curnamona Province (Mount Babbage and Mount Painter inliers; Ogilvie 2006).

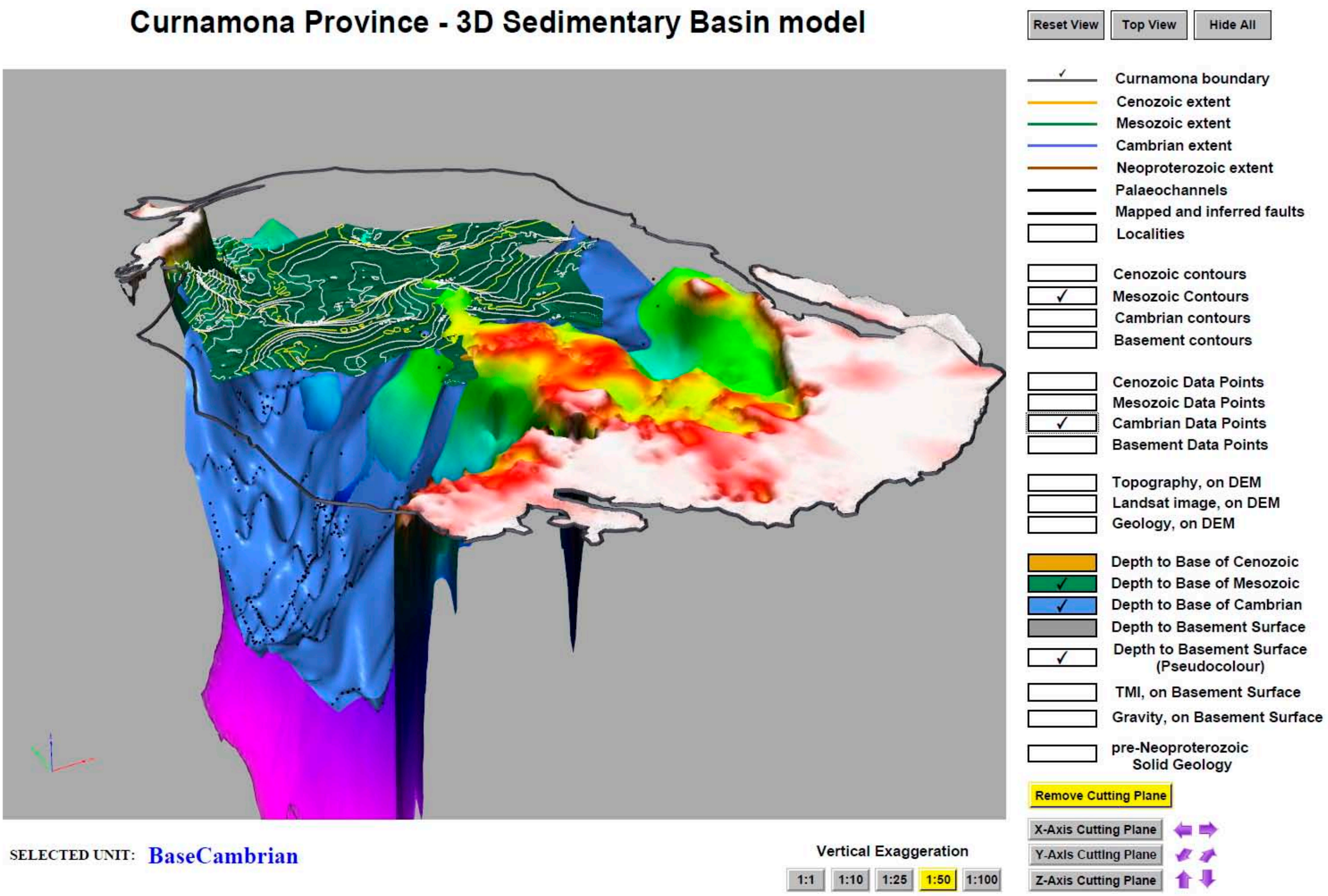


Figure 3 *A view (Adobe PDF) of the Curnamona Province 3D sedimentary basin model at 50 times vertical exaggeration. Visible layers include: depth to base of Mesozoic with depth contours, depth to base of Cambrian surface with its data points plotted, and a pseudocolour image of the top of Proterozoic basement surface.*

Neoproterozoic

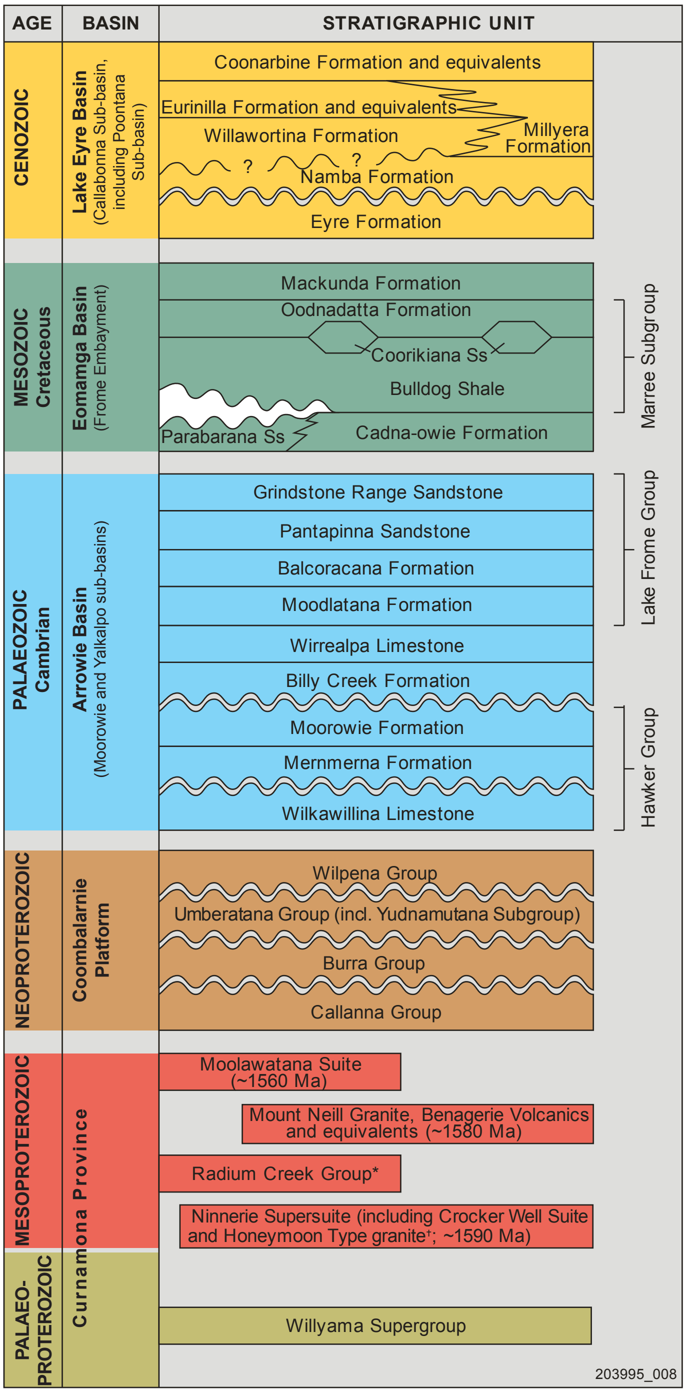
A major period of rifting in the early Neoproterozoic resulted in the formation of the tectono-sedimentary complex known as the Adelaide Geosyncline (~820–520 Ma; Preiss 1987). This now largely forms the western margin of the Curnamona Province and extends into the province as a series of grabens that host Neoproterozoic (Adelaidean) to Early Cambrian metasediments with over 3000 m of cumulative thickness. The same rifting also initiated the formation of the Benagerie Ridge, the most prominent feature of the Curnamona basement topographic image (Fig. 2). Elsewhere, Adelaidean sediments are much thinner and wedge out or have been mostly eroded over the Benagerie Ridge and in the southern Curnamona region where crystalline basement outcrops. Remnants of more extensive Adelaidean sedimentation over the Benagerie Ridge are preserved within several basins (Fig. 2).

Cambrian

Renewed rifting at the end of the Neoproterozoic, and a late Early Cambrian marine incursion, resulted in the next phase of deposition within the newly formed Arrowie Basin. Cambrian sediments deposited over the Curnamona Province, now mainly confined to the Moorowie and Yalkalpo sub-basins, are represented by marine carbonates and predominantly marginal-marine redbed clastics (Gravestock and Cowley 1995; Zang 2002). Cambrian fill is thickest within the Moorowie Sub-basin where it typically exceeds 1000 m, but thickens to 2500 m over the western margin of the province. Rifting was not as extensive in the Yalkalpo Sub-basin and Cambrian sediments rarely exceed a thickness of 700 m. Cambrian strata is absent over all but the northern portion of the Benagerie Ridge. Thinning of Cambrian units towards the margins of the Benagerie Ridge is seen in seismic lines 84-SPL and 84-SPG and indicates that the Benagerie Ridge was at least partly elevated at the time of deposition, although there is also clear evidence for subsequent removal of Cambrian sediments by erosion (Fig. 2). Erosion is likely to have begun during the Delamerian Orogeny (~515–490 Ma; Preiss 1995).

Mesozoic

Following periodic erosion and weathering extending into the Jurassic, rifting within the remnant Gondwana continent led to intracratonic basin formation (Krieg 1995) and the development of the Eromanga Basin. The Frome Embayment, the name given to the southern extension to the Eromanga Basin, overlies much of the central and northern Curnamona region (Figs 2, 4). The southern extent of the Frome Embayment is difficult to define; palaeotopography and post-depositional erosion have been responsible for patchy distribution around its southern margin. Mesozoic sediments most obviously pinch out in seismic line 86-AHT (Fig. 5). Mesozoic sedimentation over the Curnamona Province is dominated by sands and silts of the Cadna-owie Formation and the overlying, monotonous greenish-grey to bluish-grey mudstones of the marine Bulldog Shale (late Early Cretaceous). A unit that is equivalent in age to the Bulldog Shale is host to uranium mineralisation at the Four Mile West deposit (Stoian 2010). The Parabarana Sandstone



* This name is a revision of the nomenclature of the Radium Creek Metamorphics that is in the process of being formalised.

† First identified in Fricke (2008) and in the process of being formalised.

***Figure 4** Stratigraphic column for the Curnamona region.*

(equivalent to the Cadna-owie Formation), Coorikiana Sandstone and Oodnadatta Formation are known in the northern regions of the province (Fig. 4). Mesozoic sediments thicken from a few metres around their southern margin, up to 450 m along the northern margin of the Curnamona region. Generally, the base Mesozoic surface deepens to the north (Fig. 3) below the Cenozoic Poontana Sub-basin.

Cenozoic

Following the breakup of Gondwana, Australia gradually moved north resulting in climatic warming and increased rainfall (White 1994), intensifying rock weathering and fluvial

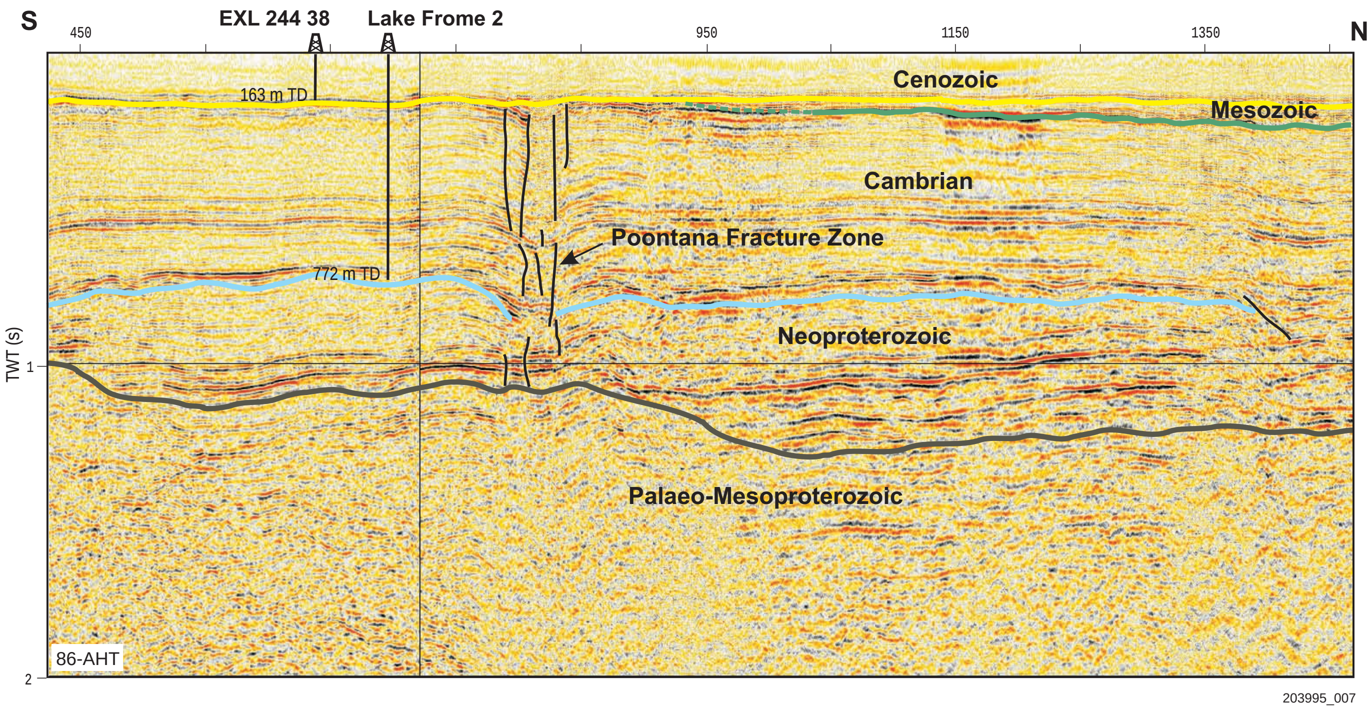


***Figure 5** Seismic section interpretation, line 86-AHT. Section is located in Figure 2.*

erosion. Major river systems incised into the Curnamona Province and drained in a northerly direction from the Olary Ranges, and also towards the NW from the Barrier Ranges in New South Wales. Sediment thickness within these palaeodrainage features is typically around 30 m but is known to be greater than 50 m, such as in the Yarramba Palaeovalley. Palaeodrainage features are visible in the depth to base of Cenozoic data (Fig. 6), and are known to host significant uranium occurrences, including the Beverley, Honeymoon Four Mile East and Pepegoona ore bodies (Wilson and Fairclough 2009). Fluvial sediments, along with alluvium associated with lower energy streams and alluvial plains, were deposited throughout the basin and form the basal member (Eyre Formation) of the Callabonna Sub-basin (Lake Eyre Basin; Cenozoic). The Callabonna Sub-basin refers to the southwestern portion of the Lake Eyre Basin which includes areas over the Curnamona Province.

An important feature of the base of Cenozoic surface is a large depression west of Lake Frome known as the Poontana Sub-basin (also referred to as the Poontana Trough; Fig. 6; Callen 1981). Fault reactivation during the Cenozoic along the margin of the Flinders Ranges has resulted in a substantial increase in the depth to base of Cenozoic and, in particular, thickening of Miocene Namba Formation sediments. The development of the Poontana Sub-basin, and smaller depocentres within it, were facilitated by fault movement along numerous NNW–SSE and NE–SW trending structures, of which only a few have been accurately mapped under cover (Fig. 6). One of the most significant of these structures is the Poontana Fault (Fig. 7) against which the Beverley uranium deposit is juxtaposed. The published ore outline of this deposit shows that it is developed in a meandering channel within the Namba Formation (Heathgate Resources 1998), and parts of the deposit clearly share the same NNW–SSE and NE–SW signature of the aforementioned regional faulting. Thus, it is likely that the (mineralised) meandering channel sands at Beverley are structurally controlled, which highlights the importance of these structures to the location of uranium mineralisation in this region.

Seismic lines 84-SPH, 84-SPJ and 84-SPG indicate a long history of fault movement along the Poontana Fault, including neotectonic movement and uplift of the (Neoproterozoic) Flinders Ranges and their overthrusting upon Cenozoic sediments of the Lake Eyre Basin (Fig. 7). This foreland basin structural style is evident in outcrop along the western margin of the Flinders Ranges (e.g. along Lady Buxton Fault). Significantly, the structural history of this region appears to have been an important control on uranium distribution east of Mount Painter and may be an important ingredient to the prospectivity of the region.

By the mid Miocene, the Poontana Sub-basin became the depocentre for clay, silt, sand and carbonate units of the Namba Formation within a fluviolacustrine setting (Callen and Tedford 1976). Deposition of the Namba Formation was widespread and included areas over the Benagerie Ridge, although some units are absent or very thin. The basin margins were sites of fluvial-deltaic and lacustrine offshore bar deposition, particularly within the Poontana Sub-basin, and form potential hosts for sediment-hosted uranium deposits.

Uplift of the Flinders Ranges continued throughout the late Neogene and sedimentation along the western Curnamona region became dominated by fluvial/colluvial regimes (Willawortina Formation). Elsewhere in the Callabonna Sub-basin, lacustrine environments were replaced by alluvial, floodplain and aeolian environments. Erosion during the ?latest Neogene incised the landscape to create the modern land surface.

Implications for exploration

Updated depth-to-basement model

An accurate depth-to-basement model is important in outlining financial risk of drilling basement targets. The depth-to-basement model highlights large areas of the Curnamona Province that are within explorable depths but where there are presently few drillholes to basement (Fig. 2). Two areas of particular interest include the Mulyungarie Domain (Conor et al. 2006) and the Benagerie Ridge (Fig. 2). The latter has been reported to have potential for iron oxide – copper–gold–uranium style mineralisation (Burtt,

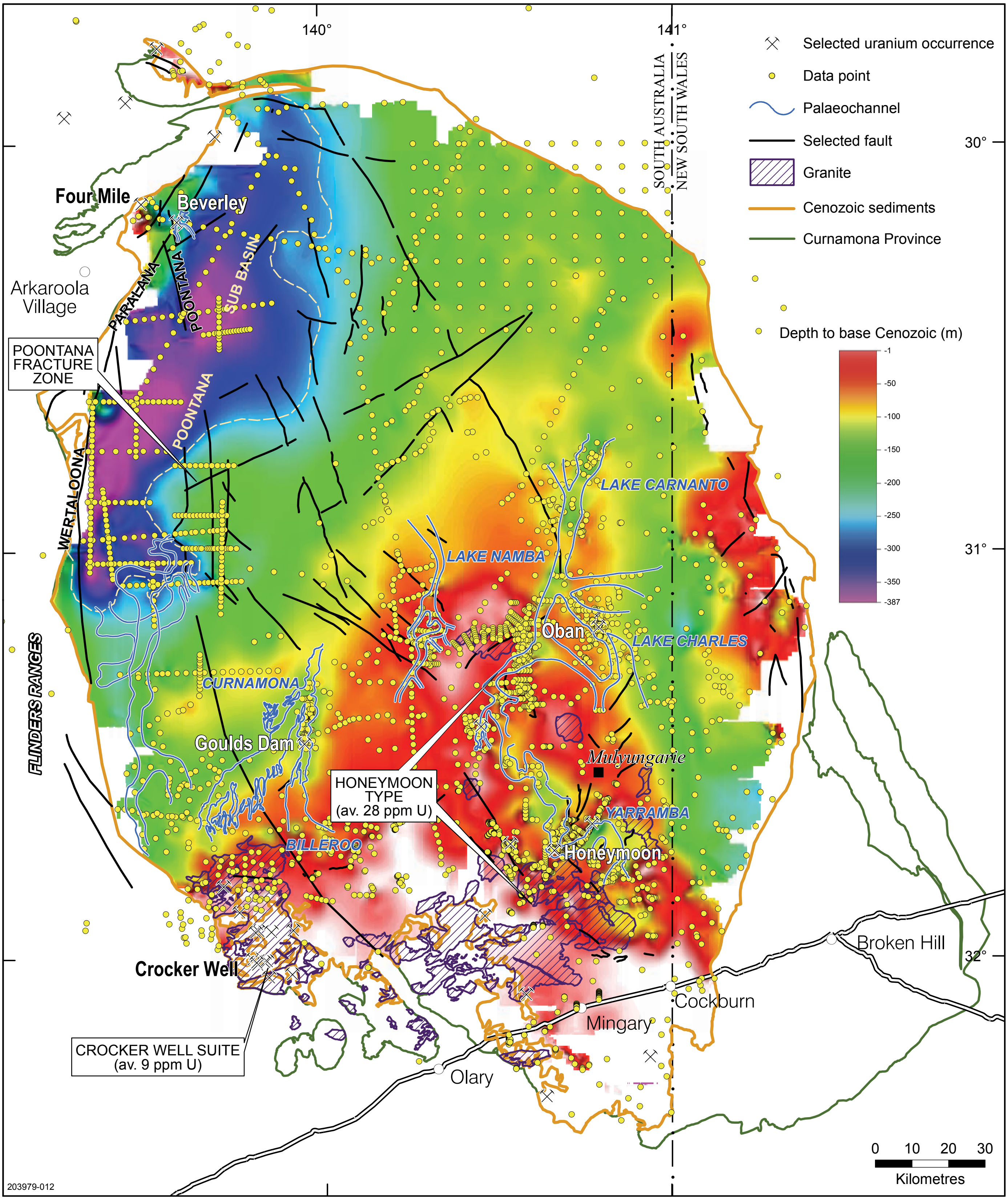


Figure 6 Pseudocolour image of the depth to base Cenozoic surface for the Callabonna Sub-basin overlying the Curnamona Province. Data points used to create the surface are shown. Major palaeodrainage and occurrence of uranium-rich granitic source rocks are highlighted.

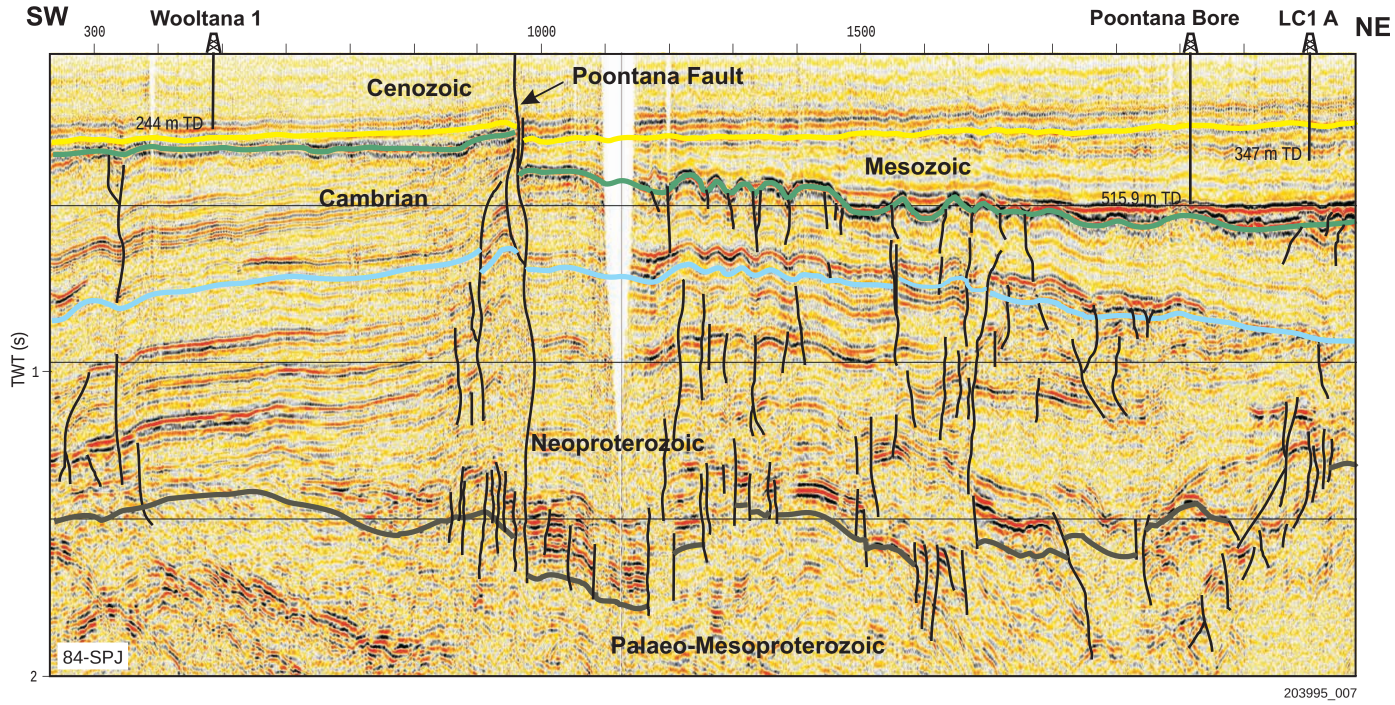


Figure 7 *Seismic section interpretation, line 84-SPJ. Section is located in Figure 2.*

Conor and Robertson 2004), but only 12 holes have been drilled to basement to test for this style of mineralisation (Fig. 2). Moreover, preliminary interpretation of the recently acquired deep seismic line 08GA-C1 highlights a thick sedimentary package below the Mesoproterozoic Benagerie Volcanics but above Palaeoproterozoic Willyama Supergroup rocks that outcrop in the Olary region (Korsch et al. 2009). The prospectivity of these sediments is untested.

The Mulyungarie Domain as defined by Conor et al. (2006) is a highly prospective region of the Curnamona Province, albeit underexplored due to the challenge of exploring in regolith-dominated terrains. The most significant discovery to date is Cu–Au–Mo mineralisation found at the Kalkaroo deposit. Numerous prospects of similar style, as well as zinc-dominated mineralisation such as that of the Hunters Dam, McBrides Dam and Deep Well prospects, highlight the regions potential. Approximately 70% of this domain is covered by <100 m of sediment.

Uranium exploration

An important aspect of exploring for palaeochannel-hosted sedimentary uranium is defining the position and geometry of palaeodrainage networks and determining their flow direction. The depth to base of the Cenozoic model, based on over 3000 data points, provides a regional context to the location of channels; and indicates the likely target-depths required to test their prospectivity (Fig. 6). The model can also be used to determine probable source provinces. The various extents of the stacked sedimentary basins that rest upon the Curnamona Province indicate whether palaeochannels have incised Phanerozoic sediment or Proterozoic basement. Where the depth to Proterozoic basement and the base of Cenozoic is similar, representing areas of likely outcrop or subcrop during the early Cenozoic, possible sediment provinces are indicated, although post-depositional erosion and tectonics need to be considered. Sediment sources of particular interest include sodic granites from the Crocker Well region for the Billeroo and Curnamona palaeovalleys, interpreted granite and volcanics along the Benagerie Ridge for the Lake Namba Palaeovalley and numerous granites along the Yarramba Palaeovalley (Fig. 6).

Some of the world's largest sand-hosted uranium deposits occur within petroliferous basins of southern Kazakhstan. It is postulated that the generation of petroleum (including methane and H_2S) and its migration or leakage into the basins' margins has played an important role in the reduction of uranium within these deposits (Fyodorov 2005; Jaireth, McKay and Lambert 2008). Both the Arrowie and Eromanga basins that overlie the Curnamona Province have demonstrated petroleum potential (PIRSA 2010) and therefore it is conceivable that hydrocarbons have acted as a reductant to the sand-hosted uranium deposits within the Phanerozoic basins that blanket the Curnamona Province. Using this exploration concept, distance from source is less important than the location of sedimentary basins with petroleum potential and, critically, the location of permeable faults that allow migration of a reductant from depth (Fig. 6). Mapped and inferred faults are provided in the 3D model; however, a more detailed fault analysis would benefit future investigations based on this exploration model. Where there is sufficient leakage to the overlying units, petroleum trap sites offer potential to reduce and concentrate uranium. Petroleum explorers in the region have employed several hydrocarbon migration and trapping models, most of which concentrate on Cambrian and Neoproterozoic petroleum systems (Zang 2002; Delhi Petroleum 1986; Youngs and Moorcroft 1982; PIRSA 2010). The main models include:

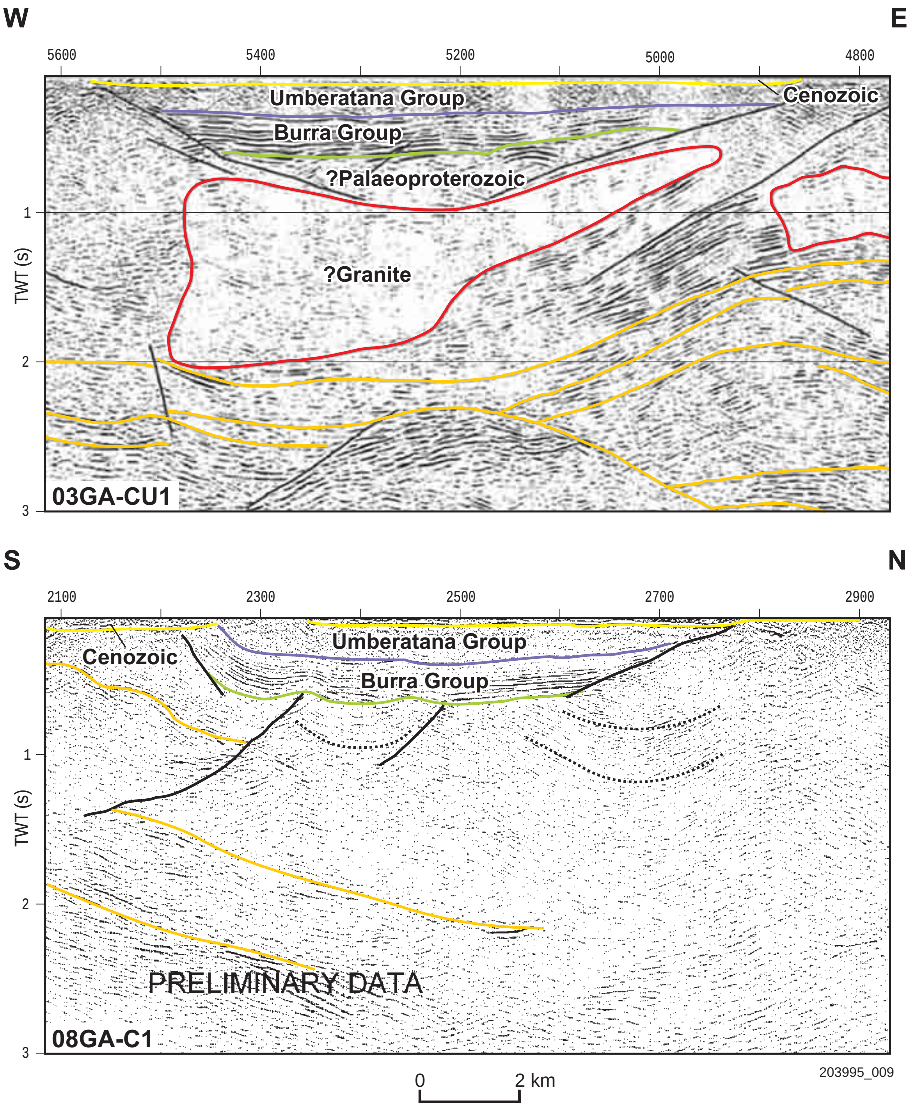


Figure 8 Portion of seismic lines 03GA-CU1 (after Preiss et al 2006) and 08GA-C1 showing a Neoproterozoic sediment-filled basin. Maximum sediment thickness is estimated at 1.3 km. Section lines are highlighted in Figure 2.

- Migration into partially sealed subvertical faults of the Poontana Fracture Zone (cluster of NS-trending wrench faults, see Fig. 6; McLean 1999; Broomfield 1997).
- Migration of hydrocarbons along a thrust fault into anticlinal traps within Cambrian strata east of the Wertaloona Fault (Fig. 6; Broomfield 1997).
- Migration into updip (pinch-out) stratigraphic traps along the Benagerie Ridge.
- Migration to the edge of Mesozoic sediments where the Bulldog Shale acts as a seal. This would involve migration from significant hydrocarbon resources known to the north. Evidence of long-distance migration in the Eromanga Basin has been reported (Michaelsen 2002; Habermehl 1986; McKirdy and Willink 1988; Youngs and Moorcroft 1982). The potential for hydrocarbon migration into the Frome Embayment is enhanced by southerly flow directions within aquifers and demonstrated by reported hydrocarbon odours and gas flares from mound springs (Youngs and Moorcroft 1982) and water bores (Sprigg 1959; Sheard 2009) around the north and NE of the Curnamona Province.

Geothermal energy

Geothermal energy is a sector that has rapidly gained importance and, in South Australia, the Curnamona region is regarded as one of the most prospective areas for this resource. Its high prospectivity is due to thick sediment cover (which imparts effective insulation) within, in particular, the Moorowie and Yalkalpo sub-basins, and the presence of high heat producing radiogenic source rocks such as intrusives of the Mount Painter Inlier and Crocker Well area. One of the most advanced geothermal projects in the state is the Paralana Project (Petratherm Limited 2010; Fig. 2). Application of the depth-to-basement model and the known distribution and thicknesses of the basins that comprise sedimentary cover allows preliminary thermal modelling and assessment of the prospectivity within the Curnamona region.

The most recently conducted government-funded seismic lines 03GA-CU1 and 08GA-C1 reveal a previously unknown Neoproterozoic basin (possibly a preserved remnant or subsidiary depocentre of the Coombalarnie Platform) west of Kalkaroo (Korsch et al. 2009; Preiss et al. 2006; Figs 2, 8). Interpretation of the seismic sections indicates that the total sediment thickness in this area is at least 1.3 km. Sediment fill is interpreted to comprise ~700 m of Burra Group, ~550 m of Umberatana Group and covered by ~50 m of Cenozoic sediment. Although the dimensions of the basin (11 x 14 km) are marginal for a geothermal project due to lateral dissipation of heat, proximity to infrastructure could make such a project economically viable.

Conclusion

A 3D model has been created of sedimentary basins that overlie the Palaeo-Mesoproterozoic rocks of the Curnamona Province using stratigraphic picks from drillholes and seismic interpretation. Surfaces modelled include top of Palaeo-Mesoproterozoic basement and base of Cambrian (Arrowie Basin), Mesozoic (Eromanga Basin) and Cenozoic (Callabonna Sub-basin) sediments.

One of the benefits of 3D modelling is the ability to visualise multiple datasets simultaneously and, in the case of the Curnamona 3D sedimentary basin model, obtain an instant impression of the thickness, nature and extent of sedimentary cover. The process of creating a 3D model requires critical assessment of large volumes of data and resolving conflicts that are not readily identifiable in 2D space. This encourages and facilitates development of a geological interpretation that best suits all datasets.

Our model has application to exploration for a number of commodities, including targets within as well as below sedimentary cover. Such 3D models are useful in the early stages of exploration, to assess prospectivity and generate large-scale concepts.

With the demonstrated uranium potential of the Curnamona Province and sedimentary cover, there remains considerable scope to apply new exploration models and concepts to this region. The Curnamona 3D model can be used to highlight areas that are within exploratory depth but are presently underexplored.

Acknowledgements

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