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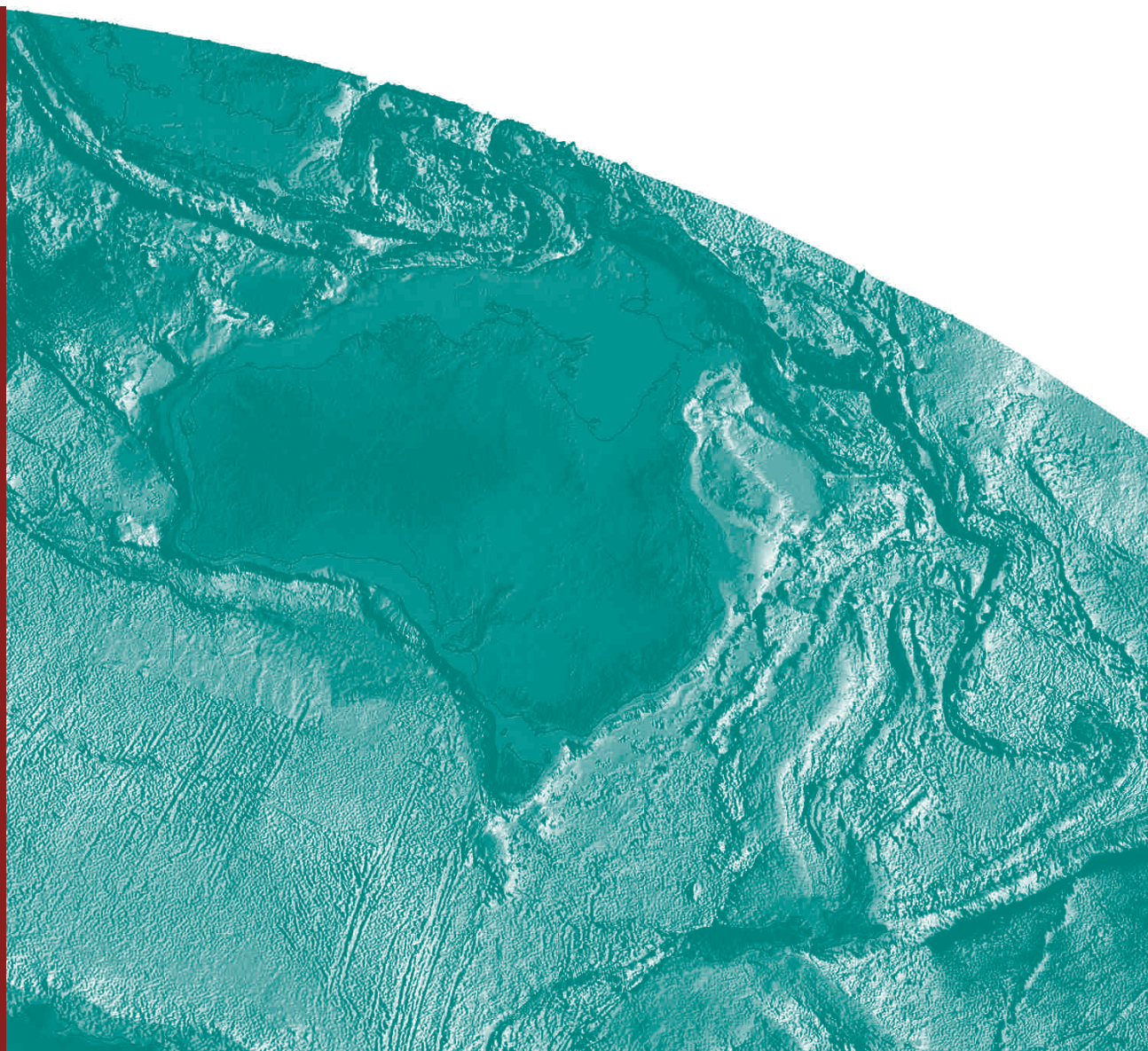
The 2003-2004 Curnamona Province Seismic Survey

Workshop Notes

B.R. Goleby, R.J. Korsch, T. Fomin, C.H.H. Connor, W.V. Preiss, R.S. Robertson and A.C. Burt

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THE 2003-2004 CURNAMONA PROVINCE SEISMIC SURVEY: WORKSHOP NOTES

GEOSCIENCE AUSTRALIA
RECORD 2006/12

by

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Executive Summary

For over a decade Geoscience Australia has adopted a practice of releasing the processed seismic reflection data, together with an initial interpretation, as soon as possible after the completion of data acquisition. This policy reflects recognition that new data and ideas are a valuable resource for both researchers and the exploration industry, and that seismic data often provides new insights into the structure of the crust at depth. This data and interpretation release is normally done in a workshop that is open to all, with an understanding that not all ideas are fully developed.

The Curnamona Project is a collaborative project between PIRSA Minerals and Energy Resources, the predictive mineral discovery Cooperative Research Centre (*pmd**CRC) and Geoscience Australia using the seismic acquisition facilities of the National Facility for Earth Sounding (ANSIR). The aim of the Curnamona survey was to provide information on the crustal architecture of the southern Curnamona Province in both the highly prospective Palaeo- and Mesoproterozoic rocks and the overlying Neoproterozoic and Cambrian succession in South Australia. A particular objective was the imaging of the deep crust and major structural features that may have influenced hydrothermal fluid flow, and hence mineralisation.

The Curnamona seismic workshop is the first public display and discussion of data and results of the Curnamona seismic survey commenced in 2003 and completed in 2004 after being washed out by floods in 2003. Feedback on the seismic results back to GA and PIRSA project staff at this workshop is as valuable as the information flow to the workshop attendees, because it helps to further develop the geological understanding that is emerging from the seismic data.

The seismic results reveal a crustal architecture for the Curnamona Province of eastern South Australia that provides important information on basement architecture that will enhance investment and targeting strategies for mineral explorers in the province. One example, the observation that the Kalkaroo prospect appears to be related to s order faults associated with hanging wall anticlines above a major bounding east-dipping fault at depth, opens up the possibility for further mineral deposits associated with other hanging wall anticlines above east-dipping faults.



CURNAMONA PROVINCE: DEEP SEISMIC PROPOSAL

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SUMMARY

The Curnamona Province deep crustal seismic survey was carried out in August 2003 and July 2004 across the southern Curnamona Province in South Australia (Figure 1-1) as a collaborative project between PIRSA Minerals and Energy Resources, the predictive mineral discovery Cooperative Research Centre (*pmd**CRC) and Geoscience Australia, using the facilities of ANSIR (National Research Facility for Earth Sounding).

The overall aim of the survey was to provide information on the crustal architecture of the southern Curnamona Province in both the highly prospective Palaeo- and Mesoproterozoic rocks and the overlying Neoproterozoic and Cambrian successions. A particular objective was the imaging of the deeper crust and major structural features that may have influenced hydrothermal fluid flow, and hence mineralisation. The survey results also provide fundamental information relevant to exploration for geothermal energy.

The survey transect (03GA-CU1) adjoins the deep crustal seismic transect (96AGS-BH1A) carried out across the Broken Hill region in NSW in 1996. Line locations are shown on outcrop geology (Figure 1-2), interpreted solid geology (Figure 1-3), magnetics (Figure 1-4), gravity (Figure 1-5) and depth to basement (Figure 1-6). The 1996 survey used explosion sources whereas the Curnamona Survey used vibroseis sources. The Broken Hill survey will not be discussed here but reprocessing of the data using current processing methods is planned and it is hoped that the reprocessed data will enable the development of a coherent interpretation for the whole province. The western end of the survey crosses the interpreted (and uncertain) boundary of the Curnamona Province into the Adelaide Geosyncline (Adelaide Fold Belt).



Figure 1-1: South Australian Geological Provinces with deep crustal seismic lines in the Curnamona region.

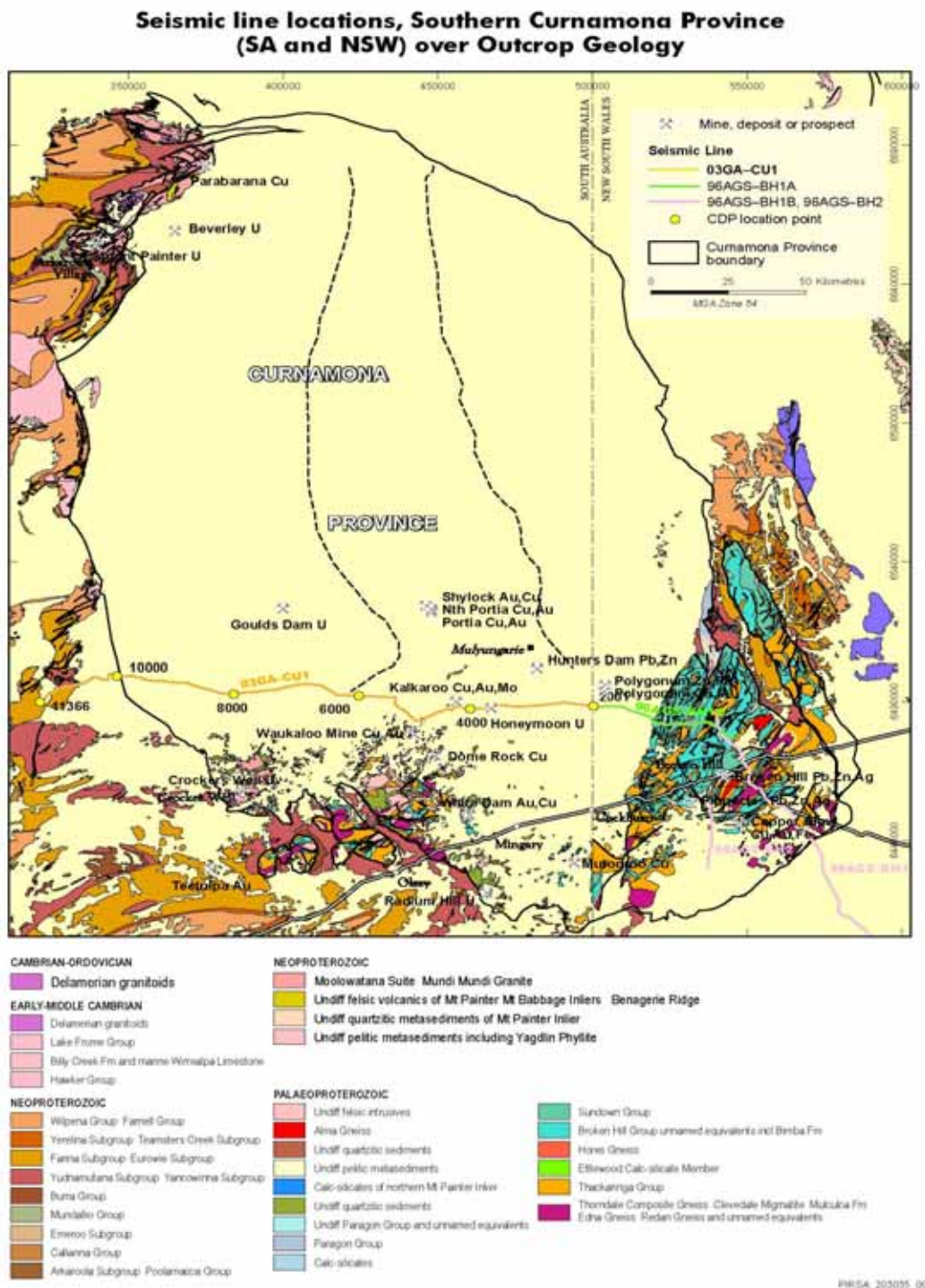


Figure 1-2: Outcrop Geology of the Curnamona Province and location of the seismic lines.

Seismic line locations, Southern Curnamona Province (SA and NSW) over Solid Geology

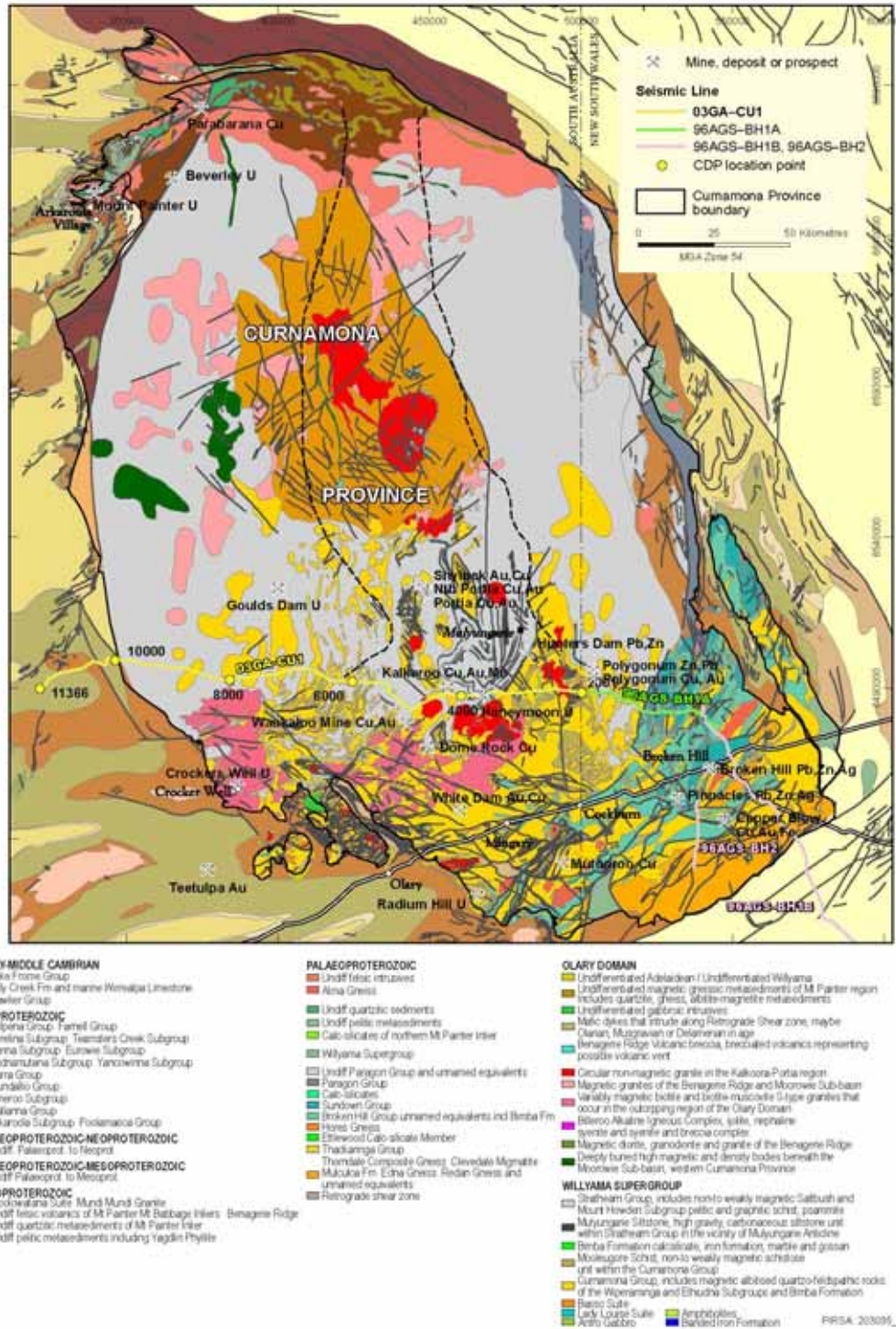
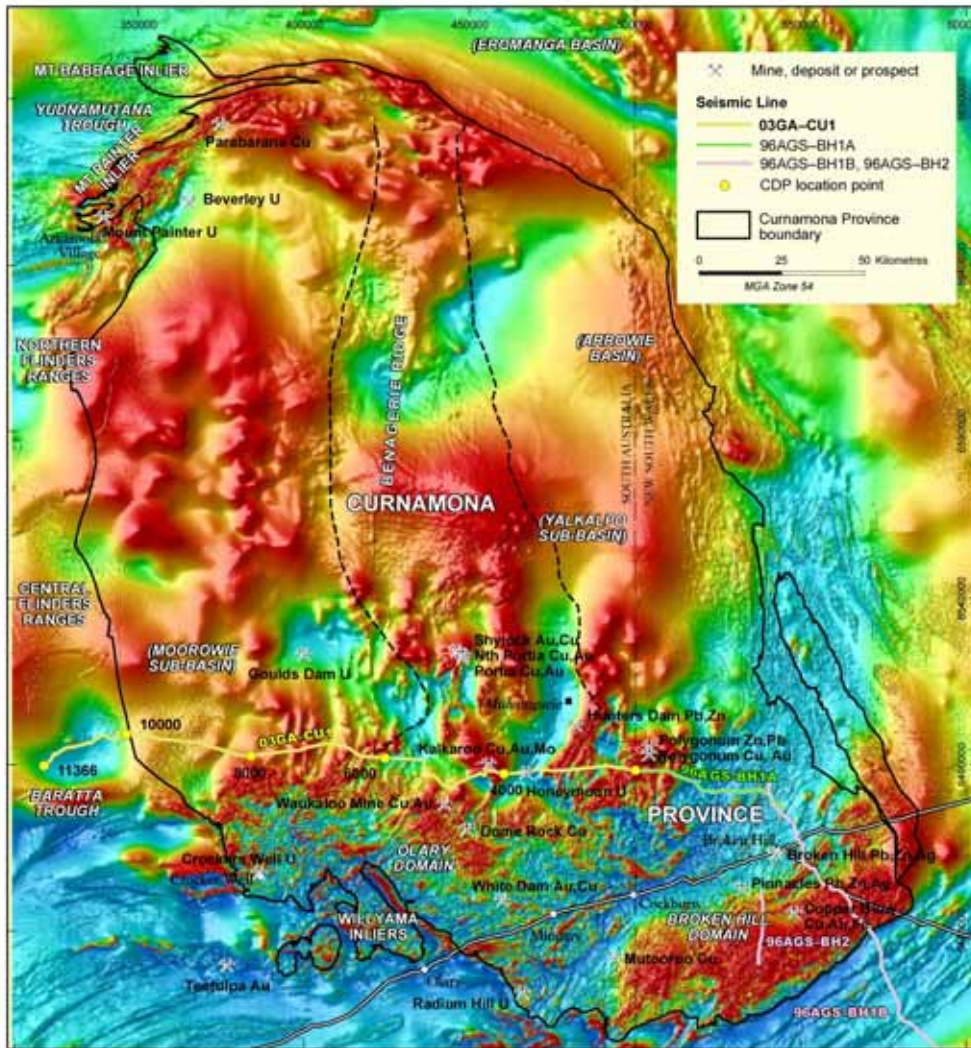


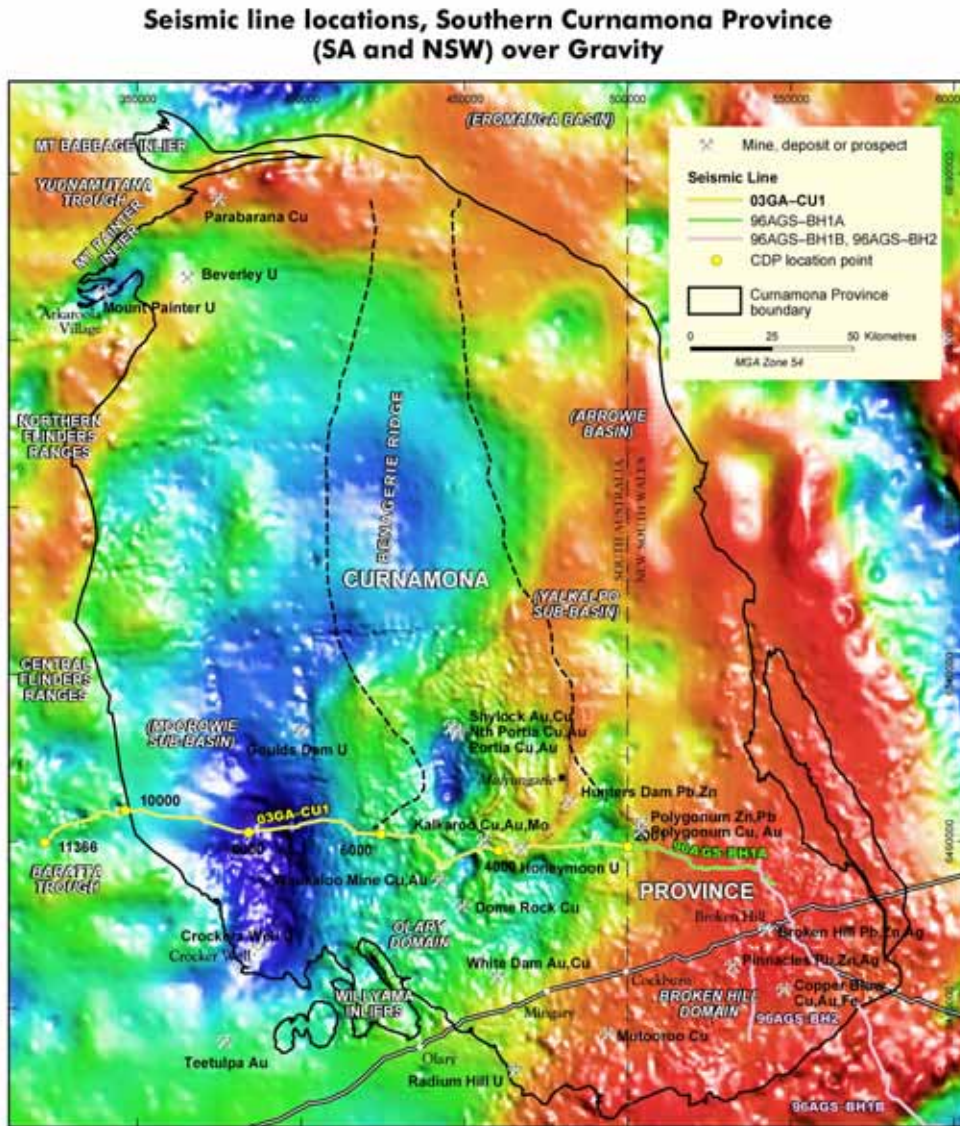
Figure 1-3: Interpreted Solid Geology of the Curnamona Province on locations of the deep seismic lines.

**Seismic line locations, Southern Curnamona Province
(SA and NSW) on pseudocolour Total Magnetic Intensity (TMI)**



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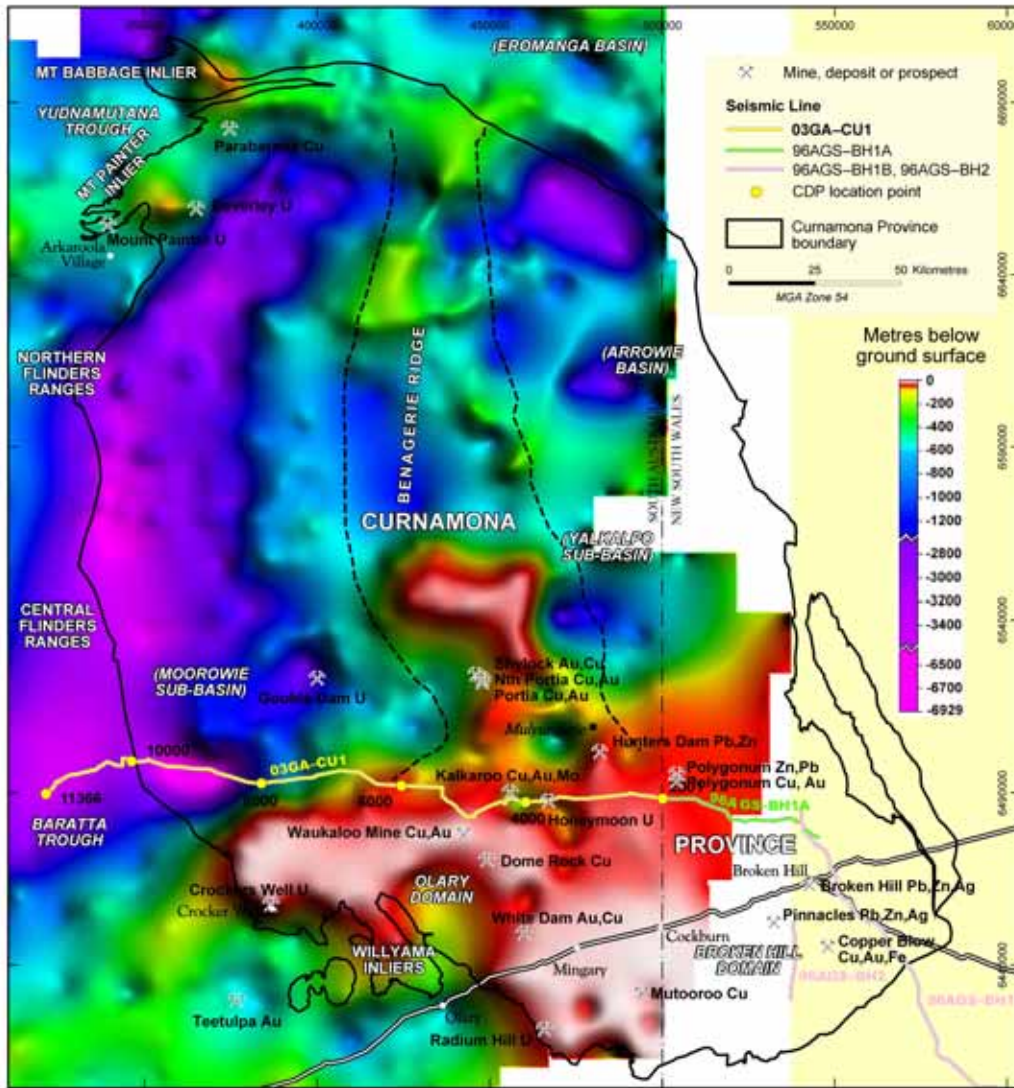
Figure 1-4: Magnetic (TMI) Image of the Curnamona Province and locations of the deep seismic lines.



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Figure 1-5: Gravity Image of the Curnamona Province and locations of the deep seismic lines.

Seismic line location, Southern Curnamona Province (SA and NSW) on Depth to Basement Image



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Figure 1-6: Depth to Basement (Palaeoproterozoic and Mesoproterozoic) map of the Curnamona Province and locations of the deep seismic lines.

The August 2003 part of the survey (39 km) was undertaken immediately after the 2003 Eastern Gawler Craton Seismic Survey across the Olympic Dam region. Heavy rain forced curtailment of the survey and the remainder of the survey was completed in July 2004. The total survey traverse length is 197.6 km. All of the survey transect was along existing unsealed roads and station tracks.

The Curnamona Survey has been undertaken following deep crustal seismic surveys in other Australian Archaean and Proterozoic mineralised provinces, including the eastern Yilgarn Craton, Mt Isa region, the Curnamona Province in New South Wales and eastern Gawler Craton regions. In the longer term, further seismic data acquisition across the Adelaide Geosyncline, Delamerian Fold Belt, Torrens Hinge Zone and Gawler Craton is envisaged.

PROJECT SUMMARY AND AIMS

The proposed seismic reflection work is to be carried out within a framework of an ongoing program of seismic data acquisition initially across the Curnamona Province, and eventually southern Australia. Eventually, linking this transect across the Curnamona Province and surrounding Neoproterozoic 'Delamerian mobile belts' with the Gawler Craton will enhance the geological and metallogenic framework, and help our understanding of the crustal evolution of southern Australia.

The Curnamona Project will focus on obtaining seismic images of the Meso-Palaeoproterozoic basement architecture of the Curnamona Province in South Australia. It will use these images to constrain the basement structure of the Curnamona Province and develop implications for hydrothermal fluid flow and for Pb-Zn-Ag and IOCG mineralisation.

As part of achieving this objective, the seismic results will be used to help define the nature of the link between the prospective Palaeo- to Mesoproterozoic Curnamona Province, which contains the Broken Hill deposit and a number of significant IOCG prospects, with the Gawler Craton; which contains the world class Olympic Dam IOCG deposit. Both styles of deposits are probably controlled or influenced by crustal-scale structures which can be imaged by the seismic method. Adelaide Geosyncline sediments obscure the basement in the Gawler-Curnamona contact(?) zone, making interpretation of the tectonic history of the area difficult. Interpretation of the seismic data will enable solid geology models based on geophysical data to be more accurately constrained.

This deep penetrating profile will contribute important information about basement and basin architecture. Recent geochronology and tectonic reconstructions have strengthened the case for linkages between the Curnamona Province, Gawler Craton and the Mt Isa Province. The Mt Isa Province shares the attributes of world class Pb-Zn-Ag mineralisation, and lesser but important IOCG mineralisation. It is expected that a future seismic transect joining the Curnamona Province and Gawler Craton will prove of similar value to the traverse across the Mt Isa Eastern and Western Successions. It is intended that the data presented here be used to enhance exploration investment and targeting.



CURNAMONA SURVEY OBJECTIVES

Specific objectives of the Curnamona Seismic survey are:

- Determine the depth, geometry and distribution of the Palaeo- to Mesoproterozoic basement, and unconformably overlying Neoproterozoic, Cambrian, Mesozoic and Tertiary sediments.
- Determine the geometry, depth extent and significance of major crustal-scale structures.
- Determine which structures controlled the original sedimentary basin geometry and changes in sedimentary facies across the region. This involves developing a model that will distinguish on a seismic profile between steep late faults that offset stratigraphy and steep or deformed early faults that controlled stratigraphy.
- Investigate the geometry of known and potential major fluid conduits and determine their role in the development of a) hydrothermal IOCG deposits (e.g. Benagerie Ridge-North Portia, Kalraroo), and b) growth faults controlling potential syngenetic Pb-Zn metal deposition. The principal objective is to vector to economic mineralisation under areas of barren cover.

LOCATION OF THE CURNAMONA SEISMIC TRAVERSE

A preferred traverse location was determined by the PIRSA Curnamona Project staff. This traverse location was positioned so as to have the best possibility of achieving all the defined survey objectives. The final traverse location was refined after liaison with ANSIR (Australian National Research Facility for Earth Sounding) representatives. The location of the Curnamona traverse is shown in [Figure 1-1 to 1-6](#).

Aspects important in determining the location of the traverse were:

- Integration of the proposed seismic reflection work into other work being undertaken by PIRSA Curnamona Project staff.
- Image key structures at near-orthogonal angles to their strike.
- As much as possible, avoid areas where complex geology or very oblique geological structures as well as aliasing of subsidiary structures may reduce data quality.
- Avoid any areas where near surface outcrop or subcrop may reduce data quality.
- Avoid sensitive land use areas such as National Parks, conservation and wilderness areas, heritage sites, mine leases, and seismically noisy built up areas.
- Minimise land clearance, both in order to reduce environmental impacts and cost.

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GEOLOGICAL OVERVIEW OF THE OLDEST SUB-CROPPING ROCKS: LATE PALAEOPROTEROZOIC WILLYAMA SUPERGROUP AND EARLY MESOPROTEROZOIC NINNERIE SUPERSUITE

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The Curnamona Province represents a fragment of a late Palaeoproterozoic basin, which hosts the 300mt Broken Hill Pb-Zn-Ag deposit (Figure 2-1), and that probably included the Pb-Zn-rich basins of northern Australia. Apart from relatively small inliers in the northwest (Mt Painter and Mt Babbage Inliers) and the southeast (Willyama Inlier), the Curnamona Province is blanketed by cover of Neoproterozoic, Cambrian, Cretaceous, Tertiary and Quaternary ages.

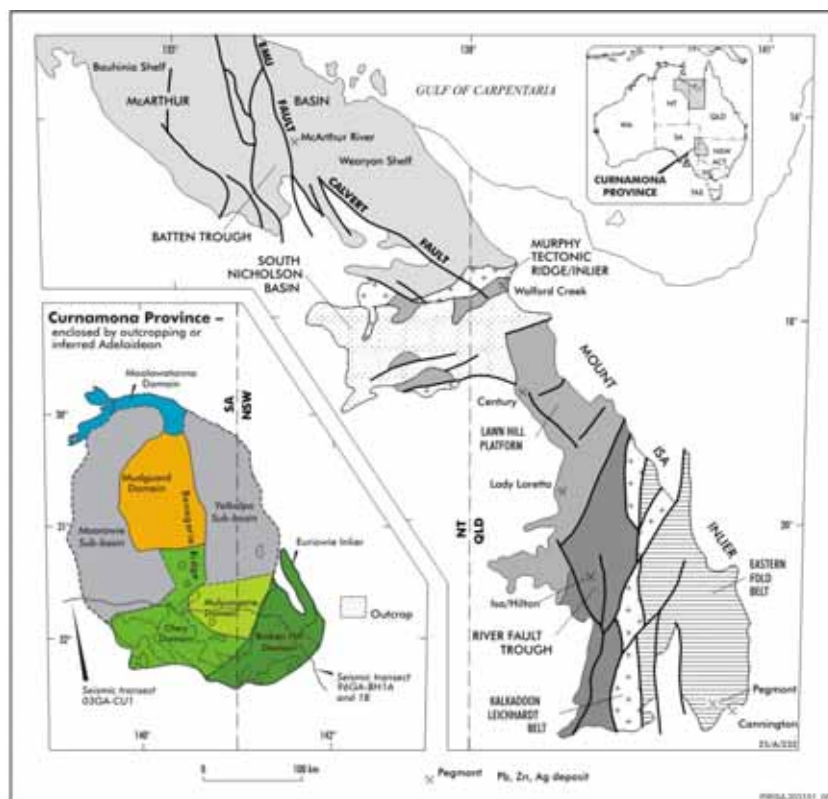


Figure 2-1: Location of the Curnamona Province with respect to the Northern Australian Pb-Zn Belt (inset), and geological domains of the Curnamona Province.



Pragmatically, the Curnamona Province can be divided into seven Palaeo-Mesoproterozoic domains (Figure 2-1), two of which are covered by sub-basins of the Cambrian Arrowie Basin. These domains and sub-basins are as follows:

1. Broken Hill Domain (BHD) (including the Euriowie Inlier) in the southeast, consisting of outcropping Willyama Supergroup intruded by Mesoproterozoic granite,
2. Olary Domain (OLD), the area to the west of the BHD and generally similar to the Broken Hill Domain, but with important differences within the Willyama Supergroup,
3. The Mulyungarie Domain, separating the northern parts of BHD and OLD and representing transitional Willyama Supergroup facies,
4. The Mudguard Domain, characterised by the flat-lying Mesoproterozoic Benagerie Volcanics bimodal volcanic sheet overlying deformed, granite-intruded Willyama Supergroup,
5. The Moolawatana Domain, consisting of the Mount Painter and Mount Babbage inliers in the northwest and their buried easterly extensions that mark the northern limit of the Curnamona Province.

The two Cambrian sub-basins, contained in synclines that include underlying Neoproterozoic sediments, are:

1. the westward deepening Moorowie Sub-basin, which oversteps Neoproterozoic strata to the east,
2. the thinner Yalkalpo Sub-basin, defining the eastern margin of the Benagerie Ridge and blanketing the northeastern extremity of the Curnamona Province.

The Moorowie and Yalkalpo Sub-basins are separated by the Benagerie Ridge, a buried, but structurally elevated (<200m cover) narrow north-south zone with similar geology to the OLD and the volcanics of the Mudguard Domain. For the purpose of this summary paper, the Olary Domain can be considered to consist of the following two parts:

1. the southern Benagerie Ridge area, a northern region approximating the southern part of the Benagerie Ridge in which the fold fabric is dominated by north-south trending F3 folds, a comparatively low frequency of west-east trending faults and relatively low metamorphic grade, and,
2. adjoining to the south, a region exhibiting higher metamorphic grade, greater frequency of easterly-trending shear zones, and with the F3 fold fabric trending northeasterly.

Commencing from the east at the SA-NSW border, the Curnamona Province Deep Seismic Transect crosses the Mulyungarie Domain, and a portion of the Olary Domain immediately north of the southern boundary of the southern Benagerie Ridge area. It then crosses the Moorowie Sub-basin and terminates in exposed, folded Neoproterozoic strata in the central part of the Flinders Ranges. Cover thickness above the Palaeo-Mesoproterozoic basement along the seismic transect varies from zero in places on the Benagerie Ridge to approximately nine kilometres in the Moorowie Sub-basin, and significantly more in the Flinders Ranges.

This article summarises the geology of both the known Palaeoproterozoic basement in the southern part of the Curnamona Province, that is the <1720 Ma to <1640 Ma Willyama Supergroup, and the ~1600 Ma to ~1580 Ma Mesoproterozoic granites and volcanics of the Ninnerie Supersuite (new name). These rocks, as well as thicker parts of the cover successions, are imaged by the shallow portion of the seismic survey (i.e. ~3 ss TWT or less).



WILLYAMA SUPERGROUP

The Willyama Supergroup (Figure 2-2) is observed in the southern portion of the Curnamona Province (Broken Hill, Olary and Mulyungarie Domains), with the possibility of some elements being present in the Moolawatana Domain. The known lithostratigraphy of the Willyama Supergroup spans the period 1720 Ma to 1640 Ma, and can be considered in three parts.

The lowest part of the succession, the Curnamona Group, is known only from the Olary Domain and is predominantly quartzofeldspathic, but with the upper part, the Ethiudna Subgroup, being locally calcareous and evaporitic. The Curnamona Group is characterised by 1718-1712 Ma A-type magmatism of the Basso Suite and restricted mafic volcanics; it is relatively oxidised when compared with the upper parts of the succession. Cu-Au deposits cluster along the zone of redox change. It is possible that the Redan Gneiss in NSW is in part the equivalent of the Ethiudna Subgroup.

The central part of the Willyama Supergroup succession is best represented in the Broken Hill Domain and consists of the Thackaringa and Broken Hill Groups. The Broken Hill Group hosts the 300 mt Broken Hill Pb-Zn-Ag deposit, and mafic and felsic igneous rocks deposited synchronously with the metasediments. The Thackaringa Group has not been recognised in the Olary Domain, although igneous rocks of equivalent timing have. The Broken Hill Group is extremely restricted in the Olary Domain, being mainly represented by the extensive but thin Bimba Formation, which is a pyritic carbonate-bearing unit that is base-metal anomalous. The presumed equivalent of this unit thickens up to 250-350 m in the Mulyungarie Domain where it hosts such prospects as Kalkaroo, Portia and Polygonum. Above the carbonate in the Mulyungarie Subdomain, is extensive low-grade Pb-Zn mineralisation (e.g. Polygonum, McBrides, Hunters Dam, Benagerie prospects).

The uppermost part of the Willyama Supergroup (Sundown, Paragon and Strathearn Groups) is predominantly psammopelitic to pelitic and devoid of synchronous volcanic units. Recent geochronology (Page et al., 2005) has equated these rocks with the northern Australian Pb-Zn basins, and for that reason they must be considered prospective for both Mount Isa and Century styles of mineralisation.

Geological data accumulated over the past 50 years have established a generally reliable lithostratigraphy for the Willyama Supergroup. This is especially true of the Broken Hill Domain (mainly represented in NSW), where the stratigraphic scheme of Stevens et al. (1983) suggested relatively continuous sedimentation. Recent systematic geological mapping and geochronological work under the auspices of the Broken Hill Exploration Initiative has demonstrated that, in the Olary Domain of South Australia, sediment distribution is not as continuous. Thus, in the lower part of the succession, very different lithological packages appear to occupy an apparently similar stratigraphic position (e.g. George Mine, Tommie Wattie and Mooleugore Formations), and the Thackaringa Group (>10 m.y. gap) is apparently missing from the Olary Domain, whereas in the upper part, interpreted sedimentary breaks are locally indicated to be as great as 40 m.y. (e.g. Plumbago Formation-Mount Howden Subgroup contact). A number of explanations for the variability of lithostratigraphic thickness and facies have been suggested, both depositional and structural, for example see Conor and Page (2003).

The lateral extent of the Willyama Supergroup approximates 20,000 km², but its exposed thickness is only about 7 km. This is a minimum figure, because, in spite of two major orogenic events that might have been expected to rotate the whole succession into view, neither the top nor base of the Willyama Supergroup has been observed. Thus, it would appear that the envelope



containing the deformed Willyama Supergroup is relatively flat, a feature that has important implications when considering the seismic imagery.

The near-surface component of the seismic transect is restricted to the stratigraphy of the Olary Domain (Figure 2-2). The lower part of the succession, the Curnamona Group, represents deposition within an extensional environment, with evidence for a thin and attenuated crust coming from the presence of hot A-type volcanics and intrusives (~1718-1712 Ma Basso Suite) and synchronous, though minor, mafic volcanism (Montstephen Metabasalt) and I- and S-type magmatism (Poodla Hill). That crustal extension continued during Broken Hill Group times, even though the Broken Hill Group sediments are sporadic in occurrence in the Olary Domain, is indicated by a mafic-dominated fractionated set of intrusives, the ~1685 Ma Lady Louise Suite. Evidence for partial melting of the deeper parts of the crust extends from the earliest times (S-type metagranite near the Bimba Mine), through the periods ~1705~1700 Ma and 1693-1685 Ma, the latter two represented mainly by evidence from the Broken Hill Domain. All these syn-Willyama igneous rocks tend to be sill-like in character, and therefore could potentially enhance reflections parallel to the stratigraphy.

From 1685 Ma, igneous activity apparently ceased but sedimentation continued with deposition of the Saltbush and Strathearn Groups in the Olary Domain and Sundown and Paragon Groups in the Broken Hill Domain. It has been suggested (Barovich, 2003) that the sediment supply switched from a source isotopically similar to central Australia (Arunta Province) to a more juvenile source during deposition of the >1650 Ma to <1640 Ma Strathearn and Paragon Groups.

MODIFICATION OF THE WILLYAMA SUPERGROUP

Deformation during initial stages of a major tectono-thermal event, the ~1600 Ma Olarian Orogeny, created features that are unlikely to be distinguished seismically from sedimentary layering, e.g. bedding-parallel foliation, isoclinal fold limbs. Distortion of seismic reflectors can be expected as a result of later deformation, e.g. Olarian F3 and F4 folding, and also the Cambrian Delamerian Orogeny D5 and D6.

Although, in general, there is agreement as to structural history of the Willyama Supergroup, there is considerable difference of opinion about the details. In general the three-stage scheme (D1-D3) of Berry et al. (1978) provides a favoured basis, although an extra event has been added, i.e. D4. Since no major F1 folds have been recognised, there is discussion now about whether D1 was contractional, resulting in an initial phase of nappe-style folding with largely bedding-parallel axial plane foliation and regional overturning, or an extensional event with overturning imposed during D2 (Gibson et al., 2004). Irrespective as to which of these is correct, D1 saw the development of the earliest metamorphic (migmatitic) and early metasomatic (albitite granofels) layering and foliation.

Reinterpretation of previous work and recent mapping (by GA, Monash University, and the Geological Survey Branch of PIRSA) has demonstrated that D2 produced isoclinal recumbent folds of substantial size and caused significant overturning, which in places has elevated migmatitic layering from deeper in the pile. Deformation was ductile and there is increasing evidence for sheath-style geometry, e.g. Forbes et al. (2004).

Sedimentary stratification, metamorphic zonation and foliation (D1) and large-scale recumbent folds (D2) can be expected to produce sub-parallel seismic reflectors, but perhaps exhibiting some divergence.



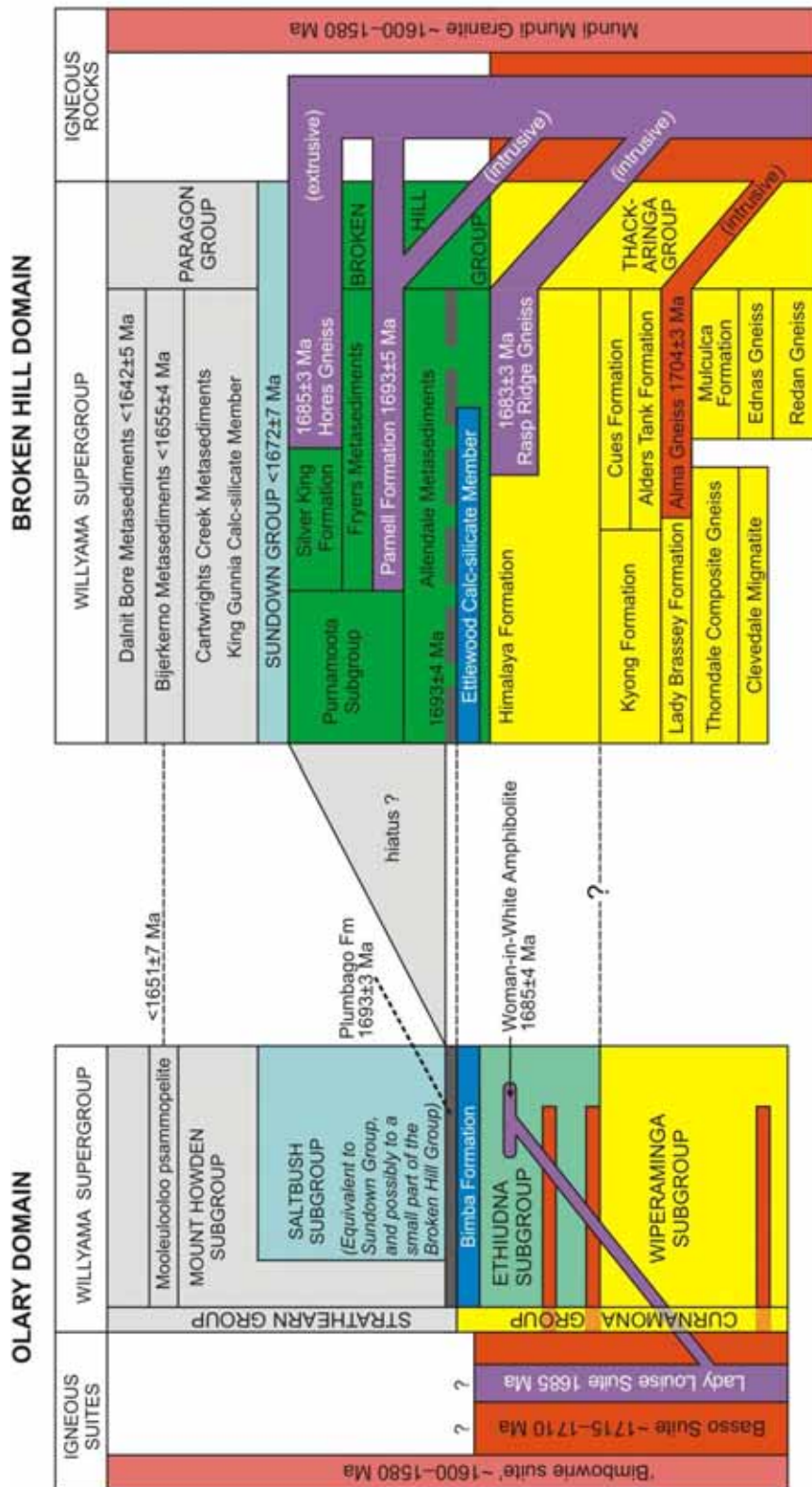


Figure 2-2: Lithostratigraphy of the Willyama Supergroup, modified from Conor (2004). It is now known that the Thackaringa Group is missing from the Olary Domain, and the Ethiudna Subgroup and Redan Gneiss are possible equivalents of each other.



F3 folds are less ductile, more open and upright, trending northeasterly across the Willyama Inliers in the Olary Domain, but swinging northerly in the southern Benagerie Ridge area, a trend echoed in the Broken Hill Domain. The position of the seismic transect approximates the axis of change of orientation. The vergence of F3 folding is northwesterly towards the Mudguard Domain (Fig. 2-1), and there is a tendency for the steep to overturned northern limbs of anticlines to form reverse faults or shear zones. Some open west-east trending upright folds are possibly attributable to D3, and may have been rotated during shearing, i.e. D4. It has been established that F3 anticlinal cores are the common loci for pervasive alkali-feldspar alteration and hydrothermal brecciation (Ashley et al., 1998).

D3 can be expected to have produced domains of curved reflector-sets within a sub-horizontal envelope, the domains being separated by discontinuities representing, locally altered, reverse faults.

The most striking aspect of D4 is the development of a regional-scale set of major anastomosing sheared zones varying in trend from ENE to WSW with some of the former possibly nucleated upon the sheared limbs of F3 folds, but with the latter being dominant. Some west-east trending, open upright folds are interpreted to have formed during this event (i.e. F4). It is postulated that in the southern Benagerie Ridge area, the interaction of long north-south trending F3 folds and orthogonal west-east trending F4 folds produced Type-1 interference, giving rise to such structures as the Kalkaroo North and South Domes. Some, perhaps many, F4 faults were reactivated during the later Delamerian Orogeny.

Potentially, the major influence of D4 structures upon the seismic reflection images is segmentation to form separate structural domains. The probability of the transect intersecting a major D4 structure, however is relatively low, because not only is the strike of D4 faults at an acute angle to the transect, but also the frequency of F4 faults is not high in the southern Benagerie Ridge area.

Deformation during the Cambrian Delamerian Orogeny (D5, D6 and regional-scale shearing) is intense in the south, but its effects are probably limited in the region of the seismic transect, i.e. in the southern Benagerie Ridge area. There is, however, the potential for minor offsetting of some stratigraphic horizons such as the Neoproterozoic unconformity.

The Willyama Supergroup underwent burial to significant depths, possibly partly by post 1650 Ma deposition and partly by tectonic thickening during Olarian Orogeny. Deformation relating to the later stages of the Olarian Orogeny, in combination with the Delamerian Orogeny, has caused northwesterly-directed exhumation of the Willyama Supergroup. This exhumation resulted in the apparent telescoping of metamorphic isograds, such that the metamorphic grade increases from granulite-facies at Broken Hill in the southeast, via a zone of granite 'melt'-rich amphibolite facies rocks, to greenschist-facies in the vicinity of the seismic transect. While all stratigraphic levels, at least below the Strathearn and Paragon Groups, exhibit the full metamorphic range, the lower part of the sediment pile appears to have been preferentially migmatized.

The seismic transect occurs north of the zone of fold stacking of metamorphic isograds. It is to be expected, however, that horizontal metamorphic zonation might be visible at depth in the seismic imagery; such zonation might include:

1. an uppermost zone of lower metamorphic grade consisting of domains of strong, curved reflections derived from folded well-developed compositional layering,



2. an intermediate zone of granite and migmatite that would be recognisable in seismic imagery as a horizontal belt characterised by patchy bland domains and domains containing short discontinuous reflections, and
3. a lowest zone of relatively dense granulite-facies restite from which the granitic partial melts have been driven.

In addition, reflections may be expected to be sporadically attenuated in the Curnamona Group, where locally, especially in association with Olarian F3 fold axis-parallel structures, there is extensive pervasive alkali-feldspar iron-oxide metasomatism and hydrothermal brecciation. Economic elements known to have been leached in the outcropping areas, have potentially precipitated elsewhere in the same structures.

A more extreme result of crustal melting during the latter part of the Olarian Orogeny was the development of the late stage granites of the 'Hiltaba-aged' Ninnerie Supersuite. The Ninnerie Supersuite in the main consists of voluminous S-type granites, e.g. muscovite + biotite Bimbowrie and biotite-only Crookers Well Suites, but with a small component of mantle-derived material. It would appear from mapping and magnetic imagery that margins to plutons are commonly diffused by migmatite in the lower part of the succession, but are quite sharply-defined around stocks penetrating the Strathearn Group. The Ninnerie Supersuite includes (to the north of the traverse) the flat-lying ~1580 Ma Benagerie Volcanics of the central Curnamona Province, which overlie folded Willyama Supergroup metasediments. Granite plutons would be expected to be represented by bland featureless domains in the seismic imagery.

Current information, like that in the Gawler Craton, tends to equate timing of the widespread IOCG-type alteration and mineralisation with the late stages of the Olarian Orogeny and the intrusion of the Ninnerie Supersuite.

POST - WILLYAMA SEDIMENTATION AND TECTONISM

The Curnamona Province is overlain by Neoproterozoic and Cambrian sedimentary cover deposited in rift and sag basins (see Preiss et al., this volume, for detail). The Cambrian Delamerian Orogeny, though locally intense to the south, had little effect on the basement in the vicinity of the seismic transect and to the north.

Tertiary sediments (Lake Eyre and Namba Formations) were deposited upon an irregular weathered basement, and host roll-front uranium deposits such as Honeymoon, Goulds Dam and Beverley. These sediments are thin (<100m) and hence not easily resolved along the seismic transect.

Traversing from east to west, the seismic transect covers the following:

CDP Start – 3400. Curnamona Group in the core of the Mulyungarie Anticline.

CDP 3400 – 4100. Across thin Bimba Formation and parallel to the Mooleulooloo Formation (Strathearn Group) along the southern limb of the Mooleulooloo Syncline.
Prospects nearby: McBrides (Pb-Zn, Cu), Hunter Dam (Pb-Zn) and Honeymoon (U).

CDP 4100 – 4300. Crosses the Kalkaroo Dome
Prospects nearby: Kalkaroo (Cu-Au-Mo), Portia (Cu-Au-Mo).

CDP 4300 – 4800. Parallels a mineralised fault-controlled anticline to the west of Kalkaroo.



Prospects nearby: Kalkaroo West (Cu-Au-Mo)

CDP 4800 – 5600. Traverses a small graben containing Neoproterozoic sediments

CDP 5600 – 6600. Traverses westward from Strathearn across a set of north-south fold axes in the Olary Domain deforming the Curnamona Group-Strathearn Group unconformity.

Station 6600 – western end. Onlapping Cambrian and Neoproterozoic sediment-fill of the deep Cambrian Moorowie Sub-basin.

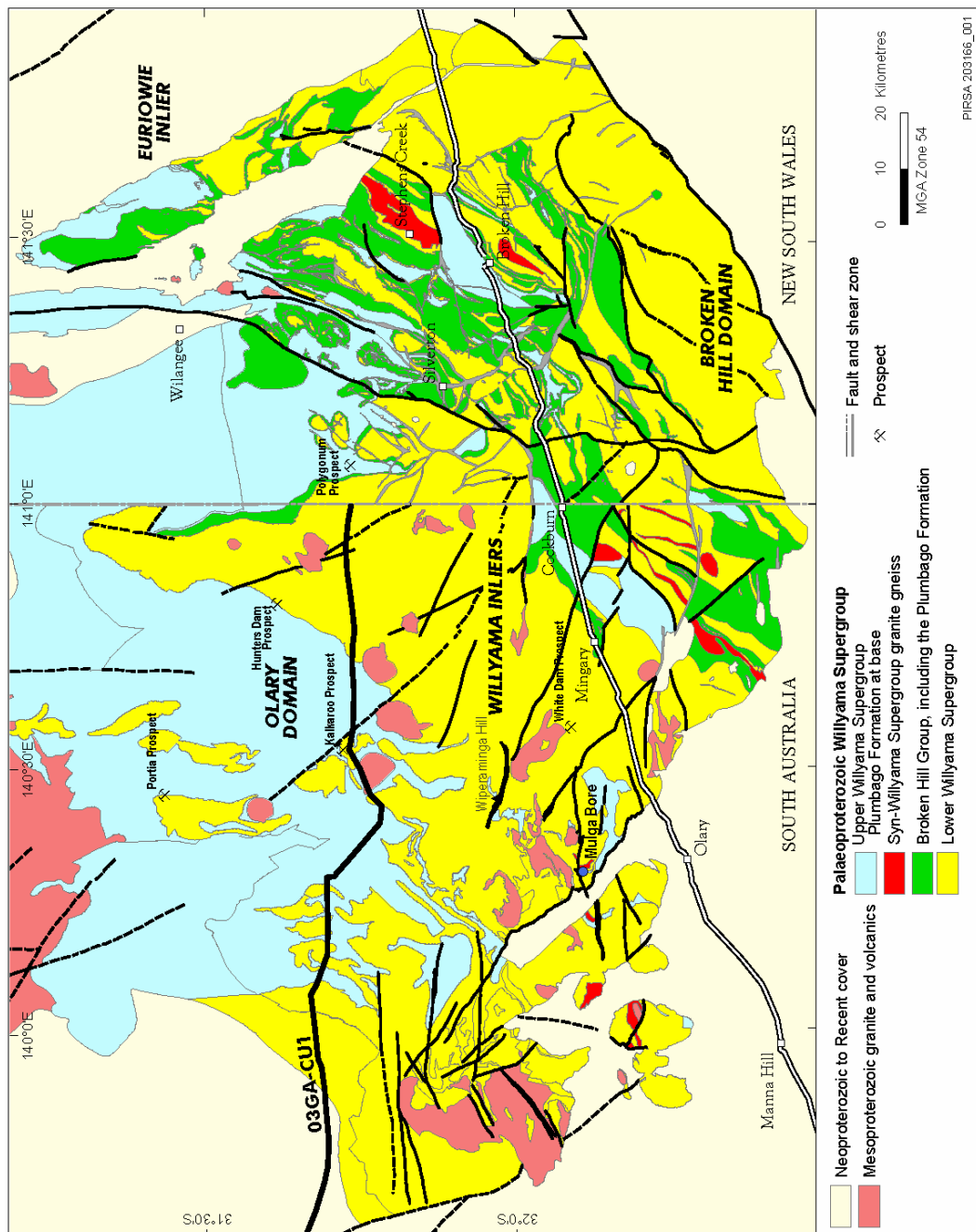


Figure 2-3: Southern Curnamona Province showing the location of major Cu-Au prospects near the Curnamona Deep Seismic Transect (03GA-CU1)



CURNAMONA INTERPRETATION COLOUR SCHEME

The colour scheme used in the interpretation of the Curnamona seismic sections is based on the geological legend for the Curnamona Province and then adjusted to the nearest available colours in Geoquest package. The final version of the colour scheme is shown in the [Figure 2-4](#).

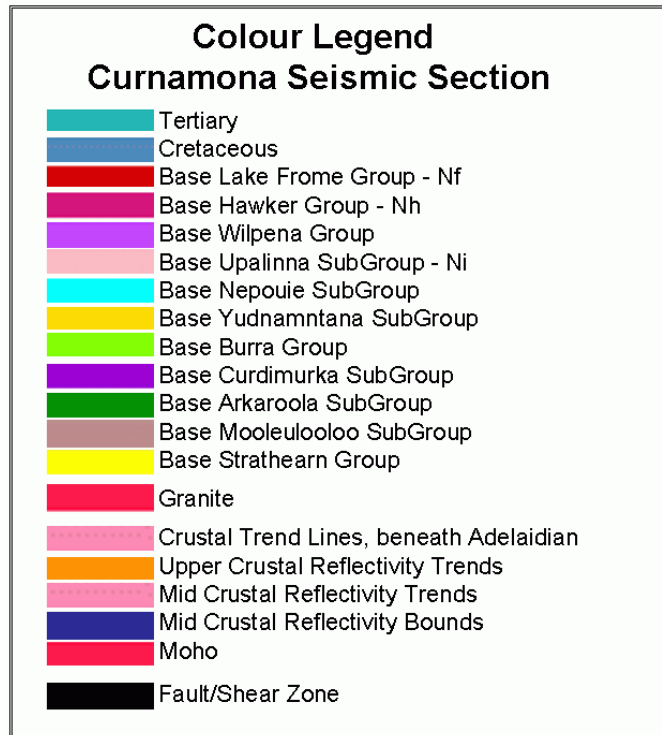


Figure 2-4: The colour scheme used in the interpretation of the Curnamona seismic sections.

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SEISMIC ACQUISITION AND PROCESSING: 2003-2004 CURNAMONA PROVINCE SEISMIC REFLECTION SURVEY (L164)

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DATA ACQUISITION: 2003-2004 CURNAMONA PROVINCE SEISMIC REFLECTION SURVEY (L164)

INTRODUCTION

A deep seismic reflection survey was carried out in the Curnamona Province of South Australia, to the west of Broken Hill, NSW and passed through the Honeymoon Mine site and close to Kalkaroo, Strathearn and Curnamona stations. The main objective of this survey was to provide a regional deep crustal seismic image of the Curnamona Province.

The survey was a collaborative project between several organisations. It was funded by PIRSA (Primary Industries and Resources South Australia) and the *pmd**CRC (Predictive Mineral Discovery Cooperative Research Centre) with support from Geoscience Australia (GA). The Australian National Research Facility for Earth Sounding (ANSIR) provided the seismic equipment and expertise during field acquisition, and contracted Terrex Seismic Pty Ltd (formerly Trace Energy Services Pty Ltd) to conduct the field operations.

FIELD ACQUISITION

The Curnamona seismic survey commenced in August 2003 but was interrupted due to wet weather. The survey recommenced and was completed in July 2004.

The survey consisted of a single traverse. This line, 03GA-CU1, started at the NSW-SA border at a point coincident with a seismic transect in the Broken Hill Region recorded by the Australian Geological Survey Organization (AGSO) in 1996-97 and continued in a westerly direction towards the Flinders Ranges ([Figure 3-1](#)). A total of 197.6 km of 2D vibroseis seismic reflection data and coincident gravity observations were collected.

The traverse followed existing tracks and minor roads. No line clearing was required for this survey.

Line pegging, surveying and gravity readings for the survey were carried out by Dynamic Satellite Surveys (DSS). Commencing with station number 1000 at the NSW-SA border, stations were pegged and surveyed using a 40 metre station interval. Gravity readings were made at every 10th station (400 metres) and the surveying and gravity tied to the permanent marker for the 1996 AGSO line (96AGS-BH1A). Gravity data for the western end of the seismic line (~20 km), north



of Yunta were collected by Haines Surveys, Adelaide. DSS reports describe the operational and technical details of the surveying (Dynamic Satellite Surveys, 2003, 2004).

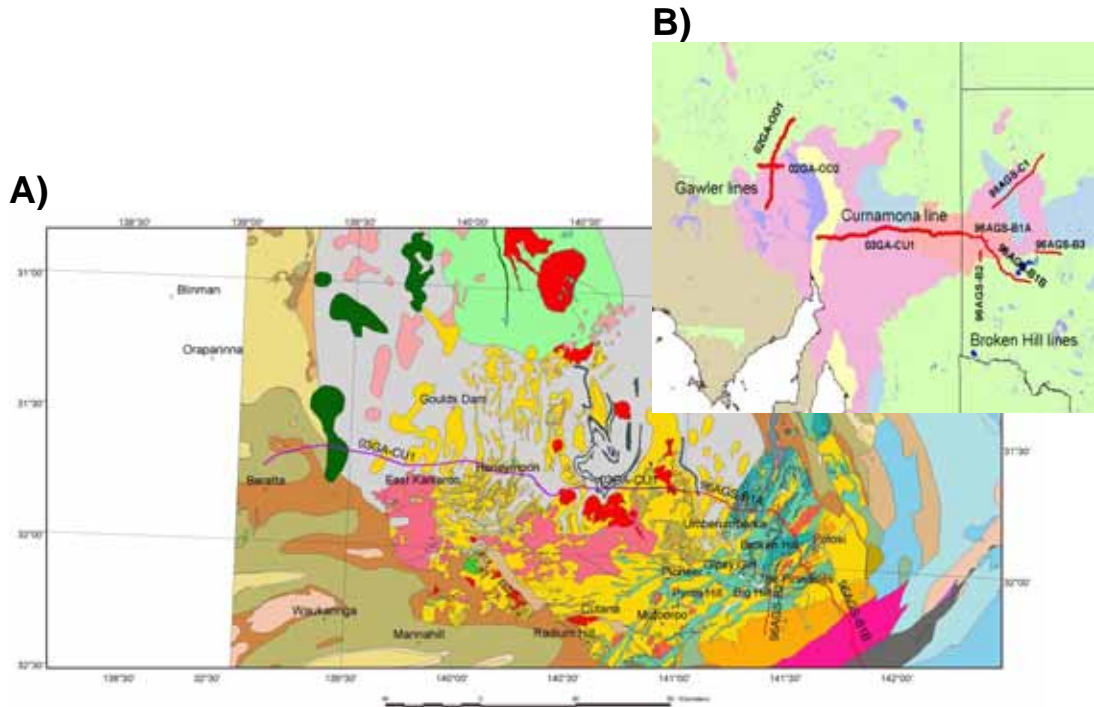


Figure 3-1: Location map: A) Geological Map - Curnamona traverse 03GA-CU1 in purple, Broken Hill traverse 96AGS-B1A/B1B in red, B) Inset: Curnamona, Broken Hill and Gawler seismic traverses.

Prior to seismic acquisition, an experimental program, carried out to determine the optimum acquisition parameters for the survey, was designed to allow a comparison of a number of seismic source parameters. Both monosweep and varisweep configurations were tested over different sweep frequencies, sweep lengths and source configurations. The acquisition parameters such as group interval, number of channels, CDP fold, vibrator point interval and record length were selected from previous experience in hard rock seismic data environments.

A summary of acquisition parameters is given in [Table 3-1](#); additional details are given in Appendix 1. Further details are provided in the Operations Report (Johnstone et al., 2006).

A total of 197.6 km of 60-fold seismic reflection data were recorded to 18 s TWT using three HEMI-60 (60,000 lb or 218,000 N) peak force vibrators and an ARAM 24-bit 240 channel recording system.

A set of 3490 magnetic field tapes and CD-ROMs of correlated SEG Y data was collected, with an additional backup copy written to DVD. The DISCO/FOCUS seismic processing software was used to QC field tapes and data on a daily basis. Brute stacks were routinely produced in the field to further monitor data quality.



Table 3-1: Summary of acquisition parameters for Line 03GA-CU1.

LINE	03GA-CU1
AREA	Curnamona Province (SA)
DIRECTION	East to West
LENGTH	197.6 km
STATIONS	1000 – 5940
CDP RANGE	2001 – 11385
GROUP INTERVAL	40 m
GROUP PATTERN	12 in-line @ 3.33 m
SOURCE TYPE	3 x IVI Hemi-60
VP INTERVAL	80 m
SWEEP TYPE	7-56, 12-80, and 8-72 Hz
NUMBER OF SWEEPS	3 x 12 sec
SOURCE MOVE-UP	15 m, 15 m pad-to-pad
CHANNELS	240
FOLD (NOMINAL)	60
RECORD LENGTH	18 s (approx. 50-km depth)
SAMPLE RATE	2 msec
RECORDING FORMAT	SEGY

PROCESSING OF SEISMIC REFLECTION SURVEY L164, CURNAMONA PROVINCE, 2003-2004

INTRODUCTION

Seismic data were processed using the DISCO/FOCUS seismic processing package. The final processing stream for Curnamona traverse 03GA-CU1 is summarised in [Table 3-2](#). A description of some of the major processing steps is given below.

CROOKED LINE DEFINITION

The geometry for the seismic line is defined according to the location of the shots and receivers. As the line followed existing roads or tracks, the line was far from straight. In order to perform optimal common mid-point stacking, it is necessary to define a CDP (common depth point) line, which is essentially a line of best fit to the common midpoints generated by the various shot-receiver pairs that exist. This line is less contorted than the actual seismic traverse and can be up to 300 m from the traverse, depending on the severity of the bends in the roads and tracks. All seismic sections that were produced for display and interpretation refer to the CDP line, not the traverse used during acquisition.



Table 3-2: Final processing stream for Curnamona Traverse 03GA-CU1

1. Field SEGY data to DISCO/FOCUS format
2. Quality control of the data and trace editing
3. Line geometry and crooked line definition
4. Resample to 4 ms
5. Spectral equalisation
6. Common midpoint (CMP) sort
7. Gain balance (spherical divergence corrections based on velocity function)
8. Refraction statics (datum 100 m) and automatic residual statics corrections
9. Band pass filter
10. Velocity analysis (1st pass after statics application, 2nd pass after dip moveout (DMO) correction)
11. Normal moveout correction (30 % stretch mute)
12. Stack of the data
13. Migration of the data (finite difference algorithm)
14. Signal enhancement (DIGISTACK)
15. Weighted trace mixing
16. Linear gain and amplitude balancing
17. Display data

REFRACTION STATICS CORRECTIONS

The near-surface layers are often heavily weathered and exhibit substantial variations in thickness and seismic velocity. These effects cause variable travel times from one seismic trace to the next that are not related to the configuration of the deep-seated reflectors. If these variations are not accounted for prior to CDP stack, a poor final seismic section will result. Refraction statics computation is a technique to determine such corrections based on the travel times picked from the first arrivals on the shot records. These times are assigned to the appropriate refracting horizon(s) and solutions are obtained for the depth variation(s) and the velocity distribution(s) of the various horizons (Figure 3-2). This enables corrections to be determined for delays in travel-time due to such variations in the near surface.

The thickness of the weathering layer varies from only a few metres to 200 m (in the western part of the line) with an average thickness along the line of about 100 m. The velocity for the refractor underneath the weathering layer (top of bedrock) is very high, varying from 5.0 km.s⁻¹ to 6.5 km.s⁻¹ in some areas. The application of the derived statics corrections improved the quality of reflections in the seismic data, especially for the upper 2 s.



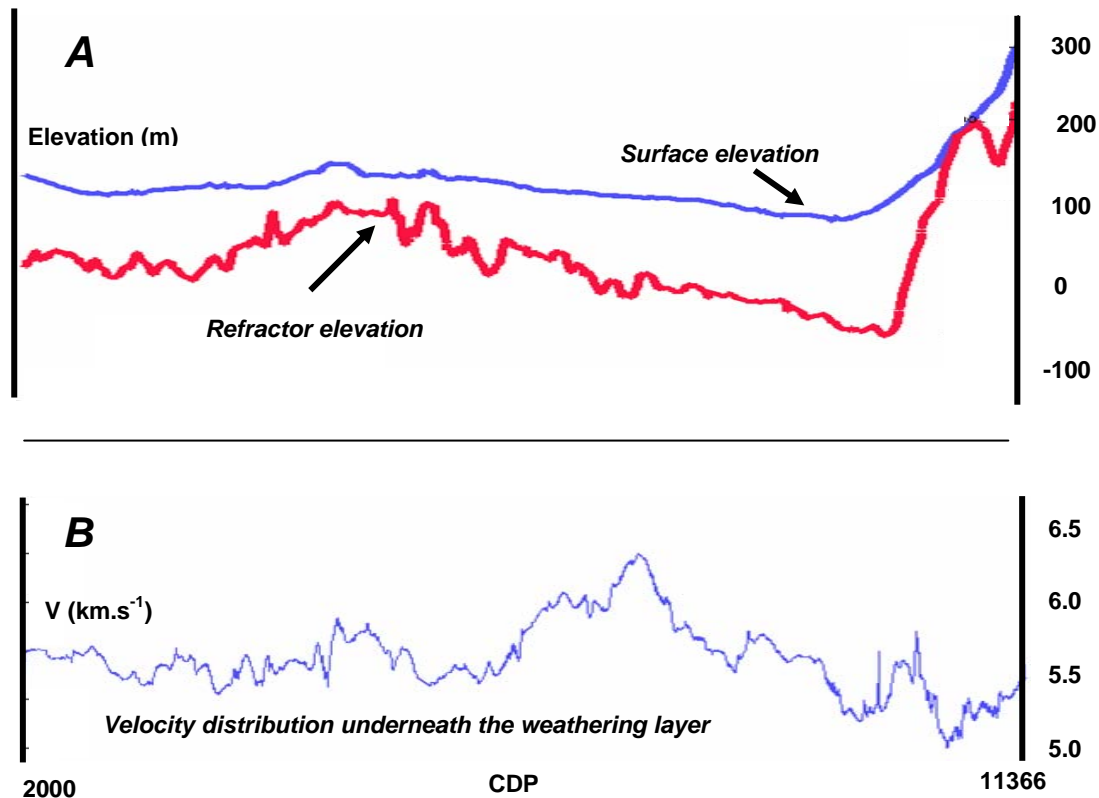


Figure 3-2: A) Results of refraction statics calculation for line 03GA-CU1. Surface and refractor elevations in metres. B) Velocity profile in km.s^{-1} .

VELOCITY ANALYSIS AND STACK OF THE DATA

Velocity analysis is a very important step in processing of seismic data, as the velocities are used to apply the normal moveout (NMO) correction prior to CDP stacking of the seismic data.

Stacking velocity analysis was carried out at two stages during the processing of the seismic data: after statics corrections and after DMO (dip move out) corrections. Velocities were picked interactively on the basis of coherency of seismic events observed in a small range of post-stack data. Therefore, stacking velocities are not velocities in a true physical sense.

Almost one hundred velocity functions (on average at ~ 2 km steps along the line) were used to produce the velocity model for the seismic line (Figure 3-3).

For the sedimentary basin portion in the western part of the traverse, the stacking velocities were low compared to the rest of the line. Towards the western and the eastern ends of the line, outside the basin, velocities are higher which is typical for the hard rock environment. In these areas, stacking velocities as high as $5.7\text{-}6.0 \text{ km.s}^{-1}$ near the surface were commonly used. Constraining a stacking velocity model in the hard rock environment is not easy, because the continuity of individual reflections is low. In the areas where dipping and sub-horizontal reflections are located, additional velocity functions were added.



After applying NMO corrections, the seismic traces were stacked. Stacking of seismic data improves the signal-to-noise ratio by suppressing noise and multiples, and therefore improves quality of the data.

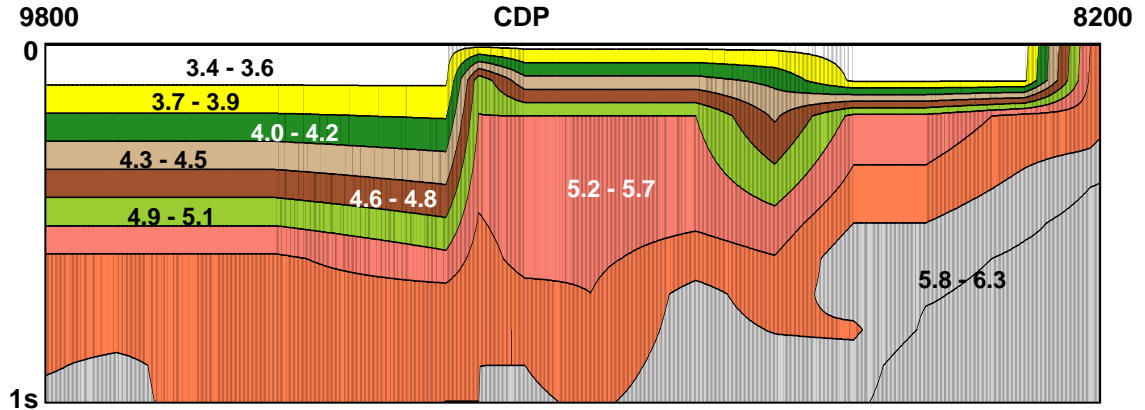


Figure 3-3: Fragment of stacking velocity display for the sedimentary basin in the western part of Curnamona traverse 03GA-CU01, CDPs range from 8200 to 9800 (~32 km), velocity in km.s^{-1} .

MIGRATION OF THE SEISMIC DATA

The main purpose of seismic migration is to bring reflections to their true spatial position in the seismic section. Figure 3-4 illustrates the situation. Seismic rays travelling at right angles to the dipping reflector from points P1, P2 and P3 are plotted in the vertical positions in the stacked section. Migration brings these reflections back to their true positions (the reflector). As a result of the migration procedure, reflectors seen on a stacked section become steeper, shorter and closer to the surface on the migrated section.

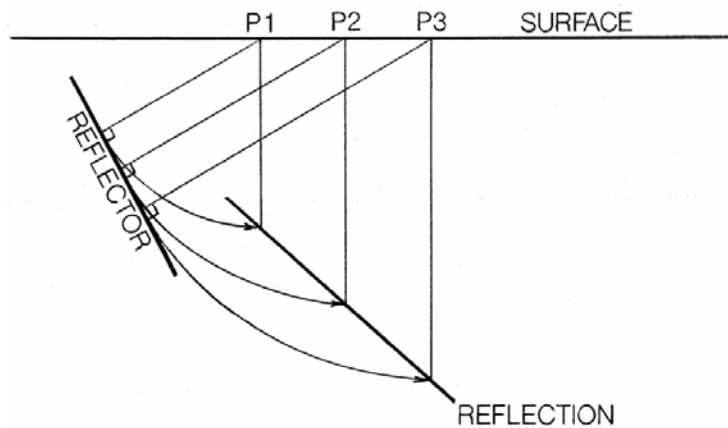


Figure 3-4. Scheme for the migration of seismic data. Arrows show how each point of the reflector is being misplaced in the non-migrated data.

In the western end of the traverse, the initial migration procedure partly destroyed data quality by producing 'smiles', possibly from spikes in the data. Several different migration algorithms were tried and various techniques were used to avoid this problem, without success. Finally, 20 CDPs were edited to remove large amplitude events and the final migration was considerably improved. A finite-difference algorithm with a velocity model based on the stacking velocity functions was



used to migrate the post-stack data. Generally, velocities that are lower than stacking velocities (60 to 90% of stacking velocity values) are used to migrate data. For the Curnamona data, 75 % of stacking velocity values (25% reduction) were used for the final migration.

The final migrated sections were used for geological interpretation of the Curnamona seismic data.

DISPLAY OF THE SEISMIC DATA

It is very important to choose appropriate display parameters for the final presentation of the data. It is difficult to present small features and large scale crustal structures in the same display with the same display parameters. Consequently, three scales, using different display parameters, were used to display seismic sections:

4. A detailed section for a limited range of CDP's (from 7400 to 11366) with only 3 s of data (~9 km in depth) was plotted at 1:25,000 scale to interpret the Neoproterozoic basin in the western part of the seismic line;
5. A 1:50,000 scale section to interpret the upper crust (0-6 s display, to ~ 18 km in depth);
6. A 1:100,000 scale for interpretation of crustal scale features including the Moho boundary (0-18 s display, to ~ 54 km in depth).

All sections were displayed at V:H = 1 assuming an average crustal velocity of 6.0 km.s⁻¹. After all the processing steps had been completed, an amplitude balancing program was used to improve the appearance of the seismic data (Figure 3-5).

Different scaling gates for the different display scales were employed to emphasise the desired features: narrow gates to interpret small size structures (1: 25,000 displays) and broader gates for large scale features (1:100,000 displays).

A semblance filtering program developed at the Geological Survey of Canada (Milkereit and Spencer, 1989) and adjusted to the DISCO/FOCUS package by A.J. van der Velden and B.R. Goleby, was used to produce small scale sections that can be plotted at very reduced scales, and are suitable for figures in publications (Figure 3-6). This program enhances reflections which are laterally continuous, and suppresses reflections with only limited lateral continuity. The resultant display allows one to identify regional reflection patterns that are not obvious in the bigger scale sections.

SEISMIC RESOLUTION

Resolution of the reflection seismic method is limited by number of factors. An understanding of these limitations can improve the geological interpretation of seismic data. A detailed explanation of the capabilities and limitations of this method in hard rock environment is discussed by Jones et al. (2003). These notes are reprinted from earlier Workshop Notes and included as Appendix 2. A short version of several key factors is given here.

Vertical resolution

The key factor controlling vertical resolution is the seismic wavelength (λ). Wavelength is a function of velocity (V) and frequency (f) (i.e. $\lambda=V/f$). For hard rock areas, wavelength is ~ 150 m (the typical parameters are V ~ 6.0 km.s⁻¹, f ~ 40 Hz).



When the thickness of a layer is $\frac{1}{4} \lambda$ (37.5 m) it will be detected as a single boundary, because the reflections from its top and bottom will not be resolved as separate seismic events. Thinner layers are unlikely to be detected. Only when layer thickness starts to exceed $\frac{1}{2} \lambda$ (75 m) can separate reflections be interpreted to resolve both the top and the bottom of the layer.

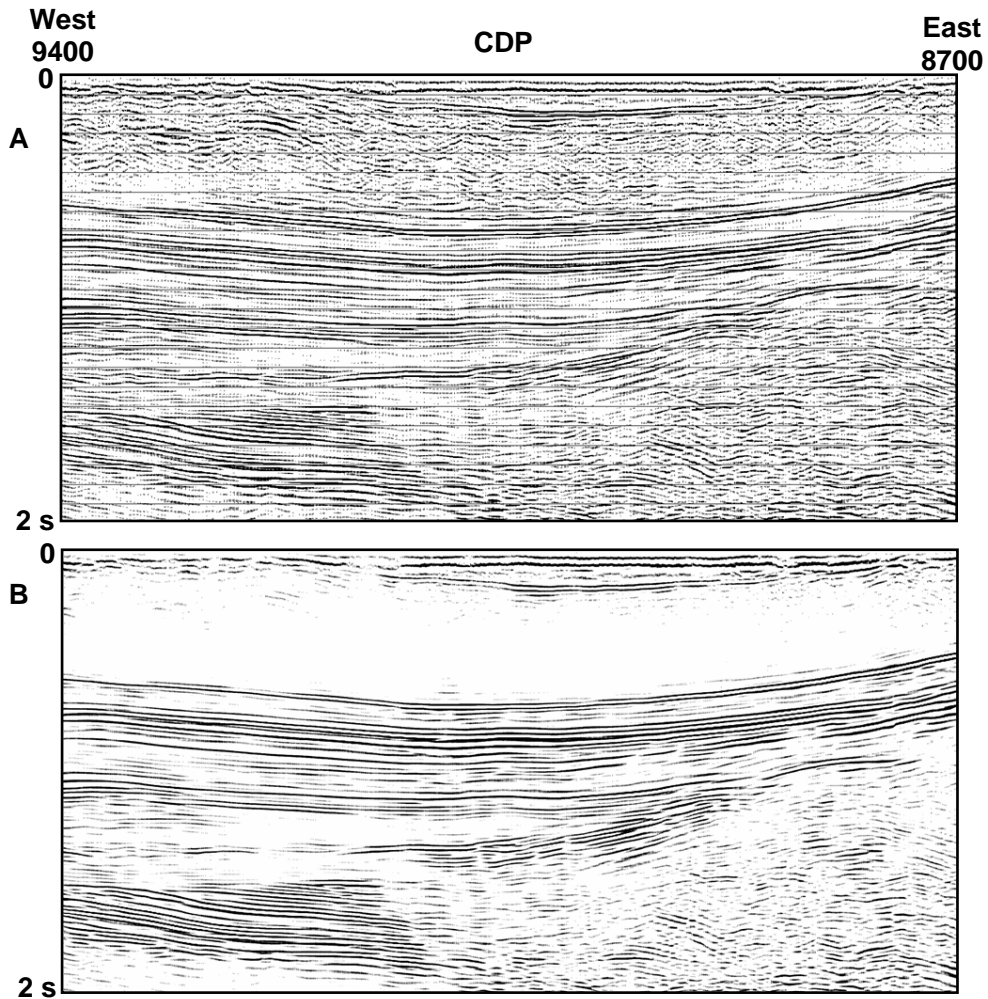


Figure 3-5. Fragment of the Neoproterozoic basin with different amplitude scalar applied. A) Narrow time gates – 200 ms window. B). Broad time gates – 1500 ms window.

Horizontal resolution

The minimum length of a layer in a lateral direction that can be imaged by the reflection method is determined by the Fresnel Zone. When a spherical wave front incident on a surface is reflected, there is a circular zone outside of which the incident and reflected waves are not in phase and cancel each other. Elements of surfaces smaller than the width of the First Fresnel Zone are not imaged.

For typical parameters of our survey, the width of this zone increases with depth from ~0.5 km at 1 s two-way time (TWT) to 3.0-4.0 km at 15-20 s TWT.



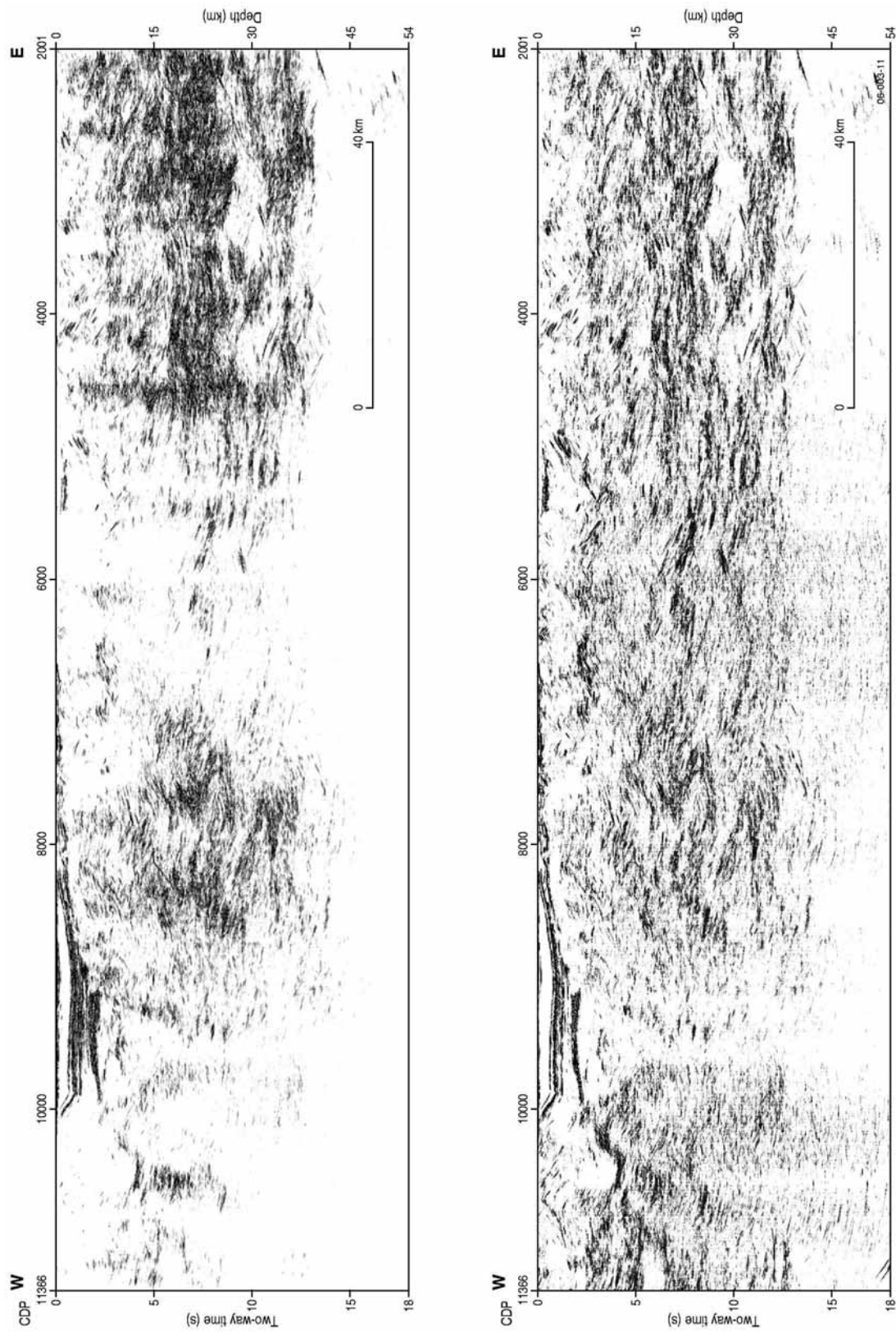


Figure 3-6. Curnamona migrated seismic section (~197 km in length) after semblance filtering. A) Section with no amplitude scaling applied, and B) section with amplitude scaling applied (broad time gates – 5000 msec).

Dip resolution

The ability of reflection technology to image dipping reflectors decreases with depth. Steep dips are easier to map in the upper crust. To image a steeply dipping boundary in the middle or lower crust, long recording lines and long recording times are required. Example of imaging shallow and dipping structures is shown in [Figure 3-7](#).

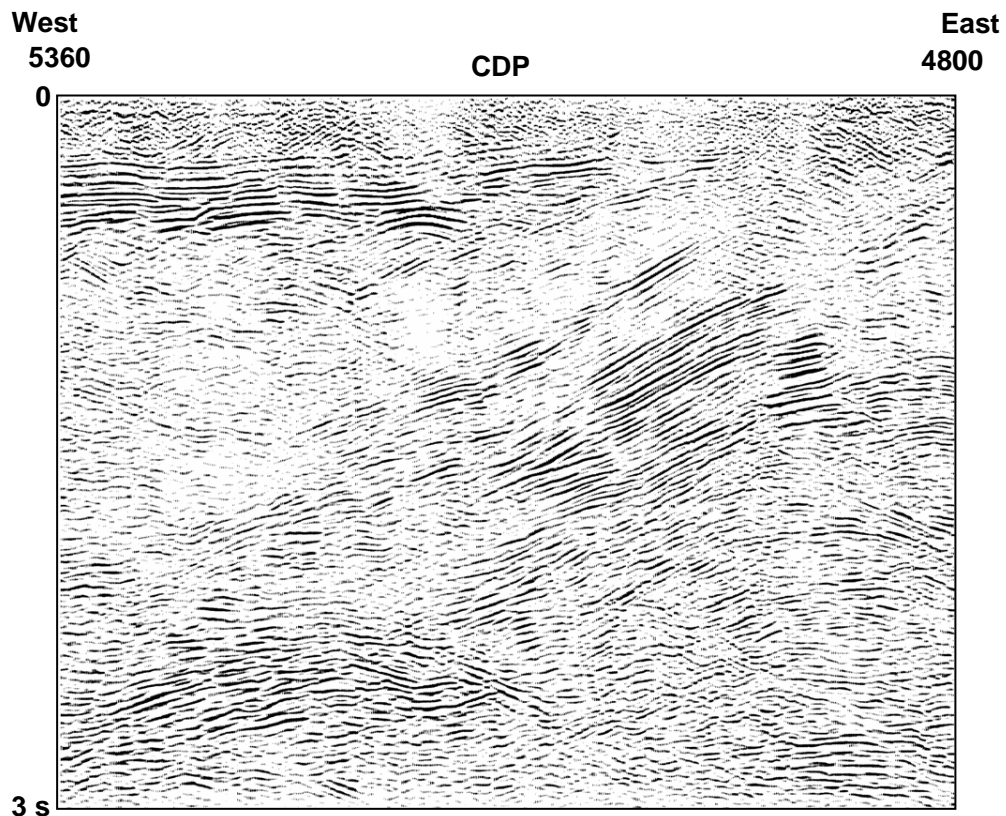


Figure 3-7. Fragment of migrated data (~ 11 km in length) across the shallow subhorizontal Adelaidean succession and dipping faults underneath it.

For a typical deep seismic survey with 20 s record length, dips of $\sim 70^\circ$ can be imaged no deeper than about 20 km, $\sim 50^\circ$ dips can be imaged no deeper than 40 km. Very steep reflectors with dips $\sim 80^\circ$ can only be imaged in the upper 10 km of the crust.

SEISMIC SECTIONS PREPARED FOR INTERPRETATION

The initial interpretation of seismic data was carried out on hard copy sections at PIRSA. During these initial interpretation sessions, areas that were identified for further processing included:

1. The western end of the traverse (from 10100 CDP to the end of the line)
2. The area of the fault at CDP 7520
3. The area between CDP's 3000 and 5500

With these areas reprocessed, the final migrated data (in SEG-Y format) were loaded into the GEOQUEST seismic interpretation software application. The paper based interpretations were



then digitised and imported into GEOQUEST, where they were refined and plotted as an overlay of the final migrated seismic sections (Figure 4-1).

For all figures, V/H is as close to 1:1 as possible, assuming a velocity of 6.0 km/s and the horizontal scale is based on 1 CDP = 20 m.

Interpretation Methods

The method used to interpret the deep seismic reflection data follow those principals developed during previous surveys and are as follows:

1. Identify prominent trends in the seismic reflectivity by highlighting the main trends defined by the stronger reflections.
2. Identify angular relationships between different reflective packages, which indicate an inferred discontinuity in geology.
3. Draw boundaries around regions of similar reflectivity and/or between regions of different reflectivity to create packages or domains of consistent reflectivity. To be consistent, the tops of highly reflective zones were used to define the boundary to the domain (here we used similarities in the amplitude, coherency and dip of the seismic reflections to define the regions).
4. Identify major large-scale trends in reflectivity, for example, reflectivity that extends over large distances, either as dipping bands or sub-horizontal bands (e.g., the Moho),
5. Using the known surface geology, project the mapped faults and geological units to depth along previously defined reflective zones.
6. Identify any kinematic indicators that suggest movement directions or sense of displacement.
7. Link the surface information projected to depth to the major large-scale trends and package or domain boundaries to create a crustal structure that is consistent with the geology and the seismic data.
8. Add interpretations to the section for those features identified in the geological mapping but not imaged by the seismic data. It is assumed that these structures or units are non-reflective.
9. The seismic interpretation was then cross-checked against the geology, and the results discussed by the project team, and evaluated against all known geological and geophysical data.
10. The seismic interpretation is presented to geoscientists (e.g., at this workshop) for further feedback and improvement.

SUMMARY

A total of 197.6 km of high quality, deep seismic reflection data were collected using vibroseis sources in the Curnamona Province in 2003/2004. The DISCO/FOCUS seismic processing package was used to process the data which were interpreted and displayed using a combination of Geoquest and paper plots. Several major processing steps, including the application of refraction and automatic residual statics, stacking velocity analysis and migration improved the resolution of the seismic images.

The Curnamona Province seismic data quality is very good. The recorded frequencies were high; indicating that seismic wave attenuation is low within the basement. The coherency of the returned seismic signal was variable. This has been interpreted to represent changes in geological conditions rather than seismic acquisition variations. On average, the continuity of reflections extended up to several kilometres within the basement regions and longer with depth. In places, complex deformation has partially destroyed reflection continuity. In a few places, this has resulted in making the interpretation more ambiguous.



The major cause of the reflectivity throughout the section is interpreted to represent both lithological variations and structural features like shear zones.

As a result, the Curnamona seismic survey provided high quality images of the entire crust with the Moho boundary imaged at ~ 37-40 km. The seismic section shows different reflectivity patterns along the traverse from highly reflective crust to weakly reflective crust, and almost blank crust in some areas.

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THE WILLYAMA SUPERGROUP COMPONENT OF THE CURNAMONA PROVINCE DEEP CRUSTAL SEISMIC TRANSECT

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INTRODUCTION

The Curnamona Province Deep Crustal Seismic Traverse 03GA-CU1 extends approximately 197 kms east-west from the South Australian–New South Wales border to the Central Flinders Ranges. This seismic line crosses covered rocks of the Willyama Supergroup, Neoproterozoic–Palaeozoic sub-basins and low-grade metasedimentary rocks of the Adelaide Geosyncline.

These notes are a brief summary of the major features observed in the upper 6 s two-way-travel time (TWT – two-way time). Where possible, interpretation has been supported by information from the outcropping portions of the Willyama Inliers and Adelaide Geosyncline, potential field data, solid geology interpretation and drilling.

Figures 4-1 through 4-8 show portions of the interpreted seismic section within the Willyama Supergroup succession within the Curnamona Province.

UNITS

The eastern portion of 03GA-CU1 crosses covered Willyama Supergroup rocks that are intruded by late Olarian Orogeny granitoids of the Ninnerie Supersuite (1595 – 1580 Ma). Layered rocks of the Willyama Supergroup have been deformed by several generations of folding during the Olarian Orogeny; two of these sets are evident in airborne magnetic and gravity data, particularly for the Kalkaroo dome and Mooleulooloo Syncline. The outcrop pattern in the Olary Ranges, to the south, is dominated by upright northeast trending folds and northwest and northeast trending shears and faults. These structures can be interpreted, using potential field data, to continue under cover to the north of the outcropping portion of the Willyama Supergroup, but swing into a more northerly orientation.

The upper 6 s TWT can be divided into two main zones i.e. 0–2 and 2–6 s TWT. An interpretation of these zones and how they relate to Curnamona Province outcrop geology is set out below.



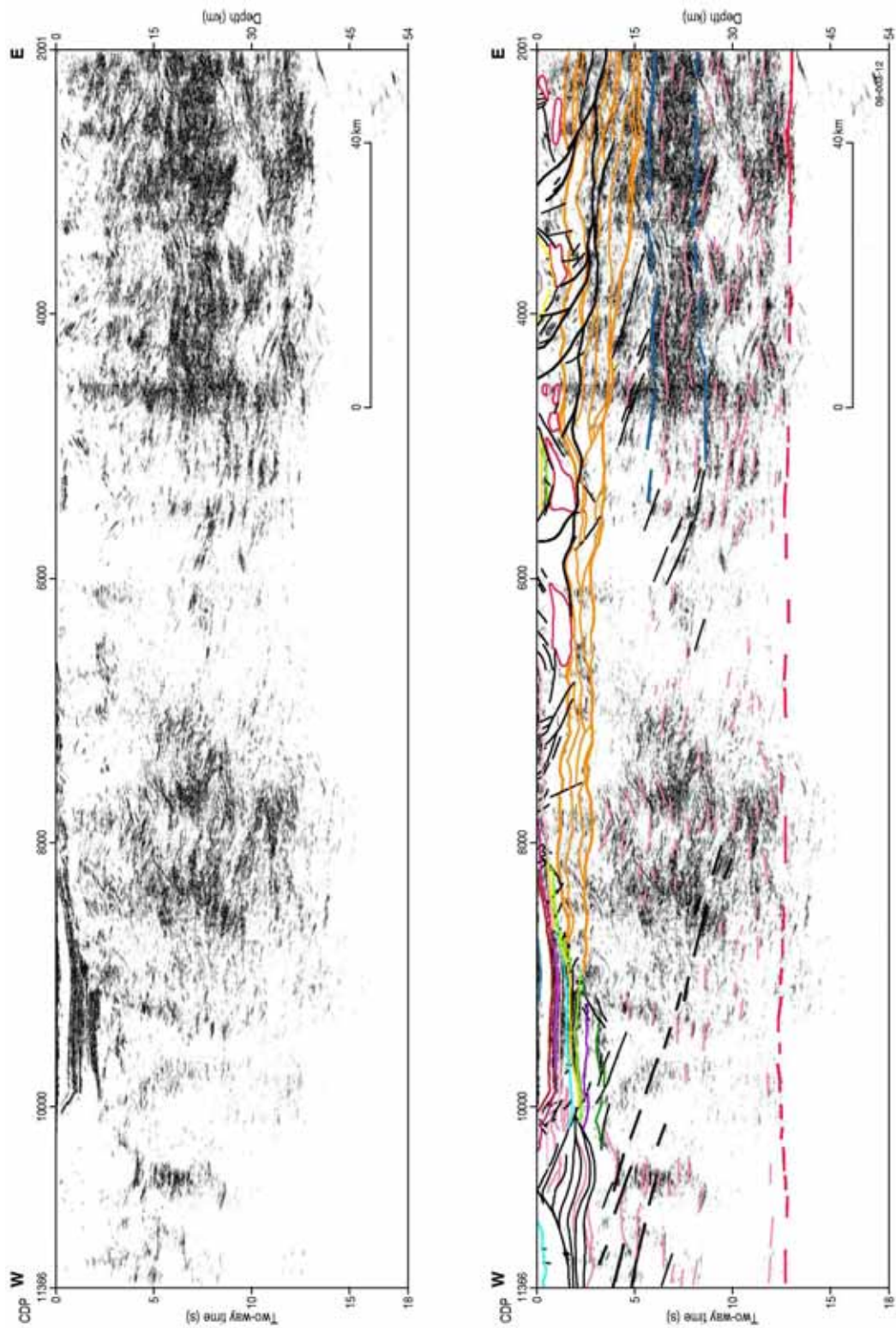


Figure 4-1: Entire length of seismic traverse 03GA-CU1, showing eastern Willyama section and the western portion covered by Adelaidean units. Sections show semblance filtered migrated data. Colour scheme is given in [Figure 2-4](#). Horizontal scale is based on 1 CDP = 20 m.

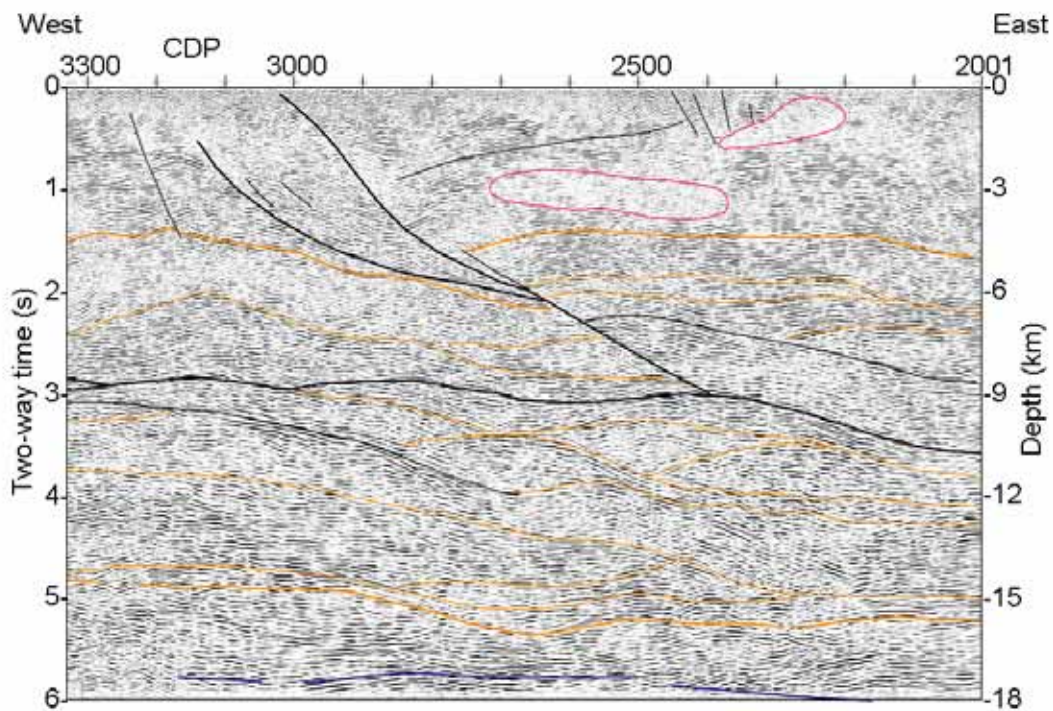
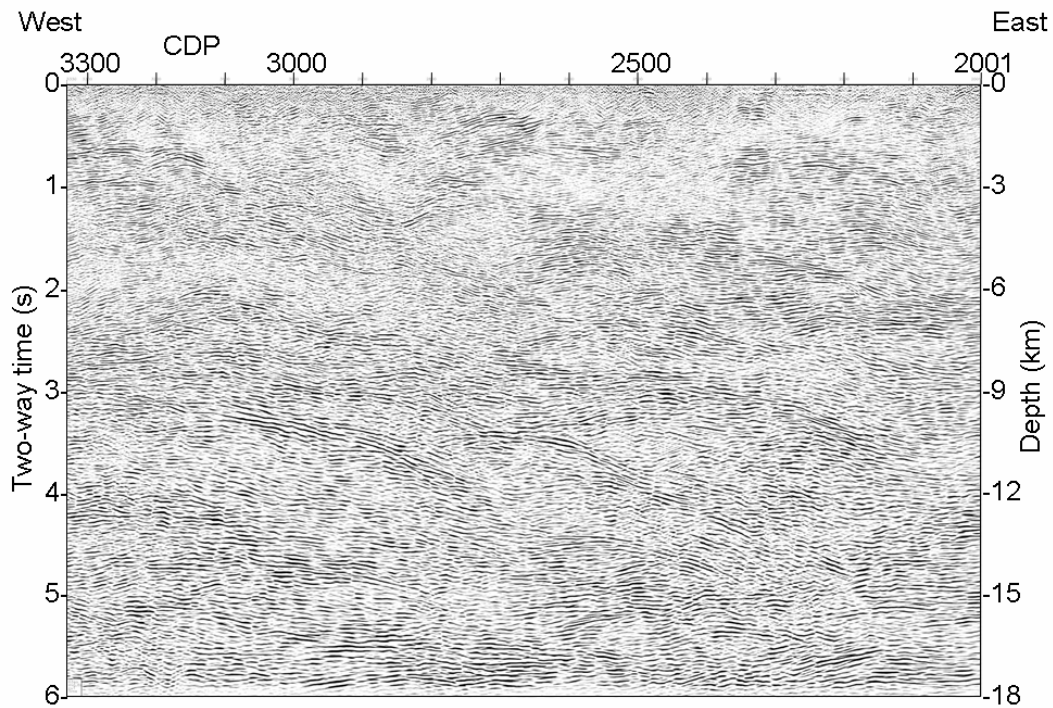


Figure 4-2: Eastern end of upper 6 s TWT of seismic traverse 03GA-CU1 (CDP 2100–3300). Colour scheme is given in [Figure 2-4](#). Horizontal scale is based on 1 CDP = 20 m.

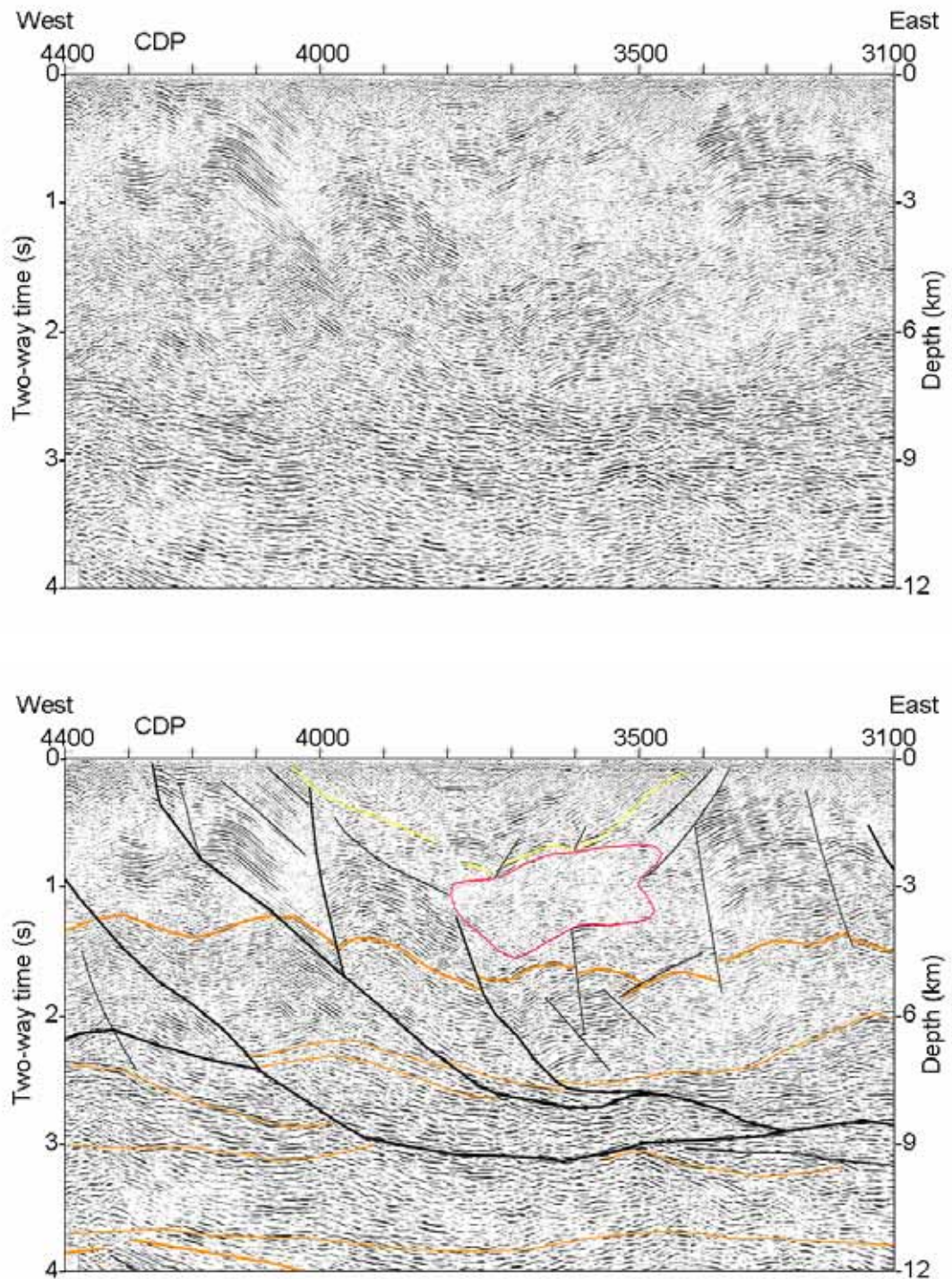


Figure 4-3: Zoom of upper 4 s TWT of portion of seismic traverse 03GA-CU1 (CDP 3100–4400). Colour scheme is given in [Figure 2-4](#). Horizontal scale is based on 1 CDP = 20 m.

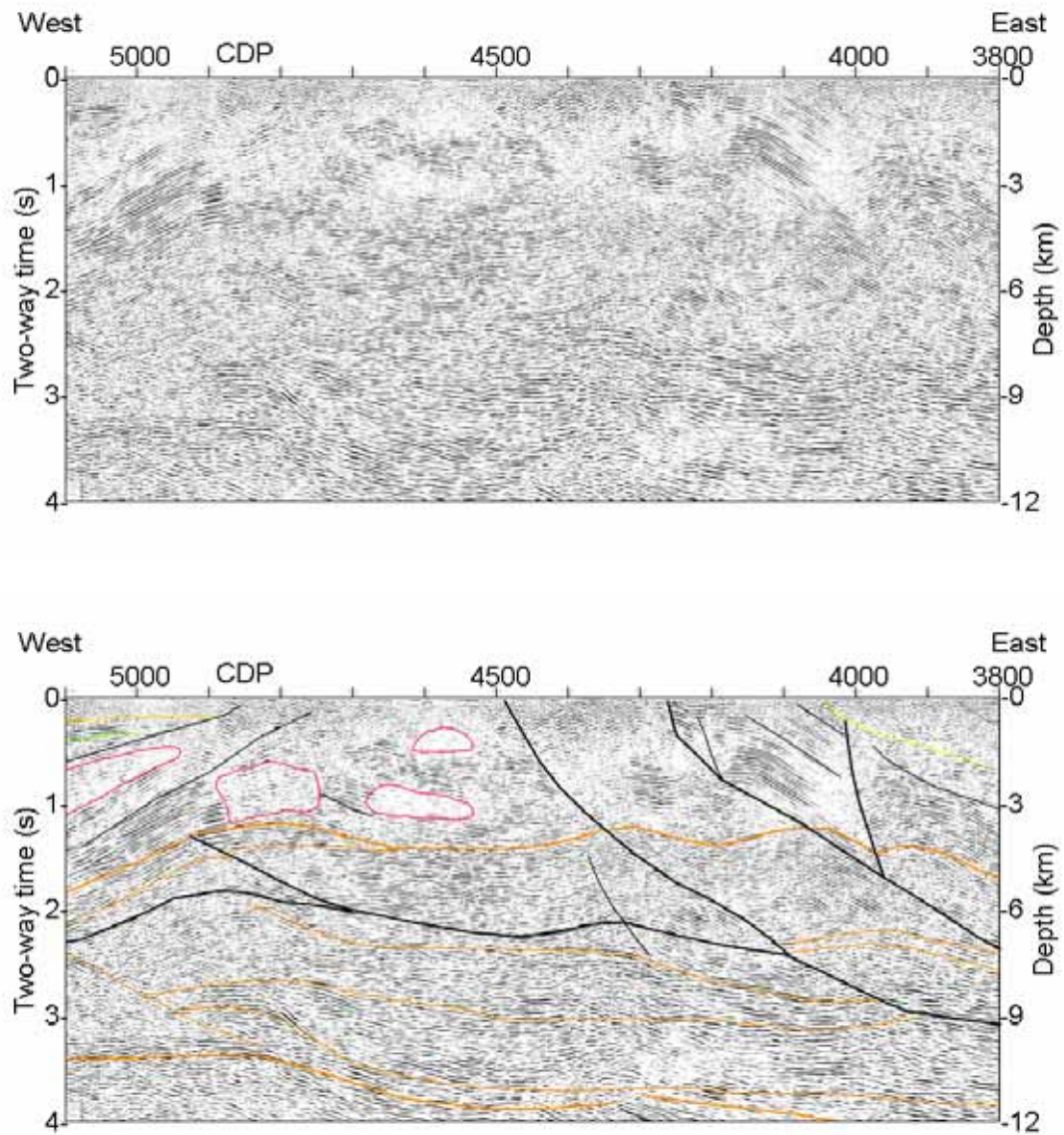


Figure 4-4: Part of upper 4 s TWT of portion of seismic traverse 03GA-CUI (CDP 3800–5100). Colour scheme is given in [Figure 2-4](#). Horizontal scale is based on 1 CDP = 20 m.

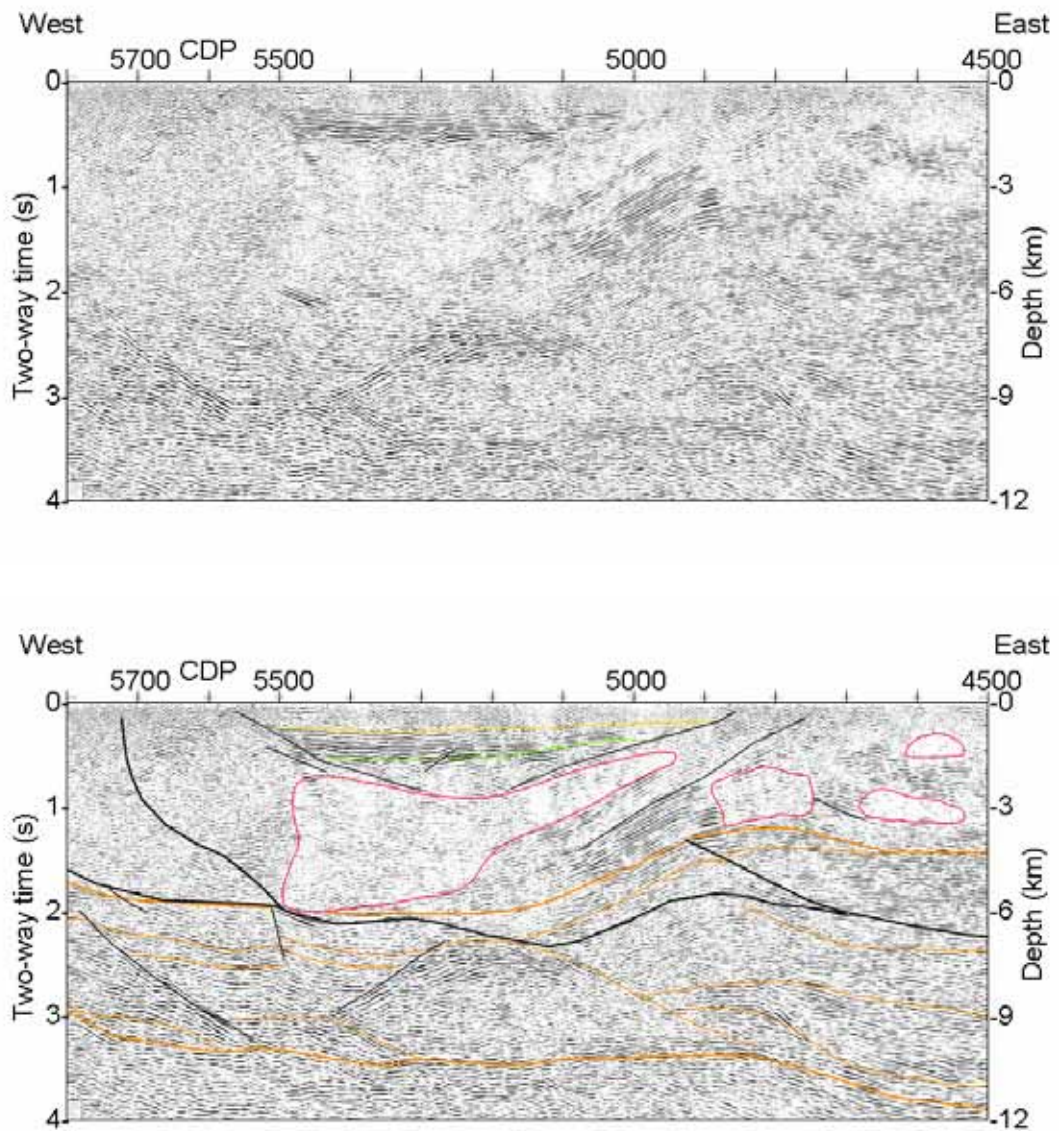


Figure 4-5: Part of upper 4 s TWT of portion of seismic traverse 03GA-CU1 (CDP 4500–5800). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP = 20 m.



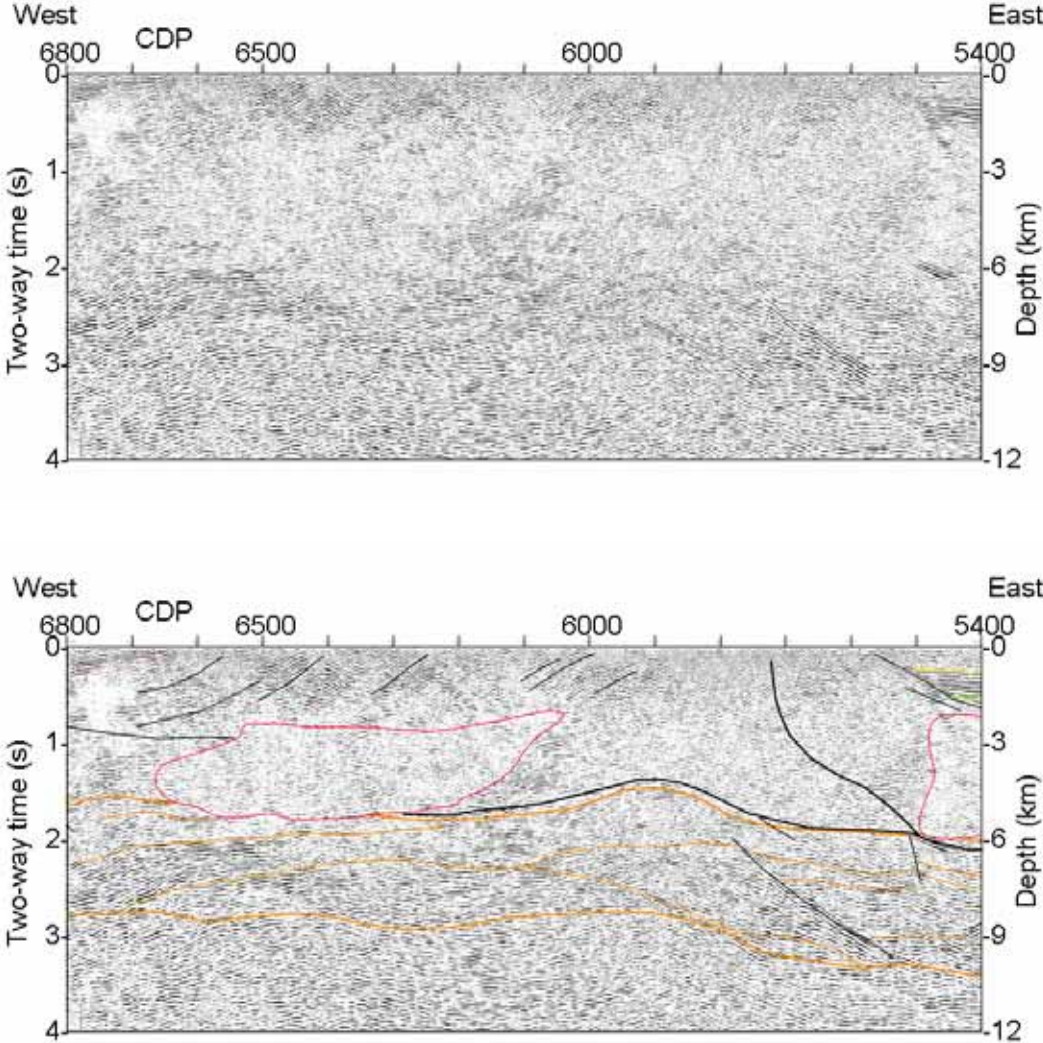


Figure 4-6: Part of upper 4 s TWT of portion of seismic traverse 03GA-CUI (CDP 5400–6800). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP = 20 m.

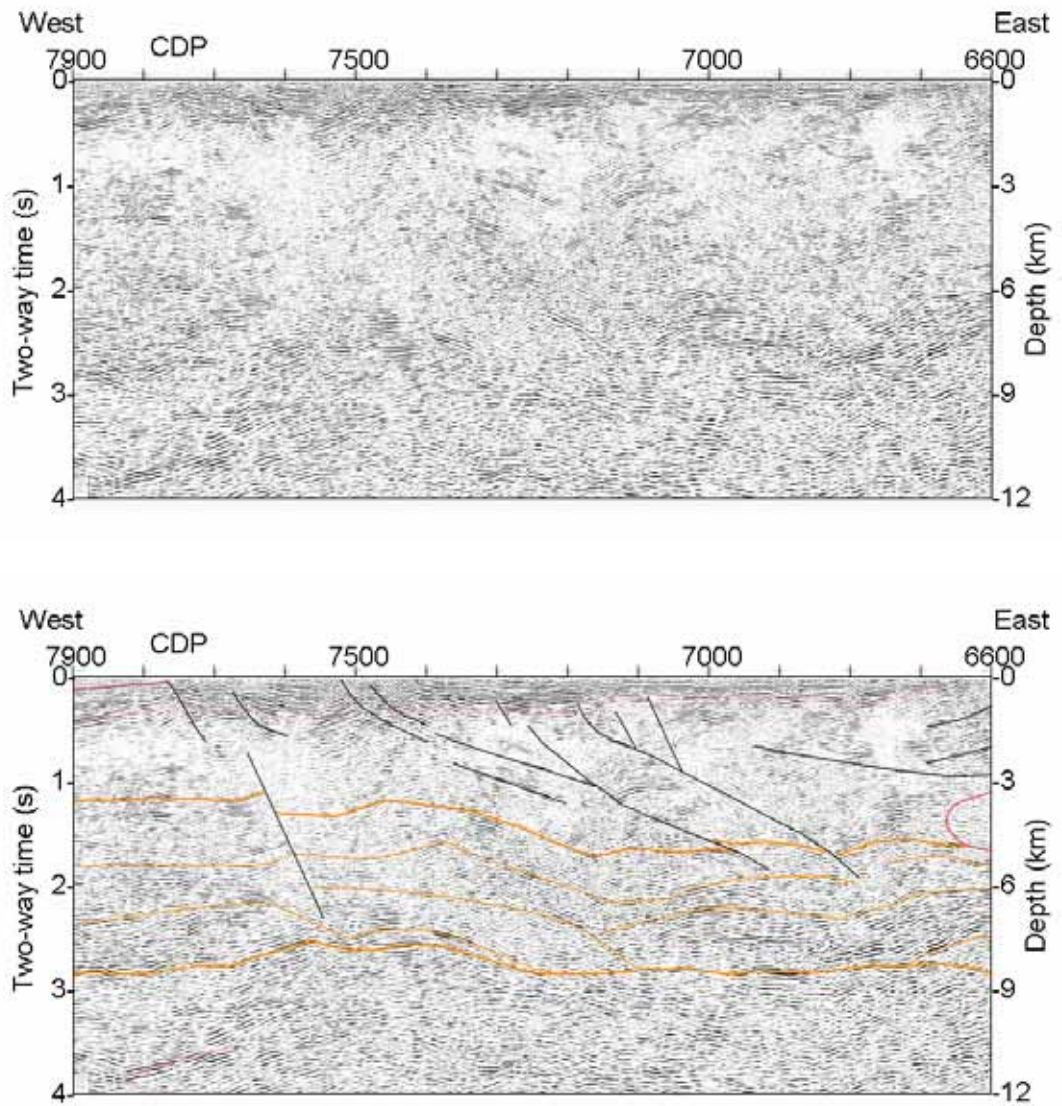


Figure 4-7: Part of upper 4 s TWT of portion of seismic traverse 03GA-CUI (CDP 6600–7900). Colour scheme is given in [Figure 2-4](#). Horizontal scale is based on 1 CDP = 20 m.

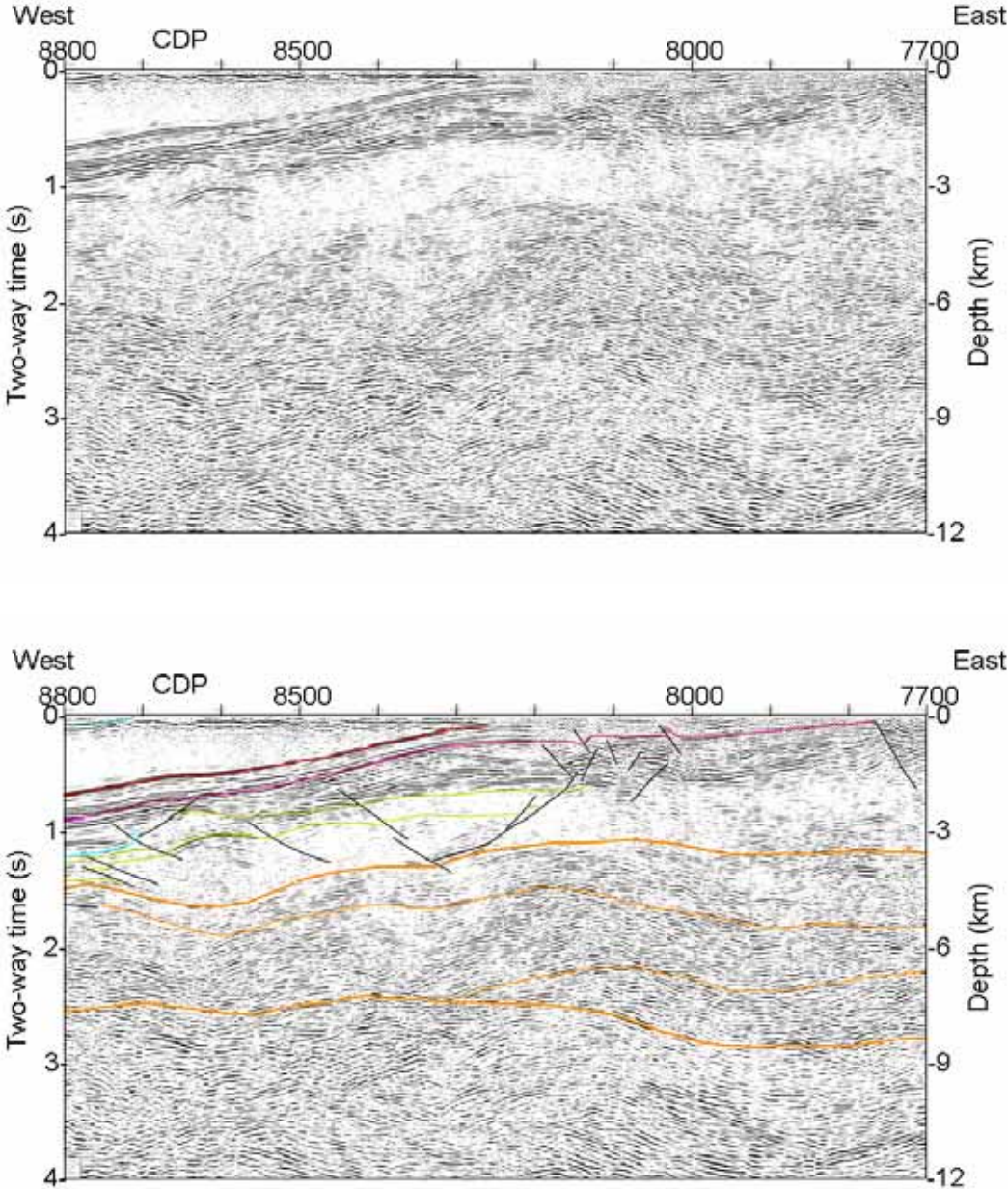


Figure 4-8: Part of upper 4 s TWT of seismic traverse 03GA-CU1 (CDP 7700–8800). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP = 20 m.

0–2 s TWT ZONE

The 0–2 s TWT section forms a discrete seismic reflection package, with several zones of dipping reflections interpreted to be folded and layered Willyama Supergroup rocks.

In the uppermost part of the crust (0–2 s TWT) there are several regions of attenuated or discontinuous seismic reflections. These are interpreted to represent granitic intrusives, or zones of partial melting of rocks of the Willyama Supergroup, or albite metasomatism. This interpretation is consistent with studies that have shown the Ninnerie Supersuite to consist predominantly of crustal derived S-type melts with some input of I-type mantle-derived magmas. The margins of granite bodies in outcrop are either sharp or have extensive migmatite aureoles. To these observations the third dimension is added by the seismic imagery, suggesting that the majority of granite bodies are sill-like.

The base of the 0–2 s TWT zone is interpreted to image the lower most portion of what can be confidently interpreted as greenschist or amphibolite-grade Willyama Supergroup stratigraphy.

CDP 2001–3300 Mulyungarie Anticline

In this region ([Figure 4-2](#)), magnetic Curnamona Group metasediments form the core of a broad anticline, with non-magnetic zones interpreted to be post-tectonic Ninnerie Supersuite granitic intrusions, which are imaged as bland zones in seismic imagery. Shallowly east-dipping reflections and truncations are interpreted as shear zones and thrust faults (black lines). Upper crustal reflectivity trends (orange lines) are interpreted as subhorizontal shear zones or boundaries between zones of different lithological character (e.g. granulite).

CDP 3100–4400 Mooleulooloo Syncline

Reflections follow a geometry that is consistent with the dip of the limbs of the Mooleulooloo Syncline ([Figure 4-3](#)), which contains upper Willyama Supergroup stratigraphy, that is, Strathearn Group. On the western limb, reflections roll over and are truncated by structures interpreted to be thrust faults, which carry the steeper and sometimes overturned western limbs of F3 folds in their hanging walls.

A bland zone in the seismic is interpreted to represent a granite body. Although no granites have been interpreted from potential field data in this part of the seismic transect, large granite plutons are interpreted to the south and the seismic may be imaging these as sills plunging below the seismic line. Alternatively, the bland zone may represent a zone of alteration or metasomatism.

CDP 3800–5100 Kalkaroo Dome

In this region ([Figure 4-4](#)), the Curnamona Seismic transect crosses over the portion of a north-south trending F3 fold called the Kalkaroo Dome. It then follows the strike of as, but west-southwest trending anticline, and then at CDP 5000 it turns northwesterly to be orthogonal to Willyama Supergroup metasediments.

A series of truncations in the reflections are interpreted as a shear zone almost reaching the surface at CDP 4260 at the western side of the Kalkaroo Dome ([Figure 4-3](#) and [Figure 4-9](#)). This geometry is consistent with field observation that western limbs of F3 west- to northwest-verging anticlines are commonly sheared.



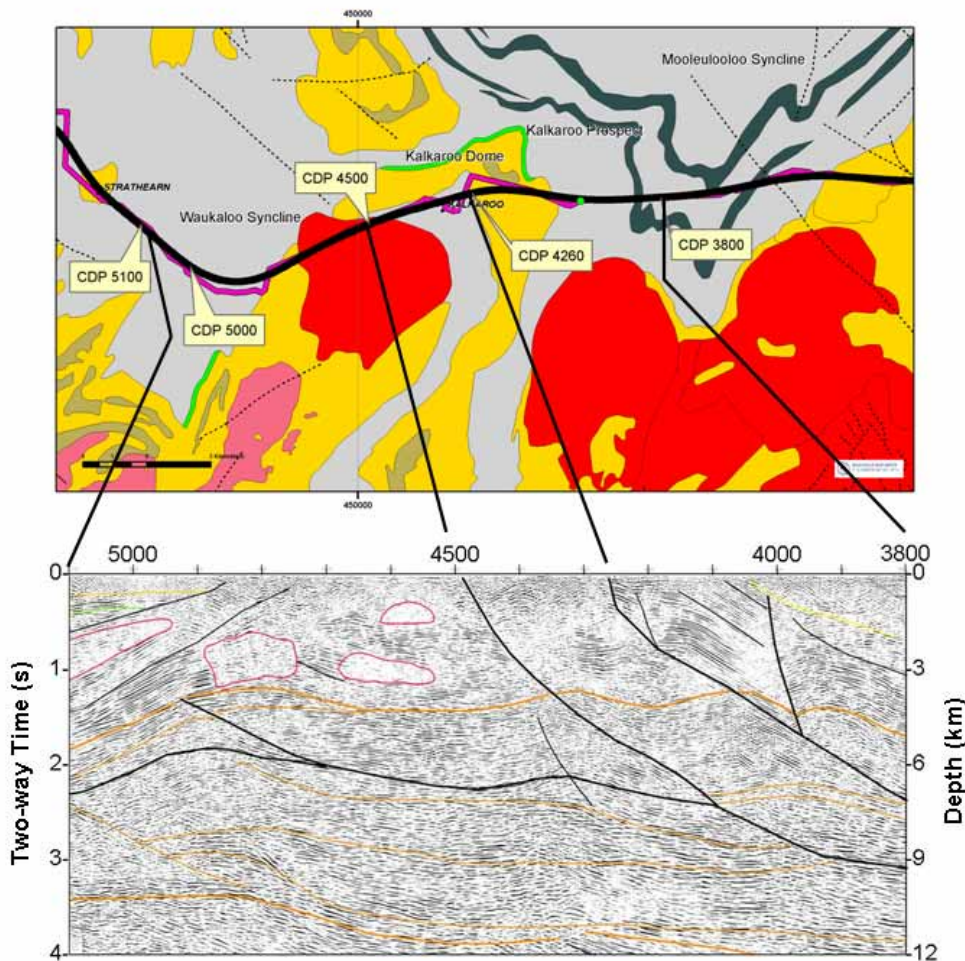


Figure 4-9: Portion of the Curnamona Seismic transect in relation to various structural and lithological features of the Curnamona Solid Geology in the region of the Kalkaroo Dome. Horizontal scale is based on 1 CDP = 20 m.

A large shear zone, interpreted at CDP 4500 and recognised as a northwest trending structure in magnetic data, extends to approximately 7 km depth, where it intersects the F3 fold south of the Kalkaroo Dome (Figure 4-9). Both the CDP 4260 structure, which is adjacent to the Kalkaroo Cu-Au-Mo deposit, and the CDP 4500 structure extend to deep crustal levels, and are potential pathways for mineralising fluids. Bland zones next to the interpreted shear zones represent possible alteration zones.

Several bland zones are imaged at 1 and 3 km depth between CDPs 4500 and 4900 and are interpreted as granite. Granite is interpreted from gravity data in this part of the seismic transect.

CDP 4500–5800 Waukaloo Syncline

Reflections dip to the west, which is consistent with the interpreted dip of metasediments that form a broad syncline cored by upper Willyama Supergroup stratigraphy in this region (Figure 4-5).

Between CDP 4900 and 5500 there is a zone of relatively flat-lying seismic reflections. These reflections are interpreted to represent Neoproterozoic strata within a small fault-bounded basin. This may be an embayment of the main Neoproterozoic to Cambrian basin to the north and west, although its relationships are uncertain. A large bland zone below the Neoproterozoic basin corresponds to a large regional gravity anomaly and is interpreted to be a zone of non-reflective material or a zone of alteration.

CDP 5400–6800 Strathearn

The airborne magnetic interpretation of this section shows a series of anticlines cored by lower Willyama Supergroup, with upper Willyama Supergroup in the intervening synclines. There is some support for this in the seismic (Figure 4-6), though there are numerous reflection truncations that dip to the west, opposite to the general dip of structures along the transect.

A bland zone from CDP 6000 to 6700 is interpreted as granite, although there are no interpreted granites from potential field data in this region. This zone may instead represent metasomatic alteration.

CDP 6600–7900 and CDP 7700–8800 Moorowie Syncline

CDP 6600 is the eastern margin of the Moorowie Syncline (Figures 4-7 and 4-8), a relatively open fold of little-deformed Neoproterozoic and Cambrian cover unconformably overlain by Mesozoic and Cainozoic sediments. These strata unconformably overlie Willyama Supergroup rocks, which contain numerous structures, some of which transgress the Neoproterozoic unconformity. These structures could have been generated in basement rocks during the Olarian Orogeny and subsequently reactivated during Cambro-Ordovician Delamerian Orogeny contraction.

Gravity data for the Curnamona Province reveal regional lows that have been interpreted as granite plutons, an interpretation supported by the seismic data, where amorphous seismic zones below high reflection zones correspond with gravity lows. The most striking example of this is at the western margin of the Curnamona Province, where the largest of the gravity lows corresponds with a seismically attenuated zone that is approximately 0.5 s TWT thick and is approximately 30 km wide (Figure 4-10, CDP 7200–8500). Some reflections within this amorphous zone are preserved and could represent remnants of Willyama Supergroup, exemplified by the Crockers Well Suite pluton to the south, where large enclaves of Willyama Supergroup metasediments are often preserved, but with varying degree of ingestion.

2–6 S TWT ZONE

The 2–6 s TWT zone (Figure 4-1) forms another discrete package of seismic character of short strong reflections that is of unknown composition. This zone thins from the east where it is thickest (1.8–5 s TWT) to the west (1–3 s TWT) where it becomes less definable due to greater attenuation of seismic energy by a thick (~ 9 km), reflective, flat-lying sedimentary sub-basin.

Within this seismic package, zones of higher amplitude reflections are interpreted to represent Willyama Supergroup granulites, which, in the Broken Hill region, have been exposed at the surface by the Mund Mundi Fault. This package is interpreted to retain little or no melt component, which now resides in the upper 0–2 s TWT zone.



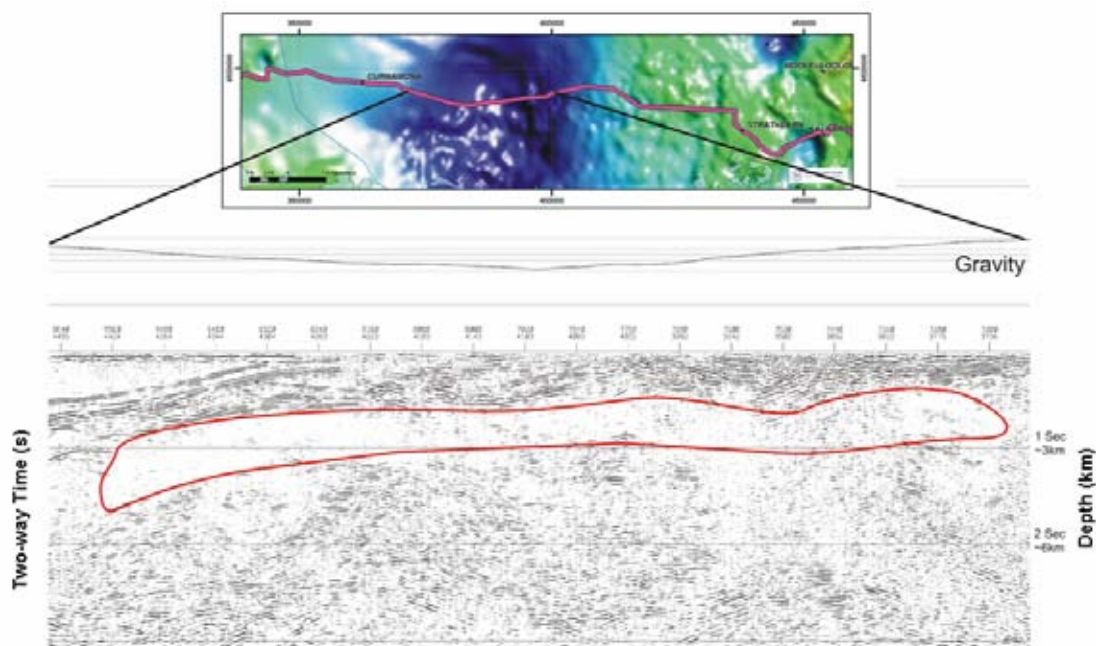


Figure 4-10: 0–3 s TWT of 03GA-CU1 with position of inferred low density body (red) corresponding to regional gravity data (top). Horizontal scale is based on 1 CDP = 20 m.

Within the 2–6 s TWT zone, shallowly east-dipping breaks in seismic reflections, that steepen on their upper western ends, are interpreted to represent faults or shear zones. These display connectivity to similar structures in the 0–2 s TWT zone, indicating a shared tectonic evolution. Based on this structural connection the 2–6 s TWT zone is interpreted to be either a structural repeat of Willyama Supergroup or granulite basement to the Willyama Supergroup that is of similar composition to the 0–2 s TWT zone. The evidence for similar composition comes from the Broken Hill Domain where syn-Willyama S-type granites were generated at depth but have a geochemical signature similar to the Willyama Supergroup rocks.

Below the 2–6 s TWT zone are two more distinctive seismic reflection packages at 6–8 s TWT and 8–13 s TWT. Within these zones, seismic reflections are dominantly horizontal, with some large-scale scalloping in the 8 – 13 s TWT zone. Flat-lying seismic reflections at the base of the 2–6 and 6–8 s zones are possible detachments, which have allowed transport and ramping within the basement - resulting in significant crustal thickening during basin inversion in the later stages of Orlarian contraction.

Interpretation of reflections from the east to west for the 6–8 and 8–13 s TWT zones becomes progressively more difficult, as there is an extensive zone characterised by poor reflection extending laterally from CDP 6000 to 7000, and vertically from the mantle, though the lower and middle crust, and including the 2–6 s TWT zone (CDP 6000–7000). The limited reflectivity could result from reduced acoustic impedance contrasts due to partial melting or a zone of pervasive metasomatism, where high fluid flow has homogeneously altered a large part of the crust. It is interesting to note that similar bland zones have been imaged on seismic sections proximal to the Olympic Dam Iron-Oxide Copper Gold and Kalgoorlie Gold deposits.



From CDP 8000 to 10000, an approximately 9 km deep basin, containing relatively little deformed Neoproterozoic, Cambrian, Mesozoic, Tertiary and Quaternary strata, passes westward into folded and faulted Neoproterozoic and Cambrian very low-grade metasedimentary rocks of the Adelaide Geosyncline. Because of its blanketing effect, it is unclear if the seismic reflection packages (i.e. 0–2 and 2–6 s TWT zones) continue from the east below this basin.

Importantly, a large, shallowly east-dipping structure is interpreted from below Adelaide Geosyncline metasedimentary rocks (CDP 10300) to continue to the Moho (CDP 8000). This structure could represent the boundary between two different crustal entities and may mark the western limit of Willyama-like rocks.

WILLYAMA STRUCTURE

The overall structural character shown in the seismic section is generally flat-lying, but with some shallowly east-dipping structures. The latter steepen on their upper western ends and are generally restricted to the upper crust (i.e. 0–6 s TWT). The dip and orientation of these structures is consistent with other seismically observed faults such as the Mundi Mundi Fault imaged by the Broken Hill Seismic Transect.

Within the 0–2 s TWT and also the 2–6 s zone, there are sharp changes in the orientation of reflections, particularly in the presence of interpreted ramp anticlines, which indicate that the east dipping structures represent reverse faults and thrusts. The thrusts appear to sole onto a subhorizontal reflective band at approximately 3 s TWT for the far eastern section of 03GA-CU1. Also, there are many reflections parallel to, and above, the faults, and these are interpreted to represent hanging-wall flats.

Broad open Olarian F3 folds observed in potential field data are supported by the seismic reflection data, particularly in the Mulyungarie region. Thrust faults observed in the 0–6 s TWT zone are interpreted to have developed in the overturned western limbs of F3 hanging-wall anticlines and extend to lower crustal levels. These thrust faults could be significant in controlling mineralisation by providing pathways to higher crustal levels for fluids that were generated during the Olarian Orogeny. This concept is supported by observation in outcrop where F3 folds cores are commonly the loci of alkali feldspar alteration and brecciation.

CONCLUSIONS

The Curnamona Deep Crustal Seismic line has provided significant insights into the crustal architecture of the Curnamona Province. East-dipping structures and seismic packages observed in these data are complementary to similar features observed in existing seismic data (1996 Broken Hill Seismic Line). Similarly, various geological features interpreted from potential field data have been complemented and confirmed. The recognition of a major discontinuity that extends to the Moho below Adelaidean metasediments of the Moorowie Basin is significant because it possibly separates two different crustal entities and thus has implications for the relationship of the Curnamona Province to other Paleo- to Mesoproterozoic terranes.

Evidence for deep penetration of late stage Olarian, F3 fold-related faults has important metallogenic implications.

Reprocessing of the 1996 Broken Hill Seismic line and comparison to 03GA-CU1 is a priority, as it will allow for a better-constrained interpretation of structures imaged in the far eastern section.



Extension of 03GA-CU1 across the Adelaide Geosyncline to the eastern margin of the Gawler Craton is recommended, as it will provide significant insight into the connection between the Curnamona Province and Gawler Craton. Similarly, north-south transects across the southwestern margin of the Moorowie Syncline and along the Benagerie Ridge are recommended as they would provide significant information on the crustal architecture of the Curnamona Province, especially of the volcanic-dominated, IOCG prospective, central Curnamona Domain

