Re-evaluation of Crustal Structure of the Broken Hill Inlier through Structural Mapping and Seismic Profiling

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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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The Broken Hill Exploration Initiative is a collaborative National Geoscience Mapping Accord project between the Australian Geological Survey Organisation, the NSW Department of Mineral Resources, and Primary Industries and Resources, South Australia

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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY
CANBERRA

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Summary

Deep seismic reflection data collected from the Palaeoproterozoic Willyama Supergroup by AGSO as part of the Broken Hill Exploration Initiative are at variance with previously proposed structural models for the region. Contrary to earlier expectations, the major structures in the Broken Hill region (1) dip southeast rather than northwest and (2) accommodate a much greater degree of thrusting, transposition, and internal disruption (imbrication) than previously envisaged.

Furthermore, many important shear zones extend to middle and lower crustal depths and have probably served as important conduits for fluid flow at various times; recognition of these structures not only has major implications for mineral exploration strategies relating to known Ag-Pb-Zn deposits in the Broken Hill region but suggests that the area may also have an unrealised potential for other forms of shear-hosted mineralisation (e.g. Cu, Au). Some shear zones flatten out at mid-crustal depths into major detachments. Tectonic transport on these and other structures recognised in the seismic profiles was largely directed towards the west and northwest.

Particularly conspicuous in the seismic profiles is a 20-25 km wide, southeast-dipping imbricate zone (central zone) centred on the Apollyon Valley shear zone; it has the character of a fold and thrust belt, and separates a western block characterised by sub-horizontal or shallow-dipping reflectors from an eastern block in which an apparent rift geometry (rotated fault blocks, asymmetric sedimentary basins) of uncertain age is preserved.

The central zone is bounded to the west by the Mundi Mundi Fault which may also constitute the boundary between the Olary and Broken Hill Blocks.

Superimposed upon the earlier structures are a large number of retrograde shear zones, trending northeast and northwest. Some of these shear zones may simply be reactivated older structures whilst others may owe their origin to late Neoproterozoic continental rifting or the early Palaeozoic Delamerian orogeny. Northwest-trending shear zones are host to hydrothermally altered ultramafic dykes which carry conspicuous Cu mineralisation. Whilst the age of hydrothermal alteration is not precisely known, the dykes are most likely time equivalents of the Little Broken Hill Gabbro recently dated at 827 Ma.

REGIONAL GEOLOGY AND TECTONIC SETTING OF BROKEN HILL AREA

The Broken Hill region lies just inboard of the late Neoproterozoic continental rift margin (Tasman Line; Fig. 1) and comprises rocks of the Willyama Supergroup, a varied sequence of Palaeoproterozoic sediments and minor felsic volcanic rocks metamorphosed up to the granulite facies (Willis et al., 1983; Stevens et al., 1988). High grade metamorphism and deformation in these rocks was largely complete by 1590 Ma (Page and Laing, 1992) and occurred in response to the Mesoproterozoic Olarian orogeny.

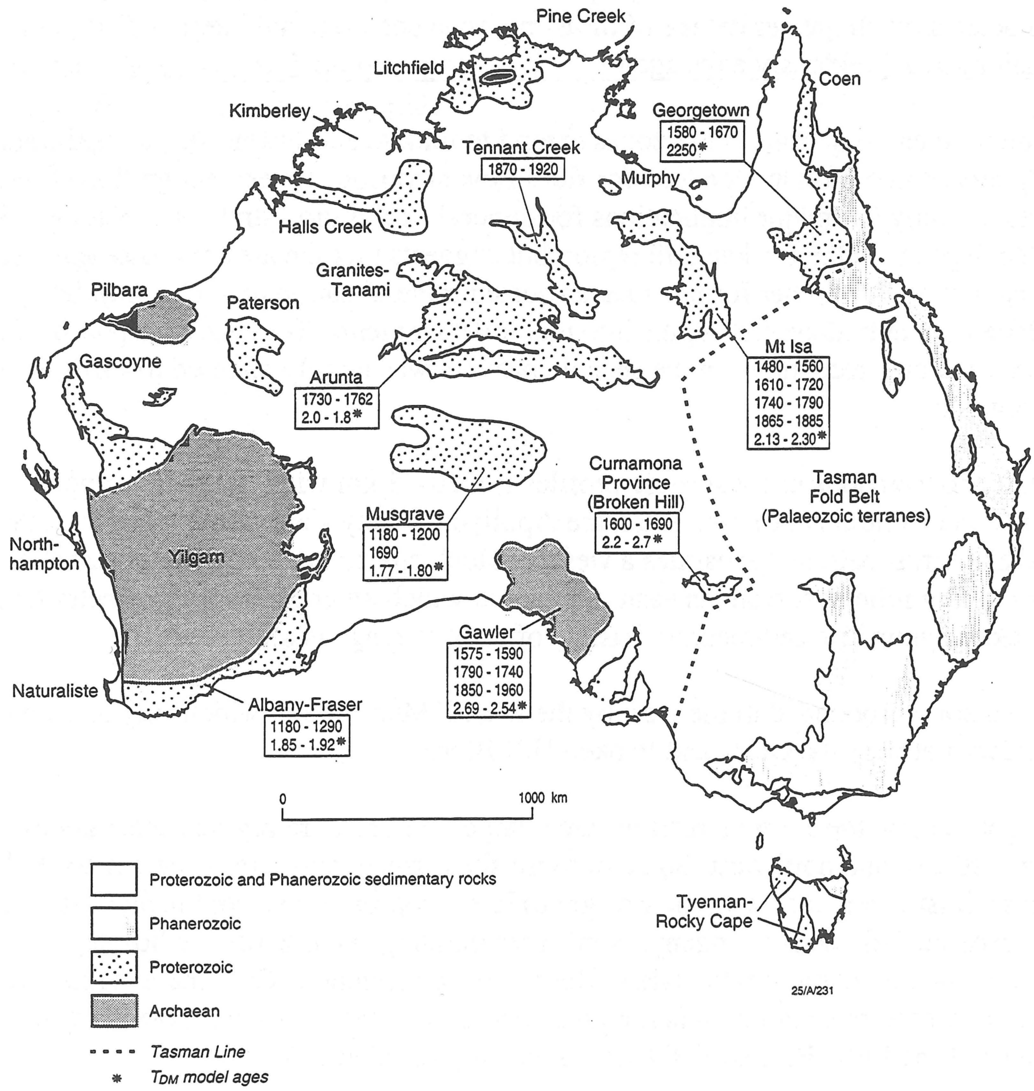


Figure 1: Location of Curnamona Province (including Broken Hill and Olary blocks) in relation to Tasman Line and Palaeozoic Tasman orogen. Limits of outcrop of Willyama Supergroup (Broken Hill) and other Proterozoic provinces are shown along with their U-Pb ages and T_{DM} model ages.

REGIONAL STRATIGRAPHY

Following detailed lithological mapping at 1:12 000 scale in the mid-1970's to early 1980's, staff of the New South Wales Department of Mineral Resources (NSWDMR) published the first comprehensive stratigraphic map for the Broken Hill region (Willis et al., 1983). Central to their analysis was the proposal that the original stratigraphy had been modified but not destroyed by the subsequent intense deformation. In essence the same stratigraphic units could be recognised in many parts of the Broken Hill block and neither the early Olarian deformation nor the many late stage retrograde shear zones had disrupted the stratigraphic sequence to any great degree. Transposition features, high temperature shear zones and other structures (eg. thrust faults) that might be expected in a multiply-deformed terrain were not conspicuously developed and lent confidence to the suggestion that repetitions in the

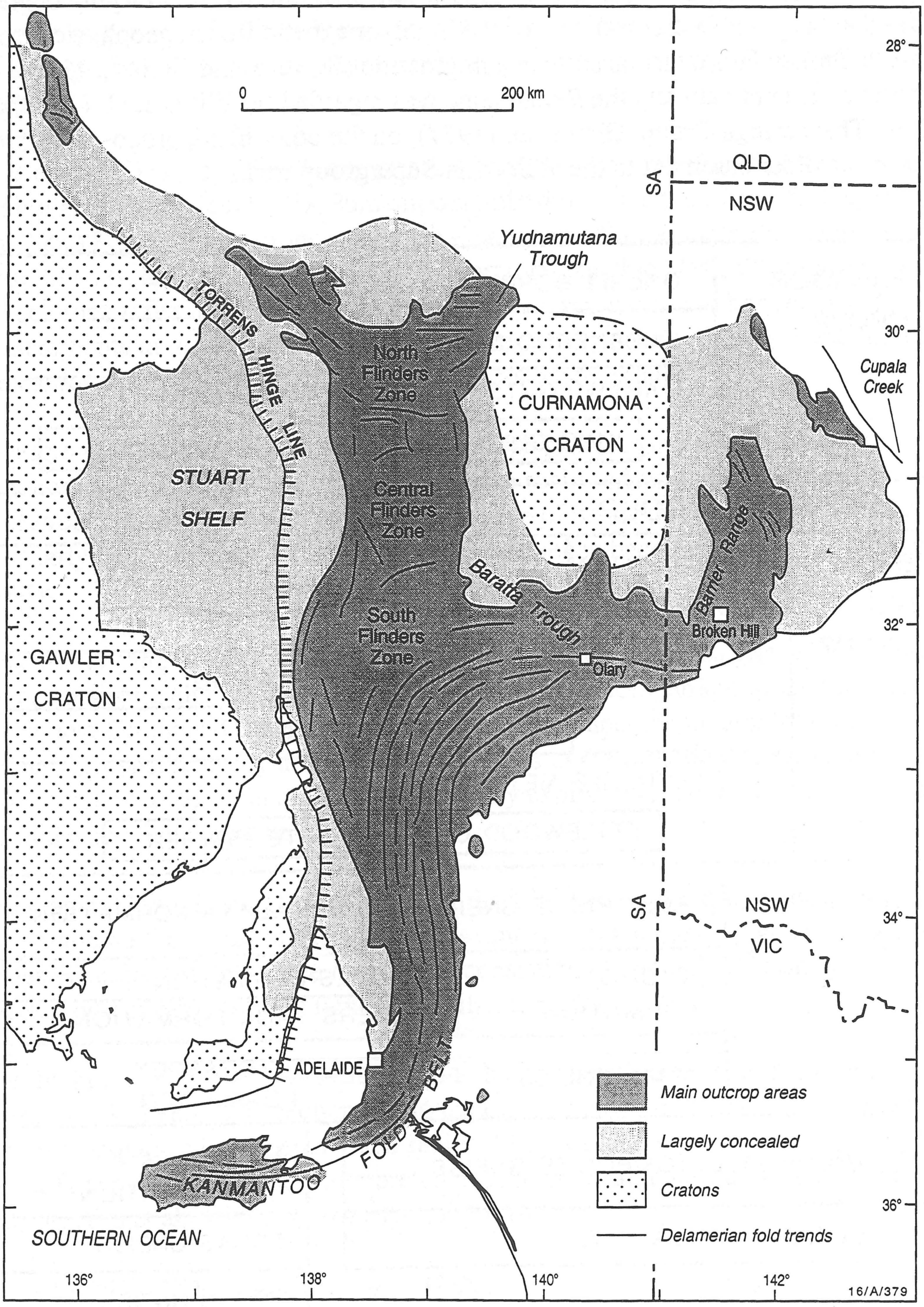


Figure 2: Location of Broken Hill and Olary areas and the extent of subcrop beneath younger sedimentary cover (after Preiss, 1987).

stratigraphy were due to the effects of folding, and particularly nappe formation (Marjoribanks et al., 1980; Laing et al., 1978; Laing, 1996), rather than through the development of high temperature shear zones (cf White et al., 1995).

Willis et al (1983; see also Stevens et al., 1988) divided the Willyama Supergroup into four groups and sixteen formations (Fig. 3). The lowest part of the sequence, incorporating the Clevedale Migmatite and Thorndale Composite Gneiss suites, has undergone varying degrees of partial melting and is possibly a correlative of the highly magnetic Redan geophysical zone to the southeast of Broken Hill which is similarly migmatitic (Stevens and Corbett, 1993). However, correlation is uncertain and the Redan zone was regarded by Willis et al. (1983) as a correlative of the Thackaringa Group. Glen et al. (1977), on the other hand, proposed that the Redan zone forms an older basement to the Willyama Supergroup rocks.

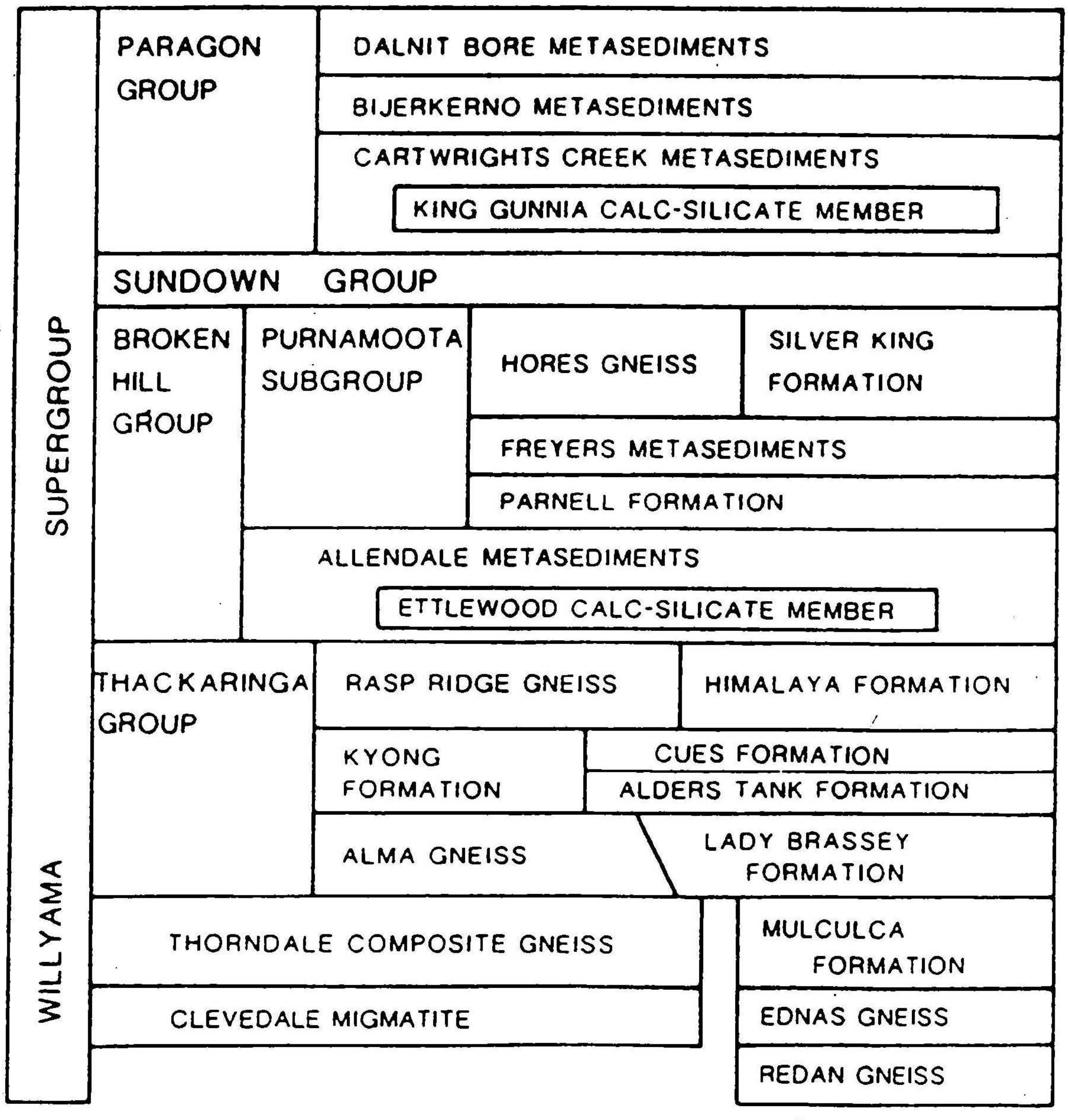


Figure 3: Regional stratigraphy of Broken Hill block (Willyama Supergroup). (After Stevens et al., 1988)

The Thackaringa Group conformably overlies the Thorndale Composite Gneiss and is characterised by a large number of quartzofeldspathic units. These include sodic plagioclase-quartz rocks and medium to coarse-grained, quartz-feldspar-biotite ± garnet gneisses (Alma Gneiss and Rasp Ridge Gneiss) known locally as "granite" gneisses. There has been considerable debate regarding the origin of these "granite" gneisses. Some workers have argued that they represent metamorphosed volcanics or tuffs (e.g. Brown et al., 1982; Willis et al., 1983) whilst others have suggested that they include highly deformed intrusive rocks such as granite (e.g. Stillwell 1922; Vernon and Williams 1988). Other common lithologies in the Thackaringa Group include migmatitic metasediments, basic gneisses and quartz-magnetite bodies.

The Broken Hill Group (Fig 3) comprises a basal metasediment unit (Allendale Metasediments) overlain by the Purnamoota Subgroup which has been further subdivided into Parnell and Freyers Formations and Hores Gneiss. The Purnamoota Subgroup contains metasediments, amphibolites, garnet-rich quartzofeldspathic "Potosi" gneisses, and "lode horizon" rock types (e.g. quartz-gahnites, garnet-quartz rocks and banded iron formations). Metasediments in the Purnamoota Subgroup are largely pelitic to psammopelitic in composition and commonly contain zoned calc-silicate nodules.

The origin of the Hores Gneiss, and "Potosi"-type gneisses in general, is contentious and these rocks have been variously described as intrusive rocks, arkosic sediments and felsic volcanics (see Haydon and McConachy, 1987). Irrespective of its origin, the Hores Gneiss is a particularly important unit in the stratigraphic sequence because it hosts the Broken Hill orebody.

Directly overlying the Purnamoota Subgroup (and included Hores gneiss) is the Sundown Group, consisting almost entirely of metasediments. In comparison to the underlying Purnamoota Group and lower units in the Willyama Supergroup, amphibolites and felsic gneisses are conspicuously absent. Metasediments in the Sundown Group are dominantly pelitic to psammopelitic in composition, usually exhibit well-developed bedding and contain scattered calc-silicate nodules.

The Paragon Group is situated at the top of the Willyama Supergroup and mostly occurs in the lower-grade northern part of the block. This unit is characterised by graphitic metasediments and has been divided into three formations consisting of spotted and non-spotted phyllites and schists, albitic psammites and minor calc-silicate rocks.

Total thickness of the Willyama Supergroup has been estimated at approximately 7-11 km (Stevens et al., 1988). The sequence also appears to be one in which there is a progressive change up sequence into deeper water facies. Many of the amphibolites hosted by the Willyama Supergroup are best interpreted as former basaltic sills and /or dykes (Willis et al., 1983; Stevens et al., 1988; Gibson et al., in prep).

METAMORPHISM & DEFORMATION

Structural models for the Broken Hill region largely reflect work undertaken in the late 1970's (eg Laing et al., 1978; Marjoribanks et al., 1980) and incorporate a series of northerly-trending nappes (D_1) refolded in a coaxial manner about more upright D_2 folds. Nappe formation coincided with amphibolite-granulite facies metamorphism and brought about regional overturning of the stratigraphy with little or no disruption of the overall stratigraphic package. Moreover, it was generally agreed that that the majority of nappes closed towards the southeast consistent with tectonic transport having been directed from northwest to southeast (see Laing 1996 for review). The D_2 deformation was thought to have occurred under high grade metamorphic conditions before being followed by further folding and development of retrograde shear zones.

White et al (1995) proposed a very different structural history for the Willyama Supergroup. They rejected the earlier nappe model and reinterpreted the Broken Hill block as a series of discrete thrust packages, each with its own internal geometry and separated from its neighbours by high temperature shear zones (thrusts). According to White et al (1995), the retrograde shear zones were much older structures that had been reactivated during later deformation. In their view, the retrograde shear zones represent former thrusts which originated during high grade metamorphism accompanying the Olarian orogeny. Unlike most previous workers (eg Willis et al., 1983; Stevens et al., 1988; Stevens, 1996), White et al. (1995) argued that continuity of the regional stratigraphy could not be assumed, particularly between thrust sheets, and had to be re-evaluated in the light of the new structural data.

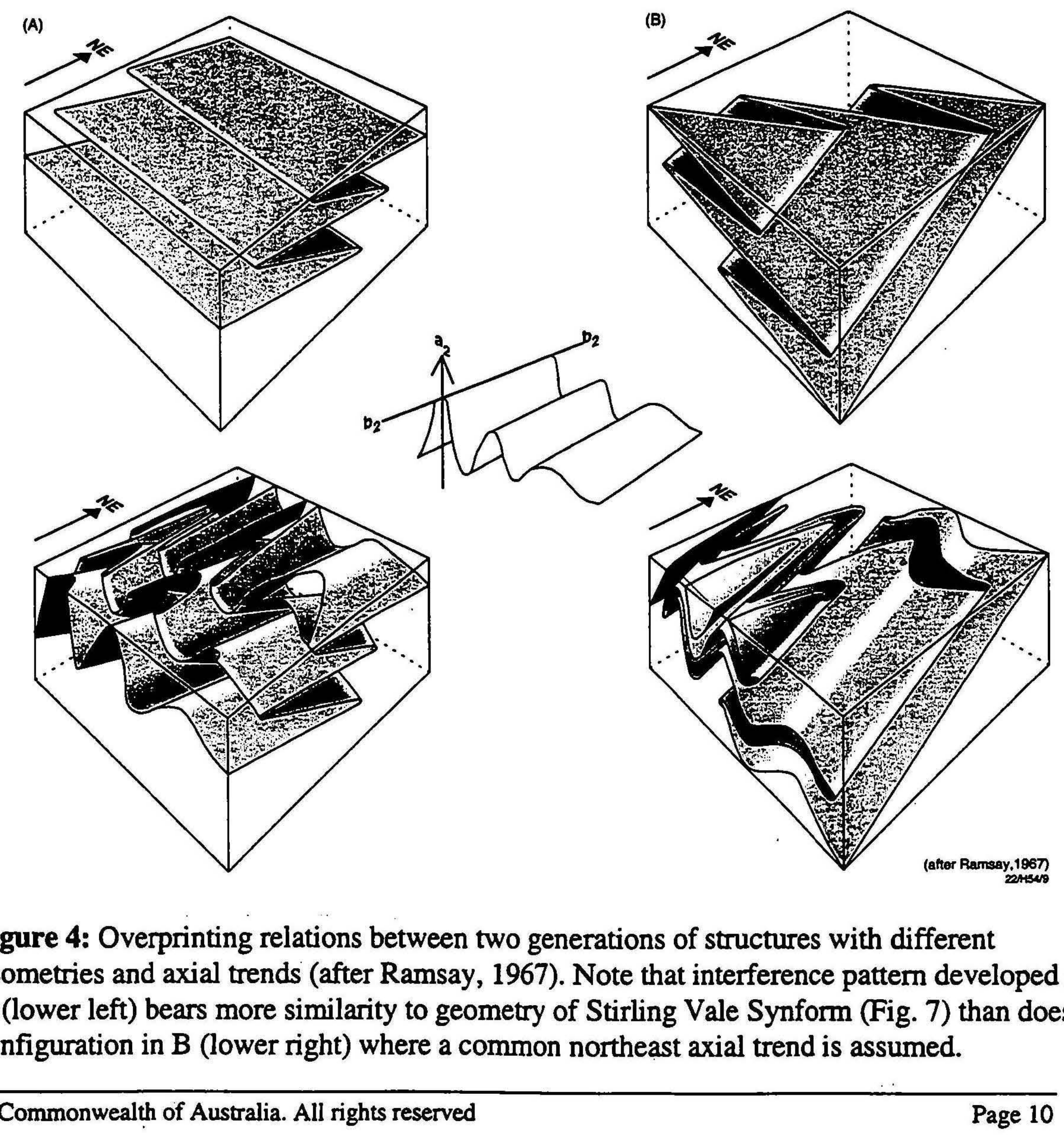


Figure 4: Overprinting relations between two generations of structures with different geometries and axial trends (after Ramsay, 1967). Note that interference pattern developed in A (lower left) bears more similarity to geometry of Stirling Vale Synform (Fig. 7) than does configuration in B (lower right) where a common northeast axial trend is assumed.

However, in common with previous workers (eg Laing et al., 1978; Laing, 1996), White et al. (1995) thought that tectonic transport was principally directed towards the southeast. They also recognised a number of late southeast-dipping thrusts which they attributed to the early Palaeozoic Delamerian orogeny.

Hobbs et al (1984), and more recently Haren et al (1997), presented data inconsistent with many of the earlier structural models. These workers pointed out that fold interference patterns in the Willyama Supergroup are inconsistent with coaxial deformation and in some areas require the earlier folds to have been oriented at a high angle to the later structures (Fig 4). Gibson et al (1996) also presented evidence that some shear zones may be related to the breakup of Rodinia and thus casnnot have any bearing on the earlier deformational history and associated high grade metamorphism. These "Rodinian " shear zones not only disrupt the regional stratigraphy but several earlier high grade shear zones and mylonites. A more complete description of these late shear zones follows.

Late stage (Retrograde) Shear zones

High grade metamorphic fabrics in the Willyama Supergroup are cut by retrograde schist zones trending northeast or northwest (Fig. 5). The origin of these shear zones is not always immediately obvious and several different generations of structures are probably represented, including older structures reactivated during later deformation as well as new structures developed during late Neoproterozoic continental rifting and breakup of Rodinia. Northwest-

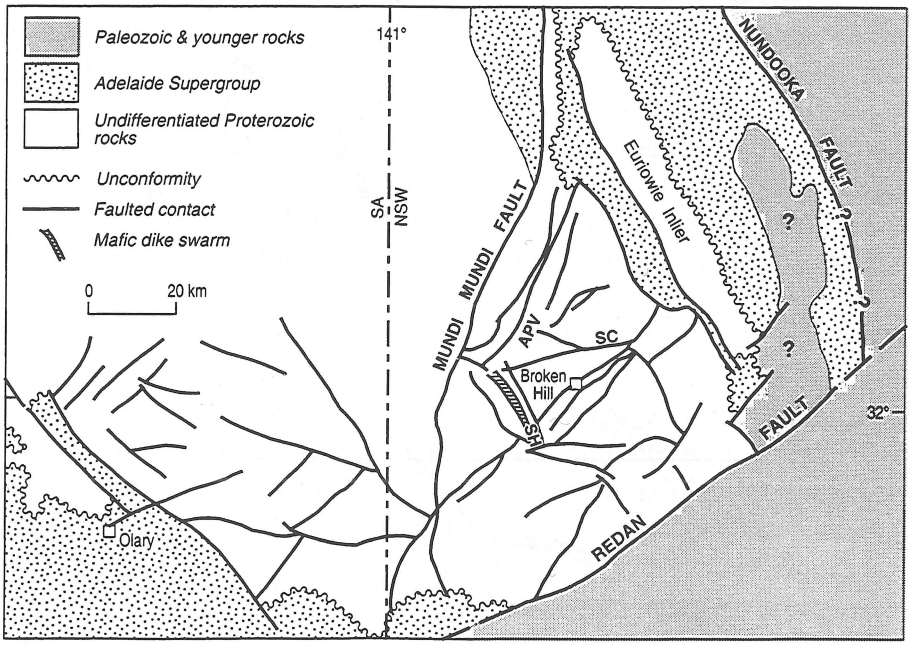
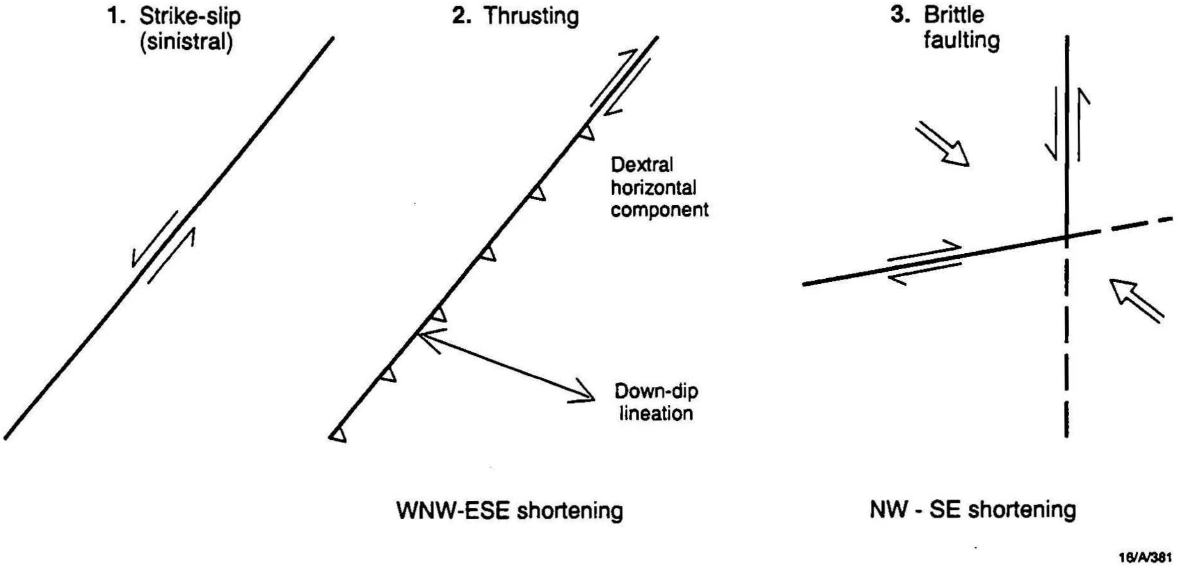


Figure 5: Simplified geology of the Broken Hill region showing shear zones oriented both parallel and orthogonal to the late Neoproterozoic continental margin (Fig. 1). Note Neoproterozoic sedimentary basins (Adelaidean) and the Stirling Hill dyke swarm are similarly oriented parallel to the continental margin. SC= Stephens Creek shear zone; SH=Stirling Hill shear zone; APV= Apollyon Valley shear zone.



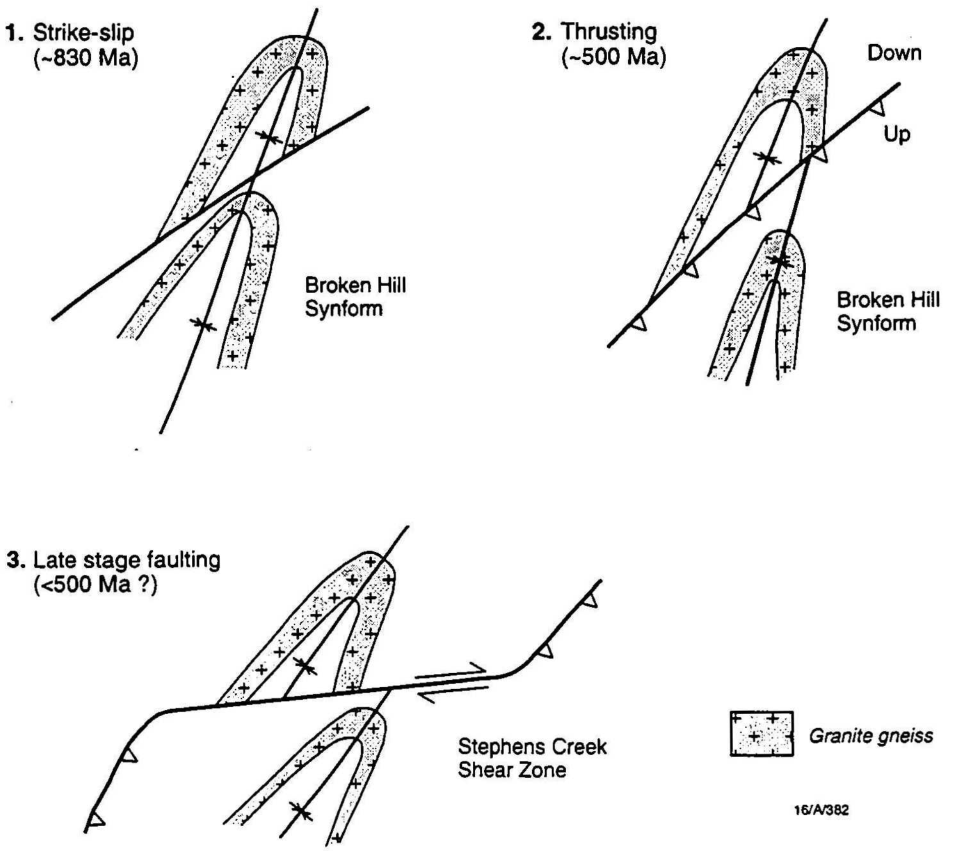


Figure 6: (a) Schematic representation of shear-related deformation in the Broken Hill block; (b) Origin of Stephens Creek shear zone through re-orientation of earlier northeast structure by superposition of later east-west shearing.

trending shear zones are oriented parallel to the Neoproterozoic continental margin (Fig. 1) and preserve a history of early normal faulting followed by later reactivation. Sericitic schists developed during reactivation commonly carry staurolite and garnet, and in the case of the Stirling Hill shear zone overprint an earlier mylonitic fabric containing a steeply-plunging lineation. This lineation was originally less steeply inclined and, along with the mylonitic fabric, was subsequently rotated into its present steep attitude. Shear bands and other kinematic indicators (eg asymmetric boudins, rotated quartz veins) indicate that the latest movement on these shear zones was sinistral and dominantly strike-slip (cf White et al., 1995).

Northeast-trending shear zones have been variously interpreted as post-metamorphic shear zones effecting little or no displacement (Willis et al., 1983), strike-slip faults (Katz, 1976; Williams and Vernon, 1991) or reactivated thrust faults that originated during the earlier high grade metamorphism (White et al., 1995). However, several of them are oriented at a high angles to the late Neoproterozoic continental margin and preserve shallow-plunging lineations more in keeping with a strike-slip origin. One such lineation developed in the Apollyon Valley shear zone takes the form of pressure shadows around garnet formed during earlier higher grade metamorphism and plunges 20° to the northeast.

It is also evident that some northeast-trending shear zones have displaced important marker horizons such as the Potosi gneiss and Rasp Ridge gneiss by appreciable amounts. This is particularly evident in the case of the Lakes Creek discontinuity where a unit of Potosi gneiss has been sinistrally offset by more than 10 km. A parallel, and presumably related, NE-trending shear zone has displaced the Rasp Ridge gneiss and other important marker horizons (quartz-magnetite rock) in the Stephens Creek region by equally significant amounts, and again in a sinistral sense (Maidment et al., 1997). Shear fabrics and stretching lineations in these shear zones, however, frequently yield a reverse sense of displacement indicative of thrust faulting towards the northwest, or less commonly towards the southeast (cf White et al., 1995). Moreover, where a component of strike-slip displacement can be detected in these shear zones, it is commonly dextral in sense and in the opposite direction to that determined from the offsets in regional stratigraphy. It is therefore concluded that these shear zones preserve the record of more than one event. Early deformation was predominantly strike-slip in character but during later events these structures were reactivated as thrust faults (Fig. 6).

Syn-extensional shear zones in the Willyama basement are frequently overprinted by later shears striking east-west and north-south (Fig. 6). These later shears form a conjugate system (see also Katz, 1976) and normally effect only minor displacements in the regional stratigraphy. A notable exception is the east-west-trending Stephens Creek shear zone which not only overprints the earlier northeast-trending structures but has brought about a marked change in their orientation (Fig. 6). The Stephens Creek shear zone has previously been interpreted as an important boundary between different structural domains (Marjoribanks et al., 1980; White et al., 1995) but this is not borne out by the analysis presented here. Rather the Stephens Creek shear zone is of subsidiary importance and has simply brought about a change in the orientation of the earlier northeast-trending shear zones. Kinematic indicators (shear bands, rotated quartz veins, and asymmetric boudins) within the Stephens Creek shear zone support dextral, dominantly strike-slip, movement (Fig. 6) whereas offsets in the regional stratigraphy require an earlier and even greater amount of sinistral displacement (see also Bradley, 1978). It is this earlier geometry which is reflected in the seismic data.

Other Neoproterozoic events

Following high grade regional metamorphism, the Willyama Supergroup was intruded by ultramafic dykes and minor gabbroic intrusions (eg Little Broken Hill Gabbro). The former are largely associated with the northwest-trending Stirling Hill Shear Zone (Fig. 7) and are both mineralised (Cu) and conspicuously magnetic; they are also thought to be age equivalents of the Gairdner Dyke Swarm in South Australia and, like the latter, were intruded in response to an episode of late Proterozoic continental rifting. A younger suite of non-magnetic metadolerite dykes trending WNW in the Broken Hill area is tentatively correlated with minor ultramafic bodies dated at 561 Ma (Harrison and McDougall, 1981). Alternatively, these younger dykes may be related to 590 Ma volcanic rocks reported from the Wonominta Block (Crawford et al., 1997).

The Willyama Supergroup is unconformably overlain by sediments of the late Neoproterozoic Adelaidean succession. These sediments were largely deposited in fault-angle depressions and half-grabens, commencing around 830 Ma (Van der Bosch, 1980; Preiss, 1987), and represent the northern extension of the Adelaide fold belt into the Broken Hill region (Drexel et al., 1993). Late Neoproterozoic sedimentary basins cut across the earlier fabrics in the Willyama Supergroup and typically trend northwest (Figs 5 & 8). Original contacts between the Adelaidean sequences and Willyama Supergroup at Broken Hill are commonly faulted

Figure 7: Second vertical derivative aeromagnetic map for part of Broken Hill area showing Stirling Vale Synform (lower right) truncated to the southwest by a northwest-trending shear zone along which there has been significant retrograde metamorphism. The prominent linear features in the lower left of the figure correspond to a suite of northwest-trending dolerites and hornblende gabbro dykes.

(Cooper et al., 1978) and at several localities rocks of the Adelaidean sequence have been thrust over the underlying Willyama basement. Thrust faulting, and other late deformational

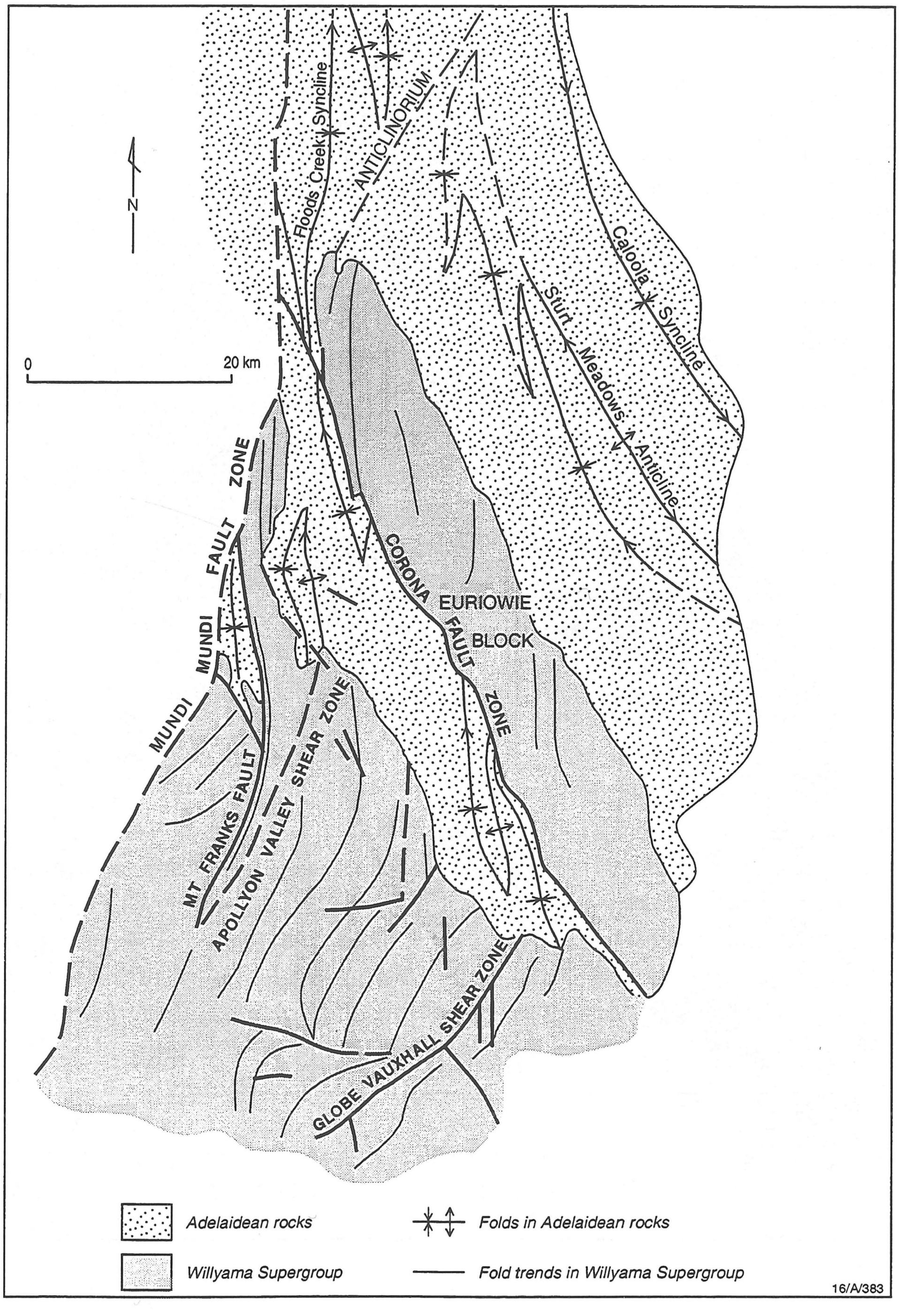


Figure 8: Distribution of Late Neoproterozoic Adelaidean rocks in Broken Hill area. Note northwest trend of sedimentary basins and subsequent fold structures (after Cooper et al., 1978).

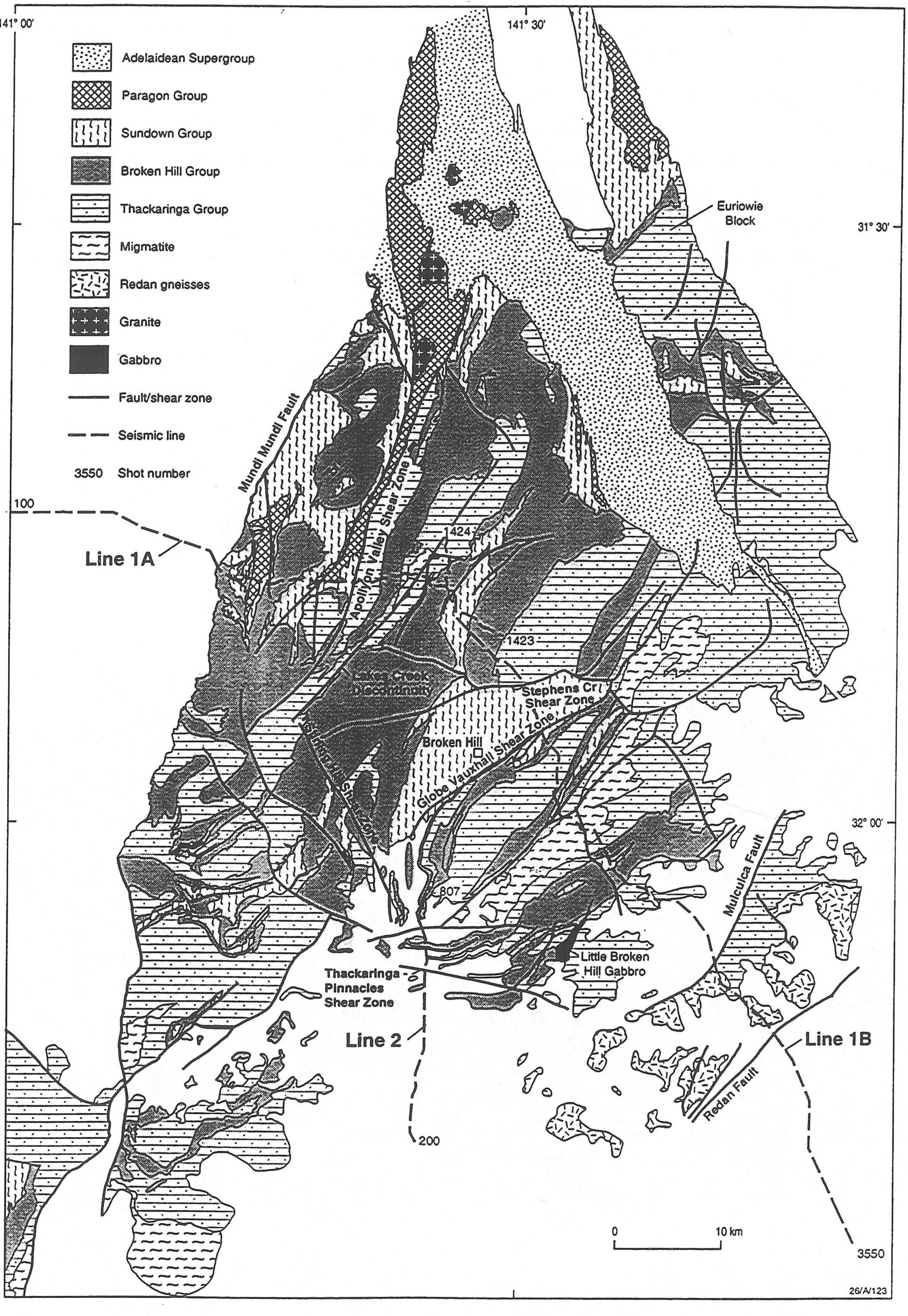


Figure 9: Location of seismic lines superimposed on regional stratigraphy. Note that lines 1A and 1B are oriented approximately perpendicular to regional strike. Line 2 is orientated north-south, and at right angles to the Thackaringa-Pinnacles shear zone. Refer to earlier figures for names of other structures.

events affecting the Willyama and Adelaidean sequences, are attributed to the lower Palaeozoic Delamerian Orogeny and younger Palaeozoic events (see Preiss, 1987).

SEISMIC PROFILE THROUGH BROKEN HILL REGION

Profile Locations and Main Geological Features Traversed

The three profiles whose results are presented here were oriented at approximately right angles to the regional strike in the Willyama Supergroup, and made use of existing farm tracks and public roads wherever possible. Line 1A extends from the border with South Australia eastward across the Barrier Range (just north of the Umberumberka Reservoir) to the junction of Nine-Mile road with Stephens Creek road, and was positioned to cross the Mundi Mundi fault (Fig. 9) and the Apollyon Valley and Mt Franks shear zones. Line 1B extends from the junction of Nine-mile and Stephens Creek roads southwards across Stephens Creek and the Darling Range to a point 25 km southeast of the Redan Fault (Fig. 9); it crosses the line of lode just north of Broken Hill city and was determined by the need to test recent suggestions (White et al, 1995) that the region south of Stephens Creek shear zone is disrupted by a series of northwest-dipping thrust faults. This line also traverses the Broken Hill synform as well as the Mulculca and Redan Faults and several major retrograde shear zones (Fig 9). Together lines 1A and 1B constitute a 160 km profile through the Broken Hill block.

A third profile (Line 2), about 20 km in length, was oriented north-south (Fig. 9) and positioned to cross: (1) the Thackaringa-Pinnacles shear zone and (2) the boundary between rocks of known Willyama affinities and the more problematic rocks of the Redan zone to the south (Stephens and Corbett, 1993). This line also crosses an area of magnetically "quiet" rocks at the northern edge of the Redan Geophysical Zone.

LIMITATIONS OF THE SEISMIC REFLECTION METHOD

The seismic reflection method was developed primarily for use by the petroleum industry in sedimentary basins. Several factors need to be considered when it is used in "basement" terrains. Firstly, the velocities at which seismic waves travel in sedimentary basins are relatively slow compared to those of seismic waves through basement. This affects the resolving power of the method. This must be taken into account when the data are collected, processed and interpreted. Secondly, the strata in sedimentary basins are mostly sub-horizontal whereas those in basement terrains are often steep (highly folded and faulted), and the steep structures may not be imaged.

In this section, the factors affecting vertical and horizontal resolution are addressed. Consideration is then given to the dips that can be resolved. This leads to a brief discussion of the process of migration.

What causes reflections?

Seismic impedance is the basic parameter which governs how seismic waves propagate within a rock and across the boundary between two different rocks. Seismic impedance (Z) is the product of the density of the rock (ρ) and the seismic velocity (V) at which the seismic waves travel through the rock ($Z=\rho V$). When two rock types are in contact, a wave will be reflected off the interface between the rocks if the impedances of the two rocks are different (ie., $\rho_1 V_1 \neq \rho_2 V_2$). The amplitude ($A$), or strength, of the reflection will be determined by the differences in the impedances:

$$A = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \qquad \text{Equation 1.}$$

Rocks typically found in basement regions are usually lithified, contain igneous members, and are often metamorphosed. Empirical relations show that in such rocks, velocity is approximately proportional to density - dense rocks have higher velocities than less dense rocks. Hence, reflections tend to occur at boundaries between rocks with different densities, and the bigger the difference in densities, the stronger the reflection. Seismic reflections therefore usually map the primary bedding of the rock. They are unlikely to respond to foliations or fabric in the rock. Thus rocks which are highly foliated at a high angle to the bedding usually produce reflections only from the bedding.

Vertical Resolution

When a pulse of energy in the form of a wavelet like that shown in the bottom right of Figure 10 reaches a layer in the Earth, some of its energy is reflected off the top of the layer (R1), and some passes into the layer and reflects off the bottom (R2). This is shown diagrammatically in ray diagram in the top left of Figure 10. In the example in Figure 10, the velocity in the layer is higher than that in the medium above and below; however, a qualitatively similar result would occur if it was lower.

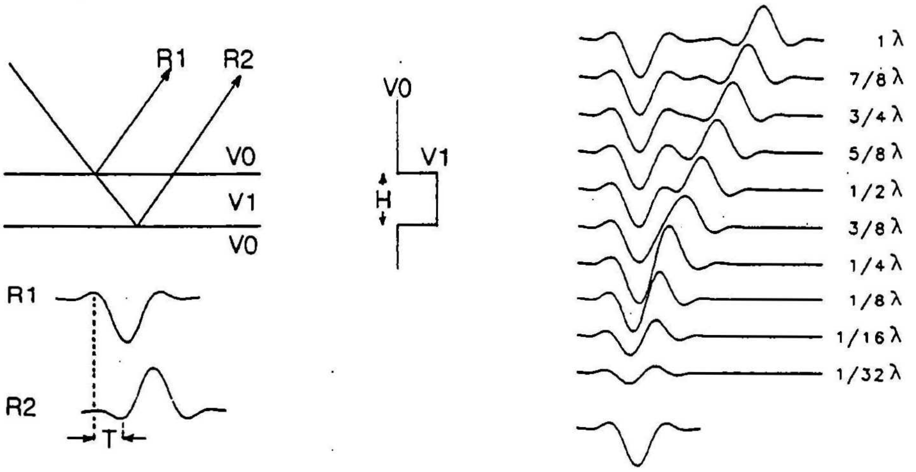


Figure 10: Vertical resolution, or the ability to a identify layer interbedded within other rocks, is determined by the interaction of the reflection off the top of the layer and the reflection off the bottom. Because these two reflections are out of phase, and the reflection off the bottom is delayed in time by its passage through the layer, they can cancel each other for thin layers and reinforce each other for thicker layers.

Note that in R1, the main lobe of the wavelet is downwards, whereas in R2 it is upwards. That is, the wavelets are out of phase. This is because R1 has reflected off a surface where the velocity above the surface is lower than the velocity below the surface, whereas R2 has reflected off a surface where the velocity above is higher than below. This is a consequence of Equation 1 above. When the impedance Z_2 in the layer below the interface is higher than the impedance Z_1 in the layer above the interface, A will be positive, but A is negative for interfaces where Z_2 is less than Z_1.

The total reflection character of the layer is obtained by adding the wavelets R1 and R2. Note that R2 is delayed by an amount of time T relative to R1 because of its passage down and back through the layer. If T is small, that is, the layer is thin, the wavelets will almost cancel each other, whereas if T is large because the layer is thick, they will not, and separate reflections will be seen off the top and bottom of the layer. This is what determines the vertical resolution of the method.

Some examples are given on the right side of Figure 10. The thickness of the layer is given by the parameter λ, the dominant wavelength in the wavelet. This is done so that the diagram has universal application; note however, that for rocks typical of the Broken Hill region, λ is of the order of 100m.

When the layer is thin $(\frac{1}{32}\lambda \approx 3m)$, very little energy is detected. However, at around a thickness of $\frac{1}{4}\lambda$ $(\approx 25m)$, zero to peak amplitudes are almost the same as the incident wavelet. At this thickness, a boundary is clearly present in the Earth, but it is not obviously a thin layer because the reflections from both the top and bottom are not resolved. A different shaped seismic wavelet impacting on a single interface between two layers could equally have produced this result. It is not until bed thicknesses greater than $\frac{1}{2}\lambda$ $(\approx 50m)$ are exceeded that separate reflections can be interpreted to resolve both the top and bottom of the layer. Even then, the two reflections are out of phase, requiring an alert interpreter.

Horizontal Resolution:

Seismic energy travels outwards from the source in wavefronts which are approximately spherical. When they reflect off the surface, the upwards going wave also has a spherical shape, and can interfere with the downgoing wave. The interference is alternately constructive and destructive with increasing distance from the first point of reflection. The zones of interference therefore form annular rings, called Fresnel Zones. In general, surfaces smaller than the width of the first Fresnel Zone are not imaged.

The width of the first Fresnel Zone is a function of the wavelength of the seismic signal used and the depth of the reflector. The width increases with greater depth. The solid line in the graph in Figure 11 illustrates the diameter of the first Fresnel Zone for rocks typical of the

Broken Hill region. The base of the crust is around 14 s two-way-time (TWT). To convert TWT to approximate depth in kilometres, multiply by 3. Consequently, bodies within the crust must in general have reflecting surfaces more than a kilometre in width to be visible.

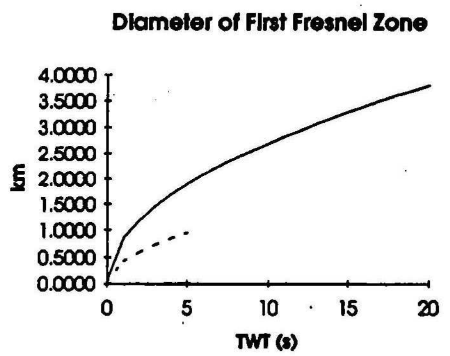


Figure 11: Diameter of the First Fresnel Zone. Solid line is for rocks typical of the Broken Hill region. Dashed line is for rocks typical of sedimentary basins. In sedimentary basins, seismic velocities are lower because the rocks are predominantly sediments, so wavelengths are shorter and resolution is greater.

This contrasts with similar parameters for a survey in a typical sedimentary basin, where the width of the First Fresnel Zone is given by the dotted line in the graph. Because seismic waves travel with lower velocities in sedimentary basins, they have shorter wavelength at any frequency, and therefore have more resolving power.

Dip Resolution:

Rocks in "basement" terrains are often highly folded. What is the greatest dip that can be resolved by the reflection method? In the following description, any effects due to the geometry of the recording system are ignored.

The maximum dip is determined by two parameters which relate only to field logistics, and not to any intrinsic properties of the Earth. They are the length of the seismic line, and the length of time the recording system is allowed to record for each energy pulse put into the ground. They are illustrated in Figure 12.

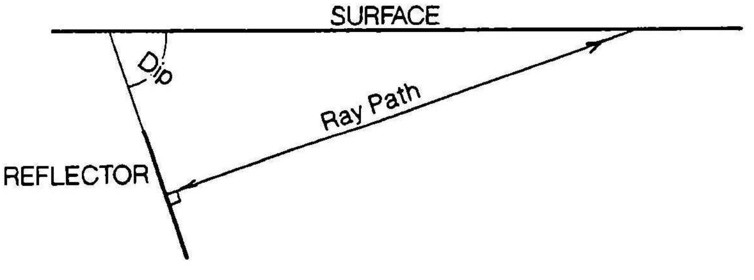


Figure 12: Dip resolution. For steep dips to be recorded, the recording system must be off to the side of the reflector, and allowed to record for enough time for the seismic energy to travel out to the reflector and back again.

A reflection from a source at the surface on the right of the figure returns from the reflector along a trajectory that is at right angles to the reflector. If the reflector is sub-horizontal, the reflection will come from below the source, but if the reflector has a high dip, as in Figure 12, the reflection must come from off to the side of the recording system. To resolve structures with a high dip, the seismic transect must therefore be long enough so that the recording system can be set up on the down dip side from dipping reflectors of interest.

The second parameter is the recording time for which the recording instrument is operated. It must be long enough for the signal to travel to the reflector and return.

These two parameters are summarised in Figure 13 for conditions similar to those in the Broken Hill transect. The horizontal axis represents kilometres across the surface of the Earth. The vertical axis represents depth into the Earth. The vertical scale equals the horizontal scale.

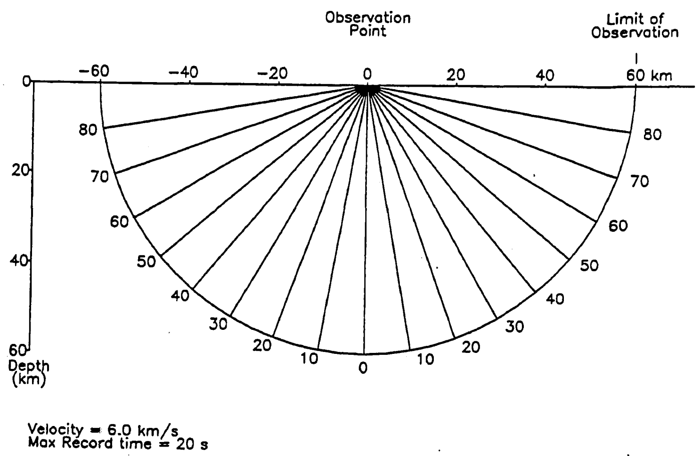


Figure 13: Dips likely to be resolved at depth in the Broken Hill transect.

The semi-circular region that is divided into wedge shaped segments represents the region in the earth that is imaged from an observation point on the surface at ***0***. The numbers at the ends of the radii defining the wedge shaped segments show the dips that can be imaged within the segment. For example, in the wedge defined by the number "80" and the surface, surfaces with dips greater than 80° towards the observation point can be imaged. In the wedge bounded by "0" and "10", only shallow dips can be imaged.

Consequently, surfaces with shallow dips are imaged when the observation point is above the surface, and steep dips are imaged from the side. In a long seismic traverse such as the Broken Hill transect, very steep dips can be imaged in the near surface, and if reflectors with dips as high 40° occur in the middle and lower crust, reflections can be reasonably expected.

Dipping Reflectors and the Process of Migration:

Dipping reflectors do not plot on seismic record sections in their correct spatial position unless they undergo a specific process called migration. This is illustrated in Figure 14.

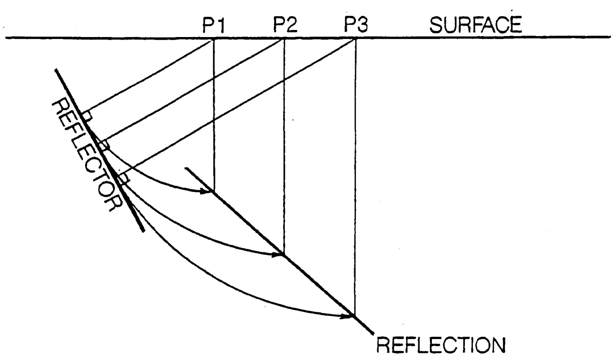


Figure 14: A dipping reflector will be placed in the seismic section initially below the recording point down dip from the reflector. The process of moving it back to its correct spatial position is known as migration.

When the seismic record section is being compiled, in the absence of any a priori information about the correct position of the reflector, the reflection recorded at P1 is assumed to have come from vertically below P1. The same is true for other points (P2 and P3). The reflection will therefore be plotted below the receivers, as indicated. The process of migration moves the reflection back to its correct spatial position; ie., it moves up dip and the dip increases.

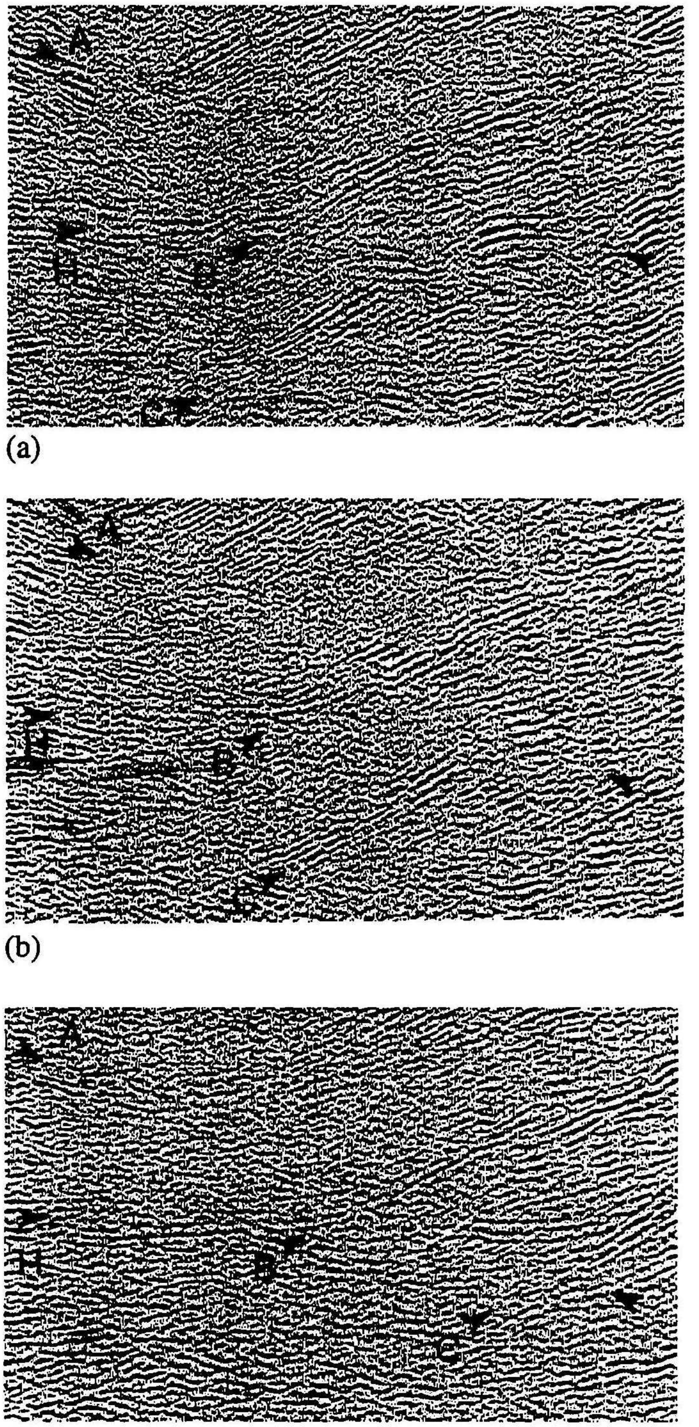
Figure 15 illustrates the migration process applied to a portion of the data from the Broken Hill Transect.

In Figure 15(a), the data are unmigrated; that is, the reflections are placed vertically below the point at which they were recorded. Three distinct sets of reflections occur on this section. Reflections (B) and (C) are the most prominent and dip from right to left across the section. Reflection (A) dips from left to right. It is strongest at the top left, but parts of it show through (B) and (C) lower down in the section. Reflection H is sub-horizontal and is strongest on the left but is also seen near the right side of the figure.

The process of migration depends on seismic velocity; this is an important parameter to the migration process. The higher the velocity value applied, the more reflections will move in the section. Hence reflections can be partially, fully or over migrated depending on the velocity used. This is shown in Figures 15(b) and (c), where the data have been partially and almost fully migrated, respectively.

In Figure 15(b), reflections (B) and (C) have been moved slightly up dip, and are slightly steeper than in (a). Reflection (A) has lost a lot of its strength, particularly in the top left of the figure, and (H) is still present. In Figure 16(c), which is close to full migration, (C) and (B) have moved up dip and now sit above (A). Reflection (A) is from a fault which truncates bedding represented by (B) and (C). Reflection (H) has hardly moved; reflection (A) soles on to it. Hence, three sets of apparently overlapping reflections in (a) have been resolved into bedding and faults with apparently normal structural relations in (c).

The migration process can be applied easily to data which have a strong lateral continuity, such as those from uniform strata in a sedimentary basin. They are not so easily applied to data from basement areas, such as those from the Broken Hill Transect, because the lateral continuity of the reflections is poor. The migration process tends to break up even more reflections which are laterally discontinuous. This is clear in Figure 15, where the unmigrated reflections (A), (B) and (C) in (a) are much stronger than in (c). Hence the unmigrated data are very useful for identifying the relative strengths of reflections; this gives an indication of impedance, and therefore density contrasts across the reflecting boundary, whereas the migrated data give a clearer picture of the overall geometry of structures but detail is lost.



(a) (b) (c)

Figure 15: (a) Unmigrated data, (b) partially migrated data, and (c) data close to fully migrated. Note that as the data are migrated, reflections (B) and (C) move up dip above reflection (A). The sub-horizontal reflection (H) hardly moves.

THE SEISMIC SIGNATURE OF FEATURES IMAGED ALONG THE TRANSECT

Bedding

When sedimentary and interbedded volcanic rocks are metamorphosed, the differences in density and seismic velocity that are obvious when they are fresh become less marked; ie., impedances become much more uniform. Hence, the strength of reflections from interfaces will become much weaker than from similar rocks in, say, a sedimentary basin. As the seismic velocities increase, the wavelength of a signal for any given frequency will become greater, so the vertical resolution will become less.

When the effects of weaker signals are combined with lower vertical resolution, the signals that that might be expected from metamorphosed sedimentary and volcanic strata are likely to be less spectacular than those from unmetamorphosed equivalents. This is shown in Figure 16. Layers L1-L6 are interpreted as sedimentary rocks, perhaps with some volcanics (see below).

Note that for any given package of rocks, the general dip and trend of the strata are obvious over several kilometres, but the lateral extent of any individual reflector is generally much less.

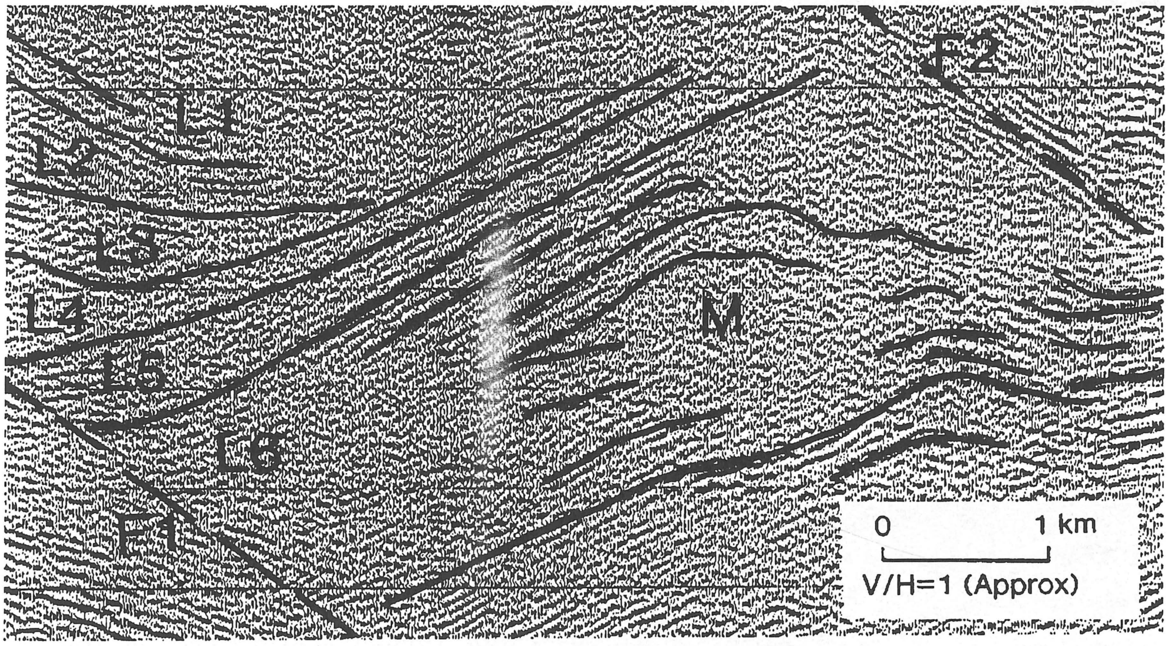


Figure 16: Portion of the seismic data from line 1B. L1 - L6 indicate separate layers of stratified rock interpreted in the section. Note that bedding can be seen, but while the groups of reflections which define any bed are continuous for some distance, individual reflections are not. M is interpreted to be volcanic rock. F1 is a fault interpreted by the truncations of bedded rock (L1-L6, and particularly L5 & L6 in this example), whereas fault F2 is intrinsically reflective.

A Volcanic Pile

The bulbous region of reflectors surrounding a centre of less reflective rock, marked M, just to the right of centre in Figure 16, is interpreted to be a pile of volcanic rocks. The reflectors stratigraphically above this zone, but found just to the left in the image because they are dipping to the left, are stronger than others in the region, consistent with a higher impedance between the sedimentary rocks surrounding the bulb (M)and the volcanic rocks within the bulb. This feature is very similar in reflection character to a basalt mound interpreted along strike from the Hellyer Mine in the Mount Read Volcanics in northwest Tasmania by Yeates et al. (1997).

A Deep Basement Discontinuity

A regional discontinuity or truncation has been interpreted along a large portion of Line 1B beneath the rocks labelled L6 in Figure 16. Although the reflection strength and lateral continuity are generally as described above, ie., generally weak reflections, with individual reflections having little lateral continuity, the unconformity can generally be identified by the angular relationship between a fairly continuous upper reflector overlying strata with (relatively) east dipping reflectors, as shown in Figure 17.

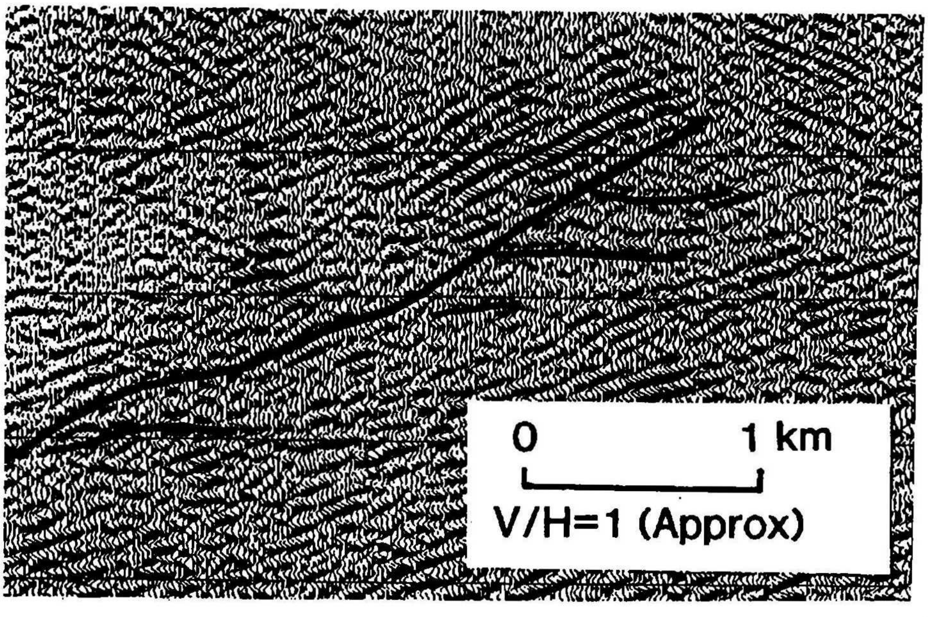


Figure 17: Regional discontinuity or truncation along a large portion of Line 1B

Folds and Thrusts

The rocks of the Broken Hill region are acknowledged to be highly folded. In the seismic section, those near the surface are demonstrably highly folded on a number of scales. Figure 18 shows a portion of the section from just west of the Line of Lode near Broken Hill. The structures are reminiscent of a thrust on an anticlinal structure. The structures in this portion of the section are typical of those found in the region. The thrusts are often bounded by shear zones with apparent dips to the left in the section - see below.

Granite

Granites generally have homogeneous physical properties and therefore typically appear in seismic sections as unreflective zones. Metamorphosed granites should also be unreflective, because even though metamorphism might emplace a fabric at the mineral grain scale, it will not alter the overall relative density distribution within the rock.

The Stephens Creek granite gneiss is the largest area of granite (gneiss) crossed by the transect. Figure 19 shows its seismic response. The granite gneiss is bounded on either side by shear zones. The upper 2 km (approx.) of seismic image is generally bland. However, sub-horizontal reflections occur at about 2 km depth under the left of the outcrop area, and weaker reflections are found slightly deeper under the right. These are taken to indicate the probable depth extent of the granite gneiss. Two shear zones mapped by right-dipping reflectors which project to the surface near the middle of the outcrop area may offset the bottom of the granite gneiss.

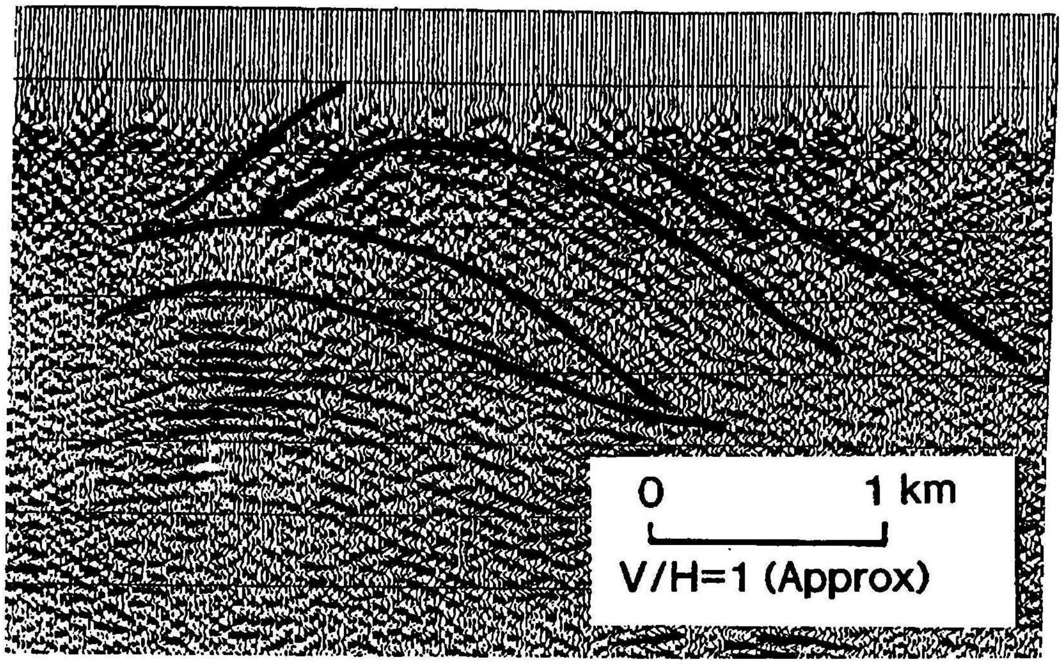


Figure 18: Examples of folded rocks on Line 1B.

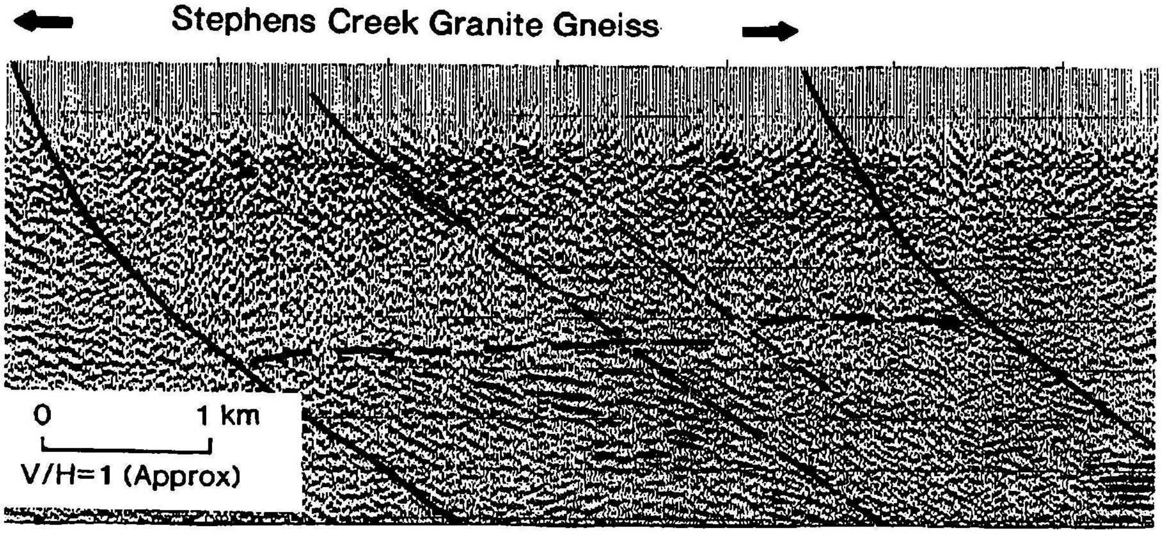


Figure 19: Seismic response of the Stephens Creek granite gneiss.

Faults and Shear Zones

Faults and shear zones along the Broken Hill Transect were interpreted in two ways: those that truncate bedding but whose fault trace is either poorly reflective or not reflective at all, and those whose fault trace is intrinsically reflective.

<u>Faults and Shear Zones Defined by Truncated Reflections</u>

In Figure 16, the fault labelled F1 was interpreted by the truncations of bedding, particularly L5 and L6. Faults interpreted this way are often clearly defined on the seismic section, but their accurately located position relies very much on having the data correctly migrated, because as shown in Figure 15 above, the lateral extent of dipping reflectors in the section depends very much on whether the data are correctly migrated.

<u>Intrinsically Reflective Faults and Shear Zones</u>

In contrast to the fault labelled F1 in Figure 16 which is not reflective, the fault labelled F2 is highly reflective. Many planar, east-dipping faults along the transect are highly reflective.

Figure 20 shows two faults F1 and F2 from the eastern end of line 1A. The arrow heads indicate the apparent east dip of the shear zones. Shear zones with this form; ie, high intrinsic reflectivity and apparent east dip, can often be traced to mid- to lower-crustal levels, particularly near the centre of the transect. Note another strong east dipping reflection which links the top left of F1 with the bottom right of F2. Reflections of this form are commonly found linking parallel shear zones, and are interpreted to be phacoidal remnants of the original rocks rotated and cut by the shear zones.

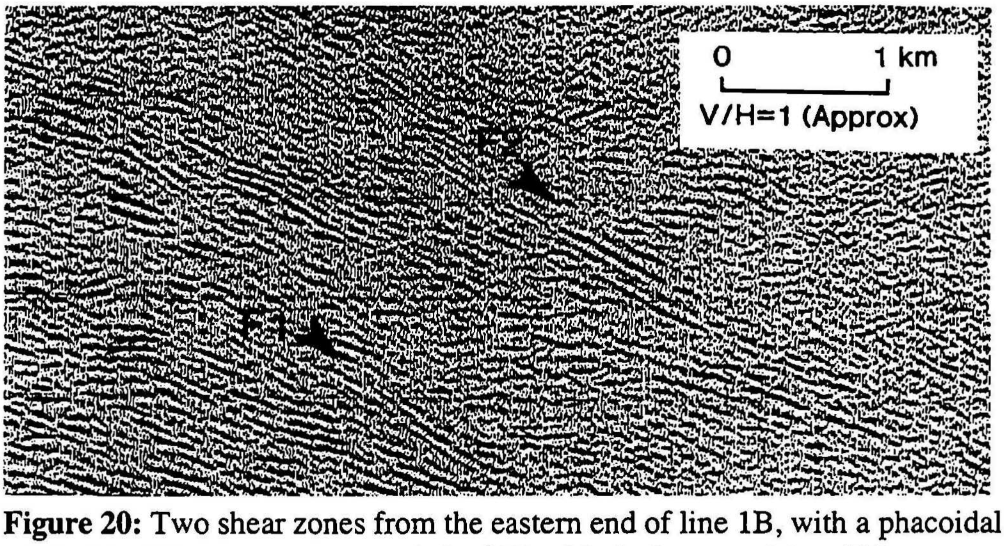


Figure 20: Two shear zones from the eastern end of line 1B, with a phacoidal remnant of original bedding linking the top left of F1 with the bottom right of F2.

INTERPRETATION OF DEEP SEISMIC DATA

The regional crustal structure along line 1 is summarised in Figure 21. Major structures are labelled for reference. The results for line 2 are described separately (p. 42) and illustrated in Figure 29.

The crust in the Broken Hill region is about 40 km thick. The Moho is interpreted as a band of strong reflections at ~13 s two-way time. The band of reflections is very thin in the west, where it occurs over a depth (time) range of about 3 km (1 s). In the east, however, it is much thicker (~2 s, or 6 km). The mantle below the Moho is generally unreflective, which is quite common elsewhere. The reflection character of the crust above the mantle varies along the transect, permitting a three-fold subdivision of the transect into three zones from west to east. For convenience these zones are labelled the western (A), central (B) and eastern blocks (C).

Western Block (West of Mundi Mundi Fault)(A)

The western block is unexposed but extends to lower crustal depths beneath the Mundi Mundi Plain. Its middle crust is dominated by flat-lying reflectors, and compared to the other two crustal blocks, has the appearance of having been least disturbed by the deformation so evident in the rest of the seismic profile. Unfortunately, in the absence of more definite data (eg drill core) it is impossible to determine the extent to which the Willyama Supergroup is represented in this region. Apart from a thin veneer of sediments thought here to include both Adelaidean and Cretaceous material, it is conceivable that large tracts of the block are underlain by rocks other than the Willyama Supergroup.

Central Block (Barrier Range and Apollyon Valley to Stephens Creek)(B)

The central crustal block is characterised by an array of strong reflectors dipping southeast. Several of these reflectors correspond to known faults at the surface and thus most likely represent shear zones. Particularly conspicuous in the seismic data are the Apollyon Valley and Mt Franks shear zones. Another major shear zone, previously unmapped, breaches the surface just west of the present Mundi Mundi Fault scarp. It represents the approximate western limits of the central crustal block and has been active in recent times (Gibson, D, 1997). Reactivation and associated recent uplift on this structure are partly responsible for the present day topography in the Barrier Range. This shear zone also marks the eastern extremities of the thin (Adelaidean-Mesozoic?) sedimentary basins seen under cover below the Mundi Mundi plain, indicating that this structure may have been reactivated more than once. The eastern limits of the central block lie in the region of Stephens Creek. Total width of the central block is about 20 km.

Many of the southeast-dipping structures are well developed and penetrate to mid-crustal levels or deeper. Moreover, they truncate, and thus appear to postdate, the flat-lying fabric observed farther west. Their age and origin, however, remain enigmatic. The most obvious possibility is that they represent a series of major thrust faults developed in response to strong compression across the Broken Hill block during the Delamerian Orogeny or some earlier event (Grenvillian ?). A thrust related origin is consistent with the internal geometry of individual fault-bounded packages which in many instances bear a striking resemblance to duplex structures. However, surface mapping undertaken by AGSO indicates a significant component of early sinistral strike-slip motion on these shear zones (Fig. 6) and it seems probable that this highly deformed crustal block has a long and complex history. Indeed, in common with many other shear zones developed in the Broken Hill region, these faults

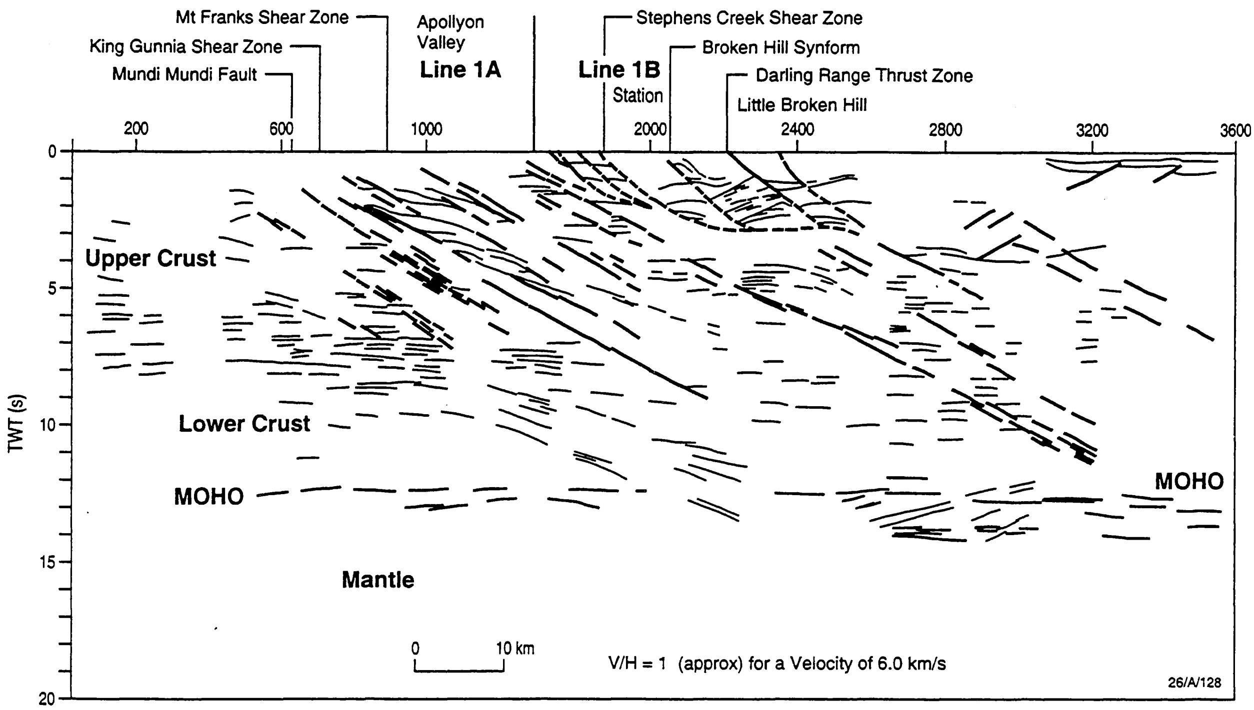


Figure 21: Line drawing summarising the main reflections observed on the seismic transect. (Based on unmigrated data). The top scale is in station numbers along the transect; stations were 40 m apart. The scale bar at the bottom indicates kilometres. The boundary between the two seismic lines 1A and 1B is shown on the top scale for future reference.

preserve a record of early strike-slip displacement followed by later thrusting (Fig. 6). Kinematic indicators observed in outcrop support late reverse dip-slip on the Apollyon Valley shear zone whilst offsets in the regional stratigraphy point to earlier strike-slip faulting on this same structure. Late-stage retrogression observed in this and other shear zones throughout the block is attributed to late-stage reactivation during the Delamerian Orogeny (see Fig. 6)

Eastern Block (Broken Hill to Redan fault)(C)

The eastern block is remarkable in that appears to preserve a rift geometry and one or more half grabens lying above a major detachment which flattens out at mid-crustal depths (~ 10 km; 3s two-way time) into a zone of near-horizontal reflectors. A second detachment lies at deeper levels (~ 18 km, 6 s two-way time).

In contrast to the central block, shear zones in this region are conspicuously listric. Both the Rupee and Globe Vauxhall shear zones exhibit this geometry as does the younger Stephens Creek shear zone. There is also some evidence that the same rift geometry and same packages (3) of strongly reflective structures can be recognised on both sides of Stephens Creek shear zone; the latter are only very weakly deformed and show rapid lateral variations in thickness consistent with sedimentation in a rift environment.

Both rift fill and sedimentary sag phases appear to be represented in the seismic data. This suggests there has been minimal inversion of the original basin geometry despite subsequent deformation. Why this should be so is not immediately obvious although one explanation is that any shortening associated with the Olarian and Delamerian events was accommodated elsewhere (?central block) and the western block simply moved as a single entity on the original detachment without much internal deformation, apart from broad folding and tilting, possibly because it had been subjected to granulite facies metamorphism, was dry and thus behaved in a rigid fashion. Alternatively, extension is not an early feature as suggested above but originated during some later event, possibly an unrecognised episode of late Neoproterozoic rifting (at 590 Ma?). In this case the rapid variations in sedimentary thickness owe less to sedimentation than to the effects of thinning accompanying later deformation. Further work is in progress to resolve these issues.

Particularly useful in this respect would be additional information on the early movement history of the shear zones. Kinematic data obtained by AGSO indicate that the last phase of movement on these shear zones was thrust-related but this is not immediately apparent in the seismic data. Indeed, there are very few significant offsets in the seismic data which could be ascribed to major thrust faulting. However, several shear zones preserve evidence of earlier strike-slip displacement and it may be that much of the strain superimposed during later events was accommodated by lateral rather than vertical movements.

In contrast to the region above the detachment surface, the middle to lower crust in block C has a character more like that observed in crust below the Mundi Mundi Plain (block A). Flat-lying or shallow-dipping reflectors are again very much in evidence. This suggests that the eastern and western blocks may not be entirely independent of each other. Rather, they are made up of older, although not necessarily identical, rocks which represent basement to the Willyama Supergroup (cf earlier suggestion for the Redan zone; Glen et al., 1977). Following initial rifting and consequent deposition of the Willyama Supergroup, they were once again brought into close proximity thereby giving rise to the intense deformation observed in block B. In any event, the crustal architecture in block B cannot be any older than 1690 Ma because feldspathic gneisses (Hores gneiss) of this age (Page and Laing, 1992) are caught up in the Apollyon shear zone.

Redan Region

The Redan area and environs to the southeast are underlain by crust in which crustal reflectors are poorly resolved or of short length. This same pattern is also repeated in the seismic data from the area just west of the Mulculca Fault and is peculiar to those parts of the Broken Hill region that have undergone varying degrees of late brittle fracturing accompanying subvertical faulting. Exposures of bedrock in these areas are often few in number or nonexistent, presumably because of the relative ease with which such highly fractured (?and hydrothermally altered) rocks may be eroded. This zone of fractured and highly faulted rock is up to 25 km wide and extends from the Redan Fault southeastward into an area of extensive cover and regolith. The Redan Fault itself has only a weak seismic expression but appears to dip southeast in common with most other major shear zones in the Broken Hill area. In any event, these late brittle faults do not appear to extend beyond depths of about 10 km (2-3s two-way time) and are therefore largely confined to the uppermost part of the crust. Two small

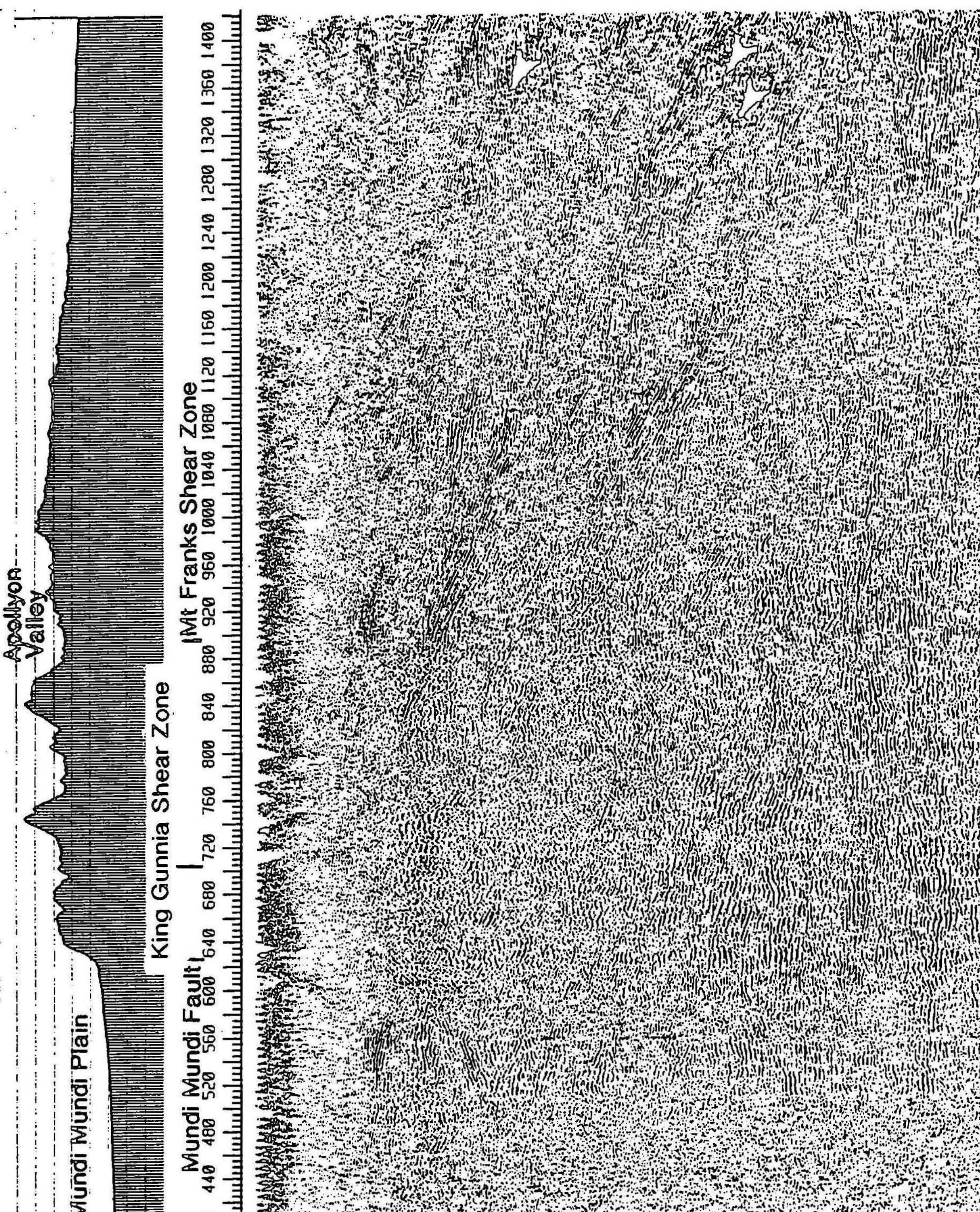


Figure 22: Portion of the seismic data from the eastern end of line 1A. Refer to Figure 21 to find where this is on the entire transect. The arrows indicate the three named shear zones. They continue farther into the crust on line 1B (see Fig. 21).

sedimentary embayments underlying the Murray Basin to the southeast of the Redan fault, and separated by a basement "high", are most likely of Devonian age but may also include sediments of Mesozoic, or younger, age. If Devonian sediments are indeed present in these basins, it would imply that the faulting is also of this age. The overall style of faulting is consistent with deformation in a transtensional or strike-slip tectonic regime.

Basement

Total stratigraphic thickness of the Willyama Supergroup is estimated at 7-11 km (Stevens, et al., 1988). Current crustal thickness in the Broken Hill region is about 40 km. Yet rocks at the surface include granulite facies rocks metamorphosed at depths of 18-20 km (pressures of 6 kbar). Prior to exhumation, total crustal thickness was therefore probably of the order of 60 km, and not far short of that developed in modern orogens such as the Himalayas. It therefore seems inconceivable that the whole crustal section is composed of Willyama-type rocks. By analogy with modern orogens it is much more likely that the Willyama rocks are underlain by an older basement. However, to date no basement has been unequivocally identified in the region. Suggestions (eg Glen et al., 1977; Tucker, 1983) that the Redan zone constitutes basement to the Willyama Supergroup have been disputed (Stevens and Corbett, 1993) and published geochronological data are inconclusive in regard to this issue. However, the seismic data (line 1B; Figs. 26-27) reveal a prominent truncation in some reflectors at around 10 km below the Broken Hill synform. This surface is of uncertain origin but possibly represents a major unconformity or structural discontinuity at the base of the Willyama Supergroup. Whatever its origin, this surface apparently dips northwestward and lies at much shallower crustal levels in the Redan area compared to elsewhere, possibly indicating that the Redan area may be underlain by rocks of a very different age and/or character. Tucker (1983) identified a comparable northward-dipping surface at the base of the Willyama Supergroup based on modelling of the then available magnetic and gravity data. A prominent, apparently northward-dipping, reflector is also evident in line 2 (Fig. 29) and may be an expression of the same unconformity/structural discontinuity.

Bedding

Subhorizontal or gently curving reflectors of varying length are present in the upper part of the seismic profile (0.02-1.0s two-way time) and are taken here to represent bedding. None of these reflectors can be traced for more than a few kilometres. Indeed, the overall impression is one of bedding that has been asymmetrically folded and subsequently disrupted by high angle shear zones This same pattern has been mapped at outcrop scale by members of AGSO and lends weight to this interpretation. It is also evident from the seismic profiles that both the scale and intensity of folding diminish with increased crustal depth.

At deeper levels within the seismic section, bundles of stronger reflectors are very much in evidence. Some of these may be due to the presence of mafic lithologies at depth but others are interpreted here as metasedimentary units. Particularly important in this respect are three bundles of reflectors recognised in the profile below the Broken Hill Synform (Fig. 28). These same bundles have been recognised and correlated across several major shear zones and place important constraints on both the original rift geometry and any estimates about the amount of subsequent inversion on the bounding shear zones.

DETAILED INTERPRETATION OF INDIVIDUAL UPPER CRUSTAL STRUCTURES

This section is primarily concerned with a more detailed description of individual structures imaged in the seismic data and is not intended to be a comprehensive account of the regional geology and stratigraphy. Refer to Figure 21 for the overall geometry of the crust in the region. Figure 22 shows data from the central and eastern part of line 1A, and Figure 23 has a more detailed interpretation of the upper crust from the Mundi Mundi Fault to the eastern end of line 1A. Figures 25-27 show data and an interpretation of the upper crust from line 1B; Figure 28 gives a summary of line 1B. An interpretation of crustal structure along line 2 is presented in Figure 29.

Mundi Mundi Fault (Figs 21, 22 & 23)

The Mundi Mundi Fault (Fig. 8) is a major north to northeast-trending structure (or series of structures) mapped along the western edge of the Barrier Range. In this region, the fault is unexposed and lies buried beneath alluvial fans originating from the Barrier Range to the east. Nonetheless, its surface trace is readily mapped and coincides with the abrupt change in slope, marking the transition from the alluvial-dominated Mundi Mundi Plain to the more rugged topography of the Barrier Range to the east. Its position is confirmed by the seismic data which also show the Mundi Mundi Fault dipping 30-35° to the southeast. It is one of the more prominent southeast-dipping reflectors in the profile and is readily identified as the shear zone marking the western limits of crustal block B. It is unquestionably a major structure and has the character of a frontal thrust; it may also represent the boundary between the Broken Hill and Olary Blocks. In any event, it has probably accommodated a significant amount of vertical movement, both in post-Miocene time and earlier (Gibson, D., 1997). Previous estimates of vertical movement based on aeromagnetic data ranged up to 300m (Willis, 1979) but in view of the new seismic data this is almost certainly a minimum.

King Gunnia, Mt Franks and Apollyon Valley Shear Zones (Figs 21, 22 & 23)

The King Gunnia shear zone trends north-south and juxtaposes rocks of the Sundown and Broken Hill Groups (west side) against younger rocks of the Paragon group (east side) implying the east side has been down thrown. There is also a marked change in the orientation of the regional foliation across this shear zone. It is one of the more important structural discontinuities in the Barrier Range, but apart from its north-south trend, there is nothing in the seismic data to distinguish it from other shear zones like the Mt Franks and Apollyon Valley shear zones which trend northeast. In fact, the King Gunnia shear zone not only shares the same southeast dip, but in common with the other two shear zones penetrates to mid-crustal depths. Rocks adjacent to this shear zone also have the same internal geometry and structure as other fault-bounded packages associated with the Mt Franks and Apollyon Valley shear zones, both of which are considered here to be thrust-related or transpressional in origin. Either a different structure has been captured by the seismic data or the King Gunnia shear zone has been subjected to a different crustal history involving later normal displacement. Alternatively, the King Gunnia shear zone is an early normal fault or transtensional structure that saw very little reverse displacement during later thrust faulting.

Late stage reactivation of the Apollyon Valley shear zone gave rise to younger shear zones with steep to vertical attitudes. Kinematic indicators associated with these late shear zones are consistent with thrusting from the southeast.

Lakes Creek Discontinuity (Fig. 23)

This previously unmapped feature coincides with a pronounced linear magnetic anomaly and is thought to have originated during the extensional events leading up to the onset of late Proterozoic continental rifting. It has effected an appreciable amount of left lateral displacement and truncates and/or disrupts a number of important marker horizons, including Potosi gneiss and a suite of post-tectonic granite sheets (Champion-type) correlated with the Mundi Mundi granites dated at 1490 Ma (Harrison and McDougall, 1981). This last date is important because it possibly provides a maximum age for the southeast-dipping structures observed in the seismic profile. It also supports the suggestion made elsewhere in this report (see earlier section) that parallel, and presumably contemporaneous, structures such as the Apollyon Valley shear zone underwent earlier strike-slip motion before being reactivated at a later stage as thrust faults. Magnetite-bearing pegmatites intruded along the shear zone are partly responsible for the prominent magnetic anomaly in this region.

Stephens Creek Shear Zone (Figs. 5, 9, 24, 25)

The east-west trending Stephens Creek shear zone (Fig. 24) has long been regarded as a major structure in the Broken Hill region and in its central section juxtaposes Rasp Ridge gneiss (Thackaringa Group) against pelitic and psammitic schists of the Sundown Group. In the analysis presented here (see earlier section on retrograde shear zones) early strike-slip motion (sinistral) on this shear zone was followed by thrust faulting and an even later episode of dextral displacement. It is the effects of this later deformational event that are reflected in the kinematics (S-C fabrics etc) and present day orientation of the Stephens Creek shear zone. The east-west orientation of the Stephens Creek shear zone (Fig. 24) is not original but reflects the effects of later deformation on a formerly northeast-trending structure. It is the geometry of this earlier structure that is reflected in the seismic profile. Thus, contrary to some previous expectations, the Stephens Creek shear zone is not a vertical or steeply dipping structure but dips moderately southward or southeast in common with many other shear zones in the Broken Hill region. A minimum strike-slip displacement of 10 km is estimated for the original northeast-trending shear zone as evidenced by offsets on Rasp Ridge gneiss and a few quartz-magnetite horizons in the region (Maidment et al., 1997); the amount of vertical displacement (southeast side up) is unknown.

Line of Lode

Besides offsetting Rasp Ridge gneiss, Stephens Creek shear zone (Fig. 24) has also effected a significant displacement of the rift structures captured in the seismic profile for block C. Equally important, this structure may have disrupted and displaced the line of lode such that it now lies north of Stephens Creek (Gibson et al., 1996).

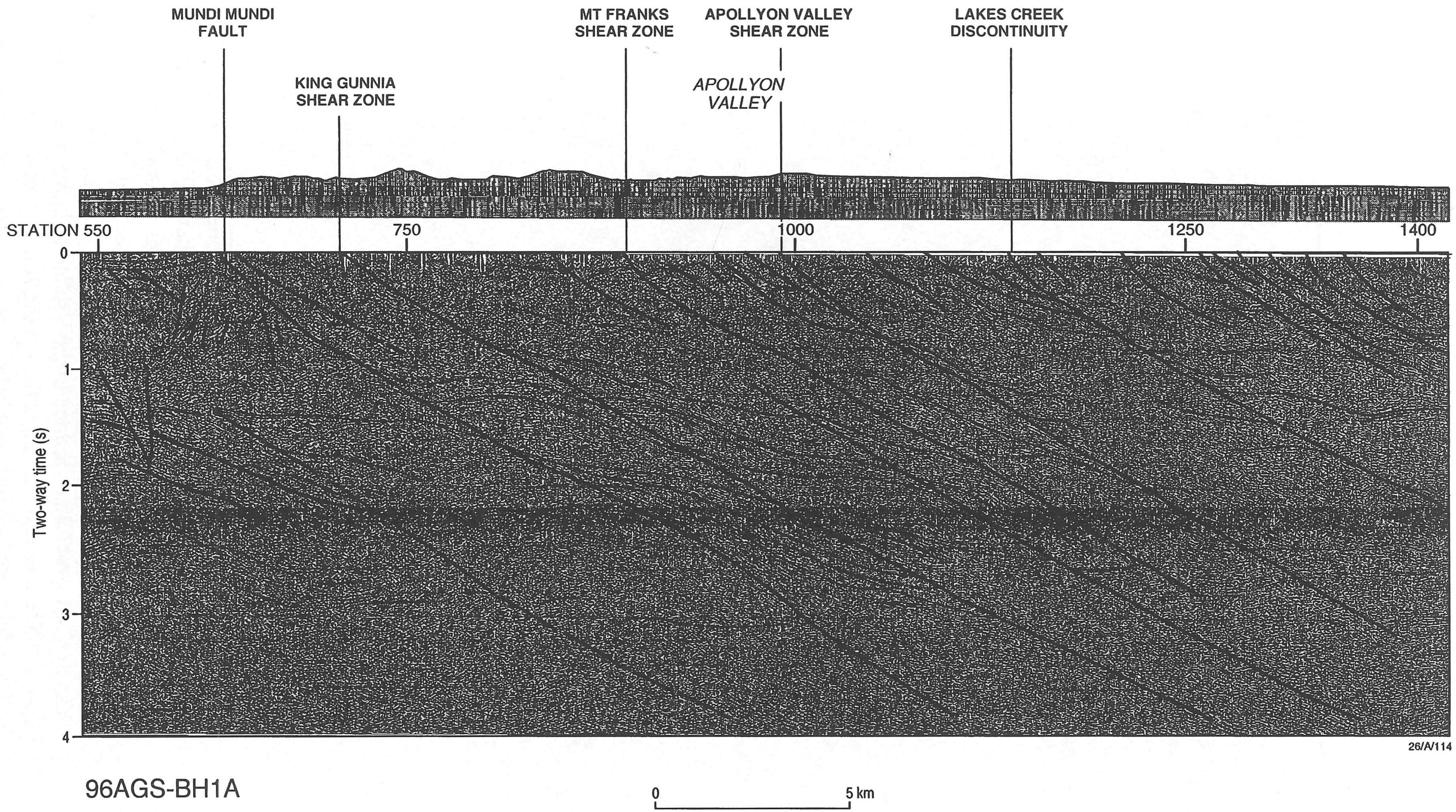


Figure 23: Summary of main features in the upper crust on Line 1A. Note the prominent SE dipping shear zones bounding packets with phacoidal form and internal structure reminiscent of duplexes.

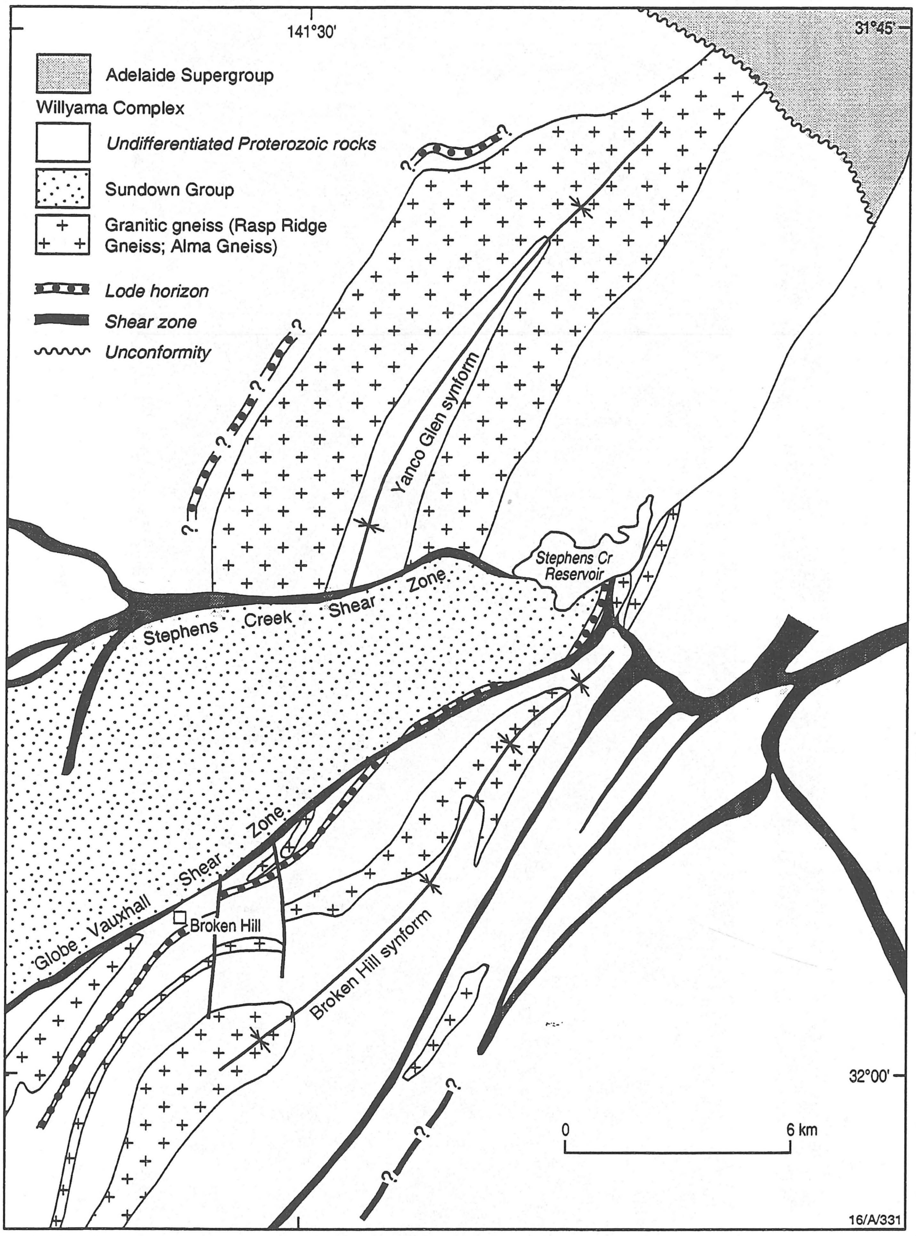


Figure 24: Geology in the vicinity of the Stephens Creek Shear Zone. Note sinistral offset of the Rasp Ridge and Alma Gneisses and associated structures (Broken Hill and Yanco Glen synforms from Marjoribanks et al., 1980). Although the Yanco Glen synform was previously interpreted as a D1 structure, both it and the Broken Hill synform deform an earlier gneissosity, and for this reason are probably of equivalent age. If the lode horizon bears the same relation to the Yanco Glen structure as it does to the Broken Hill synform, then it may continue north of Stephens Creek, as shown, rather than being folded around the Broken Hill synform. Equivalents of the lode horizon have not been observed on the eastern limb of the Yanco Glen Synform. Late-stage (Delamerian) reactivation on the Stephens Creek Shear Zone was mainly dip-slip (south side up) with only minor dextral movement (see also White et al., 1995).

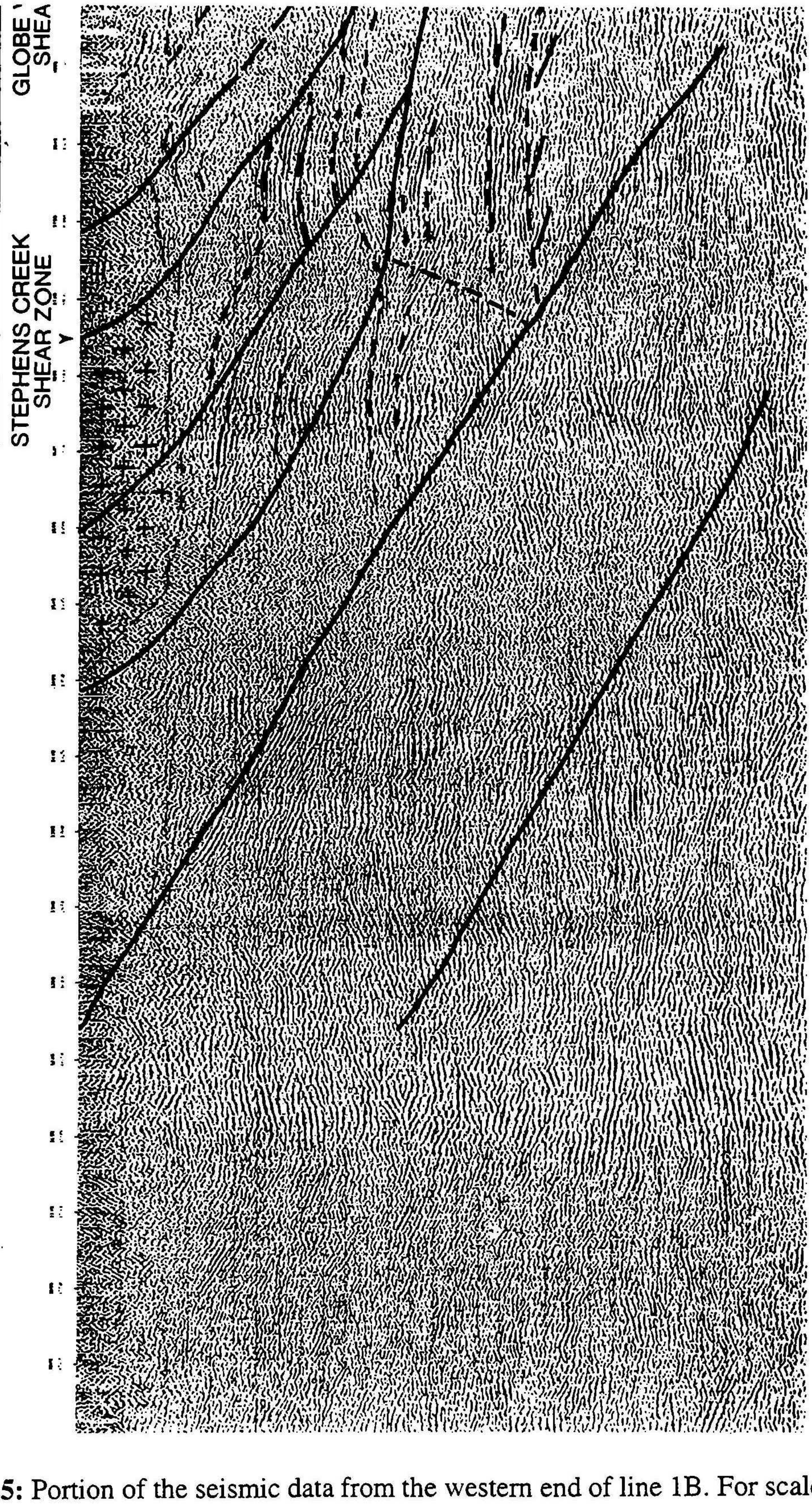


Figure 25: Portion of the seismic data from the western end of line 1B. For scale, the bottom of the section is at 12 km approximately. Figure 26 extends the seismic section to the right

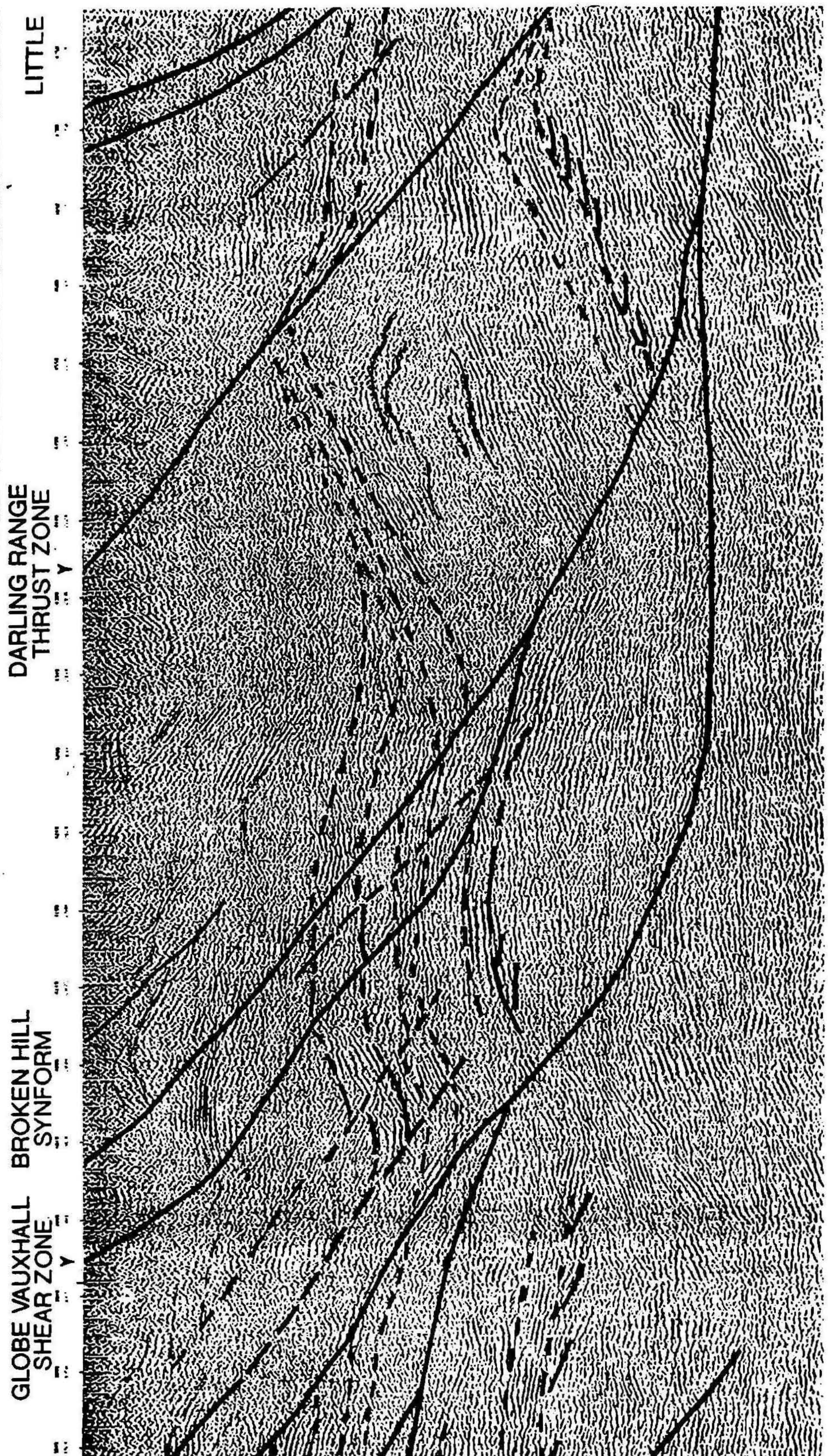


Figure 26: Portion of the seismic data from line 1B. For scale, the bottom of the section is at 12 km approximately. Figure 25 extends the seismic section to the left and Figure 27 extends it to the right.

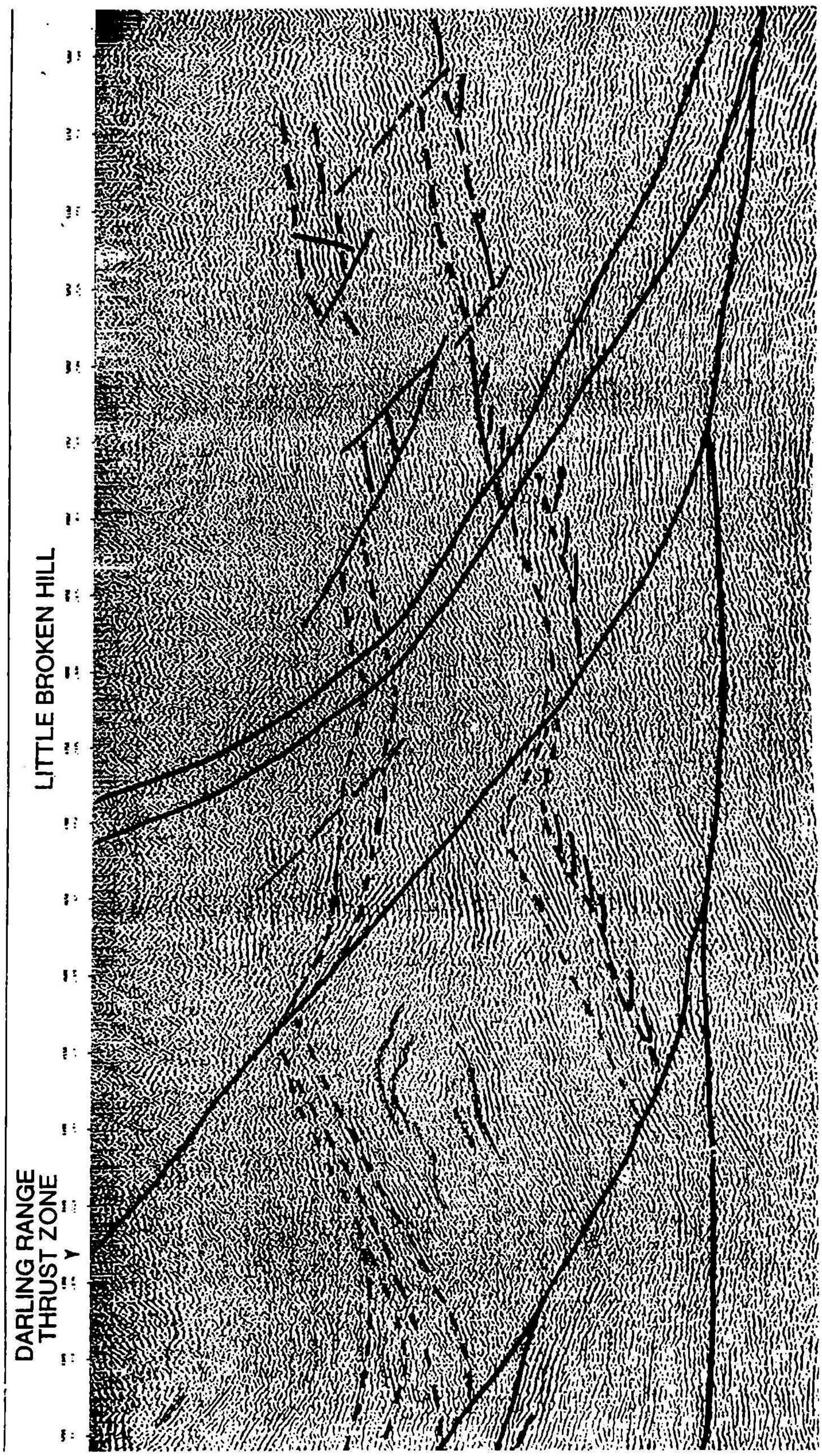


Figure 27: Portion of the seismic data from the eastern end of line 1B. For scale, the bottom of the section is at 12 km approximately. Figure 26 extends the seismic section to the left.

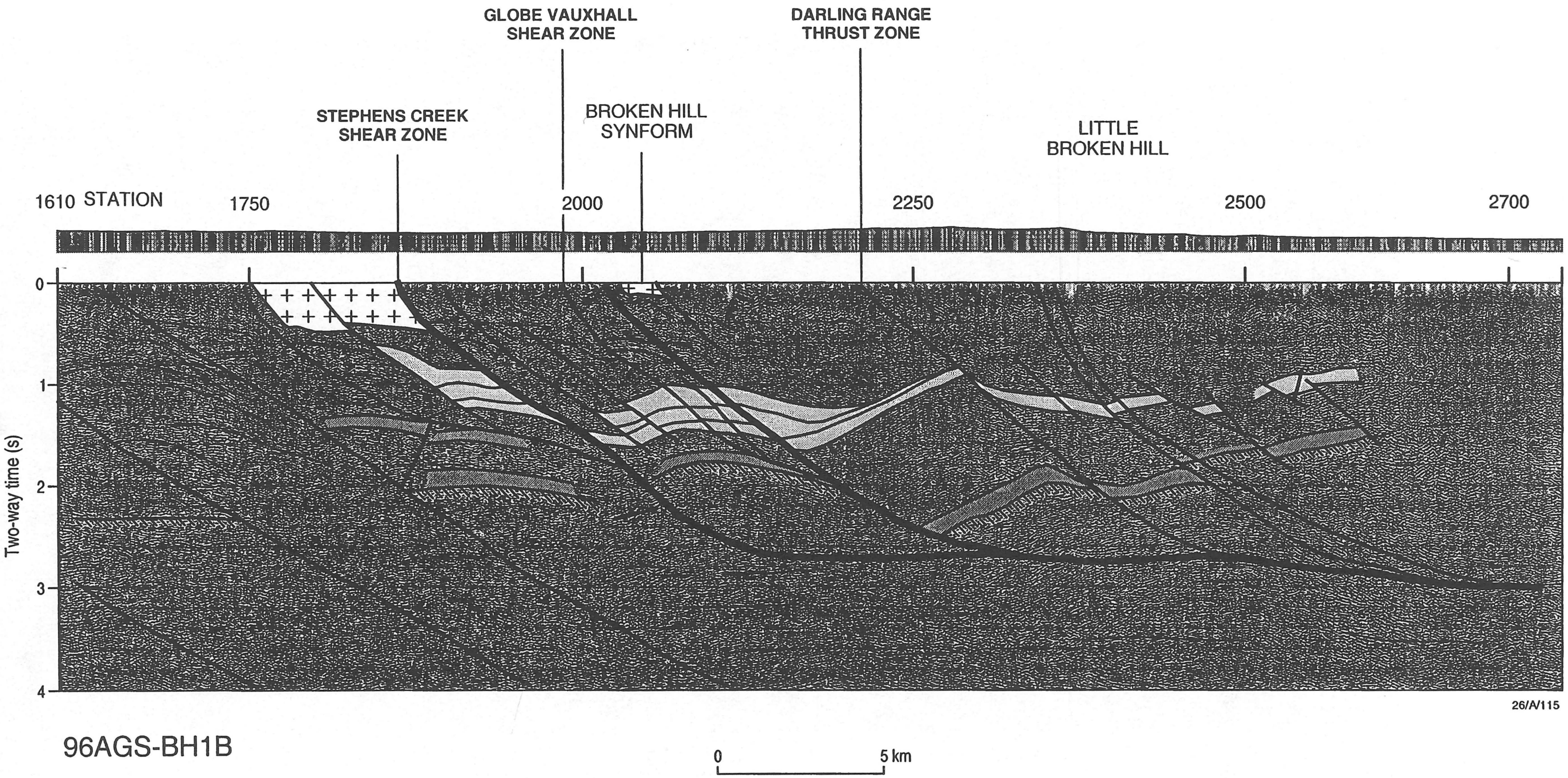


Figure 28: Main upper crustal features imaged in Line 1B. Note that main faults on this line are listric in form and sole into a major detachment at 3s TWT (~9km). The possible rift section is interpreted to be the unshaded portion between 1s and 2s TWT vertically below and to the east of the surface position of the Darling Range Thrust. The lens shaped portion to the west and above the detachment and Stephens Creek Shear zone is interpreted as basement. Much of the section above the rift phase, including the shaded portion, would be sag phase.

Rasp Ridge Shear Zone

The seismic line crosses a major shear zone just south of the Sydney road and a short distance from the old Flying Doctor station. Aeromagnetic maps of Broken Hill show a major anomaly in the same region, caused by banded iron formations and other magnetic units. This anomaly can be followed along strike for a considerable distance and coincides with a marked discontinuity in the regional stratigraphy. In several localities, highly strained units of the Thackaringa Group, including Rasp Ridge gneiss, are terminated against rocks assigned to the Sundown or Broken Hill Groups. This discontinuity is informally named the Rasp Ridge shear zone in this report and can be identified in the seismic profile as a listric structure dipping southeast at moderate angles before soling out into a major decollement at about 10 km depth.

This same structure was first identified by White et al. (1995; see also White et al., 1996) and taken by them to represent a major northwest-dipping thrust separating two discrete fault-bounded packages (Airport and Broken Hill thrust sheets). The seismic data (Fig. 21) indicate that it dips southeast instead. Moreover, it is possibly extensional in origin. Furthermore, while there was a later component of reverse-slip on this structure it was both limited in amount (the extensional geometry is still preserved) and was directed towards the northwest and thus in the opposite direction to that proposed by White et al (1995). Nevertheless, White et al (1996) are probably correct in saying that this shear zone originated under high grade conditions as fabrics in Rasp Ridge gneiss immediately adjacent to the shear zone are of comparable high grade. Late-stage reactivation along the contact with Rasp Ridge has masked the original high grade character of the shear zone.

Globe Vauxhall shear zone (Figs 26 & 28)

The Globe-Vauxhall shear zone (Fig. 24) is revealed in the seismic profile as a steeply-dipping structure with a southeast dip. This is consistent with previous observations from the mine areas (eg Haydon and McConachy, 1987) as well as structural investigations undertaken more recently by AGSO from the region around Round Hill. These same investigations indicate that the last phase of movement on the Globe-Vauxhall shear zone was dominantly transpressive in character (southeast side up).

Mt Darling Range Shear Zone (Figs 27 & 28)

The eastern limits of the Broken Hill Synform coincide with a regionally significant shear zone. This shear zone is plainly visible in the seismic data as a southeast-dipping reflector which, like the Rasp Ridge shear zone, flattens out at depth into the major decollement described in a previous section. It is also conspicuous for its scale (several hundred metres across) and the obvious structural discordance of rock units on either side of it. Other shear zones, important in their own right, have either been truncated by the Mt Darling Range shear zone or else rotated into parallelism with it. Indeed, at this point along the seismic line, several major structures all converge and it is difficult to tell from the seismic data alone whether the strongest reflections derive from the high grade structures or the later retrograde shear zones. In any event, this is one of the most important structures in the Broken Hill region. A string of mineral occurrences and other prominent magnetic anomalies in the Mt Darling Range occur along the western margin of this shear zone

In common with the Rasp Ridge shear zone, there is also good evidence that mylonites in the Mt Darling Range shear zone formed under high temperature. This is best gauged from their amphibolite facies mineralogy. However, in common with most shear zones developed throughout the region, late stage reactivation has masked the conditions under which they originally formed. Irrespective of the conditions under which they formed, late stage shear zones typically yield kinematic indicators (S-C fabrics etc) consistent with thrust faulting and a minor component of dextral strike-slip. The parallels with the Rasp Ridge shear zone are striking and it is probably significant that these two structures bound the lithological package in which the bulk of the granite gneisses occur (cf White et al., 1995).

Broken Hill Synform (Figs 26 & 28)

The Broken Hill synform (Fig. 24) is not immediately obvious in the seismic data although the available evidence is more compatible with an antiformal rather than synformal structure (cf. same structure in northern parts). The seismic data do not allow discrimination between the metasediments and granite gneisses making up the bulk of the structure.

Mulculca and Redan Faults

The seismic data indicate that both these structures dip southeast at moderate angles (50-60°). This is a considerably shallower angle than was originally anticipated for the Redan structure. The latter was expected to be subvertical in keeping with its interpretation as a major strike-slip fault.

Several northwest-dipping reflectors are also evident in the Redan zone. They appear to truncate, and thus postdate, the southeast-dipping shear zones. Their origin is unknown although they may represent a later episode of southeast-directed thrust faults.

Thackaringa-Pinnacles shear zone (Line 2; Fig. 29)

This important structure is not well exposed and is mainly known from a few scattered outcrops of retrograde schist. Line 2 (Fig. 9) was positioned to obtain more information about its attitude and character. Unfortunately, the Thackaringa-Pinnacles shear zone is not immediately obvious in the seismic data, presumably because of its near vertical attitude. Its position in Figure 29 is determined mainly on geological and aeromagnetic grounds, together with limited data (presence of diffractions) from the seismic survey.

The most obvious feature in the seismic data is a prominent northward-dipping reflector that marks the boundary between complexly folded rocks of the Redan zone and less conspicuously deformed rocks lying above (Fig. 29). This boundary is most likely a shear zone but is unusual in that it dips northward in contrast to the majority of shear zones imaged in lines 1A and 1B. The less strongly deformed rocks appear to form an asymmetric wedge bounded by this shear zone and the Thackaringa-Pinnacles shear zone to the north. Rocks to the north of the Thackaringa-Pinnacles shear zone are characterised by sub-horizontal or shallow-dipping reflectors.

The Thackaringa-Pinnacles shear zone is of particular importance in that it is one of the few major west-northwest trending structures in the Broken Hill region. It is also conspicuous for the amount of right-lateral strike-slip displacement it seems to have effected, possibly as much as 13-15 km based on offsets in the regional northeast-trending magnetic anomalies. A string of mafic and ultramafic intrusions disrupted by the Thackaringa-Pinnacles shear zone appears to have been offset by comparable amounts. These intrusions are plainly visible on aeromagnetic images of the region and because they include the Little Broken Hill gabbro recently dated at 827 Ma (Wingate et al., 1997), they also serve to give a maximum late Neoproterozoic age for displacement. Late dextral displacement on the Thackaringa-Pinnacles shear zone is consistent with the structural model presented in figure 6.

The region immediately south of the Thackaringa-Pinnacles shear zone is notable for its wedge-shaped character and weak magnetic response compared to the rest of the Redan block. This area evidently incorporates a veneer of sediments or deeply weathered rocks that have masked the normally distinctive magnetic signature of the underlying Redan rocks. It is tempting to conclude from the geometry and overall tectonic setting of this wedge that it represents some form of pull-apart basin related to strike-slip faulting along the Thackaringa-Pinnacles shear zone. However, the few scattered outcrops in the region are all made up of Willyama rocks and, apart from a veneer of Murray basin sediments encountered in several of the drill holes (Fig. 30), there is no evidence that anything but rocks of the Redan and Willyama Supergroup are represented in the area. Nor is there anything in the seismic data which might support the presence of other rocks (eg Adelaidean) in the region. Thus, whatever the origin of this wedge-shaped region , the region appears to be underlain by the normal range of high grade metamorphic rocks expected for Broken Hill.

SYNTHESIS

The seismic sections clearly provide important constraints on tectonic models for the Broken Hill block. Particularly important in this context are the following aspects:

- major shear zones dip southeast and in some cases extend to deep crustal levels; a few northwest-dipping shear zones occur in the southeastern part of the block
- upper crustal shear zones in the area south of Broken Hill City are conspicuously listric and sole into major detachments at ~10 km and ~20 km
- the apparent rift geometry preserved in the region immediately south of Broken Hill City is mirrored in the region north of Stephens Creek
- Stephens Creek shear zone dips southeast and flattens out at depth
- duplex structures are widely preserved
- basement to Willyama Supergroup is characterised by subhorizontal structures and lies close to surface below the Redan Zone

In most previous structural interpretations of the Broken Hill region (eg Marjoribanks et al., 1980; White et al., 1995; Laing, 1996) the dominant structures, including the majority of retrograde shear zones, were inferred to dip northwest. This conclusion is invalidated by the

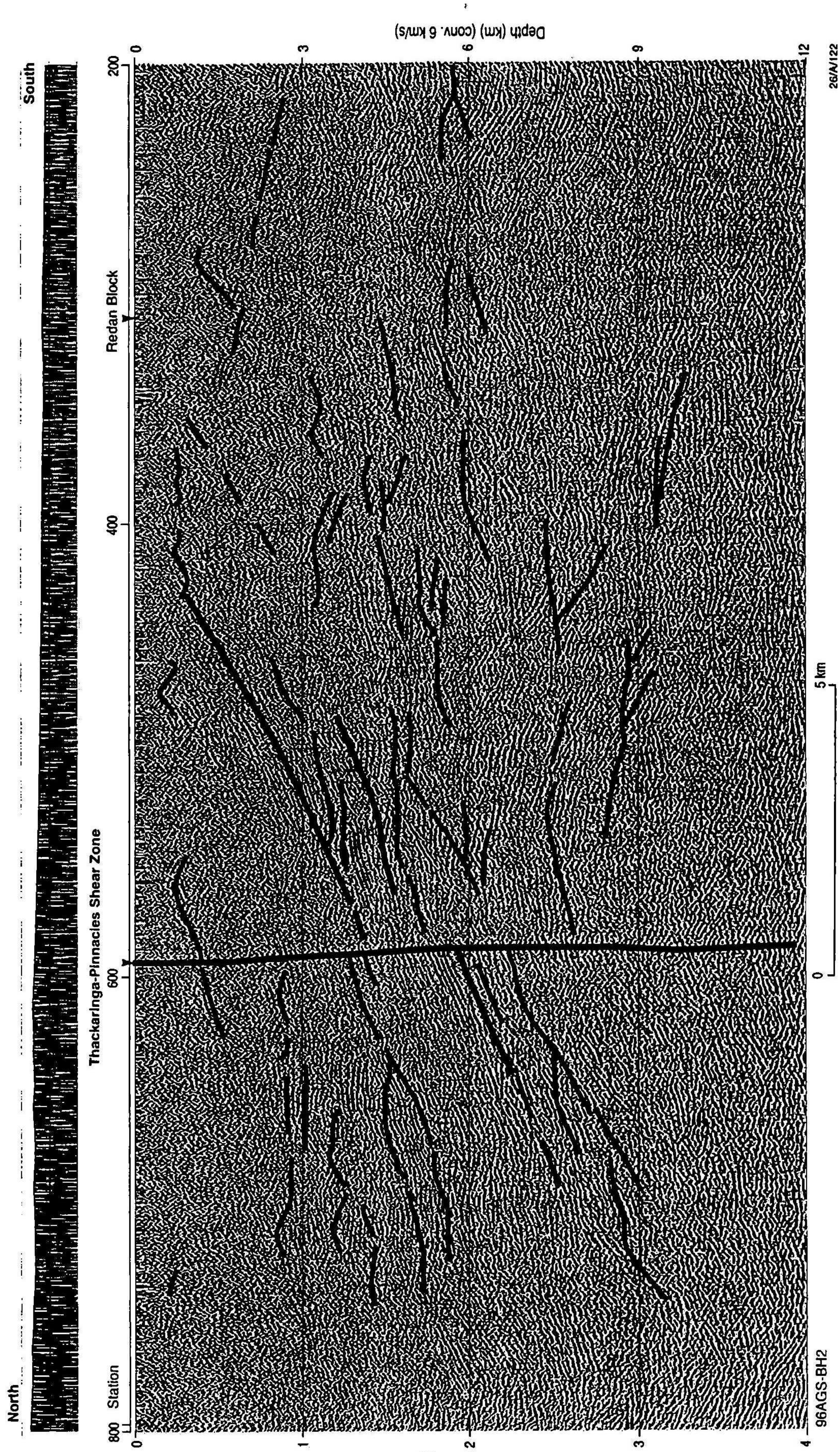


Figure 29. Geological interpretation of seismic data for Line 2. Note prominent reflector dipping north which marks boundary between Redan rocks and (?) younger overlying Willyama Supergroup rocks

seismic data presented here which show unequivocally that the major structures, including most retrograde shear zones, dip southeast.

Furthermore, in the great majority of cases, tectonic transport on these shear zones was directed towards the west or northwest. This is not only consistent with the internal geometry and asymmetry of individual structures (duplex structures) within many fault-bounded packages but explains why exhumation was greatest in the area south of the Broken Hill. It is in this region that the highest grade rocks (granulite facies) occur.

In contrast, rocks in the northern parts of the Broken Hill block were metamorphosed under significantly lower metamorphic grade, barely exceeding greenschist facies in many parts of the Paragon Group. This unit forms the highest stratigraphic levels of the Willyama Supergroup (Fig 1) and is conspicuously different from the rest of the Willyama Supergroup in that the dominant fabric in the Paragon Group is a slaty cleavage rather than a high-temperature schistosity as occurs elsewhere. These, and other observations made on the Paragon Group, are particularly difficult to reconcile with tectonic models involving thrusting, or nappe emplacement, from the northwest (White et al., 1995; 1996; Laing, 1996). Nappe structures may indeed be represented in the Broken Hill region, but they are not obviously developed in the regions proposed by Laing (1996). Nor are they readily apparent in the seismic data. Structures with a geometry reminiscent of nappes or a thrust and fold belt are certainly developed (Fig. 18), but they nearly always dip towards southeastward and thus in the opposite direction to that suggested in most existing tectonic models (eg. Marjoribanks et al., 1980). Moreover, if nappes are present in the Broken Hill block, then they must predate both exhumation of the high grade rocks and the southeast-dipping structures on which at least some of the exhumation probably took place. Unfortunately, the age of most structures, and the shear zones in particular, remains poorly known. It is also evident that many shear zones have a long and complex history involving at least some reactivation during the lower Palaeozoic Delamerian orogeny. A significant component of the exhumation history may therefore be due to lower Palaeozoic thrusting in line with the available geochronological data indicating a major regional cooling event around 480-520 Ma (Harrison and McDougall, 1981).

Suggestions that exhumation was in part driven by thrusting during the Delamerian orogeny leads to questions about how the earlier extensional geometry persisted (Fig. 28). One possibility is that the rocks were exceptionally dry following granulite facies metamorphism so that the original rift geometry was effectively locked in. In the absence of fluids further movement on existing structures became difficult. Consequently rocks above the main detachment thereafter behaved as a single coherent entity and all subsequent deformation was strongly partitioned into rocks of the highly deformed "fold and thrust belt" of the central zone. Moreover, even if the rift geometry were significantly younger than suggested here and was instead related to late Neoproterozoic continental rifting, the same difficulty arises. By what means has the late Neoproterozoic rift geometry avoided inversion during the later Delamerian orogeny? In either case, an appeal has to be made to the inherent rigidity of the eastern block relative to that of the central block.

IMPLICATIONS FOR MINERAL EXPLORATION

Whither the Line of Lode?

The seismic data reveal a close spatial association between the line of lode and the major extensional structures. On this basis it is very tempting to suggest that mineralisation originated in a rift setting as previously proposed (eg Willis et al., 1983); alternatively mineralisation may have formed during the post-rift sag phase (see fig.26). It is equally tempting to suggest that during subsequent metamorphism, this mineralisation was remobilised into the major shear zones. In this context it is important to draw a distinction between the original mineralisation and the line of lode. Mineralisation may have originated by any one of several means but its concentration and emplacement to form the present line of lode may be the result of later events. Irrespective of the original source of the mineralisation, there is a strong suggestion that the line of lode may be structurally controlled and localised above a major extensional structure. Moreover, if this interpretation is correct, then it should be possible to determine where additional mineralisation occurs if the same extensional structures can be identified elsewhere.

In the analysis presented here, the same rift geometry is repeated on the northern side of Stephens Creek shear zone (Fig. 28). This in turn suggests that the line of lode also continues north of Stephens Creek. This possibility (Fig. 24) has already been canvassed by Gibson et al (1996) on the basis of detailed structural studies carried out in the Stephens Creek area.

Stephens Creek shear zone

Stephens Creek shear zone truncates, and thus postdates, the regional D3 fabrics. It also effects a significant offset in the regional stratigraphy (Fig. 24). Early displacement was sinistral in character whereas later movement involved a component of dextral displacement (Fig. 6). Gibson et al (1996) attributed this later displacement to the effects of the Delamerian orogeny and considered that it was of minor importance compared to the earlier phase of movement. In their view the Stephens Creek shear zone originated (or was reactivated) as a strike-slip fault during the breakup of Rodinia and, before being overprinted by later events, was oriented northeast in common with many other major shear zones in the Broken Hill region. This is not to say that all northeast-trending shear zones originated at this time. Some clearly formed earlier. However, these earlier structures typically formed under higher grade conditions and are not considered further here. The critical point here is that the Stephens Creek shear zone formed comparatively late in the tectonic history of Broken Hill and thus is potentially of great significance because it not only disrupts the regional stratigraphy but the line of lode. Moreover, if the analysis presented here is correct, then the line of lode may continue north of the Stephens Creek shear zone (Fig 24). Previously the line of lode was expected to continue around the Broken Hill synform, leading some companies to direct their exploration along the southern limb of this structure.

SHOTHOLE SAMPLING AND GEOCHEMISTRY

Cuttings from all shot holes up to shotpoint 3118 in line 1, and line 2 which was farther south, were examined at 7'6" intervals (approx 2.3 m - this spacing was used to avoid difficulties, as the drillers were using pre-metric 15' rods) to determine presence of transported materials and assess degree of weathering. Rotary drilling with compressed air was mainly used, but in places with damp cuttings, air with water injection, and occasionally circulated water drilling, was used.

Virtually all shot holes were spudded into transported sediment. In many cases, this was a surface veneer of reddish-brown alluvium/colluvium, mostly only a few metres thick. However, some thick sedimentary sequences were encountered in the shotholes, which were mostly drilled to 40 m where sediment or soft weathered rock were present.

Line 1

All shot holes across the Mundi Mundi Plain were drilled entirely in reddish brown alluvium. This varied in grainsize from very coarse pebbly sand to silt. It was generally not possible to correlate between holes. Seismic first-break refraction data and drilling data from elsewhere on the plain suggest this alluvial layer reaches 90 m thick adjacent to the Mundi Mundi Fault scarp, and thins to the west to about 60 m. Refraction data indicate it is probable that the alluvium is underlain by older Miocene, Eocene, and Early Cretaceous sediments to a depth of 150-250 m.

Alluvium/colluvium across the Barrier Ranges was typically thin, but thicknesses of up to 6 m was encountered closer to Broken Hill.

In the Seventeen Mile Creek area, near the Mulculca Fault, a small outlier of Murray Basin sediments was intersected (Fig 30 - top part). Mottled sandy clay and silt up to about 11 m thick is present beneath up to 6 m of alluvium. Further east at the edge of the Murray Basin, red alluvium rapidly increases to 35-40 m thick, underlain by an also apparently rapidly increasing thickness of Murray Basin sediment. Examination of cuttings was continued for about 5 km into the Basin. At this point, the red alluvium was still about 40 m thick.

Line 2

About 35% of the shotholes in line 2 penetrated Murray Basin sediments beneath red-brown alluvium/colluvium (Fig 30 - bottom part). At the southern end of the line, sandy clays were present to about 35 m, overlying very highly weathered bedrock. This material thinned to the north, pinching out between bedrock and alluvium/colluvium in an area of low rises with a lag of bedrock fragments. A completely hidden inlier was encountered in the central part of the line, beneath up to about 17 m of alluvium/colluvium. As well as sandy clay, clayey and clean sands were encountered.

Recognition of transported materials

In many cases, field discrimination between Murray Basin sediment and the underlying weathered bedrock was difficult. Collected samples were not sieved, as it was not known if this would introduce a bias in both the transported and in situ material. However, sieving was useful to find pieces of material which could be examined in detail. Clean sands were not difficult to identify as transported, but sandy clays often superficially resembled what could be taken for highly weathered fine grained metasediments or quartz-albite rock. However, several differences were noted:

1. The transported sediments were mottled on the scale of individual cuttings chips, whereas the weathered bedrock tended to be in large zones of different oxidation colours.
2. The transported sandy clay tended to come off the blade bits in cm-sized cuttings, often obviously deformed by the bit, whereas the highly weathered bedrock was more crumbly, and tended to produce a greasy-feeling rock flour.
3. The transported material often has a very small proportion of coarse muscovite flakes, whereas apart from pegmatite, bedrock generally does not.
4. Even in the most highly weathered bedrock material, it was sometimes possible to sieve out a fragment a few mm in size which showed relict metamorphic texture (eg. foliation after biotite or sillimanite).
5. The in situ weathered rock occasionally had quartz veins, represented by very angular pieces of milky to clear quartz in the cuttings. These were generally coated with powdery material, and not easily noticed unless the sample was sieved or washed. Rain on exposed cuttings tended to make the quartz fragments easily noticeable.

In the laboratory, it was found that examination of cuttings with a 20 x binocular microscope was far easier than with a 10 x hand lens. It is recommended that such a tool would be very useful in any RAB drilling program in the area.

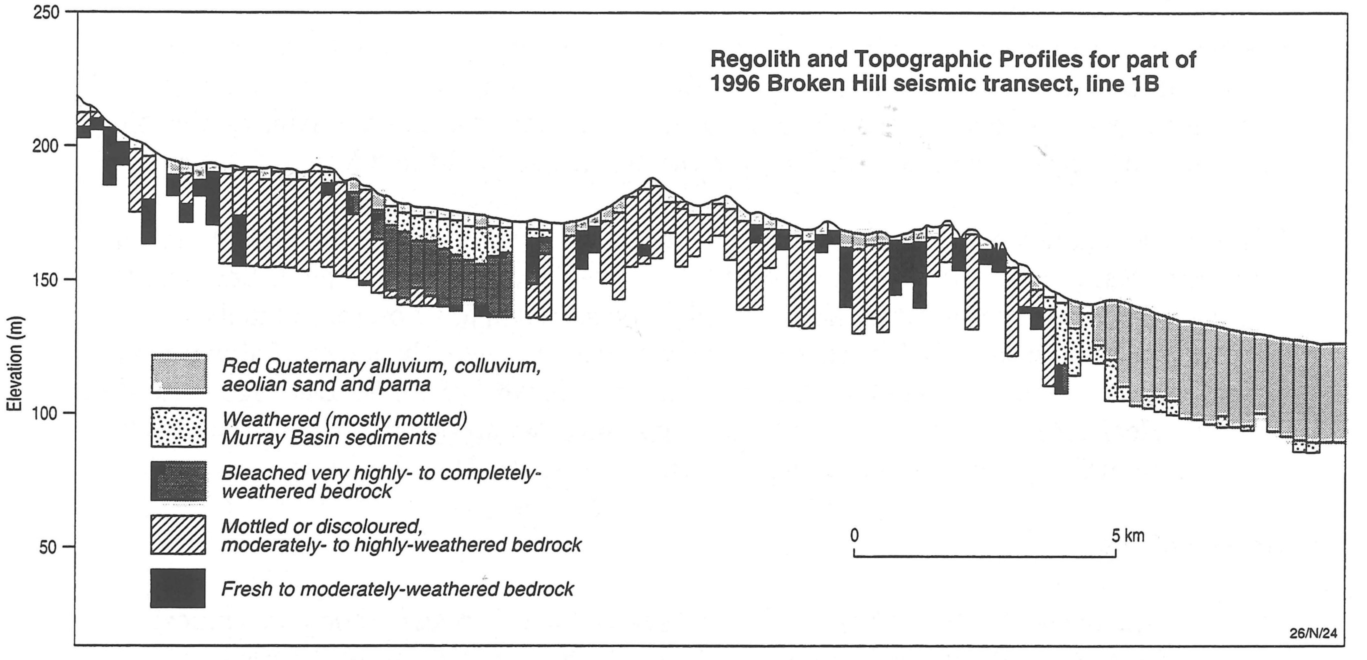
PIMA study of cuttings has commenced, but so far results are inconclusive. A disadvantage of the PIMA is that the spectra are affected by moisture, and damp cuttings must be dried before examination.

Bedrock weathering

A qualitative assessment of bedrock weathering was made from the cuttings. Very little material apart from only slightly weathered bedrock was encountered in line 1 northwest of the Little Broken Hill area. However, from here on, the degree of weathering generally increased. The degree of weathering was very variable over much of the remaining part of the line examined, but the rocks were generally more weathered in the low lying area northwest of the Mulculca Fault. Beneath all four areas where transported Murray Basin sediments are present, bedrock is very highly weathered, and bleached to at least 40 m in places. It is also very soft. It is not known whether the presence of overlying sediment has affected the rock weathering, possibly by entrapment of groundwater, or whether the Murray Basin sediments were deposited in broad valleys preferentially eroded in the least competent material, the very highly weathered bleached rock.

LANDSCAPE EVOLUTION

The degree of weathering of bedrock and amount of transported materials, combined with landscape data, including the topographic profile along line 1, has helped to erect a model of landscape evolution across the Broken Hill area. The Mundi Mundi scarp in the vicinity of the seismic line has resulted from recent reactivation of thrust movement along the southeast-dipping Mundi Mundi Fault, with possibly up to 400 m uplift post Miocene. The area to the east of the fault was tilted down to the southeast. Any weathered material and poorly consolidated transported sediment would be relatively quickly eroded from the uplifted area, and it is suggested that the thick alluvium on the Mundi Mundi Plain, and over the Murray Basin sediments at the Redan Fault, result from deposition of this material, eroded by new



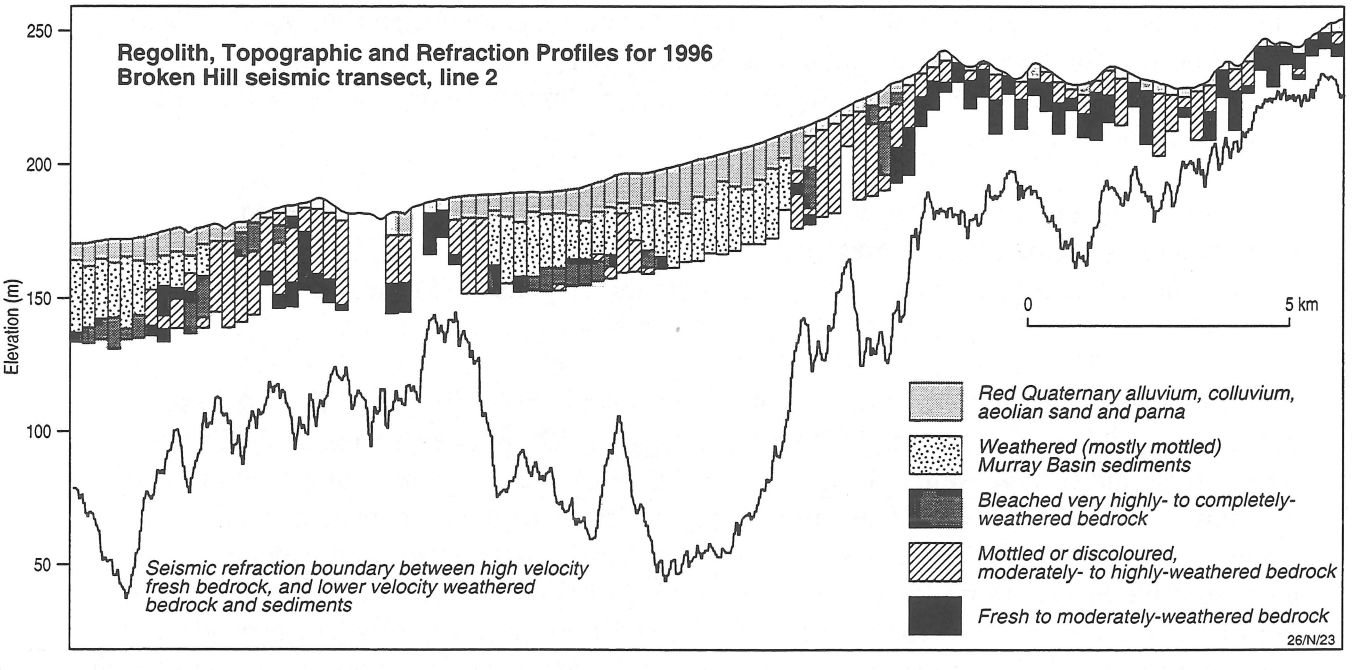


Figure 30: Regolith, topography and refraction profiles for the Broken Hill seismic lines.

streams cutting back across the fault scarp from the downthrown block to the west, and draining down the newly tilted block towards the southeast. The old, northward drainage across the block was captured and disrupted by these new streams, but remnants of this old drainage still occurs in the headwaters of streams draining to the Mundi Mundi Plain.

It is possible that reverse movement has also recently occurred on the Mulculca Fault and the Mt Darling Range shear corridor, to produce a 'sawtooth' tectonic landscape. If this were the case, weathered bedrock and thick alluvium might be expected to be preserved to the northwest of these structures. The shotholes show there is no great thickness of alluvium in either location, nor is there weathered rock preserved northwest of the Mt Darling Range shear corridor. Hence it is considered more probable that these linear topographic features result from differential weathering of different rock types on either side of the faults.

Geochemistry

Two hundred and eighty-five (285) bottom hole samples were collected for geochemical analysis. Samples were collected only from the bedrock dominated part of the transect. Sampling commenced at the foot of the Mundi Mundi scarp (shotpoint 622) and ceased a short distance past the Redan Fault (shotpoint 3118). Shotholes ranged up to 40m in depth and all struck bedrock apart from the last 26 holes beyond the Redan Fault (shotpoints 2968-3118) which bottomed out in transported material. These samples were not included in the analysis. The bedrock samples show varying degrees of weathering and/or retrogression.

The samples have been analysed for major elements and some trace elements (eg Cu & Zn) by XRF. Analysis for trace elements (including REE) by ICP-MS is underway. Although little analysis of the data has been carried out at this stage, preliminary examination of the data shows some broad trends.

Fe_2O_3 and TiO_2 (Fig. 31) track each other across the block and seem to be related to amphibolites. A distinct zone is present between the Rupee/Mt. Darling Range shear zones and the Mulculca Fault, characterised by a background response 2-3 times that of the rest of the block.

Zinc shows a number of prominent anomalies across the transect (Fig. 32). Two of these correspond with zones of known Pb-Zn mineralisation (782 ppm - extension of the line of lode near Round Hill; 767 ppm - Little Broken Hill area). Others occur in areas with little or no known Pb-Zn occurrences (2795 ppm - Paragon Group metasediments near the King Gunnia Shear Zone [NOTE: Paragon Group metasediments are currently considered unprospective for stratiform Pb-Zn mineralisation]; 1141 ppm & 506 ppm - intersections of lines 1A and 1B with a horizon west of the Stephens Creek granite gneiss (corresponding to the extrapolated position of the line of lode north of the Stephens Creek shear zone); 430 ppm - approximate position of the Redan Fault).

A more complete analysis of the full geochemical dataset will published at a later date.

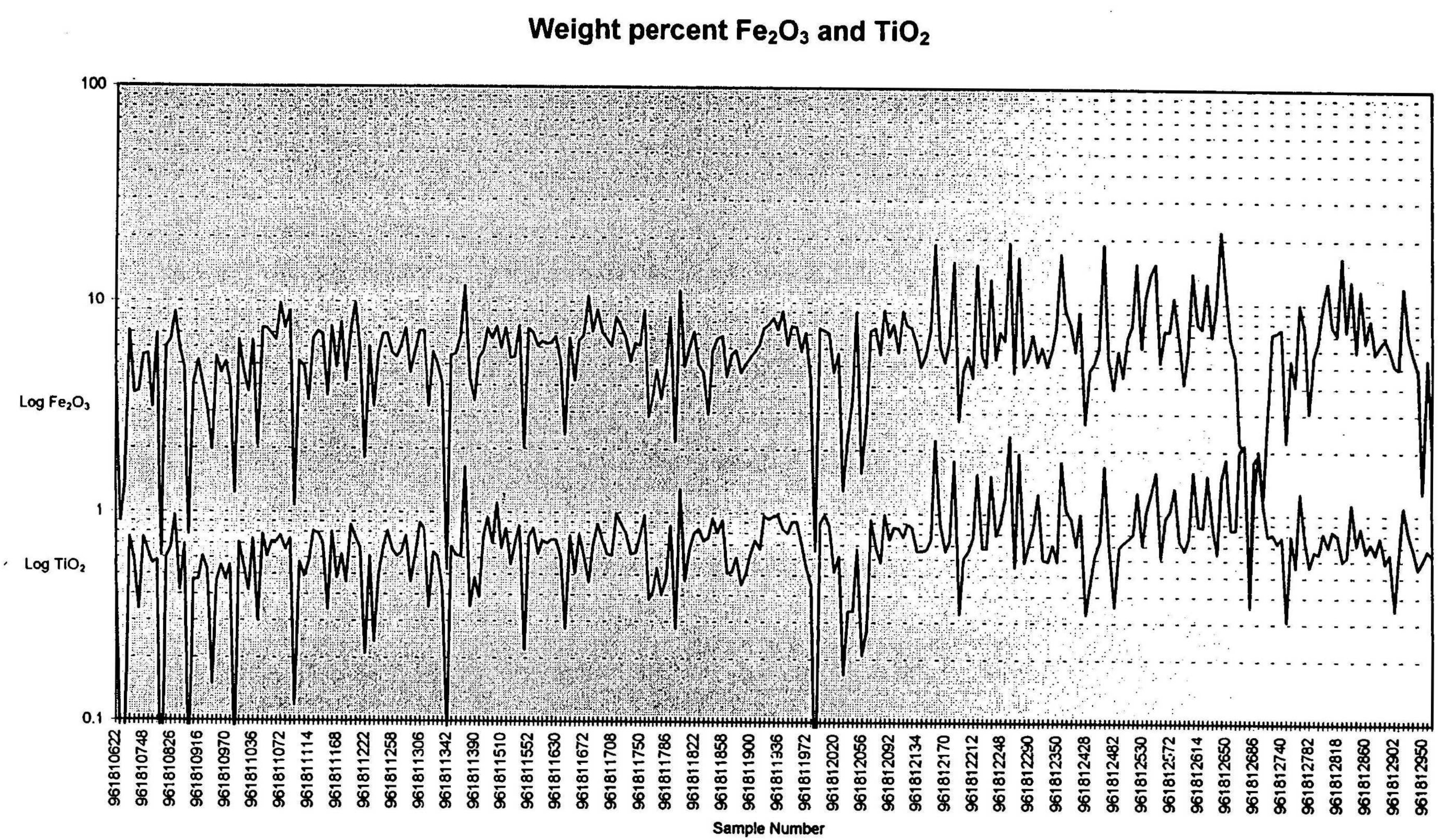


Figure 31: Logarithmic plot of Fe_2O_3 and TiO_2 (brackets wt %) from bottom hole samples along the seismic transects. Note TiO_2 tracks Fe_2O_3 indicating that highs in the diagram probably represent amphibolite.

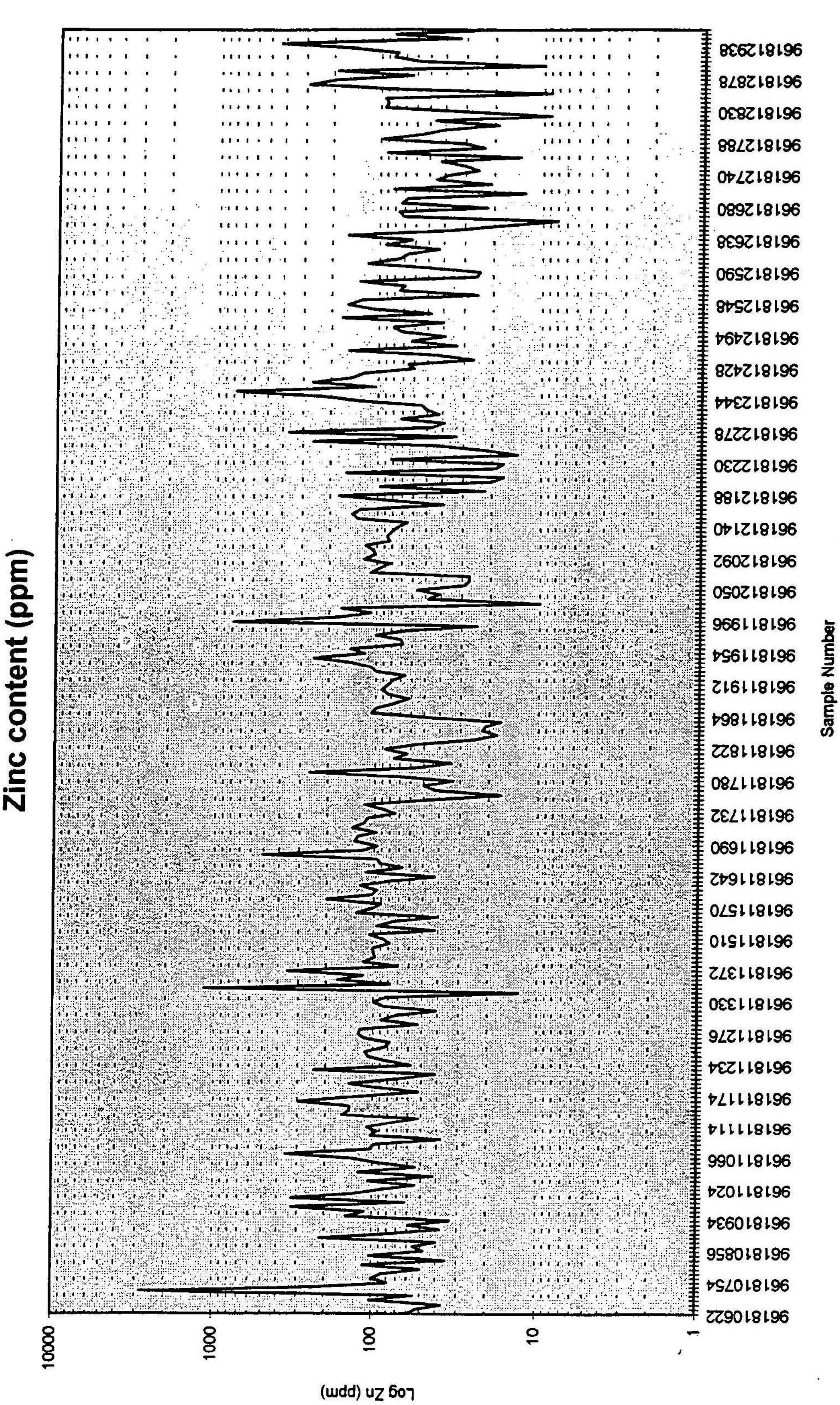


Figure 32: Logarithmic plot of Zn (ppm) from bottom hole samples along the seismic transect. High values correspond to major shear zones, possibly indicating mobilisation of Zn by fluids moving along the shear zones.

ACKNOWLEDGEMENTS

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