2008 Gawler Craton-Officer Basin-Musgrave Province-Amadeus Basin (GOMA) seismic survey, 08GA-OM1: Geological interpretation of the Arckaringa Basin

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Introduction

The Permian Arckaringa Basin has two major depocentres, separated by shallow basement covered by a thin veneer of the Permian sediments. The entire basin is covered by younger sediments of the Mesozoic Eromanga Basin and Cenozoic surficial cover. The two major depocentres are the Boorthanna Trough, adjacent to the Peake and Denison Ranges on the eastern basin margin, and the West, Phillipson, Penrhyn and Wallira troughs along the southern margin of the basin. The 2008 Gawler Craton-Officer Basin-Musgrave Province-Amadeus Basin seismic line (GOMA, 08GA-OM1) transects the Arckaringa Basin along the Adelaide-Alice Springs railway line (Figure 1), and crossed the West, Phillipson and Penrhyn troughs, but lies west of the Boorthanna Trough. This paper focuses primarily on the West, Phillipson and Penrhyn troughs in the southern Arckaringa Basin.

The Boorthanna Trough is underlain, in part, by a thick succession of Adelaide rift sedimentary rocks, including evaporites, and salt tectonics may have influenced deposition in this area. The West, Phillipson and Penrhyn troughs are underlain by Archean to Early Mesoproterozoic rocks of the Gawler Craton (Wilgena, Christie and Coober Pedy domains, Woodhouse et al., 2010).

The stratigraphy and depositional environments of the Arckaringa Basin are discussed in detail by Wopfner (1970), and the geology and resource potential of the basin are described by Hibburt (1984) and Moore (1982). Wopfner (1964) and Ludbrook (1967) considered that the marine sediments of the Arckaringa Basin were deposited in erosional features formed by glacial scour, for example, fjords. Following the acquisition of seismic and drilling data, however, Wopfner (1970) proposed that deposition occurred in graben structures. Debate over the origin of the troughs continues today – a case for both origins will be presented in this paper.

Glacial interpretation for the troughs (SAM)

Stratigraphy and depositional environments of the Arckaringa Basin in the Phillipson and Penrhyn troughs

The Arckaringa Basin consists of three major Early Permian units, the Boorthanna, Stuart Range and Mount Toondina formations (Figure 2). The Boorthanna Formation, which possibly extends down into the Late Carboniferous, consists of a lower glacigene succession, with subsequent marine facies (PIRSA, 2010). Lithologies include diamictite, rhythmically bedded sandstone and laminated mudstone.

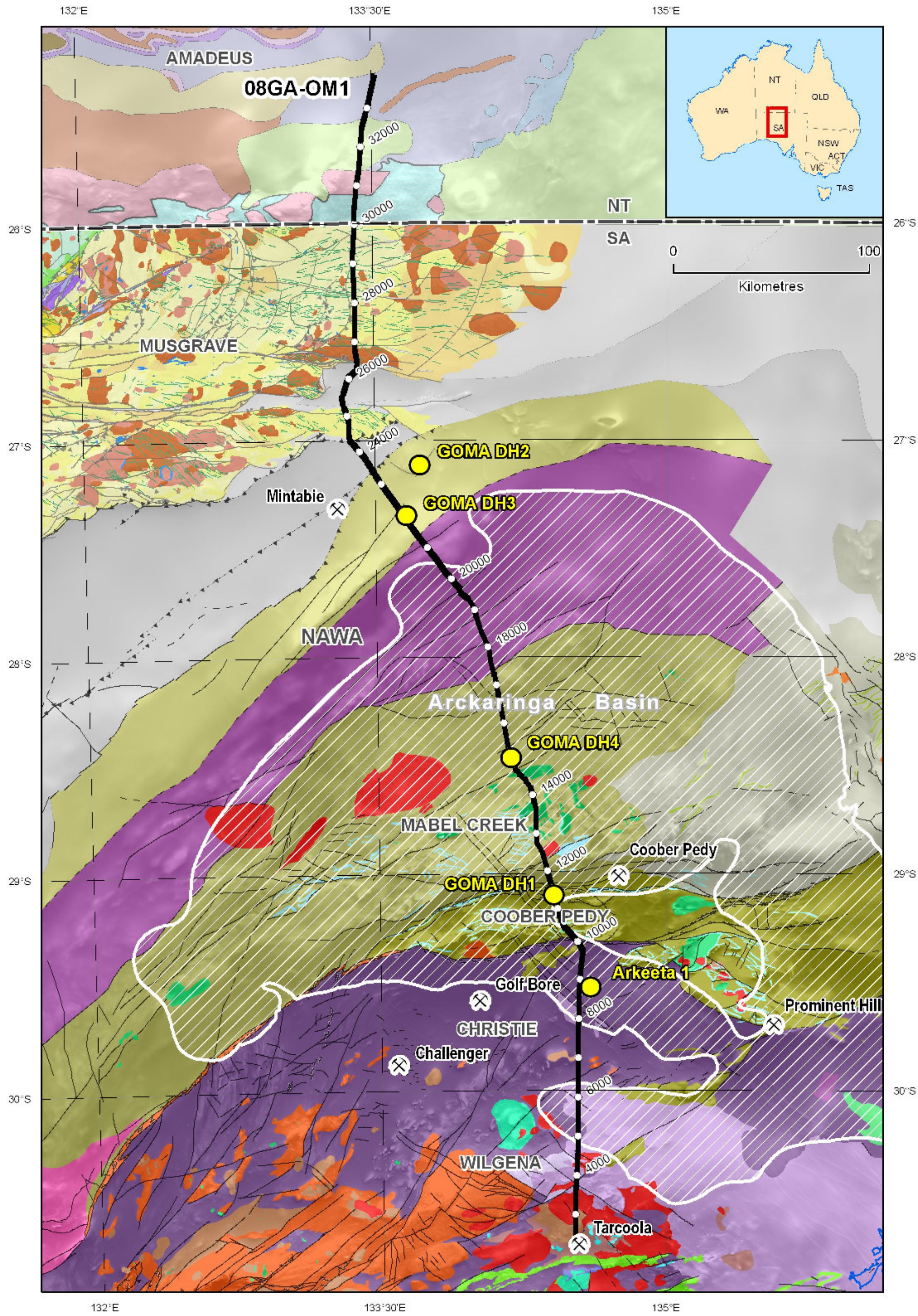
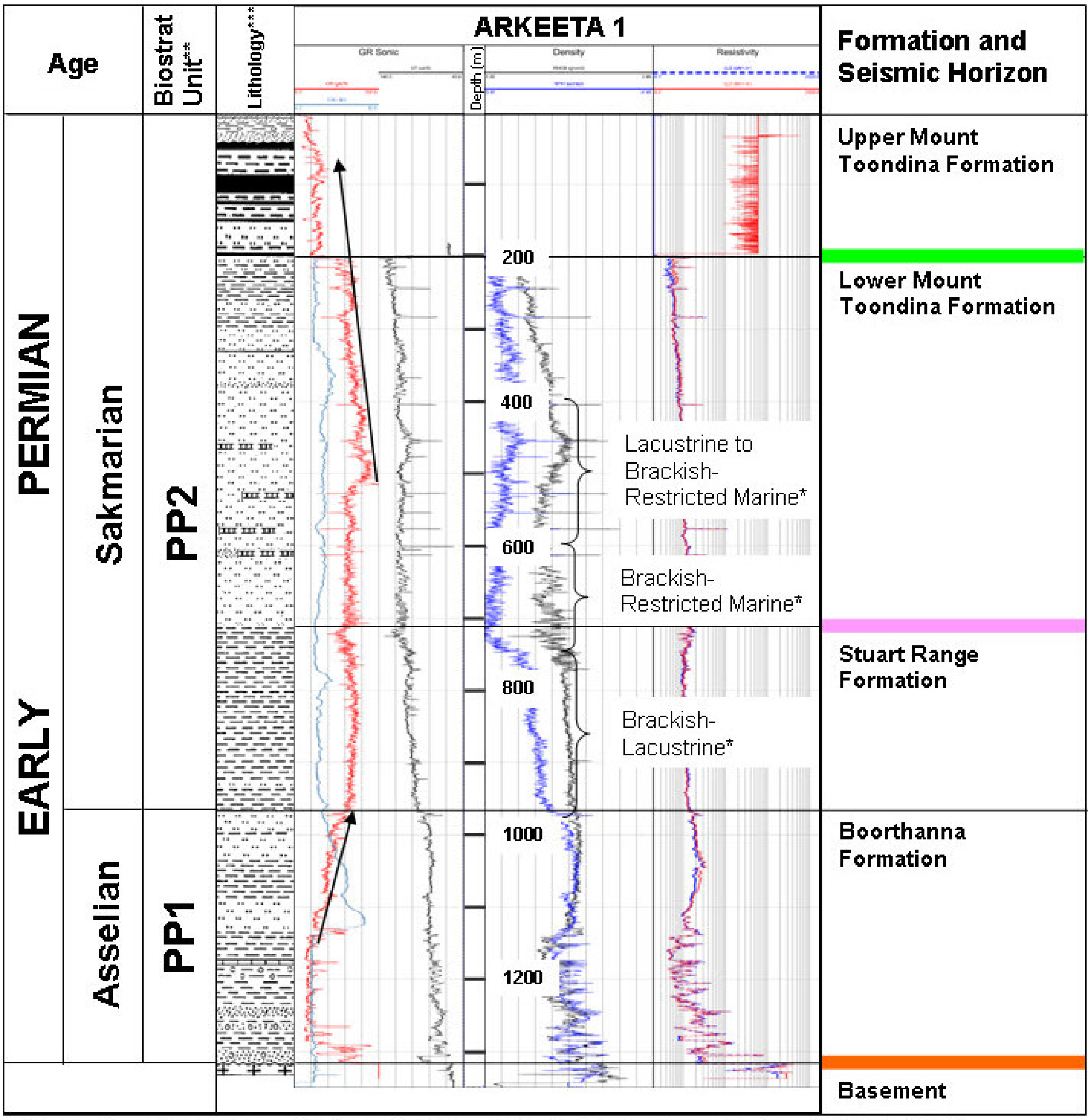


Figure 1. Map showing the outline of the Arckaringa Basin on top of the solid geology of the region covered by the GOMA seismic line (08GA-OM1) from the northern Gawler Craton to the southern Amadeus Basin, draped over a first vertical derivative image of aeromagnetic data. The solid geology for South Australia is from Cowley (2006a, 2006b, which also contains the legend), and the Northern Territory part is from Ahmad (2002). The seismic line has CDP stations labelled, and the locations of the GOMA and Arkeeta 1 drillholes are shown also.



* Depositional environment interpreted from Arkeeta 1 palynological study (McBain, 1987)
** Palynological zones from Arkeeta 1 palynological study (McBain, 1987) converted to biostratigraph units defined by Price et al, 1985
*** Lithology modified from Lake Phillipson Bore (after Hibburt, 1984, Figure 12)

Figure 2. Stratigraphic column for the southern Arckaringa Basin, showing well logs from the Arkeeta 1 well and the horizons picked on the GOMA seismic section.

The overlying Stuart Range Formation is generally homogeneous shale, with minor siltstone and sandstone, interpreted to have been deposited in quiet, restricted marine conditions, with occasional lacustrine intervals. This unit, in turn, is overlain by the Mount Toondina Formation, consisting of a prograding deltaic succession and an uppermost fluvio-lacustrine succession with intermittent coal swamp development.

Arkeeta 1, a petroleum exploration well drilled by CRA Exploration in 1986, was sited to investigate the thickest succession in the Phillipson Trough, as identified on seismic lines, and was drilled about 5 km east of the GOMA seismic line. The well intersected 43 m of Quaternary and Late Jurassic sediments overlying 1270 m of Permian sediments in the Arckaringa Basin, and terminated in basement, identified as Gawler Range Volcanics (McBain, 1987).

The gamma-ray log from Arkeeta 1 suggests a transgressive depositional environment in the upper Boorthanna Formation, followed by a generally quiet, deeper water environment during deposition of the Stuart Range and lower Mount Toondina formations (Figure 2). The upper Mount Toondina Formation records a regressive environment interpreted as a shallowingupward delta sequence with coals deposited at the top. A detailed palynological study of cuttings and sidewall core samples from Arkeeta 1 indicates a lacustrine to brackish-restricted marine environment during deposition of the Stuart Range Formation and lower Mount Toondina Formation. The high organic contents (TOC up to 7.4%, HI up to 654, McBain, 1987), of the upper Stuart Range Formation and lower Mount Toondina Formation, suggest anoxic bottom water conditions suitable for the preservation of organic matter.

The presence of mixed lacustrine to brackish marine environments and anoxic bottom water conditions is analogous with a Baltic Sea environment, where high fresh-water runoff into a restricted seaway results in density stratification of the water column. High fresh-water runoff (including melt-water) into restricted seaways in the long, narrow troughs of the southern Arckaringa Basin is likely to have resulted in similar conditions.

The Boorthanna Formation and lower Stuart Range Formation are assigned to zone PP1 (Asselian), and the upper part of the Stuart Range Formation and the Mount Toondina Formation are zone PP2 (Sakmarian) (Price et al., 1985). The succession in the Arckaringa Basin is correlated with the Merrimelia Formation, Tirrawarra Sandstone, and lower Patchawarra Formation of the Cooper Basin (Alley, 1995).

The Arckaringa Basin is overlain by Late Jurassic and Early Cretaceous sediments of the Eromanga Basin. The angular nature of this contact is highlighted in cross sections constructed from extensive drilling of the Lake Phillipson Coal Deposit by the Utah Development Company (Rowlands et al., 1982).

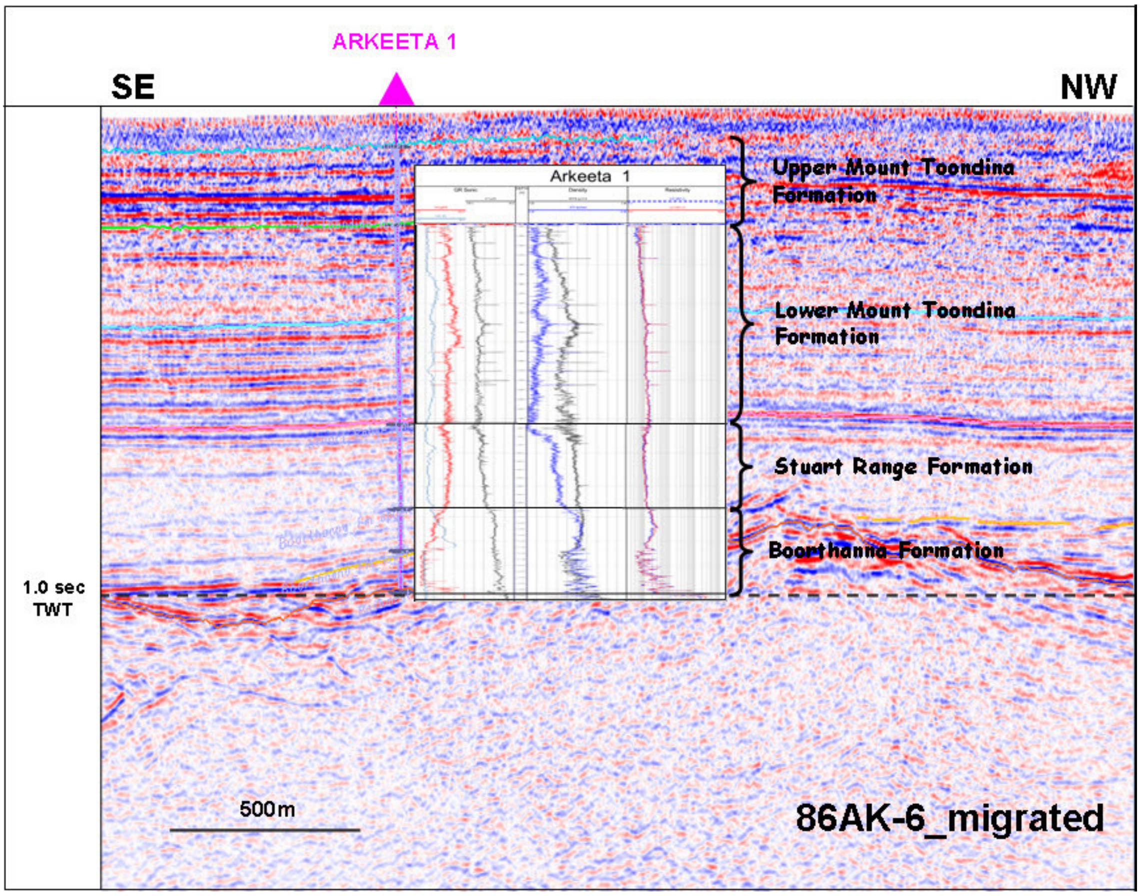


Figure 3. Migrated seismic line 86AK-6 across part of the Arckaringa Basin, showing the tie to the Arkeeta 1 well, and horizons picked on the seismic section based on the well logs (see Figure 9 for location of seismic line).

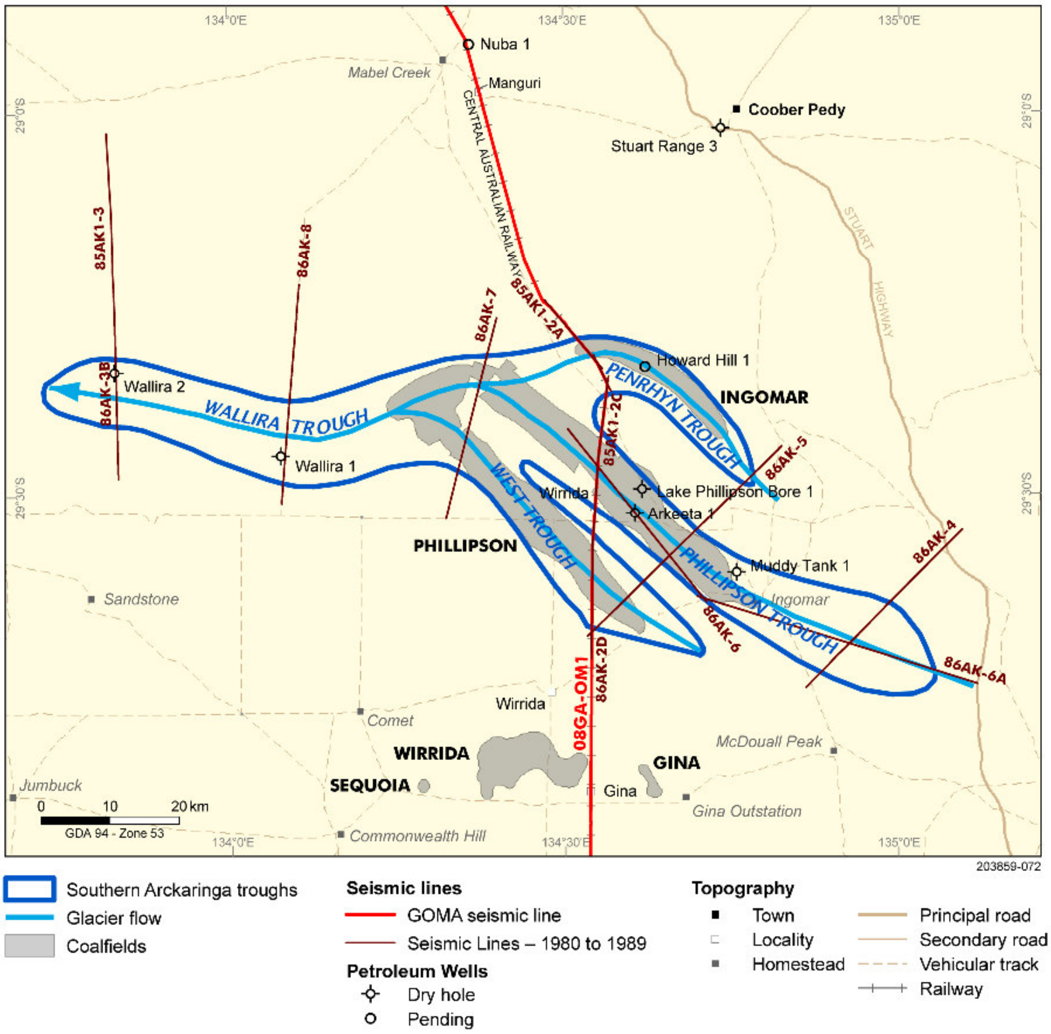


Figure 4. Location of troughs in the southern Arckaringa Basin, showing the inferred glacier flow direction.

Interpretation of the seismic data

Seismic data in the southern Arckaringa Basin include several lines of single fold data acquired by SADME in 1970, 419 line kilometres of multifold (24-375 fold) data acquired by CRA Exploration in 1985 and 1986, and the 2008 GOMA seismic line (Figure 1).

Arkeeta 1 well was sited on seismic line 86AK-6 which was crossed by the GOMA line in the vicinity of CDP 9150. A checkshot survey was acquired in Arkeeta 1, and the two seismic lines tie reasonably well; hence the succession in the troughs crossed by the GOMA line can be interpreted with reasonable confidence (Figure 3).

Three horizons have been interpreted with some confidence, being Basement (orange), Top Stuart Range Formation (pink) and Top Lower Mount Toondina Formation (green) (Figure 2). In addition, an intra-Mount Toondina Formation horizon (light blue) has been picked for the purposes of flattening, and a Base Mesozoic horizon has been picked to highlight the angular unconformity with the underlying succession, although this surface is too shallow to be seismically resolved.

The GOMA seismic line over the southern Arckaringa Basin shows three prominent troughs, the West Trough (after Utah Development Company), Phillipson Trough and Penrhyn Trough (Figure 4). Flattening of the line on successive horizons indicates the following depositional and tectonic history (Figure 5):

1. Incision of deep glacial valleys.
2. Valley fill with glacial and marine sediments of the Boorthanna and Stuart Range formations.
3. Valley fill continues, although minor contraction begins to influence deposition, as indicated by onlap of the lowermost reflections of the Lower Mount Toondina Formation onto the Top Stuart Range horizon in the West Trough. Differential compaction of the underlying valley fill may also have influenced deposition.
4. Valley fill is completed and the Mount Toondina delta progrades out over the basin. Minor differential growth of this succession, as indicated by seismic and coal seam geometries, may be the result of ongoing minor contraction and differential compaction.
5. Contraction culminates with gentle folding of the succession, uplift and erosion. The vitrinite reflectance profile at Arkeeta 1 suggests that approximately 500 m of the Early Permian section was stripped from the centre of the Phillipson Trough. The coal seam correlations map out the subcrop relationship of the coal seams beneath the Eromanga Basin, indicating that folding and erosion occurred prior to deposition of the Eromanga Basin (Figure 6).

The absence of sediments younger than Early Permian (Sakmarian) in age suggests that the termination of deposition in the Arckaringa Basin, and gentle folding of the succession, may be related to the breaks in deposition identified in the Patchawarra Formation of the Cooper Basin (Gravestock and Jensen-Schmidt, 1998). Alternatively, the final contractional event may be related to the Daralingie unconformity between the Early and Late Permian in the Cooper Basin, or the unconformity at the top of the Cooper Basin succession, which is equivalent to the end of the Hunter-Bowen Orogeny in eastern Australia.

Interpretation of five of the 1986 seismic lines in the vicinity of the GOMA line indicates a depositional and tectonic history consistent with that described for the GOMA line (Figure 7).

Discussion

Widespread glaciation affected Gondwana in the late Paleozoic, and glacigene sediments are widespread throughout South Australia (Figure 8). Glacigene sediments occupy glacially eroded valleys in the Troubridge Basin (e.g., Inman Valley on the Fleurieu Peninsula), and Gravestock and Jensen-Schmidt (1998) interpret the early fill history of the South Australian component of the Cooper Basin as being dominated by glacial geomorphology, rather than fault growth.

Glacial erosion consists of several processes, including abrasion, plucking (quarrying), subglacial fluvial erosion, and chemical dissolution by subglacial water (Harbor, 1992). Dühnforth et al. (2010) concluded that fracture spacing in bedrock controls rates of erosion, and whether glacial quarrying or abrasion is the dominant erosion process. The preponderance of one or the other process is largely responsible for the small-scale morphology of a glacially sculpted landscape.

The geology and structural features of the basement underlying the Arckaringa Basin has been interpreted from geophysical and drilling data. The location and orientation of the glacial valleys appears to be controlled, in part, by structural grain and rock types in the underlying basement (Figure 9). The three valleys crossed by the GOMA seismic line trend northwest, parallel to the Adelaidean Gairdner dolerite, dykes which intrude the Archean to Early Mesoproterozoic metamorphic rocks of the Gawler Craton (Wilgena, Christie and Coober Pedy domains). West of the GOMA seismic line, the Wallira Trough has an east-west orientation (Figure 9), and appears to be related to the shear zone between the Christie Domain to the south, and the Coober Pedy Domain to the north, referred to as the Karari Shear Zone by Korsch et al. (2010).

According to Wopfner (1980), glacial pavement features and sediment transport directions indicate that the ice flow was west to northwest in the Arckaringa Basin, originating from glaciers located to the east, on the uplifted Adelaide Fold Belt. This fits with an interpretation of the three glacial valleys meeting to the west of the GOMA line to form a single valley, the Wallira Trough (Figure 4).

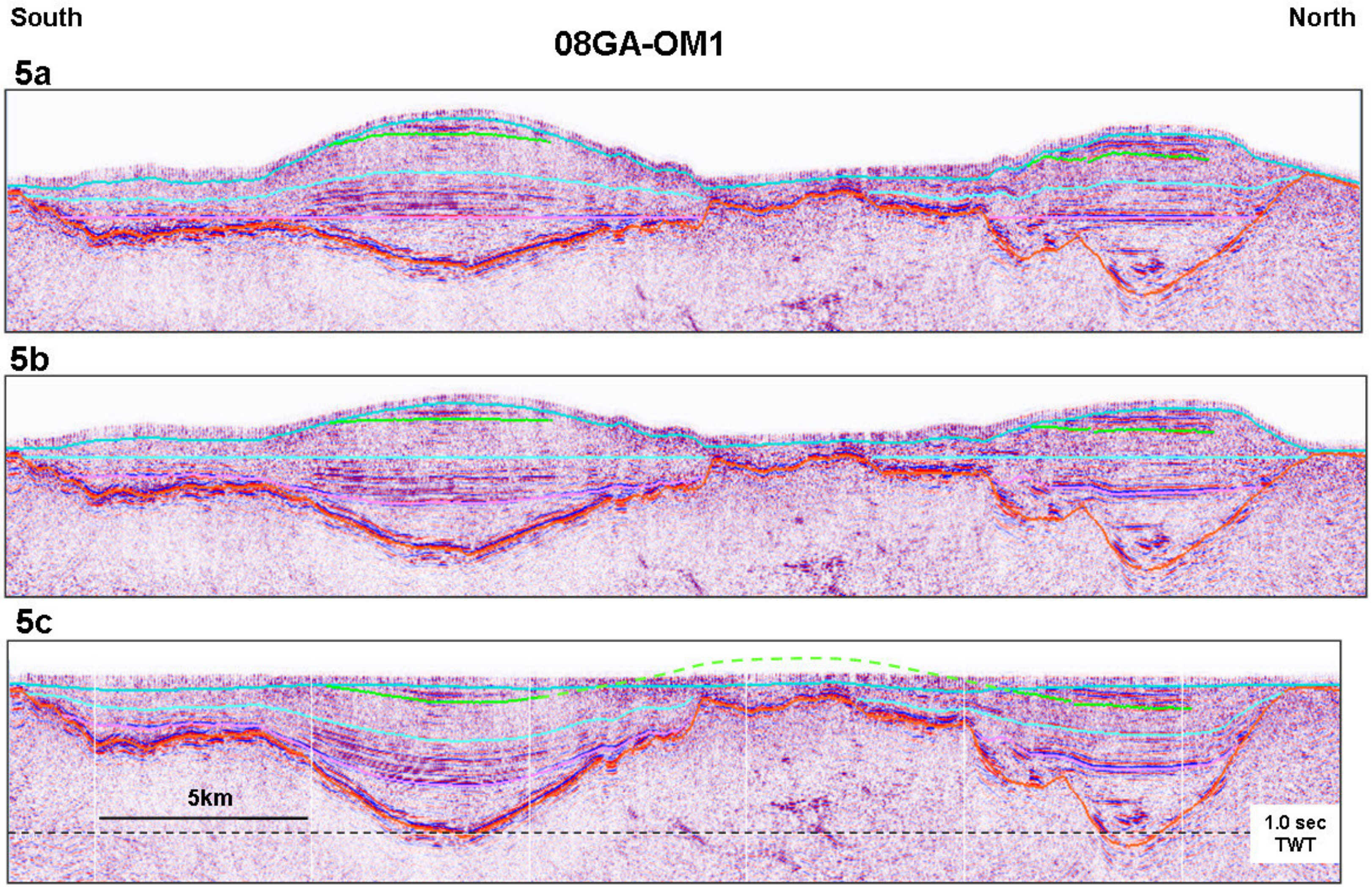


Figure 5. Interpretation of the GOMA (08GA-OM1) seismic line showing the West Trough (left) and the Phillipson Tough (right). (a) Section flattened on the Top Stuart Range horizon (pink). (b) Section flattened on the intra-Mount Toondina horizon (light blue). (c) Present day geometry (unflattened).

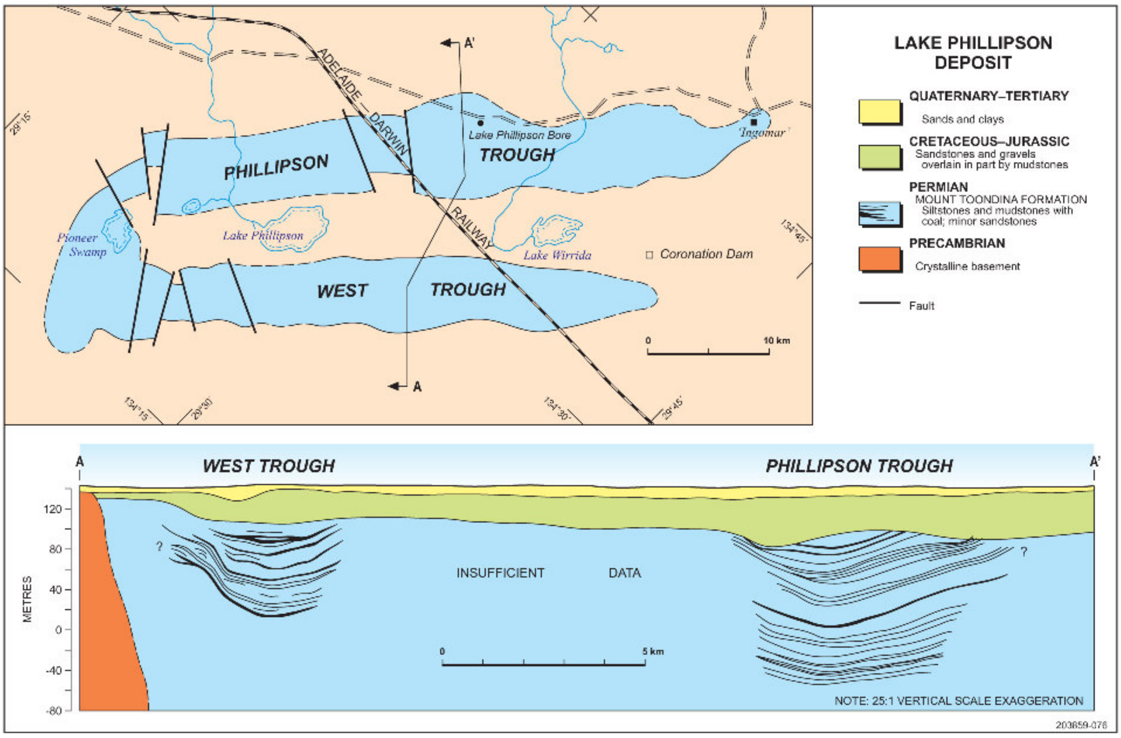


Figure 6. Map and cross section of the Lake Phillipson coal deposit in the West and Phillipson troughs. Note that north is to the top left of the map.

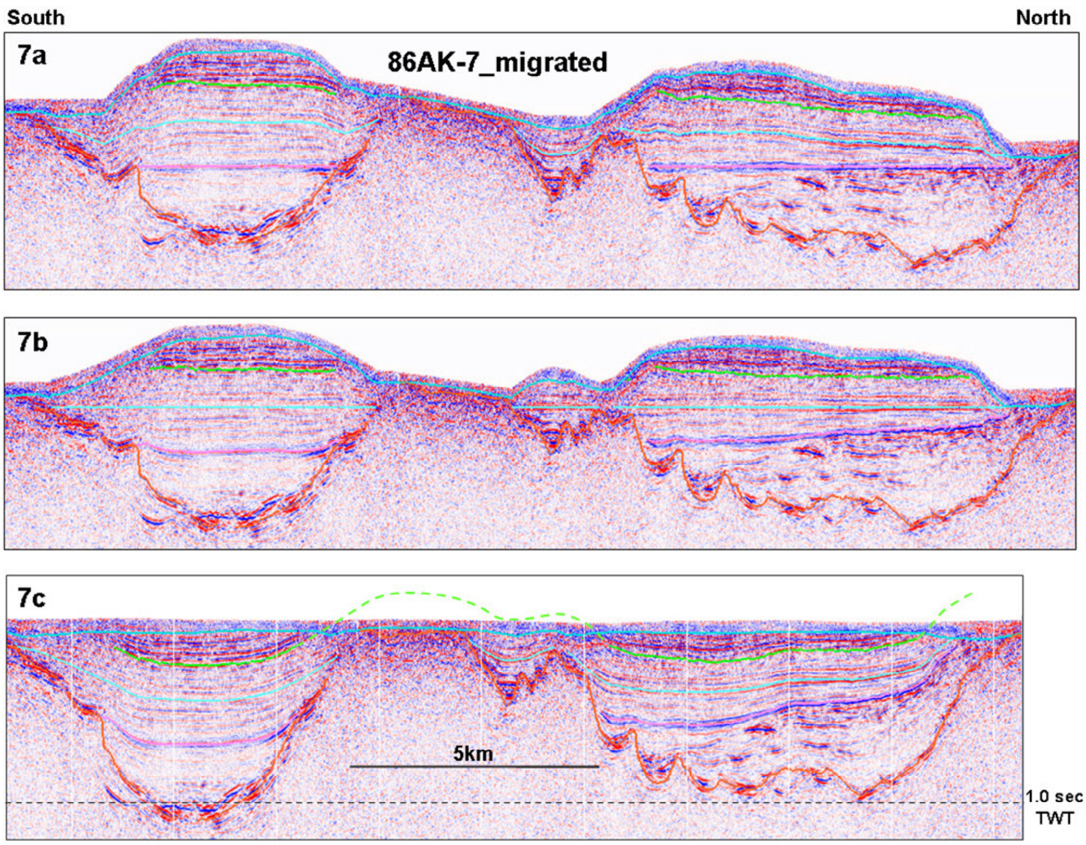


Figure 7. Interpretation of seismic line 86AK-7, showing the West Trough (left) and the Phillipson Tough (right). (a) Section flattened on the Top Stuart Range horizon (pink). (b) Section flattened on the intra-Mount Toondina horizon (light blue). (c) Present day geometry (unflattened). See Figure 9 for location of seismic line.

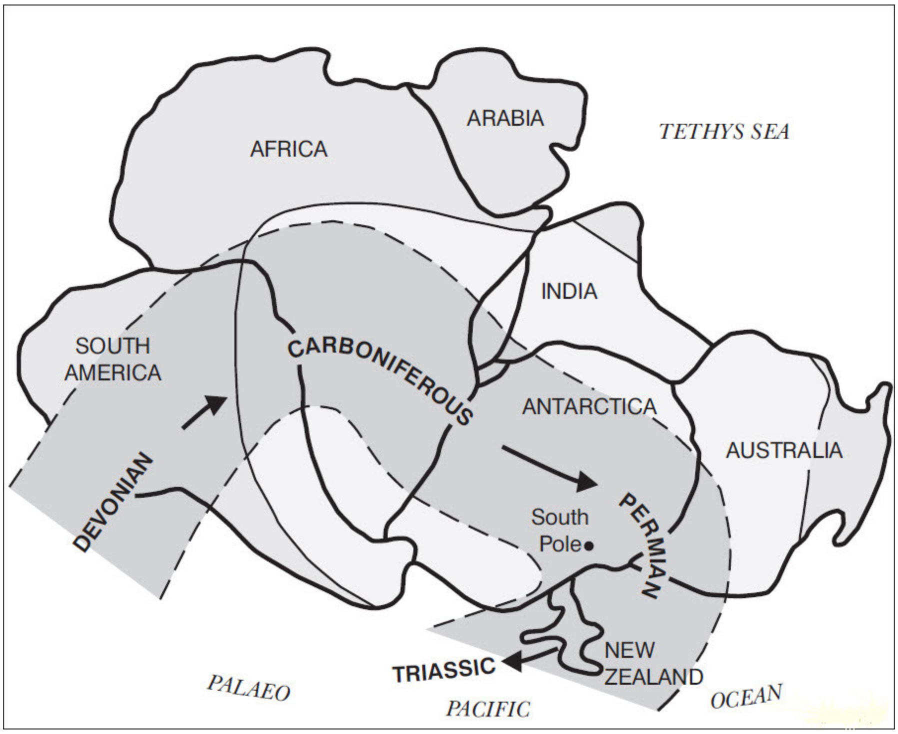


Figure 8. Migration of major ice centres across Gondwana from the Devonian to the Permian. The position of the South Pole is shown fort the time of the Carboniferous-Permian boundary (from Alley, 1995, and references therein).

Conclusion

The 2008 GOMA seismic line crosses three troughs in the southern Arckaringa Basin. Interpretation of this seismic line, and seismic lines acquired for petroleum exploration in the mid 1980s, incorporates data from the Arkeeta 1 petroleum exploration well, and the results of coal exploration drilling in the area.

Deposition in the troughs records a cycle of glacial scour, deglaciation and marine transgression (Boorthanna and Stuart Range formations), quiet, deeper water deposition (lower Mount Toondina Formation) and regression (upper Mount Toondina Formation). Palynological and Rock-Eval data indicate lacustrine to brackish-restricted marine environments, with periods of anoxic bottom water conditions during deposition of the Stuart Range and lower Mount Toondina formations. This suggests a Baltic Sea analogy, where high fresh-water runoff into a restricted seaway results in density stratification of the water column.

The three troughs are interpreted as glacial valleys in which glacial and marine sediments of the Boorthanna and Stuart Range formations accumulated. Minor, syndepositional contraction commencing in the Sakmarian (palynostratigraphic zone PP2), resulted in differential growth, with thinning and onlap of the Mount Toondina Formation onto basement ridges. Contraction culminated with gentle folding of the succession, uplift and erosion.

The absence of sediments younger than Sakmarian in age suggests the termination of deposition in the Arckaringa Basin, and gentle folding of the succession, may be related to the breaks in deposition identified in the Patchawarra Formation of the Cooper Basin. Alternatively, the final contractional event may be related to the Daralingie unconformity between the Early and Late Permian in the Cooper Basin, or was coincident with the Mid-Triassic unconformity at the top of the Cooper Basin succession.

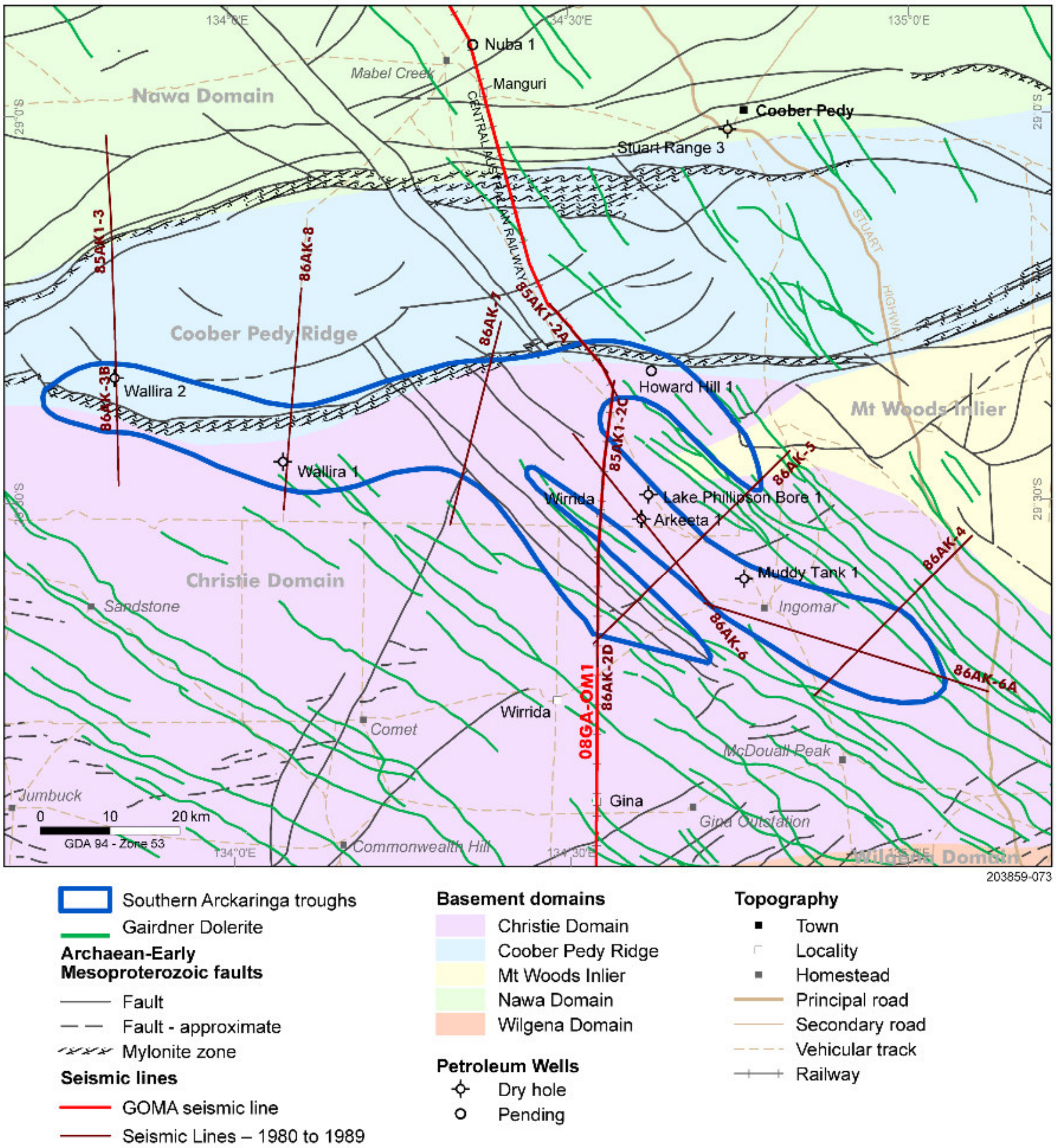


Figure 9. Location of the troughs in the southern Arckaringa Basin with underlying basement domains, Archean-Early Mesoproterozoic faults and shear zones, and the Neoproterozoic Gairdner Dolerite.

Non-glacial interpretation for the troughs (RJK and LKC)

Introduction

The Permian Arckaringa Basin is a basin which unconformably overlies older sedimentary rocks and basement in South Australia. It variously overlies undifferentiated Cambrian to Devonian sedimentary rocks of the Warburton, Officer and Amadeus basins, and the Gawler Craton. The mostly subsurface basin consists of a wide, platform area in the north, and a series of troughs (e.g., Boorthanna and Phillipson troughs) in the south, overlain by the Jurassic to Cretaceous sediments of the Eromanga Basin.

Sedimentary rocks of the Officer Basin underlie the Arckaringa Basin to the west, but, in the south and east, sediments of the Arckaringa Basin were deposited directly onto basement, as imaged by the GOMA seismic line. The basin is bounded by unconformities at its top and bottom. The lowermost unit, the Boorthanna Formation, consists of shallow marine to fluvial periglacial facies. This unit is conformably overlain by marginal marine shales of the Stuart Range Formation. The Mount Toondinna Formation overlies the Stuart Range Formation, partly conformably and partly disconformably. It contains lacustrine, meandering fluvial black swamp deposits, and also coal beds (SADME, 1989). During deposition of the Arckaringa Basin, the environment progressed from glacial marine to onshore swamp and lacustrine deposits. Between 500 m and 1000 m of section are considered to have been eroded before the deposition of the Eromanga Basin, as determined by the rank of the coal seams in the Mount Toondinna Formation (PIRSA, 2010).

Interpretation of the seismic data

In seismic line 08GA-OM1, between CDP 7500-10290 (Figure 1), the Permian Arckaringa Basin is imaged as a series of depocentres forming the West, Phillipson and Penrhyn troughs, with a much thinner succession connecting the depocentres, and extending well to the north. To assist with the interpretation of the GOMA seismic section, information from drillholes up to 15 km away were projected onto the seismic line. Some of these drillholes intersect the Arckaringa Basin (Figure 9).

The succession in the Arckaringa Basin is interpreted to contain three packages, each with distinctive seismic character. The lowermost Boorthanna Formation consists of strong, irregular reflections. The Stuart Range Formation is a package with weak reflections, consistent with this unit being dominated by shale lithologies. The uppermost Mount Toondina Formation consists of a thick package of strong, subparallel reflections, which become increasingly indistinct up section. Strong reflections of the Upper Mount Toondina Formation, at the top of the succession, are interpreted as coal measures.

The GOMA seismic line crosses a large part of the Arckaringa Basin, from about CDP 5400 in the south to about CDP 20540 in the north, a distance of over 300 km (Figure 1). In the south, the GOMA seismic line intersects a 10 km wide part of the basin margin, between CDP 5400 and CDP 5900, where the Boorthanna and Stuart Range formations are over 500 m thick. From CDP 7600, northwards, the Arckaringa Basin is essentially continuous, with the exception of a basement high between CDP 10200 and CDP 11120.

West Trough

The GOMA seismic line crosses a 16 km wide section of the West Trough (Figure 10). In the trough, the basal Boorthanna Formation consists of a series of strong, irregular reflections, from about CDP 7850 to CDP 8650, which maintains a relatively constant thickness of about 200 ms two-way travel time (TWT, ~250 m) across the trough. This suggests that the Boorthanna Formation was deposited on a relatively flat surface. The reflections now have dips of about 20º, which is too steep for the angle of repose for clastic sediments, which is usually a maximum of about 3º. Thus, the beds have been tilted to this position after initially being deposited subhorizontally.

The Stuart Range Formation consists of a package of weak reflections, which occur between the strong, irregular reflections of the underlying Boorthanna Formation and the series of strong, subparallel reflections of the Lower Mount Toondina Formation. The reflections in the Stuart Range Formation can be observed to onlap the Boorthanna Formation on both sides of the trough, indicating that the trough was actively subsiding at the time of deposition, and the trough was growing through time. This symmetrical geometry suggests that subsidence was driven by thermal relaxation, and indicates that the surface on which the Stuart Range Formation was deposited was essentially horizontal prior to subsidence and deposition of this unit. Thus, the geometry of the Boorthanna and Stuart Range Formations observed in the GOMA seismic data does not support an interpretation of incision of deep glacial valleys.

Onlap onto the Boorthanna Formation continued during deposition of the lower part of the Lower Mount Toondina Formation, again indicating subsidence of the basin at this time. The upper part of the Lower Mount Toondina Formation and the Upper Mount Toondina Formation predominantly have parallel reflections, indicating deposition on a relatively flat surface. Strong reflections in the Upper Mount Toondina Formation represent coal measures.

There is evidence for post-depositional deformation on the northern margin of the West Trough. A series of south-dipping faults, some with rollover anticlines in the hangingwall, indicate that these are minor thrusts, which formed during a period of contraction. The trough is overlain unconformably by the Mesozoic Eromanga Basin, placing an upper limit of Jurassic for the age of the deformation.

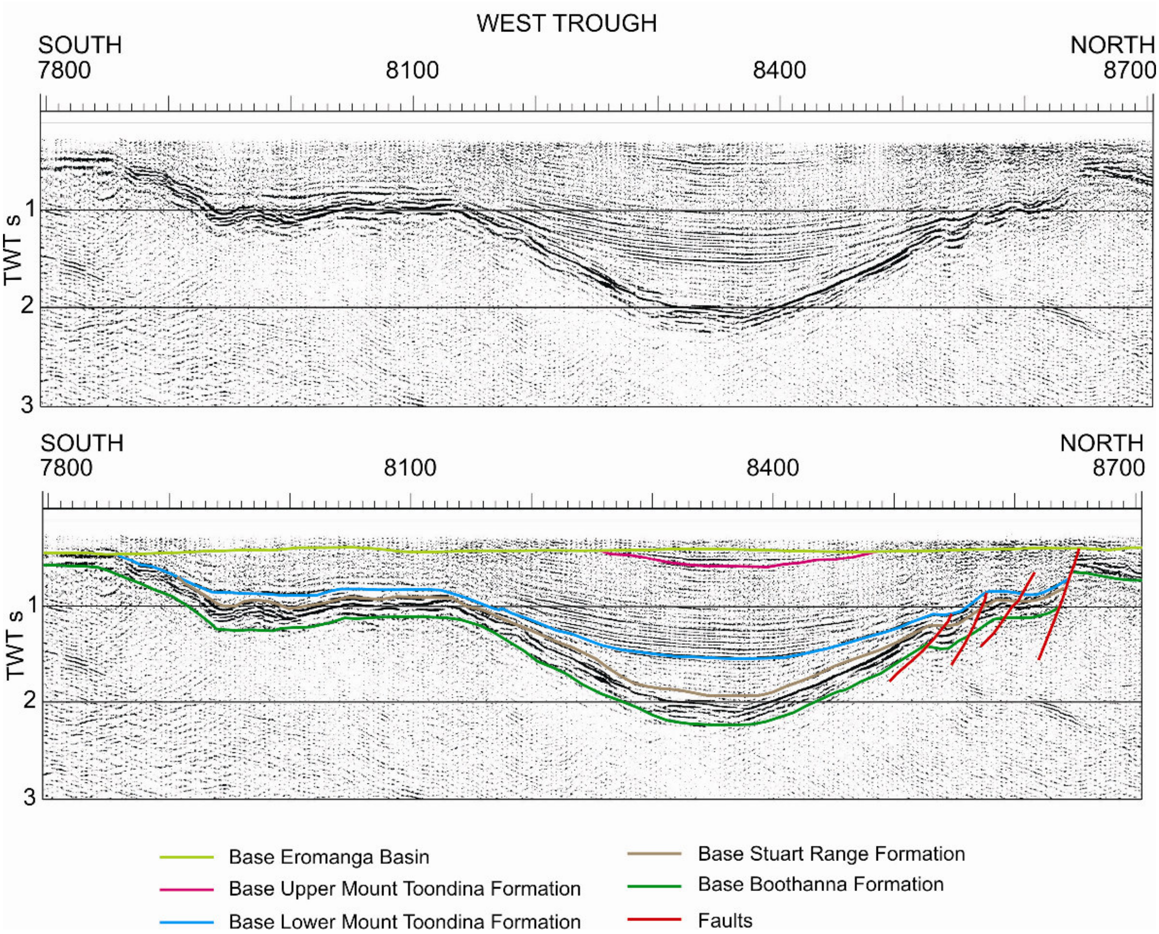


Figure 10. Portion of the GOMA (08GA-OM1) seismic line across the West Trough, Arckaringa Basin showing (a) uninterpreted migrated seismic section, and (b) interpretation.

Phillipson Trough

The upper section of the Phillipson Trough is similar in appearance to the West Trough, but shows a different geometry in its lower section (Figure 11). The trough is interpreted to be fault bounded, and is possibly extensional in origin. The Boorthanna Formation is of variable thickness, but considerably thicker in the bottom of the trough, compared with the West Trough. It is possible that some of the irregular reflections in the Boorthanna Formation could represent glacial channels (compare this to those described from the Permian Grant Group, Canning Basin, by O'Brien et al., 1998, Figure 7). Nevertheless, these only have a relief of less than 200 ms TWT (~250 m).

On the northern side of the trough, onlap of the Stuart Range Formation and the lower part of the Lower Mount Toondina Formation onto the Boorthanna Formation again indicates that basin subsidence was occurring during deposition of these units.

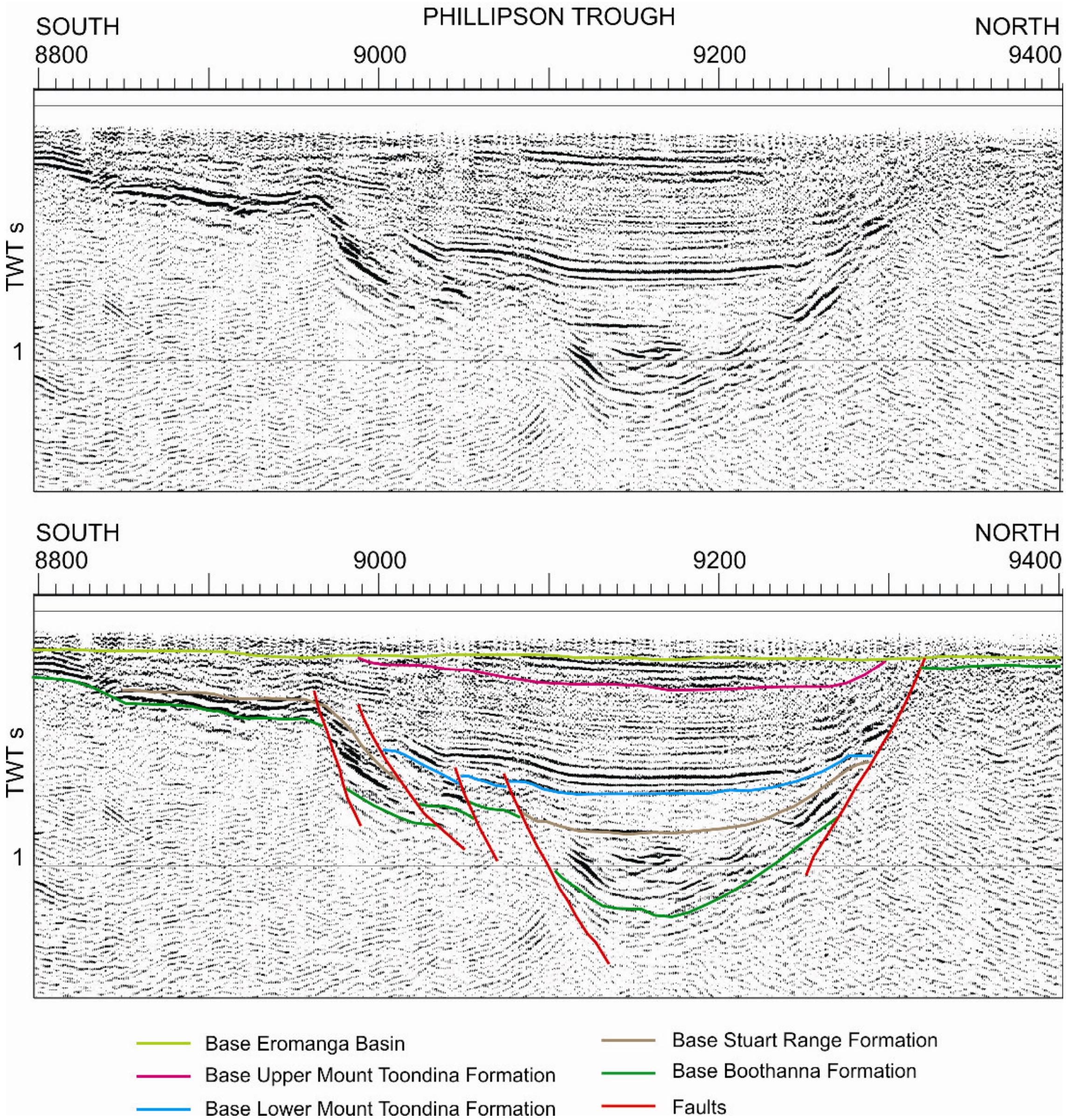


Figure 11. Portion of the GOMA (08GA-OM1) seismic line across the Phillipson Trough, Arckaringa Basin showing (a) uninterpreted migrated seismic section, and (b) interpretation.

Penrhyn Trough

In the north, the Penrhyn Trough is relatively small, about 6 km wide where it is crossed by the GOMA seismic line. It contains two basin-bounding faults on its southern margin (Figure 12). The asymmetric nature of the reflections in the Boorthanna and Stuart Range formations suggests active growth faults during deposition, and that the basin subsided due to mechanical extension at this time.

Northern succession

From CDP 11120, northwards, for a distance of nearly 190 km, the Arckaringa Basin is imaged in the GOMA seismic line as a relatively thin, continuous succession, up to 300 m thick (Korsch et al., 2010). The GOMA 1 and GOMA 4 drillholes (Figure 1) both intersect this part of the Arckaringa Basin, before ending in basement of the Gawler Craton (Dutch et al., 2010; Jagodzinski and Reid, 2010). The basin is overlain, for its entire length, by a thin cover (~30 to 200 m thick) of the Mesozoic Eromanga Basin and Cenozoic sediments.

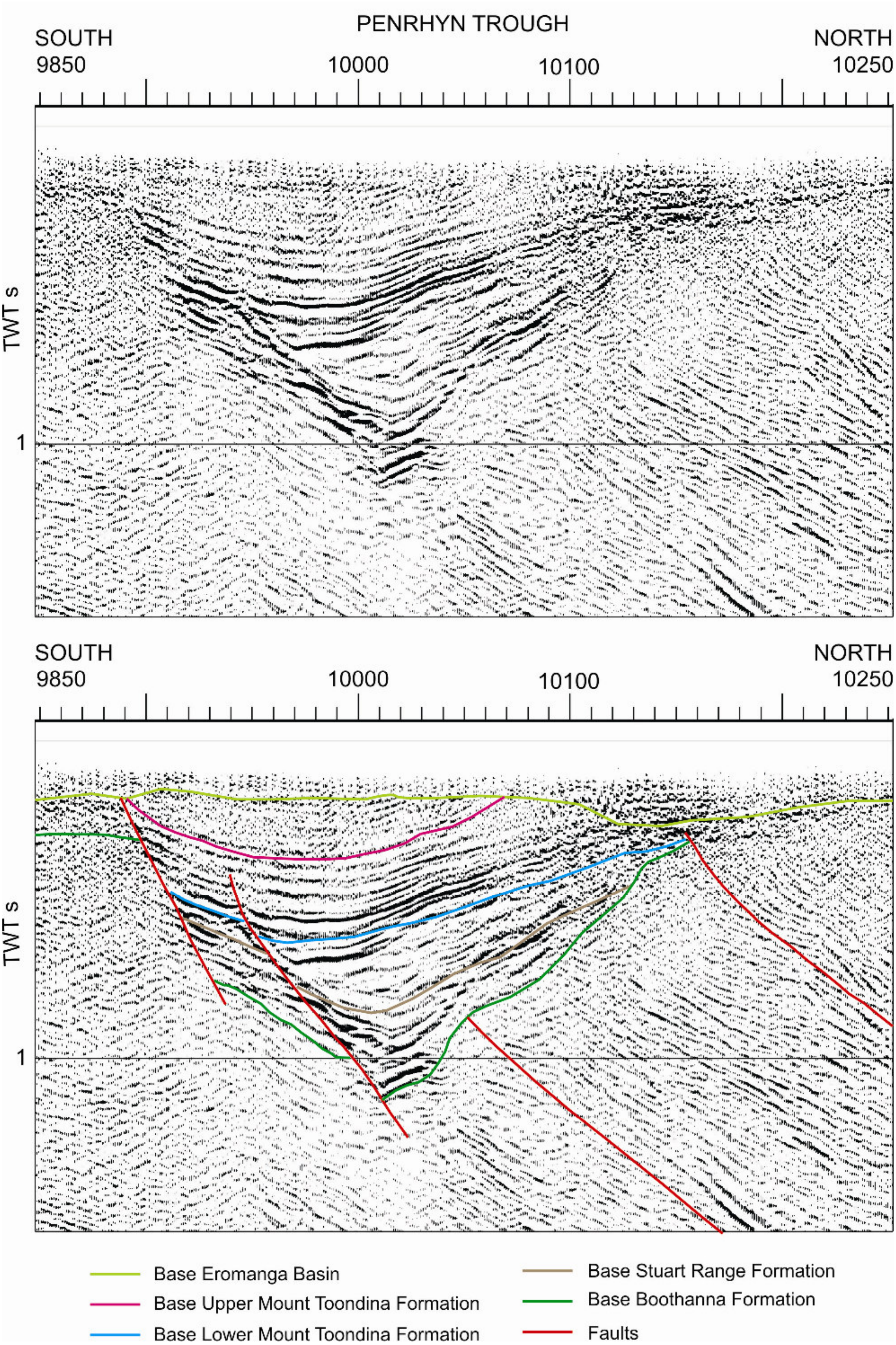


Figure 12. Portion of the GOMA (08GA-OM1) seismic line across the Penrhyn Trough, Arckaringa Basin showing (a) uninterpreted migrated seismic section, and (b) interpretation.

Discussion and conclusions

In the GOMA seismic section, the Arckaringa Basin is interpreted to consist of three sedimentary packages, each with distinctive seismic character. The lowermost Boorthanna Formation consists of strong, irregular reflections. The Stuart Range Formation is a package of weak reflections, whereas the uppermost Mount Toondina Formation consists of a thick section of strong, subparallel reflections, becoming increasingly indistinct up section. Strong reflections of the Upper Mount Toondina Formation, at the top of the succession, are interpreted as coal measures.

In the West Trough, the Boorthanna Formation has a relatively constant thickness, indicating deposition on a relatively flat surface. The overlying Stuart Range Formation, and the lower part of the Lower Mount Toondina Formation, onlap onto the Boorthanna Formation, indicating that the basin was undergoing subsidence at this time, possibly driven by thermal relaxation. Subparallel reflections in the upper part of the Lower Mount Toondina Formation again indicate deposition on a relatively flat surface. The Phillipson and Penrhyn troughs have geometries which suggest an extensional, fault-controlled origin, at least for the lower part of the succession in the Arckaringa Basin.

At some time following deposition of the Arckaringa Basin, mild deformation occurred. The rank of coals in the Upper Mount Toondina Formation, and the angular unconformity between the Arckaringa and Eromanga basins indicate that the deformation was followed by significant erosion, which removed the upper Arckaringa Basin sediments prior to deposition of the Eromanga Basin.

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