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# The 2003-2004 Curnamona Province Seismic Survey

## Workshop Notes

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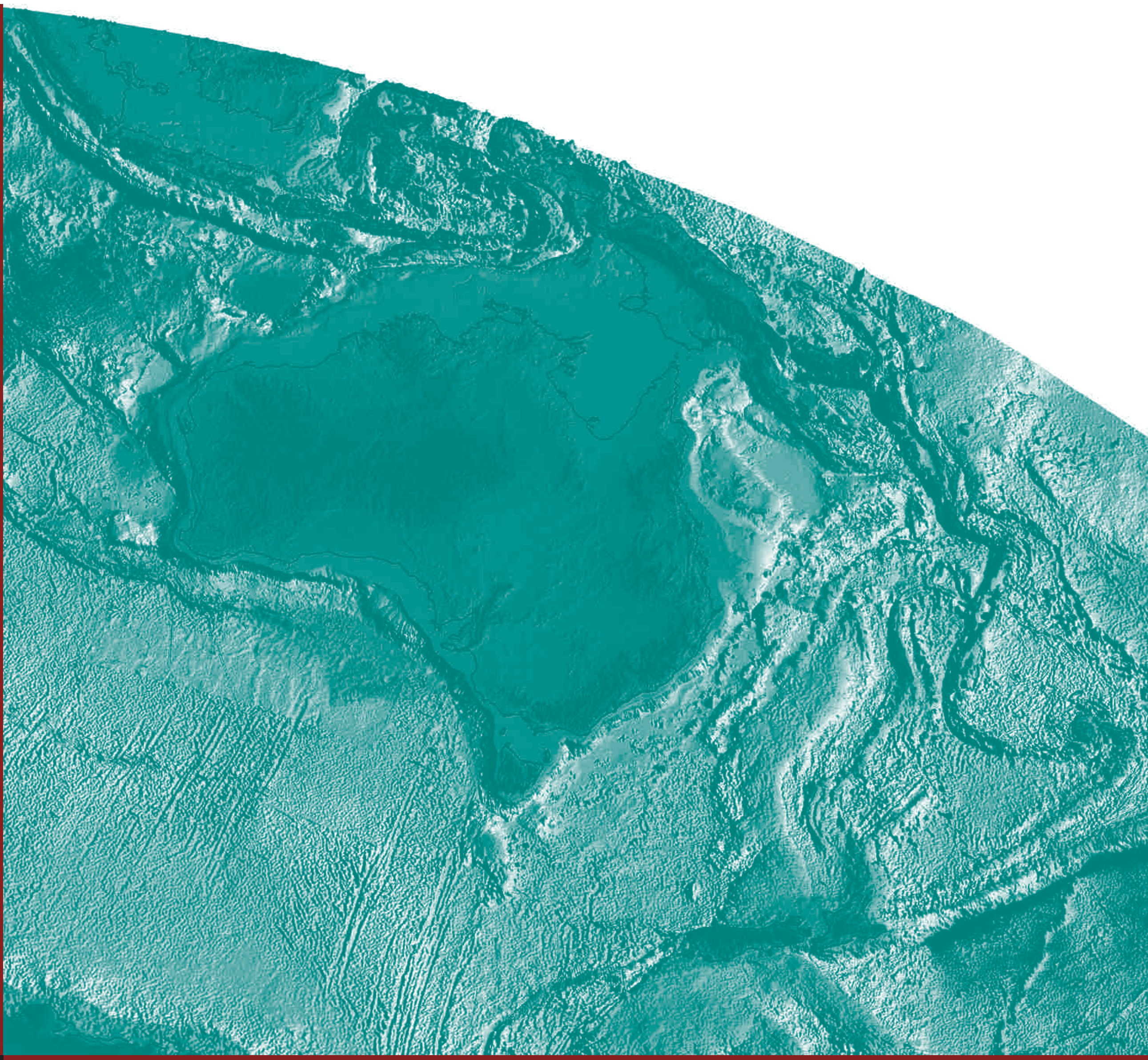

SPATIAL INFORMATION FOR THE NATION

# THE 2003-2004 CURNAMONA PROVINCE SEISMIC SURVEY: WORKSHOP NOTES

GEOSCIENCE AUSTRALIA
RECORD 2006/12

by

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This Seismic Workshop was held at the PIRSA Conference Room, Adelaide, South Australia on 30 November 2005.

# Contents

# 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).

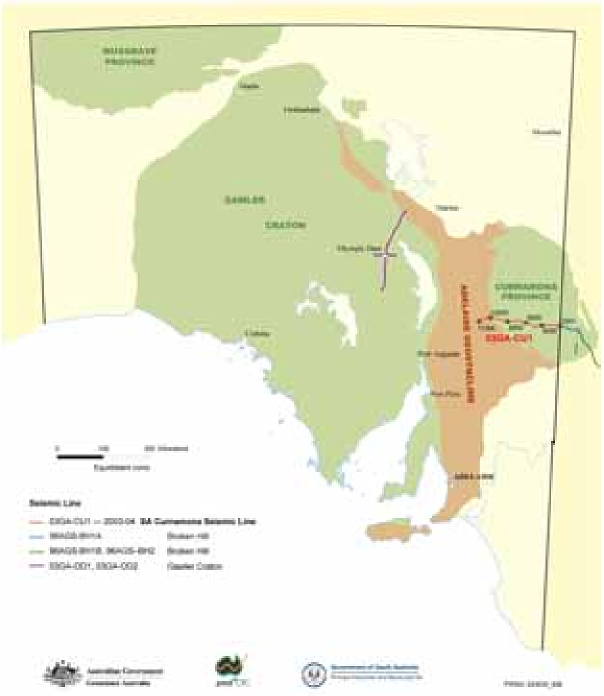


*Figure 1-1: South Australian Geological Provinces with deep crustal seismic lines in the Curnamona region.*

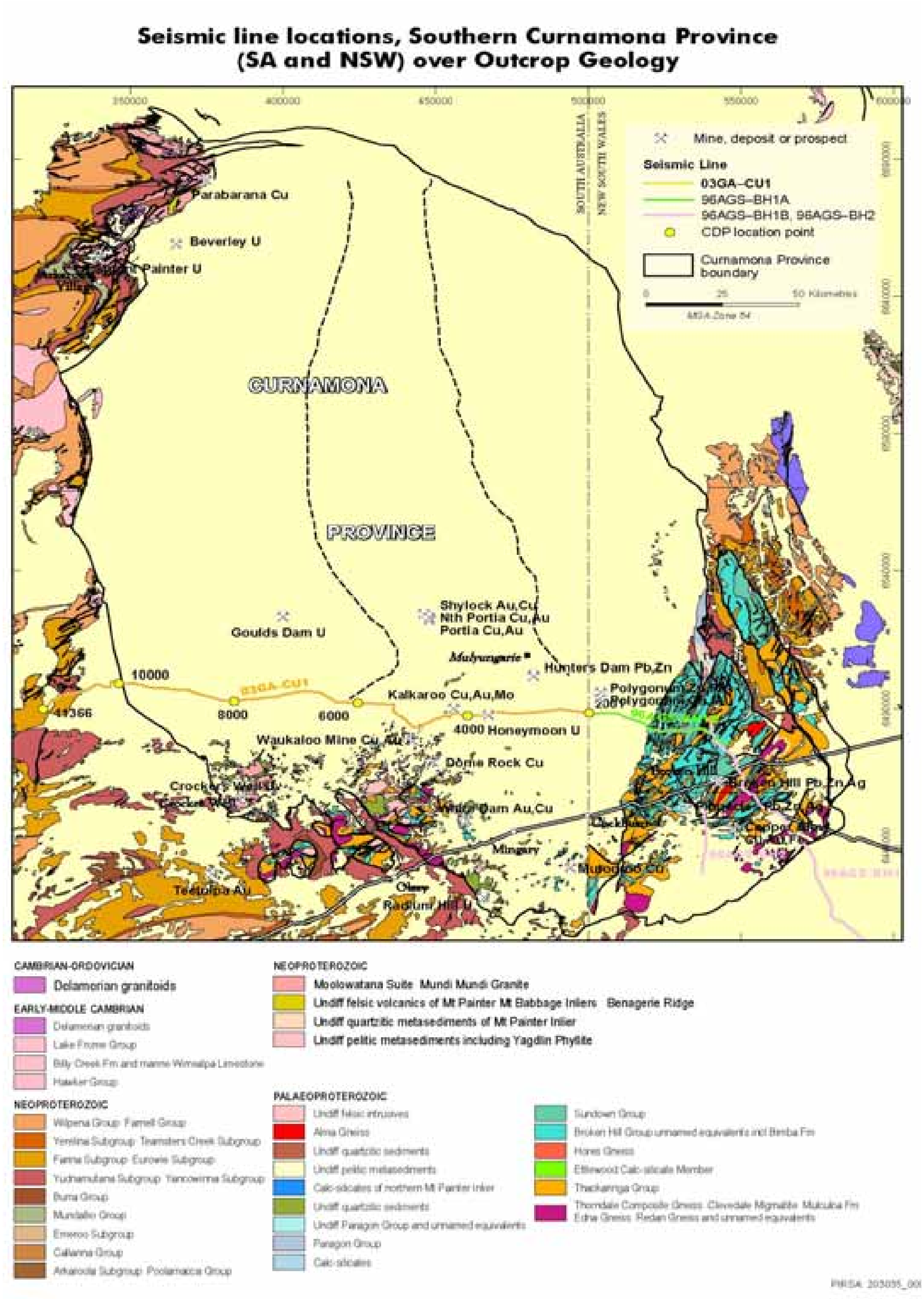


***Figure 1-2:*** *Outcrop Geology of the Curnamona Province and location of the seismic lines.*

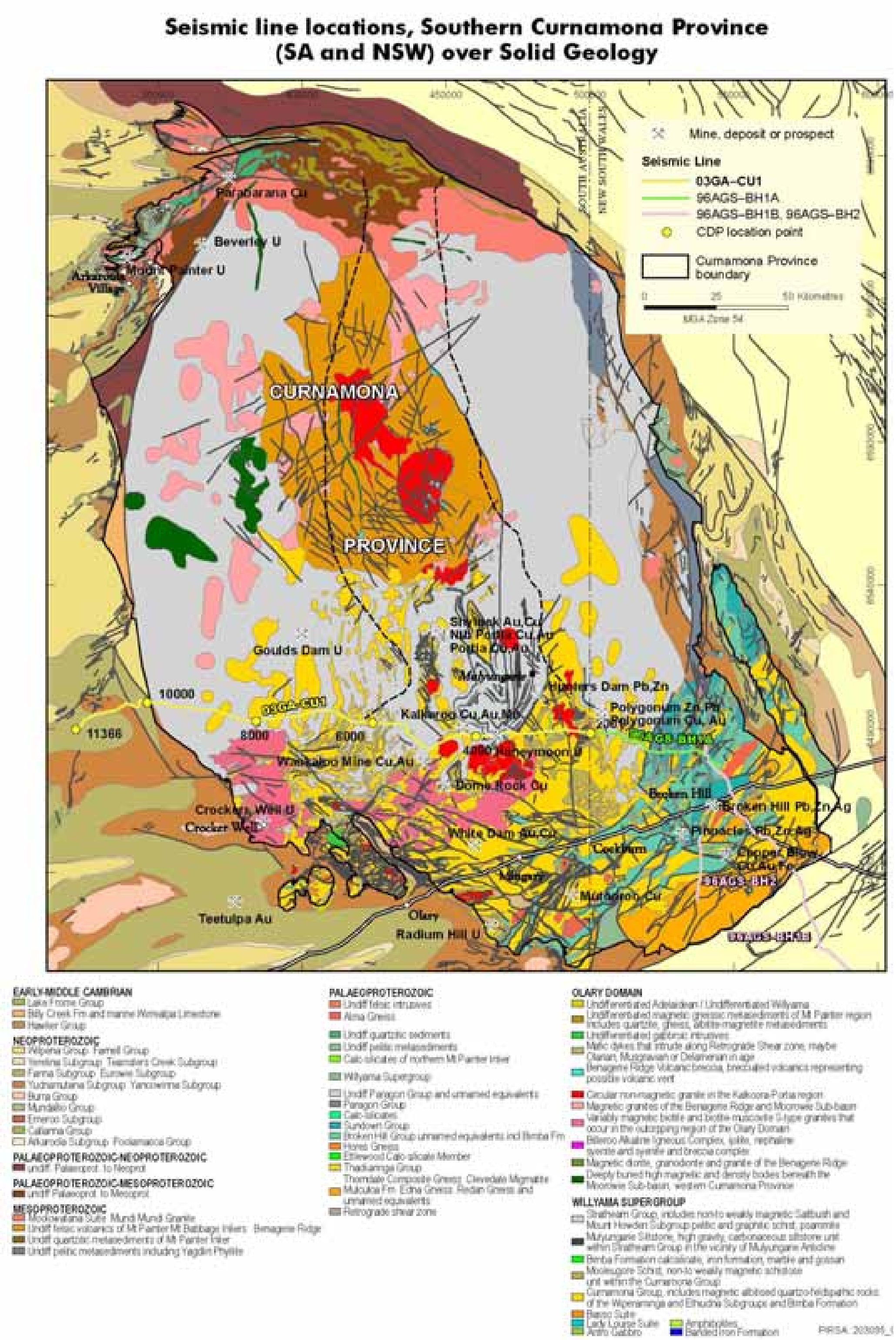


***Figure 1-3:*** *Interpreted Solid Geology of the Curnamona Province on locations of the deep seismic lines.*

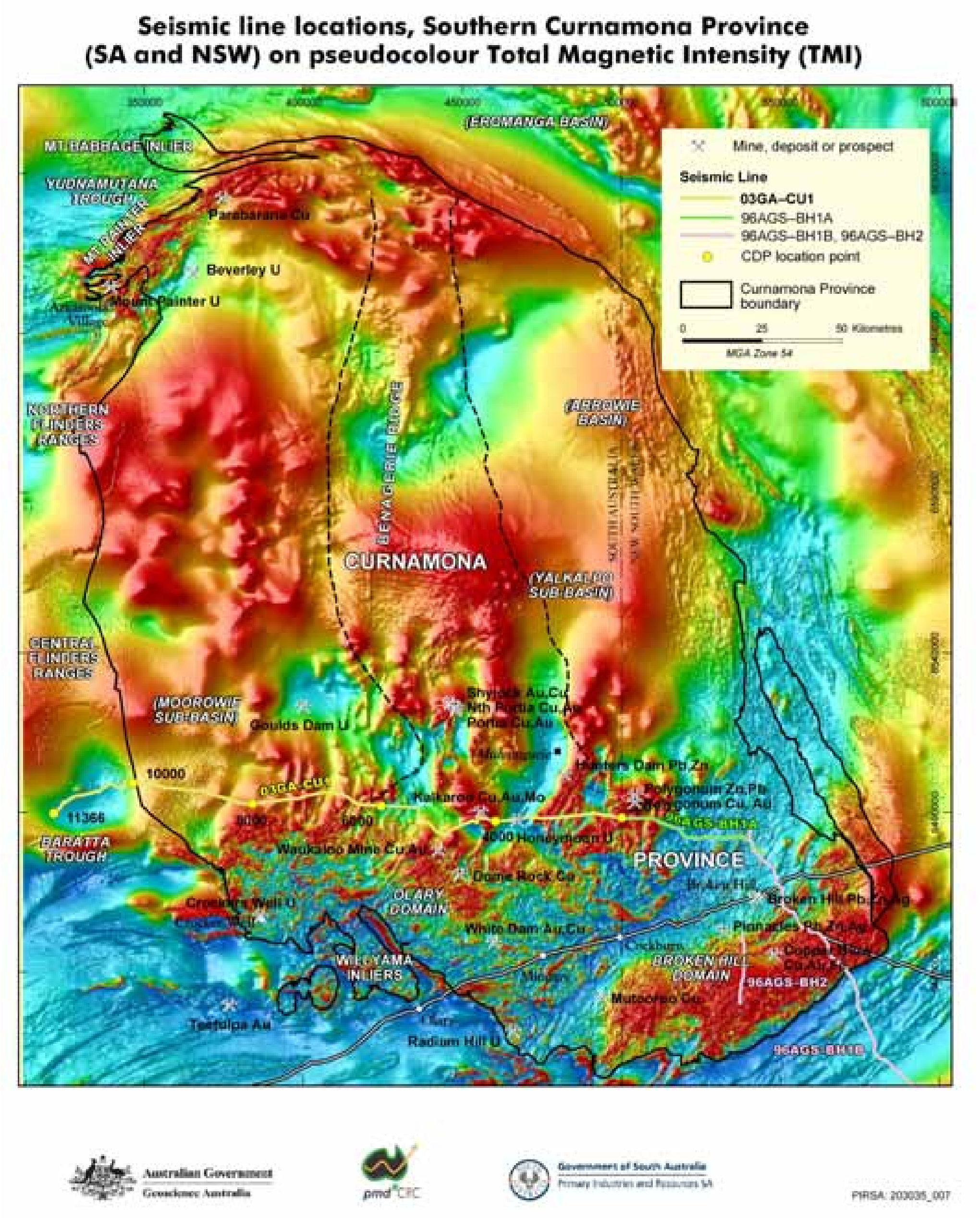


**Figure 1-4:** *Magnetic (TMI) Image of the Curnamona Province and locations of the deep seismic lines.*

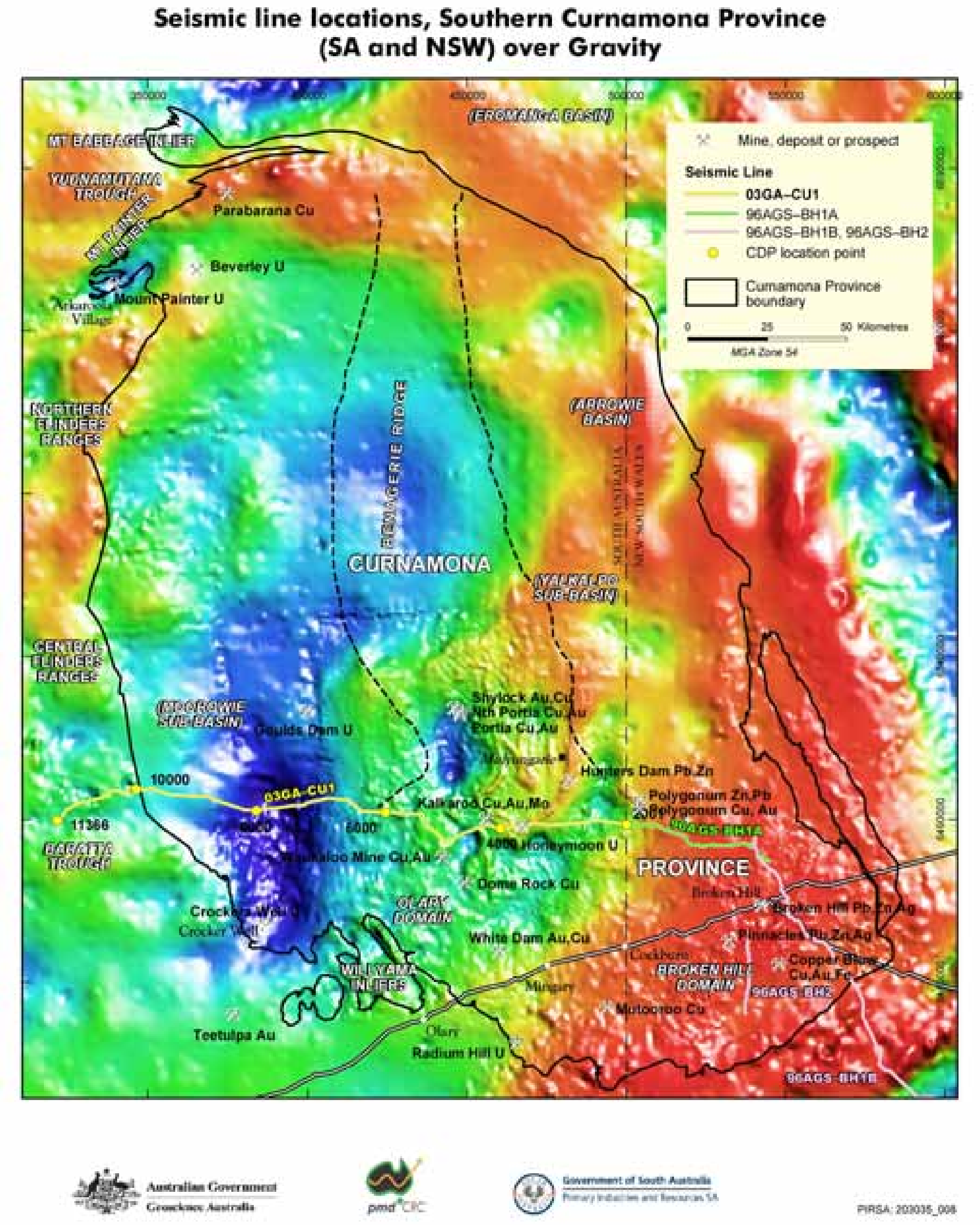
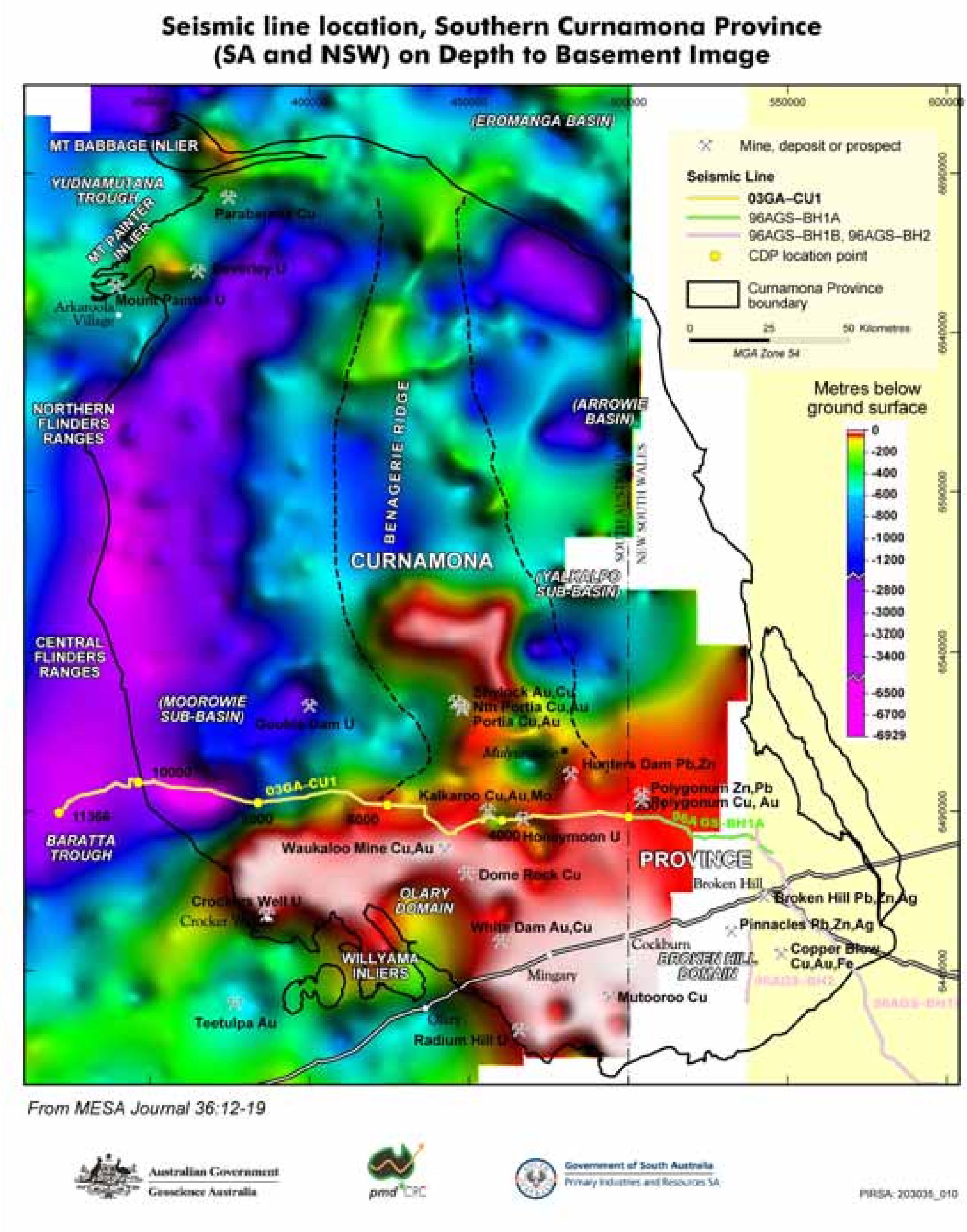


**Figure 1-5:** *Gravity Image of the Curnamona Province and locations of the deep seismic lines.*



From MESA Journal 36:12-19

***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.

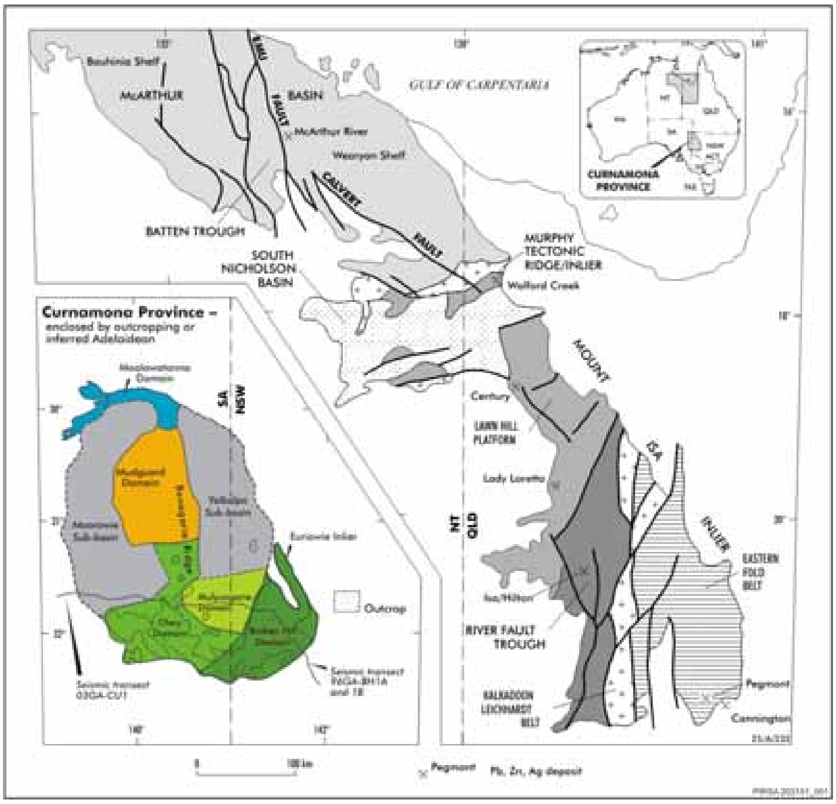


*Figure 2-1: Location of the Curnamona Province with respect to the Northern Australian Pb-Zn Belt (inset), and geological domains of the Curnamona Province.*

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 km$^2$, 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.

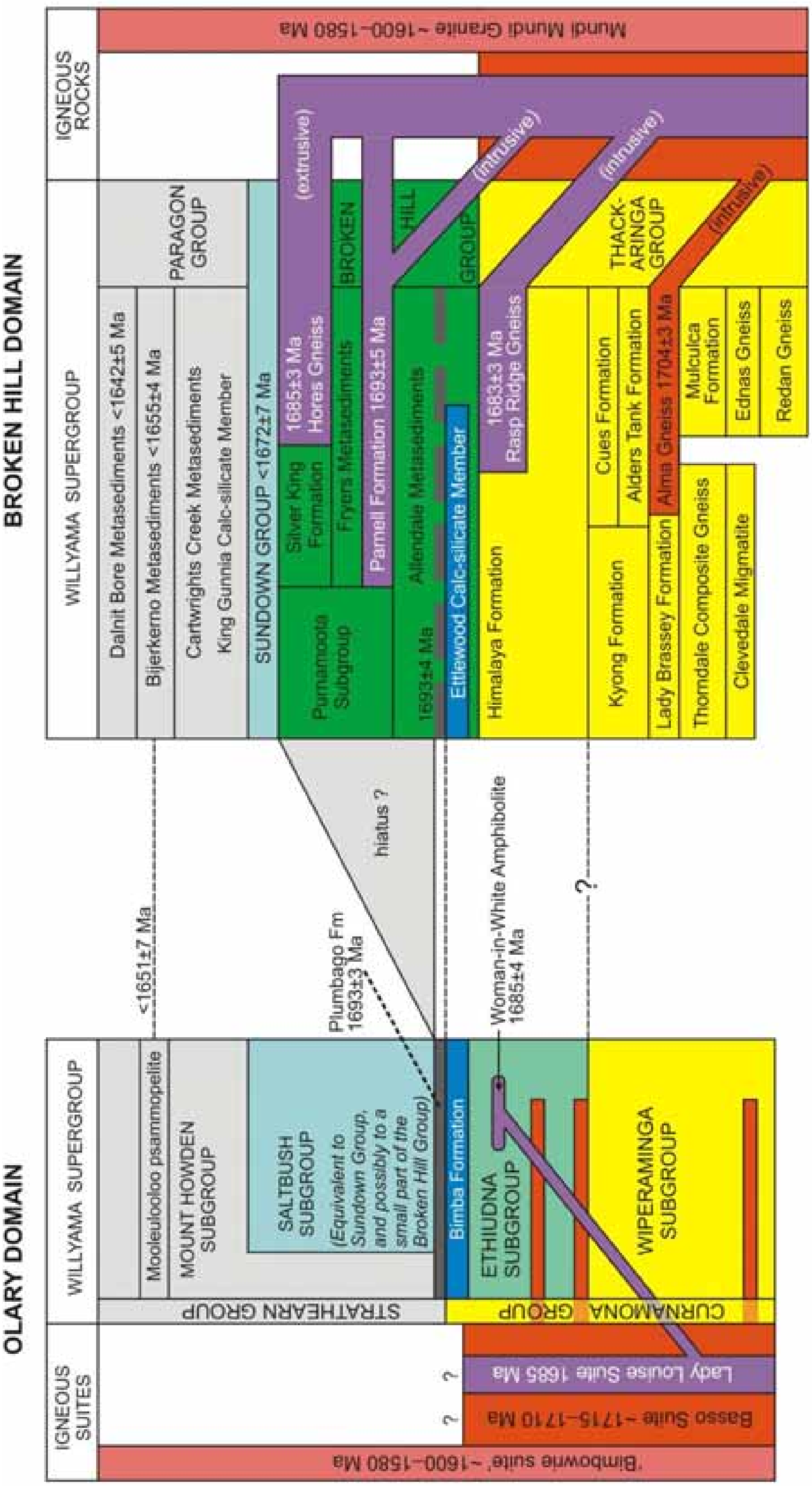


**Figure 2-2:** *Lithostratigraphy of the Willyama Supergroup, modified from Conor (2004). It is now known that the Thackaringa Group is missing from the Olary Domain, and the Ethiudna Subgroup and Redan Gneiss are possible equivalents of each other.*

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 migmatised.

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 Crockers 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.

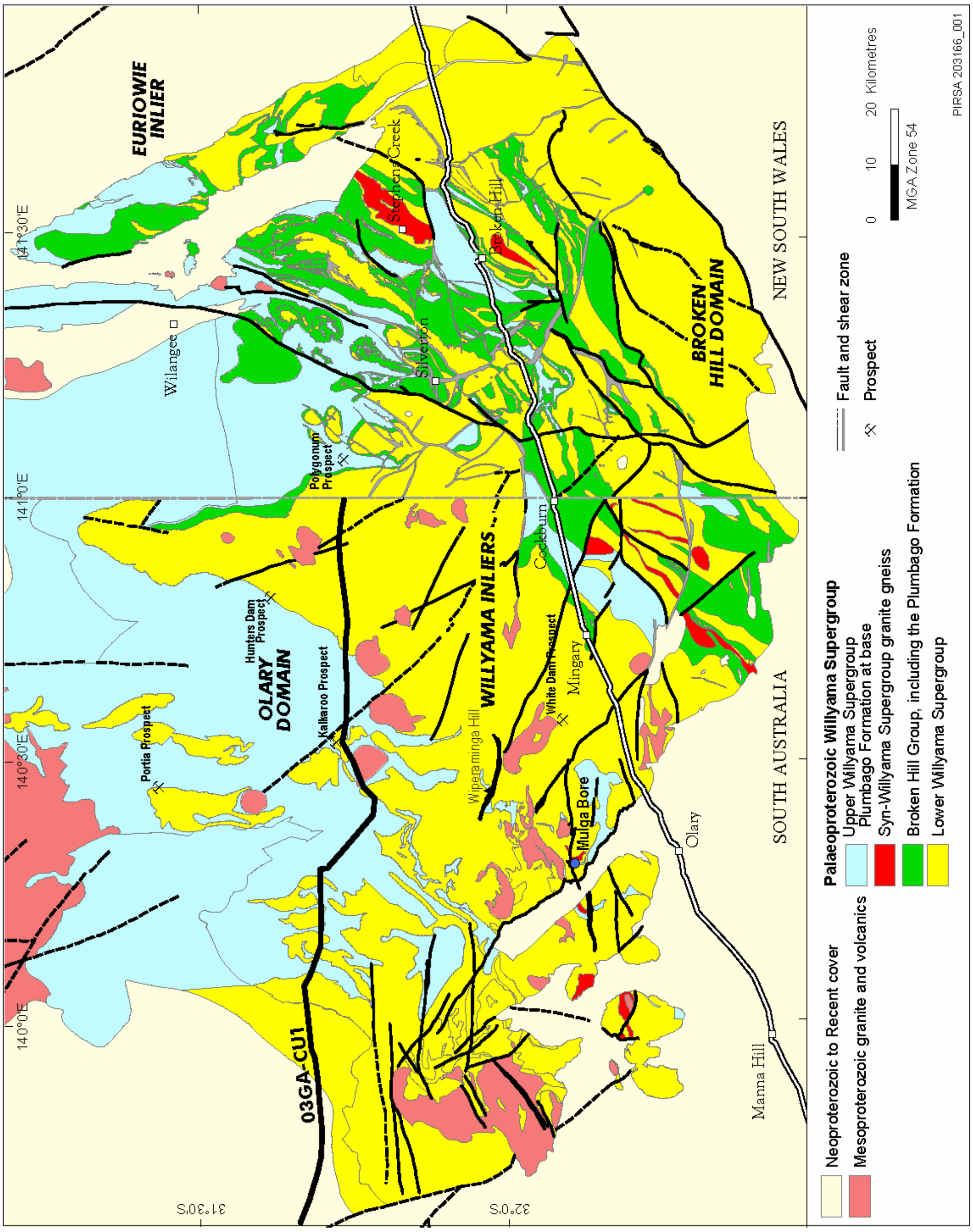
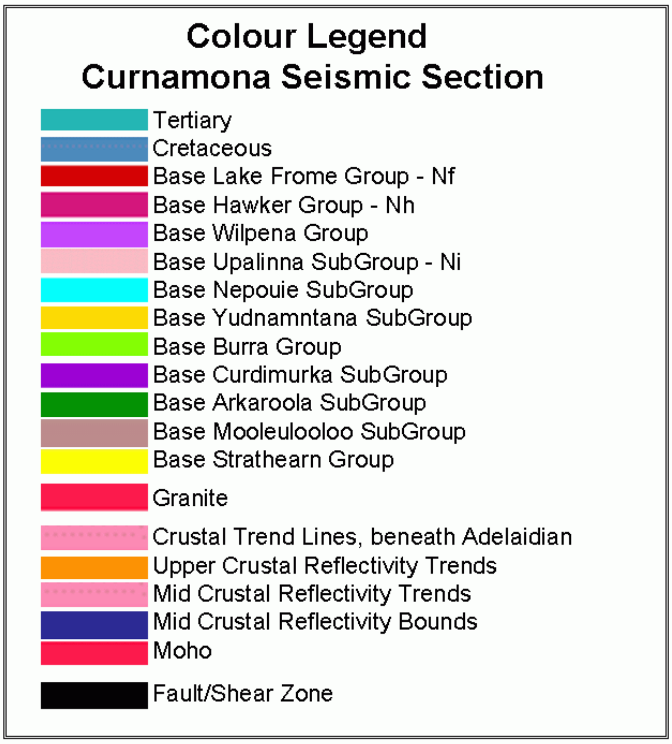


***Figure 2-3:*** *Southern Curnamona Province showing the location of major Cu-Au prospects near the Curnamona Deep Seismic Transect (03GA-CU1)*

## 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.



Colour Legend
Curnamona Seismic Section

Tertiary
Cretaceous
Base Lake Frome Group - Nf
Base Hawker Group - Nh
Base Wilpena Group
Base Upalinna SubGroup - Ni
Base Nepouie SubGroup
Base Yudnamntana SubGroup
Base Burra Group
Base Curdimurka SubGroup
Base Arkaroola SubGroup
Base Mooleulooloo SubGroup
Base Strathearn Group

Granite

Crustal Trend Lines, beneath Adelaidian
Upper Crustal Reflectivity Trends
Mid Crustal Reflectivity Trends
Mid Crustal Reflectivity Bounds
Moho

Fault/Shear Zone

***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).

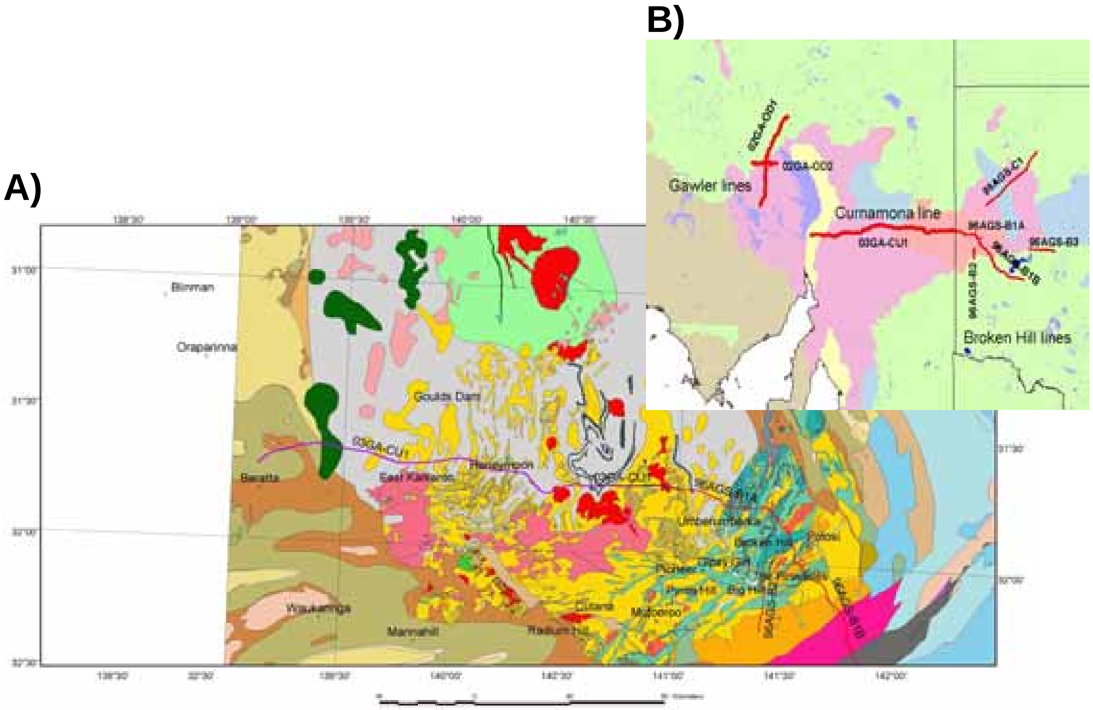

**Figure 3-1:** *Location map: A) Geological Map - Curnamona traverse 03GA-CU1 in purple, Broken Hill traverse 96AGS-B1A/B1B in red, B) Inset: Curnamona, Broken Hill and Gawler seismic traverses.*

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 SEGY 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.

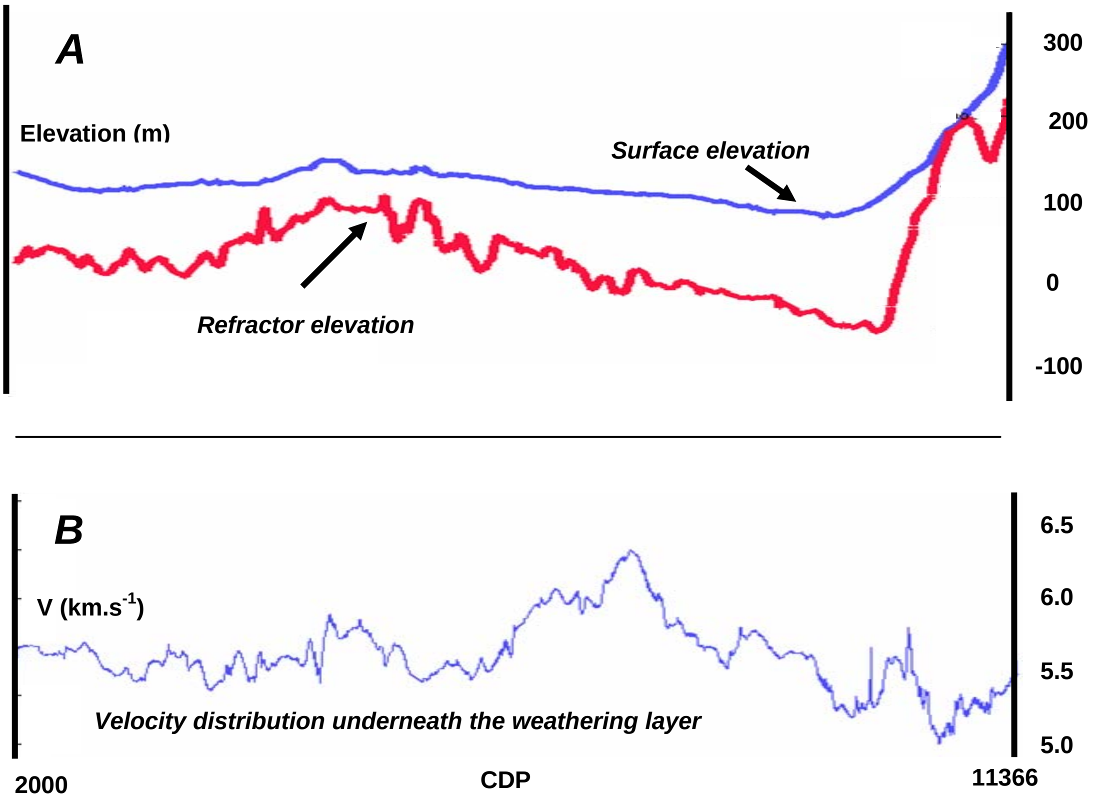

***Figure 3-2:*** *A) Results of refraction statics calculation for line 03GA-CU1. Surface and refractor elevations in metres. B) Velocity profile in km.s$^{-1}$.*

## 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 5.7-6.0 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.

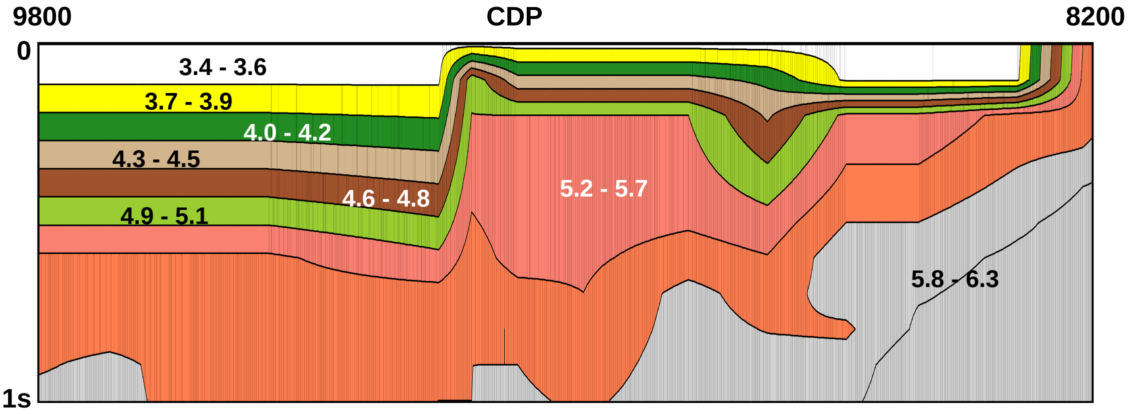

***Figure 3-3:*** *Fragment of stacking velocity display for the sedimentary basin in the western part of Curnamona traverse 03GA-CU01, CDPs range from 8200 to 9800 (~32 km), velocity in km.s$^{-1}$.*

## 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.

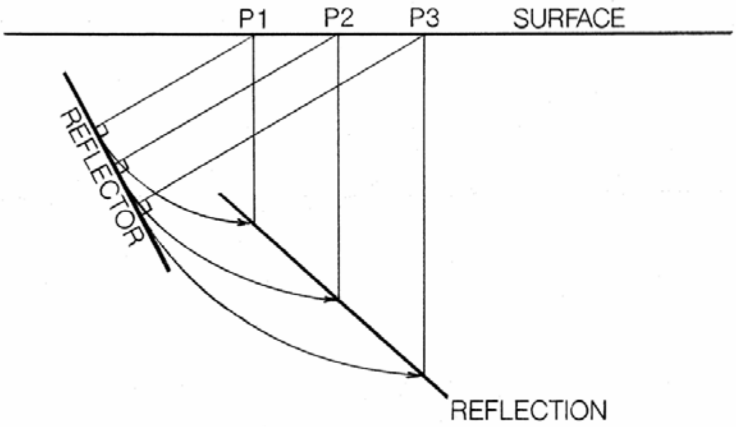

***Figure 3-4.*** *Scheme for the migration of seismic data. Arrows show how each point of the reflector is being misplaced in the non-migrated data.*

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 ($\lambda$). 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 ¼ λ (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 ½ λ (75 m) can separate reflections be interpreted to resolve both the top and the bottom of the layer.

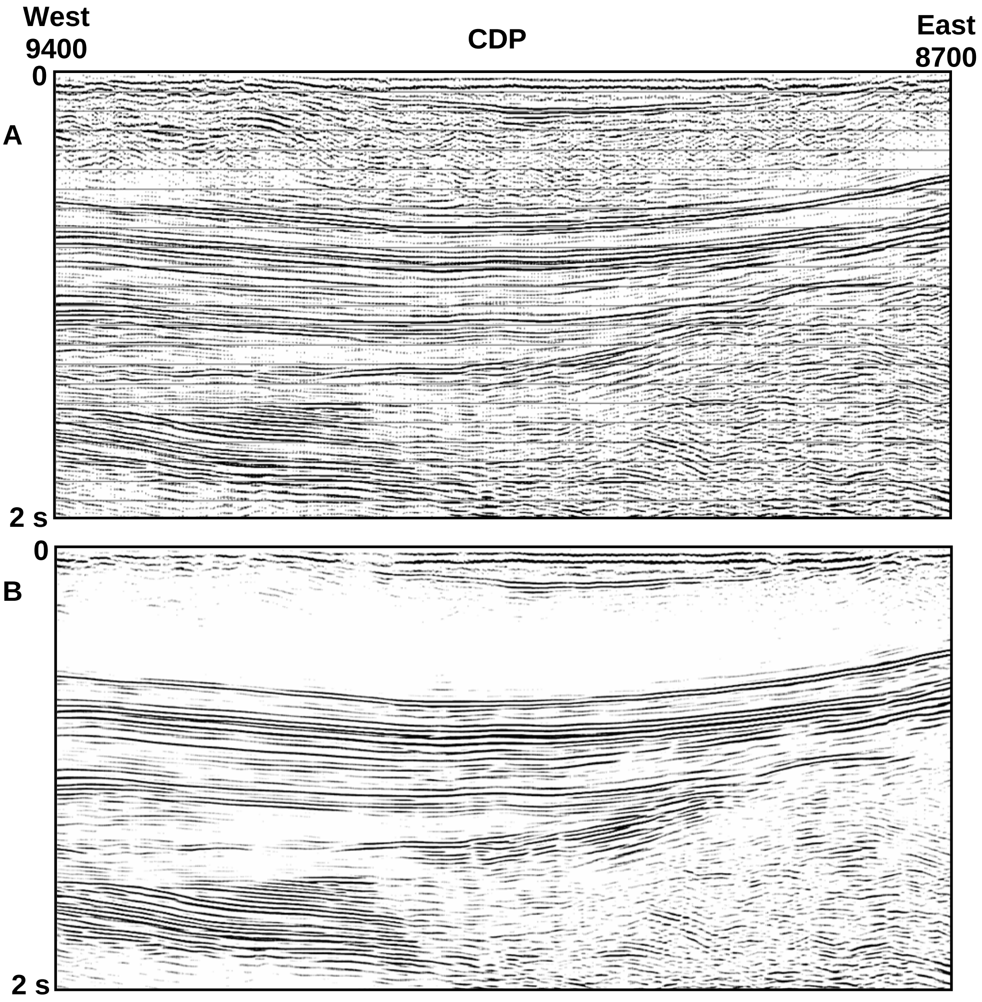

***Figure 3-5.*** *Fragment of the Neoproterozoic basin with different amplitude scalar applied. A) Narrow time gates – 200 ms window. B). Broad time gates – 1500 ms window.*

## 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.

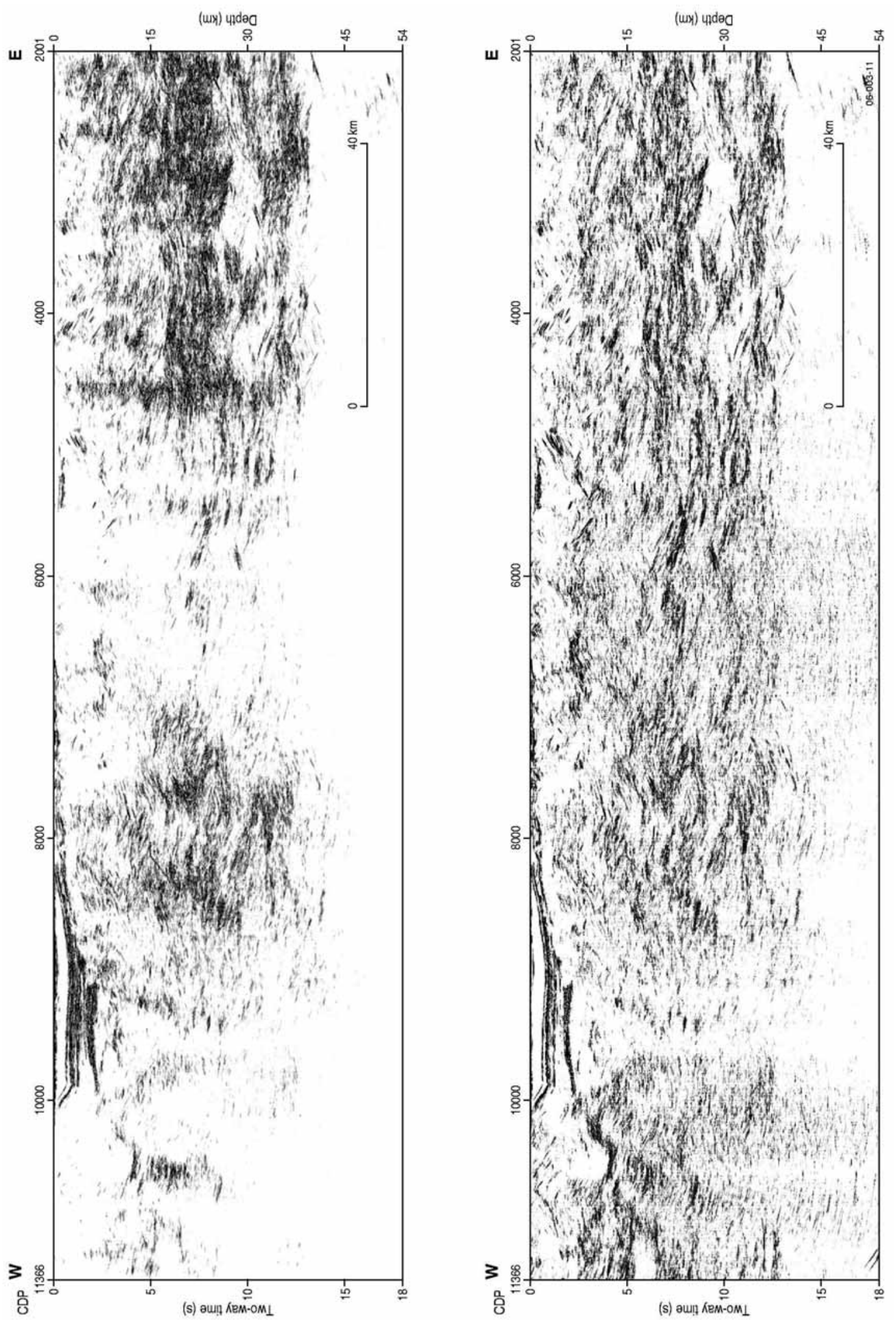

***Figure 3-6.*** *Curnamona migrated seismic section (~197 km in length) after semblance filtering. A) Section with no amplitude scaling applied, and B) section with amplitude scaling applied (broad time gates – 5000 msec).*

## 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.

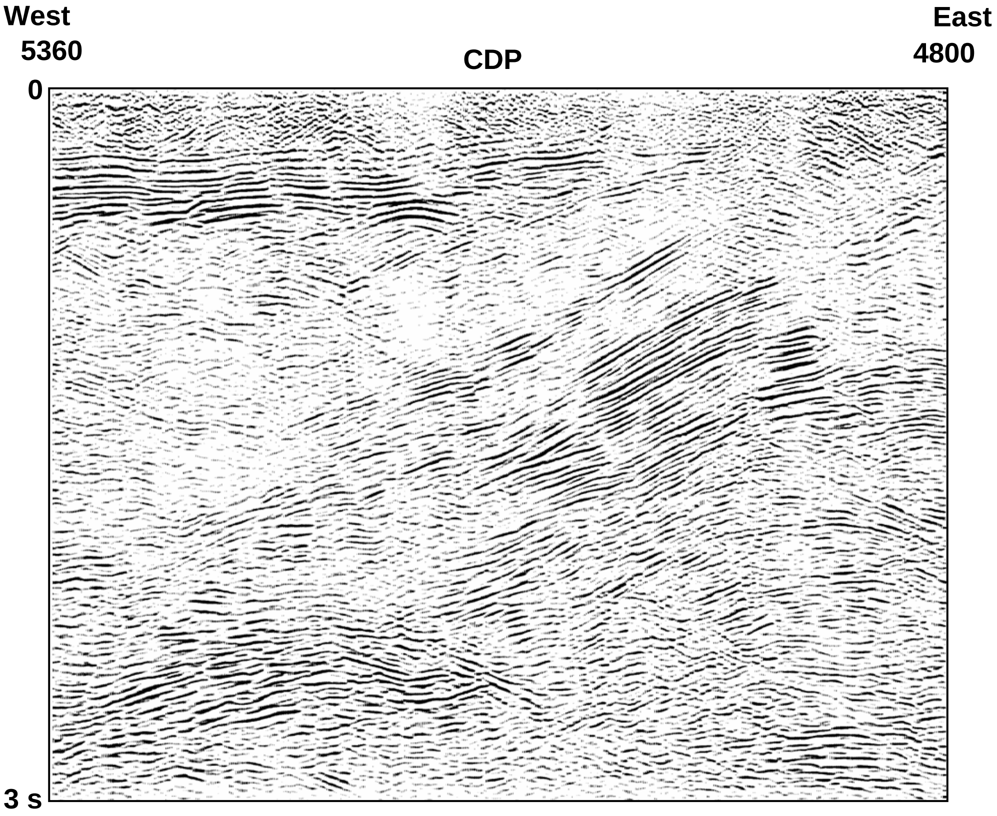

***Figure 3-7.*** *Fragment of migrated data (~ 11 km in length) across the shallow subhorizontal Adelaidean succession and dipping faults underneath it.*

For a typical deep seismic survey with 20 s record length, dips of ~70° can be imaged no deeper than about 20 km, ~50° dips can be imaged no deeper than 40 km. Very steep reflectors with dips ~80° 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 SEGY 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 pattens 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.

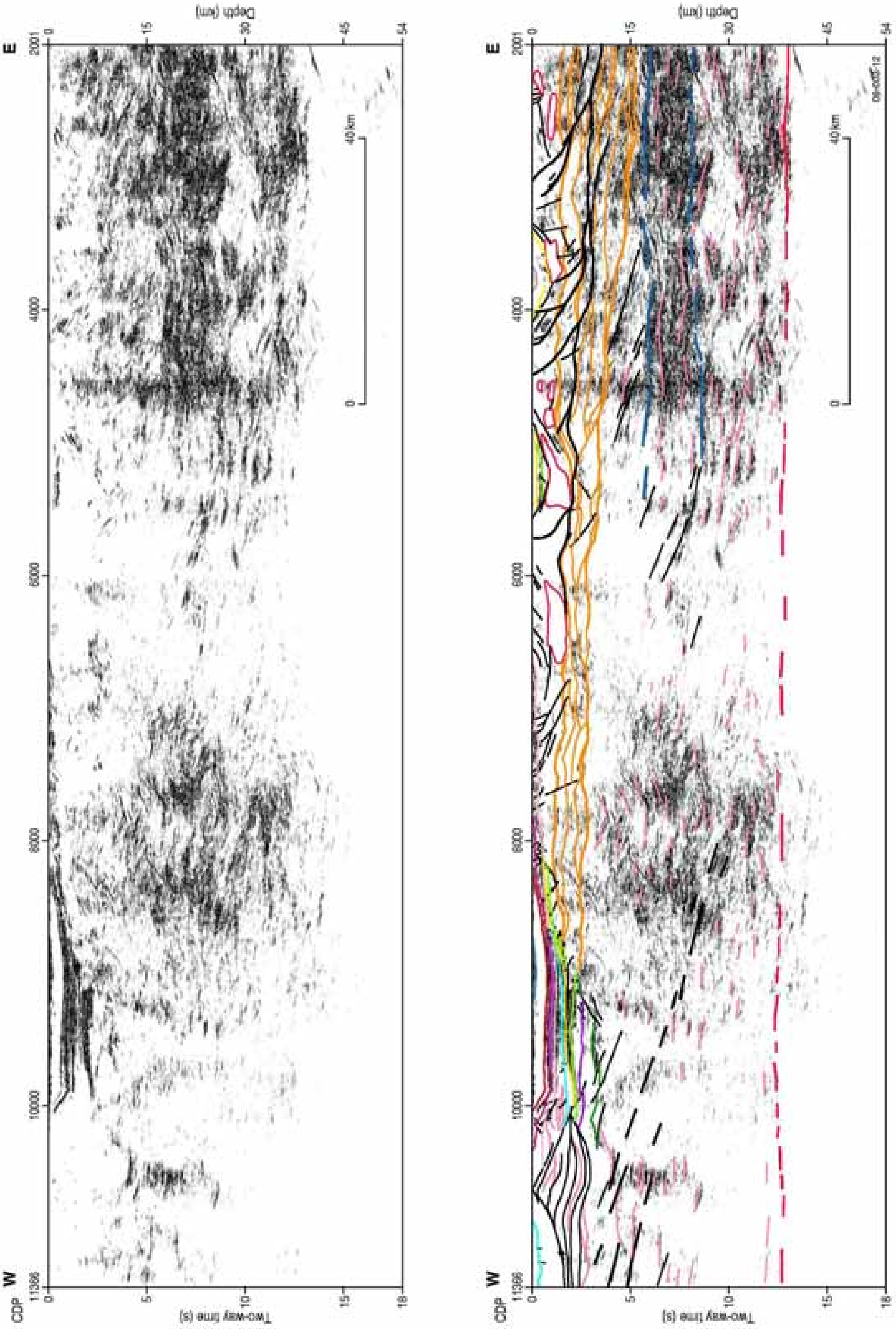

**Figure 4-1:** *Entire length of seismic traverse 03GA-CU1, showing eastern Willyama section and the western portion covered by Adelaidean units. Sections show semblance filtered migrated data. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

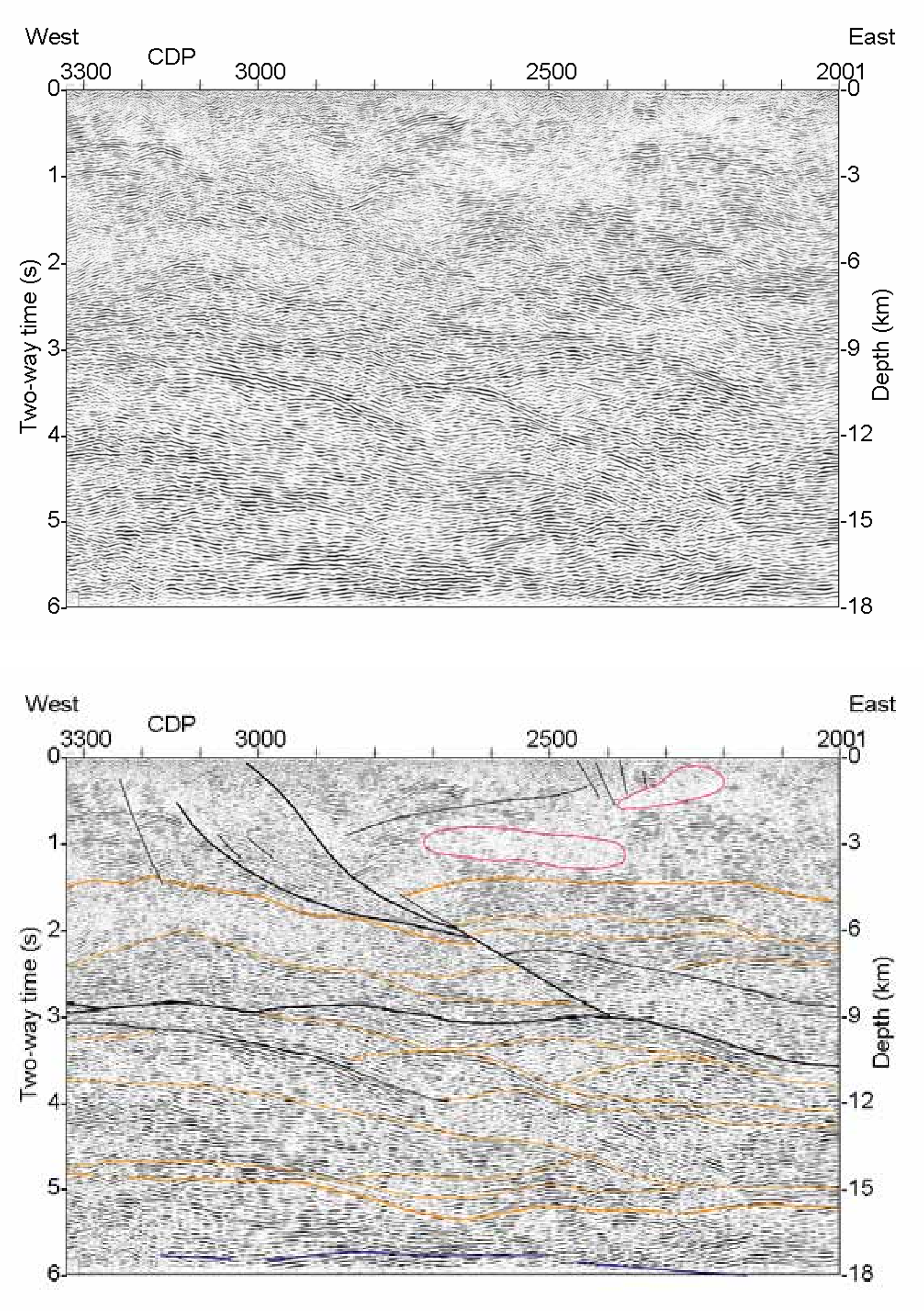

***Figure 4-2:*** *Eastern end of upper 6 s TWT of seismic traverse 03GA-CU1 (CDP 2100–3300). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

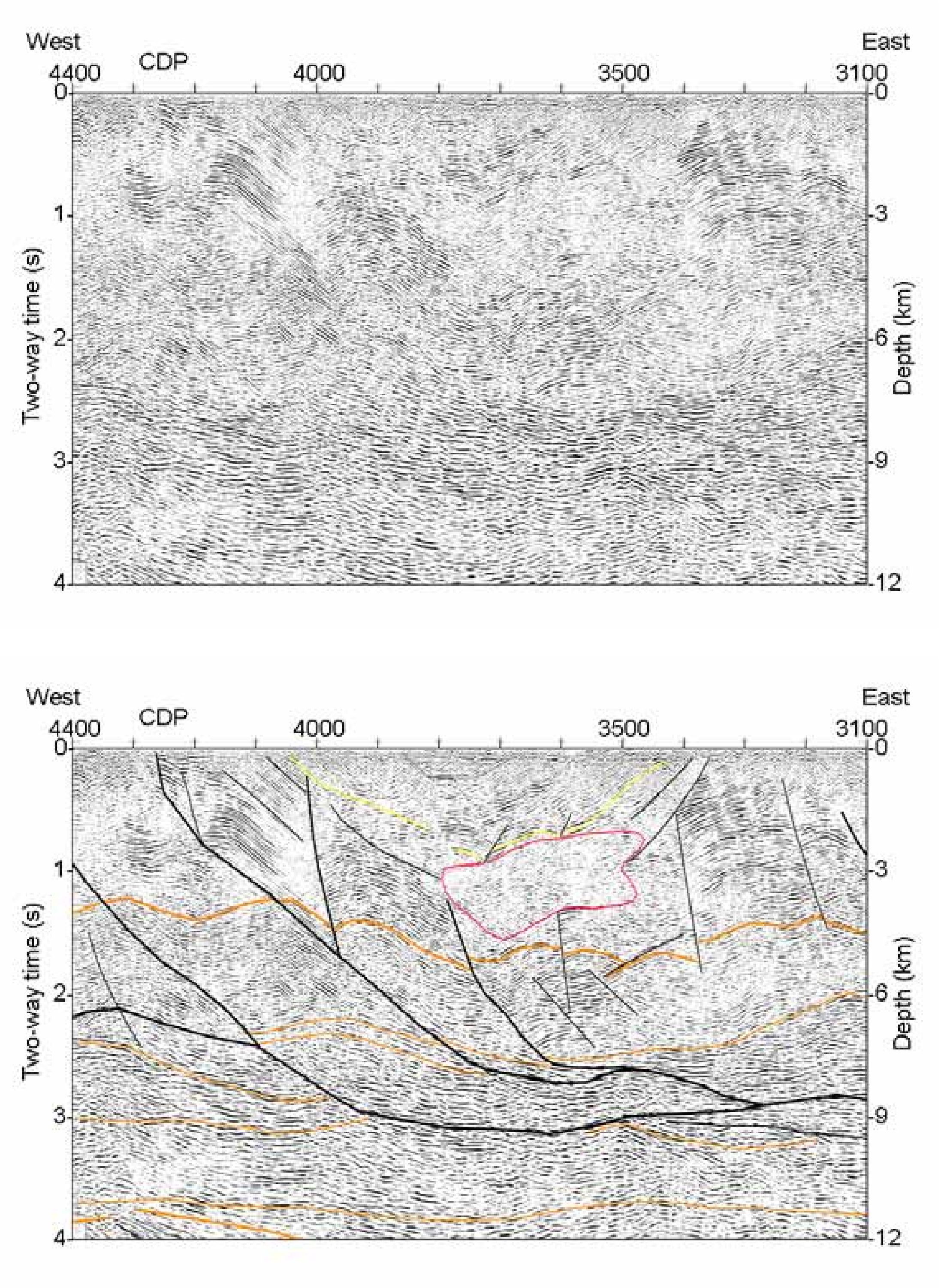

***Figure 4-3:*** *Zoom of upper 4 s TWT of portion of seismic traverse 03GA-CU1 (CDP 3100–4400). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

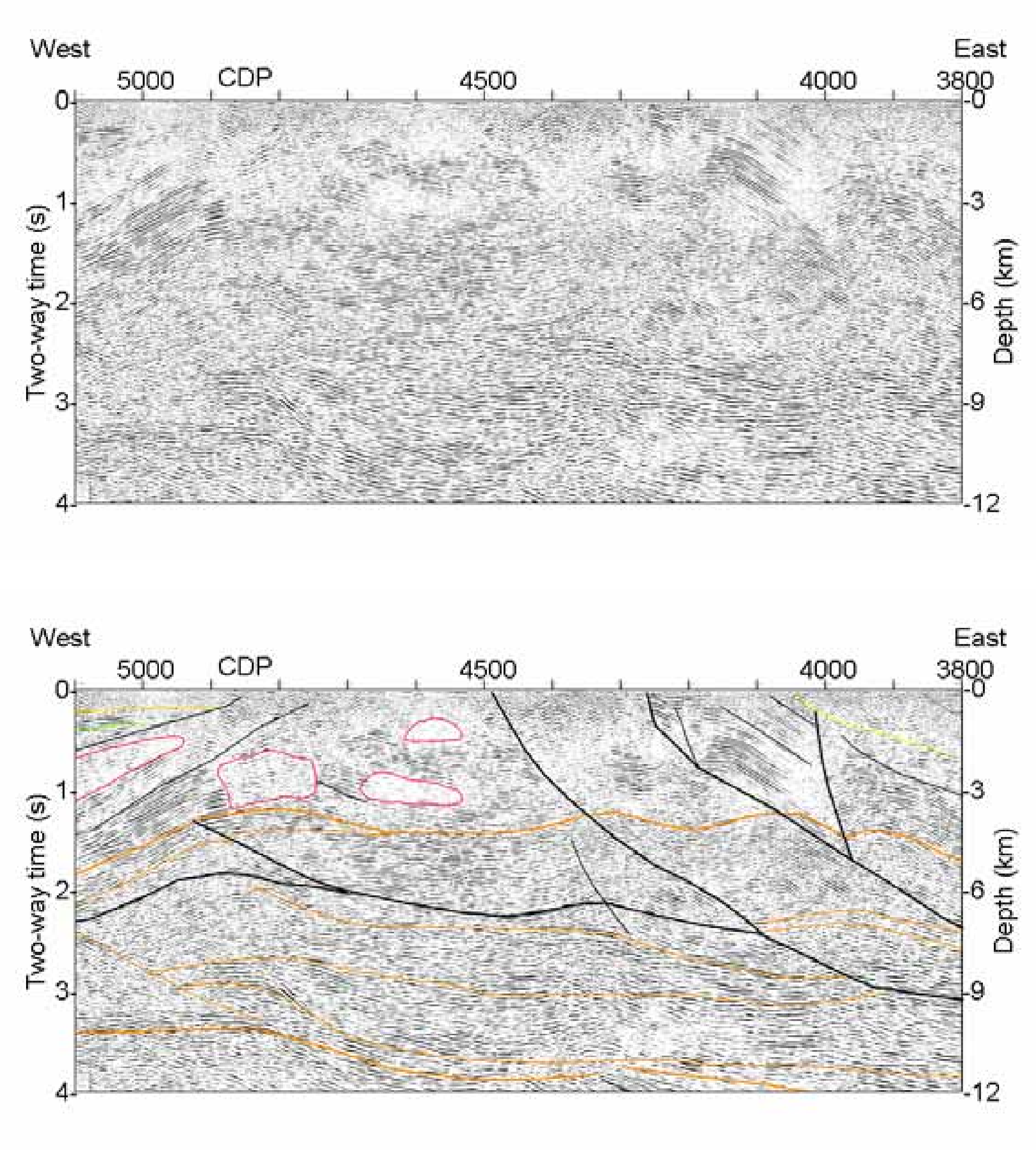

***Figure 4-4:*** *Part of upper 4 s TWT of portion of seismic traverse 03GA-CU1 (CDP 3800–5100). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

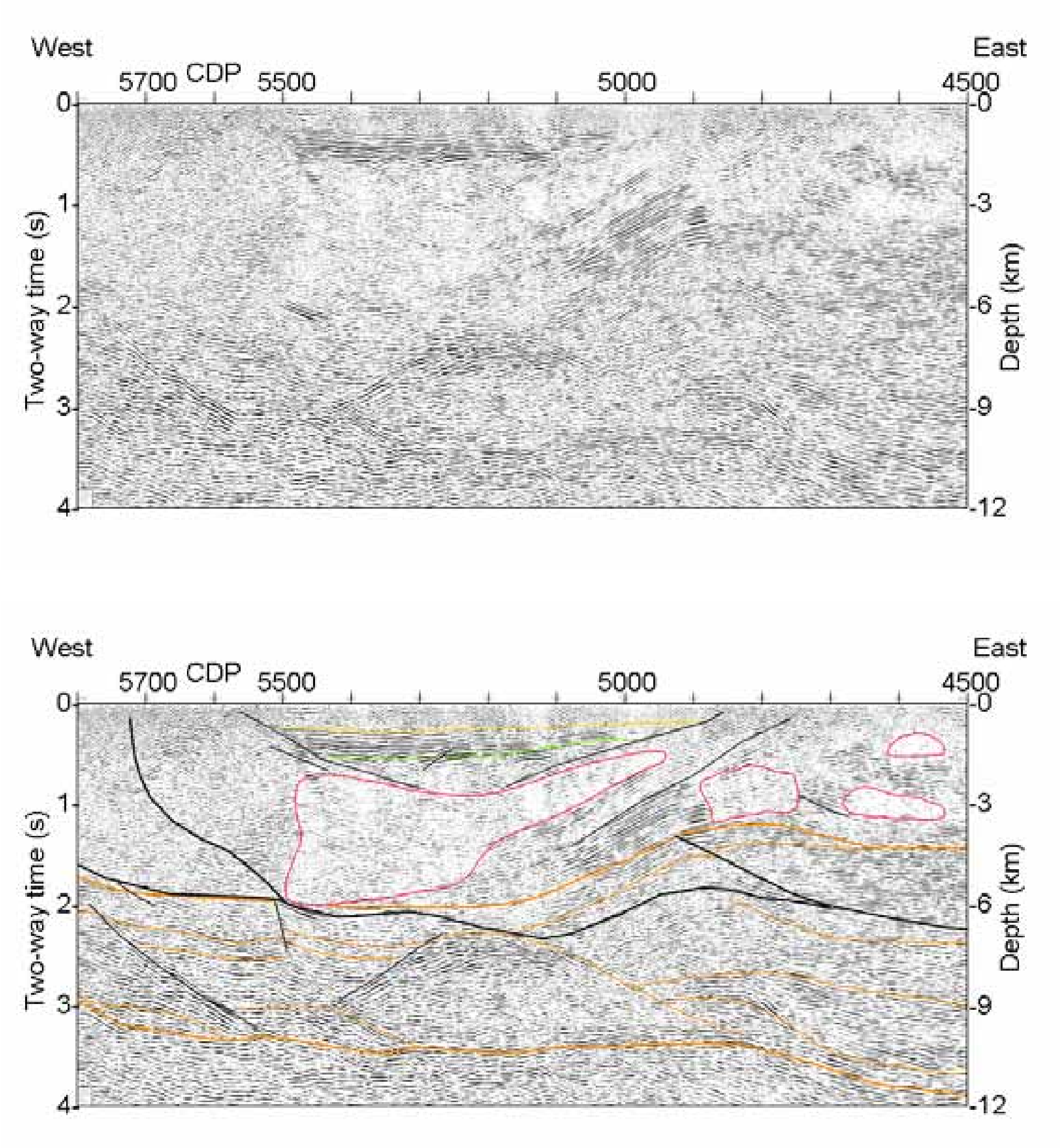

***Figure 4-5:*** *Part of upper 4 s TWT of portion of seismic traverse 03GA-CU1 (CDP 4500–5800). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

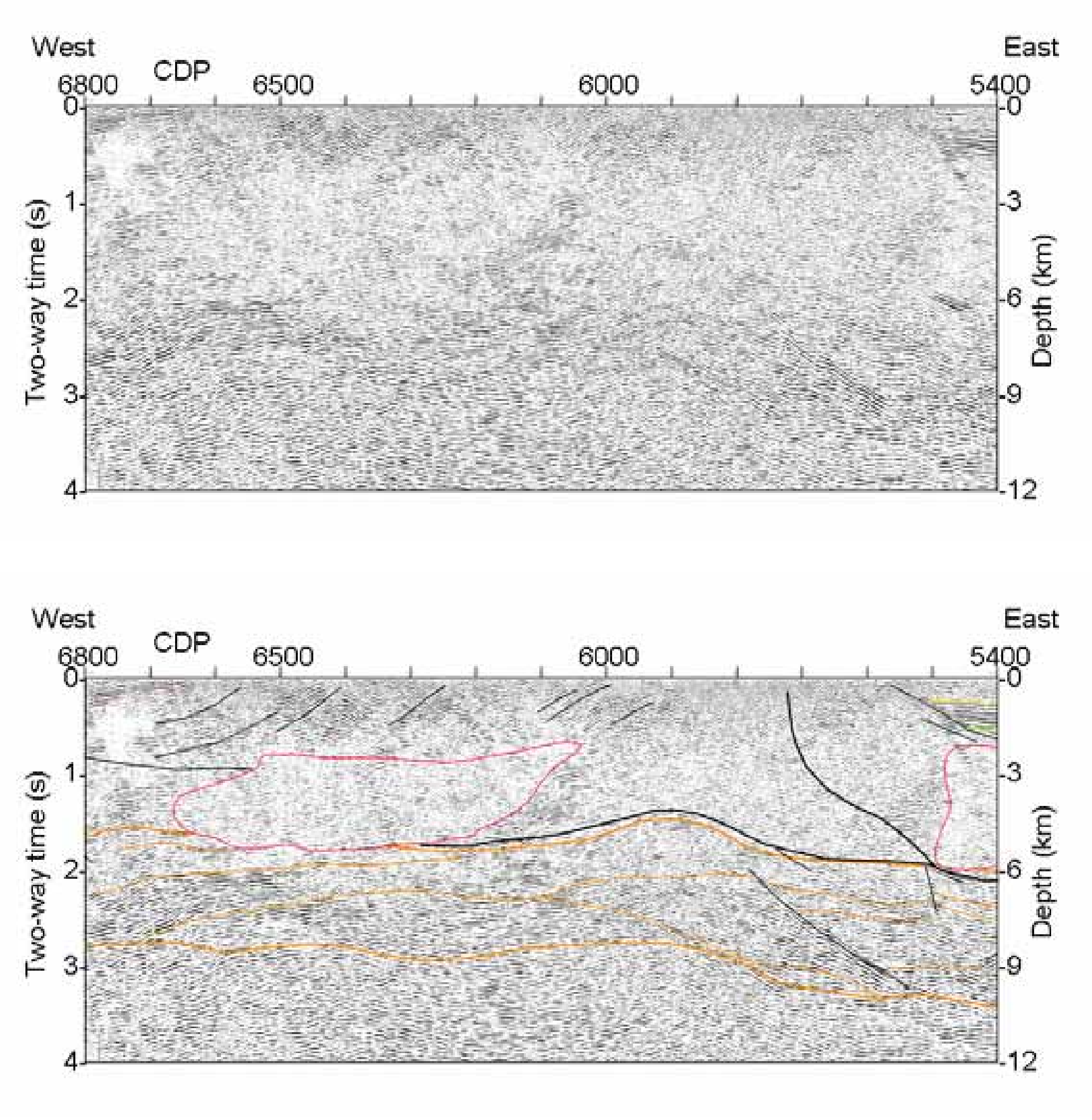

***Figure 4-6:*** *Part of upper 4 s TWT of portion of seismic traverse 03GA-CU1 (CDP 5400–6800). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

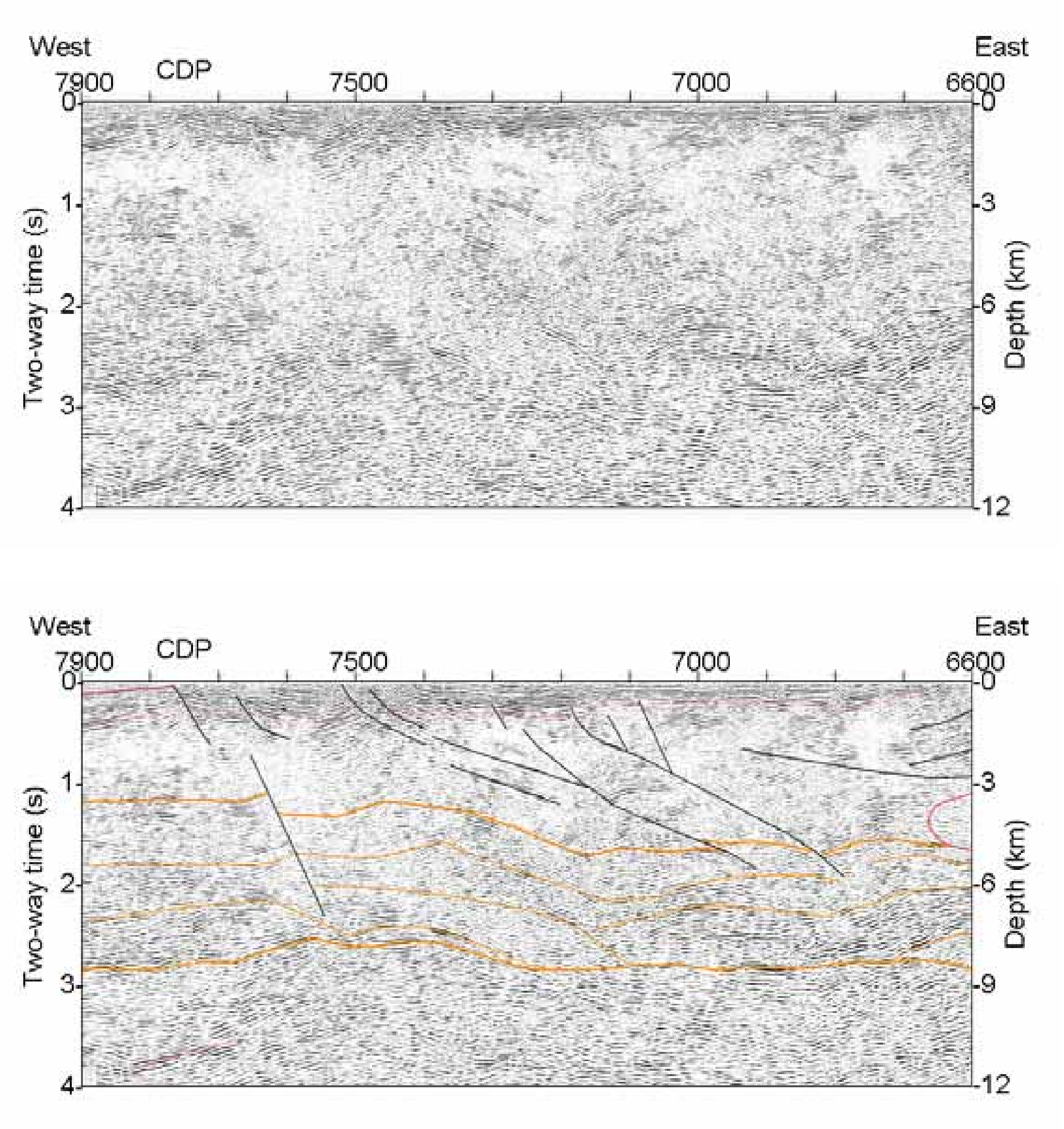

***Figure 4-7:*** *Part of upper 4 s TWT of portion of seismic traverse 03GA-CU1 (CDP 6600–7900). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

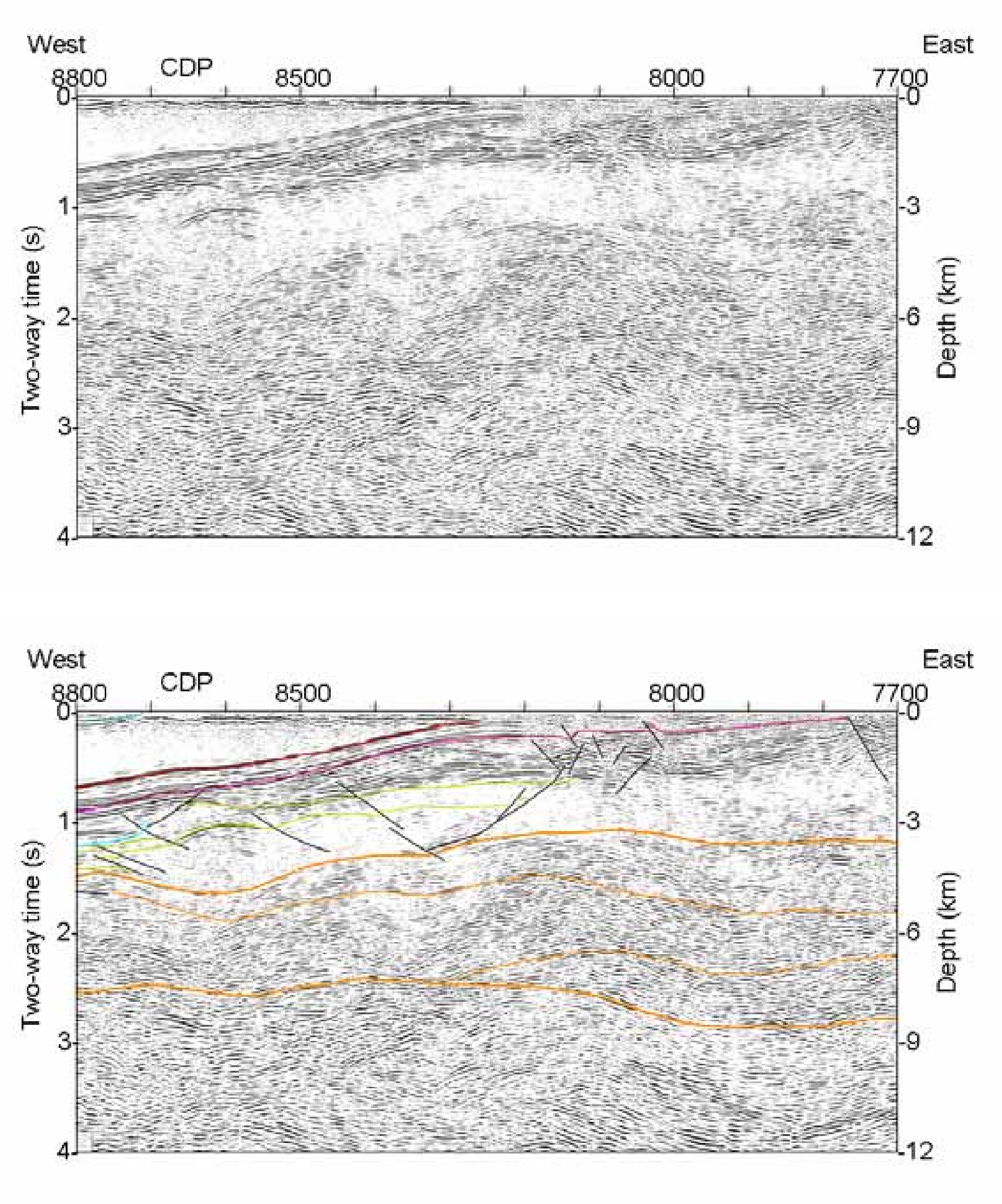

***Figure 4-8:*** *Part of upper 4 s TWT of seismic traverse 03GA-CU1 (CDP 7700–8800). Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

## 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.

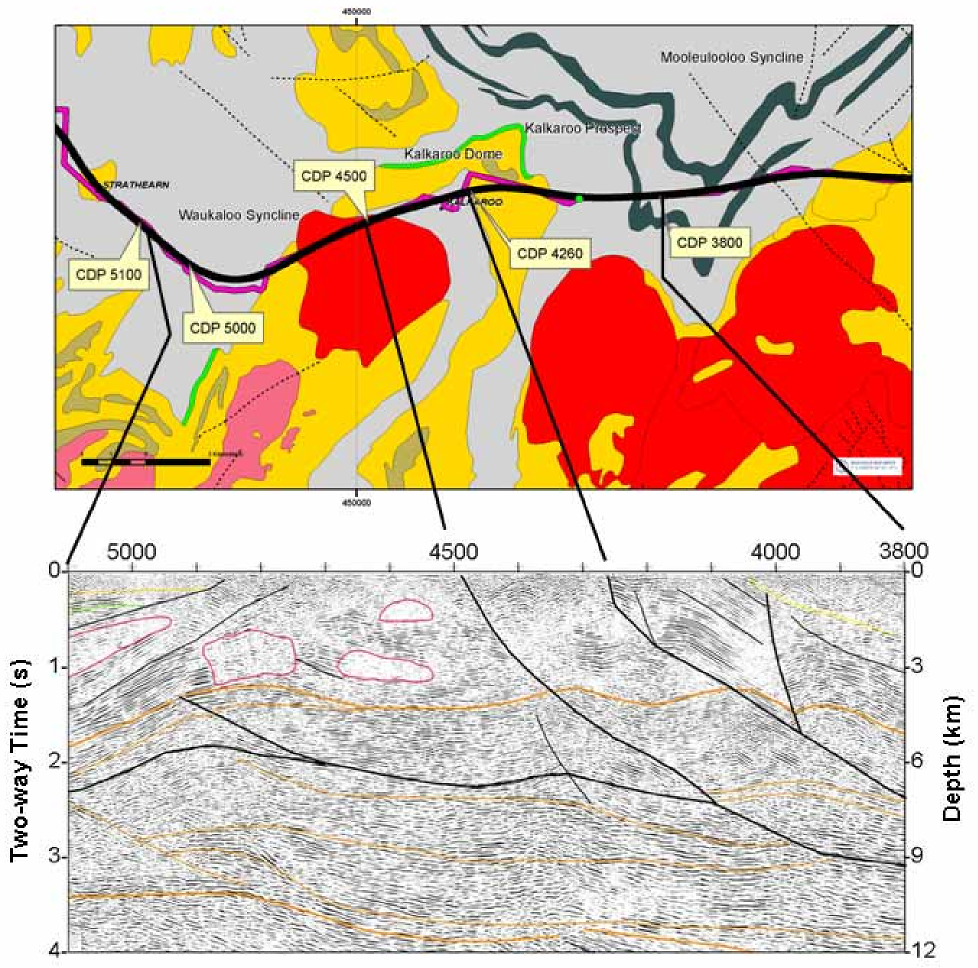

***Figure 4-9:*** *Portion of the Curnamona Seismic transect in relation to various structural and lithological features of the Curnamona Solid Geology in the region of the Kalkaroo Dome. Horizontal scale is based on 1 CDP =20 m.*

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 Neoproterzoic basin is corresponds 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.

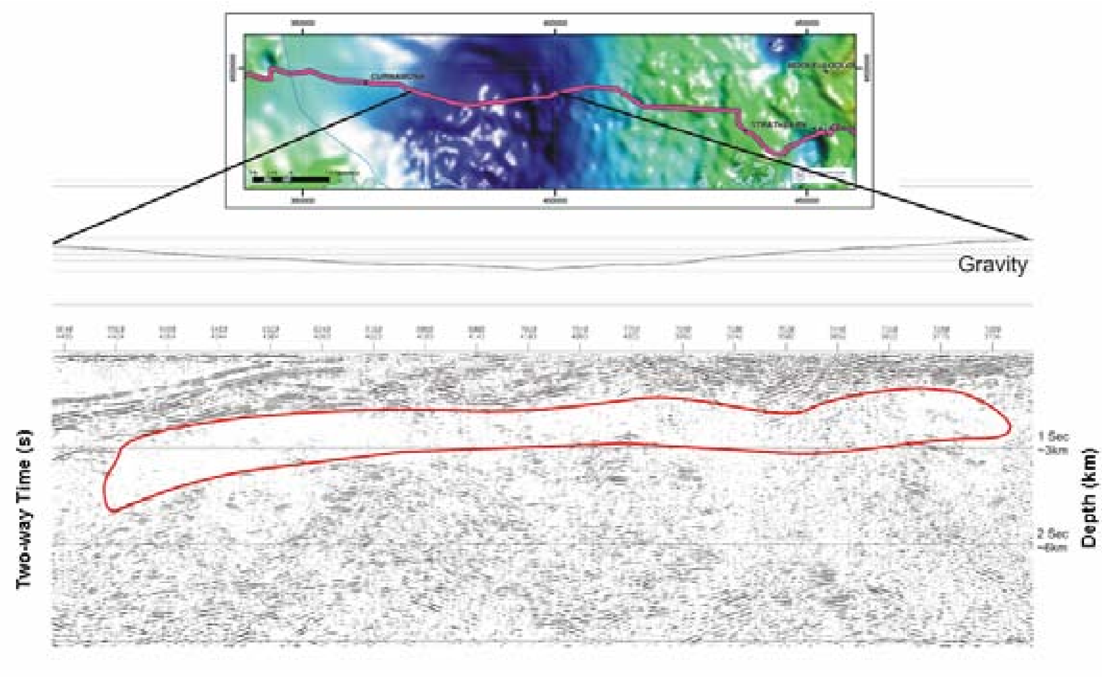

***Figure 4-10:*** *0–3 s TWT of 03GA-CU1 with position of inferred lowdensity body (red) corresponding to regional gravity data (top). Horizontal scale is based on 1 CDP =20 m.*

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 Olarian 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 Curnmona Domain

# THE ADELAIDEAN AND CAMBRIAN COVER SUCCESSION OF THE CURNAMONA PROVINCE

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## INTRODUCTION

As well as imaging the basement geology of the Curnamona Province, the seismic transect provides a clear record of its sedimentary cover. The outcropping geology of the adjacent Flinders Ranges and a number of shallow to moderate depth drillholes in the vicinity of the seismic transect provide stratigraphic control, especially in the upper parts of the cover succession. Identification of deeper stratigraphic units in the cover is more interpretative, but is facilitated by recognition of unconformities (sequence boundaries) in the seismic record, which can be correlated with those known from outcropping sections.

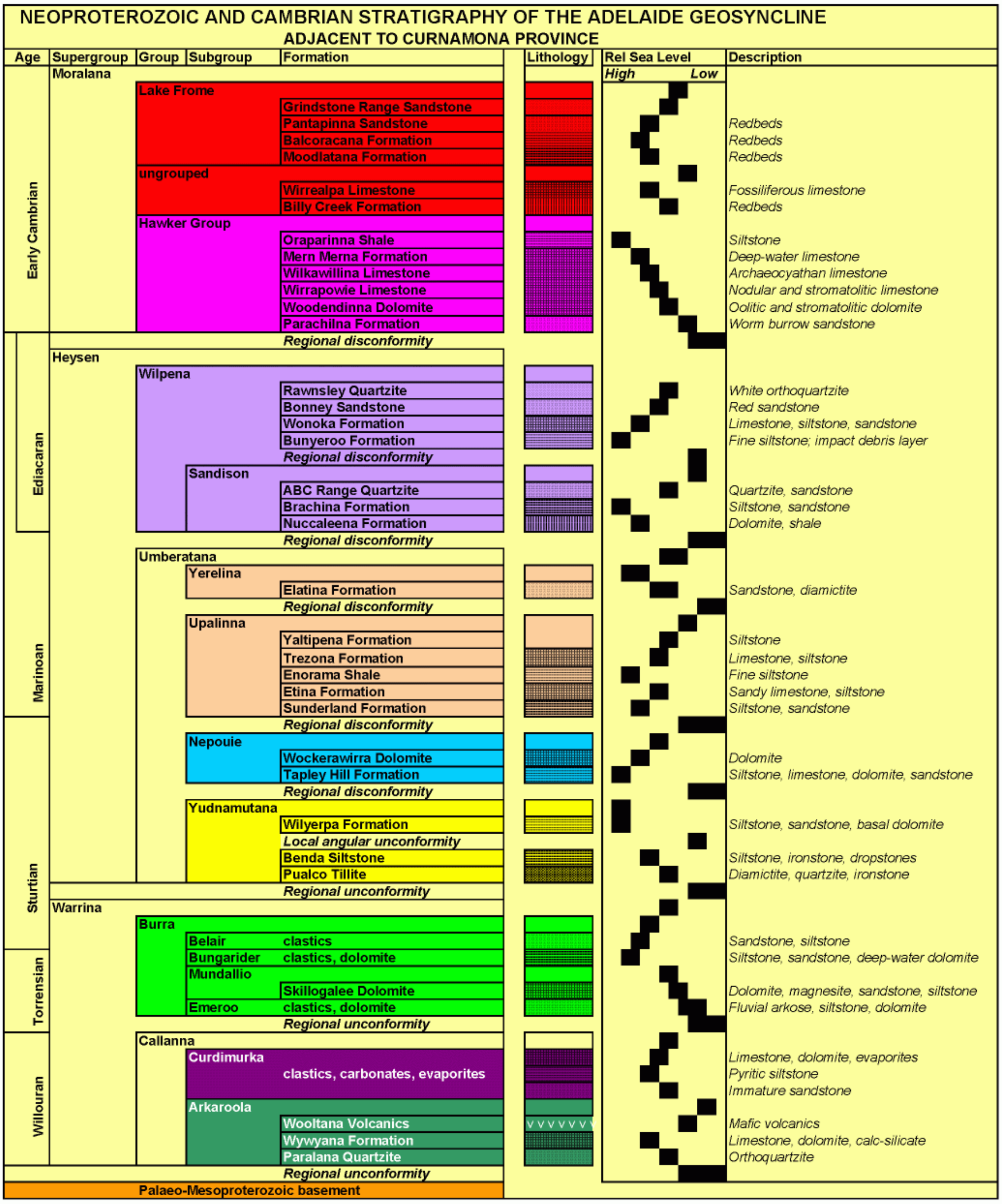
The seismic transect records the westward transition from the thin, incomplete, cratonic, Neoproterozoic (Adelaidean) and Cambrian cover overlying the Curnamona Province basement, to the very thick and more complete succession deposited in the rift- and sag-basin complex of the Adelaide Geosyncline in the Flinders Ranges (Preiss, 1987, 2000). Cambrian deposits are assigned to the Arrowie Basin, which extends from the Stuart Shelf in the west, across the Flinders Ranges, to the Curnamona Province in the east. The terms 'Moorowie' and 'Yalkalpo' have been used in previous literature to refer both to the two sub-basins of the Cambrian Arrowie Basin respectively west and east of the Benagerie Ridge, and to gentle Delamerian synclinal structures in the same regions. The terms are used in both senses below.

## STRATIGRAPHIC RECORD AND SEISMIC INTERPRETATION

Figures 5-1 through 5-6 show portions of the interpreted seismic section within the Adelaidean and Cambrian succession overlying the Curnamona Province.

The well-defined and documented Neoproterozoic to Cambrian stratigraphy in the Flinders Ranges is divided into supergroups, groups and subgroups separated by breaks in deposition (sequence boundaries) (Table 5-1). As with the cover succession in the Gawler Craton seismic transect, it was anticipated that these sequence boundaries would be apparent in the seismic and would facilitate correlation between the outcropping geology of the Flinders Ranges and the subsurface strata imaged on seismic. Generally, this promise has been fulfilled, especially in upper Adelaidean and Cambrian (for example Figure 5-1), but identification of the lowermost stratigraphic units, which are not exposed at the surface in this part of the Flinders Ranges, is more speculative.

***Table 5-1:*** *Table of Neoproterozoic and Cambrian Stratigraphy of the Adelaide Geosyncline adjacent to the Curnamona Province.*



NEOPROTEROZOIC AND CAMBRIAN STRATIGRAPHY OF THE ADELAIDE GEOSYNCLINE ADJACENT TO CURNAMONA PROVINCE

| Age | Supergroup | Group | Subgroup | Formation | Lithology | Rel Sea Level<br>High Low | Description |
|---|---|---|---|---|---|---|---|
| Early Cambrian | Moralana | Lake Frome | | | | | |
| | | | | Grindstone Range Sandstone | | | |
| | | | | Pantapinna Sandstone | | | *Redbeds* |
| | | | | Balcoracana Formation | | | *Redbeds* |
| | | | | Moodlatana Formation | | | *Redbeds* |
| | | ungrouped | | | | | |
| | | | | Wirrealpa Limestone | | | *Fossiliferous limestone* |
| | | | | Billy Creek Formation | | | *Redbeds* |
| | | Hawker Group | | | | | |
| | | | | Oraparinna Shale | | | *Siltstone* |
| | | | | Mern Merna Formation | | | *Deep-water limestone* |
| | | | | Wilkawillina Limestone | | | *Archaeocyathan limestone* |
| | | | | Wirrapowie Limestone | | | *Nodular and stromatolitic limestone* |
| | | | | Woodendinna Dolomite | | | *Oolitic and stromatolitic dolomite* |
| | | | | Parachilna Formation | | | *Worm burrow sandstone* |
| | | | | ***Regional disconformity*** | | | |
| Ediacaran | Heysen | | | | | | |
| | | Wilpena | | | | | |
| | | | | Rawnsley Quartzite | | | *White orthoquartzite* |
| | | | | Bonney Sandstone | | | *Red sandstone* |
| | | | | Wonoka Formation | | | *Limestone, siltstone, sandstone* |
| | | | | Bunyeroo Formation | | | *Fine siltstone; impact debris layer* |
| | | | | ***Regional disconformity*** | | | |
| | | | Sandison | | | | |
| | | | | ABC Range Quartzite | | | *Quartzite, sandstone* |
| | | | | Brachina Formation | | | *Siltstone, sandstone* |
| | | | | Nuccaleena Formation | | | *Dolomite, shale* |
| | | | | ***Regional disconformity*** | | | |
| Marinoan | | Umberatana | | | | | |
| | | | Yerelina | | | | |
| | | | | Elatina Formation | | | *Sandstone, diamictite* |
| | | | | ***Regional disconformity*** | | | |
| | | | Upalinna | | | | |
| | | | | Yaltipena Formation | | | *Siltstone* |
| | | | | Trezona Formation | | | *Limestone, siltstone* |
| | | | | Enorama Shale | | | *Fine siltstone* |
| | | | | Etina Formation | | | *Sandy limestone, siltstone* |
| | | | | Sunderland Formation | | | *Siltstone, sandstone* |
| | | | | ***Regional disconformity*** | | | |
| Sturtian | | | Nepouie | | | | |
| | | | | Wockerawirra Dolomite | | | *Dolomite* |
| | | | | Tapley Hill Formation | | | *Siltstone, limestone, dolomite, sandstone* |
| | | | | ***Regional disconformity*** | | | |
| | | | Yudnamutana | | | | |
| | | | | Wilyerpa Formation | | | *Siltstone, sandstone, basal dolomite* |
| | | | | ***Local angular unconformity*** | | | |
| | | | | Benda Siltstone | | | *Siltstone, ironstone, dropstones* |
| | | | | Pualco Tillite | | | *Diamictite, quartzite, ironstone* |
| | | | | ***Regional unconformity*** | | | |
| | Warrina | | | | | | |
| | | Burra | | | | | |
| | | | Belair | clastics | | | *Sandstone, siltstone* |
| Torrensian | | | Bungarider | clastics, dolomite | | | *Siltstone, sandstone, deep-water dolomite* |
| | | | Mundallio | | | | |
| | | | | Skillogalee Dolomite | | | *Dolomite, magnesite, sandstone, siltstone* |
| | | | Emeroo | clastics, dolomite | | | *Fluvial arkose, siltstone, dolomite* |
| | | | | ***Regional unconformity*** | | | |
| Willouran | | Callanna | | | | | |
| | | | Curdimurka | clastics, carbonates, evaporites | | | *Limestone, dolomite, evaporites*<br>*Pyritic siltstone*<br>*Immature sandstone* |
| | | | Arkaroola | | | | |
| | | | | Wooltana Volcanics | v v v v v v | | *Mafic volcanics* |
| | | | | Wywyana Formation | | | *Limestone, dolomite, calc-silicate* |
| | | | | Paralana Quartzite | | | *Orthoquartzite* |
| | | | | ***Regional unconformity*** | | | |
| | | Palaeo-Mesoproterozoic basement | | | | | |

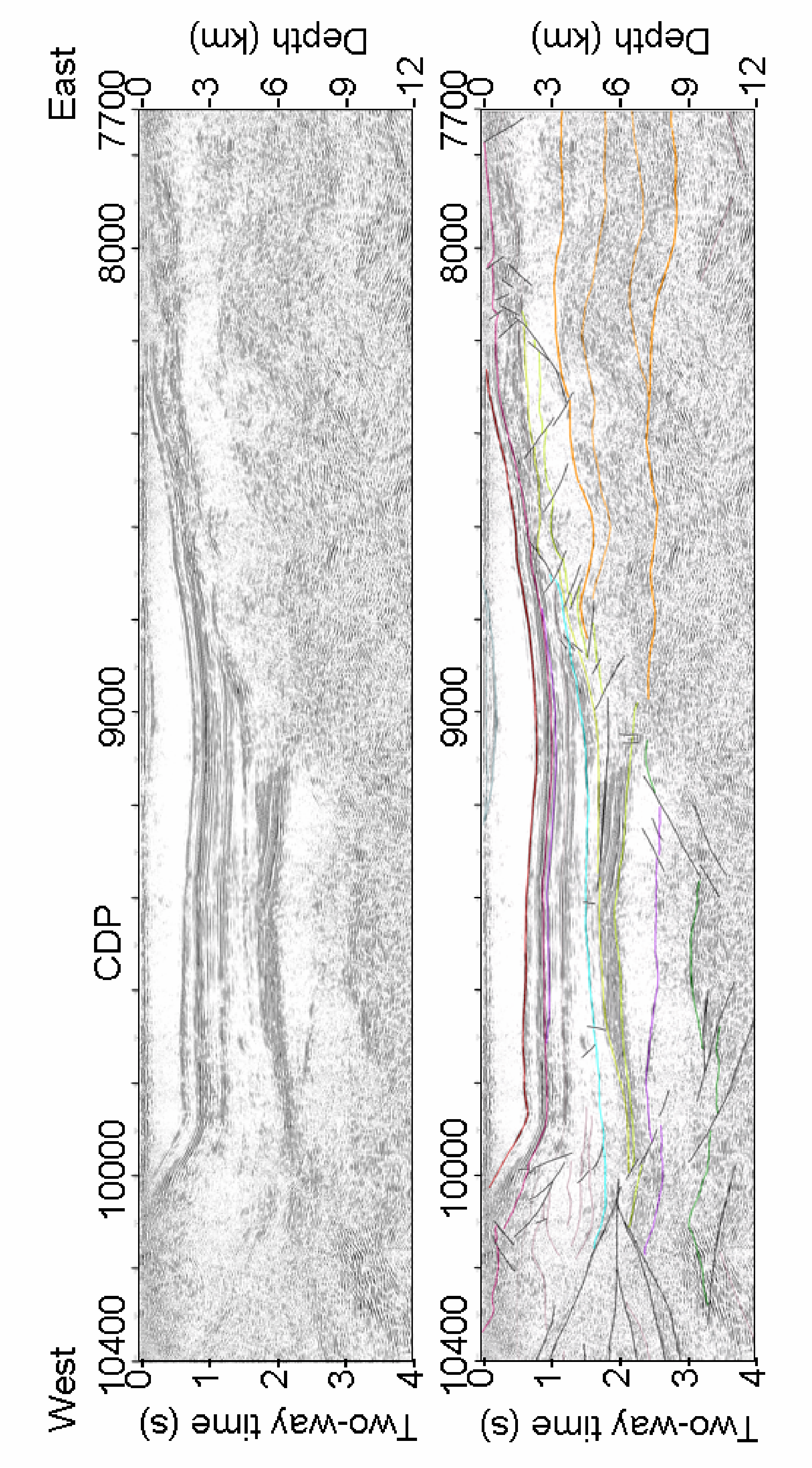


***Figure 5-1:*** *Portion of Curnamona Seismic Traverse 03GA-CU1, showing Adelaidean succession. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

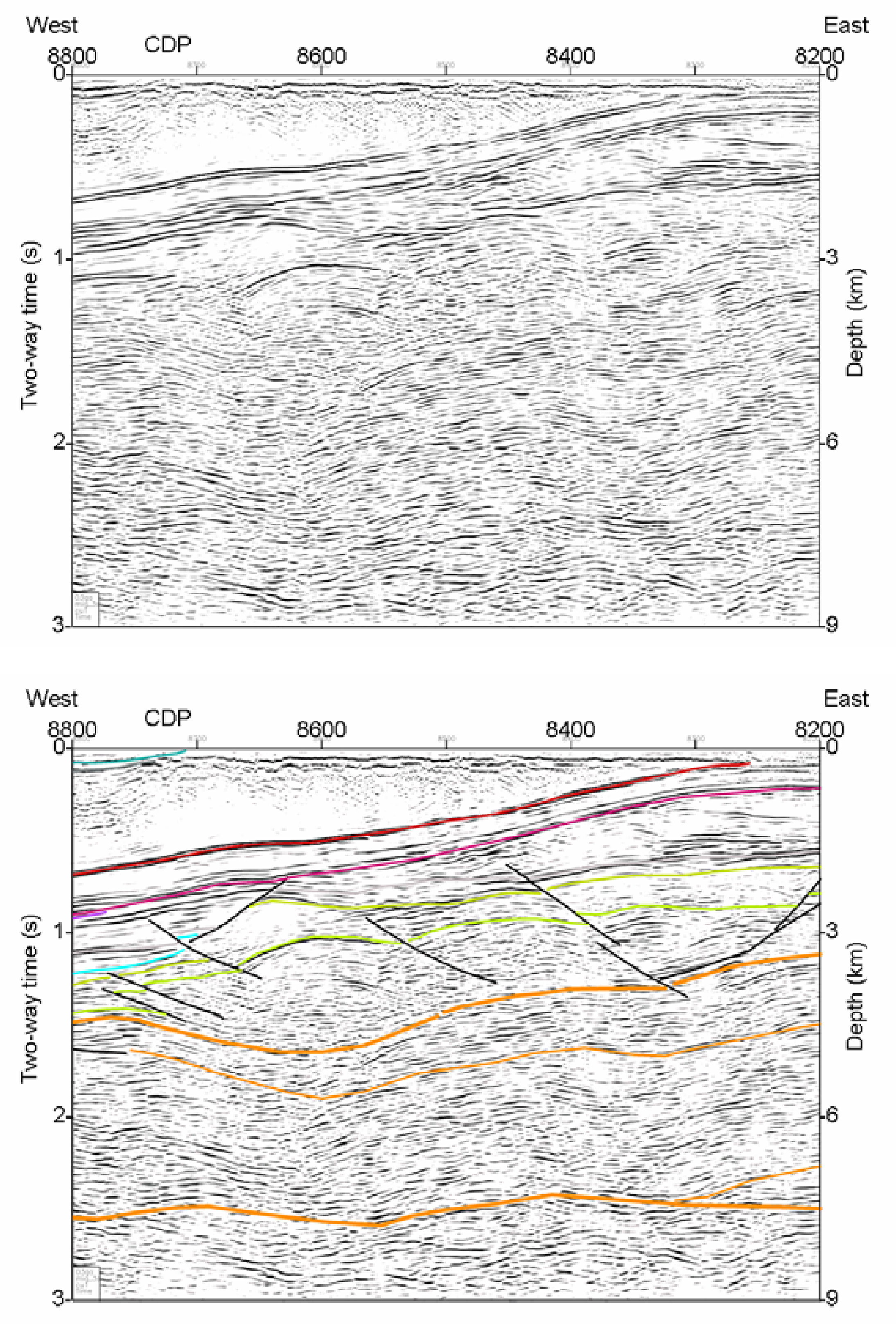


***Figure 5-2:*** *Portion of eastern edge of Adelaidean succession. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

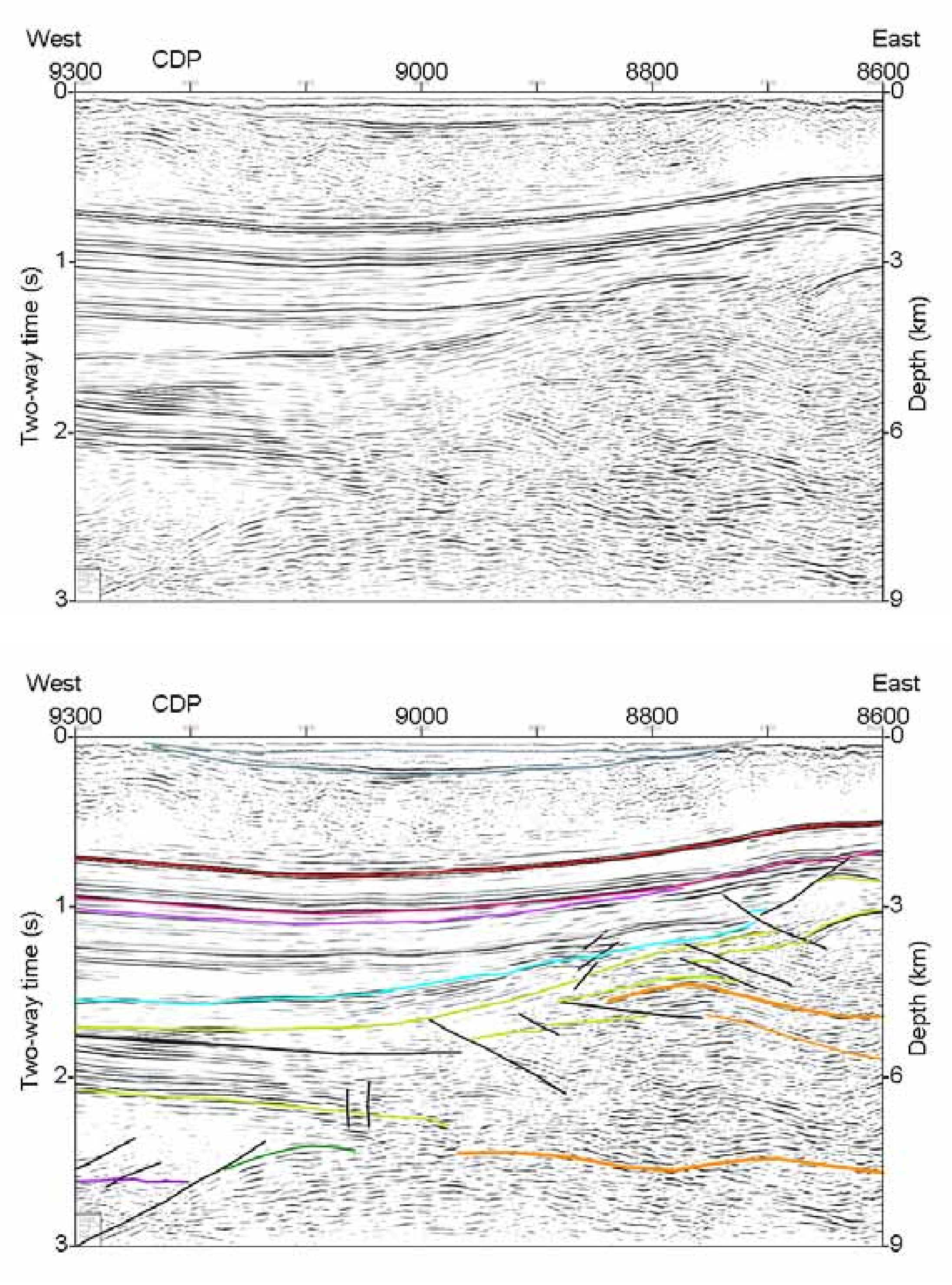


***Figure 5-3:*** *Portion of central east region of Adelaidean succession. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

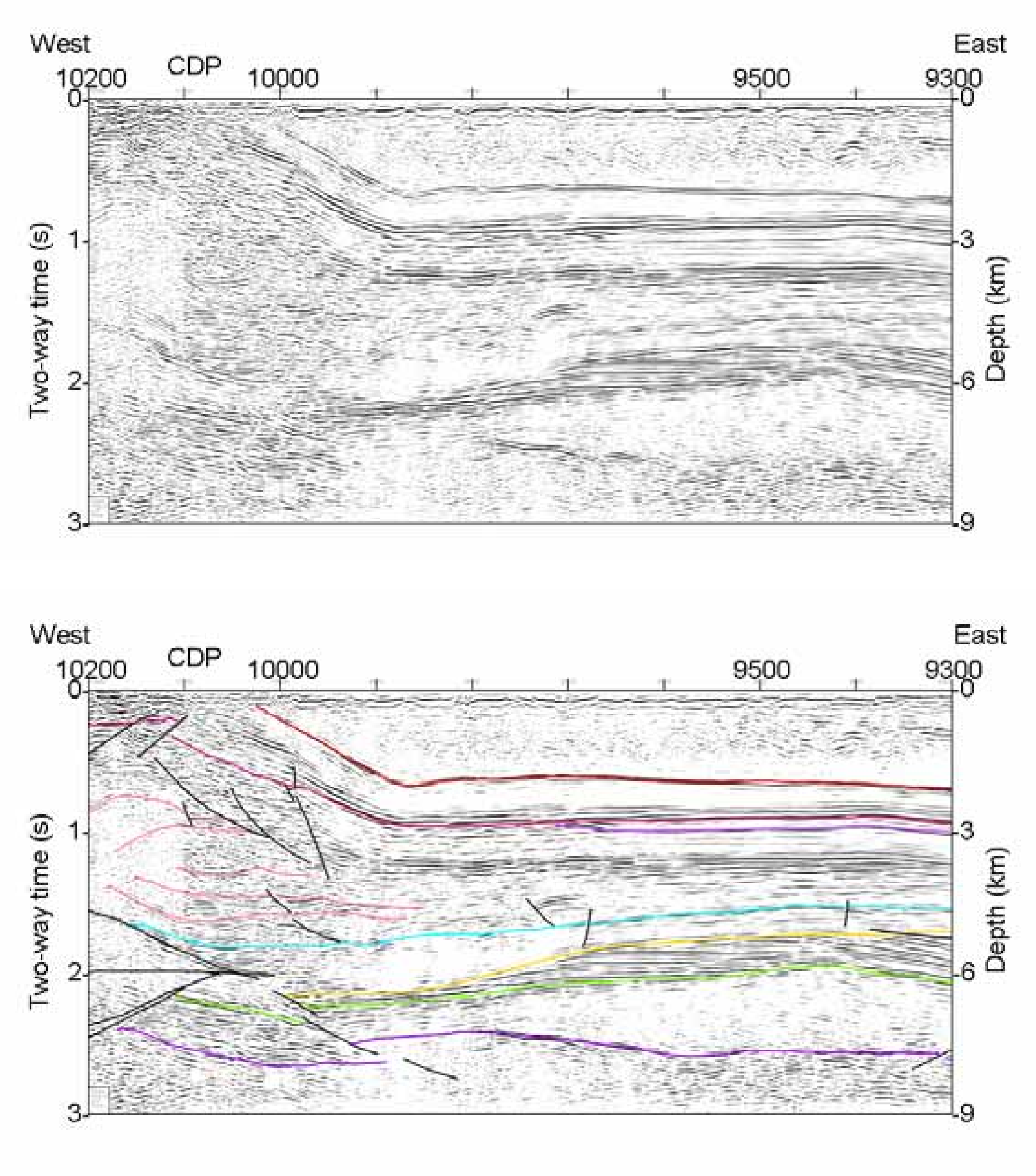


***Figure 5-4: P****ortion of western edge of Adelaidean succession. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

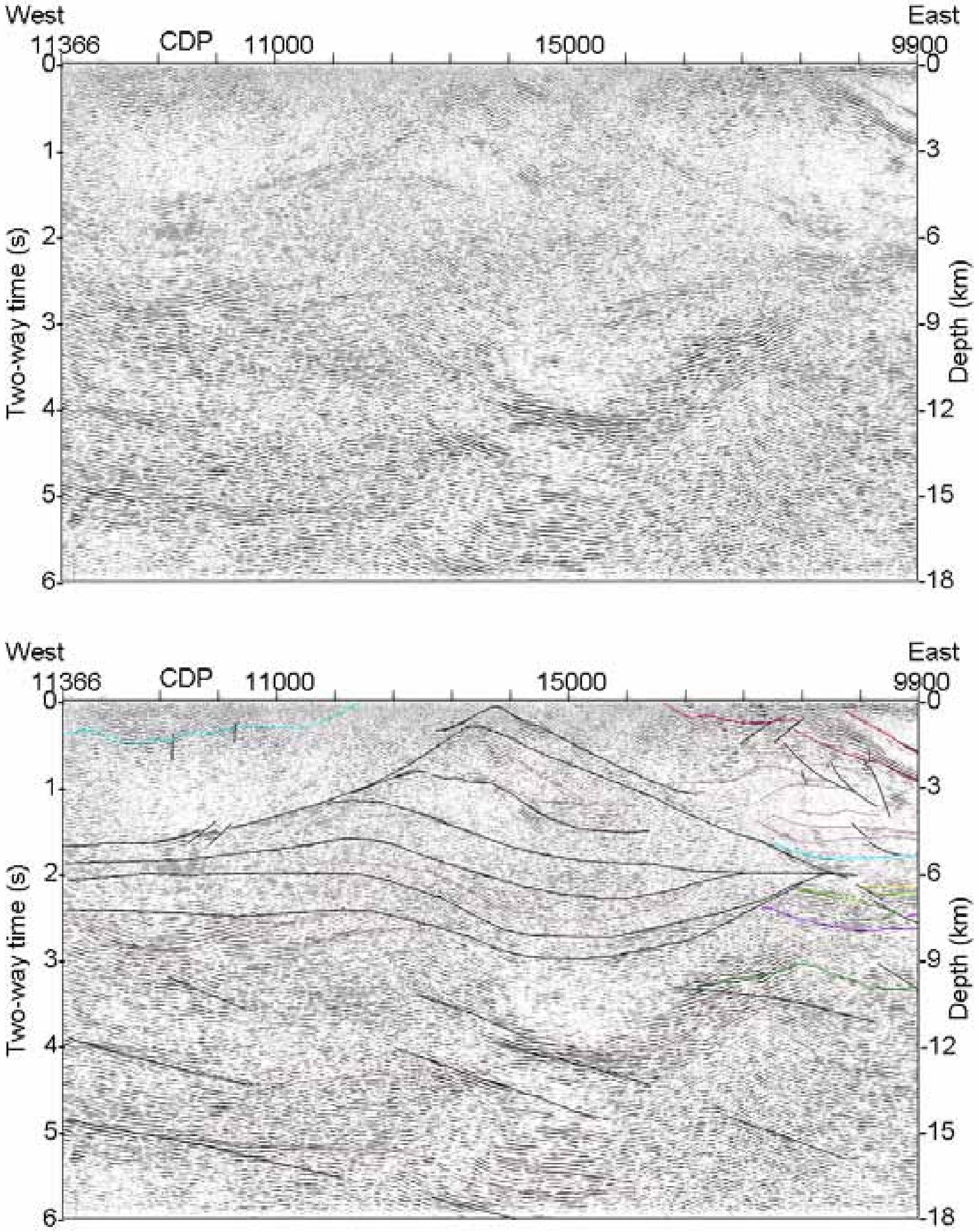


***Figure 5-5:** **P**ortion of region beneath Flinders Range. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

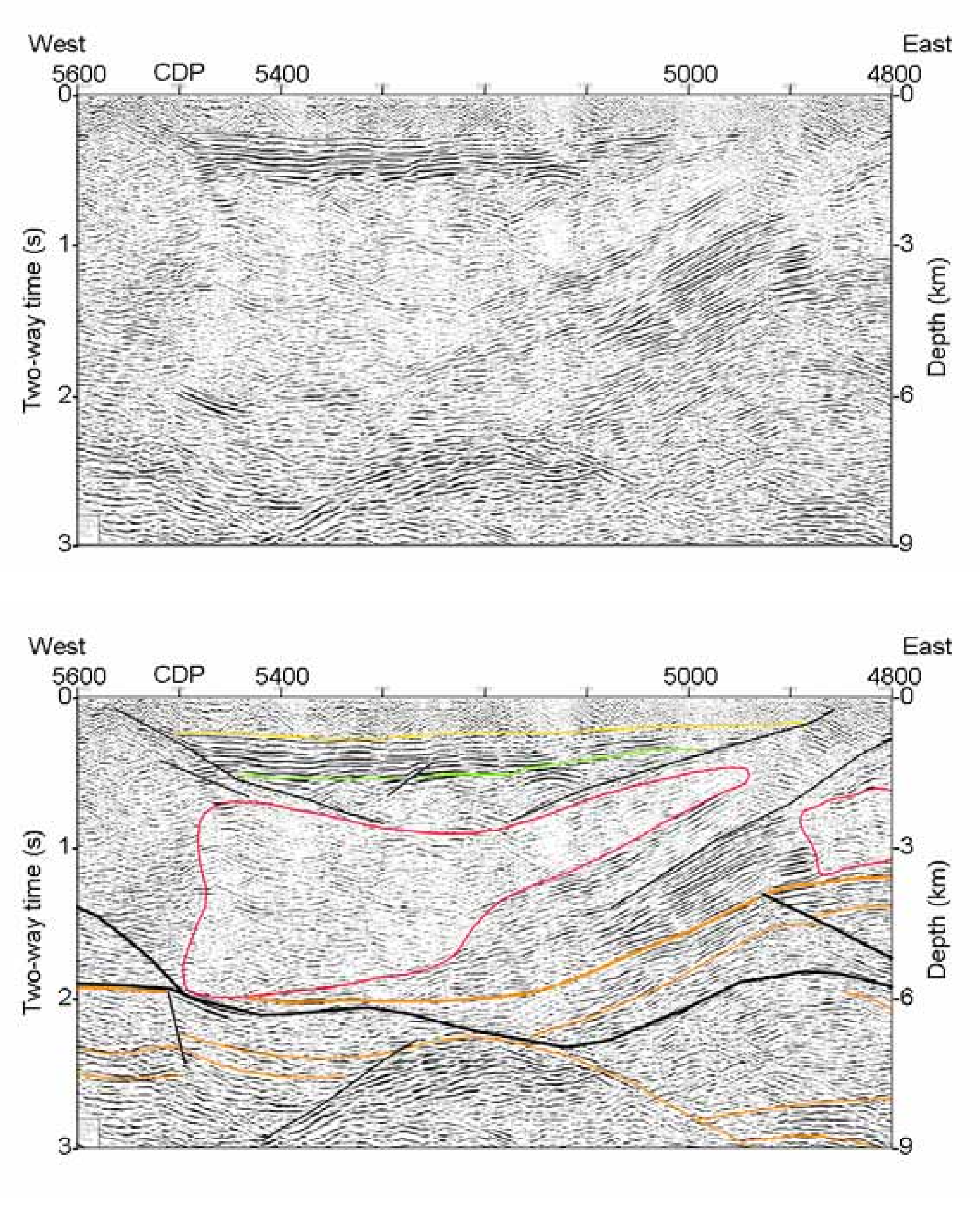


***Figure 5-6:*** ***P****ortion of in-faulted outlier of Adelaidean succession. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

The Neoproterozoic tectonic history of the region involved at least four, possibly five, episodes of rifting of the basement and deposition of thick sedimentary successions within graben and half-graben structures. A major change in tectonic style from rift-dominated to sag-dominated occurred after the Sturtian glaciation in the mid-Neoproterozoic, when the eastern margin of the Gawler Craton started to subside and was inundated for the first time by post-glacial transgression, resulting in deposition of the widespread Tapley Hill Formation of the Nepouie Subgroup. A similar inundation occurred on the Curnamona Province, but here the record is complicated by further syn-sedimentary tectonism, leading to the uplift of the Benagerie Ridge.

Sedimentation in the Adelaide Geosyncline is inferred to have commenced at ~830 Ma with deposition of an originally continuous, but now much dismembered, blanket of highly mature quartzose sandstone, represented at Arkaroola 150 km to the north of the seismic transect by the Paralana Quartzite, which is the basal clastic unit of the Arkaroola Subgroup of the Callanna Group. There, this arenite overlies either Mesoproterozoic granite with major nonconformity, or Mesoproterozoic felsic volcanics and quartzites with only slightly angular unconformity, despite the 750 million year time gap. Such structural near-concordance would make the basal Adelaidean unconformity difficult to pick on a seismic record (Figure 5-1). This may be the situation in the western extremity of the seismic section, beneath the eastern Flinders Ranges, where inferred Adelaidean strata are underlain by further layered successions. Here, the basal unconformity has been tentatively placed at a slight angular discordance (shown in dark green), within a generally strongly layered package, at about 3 s TWT. A depth of about 9 km inferred from this is consistent with the thicknesses of known correlative cover units in the Flinders Ranges. The Paralana Quartzite passes up gradationally into carbonates and calc-silicates of the Wywyana Formation, followed by altered basalt of the Wooltana Volcanics, extruded during the first major extensional event. It is uncertain if these basalts are recorded on the seismic section, but they may be represented by lenticular reflections some distance above the interpreted basal unconformity. Arkaroola Subgroup is interpreted to be confined to a graben structure west of CDP 9200 (Figure 5-3), possibly formed during the extensional event represented by these volcanics.

Curdimurka Subgroup, the upper part of the Callanna Group, was deposited in deeply subsiding graben structures during the s phase of rifting. Curdimurka Subgroup is inferred on the seismic section as a zone of poor reflections (base shown in dark purple) above the possible basalt, and may contain evaporites similar to those that facilitated diapirism in the adjacent Flinders Ranges., No diapiric structures, however, have been identified on the seismic section. Alternatively, the zone with poor reflections could represent the basal clastic-dominated Emeroo Subgroup of the Burra Group, which disconformably overlies Wooltana Volcanics at Arkaroola without any intervening Curdimurka Subgroup. This package appears to be confined to a zone west of CDP 9100 (Figure 5-3), defined partly by normal faulting and partly by onlap.

Sedimentary contacts between Curdimurka Subgroup and the overlying Burra Group are rarely seen in the Flinders Ranges, and this boundary is difficult to pick on the seismic (shown in light green). The lower clastic Emeroo Subgroup may be thin (interpretation shown on Figures 5-1, 5-3 etc), or it may be thick, occupying the zone of poor reflections shown as Curdimurka Subgroup on the seismic interpretation. It is overlain by the dominant carbonate reflections of the Mundallio Subgroup (Skillogalee Dolomite). Skillogalee Dolomite is present in the core of the nearby Willippa Dome, where it is unconformably overlain by the Sturtian Yudnamutana Subgroup (Dyson, 1996); upper Burra Group (Bungarider and Belair Subgroups) was either not deposited, or eroded during the Sturtian glaciation. On the seismic section, the Burra Group is confined to a zone west of an ill-defined extensional fault near CDP 8950 (Figure 5-3).

The base of the Yudnamutana Subgroup is clearly identified (shown in yellow) by an angular unconformity above the strong reflections of the Mundallio Subgroup. The angular relationship is interpreted to be due to eastward tilting of the Burra Group before the Sturtian glaciation. A wedge of weaker reflections appearing above the interpreted Mundallio Subgroup (between CDP 9300 and CDP 9000, Figures 5-3 and 5-4) and below the Sturtian unconformity may represent upper Burra Group. These relationships are consistent with fault-block rotation expected at the eastern rift-bounding normal faults, and with relationships observed in outcrop in the corridors between the Weekeroo, Outalpa and Kalabity Inliers south of the seismic transect (Preiss and Conor, 2001). Toward the east, the upper Burra Group package appears to overstep the rift-confined Mundallio Subgroup across a number of normal faults, perhaps as far as the western edge of the Benagerie Ridge. This overstepping is comparable to the existence of Belair Subgroup in the Macdonald Corridor, apparently directly overlying basement of the Bimbowrie Inlier, though the basal contact is not exposed there.

The Sturtian glacial Yudnamutana Subgroup is extremely thick in the adjacent part of the Flinders Ranges, where the Bibliando Dome contains Wilyerpa Formation siltstone, sandstone and minor conglomerate and diamictite (2800 m exposed, underlain by a further 750 m in drilling). Further southeast, near Olary, this unconformably overlies Benda Siltstone, including sedimentary ironstones, and Pualco Tillite, with a known combined maximum thickness of about 3 km. These sediments were deposited in the Baratta Trough encircling the Curnamona Province and represent the last major rift episode before the onset of sag-phase deposition. On the seismic transect, no major eastern bounding rift fault is evident, nor is the base of the Yudnamutana Subgroup clearly defined at the western extremity of the line in the Flinders Ranges. In the adjacent section below the Cambrian Moorowie Sub-basin (east of CDP 10000, Figure 5.4), the Yudnamutana Subgroup is represented by about 0.3 s TWT (~0.9 km), thinning eastward and being cut out by normal faulting at the western margin of the Benagerie Ridge.

Within the Benagerie Ridge, a restricted package of strong reflections overlain by weak reflections, down to a depth of about 0.5 s TWT, appears between CDP 4900 and CDP 5500 (Figure 5-6). This package is bounded by normal faults with very shallow apparent dips, and is clearly down-faulted into the basement. The chance discovery by one of us (WVP) in 1982 of a small outcrop of Pualco Tillite near the present seismic transect identifies the upper poorly reflective zone as Yudnamutana Subgroup; the underlying strong reflections are therefore interpreted as carbonates of the Mundallio Subgroup. The low apparent dips of the bounding faults of this small graben are probably due to their orientation oblique to the transect.

The late Sturtian Nepouie Subgroup is a post-glacial transgressive-regressive sequence and represents the first sag-phase deposition. The Tapley Hill Formation is transgressive over glacial deposits of the Yudnamutana Subgroup; its base (shown in mid-blue) is recognised on seismic images by low-angle cut-outs of underlying units. The Nepouie Subgroup does not show evidence of syn-depositional faulting, and thins gradually from about 0.7 s TWT (~2 km) at the eastern edge of the Flinders Ranges to about 0.1 s TWT (~300 m) at the eastern limb of the Moorowie Syncline. Its eastern limit appears to be due to gentle tectonic upturning and truncation by the unconformity at the base of the early Marinoan Upalinna Subgroup related to uplift of the Benagerie Ridge.

The total absence of Nepouie Subgroup on the Benagerie Ridge is confirmed by outcrop and drilling data, where a basal conglomerate of the Upalinna Subgroup unconformably overlies Palaeoproterozoic and Mesoproterozoic rocks (base shown on seismic images in pink). The conglomerate grades up into redbeds of the Angepena Formation and carbonates of the Etina

Formation. The Marinoan glacial Yerelina Subgroup is mainly represented by sandstone of the Elatina Formation in the adjacent Flinders Ranges as well as in drillholes on the Benagerie Ridge. These units are too thin to resolve seismically from the Upalinna Subgroup. The stratigraphy of critical drillholes was documented by Callen (1990).

The base of the Wilpena Group (shown in mid-purple) represents the Marinoan post-glacial transgression. Though very thick in the Flinders Ranges, the Wilpena Group is represented on the Curnamona mapsheet only by its two basal formations – Nuccaleena Formation (Marinoan 'cap dolomite') and grey-green siltstone of the Brachina Formation. In the Moorowie Syncline, the Wilpena Group reaches a maximum thickness of about 0.15 s TWT (~500 m) but is truncated by the Cambrian unconformity on the flanks of the syncline. Drillhole intersections on the Benagerie Ridge are also thin (<100 m).

The low-angle unconformity at the base of the Early Cambrian Hawker Group (shown in magenta) represents the ubiquitous hiatus in deposition at the end of the Proterozoic in Australia. Tectonism at this time involved very low-angle rotation and perhaps minor faulting, with general uplift of the Curnamona Province, so that the upper Wilpena Group was either never deposited or completely eroded before the onset of deposition in the Early Cambrian at around 530 Ma. The Hawker Group is carbonate dominated, including archaeocyathan limestone. The basal clastic Uratanna and Parachilna Formations of the Flinders Ranges do not occur on the Curnamona mapsheet , where only the overlying carbonates transgress onto the eroded Proterozoic rocks. The Hawker Group is represented on seismic by a zone of dominant, persistent reflections with a well-defined top and base.

The top of the Hawker Group (shown in red) is overlain by redbeds of the Billy Creek Formation, in turn overlain by the marine transgressive Wirrealpa Limestone. These latter units may be represented by a zone of impersistent reflections above the Hawker Group, but have not been differentiated in the interpretation. They are overlain by a thick succession of redbed clastics, the Lake Frome Group, with a known thickness of 2.7 km in the eastern Flinders Ranges. In the Moorowie Syncline, the seismic record shows about 0.6 s TWT (~1.8 km) for the combined Billy Creek-Wirrealpa-Lake Frome package. The upper parts of this succession have been intersected as bottom-hole samples in numerous shallow drillholes, mainly as a result of exploration for uranium in the Tertiary.

The thin Mesozoic and Cainozoic cover over much of the seismic transect is poorly resolved but, locally, horizontal reflections can be identified that truncate gently dipping older strata.

## DELAMERIAN OROGENY

Delamerian deformation commenced with northwest-directed thrusting toward the Gawler Craton at about the start of the Middle Cambrian (Preiss, 1995). It may be that deposition of the Lake Frome Group (possibly early Middle Cambrian in age) in the central Flinders Ranges and on the Curnamona Province was still under way after deformation had commenced in the south. As deformation propagated northward, the rocks of the central Flinders Ranges were folded with two interfering fold trends, resulting in overall east-west contraction. The steep dips in Adelaidean rocks recorded at the western extremity of the seismic transect reflect this folding, and appear to be related to both east- and west-directed thrusts near the eastern edge of the Flinders Ranges, but there is no single fault defining this margin at the latitude of the transect as there is further north. This is also consistent with the absence of a well-defined fault scarp at this location. Further east, the Moorowie Syncline appears to be a Delamerian amplification of a possible depositional synclinal depocentre in the Hawker and Lake Frome Groups.

The extent of Delamerian reworking of the Curnamona Province basement in the region of the seismic line is uncertain. Some Neoproterozoic extensional faults in the basement may have been slightly reactivated as reverse faults, but this does not appear to have happened on a large scale. It is not yet clear how far these small thrusts persist into the overlying cover, and what is the nature of their terminations, but they do not affect the younger parts of the cover succession.

The eastern limit of the Flinders Ranges is marked by a monoclinal structure in the cover, possibly related to underlying relatively shallow-dipping thrusts. Although the details of this are not really clear on the seismic record, these faults appear to coincide with the eastern limit of very thick Yudnamutana Subgroup, which may have been confined by west-dipping extensional faults in the Sturtian. The monocline may therefore be a structure resulting from inversion of such faults in the Delamerian Orogeny. Further interpretation of this zone is warranted to attempt resolution of such faults.

## CONCLUSIONS

1. The seismic data clearly record the Neoproterozoic rift history of eastern South Australia. During this time, the Curnamona Province was established as a relatively stable crustal block that was surrounded by Neoproterozoic rifts. The seismic transect crosses the transition from this central cratonic zone into the zone of intense rifting in the Adelaide Geosyncline.
2. The seismic data record almost the whole depositional history from the Arkaroola Subgroup at the base to Lake Frome Group at the top.
3. The continuation of sub-horizontal layered rocks in the seismic record, beneath the inferred basal Adelaidean unconformity (irrespective of exactly where this is placed), suggests a situation similar to the Arkaroola-Mount Painter area, where the Arkaroola Subgroup is broadly structurally concordant with unconformably underlying Mesoproterozoic metasediments and metavolcanics.
4. Early mafic rift volcanics may be represented in the seismic images, but are less convincing than those in the Gawler Craton seismic.
5. Early Adelaidean clastic-dominated rift successions (Curdimurka Subgroup of Callanna Group, or Emeroo Subgroup of Burra Group) and the carbonate-dominated Mundallio Subgroup are confined to the western part of the transect; the eastern bounding rift faults are overstepped by younger strata in the Moorowie Syncline.
6. Gentle eastward tilting of the Burra Group by fault-block rotation before the Sturtian glaciation led to erosion of the upper Burra Group and the formation of an angular unconformity at the base of the Yudnamutana Subgroup.
7. The Nepouie and Upalinna Subgroups record sag-phase deposition, the latter overstepping the former onto the Benagerie Ridge where, apart from an in-faulted graben of Mundallio Subgroup and Yudnamutana Subgroup, the Upalinna Subgroup is the oldest cover unit.
8. The Wilpena Group is present on the Curnamona mapsheet only as a relatively thin remnant after Early Cambrian erosion.
9. Cambrian deposition of the onlapping Hawker Group and overlying redbeds was continuous from the central Flinders Ranges onto the Curnamona mapsheet, where these are preserved in the Moorowie and Yalkalpo Sub-basins of the Arrowie Basin, but the basal clastic units are missing over the Curnamona mapsheet.
10. Delamerian deformation resulted in folding of the thick cover in the Adelaide Geosyncline and, possibly, inversion of a Sturtian rift-bounding normal fault system, and very gentle folding of the Moorowie Syncline, with little effect on the basement, apart from minor reverse faults in the basal unconformity.

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# INTERPRETATION OF THE DEEP SEISMIC REFLECTION DATA FROM THE CURNAMONA PROVINCE, SOUTH AUSTRALIA.

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## INTRODUCTION

The deep seismic data in the Curnamona Province, South Australia, were recorded to at least 18 s two-way travel time (TWT), providing an image of the whole of the crust and the uppermost part of the mantle. Figure 6-1 shows an 18 s crustal scale interpretation of the Curnamona traverse 03GA-CU1. Figures 6-2, 6-3 and 6-4 show more details of the eastern, central and western portions of this traverse. The eastern half of the seismic section has a well defined Moho at ~13 s TWT (~39 km depth) with a strongly reflective crust above a non-reflective upper mantle. In the western half of the seismic traverse, the Moho is not as well defined as in the east, but appears to be undulating and slightly deeper than the eastern half.

The entire crust along the seismic line, 03GA-CU1 (Figure 6-5), can be subdivided into four approximately vertical segments:

1. an eastern segment that is strongly reflective with the crust partitioned into at least three subhorizontal layers (CDP 2001 to approximately CDP 5600);
2. a central segment in which the mid to lower crust is relatively bland (CDP 5600 to CDP 7000);
3. a highly reflective crust in the central western part of the line (CDP 7000 to CDP 9500); and
4. a weakly reflective far western end of the line (CDP 9500 to CDP 11366).

Because reasonably strong reflections occur at various crustal levels across the entire transect, it is considered that these segments represent geology and are not artefacts due to acquisition.

## EASTERN END OF SEISMIC SECTION (CDP 2001 TO CDP 5600)

The reflective lower crust extends from the NSW-SA border at the eastern end of this traverse (CDP 2001) to the west for about 80 km before the lower crust loses its reflectivity and the Moho is not as clearly defined as in the east.

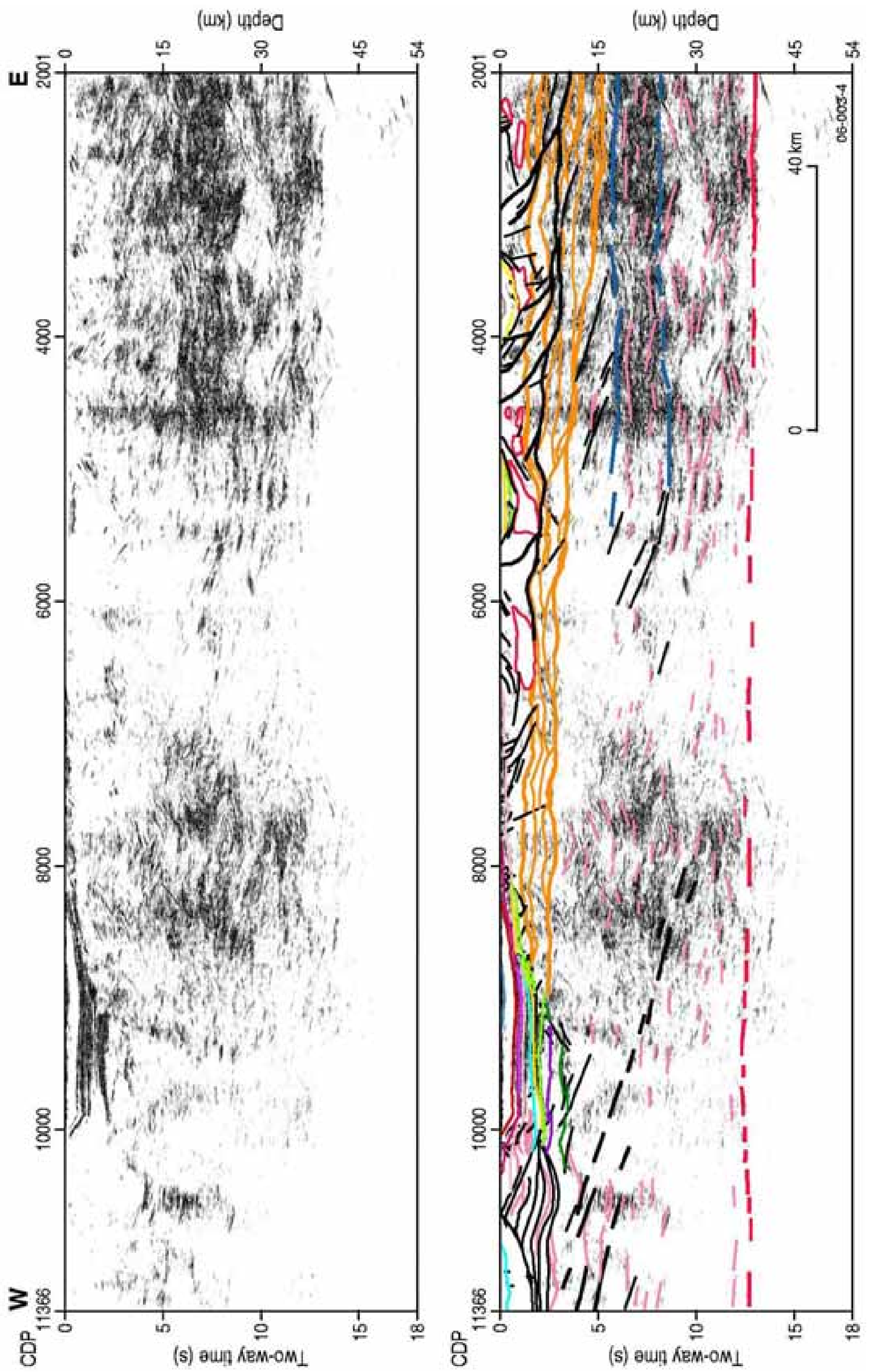

***Figure 6-1:*** *Top) Final migrated 18 s seismic section for Curnamona Province traverse 03GA-CU1. Bottom) Interpreted seismic section. Semblance filtering applied. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

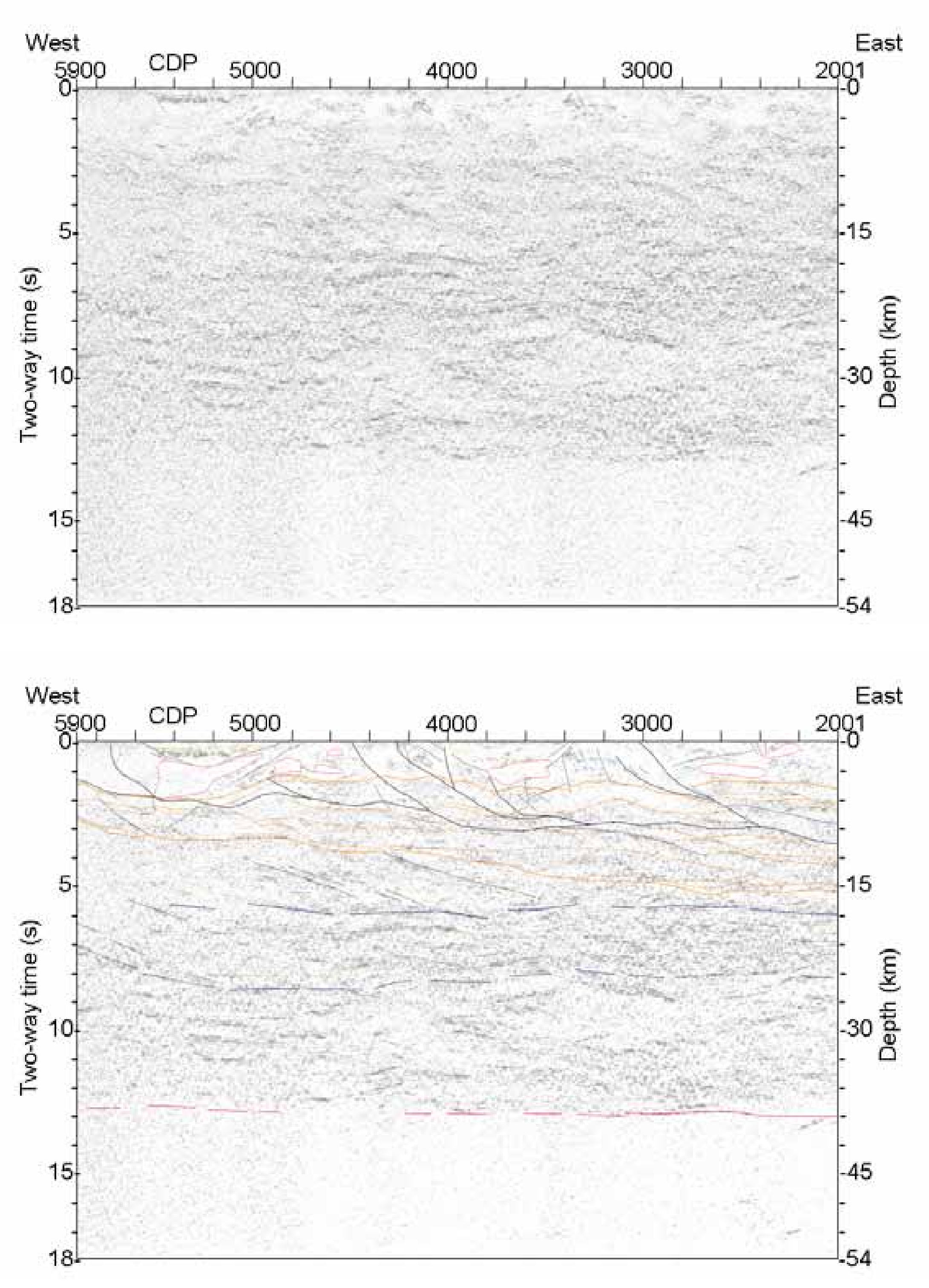

**Figure 6-2:** *Top) Migrated 18s section for the eastern third of Curnamona Province traverse 03GA-CU1. Bottom) Interpreted seismic section for above. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

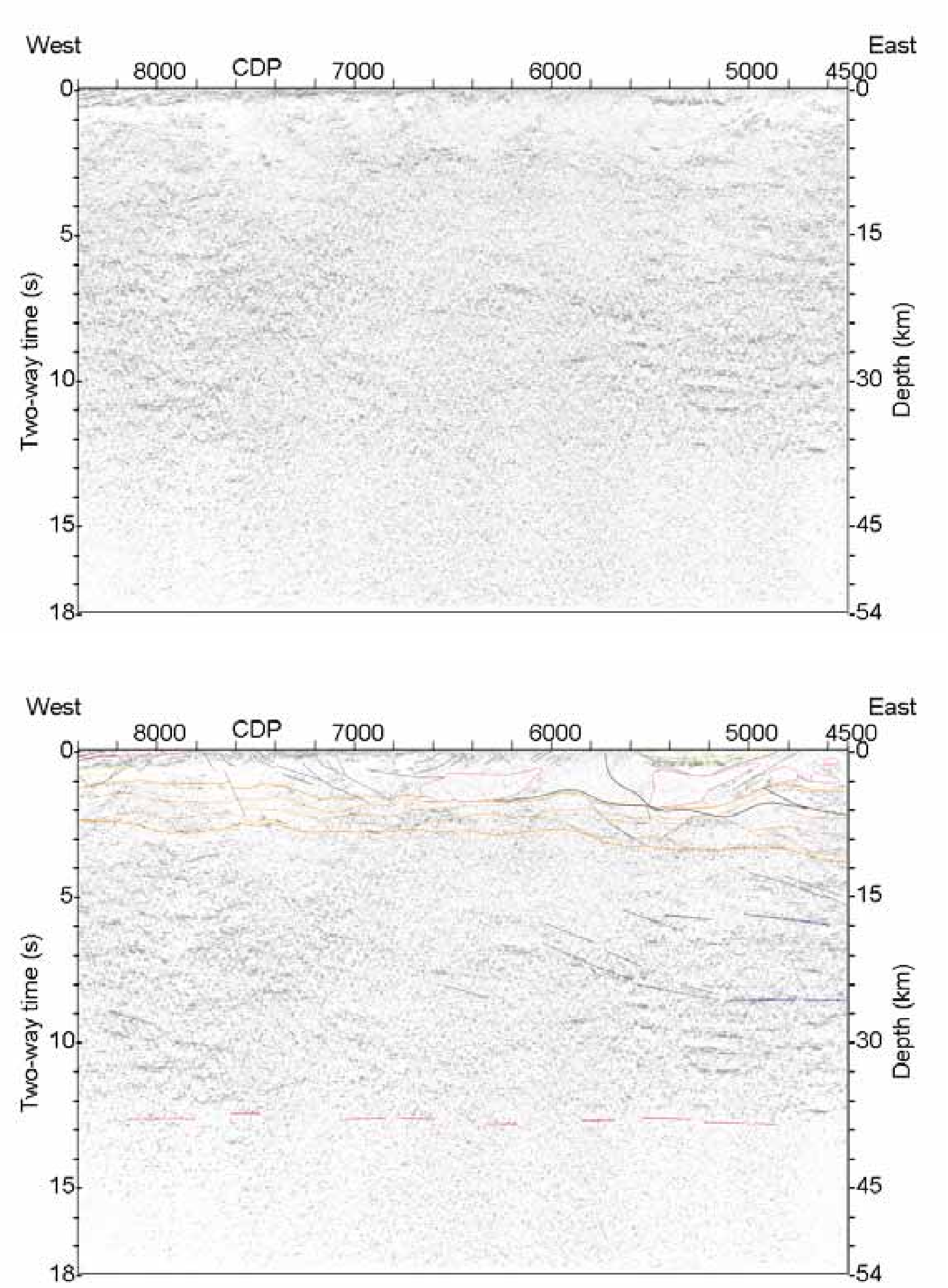

***Figure 6-3:*** *Top) Migrated 18s section for the central third of Curnamona Province traverse 03GA-CU1. Bottom) Interpreted seismic section for above. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

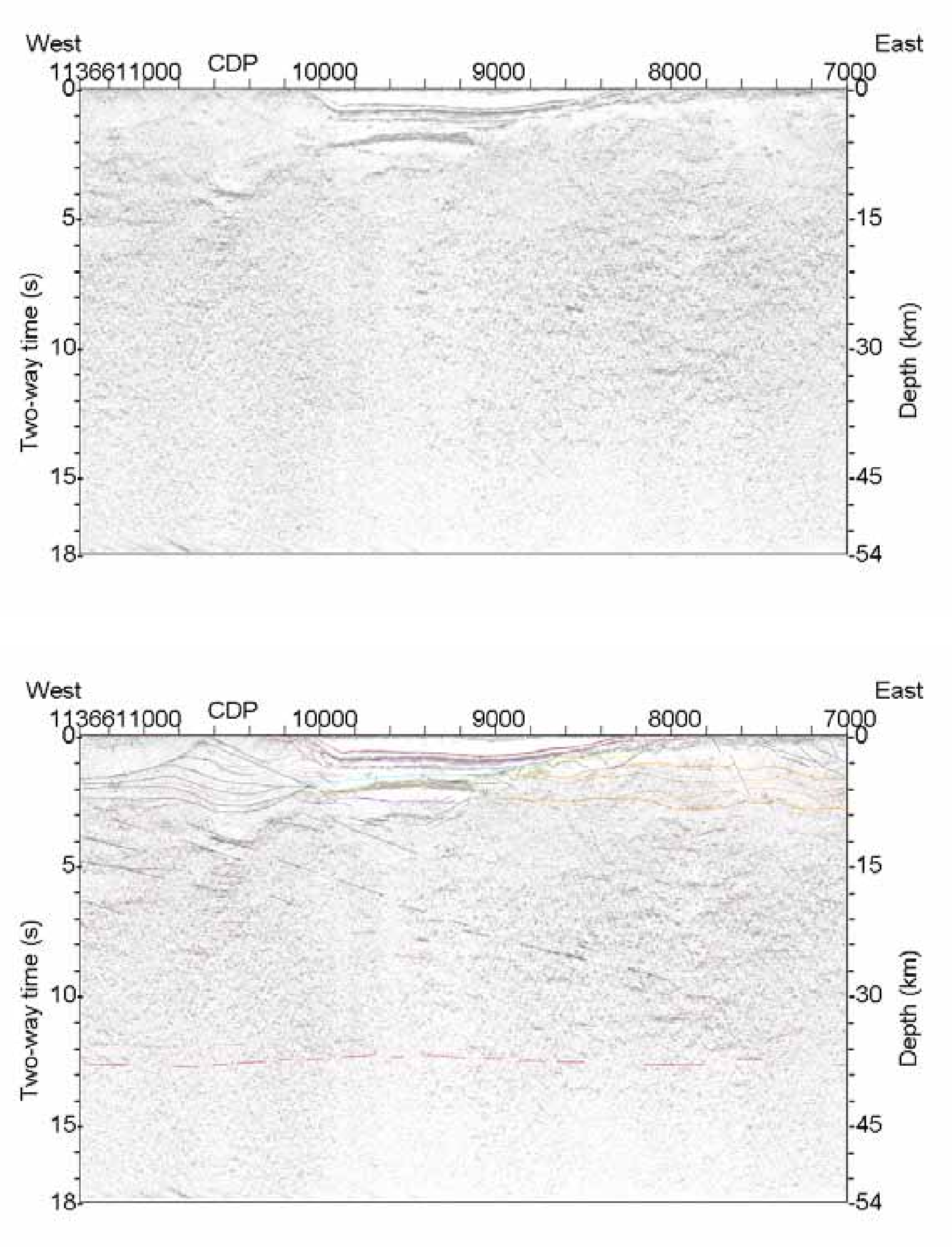

***Figure 6-4:*** *Top) Migrated 18s section for the western third of Curnamona Province traverse 03GA-CU1. Bottom) Interpreted seismic section for above. Colour scheme is given in Figure 2-4. Horizontal scale is based on 1 CDP =20 m.*

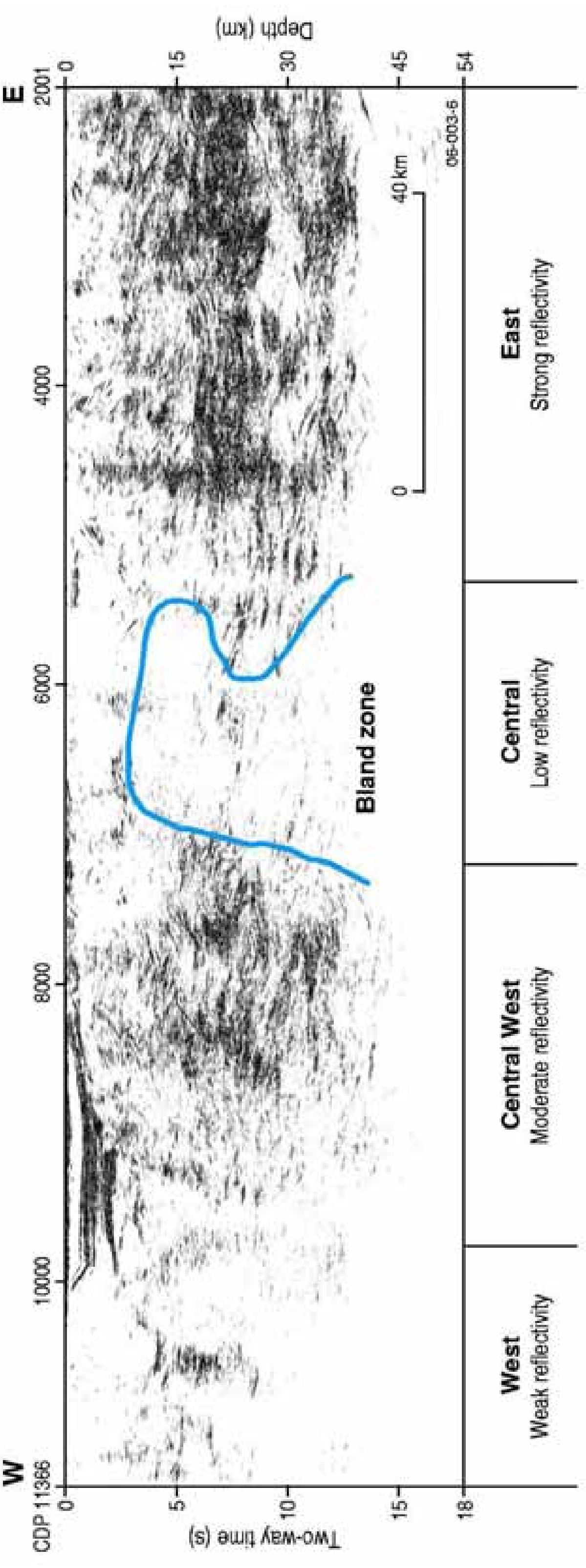

***Figure 6-5:*** *Image of the crust along the seismic line 03GA-CU1 showing that the crust can be subdivided into four approximately vertical segments. Also shown is the bland zone in the central part of the seismic section. Horizontal scale is based on 1 CDP =20 m.*

At the eastern end of the seismic line (Figure 6-6), the crust is divided into several horizontal “bands” of differing reflectivity.

1. Upper ~3 s TWT (~9 km). The base of this package is defined by an undulating, approximately subhorizontal band of strong reflections approximately 300 ms to 1 s TWT thick. The zone above this band of reflections appears to consist of a series of predominantly east-dipping structures. These structures are not imaged but are defined by sharp changes in orientation of the reflections, particularly the presence of ramp anticlines in places, indicating that the east dipping structures represent thrusts. The thrusts appear to sole onto the subhorizontal reflective band at approximately 3 s TWT (Figure 6-6).

2. Many of the reflections are parallel to, and above, these thrust faults. We interpret them to represent hanging-wall flats. These extend from CDP 2001 to at least CDP 4800. There is some difficulty linking the reflections with the mapped and interpreted solid geology on the surface, where the Curnamona Group is interpreted to be overlain by the Strathearn Group, although there is some support for the map interpretation in that reflections defining an “anticlinal” geometry occur where the oldest part of the succession is interpreted at the surface.

   There is possibly a granite pluton approximately 4 km across at very high crustal levels (~CDP 2300). It granite appears to be less than 1 km thick and is non-reflective.

3. The zone from 3 s - ~6 s TWT consists of bands of strong reflections, some with dips to the east. Again, the presence of ramp anticlines suggests that these reflections can be interpreted as a series of east-dipping thrust faults.

4. There is a package of strong subhorizontal reflections at ~5.5 s to 8-9 s TWT (~16 km to 27 km depth). The east-dipping faults at 3-5 s TWT do not appear to cut this package of reflections. This package extends for at least 60 km to the west of the NSW-SA border.

5. There is a relatively non-reflective irregularly shaped package at ~8-10 s TWT (~24-30 km depth).

6. There is a strongly reflective lower crust from ~10 s TWT to ~ 13 s TWT (~30-39 km depth), the base of which defines the Moho against a non-reflective upper mantle.

## MIDDLE PART OF SEISMIC SECTION (CDP 5600 TO CDP 7000)

Reflectivity in the uppermost part of the crust (0-~4 s TWT) is relatively low (Figures 6-1 and 6-3), although this part of the section is mostly non-reflective. Nevertheless, bands of reflections at ~3 s and 7 s suggest that the non-reflective areas relate to geology and are not an acquisition problem.

There is a distinctive bland zone in the middle to lower crust. Its significance is unknown but in terms of its origin it could result from reduced acoustic impedance contrasts due to partial melting, metasomatism, or be a zone of high fluid flow which has homogeneously altered a large part of the crust. It is interesting to note that similar bland zones have been noted on seismic sections in the Olympic Dam and Kalgoorlie regions.

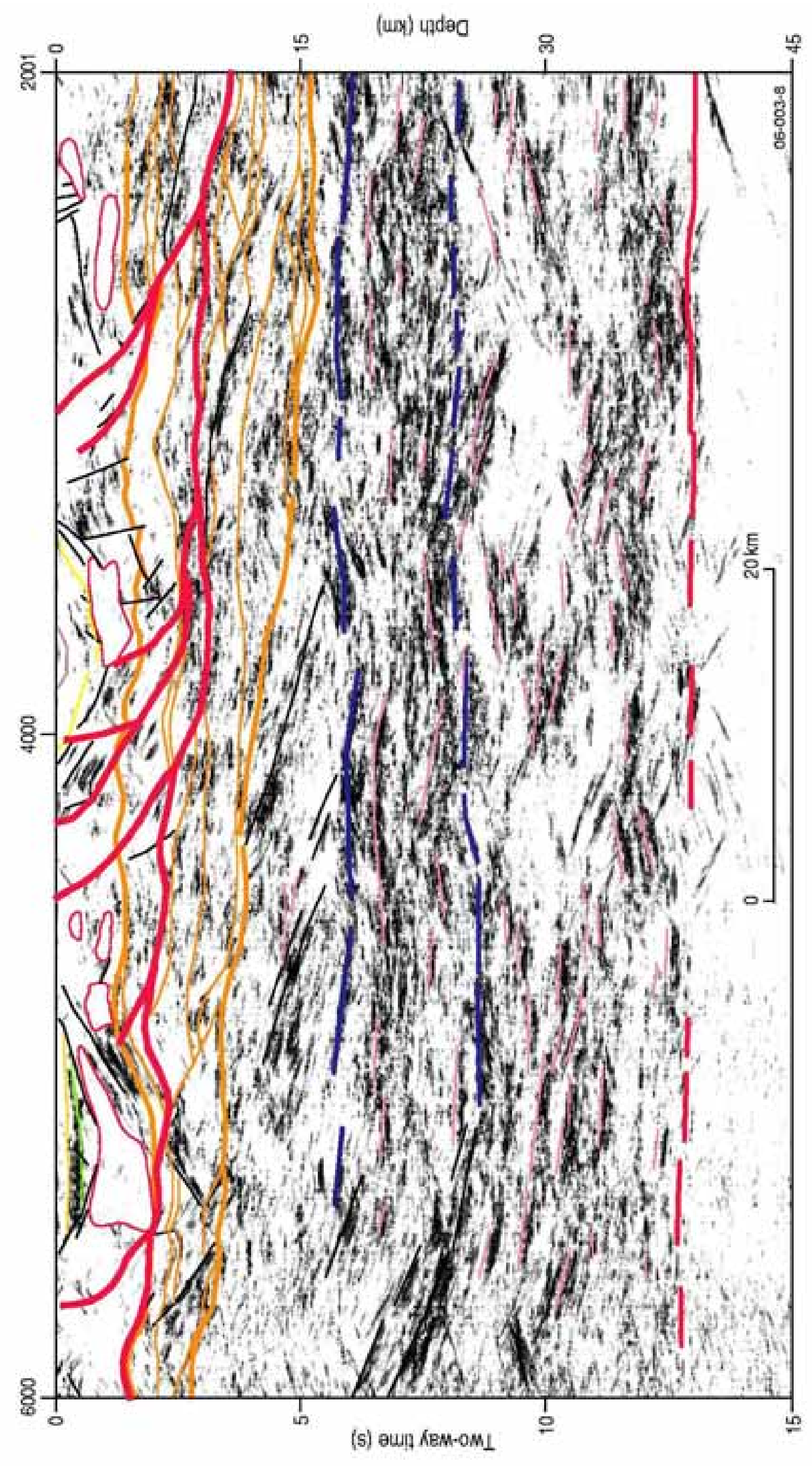

***Figure 6-6:*** *Migrated 18 s section for the eastern third of Curnamona Province traverse 03GA-CU1 showing the geological interpretation. Shown in bold red colour are the east-dipping thrusts that appear to sole onto the subhorizontal reflective band at approximately 3 s TWT. Semblance filtering applied. Horizontal scale is based on 1 CDP =20 m.*

## CENTRAL WESTERN PART OF SEISMIC SECTION (CDP 7000 TO CDP 9500)

The Moho in the central western and far western end of the seismic line is more difficult to define than in the eastern part (Figures 6-1 and 6-4). At the far western end it appears to be at about 13 s TWT, is undulating and appears to be slightly deeper than on the eastern part of the line.

In this part of the seismic traverse, a westward-thickening wedge of Neoproterozoic-Cambrian sediments up to 9 km thick overlies basement. Much of the crust beneath this basin is highly reflective, but it is not as obviously partitioned into subhorizontal layers as the eastern part of the traverse.

## WESTERN END OF SEISMIC SECTION (CDP 9500 TO CDP 11366)

At the western end of the seismic traverse, the Neoproterozoic rocks pass westwards into the even thicker, and more highly deformed, cover of the same age in the Flinders Ranges. Here, the crust is weakly to moderately reflective beneath the near surface triangle zone, the upper part of which appears to consist of west-directed thrust sheets (Figures 6-1 and 6-4). The reflections generally have apparent dips that are gentle to the east.

## KEY STRUCTURES

Superimposed on the crustal reflectivity patterns described above, are a series of narrow zones that we interpret as faults with apparent dips to the east (Figure 6-7). The western one continues to the west beyond the limits of the seismic section. Two others appear to cut almost the entire crust, from just below the Neoproterozoic basins to the Moho. The eastern two faults represent a zone that partitions the crust into two types with distinctive seismic properties, one underlying the Willyama Supergroup to the east and the other at great depth below the Flinders Ranges in the west. It is uncertain whether these represent different crustal blocks, or simply different styles or degrees of metamorphic or metasomatic alteration in the same crust, similar to the bland zone further east. If the faults represent a real crustal boundary, it raises the possibility of early amalgamation of terranes to form the deep crust beneath eastern South Australia.

If, in future, the seismic transect is extended to the west, it may resolve the relationship between the western block and the crust of the Gawler Craton, and would complement current geochemical and geochronological research at Adelaide University to determine the relationships between the Gawler Craton and Curnamona Province (Szpunar et al., 2005).

## SUMMARY

For the seismic traverse across the South Australian part of the Curnamona Province, the Moho is at ~40 km depth, but is slightly undulating in the west. The crust in the eastern part is partitioned into several subhorizontal layers. The Willyama Supergroup is possibly confined to being above a decollement at ~ 6km, with thin-skinned deformation in the upper crust. There is a bland zone in the central part of the section, and the lower crust in the west has a very different reflectivity pattern to that in the east. A Neoproterozoic-Cambrian basin up to 9 km thick occurs in the western part of the seismic transect and thickens further into the Flinders Ranges where it has been affected by severe Delamerian deformation. An east-dipping zone between two types of lower crust with different seismic properties may represent either a true crustal boundary or the margin of a zone of alteration.

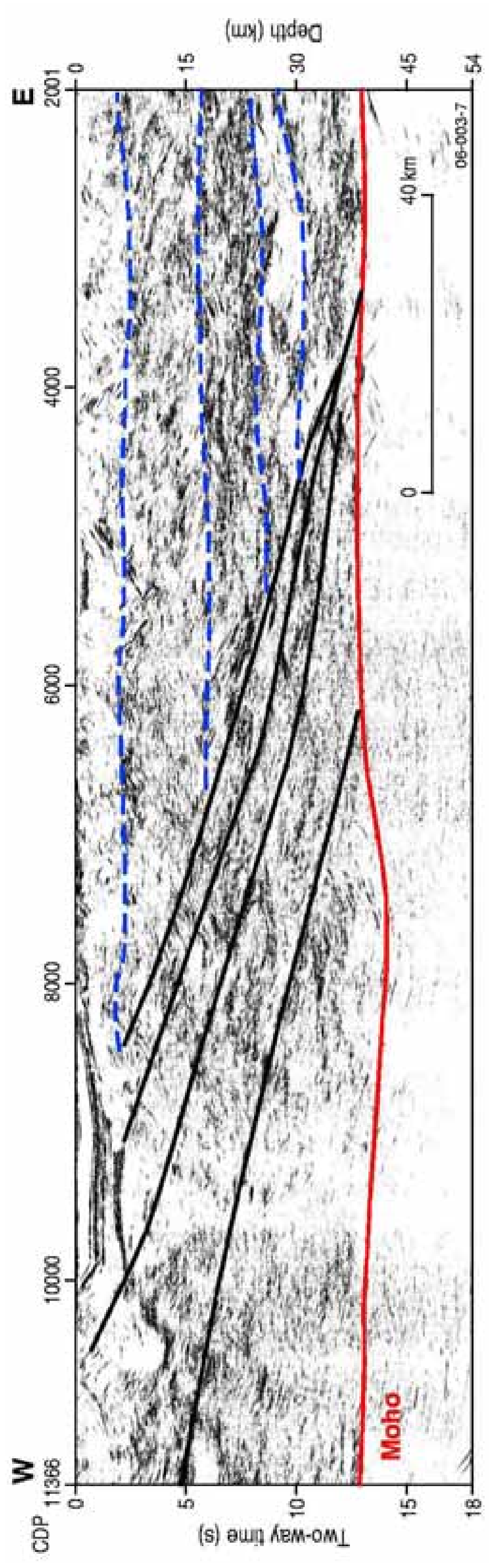

***Figure 6-7:*** *Image of the crust along the seismic line 03GA-CU1 showing key east-dipping structures that appear to transect almost the entire crust. Semblance filtering applied. Horizontal scale is based on 1 CDP =20 m.*

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# TECTONIC IMPLICATIONS BASED ON THE DEEP SEISMIC REFLECTION DATA FROM THE CURNAMONA PROVINCE, SOUTH AUSTRALIA

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## INTRODUCTION

The deep seismic reflection traverse across the South Australian portion of the Curnamona province has provided insights into the architecture and geological evolution of the Province. Here, we look at the implications of the deep seismic data for aspects of the tectonic evolution, structural history and mineralisation in the province.

## IMPLICATIONS FOR TECTONIC HISTORY OF CURNAMONA PROVINCE

Bimodal volcanic rocks, at ~1718 Ma are the oldest dated rocks in the Willyama Supergroup, while A-type plutons at ~1712 Ma intrude the sedimentary and volcanic rocks and are interpreted to be related to the early extensional phase of the Willyama basin (Page and Conor, 2006). Deposition and volcanism of the Willyama Supergroup were coeval with the Calvert and Isa Superbasins of the Mt Isa Inlier and probably occurred in the same or a closely related basin system (Giles and Betts, 2002; Page et al., 2005b). Many of the oldest preserved Willyama metasedimentary rocks show evidence of shallow-water deposition and must have been deposited on continental crust, but the nature of this crust is uncertain. The crust may consist of ancient crystalline basement rocks, but it may also include great thicknesses of supracrustal rock predating the oldest exposed rocks on the Curnamona Province, as is suggested by inherited zircons (e.g. the 1760 Ma Wallaroo Group of the eastern Gawler Craton, or equivalents of the 1800-1750 Ma Leichhardt Superbasin in the Mt Isa Inlier, which probably includes Wallaroo Group equivalents). A significant amount of crustal extension must have occurred to generate the bimodal volcanism and A-type granites; hence, the crust would have been relatively thin and highly extended at this time, with crustal thinning likely to have continued during sedimentation. The youngest bimodal magmatism was at about 1685 Ma (Page et al., 2005a). The upper parts of the Willyama Supergroup contain deeper water sedimentary rocks and possibly reflect sag-phase deposition. The youngest preserved sedimentary rocks are dated at c.1640 Ma (Page et al., 2003, 2005a), but deposition is presumed to have continued for at least 20 m.y. thereafter, thus contributing to the depth to which the Willyama Supergroup was buried to account for its metamorphic grade. Such deposits would have been equivalent to the upper McNamara Group of the Mt Isa Inlier (Page et al., 2005b).

The seismic section does not provide clear answers to the nature of the basement, but it does show that most of the crust, apart from some bland zones representing plutons or migmatitic and/or metasomatic alteration, is strongly layered, with subhorizontal to gently dipping reflections. It also suggests that the envelope of the Willyama Supergroup is relatively flat and is underlain by regional, sub-horizontal reflections (interpreted here as shears), which helps to explain why older rocks are nowhere observed at the surface. The layered crust beneath these shears may be structurally lower repetitions of Willyama Supergroup, an older supracrustal succession, crystalline basement, or a combination of all of these.

During the Olarian Orogeny (D1 to D4) at ~1600 Ma there must have been a significant amount of crustal shortening and thickening to produce crust up to 50-55 km thick. The seismic data shows that the present day crust is ~40 km thick and there has been 10-15 km eroded prior to eruption of the essentially unmetamorphosed Benagerie Volcanics, which rest unconformably on greenschist grade metasediments. This suggests that there has been crustal stacking in the order of 3-4 times to convert the thin crust at the time of extension to the 50-55 km thick crust at the end of the Olarian deformation. Uplift of the Willyama Supergroup was differential, with greater uplift and deeper stripping to the south. Moreover, at 1580 Ma when the Benagerie Volcanics rocks were extruded over exhumed greenschist facies of the Willyama Supergroup, the southern region, including the seismic transect, was still at depth while the coeval Bimbowrie granites were intruded. Some of the Bimbowrie granites have either migmatitic aureoles or show evidence of not having moved far from source, suggesting intrusion in a metamorphic environment. A major thermal anomaly is required to cause the generation of these magmas and eruption of the Benagerie Volcanics (as is the case for the synchronous Gawler Range Volcanics and Hiltaba Suite plutons to the west in the Gawler Craton) but its effect on the seismic signature of the crust is unknown.

Although an extensional detachment might provide a mechanism for rapid uplift and unroofing of greenschist facies rocks immediately after Olarian deformation, no such detachment is evident in the seismic section. The late (D4) retrograde shear zones that cut the deformed Willyama Supergroup are mostly steep, at least at the surface, and tend to be conjugate with strike-slip components of movement. East-northeast-west-southwest and west-northwest-east-southeast strikes appear dominant. Associated folds have east-west axes. The folds and the conjugate shears suggest that there was overall north-south shortening. This could have caused certain blocks to pop up, and might account for the rapid changes in metamorphic grade in the Willyama Supergroup, which are more unpredictable than the overall northerly decrease in gradient shown on regional metamorphic isograd maps of Webb and Crooks (2005).

The unconformity beneath the Benagerie Volcanics is only preserved in the central zone where the volcanic rocks occur. In the vicinity of the seismic transect and further south, it was uplifted above the present land surface so that deeply eroded coeval plutons and higher grade metamorphic rocks are now exposed. This implies differential uplift post-1580 Ma and therefore post-D3, which is consistent with a north-south shortening, retrograde D4 event. D4 shear zones cut some Bimbowrie-age granites.

In South Australia, in the vicinity of the seismic line, rocks at the surface have a metamorphic grade at or about the greenschist-amphibolite facies boundary (~10-15 km original depth). During the Olarian Orogeny (1600-1590 Ma) there was deformation, metamorphism and then intrusion of late-tectonic granites. To the north of the seismic line, the Olarian deformation was followed by rapid uplift and “peneplanation” before the 1580 Ma volcanic rocks were extruded onto a subhorizontal surface on the Benagerie Ridge. Thus, in the north, a vertical pile of Willyama rocks 10 km thick was eroded and removed rapidly. To the south of the seismic line, there must have been post-1580 Ma uplift as well, and perhaps this is the reason for exhumation to amphibolite-granulite facies levels.

Comparison of the central, cratonic portion of the Curnamona Province in South Australia with Broken Hill shows that there are greenschist- grade rocks of the same age as granulite facies in NSW (Page et al., 2005a, 2005b). This raises the question as to whether there are granulite facies equivalents of the Willyama Group at depth in the seismic section. Granulites do crop out in the South Australian, as well as in the New South Wales, portion of the Broken Hill Domain (Webb and Crooks, 2005), but this is about 60 km to the south of the seismic line. In the Broken Hill seismic section (Gibson et al., 1998), at the Mundi Mundi Fault and to the east, the faults cut deep into the crust and hence are able to transport the granulite-facies rocks to the surface. In South Australia, the upper crustal thrusts are thin skinned and focussed above the anastomosing shear zones. Hence, they appear not to cut deep enough to bring granulite facies rocks to the surface, and this is probably why pre-Willyama basement is not exposed. Thus, an unanswered question is whether the rocks below the anastomosing shear zones at 1-3 s TWT are granulite grade equivalents of the Willyama Group. There are at least 3 possibilities:

1. Using a Mt Isa "template", sedimentation and volcanism could have started at ~1800 Ma, with all the tectono-sedimentary episodes being recorded at Mt Isa. Of these, only parts of the Isa and Calvert Superbasins are represented by the known Willyama Supergroup. In this possibility, the older parts are still present, deeper in the crust and therefore imaged on the seismic section; but the Olarian tectonic style is such that they have not been exhumed. An older volcano-sedimentary succession like the ~1760 Ma Wallaroo Group of the eastern Gawler Craton, which has many similarities with the Willyama Supergroup, could also be represented. The younger parts (upper McNamara Group equivalents) were originally present, contributing to the burial of the Willyama Supergroup, but had been eroded prior to 1580 Ma (unless there are yet unrecognised remnants of such strata beneath the Benagerie Volcanics).

2. The current stratigraphic range of the Willyama Supergroup is approximately all that originally existed (but deposited on what?), and it has been structurally thickened by the Olarian recumbent isoclinal folding and thrusting. In this possibility, there would be many structural repetitions of the Willyama Supergroup. Late thrusts would then have exhumed the deeper levels in the southeast (e.g. Broken Hill) leaving shallow levels exposed in the northwest (Benagerie Ridge area). These shallow levels would still be underlain by higher-grade structural repetitions of the Willyama Supergroup.

3. Some combination of (1) and (2). In this possibility, some of the deeper crust consists of pre-1720 Ma rocks, but some are thickened and repeated Willyama Supergroup. If the pre-Willyama rocks are of similar composition to the Willyama Supergroup, they may be partial sources of the anatectic granites, as well as the deeper parts of the Willyama Supergroup itself.

The seismic data do not clearly differentiate between these alternatives. It is recommended that this question be revisited once the Broken Hill seismic section in NSW is reprocessed, to see whether packages of rock similar to the higher grade Willyama Supergroup east of the Mundi Mundi Fault can be identified beneath the sub-horizontal shear zones at the base of the interpreted low-grade Willyama Supergroup in the present transect.

## IMPLICATIONS FOR STRUCTURAL HISTORY

The following is a brief summary of the structural fabrics.

1. D1/S1 = bedding-parallel fabric, with no associated folds recognised (Gibson, 2002; Forbes et al., 2004). Gibson and Nutman (2004) and Gibson et al. (2004) proposed that the S1 fabric

was produced by syn-sedimentary extensional shear zones. An alternative is that the S1 fabric could have formed either just before the onset of, or early during, regional folding (Flint, 2002).

2. F2 = isoclinal folds (with amplitudes up to 10 km long) that fold the S1 fabric, and have an associated S2 axial plane foliation. These folds are inferred to be recumbent, because large areas of exposed Willyama Supergroup are downward-facing domains, interpreted as the overturned limbs of regional nappe folds ( Clarke et al., 1987; Laing, 1996).

   The simplest interpretation would be that D1 and D2 are structural styles rather than discrete events, and deformation was continuous and progressive. Thus, whenever there is a bedding-parallel first foliation it is called S1 and folds that deform this foliation are called F2, but there is no proof that all the “S1” foliations or “F2” folds formed at the same time. It is unlikely that, at present, geochronology will be able to resolve these differences.

   It is possible that the main, subparallel reflections in the upper part of the seismic section represent the S1 fabric parallel to primary layering. In places, these reflections converge and merge, possibly representing hinges of near-isoclinal F2 folds.

3. F3 = upright folds, often open in style, that refold the recumbent D2 folds (Gibson et al., 2004; Forbes et al., 2004). For example, the syncline containing the Mooleulooloo Formation (~ CDP 3760, Figure 7-1) is an open, upright, F3 fold.

Whether D3 is a separate event or is part of an ongoing D2-D3 shortening event is unclear. Importantly, the northwest-verging F3 folds bring up deeper rocks in the south and east. F2 and F3 often produce interference patterns and one possibility is that their axes were orthogonal to each other (e.g., Gibson and Nutman, 2004). Alternatively, the interference patterns have been explained by sheath-like geometries for the F2 folds, that formed under a regime of northwest-directed tectonic transport, being overprinted by later north-south trending upright D3 folds (e.g., Forbes et al., 2004).

(4) D4 appears be a separate event, separated from D3 by intrusion of the anatectic granites. This probably reflects north-south shortening under retrograde conditions (Wilson and Powell, 2001). The Mooleulooloo Syncline is probably an F3-F4 fold interference structure, as may also be the Portia and Kalkaroo Domes.

A major problem is that reworking of the shear zones during the Delamerian Orogeny (Dutch et al., 2005) has reset many of the isotopic clocks, and in places produced new mineral growth. Some, but not all, D4 shear zones were reactivated in the Delamerian Orogeny, those in the south apparently at quite high grade (Dutch et al., 2005). At the latitude of the seismic line, however, there appears to be no evidence for any Delamerian metamorphism in the few Neoproterozoic sedimentary rock outcrops and drill core intersections, and the deformation is quite mild, without the formation of tectonic foliations.

What is the age of the high level thrusting? Folds observed in the seismic section are interpreted to be hanging wall anticlines that sit on the thrusts, which have an apparent west-directed sense of movement. These folds are relatively open and so the thrusts are interpreted to be syn-D3 structures. Field mapping shows that the folds verge to the northwest, and have faulted western limbs, as confirmed by the seismic data.

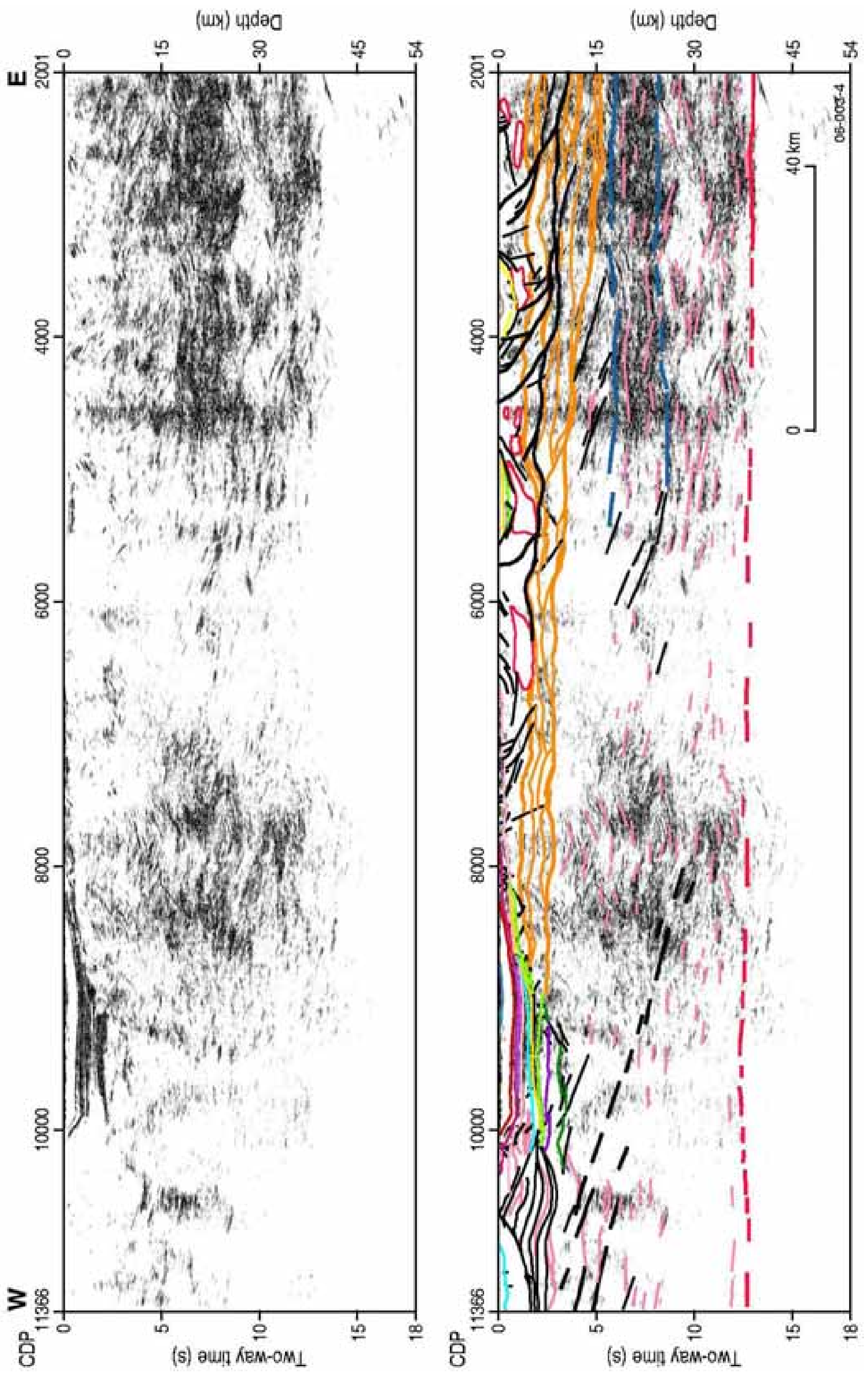

**Figure 7-1:** *Top) Final migrated 18s seismic section for Curnamona Province traverse 03GA-CU1. Bottom) Interpreted seismic section. Semblance filtering applied. Colour scheme is given in Figure 2-4.*

The upper crustal thrust belt sits on a “decollement” of strong reflectivity at 2-3 s TWT. This can be tracked across the seismic section to the Neoproterozoic basin. This high level thrust belt propagated westwards, with the amount of displacement diminishing to the west and converted into broad wavelength folds in the near surface. This is consistent with observed fold trends – if the north-south folds on the Benagerie Ridge are F3, then F3 trends can be regarded as arcuate, in both Olary and Broken Hill Domains, with a centre of curvature around Lake Frome, and the swing in the strike of fold axes is quite sharp at the latitude of the seismic line. Northwest-verging F3 folds in outcrops of the Willyama Supergroup would then be consistent with west-directed thrusting in the seismic transect.

A shallowly east-dipping surface in the deep seismic underneath the Neoproterozoic-Cambrian cover at the western end of the line appears to separate crust with different seismic characteristics (Figure 7-1). It is uncertain whether this boundary represents a juxtaposition of two different crustal blocks, or regions of the same crust that have undergone different alteration histories (e.g. partial melting or hydrothermal alteration). It may also represent the western limit of Willyama Supergroup and its underlying crust.

## IMPLICATIONS FOR MINERALISATION

We have interpreted major crustal scale structures that extend to the Moho on the deep seismic section. In other mineral provinces such as the Yilgarn and Gawler cratons, major structures that extend from the Moho to the uppermost crust are considered to be important for the transport of fluids from the lowermost crust and/or upper mantle to the upper crust (e.g. Drummond et al., 2000; Lyons and Goleby, 2005). Are the structures interpreted in the Curnamona seismic traverse important conduits for transporting fluids from the deep crust and/or mantle to the upper crust? If so, do favourable depositional sites exist in the hanging wall in the upper crust?

The Kalkaroo prospect is located on s or third order synthetic faults associated with hanging wall anticlines above a bounding east-dipping fault at depth. The fault beneath the anticline could have been the conduit for fluids moving from the deep crust to upper crustal levels where they could have migrated into favourable depositional sites associated with s or third order structures.

## SUMMARY

The Willyama Supergroup has been affected by thin-skinned deformation in upper crust during the Olarian orogeny, above a decollement at ~ 6km depth. In the western part of the line, a Neoproterozoic-Cambrian basin has been imaged above the Curnamona Province. It has been deformed by the Delamerian Orogeny, which increases in intensity towards the western end of the seismic traverse. A zone of reflections cutting almost the entire crust and dipping shallowly to the east could be a suture zone separating crust into two distinctive types, one underlying the Willyama Supergroup and the other at great depth below the Flinders Ranges. This zone could possibly have acted as a conduit enabling fluids to move from the lower crust and/or upper mantle up into the upper part of the crust.

## ACKNOWLEDGEMENTS

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# APPENDIX 1: ACQUISITION INFORMATION

## RECORDING EQUIPMENT

- **Aram 24 Seismic Data Acquisition and Processing System including**
- Real Time Parallel Processor Correlator.
- One (1) 10 metre Radio Mast on Recorder with High Gain Antenna.
- Forty Five (45) Remote Acquisition Modules (360 Channels).
- Forty Five (45) Telemetry Data Cables (360 Channels), 348 metres long with 8 Take-outs spaced at 43 metres apart.
- Geospace GS-32CT 10 Hz 395 ohm vertical geophones.
- Three Hundred and Sixty (360) geophone strings (360 Channels with 12 ph/group).
- Sensor SMT-200 Geophone Tester and QC system.

## SOURCE EQUIPMENT

- **Four (4) IVI Hemi 60 4x4 Articulated Buggy mounted Vibrators**
- Peak Force is 62,031 lbs per Vibe.
- Hold Down Weight is 63,000 lbs per Vibe.
- One (1) Pelton Advance 2 Model 6 PC based VIBRASIG.
- Real Time Similarity System.
- Five (5) Pelton Advance 2 Model 6 VCE's plus various spare boards.
- One (1) Pelton Advance 2 Model ESG for Recording Truck plus various spare boards.
- Three (3) Vibrators operating Online (186,093 lbs Force) with one on standby (Figure A1-1).
- Vibrators are equipped with Force Control and Ground Force Lock using M5 High Performance Accelerometers.
- Electronics are capable of correlating various individual sweep frequencies and compositing any range or variation of Up sweeps or Down sweeps within the same VP location. This process is Trade Marked as Varisweep.

***Figure A1-1:*** *Three Vibroseis trucks operating during the 2003-2004 Curnamona Seismic Survey.*

## RECORDING PARAMETERS – LINE 03GA-CU1

## RECORDING PARAMETER SHEET

| | | | |
|---|---|---|---|
| Client: | ANSIR | Crew: | 401 |
| Prospect Area: | Curnamona Province, SA | Line: | **03GA-CU1** |
| Survey: | 2003 Curnamona Province Seismic Survey | | |
| Instrument: | ARAM24 NT (Ver 1.309) | Direction of Rec: | East to West |
| Date Recorded: | 8 August to 12 August 2003, then 3 July 2004 to 11 July 2004 | | |

**Recording Parameters**

| | |
|---|---|
| Traces per File | 242 |
| Record Length | 18 sec |
| Sample Rate: | 2 msec |
| Tape Format | SEG-Y |
| Shot Points | 1000 to 5834 |
| Rec To Rec | 1000 to 5834 |
| Files | 2446 |

**Sweep Frequency**

| | |
|---|---|
| Sweep 1 | 7 to 56 Hz |
| Sweep 2 | 12 to 80 Hz |
| Sweep 3 | 8 to 72 Hz |
| Sweep 4 | |
| Sweep 5 | |
| Sweep 6 | |
| Sweep 7 | |

**Receiver Parameters**

| | |
|---|---|
| Station Interval | 40 m |
| Geophone Array Length | 40 m |
| Geophone Array Centre | Mid Station .5 |
| Geophone Type | OYO GS32CT |
| Strings Per Station | 1 |
| Connection | Series/Parallel |
| Spread Geometry | Symmetrical |
| # of Station Gap at SP | 0 |

**Auxiliary Traces**

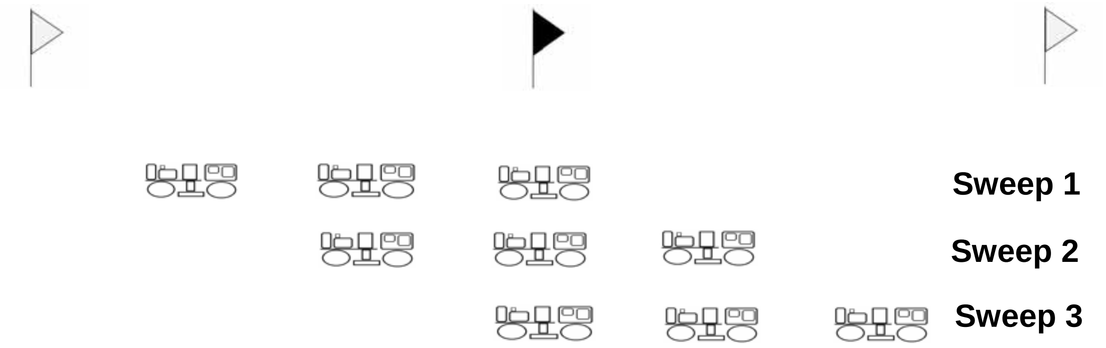
| | |
|---|---|
| Time Break | 241 |
| Time Reference | 242 |

**Source Parameters**

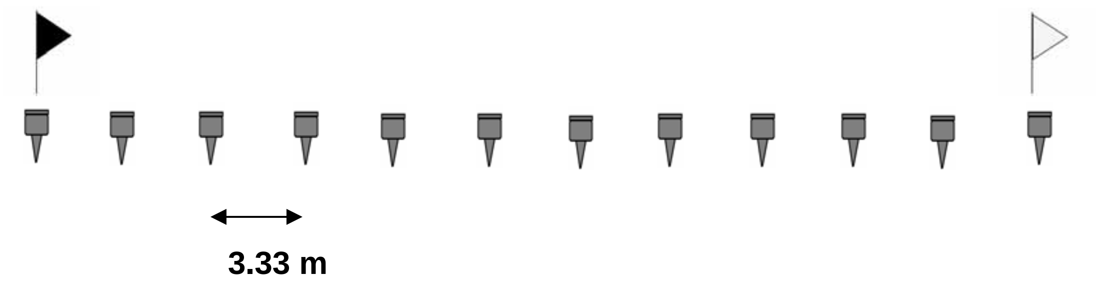
| | |
|---|---|
| No. of Sources on-Line | 3 |
| No. of Sweeps per VP | 3 |
| Sweep Length: | 12 sec |
| Sweep Type | Linear |
| Geophones Per String | 12 |
| Sweep Type Mono / Vari | Varisweep |
| VP Interval | 80 m |
| Source Array Length | 60 m |
| Vibe Spacing Pad to Pad | 15 m |
| Vibe Move Up | 15 m |
| VP Source Centre | On Station |
| Vibe Electronics | Pelton Adv II Model 6 |
| Vibrator QC | Vibra Sig |
| Force Control | Peak and Trough |
| Phase Lock | Ground Force |
| High Force Output | 90% |
| Pelton Rev. Level | 6E |

## SOURCE AND RECORDING ARRAY DIAGRAMS – 03GA-CU1

Source Array:
3 vibes over 60m, 15m pad to pad, centred on VP 15m moveups, 3 sweeps



Receiver Array:
12 Phones over 40m, 3.33m between Phones, Centred between pegs



# APPENDIX 2: CAPABILITIES AND LIMITATIONS OF THE SEISMIC REFLECTION METHOD IN HARD ROCK TERRANES

*Note: this paper is reprinted from previous Seismic Workshops.*

L.E.A. Jones[1,2], B.R. Goleby[1,2], and B.J. Drummond[2]

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## INTRODUCTION

The seismic reflection method was developed for petroleum exploration in sedimentary basins, where its accuracy, resolution, and depth penetration result in detailed pictures of structure and stratigraphy. The reflection method uses a controlled source which generates seismic waves that are reflected from interfaces between different rock units, as shown in Figure 1. An explosive or vibratory source is used. Continuous 2D coverage is achieved by moving sources and receivers along a seismic traverse.

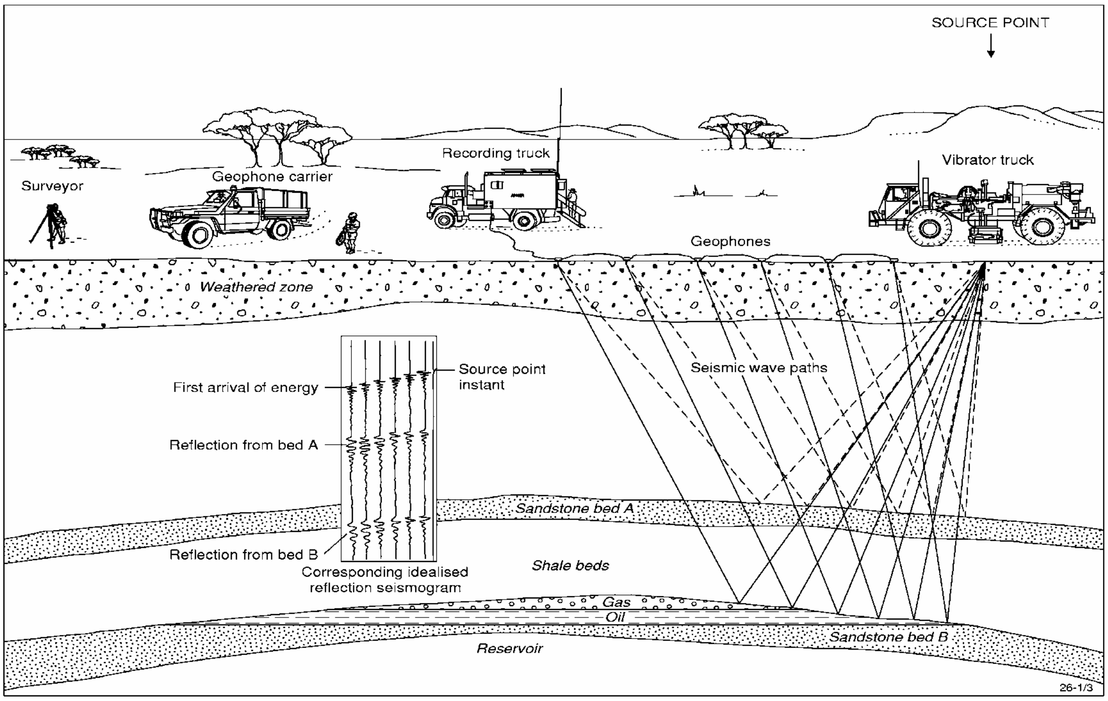


Figure 1. Schematic representation of a seismic reflection survey.

The Earth is not homogeneous or isotropic, but a good approximation in seismology is a system of layers, individually homogeneous and isotropic, which is why the seismic method works so well in sedimentary basins. In hard rock areas too, reflections are indisputably produced. The salient questions are: What causes reflections? What can't we see? What are the pitfalls?

Some of the key features of hard rocks are steep dips associated with folds and faults, and high seismic velocities. Steeply dipping events can be difficult to image. High velocities affect resolution, but also make it easier to stack reflections since there is less move-out. In hard rock terranes, there may also be more problems correcting for delays in the weathered zone and in getting sufficient energy through it. However, a counteracting factor is that hard rock should have lower intrinsic attenuation of seismic energy, resulting in greater depth penetration of the higher frequencies.

Much of the material covered here can be found in geophysics texts. However, we have selected and developed those aspects relevant to seismic imaging in hard rock.

## SEISMIC WAVES

A seismic (elastic) wave is a propagating oscillatory disturbance that travels as a series of wavefronts (equal amplitude of disturbance). Usually ray paths (path travelled by a point on a wavefront) are drawn, as in Figure 1. The distance between successive peaks (or troughs) is the wavelength, $\lambda$. The frequency of the wave, f, is the number of cycles per s, so that the velocity of the wave is $V = \lambda f$.

Two types of seismic body waves can travel within the Earth, namely P (compressional) and S (shear). In reflection surveys, P waves predominate, being preferentially generated by the commonly used sources. Surface waves (ground roll) can be a source of noise in reflection surveys, travelling along the surface at low velocity and arriving at the same time as reflections from depth.

Factors influencing P wave velocity in rocks include mineralogy, porosity (and cracks), pore fluid content, cementation and texture. For igneous and metamorphic rocks, the dominant factor is mineralogy, although micro-cracks in low concentrations can significantly reduce velocity. Empirical laws for such rocks show that the velocity is approximately proportional to density. In sedimentary rocks, the most important factors are porosity, pore fluid content and cementation. As a general statement, velocities are high in igneous and metamorphic rocks and lower in sedimentary rocks, particularly young sedimentary rocks.

## GENERATION OF REFLECTIONS

When a seismic wave encounters a boundary where there is an abrupt change in elastic properties, some of the energy is reflected depending on the size of the reflection coefficient, but most is transmitted into the s medium, as shown in Figure 2. Some energy will also be critically refracted along the boundary, and forms the basis of the seismic refraction method. The reflection coefficient RC is the ratio of the reflected wave amplitude Ar to the incident wave amplitude Ai and for near normal incidence (up to 20°) can be expressed as:

$$RC = \frac{A_r}{A_i} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

The product $\rho V$ (=Z) is known as the acoustic impedance, where $\rho$ is the density and V is the P-wave velocity. The larger the contrast in acoustic impedance, the larger will be the reflection coefficient. An impedance decrease causes a negative reflection coefficient, i.e., the reflected wave is reversed in polarity compared with the incident wave. Typically reflection coefficients are small, generally less than 0.05, but in hard rock terranes could reach 0.075 for a felsic-mafic contact ($\rho = 2.7$ t m-3 and V = 6000 m s-1 overlying $\rho = 2.9$ t m-3 and V = 6500 m s-1).

Thus the density contrast governs whether reflections occur at boundaries between different rock types (since velocity is proportional to density for igneous, metamorphic and well-lithified rocks). It is not likely that reflections will result from a foliated fabric within a rock, unless this is strongly developed into alternating bands of material on a macroscopic scale, such as in shear zones.

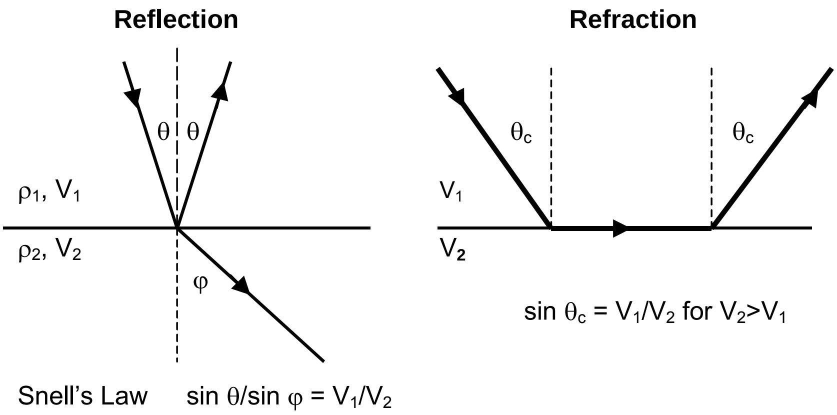


Figure 2. Reflection and refraction of a seismic wave at a boundary between two media with velocity $V_1$ and $V_2$ and density $\rho_1$ and $\rho_2$, respectively. The angle of incidence equals the angle of reflection. The wave is transmitted into the s medium with angle of refraction $\varphi$. For $\varphi = 90°$, the refracted ray follows the boundary (critical refraction).

As a seismic pulse (wavelet) travels down into the Earth, energy will be reflected back at each interface, with an amplitude governed by the reflection coefficient, and an extra time delay corresponding to the extra time down to and back from the interface. Thus a seismic reflection trace consists of a succession of "echoes" of seismic energy, as shown in the reflection seismogram in Figure 1.

Figure 1 also illustrates that the travel time for a reflection increases with increasing offset between source and receiver. It can be shown that the time, T, along a reflection ray path emerging at offset, X, from the source follows a hyberbolic relationship:

$$T^2 = T_0^{\ 2} + X^2 / V^2$$

where V is the velocity of the layer, and T0 is the two way travel time for vertical incidence. The difference between T and T0, known as normal moveout, decreases with both increasing T0 and increasing V. The high velocities typical of hard rock areas mean that moveout is generally small, so that uncertainties in moveout velocity are not so problematical for stacking the data. However, a corollary is that velocities for depth conversion are very poorly constrained.

For dipping reflectors, the above relationship is modified with V replaced by (V/cos $\alpha$) where $\alpha$ is the angle of dip, thus increasing the stacking (moveout) velocity.

## SEISMIC RESOLUTION

Seismic resolution deals with the question: How thick and how wide do features have to be to produce recognisable reflections on a seismic section?

## VERTICAL RESOLUTION

The concept of vertical resolution can be illustrated by considering waves reflected from a layer of thickness H and velocity V1 embedded in a medium of velocity V0, as shown in Figure 3. The reflection from the bottom will be reversed in polarity (reflection coefficient has opposite sign) and will lag behind the reflection from the top by a time ΔT, as shown in Figure 3. If the layer is thick, ΔT will be large and the two wavelets will appear as separate events. If the layer is thin, ΔT will be small and the two wavelets will almost cancel. A commonly used criterion for resolution is that interference effects are maximised when the wavelets are separated by half a cycle, which corresponds to a layer thickness of λ/4 (λ being the dominant wavelength for the wavelet).

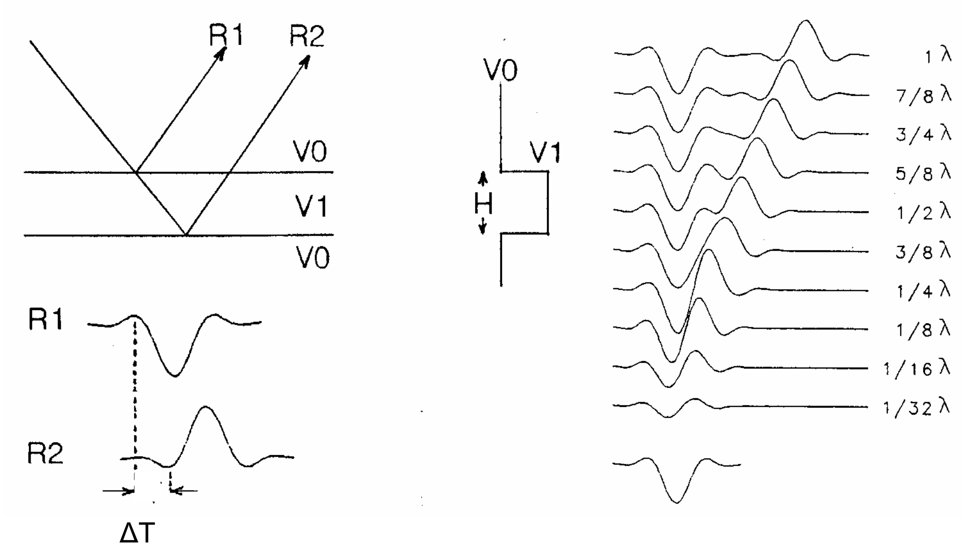


Figure 3. Vertical resolution (identification of an embedded layer) is determined by the superposition of reflections from the top and bottom of the layer. Because the two reflections are of opposite polarity they cancel for thin layers and reinforce for thicker layers.

The seismic response of layers of different thickness is illustrated on the right hand side of Figure 3. Thickness is parameterised in terms of λ. A maximum response occurs for λ/4, but the top and bottom of the layer are not resolvable and it thus appears as a single interface. In practice, the layer can still be detected as it becomes thinner, but becomes progressively harder to see. Layers thinner than λ/32 would not be detectable. It is not until the layer thickness exceeds λ/2 that reflections from the top and bottom of the layer can just be seen as two events.

What are typical values of λ in hard rock areas? The range of frequencies (band width) contained in a seismic pulse is narrow, normally from 5 Hz to 100 Hz. Because the amplitude loss with depth depends on frequency, the highest frequencies are rare at depth. Typically, the dominant frequency would be 40 Hz or less, corresponding to a wavelength of 150 m for a typical velocity of 6000 m s-1. Layers would need to be greater than 75 m thickness to be identified as such. However, a layer of about 37.5 m will produce a strong response, even if it cannot be differentiated from an interface. It would not be possible to detect layers less than 5 m thick (and probably not even less than 10 m). Thus the vertical resolution in hard rock is not as good as in sedimentary basins.

## SHEAR ZONES

Shear zones are often very strong reflectors of seismic energy, due to their layered nature on a macroscopic scale. Bands of alternating low and high velocity (density) material can explain the seismic response as shown in Figure 4. Tuning of the interference between reflections from tops and bottoms of the layers can result in a much larger seismic response than for a homogeneous layer of the same total thickness (compare Figure 4(a) and (b)). Zones in which layer thickness is variable and less than λ/4 can still produce strong reflections as illustrated in Figure 4(c) and (d). Typically shear zones exhibit a strong amplitude response, which is spatially variable. If the amplitude response is due to constructive interference of reflections from many layers, then lateral change in layer thickness could explain the variability from trace to trace.

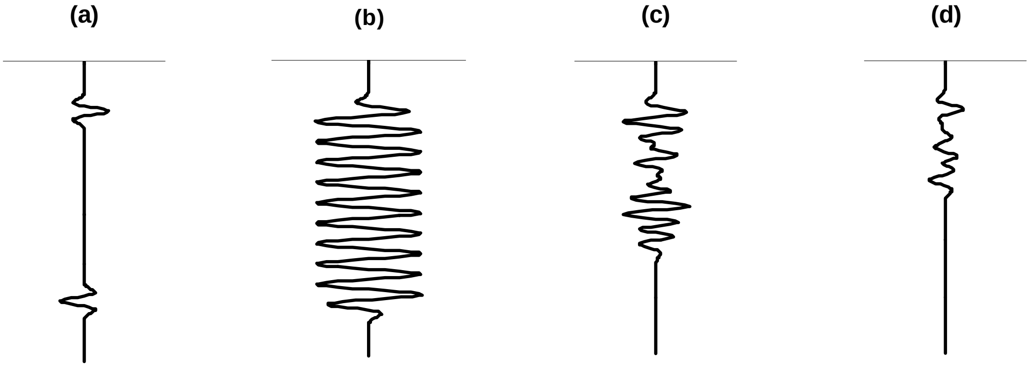


Figure 4. Modelled seismic response for (a) Single layer 4.75 λ thick. (b) 19 layers each of thickness λ/4 with the same absolute reflection coefficient as in (a) alternating in sign. (c) 19 layers as in (b) but with random thickness between λ/16 and λ/4. (d) 19 layers as in (b) but with random thickness between λ/40 and λ/10. Wavelength λ modelled as 120 m.

## HORIZONTAL RESOLUTION

Horizontal resolution is concerned with the minimum lateral extent of features that can be detected. Consider the case of vertical incidence for a reflecting point P as shown in Figure 5. Geometrical ray theory would predict that only point P contributes to the reflection recorded vertically above on the surface at S. Wave theory shows that not only P, but surrounding points within a certain radius also contribute to the reflection amplitude.

For down-going wavefronts from source S, zones on the reflector can be constructed such that the difference in path lengths from S is λ/4 as shown in Figure 5 (a). For two-way travel, the difference in path length will be λ/2. It can be shown that the innermost zone (known as the first Fresnel zone) makes the dominant contribution to the wave amplitude observed at S.

The first Fresnel zone has a radius equal to (λd/2)1/2 where d is the depth to the reflector. Thus, the width of the zone increases (resolution decreases) as both depth (two-way time) and dominant wavelength increase. In practice, features smaller than the Fresnel zone will not be resolved, since the reflected wave amplitude depends on the average properties over the width of the Fresnel zone.

In Figure 5 (b), two-way time (s) for the hard rock areas can be converted to depth (km) by multiplying by 3, using a typical velocity of 6000 m s-1. For mid-crustal depths of ~24 km (TWT

= 8 s), reflecting bodies must extend over a kilometre or two to be visible. As shown in Figure 5 (b), horizontal resolution is poorer than it would be for a typical sedimentary basin, i.e. the Fresnel zone is larger for hard rock areas, because of the greater wavelength (~150 m). However, because of the mathematical formulation above, the Fresnel zone radius increases by a factor of only 1.4 for a doubling of the wavelength, for features at the same depth.

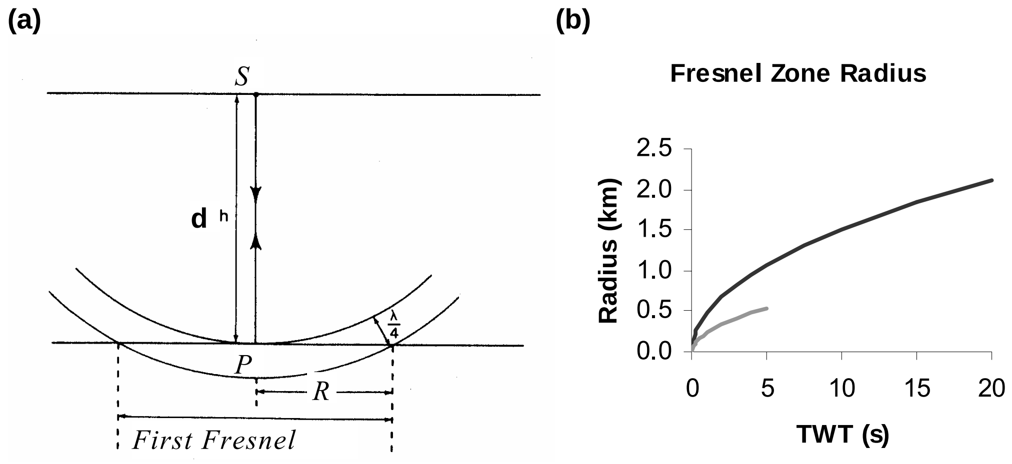


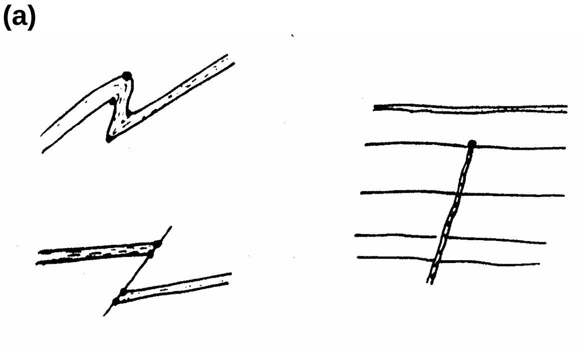
Figure 5 (a) Representation of the reflector zone (first Fresnel zone) contributing to the amplitude of a wave reflected back to S. (b) Radius of the first Fresnel zone for typical hard rock areas (black) and sedimentary basins (grey) versus two-way time (TWT).

## DIFFRACTIONS

When a seismic wave encounters a feature whose dimensions are comparable to, or smaller than the wavelength, the wave is diffracted, rather than reflected or refracted. Since the seismic wavelength in hard rock is typically 150 m, there will be many instances where geological features are smaller than this. Diffractions are commonly produced from very small geological structures or where continuous reflectors suddenly stop. Examples such as tight bends on folds, ends of fault-truncated layers, and tips of dykes are illustrated in Figure 6 (a).

The generation of diffractions can be explained by treating the feature as a point from which sary waves radiate after excitation by the incident wave. An incident wave spreading out from a source at P1 in Figure 6 (b) will generate a returning wave that will travel back along the same path; similarly for point P2. On a seismic section, the returning wave is assumed to come from vertically below P1 and P2, and will lie along a hyperbolic curve as shown in Figure 6 (c).

The crest of the diffraction locates the diffracting point (in time and space). In practice, amplitude is stronger towards the crest of the diffraction curve. The curvature of the diffraction depends on the depth to and the velocity above the diffracting point, but standard overlay curves can be produced to differentiate diffractions from structure. Migration will collapse diffractions as described later. Diffracted waves will also fill in gaps in reflectors, thus making the seismic event appear continuous when the physical interface is not (another way of visualising the concept of horizontal resolution).



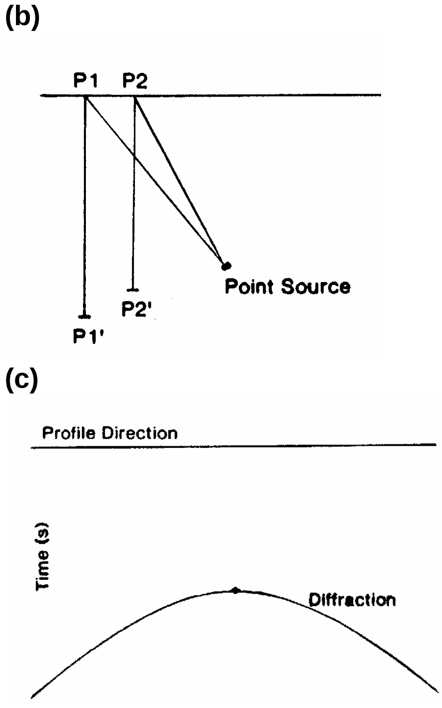


Figure 6. (a) Examples of geological structures that may produce diffractions; bends on folds, ends of faulted layers, and tips of dykes; (b) schematic illustration of the principle of diffraction generation from a point source; and (c) resulting diffraction curve from the point source shown in (b).

## DIPPING REFLECTORS

In hard rock areas, rocks are commonly highly deformed, resulting in steeply dipping rock units within folds, as well as faults of varying dips. Since the seismic method was originally developed for sub-horizontal layering within sedimentary basins, a critical issue is the greatest dip that can be imaged by the method in hard rock terranes.

The maximum dip is constrained by two parameters, the length of the seismic traverse and the duration of the seismic record. The general picture is illustrated in Figure 7. For near coincident source and receiver at P, a reflection will return along a path that is perpendicular to the reflector. To be imaged from P, sub-horizontal reflectors must lie below P, but steeply dipping reflectors will lie off to the side by a considerable distance. Thus a seismic line must be long enough to encompass both the reflecting surface and the seismic reflection system. In addition, recording time must be long enough to record reflections from the offset reflectors.
Figure 8 shows this relationship for a typical deep crustal seismic survey in hard rock. Note that a recording time of 20 ss would be necessary to record reflections from a distance of 60 km, assuming a velocity of 6000 m s-1. A semi-circular region in the Earth, centred on the observation point, is divided into equiangular segments. Each segment shows the zone within the Earth where a particular range of dips will be imaged, out to a distance of 60 km. For example, in the segments labelled 70° to 80°, only reflectors with dips in this range towards the observation point will be imaged. In the 0° to 10° segments, only shallow dips will be imaged.

Consequently, shallowly dipping structures are imaged when the observation point is directly above, and continuous coverage will be obtained as the point moves along the line. Very steep dips near the surface can be imaged from the side. For lines of approximately 100 km length, it could reasonably expected that dips as high as 50° in the middle crust may be seen.

A further consideration concerns the survey acquisition parameters-whether these discriminate against steep dips at any frequencies of interest. In the field, geophone arrays are used to attenuate coherent noise and random noise, by summing the individual geophone responses. A source array is also used with typically three vibrators in line with moveup between sweeps. Arrays will pass vertically travelling energy, but will discriminate against horizontally travelling energy with wavelengths shorter than the effective length of the combined source and receiver array.

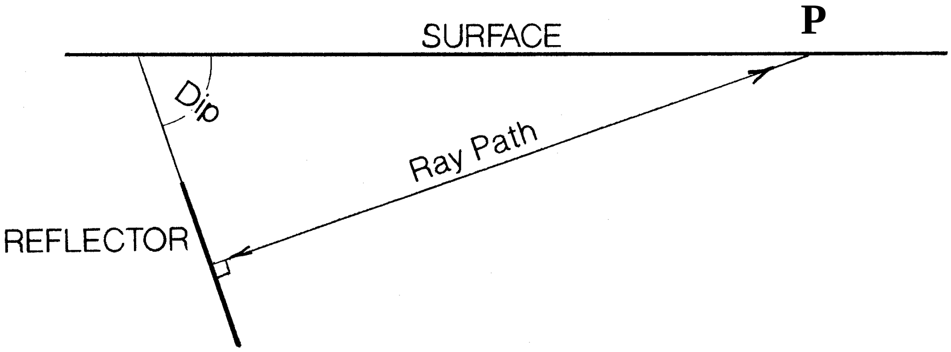


Figure 7. The length of the seismic traverse and the recording time determine the maximum dip that is imaged. For steep dips, the observation point must be off to the side, and the recording time must be long for energy to travel out to and back from the reflector.

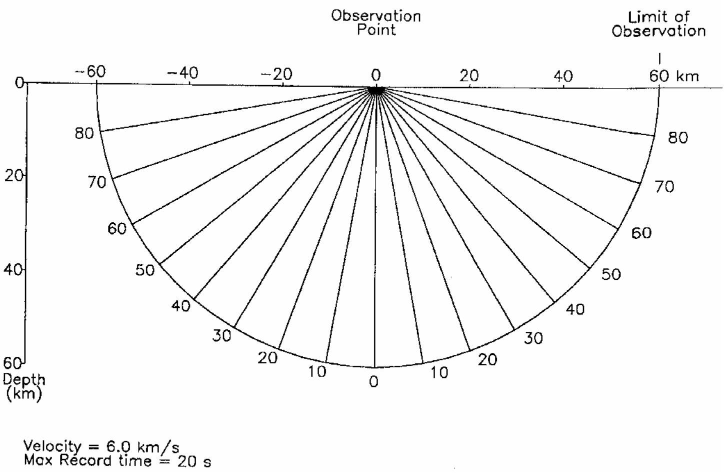


Figure 8. Each segment shows where dipping reflectors must be located, in order to be imaged from the observation point, for the dip range annotated on the segment edges.

For a ray incident at the surface at angle $\alpha$ (to the normal) the apparent velocity across the array is Va = V / sin $\alpha$ with corresponding apparent wavelength $\lambda a = \lambda / \sin \alpha$. For the ray path in Figure 7, $\alpha$ equals the dip angle. Thus, apparent wavelengths will range from infinite for reflections from horizontal reflectors to the true wavelength for reflectors with a dip of 90°. For frequencies from 40-100 Hz, the true wavelength $\lambda$ will range from 150 m to 60 m. Thus dip filtering by the array is not likely to occur for the typical combined array effective length of approximately 60 m.

A further consideration in imaging steeply dipping reflectors is that dipping reflectors require higher stacking velocities than horizontal reflectors. For example, where a horizontal reflector has a stacking velocity of 6000 m s-1, a reflector in the same material dipping at 60° would stack at 12000 m s-1 (V/cos α). The difficulty of simultaneously stacking reflectors of different dips is more pronounced at shallow depth (and TWT), since normal moveout is greater. Dip moveout (DMO) processing is required, but can be difficult to apply correctly for crooked lines where the fold may be low and the offset distribution irregular.

## MIGRATION

Migration is the process of moving reflectors to their correct positions and is essential in areas of steep dip and complicated structure. Because of the way seismic data are displayed, dipping reflectors are not correctly imaged, as shown in Figure 9.

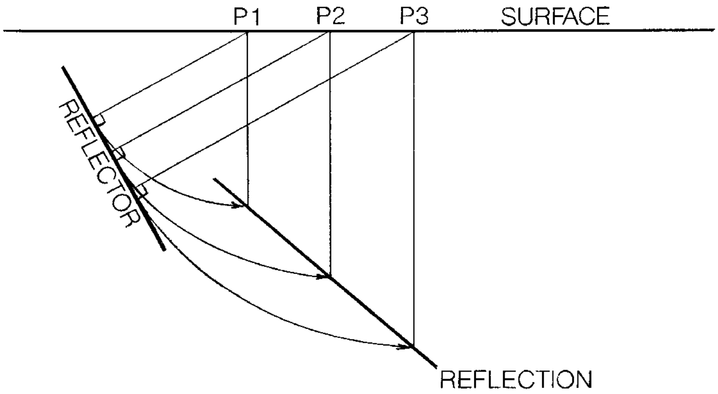


Figure 9. On a stacked seismic section, reflecting points will appear vertically below the coincident source-receiver points on the surface. Thus dipping reflectors will appear deeper than their true position, with a lower apparent dip. The process of moving reflectors to their correct positions is known as migration.

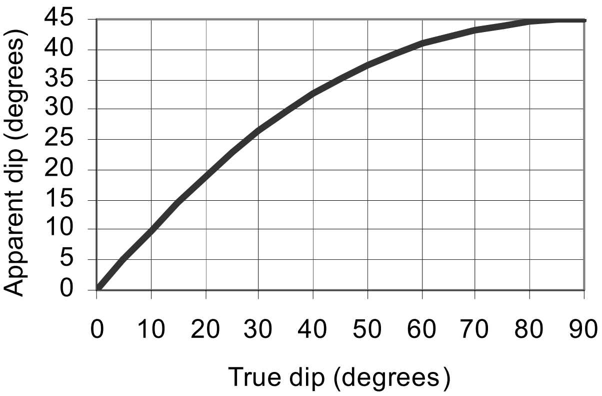
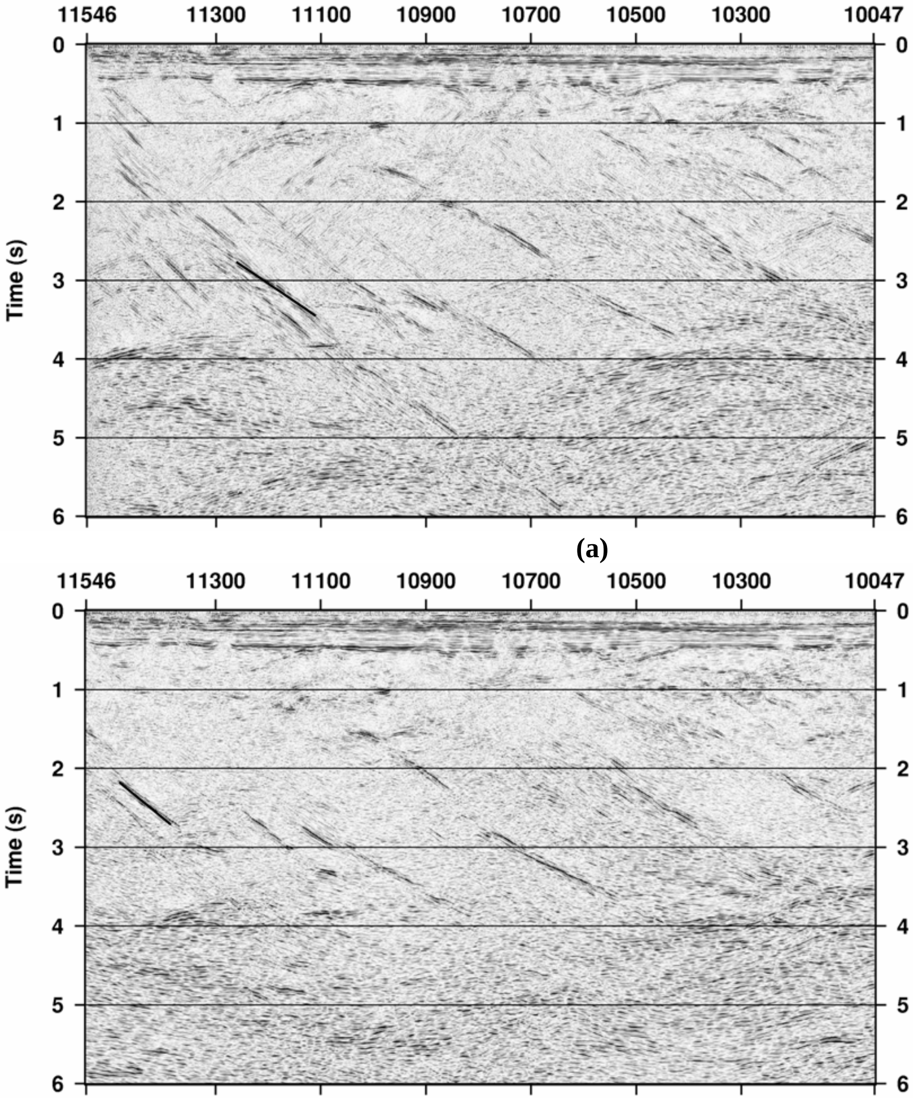


Figure10. Apparent dip of a dipping reflector on an unmigrated section versus true dip.

The ray paths for coincident source and receiver at points P1, P2, and P3 must be perpendicular to the reflector at the corresponding reflecting points. However, on the seismic section, these reflecting points appear to be vertically below points P1, P2, and P3. Thus the reflector segment is shifted downwards and its apparent dip, β, is less than the true dip, α, such that tan β = sin α.

Dipping reflectors, such as faults, and the flanks of synclines and anticlines, will not appear in their correct positions. Moreover, such features will appear to have lower dip as illustrated in Figure 10. A consequence of the relationship between true dip and apparent dip is that dips will never appear to be greater than 45° on an unmigrated section.

The effect of lack of migration is shown in Figure 11 (a) for the southern end of line 03GA-CU1. Arcuate features and dipping events can be seen throughout, crossing one another to give a 'basket-weave' pattern. Some of these are diffractions emanating from lithological discontinuities. Dipping features appear shifted downwards from their true position, and anticlinal features appear to be broad.



(a)

(b)

Figure 11. Seismic sections the Gawler Craton at V/H ~ 1. 100 CDP = 2 km. 1 s = 3 km. (a) Final stack. (b) Migrated section. The black line shows the position of a single dipping reflector before and after migration.

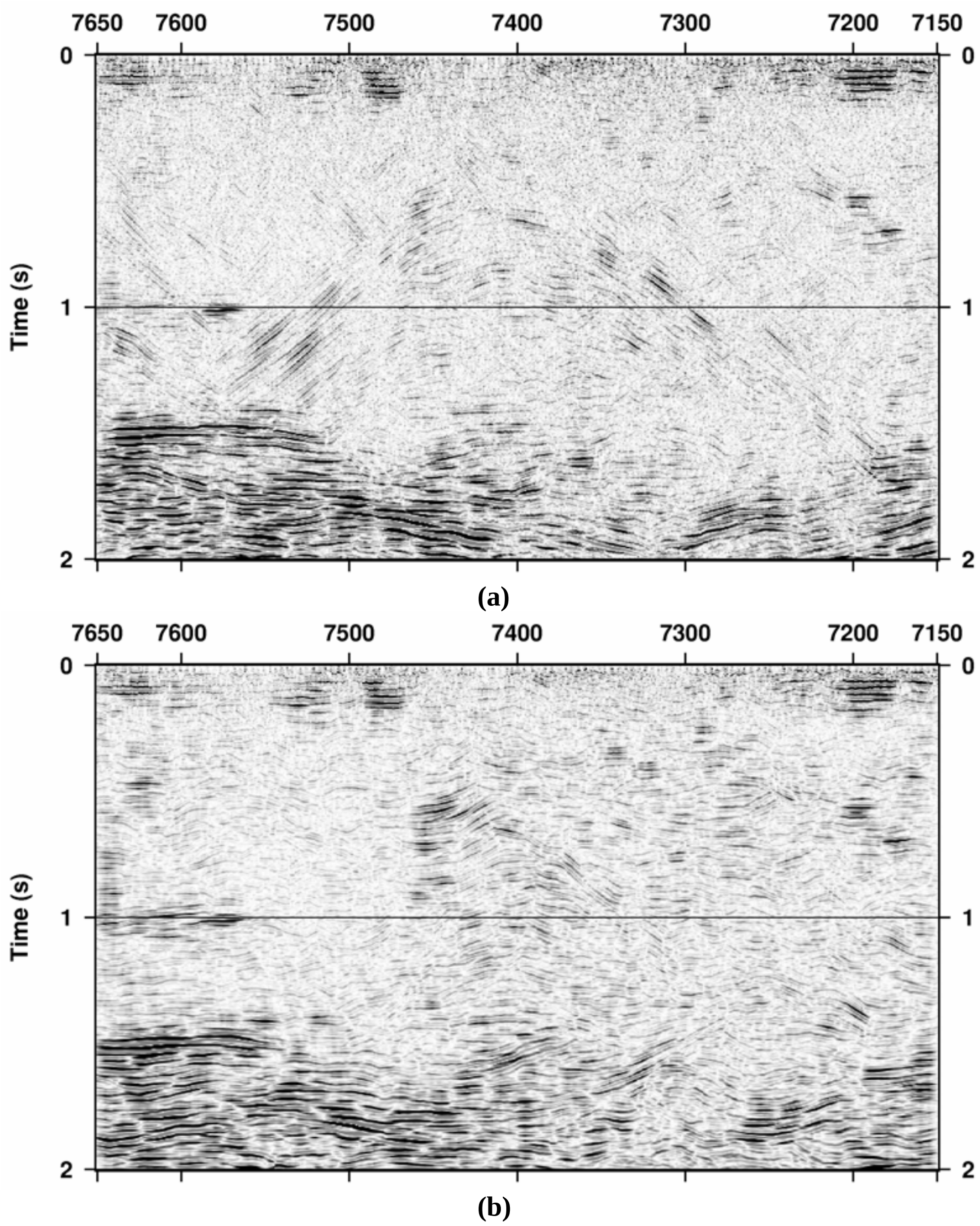


Figure 12. Seismic sections from the Gawler Craton at V/H ~ 1 and 100 CDP = 2 km. 1 s = 3 km. (a) Final stack. (b) Migrated section.

Conceptually, migration is a simple procedure. In principle, the position of the reflector shown in Figure 9 just needs to be swung back through an arc equal to the true dip angle. In actual implementation, migration is a complicated process, not only because of velocity variations, but also because of out of plane energy. Because most of the migration algorithms use the wave equation, diffractions will also collapse to a point, thus improving horizontal resolution. It is important to note that 2D migration can only be carried out in the presence of dip. Thus strike lines with apparently horizontal reflectors cannot be migrated. Migration works best for seismic data with strong lateral continuity. However, in hard rock terranes, lateral continuity of reflections is often poor, making it difficult to implement migration successfully.

The result of migration is shown in Figure 11 (b). Migration has collapsed e diffractions, cleaning up the image and leaving only reflections from continuous surfaces, which are shifted back to their correct position. Dipping parts of reflectors have moved up and become steeper and anticlines have thus become narrower in the process. More steeply dipping events have been migrated greater distances. For example, the steeply dipping reflectors on the left hand side of the section have been moved up to the left, off the end of the section. Note that care must be exercised in interpreting events on the ends of migrated lines. If events are dipping towards the end of the line, they will be moved updip, but no more data exists to be migrated to fill in the gap.

Several criteria can be used to decide whether the sections are under-migrated or over-migrated. Since migration moves reflectors upwards and steepens them, the termination of reflectors against another surface can be used as a guide to the correctness of migration. On under-migrated sections, the diffractions still look like diffractions, whereas on over-migrated sections, the diffractions turn into 'smiles'. Figure 12 shows a diffraction hyperbola which is collapsed by migration. If this diffraction is associated with the ore body, then in this case it would be useful to interpret both the stack and migrated sections.

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