AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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ARCHAEAN CRUSTAL STRUCTURE FROM SEISMIC REFLECTION PROFILING, EASTERN GOLDFIELDS, WESTERN AUSTRALIA

Results from the Kalgoorlie Seismic Transect

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1. Australian Geological Survey Organisation
2. Geological Survey of Western Australia

AGSO

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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Resources: The Hon. Alan Griffiths
Secretary: Geoff Miller

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EXECUTIVE SUMMARY

Crustal seismic reflection profiling has successfully imaged the depth extent and the internal structure of the Archaean greenstone of the Kalgoorlie Terrane and adjacent belts. The basal contact of the greenstones is subhorizontal and gently undulating, reaching a maximum depth of 7 km. Strongly reflective, subhorizontal layering occurs below the basal contact interpreted to be gneissic basement. The basal contact is offset in several places by moderate- to shallow-dipping, strongly reflective zones which project to the surface at the position of previously mapped shear zones. These shear zones show clear normal displacement of greenstone stratigraphy and the basal greenstone-gneiss; some sole out into the basal greenstone contact and others extend considerably deeper into the gneissic basement. Stratigraphy and major fold structures are well delineated, and granite plutons have been constrained to tapering surf-board shapes, rather than the sheet-like forms, or diapirs. Stratigraphic units appear to truncate abruptly at the basal greenstone contact in many places suggesting significant decollement has occurred at the contact during low-angle thrusting.

In association with the seismic traverse, a gravity traverse (200m station spacing) and airborne magnetic traverse were carried out. The geological interpretation of seismic units is usefully constrained by the gravity data, which also provide evidence of changes in crustal structure along the line.

Geochemical analysis was carried out on material collected from the bottom of each shot hole (883 samples). A suite of 30 trace elements were analysed, and these data demonstrate significant differences in granite chemistry along the line. A number of anomalous values for a variety of elements have been identified.

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1. THE SEISMIC TRANSECT

The Kalgoorlie Seismic Transect is a 213 km long deep seismic reflection profile oriented approximately east-west 30 km to the north of Kalgoorlie (Fig. 1).

The seismic profile was designed to cross many of the main features of the greenstone belts within the Eastern Goldfields Province, as well as the boundary with the adjacent Southern Cross Province to the west.

This study forms part of the Eastern Goldfields NGMA project undertaken jointly by the Australian Geological Survey Organisation and the Geological Survey of Western Australia. The National Geoscience Mapping Accord, endorsed by the Australian (now Australia and New Zealand) Minerals and Energy Council in August 1990 is a joint Commonwealth/State/Territory initiative to produce, using modern technology, a new generation of geoscientific maps, data sets and other information of strategically important regions of Australia over the next 20 years.

1.1 Aims of the Seismic Transect

The Aims of the Regional Seismic Profile were to:

- map the three-dimensional geometry of the greenstone belts, and in particular,
- their shape and thickness,
- the geometry of their boundary faults,
- the geometry and extent of shear zones within the greenstone belts, (The relative importance of different types of shear zones to the pattern of mineralisation was poorly understood),
- the geometry of the intrusive granites within the greenstone belts,
- investigate the structural relations of the greenstones with the adjacent areas of granitic rocks, and
- study the differences in structure, form and crustal thickness in the Eastern Goldfields and Southern Cross Provinces as a means of comparing and understanding their tectonic evolution.

1.2 Rationale for the Seismic Transect

The Eastern Goldfields region has historically been, and continues today to be a major gold and nickel producer. The gold mineralisation is largely on or adjacent to major fault structures. The seismic survey was predicated on the assumption that the crustal geometry has a direct bearing on the style of these structures and the processes which operated to localise gold deposition. A knowledge of the mid to upper crustal structure would therefore greatly improve the predictive capacity of ore genesis models.

Two classes of tectonic models have been used to describe the generation of the Archaean crust of the Yilgarn Craton. They can be categorised as either
- vertical tectonic models, or
- horizontal tectonic models.

These models predict different crustal structure.

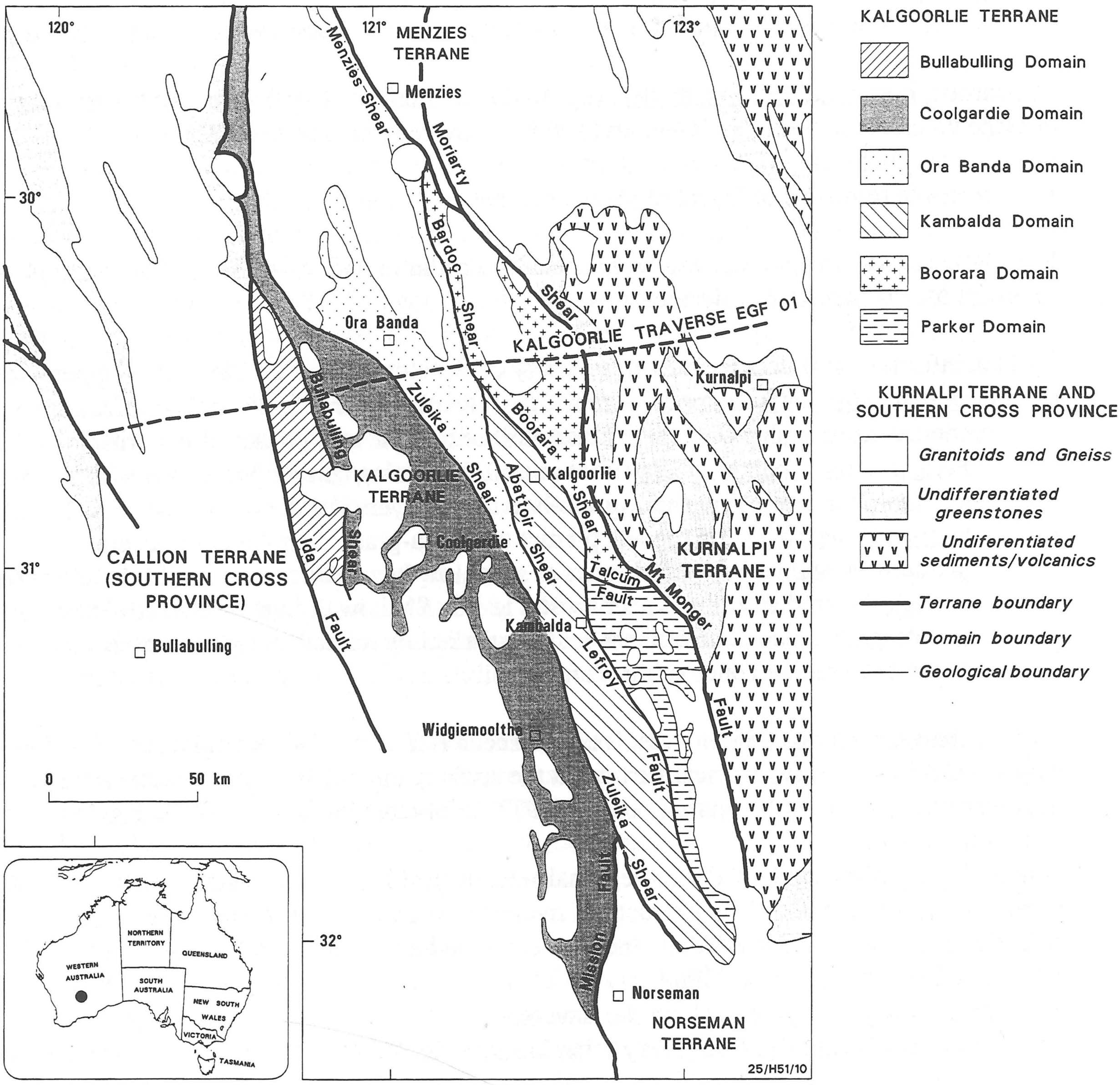

120°
121°
123°
30°
31°
32°
MENZIES
TERRANE
Menzies
Menzies Shear
Moriarty
Bardoc Shear
Shear
Ora Banda
KALGOORLIE TRAVERSE EGF 01
Kurnalpi
Bullabulling
Zuleika Shear
Boorara
KALGOORLIE
TERRANE
Kalgoorlie
Abattoir Shear
Shear
Ida Fault
Shear
Coolgardie
Talcum Fault
Mt Monger
KURNALPI
TERRANE
CALLION TERRANE
(SOUTHERN CROSS
PROVINCE)
Bullabulling
Kambalda
Lefroy Fault
Fault
Widgiemooltha
0
50 km
Zuleika Shear
Mission Fault
Norseman
NORSEMAN
TERRANE
25/H51/10
NORTHERN TERRITORY
QUEENSLAND
WESTERN AUSTRALIA
SOUTH AUSTRALIA
NEW SOUTH WALES
VICTORIA
TASMANIA
KALGOORLIE TERRANE
Bullabulling Domain
Coolgardie Domain
Ora Banda Domain
Kambalda Domain
Boorara Domain
Parker Domain
KURNALPI TERRANE AND
SOUTHERN CROSS PROVINCE
Granitoids and Gneiss
Undifferentiated greenstones
Undiferentiated sediments/volcanics
Terrane boundary
Domain boundary
Geological boundary

Figure 1.1

Vertical tectonic models (eg. Campbell and Hill, 1988) predict that

- granite-greenstone boundaries should be steeply dipping,
- the internal structure of the greenstone belts will be dominated by upright folding and homogeneous flattening, and
- the mid to lower crust should be fairly homogeneous with few and only weak reflectors.

In contrast, horizontal tectonic models (eg. Barley and others, 1989) allow for the generation of large volumes of granite in hinterland and back-arc regions, but predict

- a strongly layered upper crust, with
- possible remnants or layers of greenstone below granitoid layers.

It is likely that the lower crust will be seismically similar in both cases, but deeper lithosphere structure may be markedly different.

Surface information is consistent with a variety of structural styles for the mid to upper crust.

- Delamination or flake models predict that steeply dipping faults at the surface are connected with shallow dipping ductile shears in the middle part of the crust.
- Fold and thrust belt models predict crustal thickening contemporaneous with tectonic shortening, resulting in a strong sub-horizontal layered or duplexed mid to lower crust.
- Extension and inversion models predict that high-grade deep-level rocks are juxtaposed against low-grade rocks at a shallow level. The crust would therefore be strongly layered at mid to upper crustal levels. Shallow dipping domal structures at granite-greenstone boundaries would be marked by reflective mylonite zones along either detachment zones or thrust faults.

Surface mapping alone could not resolve the structure at depth. For example, many of the major faults in the region are near vertical at the surface, but old analogue seismic reflection data recorded by BMR (Mathur and others, 1977) imply that the faults must be listric.

A new, high quality, state-of-the-art regional seismic profile was designed to image the entire crust and test the range of likely structural models of the region, or to erect new ones. Additional new data collected along the transect included:

- gravity readings every 240m
- an aeromagnetic profile along the traverse
- bottom hole samples from every seismic shot hole.

This Record summarises the first results from the transect.

2. GEOLOGY ALONG THE TRANSECT

The seismic reflection traverse crosses several greenstone belts, including several domains within the Kalgoorlie Terrane (Figs 2.1; 2.3, 2.4; Swager and Griffin, 1990a). The Kalgoorlie Terrane is bounded by the Ida and Mt Monger Faults and has a relatively well understood stratigraphy comprising four main units (Fig. 2.5):

1: Lower Basalt
2: Komatiite
3: Upper Basalt and
4: Acid-intermediate volcanic and volcaniclastic rocks (Black Flag Beds).

These greenstones were deposited between about 2.7 Ga (Barley and NcNaughton, 1988; Claoue-Long and others, 1988). The established deformation history involves D1 recumbent folding and thrusting, followed by D2 east northeast - west southwest shortening resulting in regional upright folds and both strike and reverse slip faults (Archibald and others, 1981; Swager and others, 1992). Early major extensional faulting has also recently been proposed (Hammond and Nisbet, 1992; Williams and Currie, 1993; Williams and Whitaker, 1993). The Kalgoorlie Terrane is internally divided by the Zuleika and Bardoc Shears, amongst others, into domains characterised by slight variations to the regional stratigraphy (particularly the extent of the upper basalt unit) and differences in the nature and intensity of D1 structures.

Three episodes of granite emplacement; pre-(syn) D2, syn-D3, and late tectonic (Witt and Swager, 1989) have recently been dated at 2.68, 2.66 and 2.62-2.60 Ga (Campbell and Hill, 1988; Hill and others, 1992). The 'domal' granites along the seismic traverse (Dunnsville, Mt Pleasant, Scotia-Kanowna) are part of the earliest intrusive phase.

The Ida Fault separates the Kalgoorlie Terrane from the Barlee Terrane (Fig. 2.2) which contains basal quartzite and pebble conglomerate, as well as numerous banded iron formation layers within the dominant mafic - ultramafic volcanic rocks. This sequence is overlain by a calc-alkaline felsic complex dated at 2.735 Ga (Pidgeon and Wilde, 1990), which predates the Kalgoorlie Terrane greenstones.

The Mt Monger Fault separates the Kalgoorlie Terrane from the less well understood greenstones to the east, referred to here as the Gindalbie and Jubilee belts. The Gindalbie belt (Fig. 2.6) contains a felsic volcanosedimentary sequence which has a gently dipping fault contact with overlying komatiite and basalt. Preliminary geochronology suggests that the felsic rocks are older than the Kalgoorlie Terrane stratigraphy. The complex tectonostratigraphic package is folded into a regional doubly plunging anticline. The Emu Fault (Figs 2.1; 2.6) is the inferred contact between the Gindalbie and Jubilee belts, and is concealed below a polymict conglomerate. The Jubilee belt contains a west-dipping homoclinal sequence of komatiite, basalt, felsic intermediate volcanics and sedimentary rocks. Komatiite occurs at several horizons within this sequence, possibly as a result of low-angle imbrication.

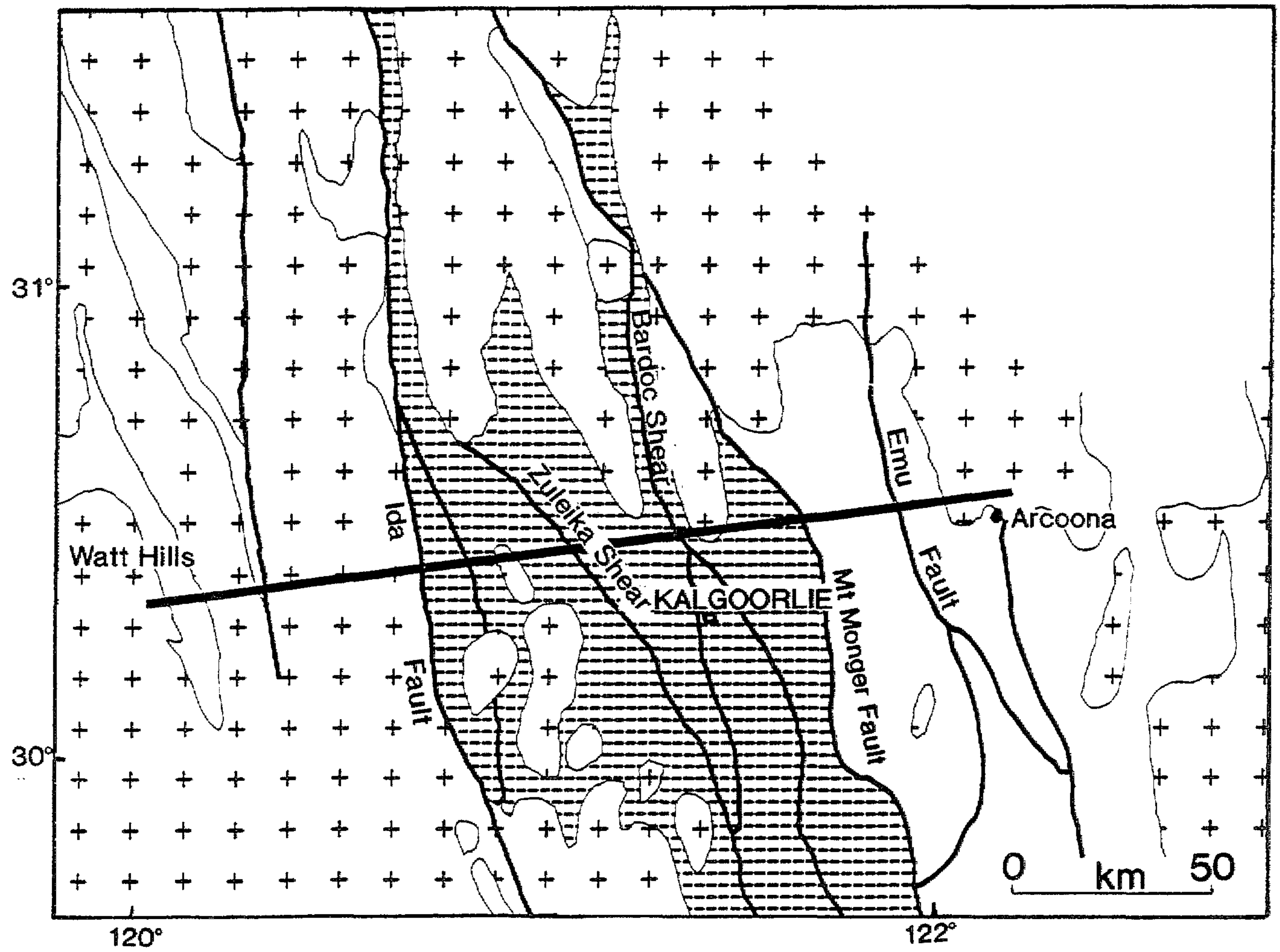
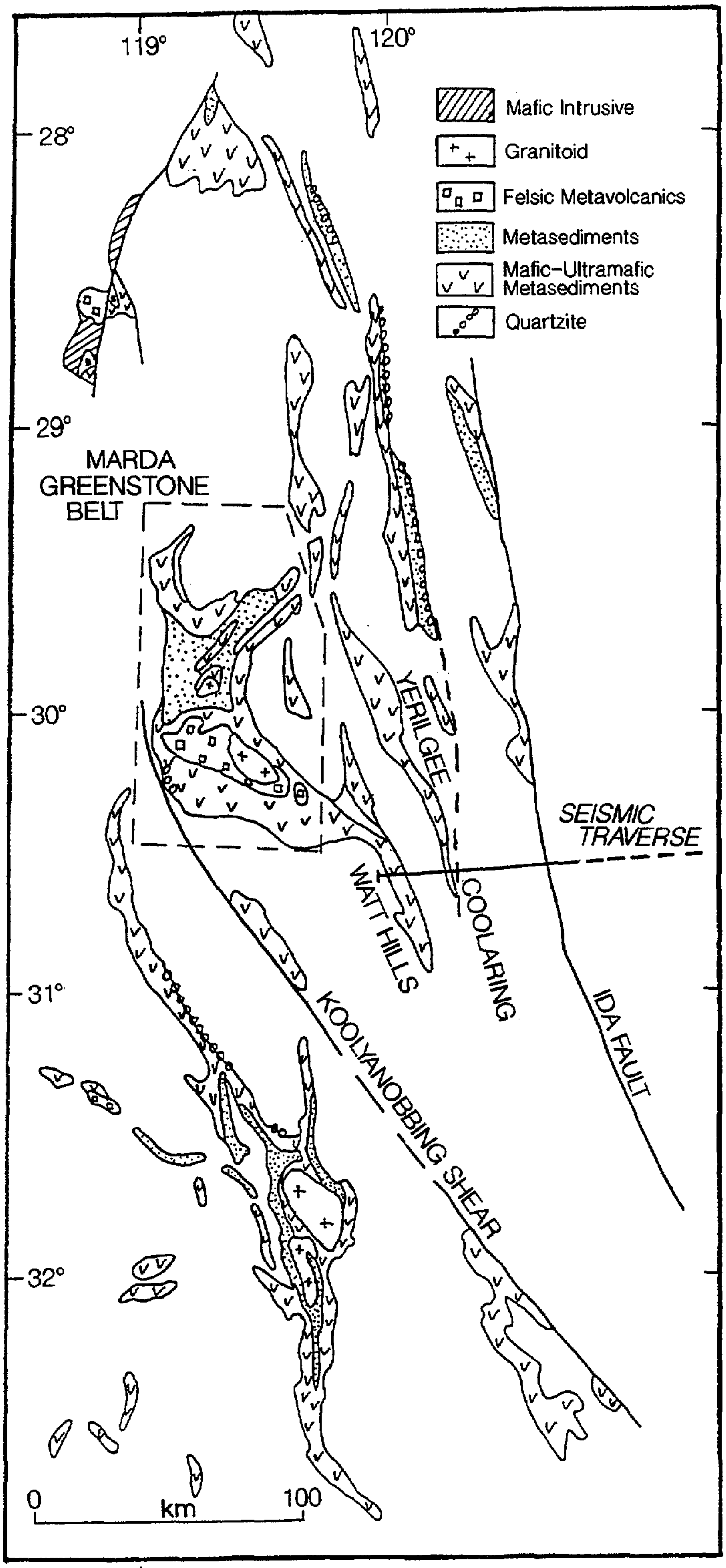


FIGURE 2.1.
Main structural features of the Kalgoorlie Terrane and adjacent regions

Areas of granite are filled with crosses; Kalgoorlie Terrane greenstones dashed; other greenstones light stipple

FIGURE 2.2
Main features of the Barlee Terrane



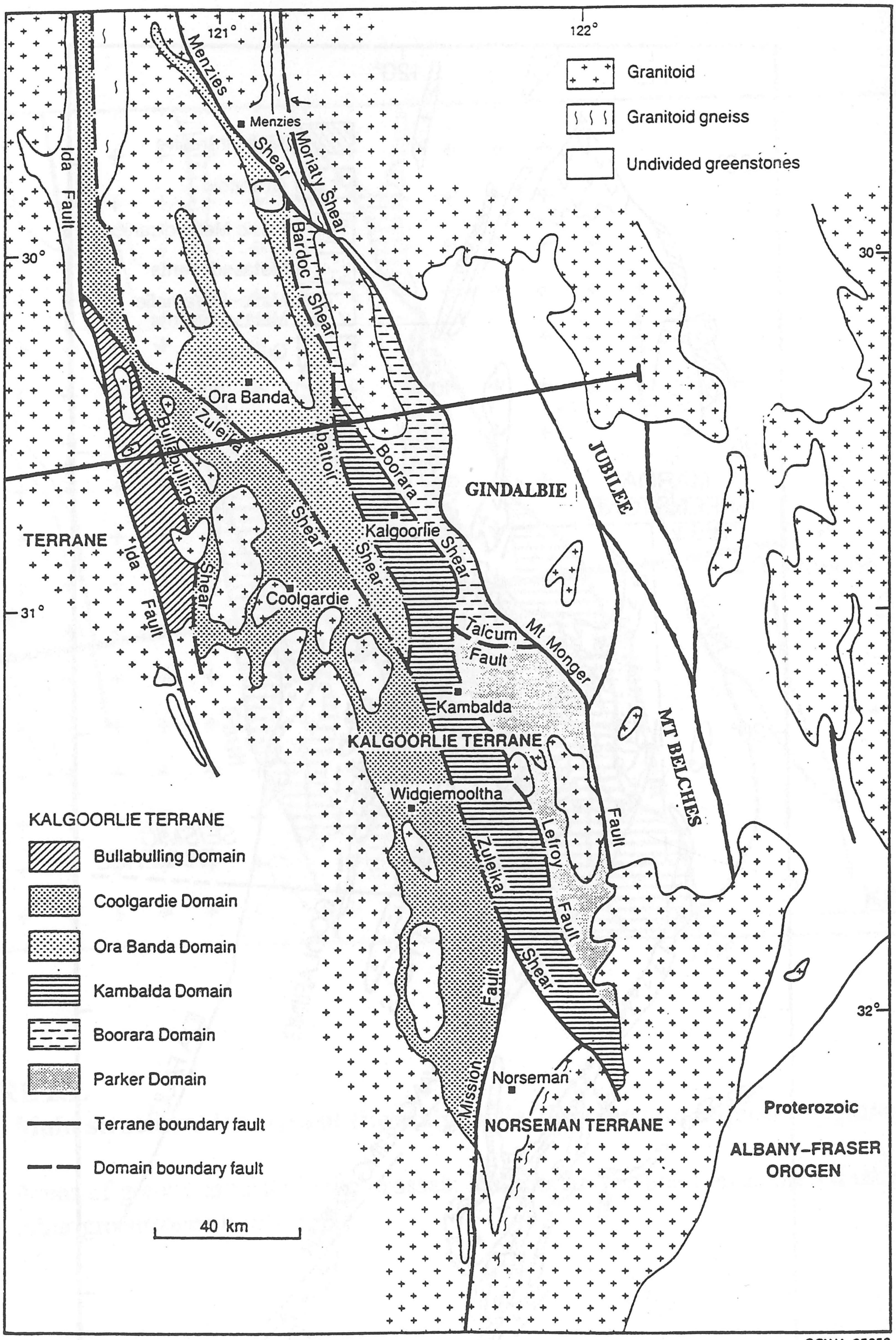
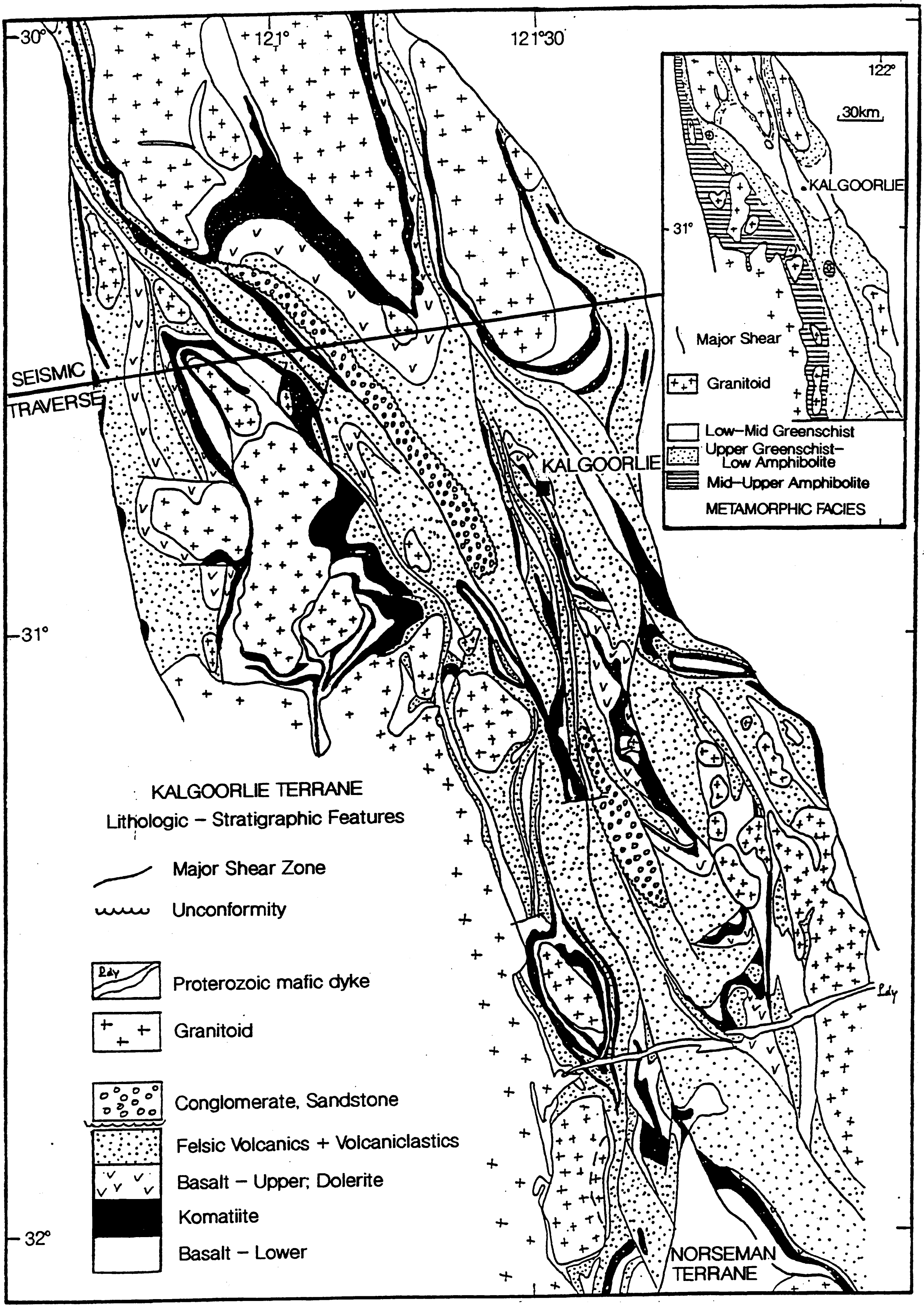


FIGURE 2.3

Subdivision of the greenstones onto structural domains



30°
121°
121°30'
31°
32°
SEISMIC TRAVERSE
KALGOORLIE
NORSEMAN TERRANE
Pdy
122°
30km
KALGOORLIE
31°
Major Shear
Granitoid
Low–Mid Greenschist
Upper Greenschist–Low Amphibolite
Mid–Upper Amphibolite
METAMORPHIC FACIES
KALGOORLIE TERRANE
Lithologic – Stratigraphic Features
Major Shear Zone
Unconformity
Proterozoic mafic dyke
Granitoid
Conglomerate, Sandstone
Felsic Volcanics + Volcaniclastics
Basalt – Upper; Dolerite
Komatiite
Basalt – Lower

FIGURE 2.4

KALGOORLIE TERRANE

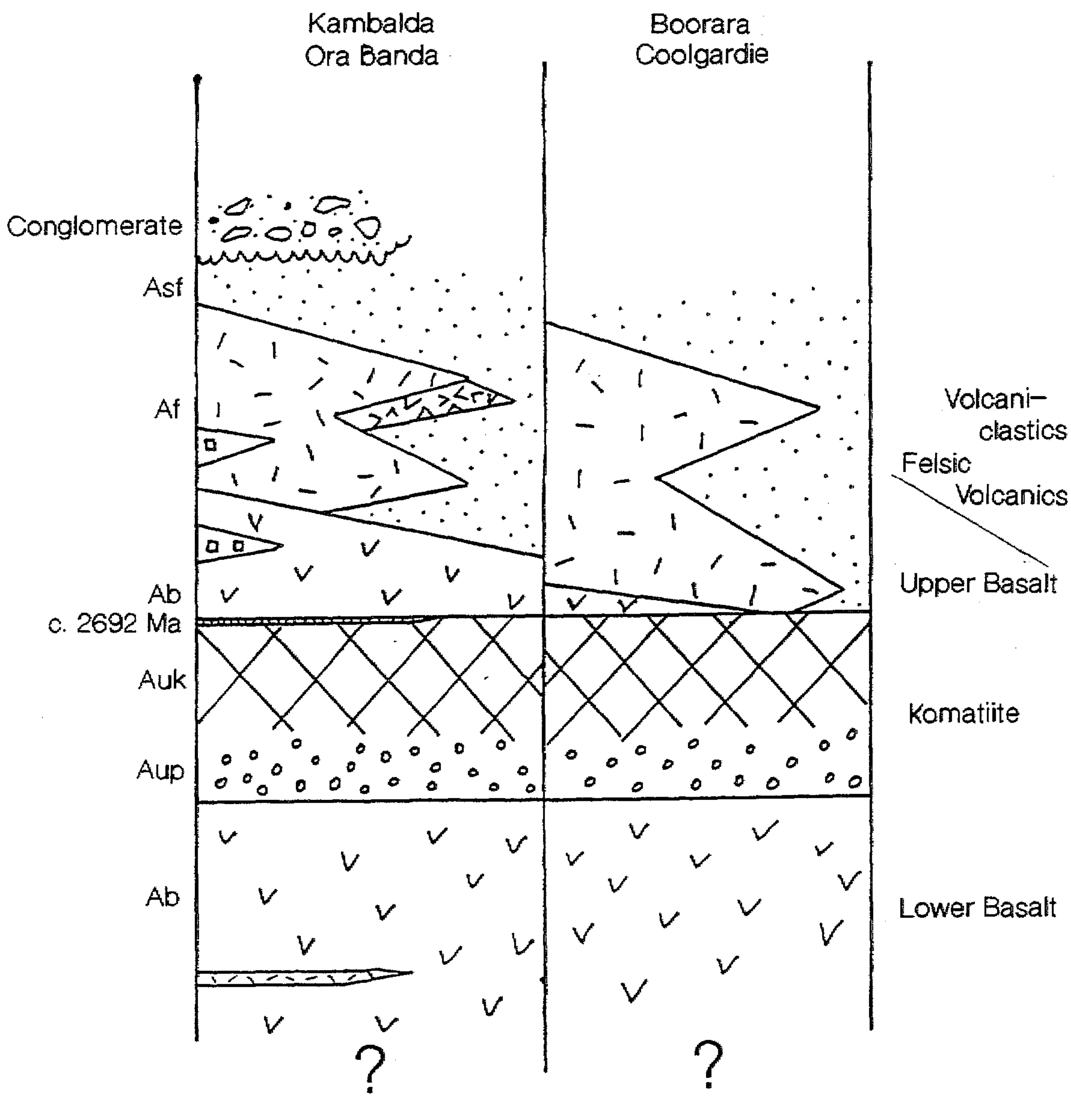


FIGURE 2.5
Stratigraphy of the Kalgoorlie Terrane

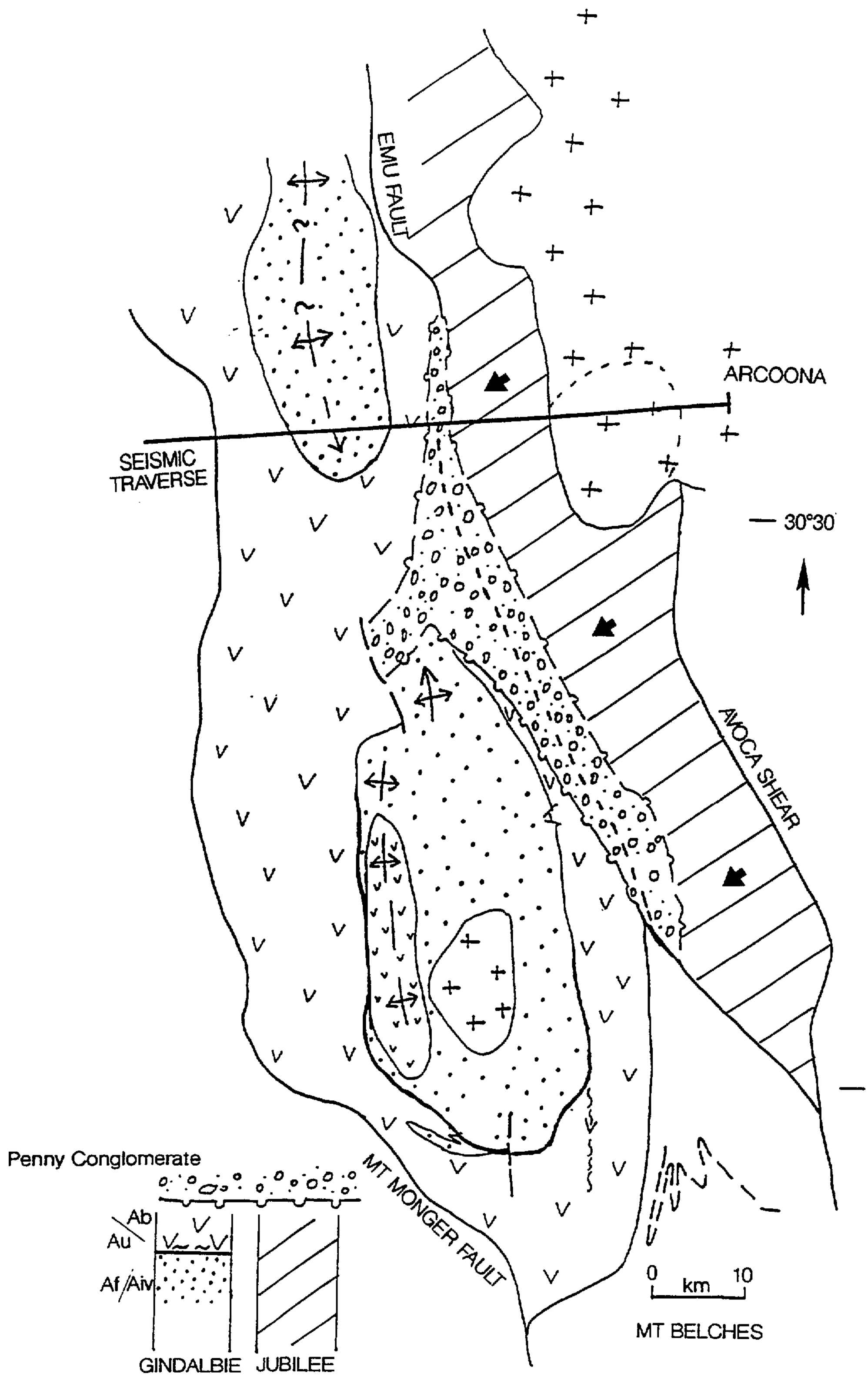


FIGURE 2.6
Geological sketch of the Gindalbie and Jubilee domains

3. SEISMIC ACQUISITION AND PROCESSING

3.1 Seismic Data Acquisition

The data were recorded using AGSO's SN368 seismic telemetry acquisition system. The seismic source used was 8 kg of explosive charge buried at a maximum depth of 36 m. Drilling was carried out by AGSO's 5 Mayhew 1000 drill crews.

The seismic signals were acquired using 96 active data channels, with each channel (geophone) spaced 40 m along the traverse. This group interval, coupled with a shot interval of 240 m (though this did vary with topography and drilling conditions), yielded 8 fold seismic data coverage. Shots were recorded for 20 seconds at a 2 sec sampling rate, producing in excess of 2.6 Mbytes of data per shot.

A split spread recording configuration was used, giving a maximum shot to receiver offset of 2 km. A list of the complete range of acquisition parameters used is given in the following tables.

Table: Traverse Details- 1991 Eastern Goldfields Seismic Survey

Traverse Name	91-EGF01
Orientation	E-W
Length	213 km
First station number	3681
Last station number	9000
Most western shotpoint #	3681
Most eastern shotpoint #	9000
Number of shotpoints	879
Station interval	40 m
Shot interval	240 m
Spread	96 chan. split, asymmetrical
Record Length	20 s
Sample Rate	2 ms

Table: Drilling Parameters- 1991 Eastern Goldfields Seismic Survey

Number of Rigs	5
No. of holes/shotpoint	1
Depth of hole (nominal)	36.0 m
Shotpoint interval	240 m
Explosive type	Powergel (ICI)
Detonators	ICI No 8 Seismic 45 m leads
Charge size per hole	8-10 kg
Charge tamping	Earth, solid fill

This combination of seismic source type, offset range and charge size was chosen as the most suitable to image structures within the entire crust whilst at the same time give some details of structures within the top 3 km.

Table: Recording Parameters- 1991 Eastern Goldfields Seismic Survey

Recording Instrument	Sercel SN-368
Number of channels	96
SN-368 inst. settings:	
Recording mode	Digital telemetry
Format	SEG-D
No. of input channels:	
Data	96
Auxiliary	4
SN-368 Tape Drive	9 track, 1/2"
Tape density	6250 GCR
Record length	20 s
Sample rate	2 ms
Gain constant	42 dB
Input filters:	
low-cut	8 Hz, 36 dB/oct
high-cut	172Hz, 72 dB/oct
notch	out
Geophone spacing int.	40.0 m
Spread length	3,800 m
CMP fold	12
Geophone Type	GSC-20D, 8Hz Resonance
No. geophones/trace	16
Geophone pattern	in-line
Geophone element int.	5.0 m

3.2 Field Processing

Some initial processing was carried out in the field to monitor data quality and to assess the benefits of making changes in some of the acquisition parameters over areas of increased geological interest.

The main data processing effort was undertaken in the AGSO seismic processing facility.

3.3 Data Processing

Seismic data were recorded on magnetic tape and then forwarded to AGSO's seismic processing centre in Canberra at the completion of the survey for processing. Preliminary seismic sections were available for interpretation in October 1991 (within 3 months of the completion of field work) (Goleby and others, 1992).

The interpretation of seismic data from hard rock terranes is not simple (see Chapter 4). The features observed within the seismic sections indicate that the field data acquisition parameters used were suitable for the objectives of the survey. However, an correct interpretation of the data requires not only a comprehensive knowledge of the geology but also seismic sections specifically produced to enhance different aspects of the data. Consequently, a variety of seismic sections were produced.

The following table lists the processing steps for a typical section. Steps marked with a "1" were not applied to all sections. For some other steps, sections were produced using a range of parameters; these are marked with a "2". Consequently, the interpretations in the chapters that follow were based on a number of different seismic sections, and not just on the examples that are shown in the figures.

Table: Typical Processing Sequence

	Demultiplex SEGD to SEGY
	Geometry definition
	Quality control displays on shot gathers
	Resample to 4 ms
	Trace edits
	Spherical divergence
	Statics corrections using refraction statics technique
1	Spiking deconvolution
2	Bandpass filter
	Shot balance
	Velocity analysis
1	Dip Moveout
	Normal moveout
2	Coherency enhancement of shot gathers
	CDP sort
	Median stack
	Balance on the stacked section
2	Coherency enhancement on the stacked section
1,2	AGC
	Display

4. THE SEISMIC SIGNATURE OF TYPICAL STRUCTURES

Seismic profiles from basement provinces such as the Yilgarn Block are unlike those collected in sedimentary basins by the petroleum exploration industry. Petroleum industry data usually depict a clear, faithful representation of the sedimentary strata. They can be used to interpret not only the distribution of the sedimentary packages and the structures within them, but also can often be used to map fine detail within individual facies.

However, just as the basement under the sedimentary section in any petroleum industry seismic section is usually poorly imaged, so too are structures within basement terranes.

There are several reasons for this.

Firstly, the seismic method is tuned for horizontal and sub-horizontal structures. This reflects its derivation in the petroleum industry, where the majority of sedimentary rocks are sub-horizontal. In contrast, structures within basement terranes are often steeply dipping, reflecting a long and complex tectonic history. Nevertheless, the method can image structures with considerable dip, although placing the structures in their proper place in the seismic section, through the process known as migration, can be difficult.

However, the main reasons for the more diffused images recorded in basement areas relate to the types of rocks present.

The seismic reflection method works by reflecting seismic waves off interfaces between rocks with different seismic impedances. Seismic impedance is the product of the density of the rock and the velocity at which the seismic waves travel through the rock. For rock types typical of those found in basement terranes such as the Yilgarn Block, empirical relations show that seismic velocity is approximately proportional to density, so that seismic impedance is approximately proportional to the square of the density.

The relative variation of rock densities in basement terranes is not as great at it is in petroleum provinces, due mainly to the effects of diagenesis, alteration and metamorphism. Consequently the strength of the reflections from the interfaces between the rocks is not as great.

The lateral continuity of the reflections in seismic sections from sedimentary basins results from the great lateral continuity of the sedimentary packages. Just as individual beds can be traced over considerable distances within the sedimentary basin, so too can the reflections off the tops and bottoms of the beds. In basement terranes, the effects of structuring, particularly faulting and tight folding, as well as the disruptions caused by igneous intrusions, have generally destroyed much of the simple patterns relating to lateral continuity in beds.

The thickness of the rock strata also has an effect on the strength of the seismic reflection. To a first approximation, reflections will result from beds which are greater than one quarter of a wavelength thick. Rocks in sedimentary basins typically have velocities of the order of 2500 ms^{-1}, so that for a typical signal with a of, say, 50 Hz, reflections will result from beds 12.5 m thick. Hence petroleum exploration seismic sections can be used to study the sedimentary section in very fine detail. However, in basement terranes, the seismic velocities are much higher. A rock with a velocity of 5000 ms^{-1} would need to be at least 25 m thick to reflect a seismic wave with a frequency of 50 Hz. Seismic velocities between 6000 and 7000 ms^{-1} are typically observed in the greenstone belts of the Yilgarn Block. Consequently, bedding less

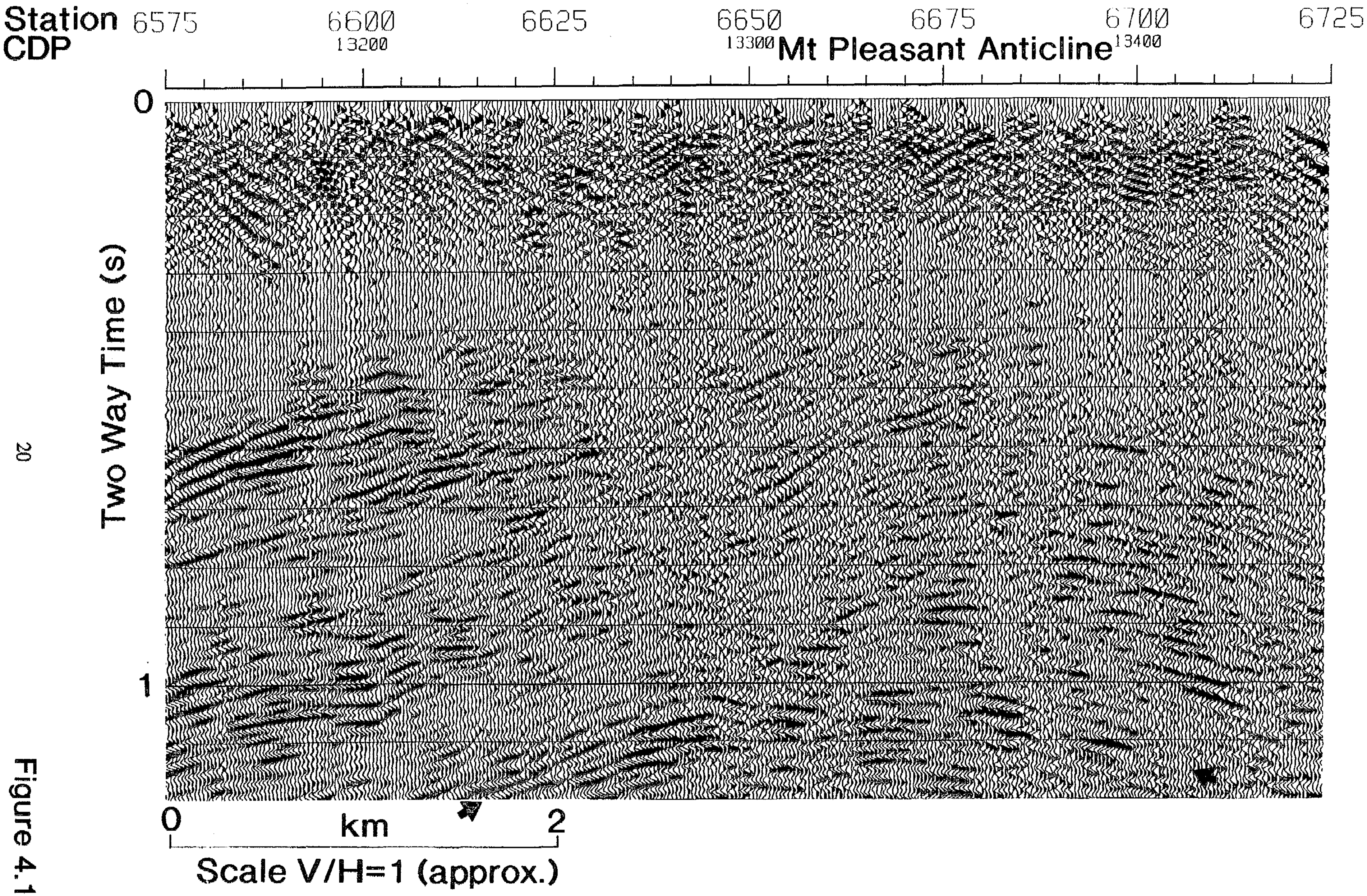

Station 6575 6600 6625 6650 6675 6700 6725
CDP 13200 13300 13400
Mt Pleasant Anticline
Two Way Time (s)
0
1
0 km 2
Scale V/H=1 (approx.)

Figure 4.1

than 35 - 40 m will not produce reflections.

In some cases, reflections can result from broad zones of small scale bedding or foliated zones because of constructive interference between the seismic wavelet and multiple reflections reverberating within the bedding or foliation. Although not primary reflections, in that they do not occur at a single, specific interface but rather from a broader zone, the resulting reflection can be very strong, and often has a lower frequency than the incident wave.

Basement terranes contain several classes of structures which provide distinctive seismic signatures, and these can be used to map significant amounts of detail within the seismic sections. Several examples are shown in Figures 4.1 to 4.4.

4.1 Bedding

Figure 4.1 shows a portion of the strata within the Mt Pleasant Anticline. The reflections have varying strength, and none can be correlated laterally for more than a few kilometres. Bundles of reflections can be correlated over longer distances. For example, a bundle of stronger than average reflections in the crest of the anticline just below 1 s TWT (Arrowed) can be traced down both limbs of the anticlines. Both the individual reflections and the bundles of reflections show the anticlinal form of the strata, although in this section the geometry of the specific rock types is difficult to map.

In the eastern Goldfields Province, regions of mafic rocks appear to be more reflective than regions of felsic rocks, probably because the impedance contrast between the igneous mafic rocks and their intercalated sediments is greater than the impedance between felsic igneous rocks and their derived sediments.

4.2 Faults

Faults have a number of different seismic signatures which may indicate their relative importance in the tectonics of the region.

Some, like the Mt Monger Fault (Fig. 4.2) are recognised because they truncate reflections in the seismic section. Where the reflections from the section are weak or absent, such as in some of the felsic areas, faults can be difficult to map in the seismic sections, and often can only be recognised because their surface positions are known. In such cases, they are mapped by extrapolating the fault trace from their surface outcrop position to a conformable reflector in the underlying detachment surface; the easternmost fault in Figure 5.2 is an example.

Other faults and shear zones which have considerable amounts of movement often have an associated broad foliated zone parallel to the fault which is reflective. The reflectivity results from several causes. Firstly, the foliation has an associated seismic anisotropy, such that the seismic impedance at right angles to the foliation is considerably higher than that parallel to the foliation. Secondly, the foliation produces constructive interferences to produce what can be extremely strong reflections. Such faults are easy to map in the seismic section, because the seismic signal maps the fault plane directly. Figure 4.3 is an example of a fault which has strong parallel foliation. It is from the eastern end of the transect, and can be traced to considerable depths.

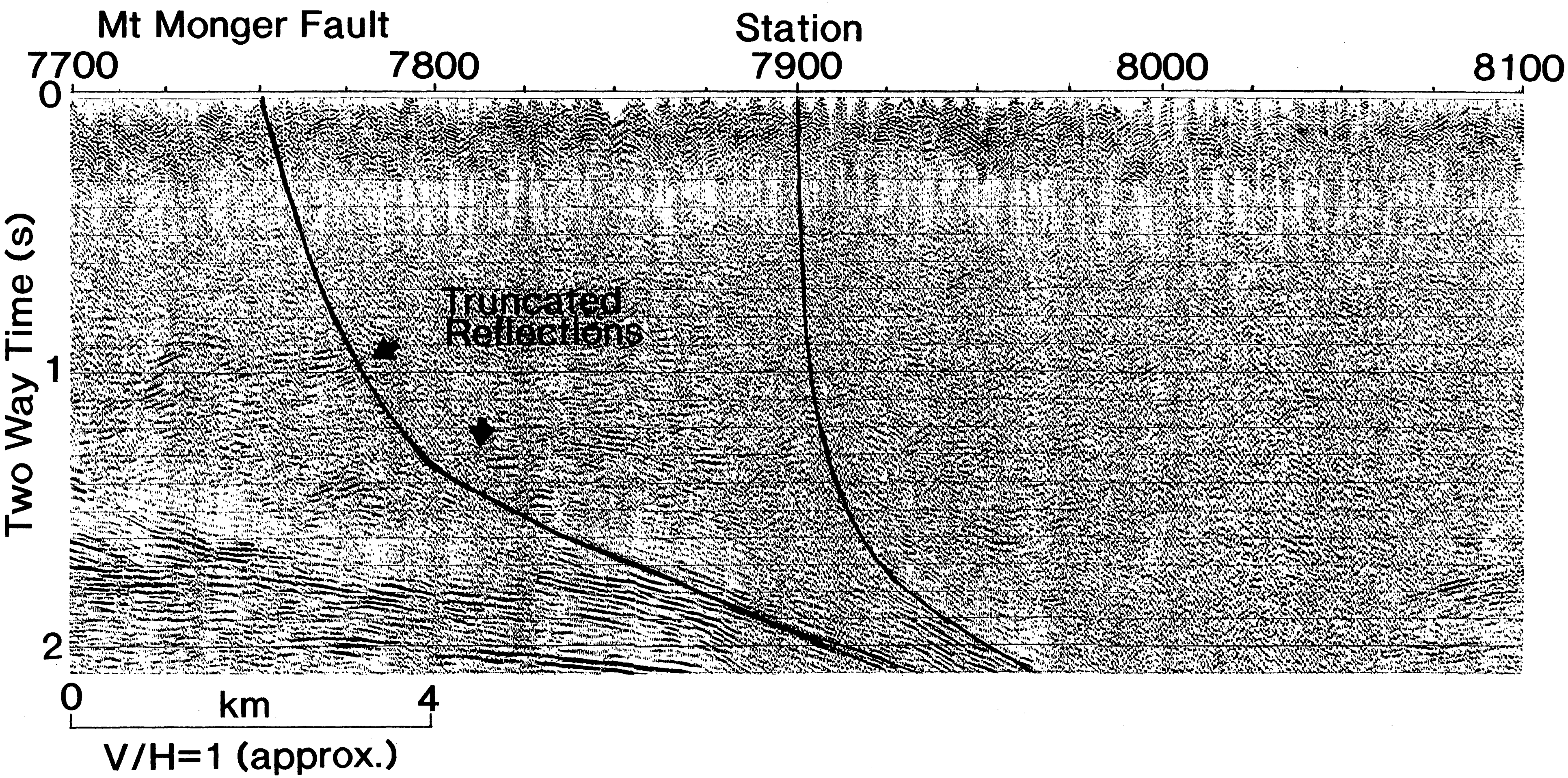

Mt Monger Fault
Station
7700
7800
7900
8000
8100
0
1
2
Two Way Time (s)
Truncated Reflections
0
km
4
V/H=1 (approx.)

Figure 4.2

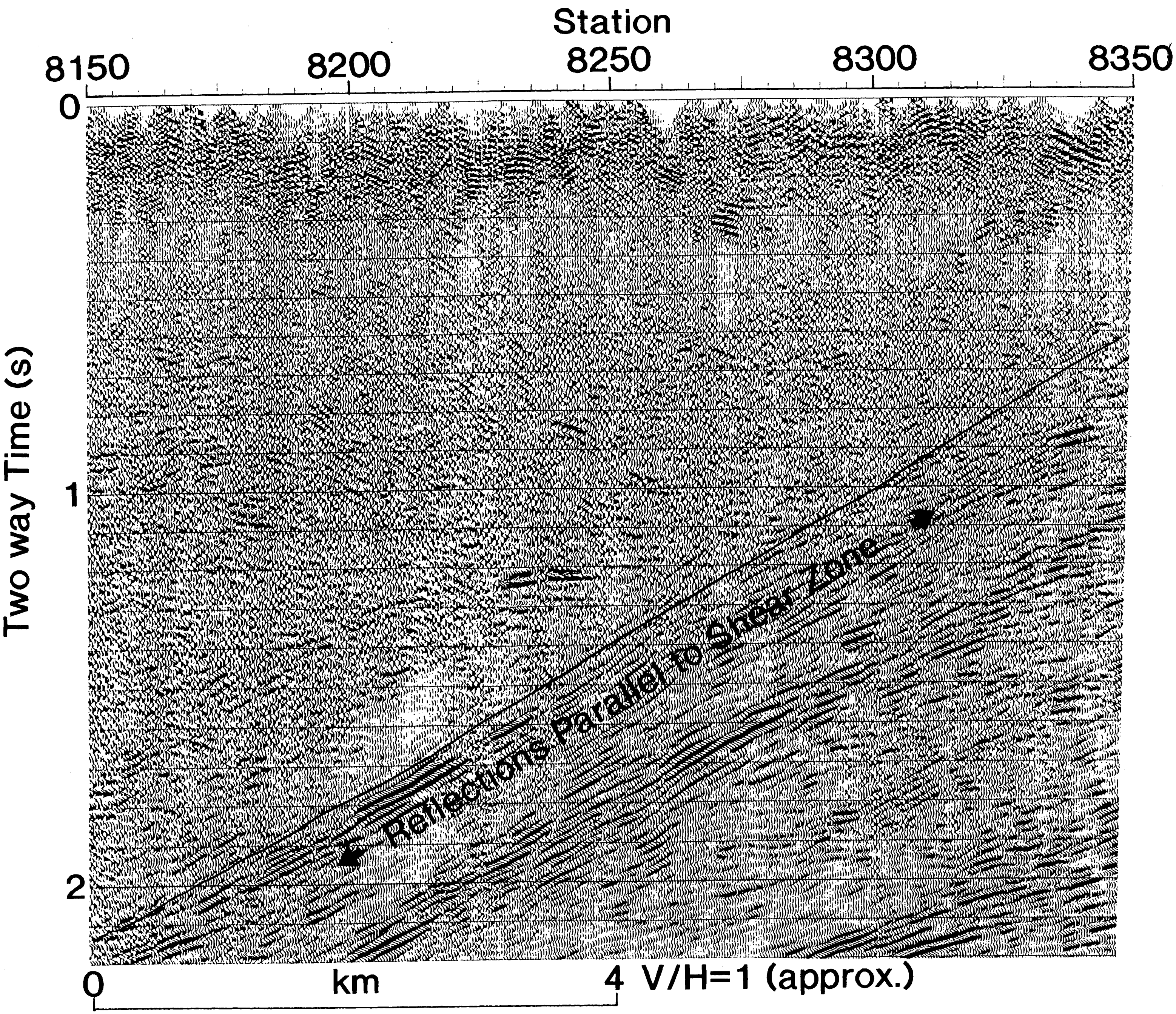

Station
8150
8200
8250
8300
8350
Two way Time (s)
0
1
2
Reflections Parallel to Shear Zone
0
km
4 V/H=1 (approx.)

Figure 4.3

4.3 Detachment Surfaces

Many of the faults mapped at the surface can be traced to considerable depths, where they detach onto strongly reflective surfaces. Figure 4.4 shows an example of a detachment surface (Arrowed). It is highly likely that the reflective character of these surfaces derives from constructive interference within a broad zone of foliated rock associated with shearing along the detachment surface. The strongest such reflectors occurs at the base of the greenstones, where the dense mafic rocks of the greenstones have probably been sheared against less dense rocks of the gneissic basement.

4.4 Granites

The positions of granites along the transect are known from surface outcrop. At depth, granites are defined in the seismic section more by an absence of clear reflections than by any other means. The Dunnsville Granodiorite (Fig. 4.5) truncates reflectors to the east and west (Arrowed), and its maximum depth extent is defined by a continuous reflector which passes underneath without obstruction.

Some granites have evidence of internal reflectors. These may be due either to shear zones or to foliation within the granite.

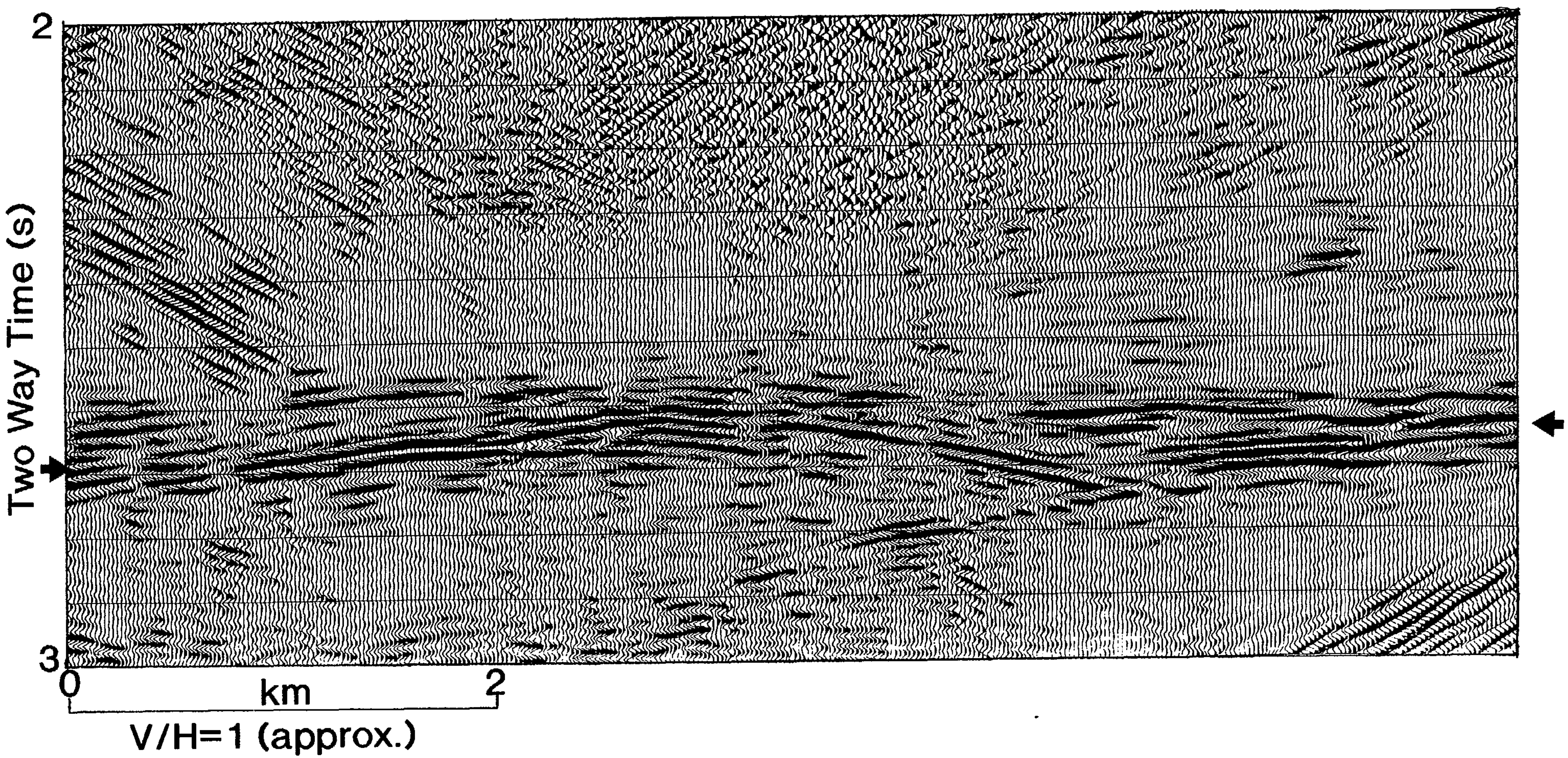


Figure 4.4

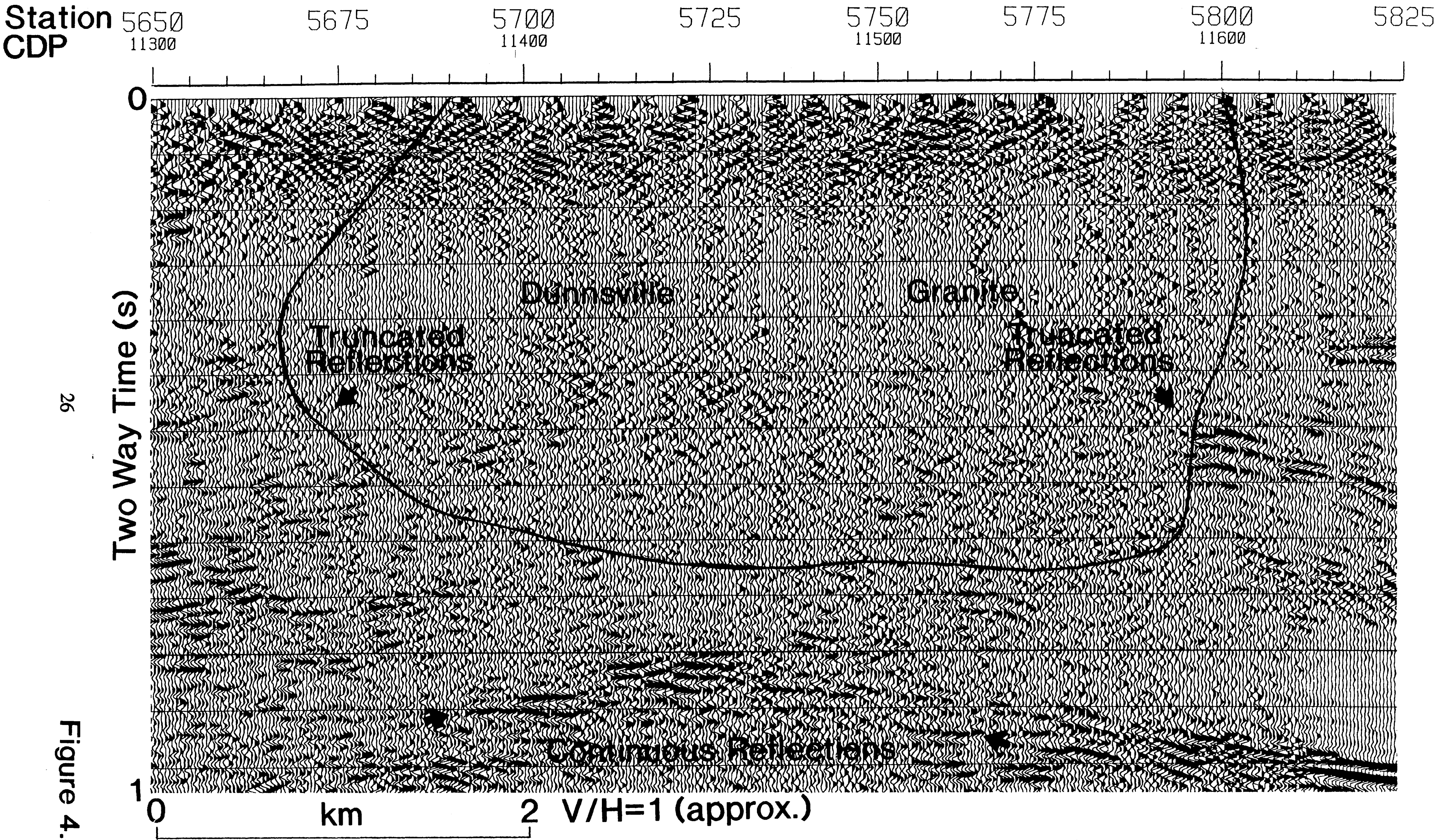

Station
CDP
5650
11300
5675
5700
11400
5725
5750
11500
5775
5800
11600
5825
Two Way Time (s)
0
1
Dunnsville
Granite
Truncated Reflections
Truncated Reflections
Continuous Reflections
0
km
2
V/H=1 (approx.)

Figure 4.5

5. CRUSTAL STRUCTURE ALONG THE TRANSECT

The crustal structure along the transect provides a regional setting within which to place the detailed structure of the greenstone belts described in subsequent chapters.

A description of the crustal structure was given by Drummond and others (1993), so only a summary is given here.

Figure 5.1 summarises the key features of the crustal section. The upper part of the figure shows the seismic data along the line. The vertical scale is approximately equal to the horizontal scale. The major boundaries in the crust are marked in the middle part of the figure. Both the upper and middle sections have time as the vertical axis, although an approximate depth scale is shown on the right. The bottom part of the figure is a line diagram designed to illustrate the effect of placing the reflections in a time section into their proper position in a depth section by the process of migration. Two types of lines are present. The finer, dotted lines mark the positions of the key reflectors and crustal boundaries in a time section (left vertical axis). The thicker lines mark their true positions in a depth section (right vertical axis). Note that the horizontal reflectors in the time sections (dotted lines) are overprinted by the thicker lines; horizontal lines in a time section plot in their true spatial position. However, the dipping reflections represented by thin, dotted lines, move up dip and steepen when placed in their true spatial position in a depth section.

The main features of the crust are shown on a seismic section from the transect in Figure 5.1. The crust in the Southern Cross Province in the west of the transect is about 33 km thick (11 s TWT). It is two layered, with an upper crust about 10 km thick (3.0-3.5 s TWT), which is largely non-reflective and interpreted to be mainly felsic, overlying a lower crust which is more reflective, and probably more mafic than the upper crust.

The seismic signature of the crust in the Eastern Goldfields Province is similar, except that it is thicker, at about 37-38 km (12 - 13 s TWT). The thickening of the crust from the Southern Cross Province to the Eastern Goldfields Province occurs at the Ida Fault. The Ida Fault is mostly planar, and dips at approximately 30° to the east, although it appears to steepen close to the surface. It can be traced to 25-30 km depth, and offsets the boundary between the upper and lower crust. It does not offset the crust-mantle boundary; rather, the crust-mantle boundary deepens over a broad zone underneath the Ida Fault.

The Ida Fault is therefore a major crustal boundary separating 2 pieces of crust which, on the basis of their seismic signatures, are very similar at depth, and whose main differences is the presence of greenstone supracrustals in the east. This indicates that the greenstones formed across a uniform crust which has bowed isostatically to compensate for the addition of higher density greenstone material.

Several other zones of reflectors parallel to the Ida Fault cut the lower crust (marked with a two dipping arrows in the bottom of Figure 5.1). When migrated to their proper place in the depth section (bottom part of Fig. 5.1), they generally fall above, and some intersect, a reasonably strong horizontal reflector which is seen at several places in the section between 20 and 25 km depth under both the Southern Cross and Eastern Goldfields Provinces (example in the east marked with arrow). Most of the dipping reflections occur in the crust under the greenstone belts, although several lie within the Southern Cross Province. One of these projects to the surface near Southern Cross, and may correlate with the Koolyanobbing Shear.

Some of the strongest reflections come from the base of the greenstones, identified as such because the reflective nature of the strata within the greenstones is not present under the strong reflections. Instead, the reflections are underlain by rocks with a seismic signature similar to the gneissic basement farther west in the Southern Cross Province.

Some of the shear zones mapped in the surface geology, such as the Bardoc Shear and an unnamed shear zone at the eastern end of the transect, cut through the base of the greenstones. The Bardoc Shear probably links with the Ida Fault. The tectonic and economic implications of this are discussed in subsequent chapters.

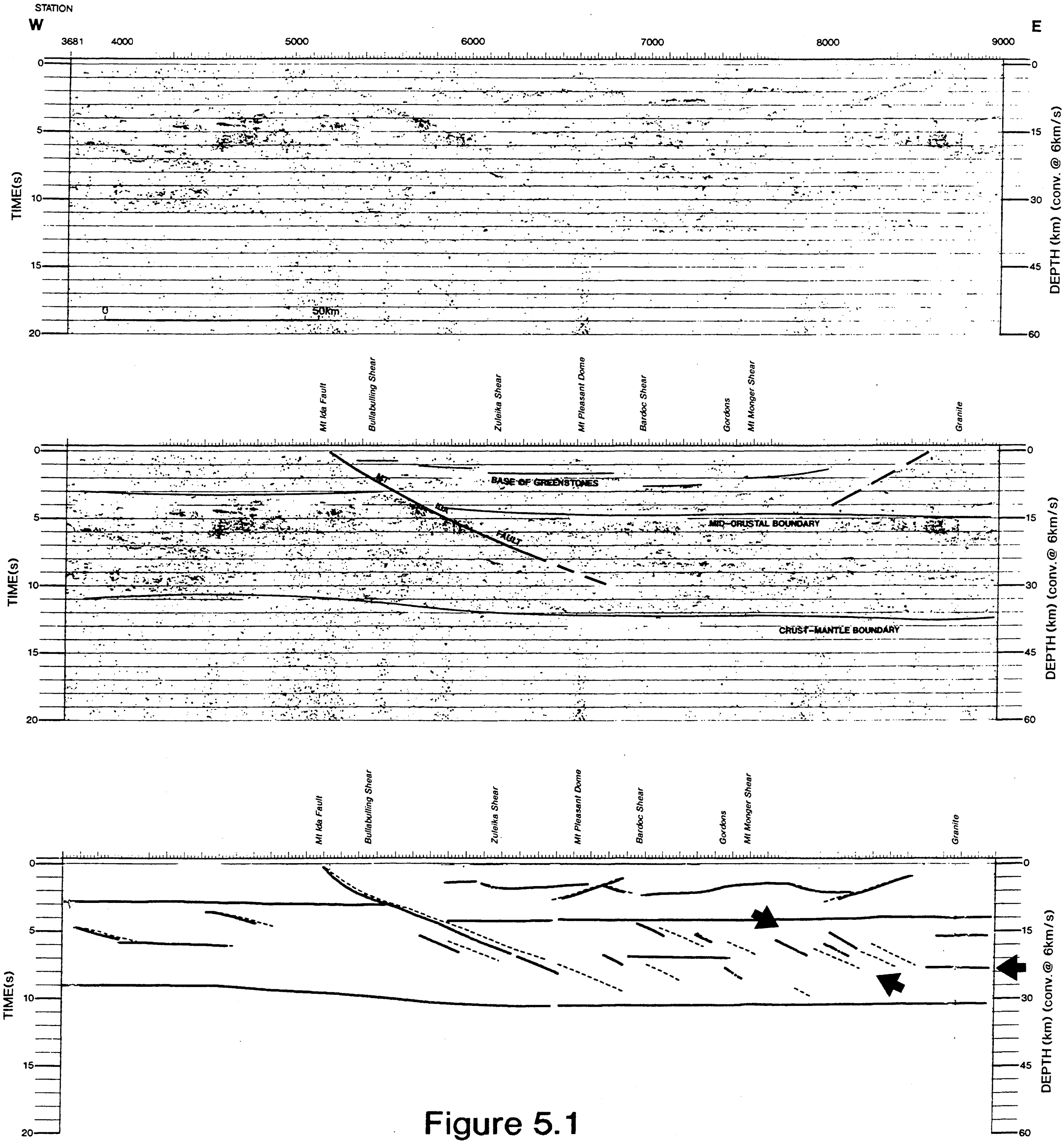


Figure 5.1

6. SEISMIC INTERPRETATION - UPPER CRUST

6.1 Individual Structures

Ida Fault

The Ida Fault marks the boundary between the Kalgoorlie and Barlee Terranes. The fault is also the boundary between the Eastern Goldfields Province and the Southern Cross Province. To the west, granite and gneiss predominate with isolated greenstone belts characterised by quartzose clastic sedimentary rocks and by voluminous basalt with interleaved banded iron formation. East of the Ida Fault is a mid-upper amphibolite facies succession of mafic and felsic metavolcanic rocks. The surface trace of the Ida Fault lies above one of the most striking features of the crustal seismic reflection data. Strong reflectors can be traced from 3 seconds TWT (~9 km depth) to about 10 seconds (~30 km depth), dipping approximately 30° east (Fig. 6.1). The Ida Fault zone offsets mid-crustal reflectors by approximately 5 km normal displacement. Within 9 km of the surface, the fault has not been directly imaged but the trace is delineated by truncated reflectors. The Ida Fault must steepen to near-vertical near its surface trace.

Bullabulling Shear

The Bullabulling Shear separates mid-upper amphibolite facies rocks to the west from mid greenschist to lower amphibolite Kalgoorlie Terrane rocks to the east. The seismic data have not imaged the shear zone except possibly by truncated reflectors in the gneissic basement (Fig. 6.1). Gravity modelling suggests there is no marked displacement of the greenstone-gneiss contact. The shear may have undergone substantial out-of-section strike-slip movement.

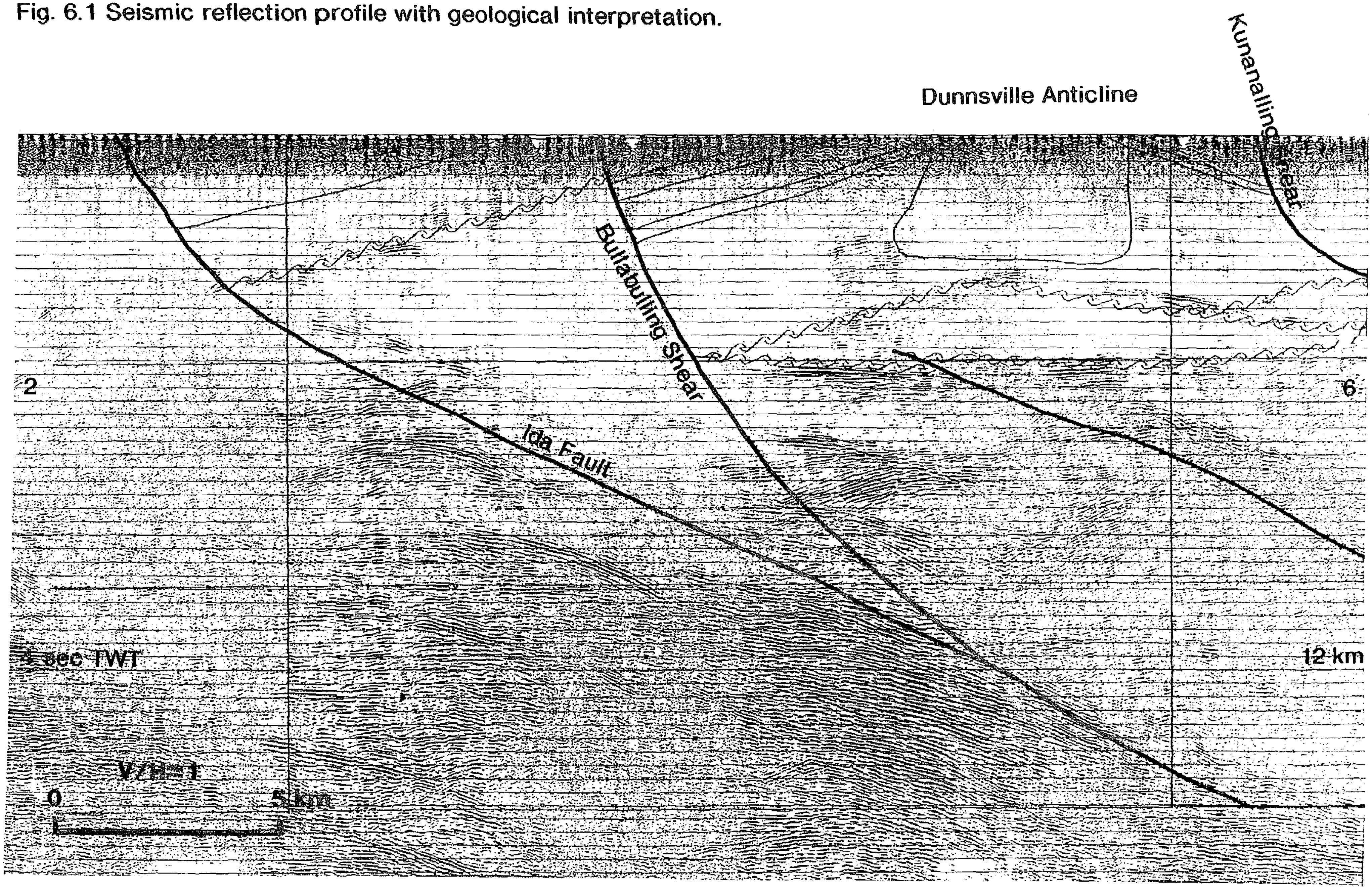
Dunnsville Anticline

The Dunnsville Anticline gently folds the Kalgoorlie Terrane stratigraphy. The Dunnsville Granodiorite occupies the fold hinge region in the area crossed by the seismic traverse. The seismic reflection data show an approximately rectangular opaque region extending down to just above 1 second (~3 km, Fig. 4.5) beneath the surface extent of the Dunnsville granite (Fig. 6.1). The opaque zone is interpreted to represent the granite body. East and west of the opaque zone, numerous reflectors dip 15-20° away from the fold crest. A thin subhorizontal zone of strong reflections beneath the granite separates another seismically opaque to weakly-layered zone. The strong reflections mimick the Dunnsville Anticline shape suggesting the zone is either a stratigraphic unit or, more likely, a layer-parallel shear zone. The underlying weakly-layered zone occurs beneath the oldest known units of the Kalgoorlie Terrane stratigraphy. Gravity modelling suggests the rock is relatively low density, that is, relatively felsic. The seismic character of the rock is unlike the strongly layered gneiss basement, and more likely an old felsic volcanic sequence (not neccessarily concordant with Kalgoorlie Terrane stratigraphy), or a slight-moderately deformed granite.

Kunanalling Shear

The Kunanalling Shear separates peridotite and Upper Basalt to the west from Lower Basalt to the east. The seismic reflection data show moderately well-defined reflectors on the eastern limb of the Dunnsville Anticline ending at a steeply east-dipping boundary with relatively opaque region. The boundary is interpreted to be the Kunanalling Shear. The shear does not

Fig. 6.1 Seismic reflection profile with geological interpretation.



appear to displace the greenstone-gneiss contact and is therefore interpreted to be listric, soling out into the basement contact zone. The stratigraphic displacement indicates predominately reverse slip, but the Kunanalling Shear has also undergone about 12 km strike-slip displacement (Swager and others, 1992).

Zuleika Shear

The Zuleika Shear is a complex zone of deformation which separates a sequence of intercalated Black Flag felsic volcanics and peridotites to the west from Black Flag felsic volcanics folded into the Kurrawang Syncline. West of the Zuleika Shear, the seismic data show reflectors within the Black Flag felsic volcanics and peridotite dipping 40-50° east. A relatively opaque seismic region in the fault zone probably reflects intense deformation, steeply-dipping structural fabrics and low seismic impedance contrasts. The Zuleika Shear dip is not well constrained by the seismic data but several reflector truncations suggest the shear zone may be listric and soles out to the east into the basement contact between gneiss and greenstone. There is no apparent offset of the basement contact.

Kurrawang Syncline

The core of the Kurrawang Syncline folds the youngest unit in the Kalgoorlie stratigraphy, a conglomerate which unconformably overlies Black Flag felsic volcanics. The western limb of the syncline is truncated by the Zuleika Shear within the plane of seismic section and no east dipping reflectors are apparent. The eastern limb of the syncline is well defined at depth but is relatively opaque near surface.

Mount Pleasant Anticline

The Mount Pleasant Anticline openly folds a relatively complete section of the Kalgoorlie Terrane stratigraphy, comprising Lower Basalt, peridotite, Upper Basalt and Black Flag felsic volcanics, without apparent internal repetition. Immediately north of the seismic line, an areally substantial core of granite has been mapped. The seismic data have imaged the fold very successfully and show numerous reflectors, particularly in the lower part of the stratigraphy (see Fig. 4.1, Fig. 6.2). The reflectors dip ~30° west on the western limb, shallow to horizontal at the fold crest and steepen to ~40° east on the eastern limb. Deep reflectors, above the gneiss basement contact, at the fold crest show less flexure. These rocks are strongly layered and gravity modelling suggests the rocks are relatively light, similar to the unit described underneath the Dunnsville Anticline. The basement contact is marked by relatively planar and particularly strong reflectors, which are discordant to the stratigraphy in the east limb of the Mount Pleasant Anticline.

Bardoc Shear

The Bardoc Shear at the surface shows complex deformation over a wide 2 km zone. The shear zone separates the coherent Mount Pleasant Anticline stratigraphy to the west from a narrow zone of greenstone and the Scotia-Kanowna granite. Strong reflectors dipping about 20-30° west have been imaged (Fig. 6.2) from about 1 to 5 seconds (~3-15 km depth) terminating against the Ida Fault. The reflectors become steeper towards the surface and project up to the eastern boundary of the Bardoc Shear zone. The shear zone clearly truncates the eastern limb of the Mount Pleasant Anticline, and possibly displaces the greenstone-gneiss basement contact by about 3 km normal movement.

Fig. 6.2 Seismic reflection profile with geological interpretation

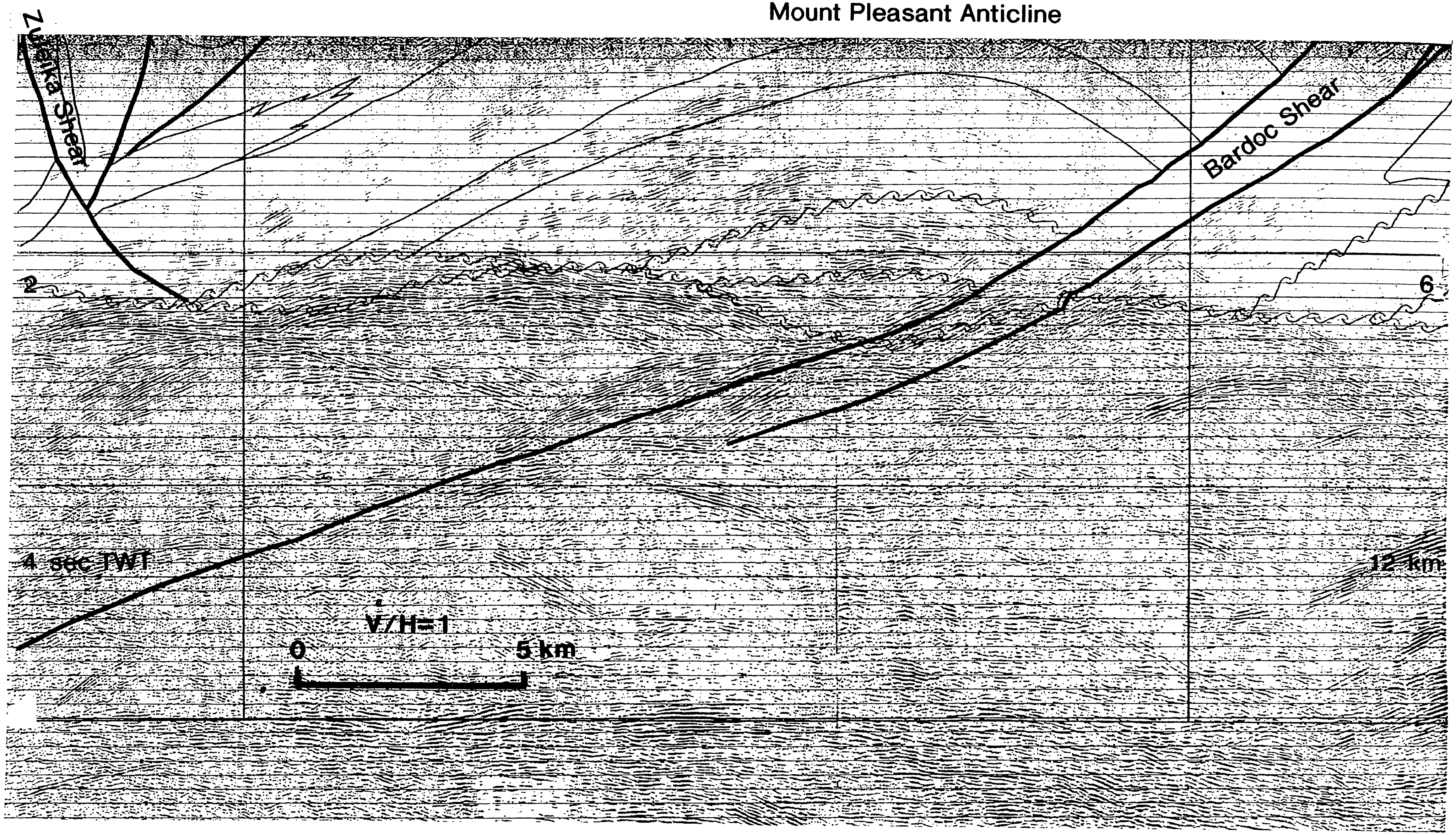
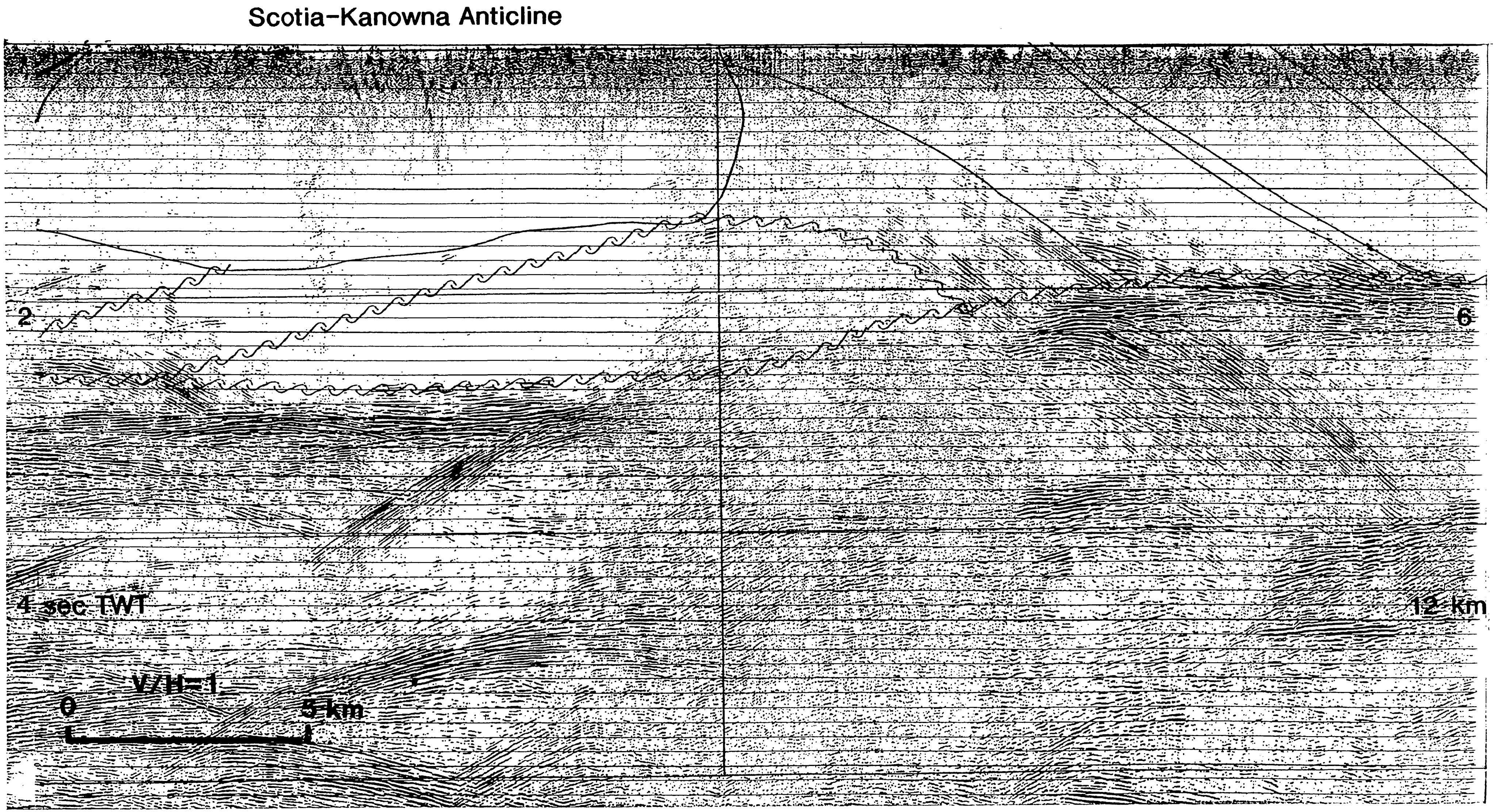


Fig. 6.3 Seismic reflection profile with geological interpretation.



Scotia-Kanowna Anticline

The Scotia-Kanowna Anticline is another domal structure of comparable scale to the Mount Pleasant Anticline, folding the Lower Basalt, peridotite and Black Flag felsic volcanic stratigraphic units. The Scotia-Kanowna Anticline also has a core of granite which the seismic line has traversed. The seismic reflection data in the vicinity of the anticline are dominated by an approximately rectangular, seismically opaque region corresponding to the Scotia-Kanowna granite (Fig. 6.3). The granite pluton extends to about 1 second (~ 3 km) depth , with steeply dipping walls defined by truncated stratigraphic reflectors within adjacent greenstone. The western fold limb of the Scotia-Kanowna Anticline has been imaged as 40° west-dipping reflectors to within 1 second (~3 km) of the surface. These reflectors are parallel to those within the Bardoc Shear. The eastern fold limb has weakly developed reflectors to about 1 second (~3km depth) with stronger reflections beneath dipping about 40° east. These reflectors are sharply truncated at the greenstone-basement contact at 2 seconds (~6 km depth). The Black Flag felsic volcanics have poorly developed and discontinuous internal reflectors. Beneath the seismically opaque zone attributed to the Scotia-Kanowna granite, are variable strength, closely spaced reflectors dipping moderately east and west into possible open folds. These reflectors are transected by shallow west-dipping layers which may be shear zones. The rock unit is relatively felsic from gravity modelling constraints and could be a felsic volcanic sequence similar to those suggested to underlie Lower Basalt in the cores of the Dunnsville and Mount Pleasant Anticlines. Strongly reflective layers at 2.5 seconds (~7.5 km depth) are interpreted to be the greenstone-gneiss basement contact. If the overlying felsic rocks are part of the late Archaean greenstone sequence, then this region has the thickest greenstone encountered on the seismic traverse.

Mt Monger Fault

The Mt Monger Fault has previously defined the eastern boundary of the Kalgoorlie Terrane in this area, juxtaposing Black Flag felsic volcanics and intercalated peridotite of the Kalgoorlie Terrane against the basalt within the Kurnalpi Terrane. The seismic reflection data do not reveal any significant reflections directly associated with the Mt Monger Fault. Several truncated reflectors could be interpreted to suggest a steeply dipping fault (Fig. 4.2). The greenstone-gneiss basement contact flexes downward to the east from 2 to 2.5 seconds (~6-7.5 km depth) which could represent a shallow-dipping (10°) ramp into which the Mt Monger Fault may sole out. East of the Mt Monger Fault, weak and discontinuous reflectors suggest gently dipping stratigraphy in the basalts between 1 and 2 seconds (~3-6 km). A possibly subsidary fault to the Mt Monger Fault separates the basalts from moderately (~30°) west-dipping basalt and felsic volcanics to the east. The subsidiary fault is also essentially unresolved in the seismic data.

Emu Fault

The Emu Fault is locally covered with a syn-tectonic(?) conglomerate unit. At depth the Emu Fault separates western felsic volcanic rocks from a mixed eastern sequence of mafic and felsic volcanic rocks. Both sequences are west-dipping which is confirmed by seismic reflection data showing numerous weak reflectors dipping about 30° west. About 1.5 seconds (~4.5 km) beneath the surface trace of the Emu Fault are strongly layered reflectors attributed to an underlying mafic-ultramafic sequence dipping 30° west. These reflectors do not appear to be displaced or offset, indicating the Emu Fault may be parallel with stratigraphic layering in the eastern sequence.

Arcoona granite

The eastern end of the seismic reflection line traverses areally extensive granite. Reflective layers beneath the granite are either absent or weak, except in localized strongly layered zones. One of these zones at about 1 second (~3 km depth) is attributed to a thin layer of basalt/amphibolite overlying gneiss/granite basement. Gravity modelling suggests relatively little dense mafic material in this area. A strongly reflective layer at 2.5 seconds (~7.5 km depth) is interpreted as a subhorizontal shear zone within gneiss basement. Some internal truncations of reflectors suggests moderate-dipping listric faults soling out into the shear zone.

6.2 Synthesis

Form of the greenstone belts

The interpreted boundary between the base of the greenstone and the underlying basement (Fig. 8.1) is a clear difference in seismic character which can be traced across the seismic line between the Ida Fault and the Arcoona granite (Figs 6.1, 6.2, 6.3). Reflectors in the basement are high amplitude and indicate a strongly layered sub-horizontal structure. Above this level, the reflectors are relatively low amplitude and discontinuous. Individual regions above the contact have internally consistent, discontinuous and generally low amplitude seismic reflection character. The overall form of the greenstone belts suggests a fault-bounded graben structure with a sub-horizontal, undulating basal surface. The greenstone varies between 4 km and 7 km thick between the Ida Fault and the Emu Fault.

Internal structures

Most previously identified or inferred major folds, faults and shear zones have been identified in the seismic reflection data. The Dunnsville, Mount Pleasant and Scotia-Kanowna Anticlines have clearly imaged stratigraphy dipping away from the fold crests (Figs 6.1, 6.2, 6.3, 8.1). Synclinal structures, such as the Kurrawang Syncline, are not well defined in the seismic data, but surface mapping indicates these structures are relatively tight with steeply dipping fold limbs or considerably sheared and complexly deformed. Shallower-dipping parts of the Bardoc Shear and the Ida Fault have strong seismic reflections which can be traced from within several kilometres of the surface extending well into the gneissic basement to mid or lower crustal levels. Other faults are not directly imaged, probably because of their steep dips, but their position and attitude can be constrained by truncated stratigraphic reflectors. Nearer the surface most faults steepen towards their surface traces. Most if not all faults appear to be listric, since significant dip-slip movements inferred from juxtaposed stratigraphy do not appear to displace the greenstone-gneiss basement, except for the Ida Fault and the Bardoc Shear. Most of the faults and shears have been reactivated during later deformation. The seismic section clearly demonstrates widespread extensional dip-slip, but kinematic analysis of the fault zones at the surface has shown reverse slip, and later strike-slip reactivation of most of these faults. The Kunanalling Shear has a known horizontal offset of 12 km, and many structural or stratigraphic differences across faults in the seismic section could be caused by out-of-section strike-slip movement.

Basal greenstone-gneiss decollement

The greenstone belt stratigraphy observed at the surface can be confidently traced below surface along reasonably continuous seismic reflectors to the gently undulating basal greenstone-gneiss basement contact. Angular discordance between the internal structure of the greenstones and the basal contact is a striking feature of some parts of the seismic line, particularly on the eastern limb of the Scotia-Kanowna Anticline (Fig.6.3) and the felsic volcanic-dominated sequences farther east. The greenstone stratigraphy appears to truncate abruptly at the contact with no detectable thinning, implying the contact is, at least in part, a significant fault decollement. The postulated felsic volcanic sequence stratigraphically beneath the Lower Basalts have a number of strongly layered zones which have been interpreted as tectonic imbricate slices. The basal decollement is interpreted to be due to a major thrust system with local ramping, imbrication and stratigraphic cut-outs.

Granitoid bodies

The seismic traverse crossed three major areas of granitoid; the Dunnsville, Scotia-Kanowna and Arcoona granites, and crossed within 2 kilometres to the south of the Mount Pleasant granite dome. The seismic section shows continuous greenstone stratigraphy across the Mount Pleasant Anticline (Fig. 6.2), however, lacking the distinctive seismically-opaque regions which characterise the granites that were traversed. The geological map pattern (Fig. 2.1; Swager and Griffin, 1990a) shows the Mount Pleasant granite has a significant areal extent within the core of the Mount Pleasant Anticline. Since the granite does not appear to extend the 2 km from the mapped surface position into the plane of the seismic section, this places a major constraint on the possible 3-dimensional form of the Mount Pleasant granite intrusion. The pluton must end abruptly. The Scotia-Kanowna granite is imaged as a tabular body about 3km thick, underlain by greenstone, and the Dunnsville granite is also clearly imaged as a small, rootless tabular body (Figs 6.1, 6.3, 8.1). The Arcoona granite exposed at the eastern end of the traverse is a post-D2 granite, and is also imaged as a tabular granite sheet rather than a deep-rooted steep-sided pluton. None of these granites are as voluminous as previously supposed (eg Swager and Griffin, 1990a). Their geometry is probably more like an flat-lying oblate ellipsoid, or surfboard shaped, with a limited depth extent. Granite bodies of this shape are clearly not diapirs but could have been fed by a number of small dykes (Clemens and Mawer, 1991). The early granites occur in the cores of major anticlines which may have caused later partitioning of strain (Vanderhor and Witt, 1991).

7. POTENTIAL FIELD DATA

7.1 Gravity Modelling

Gravity readings were taken at every shotpoint (240m interval) and at permnanent markers established along the traverse. Thus 939 new gravity measurements were obtained.

Gravity modelling was used to test the interpretation of the seismic data, and to determine whether rock bodies which do not outcrop are predominantly felsic or mafic.

The modelling was conducted by assigning each of the main bodies of rock identified in the seismic section a density contrast relative to a standard crust. The regional gravity value beyond both the eastern and western ends of the transect is approximately 60 mGal, so the standard crust was calculated in such a way that the crust in the Southern Cross Province to the west of the greenstone belts would produce an anomaly of 60 mGal. The properties of the standard crust are given in the following table:

Table: Reference Standard Crust:

Depth (km)	Density ($t.m^{-3}$)	Layer
0.0		
	2.70	Upper Crust
10.5		
	2.92	Lower Crust
28.6		
	3.30	Mantle

The following density contrasts were used:

Table: Density Contrasts Used in the Gravity Model:

Rock Type	Density Contrast $t.m^{-3}$	Absolute Density $t.m^{-3}$	Shading Fig 7.1
Mafics	0.20	2.90	Dashes
Felsics	0.00	2.70	Small +'s
Granites	0.05	2.65	Large +'s
Combination			
(mafics + felsics)	0.10	2.80	Dotted
Upper Crust	0.00	2.70	White
Upper Crust*	-0.22	2.70	White
Lower Crust	0.00	2.92	Grey
Lower Crust**	-0.38	2.92	Grey

* The portion of the upper crust below 10.5 km depth under the greenstones.
** The portion of the lower crust below 28.6 km which is modelled as displacing mantle rock

EASTERN GOLDFIELDS - TRAVERSE 1

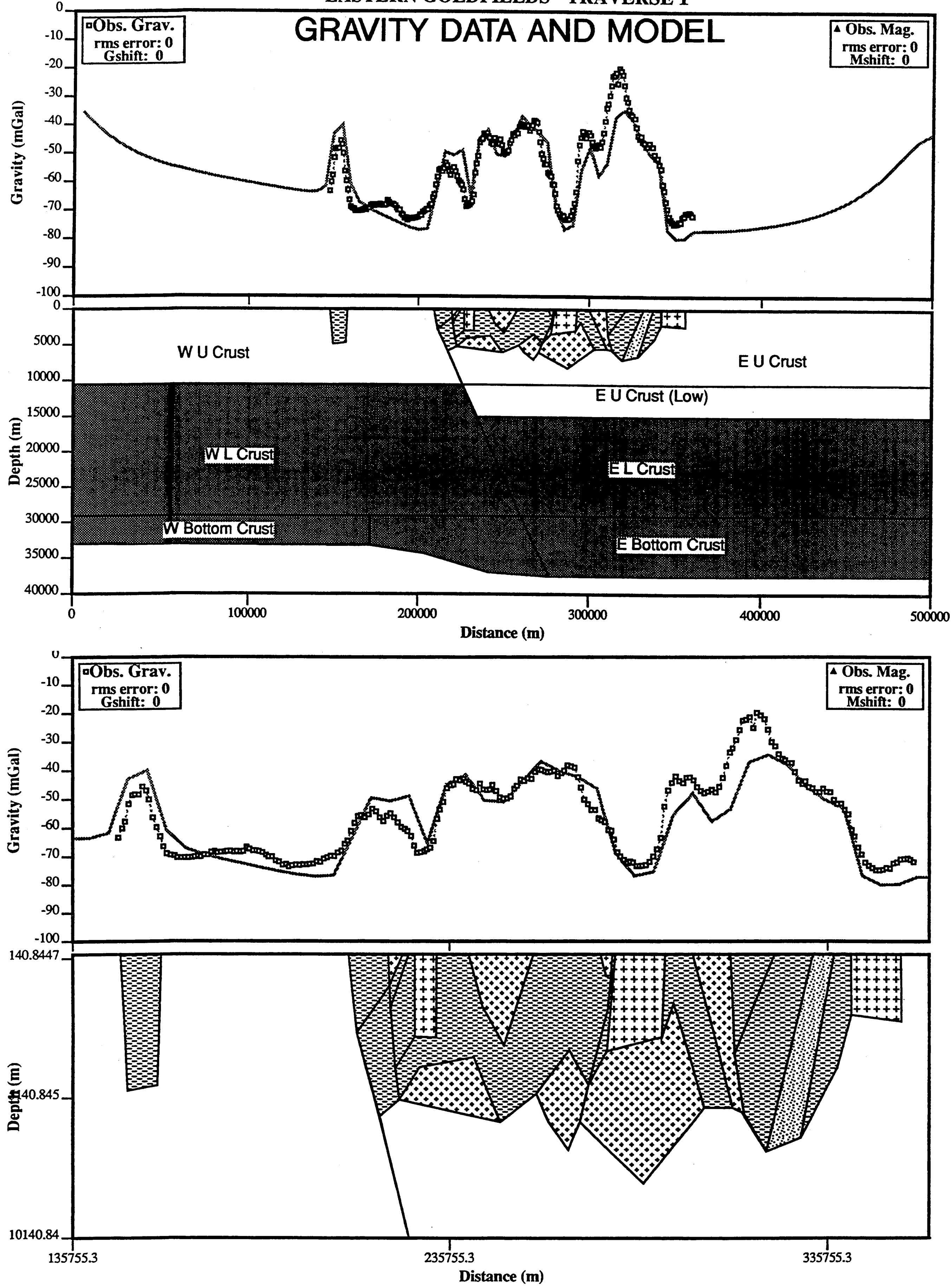


Figure 7.1

No effort was made to find a close match between the computed curve for the seismic model and the observed gravity. Rather, the shape of the bodies were fixed by the seismic data, and only the density contrasts varied depending on whether the bodies were known or assumed to be felsic, mafic, or a combination of both. The modelling assumed that the bodies were two dimensional; ie., they have polygonal cross section and infinite strike length. The model was extended 150 km laterally beyond the area of interest at each end to account for end effects.

The results are shown in Figure 7.1. The upper part shows the full model, including the extensions on each end, and the lower part is an expanded view of the upper crustal portion including the greenstone belts. The fit between modelled gravity and measured gravity is very good for such reconnaissance modelling. A better fit could have been achieved by altering the body shapes, varying the density contrasts, and limiting the strike length of the bodies, but would not have been significant in the absence of further information to constrain the otherwise inherent ambiguity of the gravity interpretation. As a first pass model it serves to confirm that the seismic interpretation is consistent with the regional gravity.

One consequence of the thicker crust in the Eastern Goldfields Province is that despite the presence of the greenstone belts, the gravity field at the eastern end of the profile should be lower by up to 70 mGal than at the western end of the profile. This is partly seen in the model in Figure 7.1, where the calculated gravity in the east, although generally tracking the observed gravity, is usually lower than the observed gravity. However, the regional observed gravity is approximately the same at each end of the profile, suggesting that the crust under the greenstone belts is slightly more dense, by up to 0.04 t m^{-3}, than the crust to the west. The seismic data contain no evidence for a change in the nature of the crust from east to west, although a difference of 0.04 t.m^{-3} is very small, may not be significant geologically, and therefore may not produce differences which are visible in the present data.

7.2 Magnetic Profile

No effort has been made yet to model quantitatively the aeromagnetic data collected along the profile. The magnetic profile is shown in Figure 7.2 plotted above the model derived from the seismic data and used to model the gravity data.

Some correlations between the magnetic data and the model are clear. The largest anomalies correlate with the Watt Hills Greenstone Belt at the western end of the profile. The gneissic basement between the Watt Hills Greenstone Belt and the greentones belts of the Eastern Goldfields Province have higher values than the Eastern Goldfields Province. Within the Eastern Goldfields Province, the largest variations in the magnetic field correlate with boundaries between rock types. Three major fault or shear zones have clear magnetic signatures: the Ida fault, Bardoc Shear and the unnamed shear zone at the eastern end of the profile all correlate with sharp fluctuations in the magnetic profiles. So too do the edges of the granite bodies which crop out along the profile.

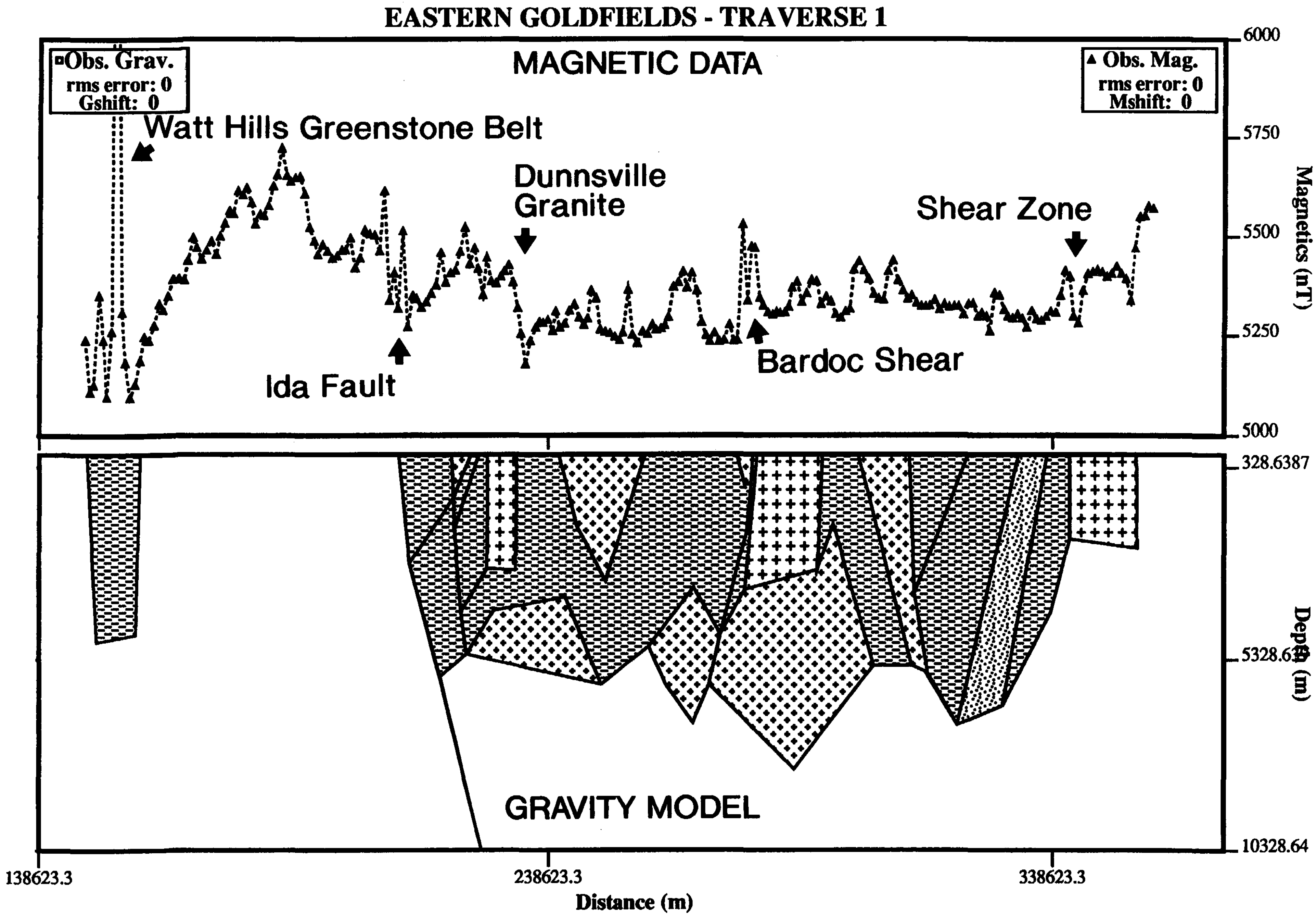

EASTERN GOLDFIELDS - TRAVERSE 1
MAGNETIC DATA
Obs. Grav.
rms error: 0
Gshift: 0
Obs. Mag.
rms error: 0
Mshift: 0
Watt Hills Greenstone Belt
Dunnsville
Granite
Shear Zone
Ida Fault
Bardoc Shear
6000
5750
5500
5250
5000
Magnetics (nT)
328.6387
5328.64
10328.64
Depth (m)
GRAVITY MODEL
138623.3
238623.3
338623.3
Distance (m)

Figure 7.2

8. STRUCTURAL IMPLICATIONS

The seismic section has provided constraints on the geometry of the greenstones and basement rocks which when combined with surface mapping evidence establishes a series of deformation events comprising:

1. Basin formation,
2. Layer-parallel thrusting,
3. Early granite intrusion,
4. East-west shortening,
5. Listric extensional faulting,
6. Strike-slip faulting.

8.1 Basin formation

The seismic reflection data show that the Archeaean greenstone basin is presently bounded to the west by a major normal fault, the Ida Fault. Within the greenstone basin are a number of similar normal faults such as the Bullabulling and Bardoc Shears. These faults juxtapose distinctive stratigraphic sequences in some instances. Whether these major faults actually controlled the basin development and deposition of the greenstone is unclear, however, for several reasons. Firstly, the areas where a common stratigraphic sequence lies on both sides of a major fault, for example, the Lower Basalt across the Bardoc Shear, do not indicate significant changes in thickness across the fault. Syn-deformational faulting during basin filling typically results in marked changes in stratigraphic thickness across the faults. Secondly, there is no apparent overall stratigraphic thinning towards the Ida Fault. Thirdly, the apparent offset on the major normal faults implies later extensional listric faulting. The deformed basal decollement zone between greenstone and basement has been offset by the extensional faults. There is no clear evidence to support the possibility of greenstone depocentres being controlled by the faults identified from the seismic reflection data. Basin formation may be due to thermal sag of the crust without significant brittle faulting in the upper crust, reflecting the relatively high heat flow generated during volcanism. The actual basin margins may have originally extended much further east than the Ida Fault.

8.2 Low-angle thrusting

Low-angle deformation along the contact between greenstone and basement can be inferred from structural truncations of stratigraphy at that contact. The low-angle deformation which occurred is probably thrust faulting. Evidence for thrust faulting includes the mapped thrust repetitions of the ultramafic units in the Kurrawang Syncline and on the eastern limb of the Scotia-Kanowna Anticline, as well as indications from the seismic reflection data of structural imbrication of the basal felsic volcanic sequence. Thrust-repeated sections have been described in a number of areas in the Eastern Goldfields (eg Swager and others, 1992). The direction of thrusting is not constrained by the interpreted seismic section but could well be dominated by an out-of-section movement component. Thrust movements from the duplex structures at Kambalda were probably north-directed (Swager and Griffin, 1990b). Out-of-section movement effectively makes tectonic restoration and section balancing of the seismic interpretation impossible. The magnitude of thrusting is also difficult to determine. The Kalgoorlie Terrane stratigraphy is for the most part preserved in the interpreted section and is only locally inverted by thrusting, within the Kurrawang Syncline and on the eastern limb of the Scotia-Kanowna Anticline. The lack of widespread stratigraphic inversion suggests the thrust faulting has been limited in displacement, and/or restricted to relatively thin levels within

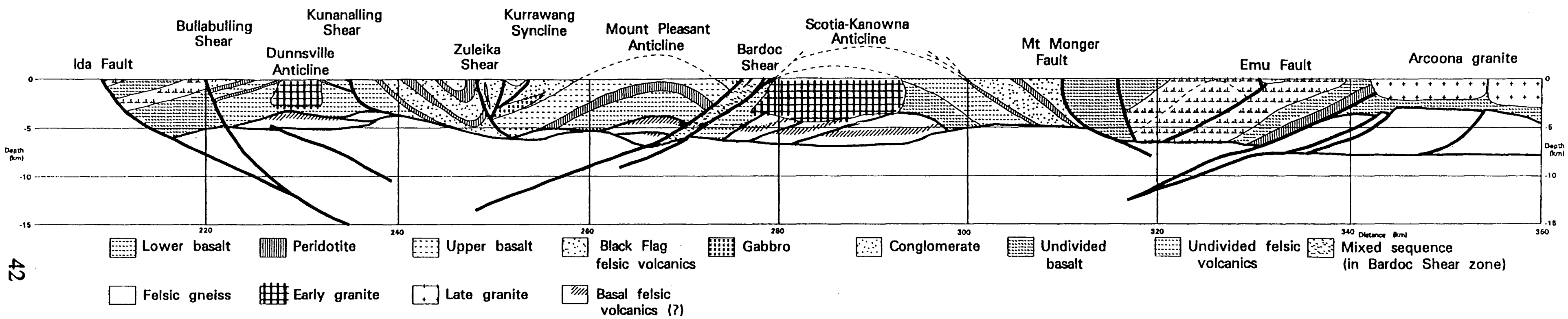


Figure 8.1 Geological interpretation of the Eastern Goldfields seismic line

the stratigraphy. The stratigraphic truncations at the basal contact decollement are difficult to explain with small-displacement thrusting, however.

8.3 Early granite intrusion

The early granite bodies occur within the hinge regions of the major anticlines but the timing of the granite intrusion relative to low-angle thrusting and east-west folding is unclear, that is, whether intrusion occurred before or during east-west fold shortening. The early granites occur in relatively low strain anticline hinge areas characterised by low angle fold limb dips, whereas intervening synclinal areas, lacking granite, have steeper dips and stronger shearing. The granites appear to have acted as rigid bodies which partitioned strain into the synclinal areas. The early granite body shapes have a tendency to north-south elongation. and the shallow depths of the plutons suggest they formed above thin feeder dykes, into zones of dilation. Dilational zones in this orientation are consistent with east-west fold shortening.

8.4 East-west shortening

East-west shortening has resulted in upright north-trending folds. Open anticlines predominate in the seismic section whereas synclines are considerably tighter or sheared out altogether. Strain appears to have preferentially partitioned into the synclinal areas during folding, and these areas have concentrated most of the subsequent strike-slip deformation also.

8.5 Listric extensional faulting

Late, listric extensional faulting has not been recognised or inferred from previous tectonic studies. Early and essentially layer-parallel extensional faulting has been postulated in recent work (Hammond and Nisbet, 1992; Williams and Currie, 1993) to explain compressed metamorphic gradients within greenstones adjacent to gneiss and the domal architecture of the gneiss (Williams and Whitaker, 1993). Listric extensional faulting is clearly imaged in the seismic reflection data. The shear zones truncate greenstone stratigraphy, and displace the basal greenstone contact with gneissic basement including the basal thrust decollement. Much, if not all, of the displacement must be younger than basin formation and early thrust deformation. The north-trending strike of the faults suggests the movement direction was substantially within the plane of the section. The relative timing between east-west folding and extensional faulting is not clear, however.

8.6 Strike-slip faulting

The seismic data do not conclusively support major strike-slip movement on the identified faults, but surface mapping has identified two significant and late episodes. Several faults which have juxtaposed different levels of the greenstone stratigraphy may have had substantial out-of-section, strike-slip movement. The main strike-slip faults identified from surface mapping appear from the seismic data to have had a significent pre-history as either thrust or extensional faults.

9. GOLD MINERALISATION

Evidence from the seismic section shows that a number of major shear zones cut through the greenstone belt and into the mid-crust. Figure 9.1 highlights these structures and also indicates the possible links between structures known on the surface and those present within the mid-crust. Of particular interest for gold mineralisation is the Bardoc Shear (Figure 9.2), which is characterised by a wide zone of west-dipping reflectors. The width of the zone suggests that there is a correspondingly wide zone of deformation in the lower part of the greenstone belt and also in the immediately underlying crust. The Shear also penetrates the base of the greenstones and extends to Ida Fault. These characteristics mark the Bardoc Shear as a unique structural zone in this part of the Eastern Goldfields. A geological map of the areas surrounding the seismic line (Fig. 1.1, 9.3) shows the regional extent of the Bardoc Shear, and its association with major ore deposits in the district. As has been highlighted by Witt (1993), most of the major deposits lie close to major shears zones, but that there is a less obvious association between the smaller deposits and the main structures.

Figure 9.3 shows the main Boulder-Lefroy Fault as a splay off the Bardoc Shear. Consequently, in cross-section (Figure 9.4) the Bardoc and Boulder-Lefroy system are probably major parallel shear zones both of which extend to a considerable depth in the crust. Movement on these structures was probably contemporaneous, as both show evidence for dip-slip and strike-slip movement during their history, and mesostructures associated with both fall in the same part of the deformation history (Witt, 1993).

The Bardoc Shear and Boulder Lefroy Fault probably are 'master structures' controlling gold mineralisation. However, like in other Archaean granite-greenstone provinces, the most significant resources occur not on these master structures but on second-order structures in their vicinity (cf. Kirkland Lake - Cadillac Break in the Superior Province; Colvine, 1989). Some of the most significant gold deposits in the Eastern Goldfields associated with these master structures include Paddington and the Golden Mile deposits. Consequently, a model of fluid movement through the crust along a series of connected mid-crustal shears, tapped by a major upper-crustal shear zone array which formed the main conduit for fluid flow, is consistent with the seismic data and the correlation of fault location and mineral deposits.

The presence of both brittle and ductile deformation fabrics associated with faults suggests proximity to the rocks were close to the Late Archaean brittle-ductile transition zone. Some of the most significant mineralization is located in the relatively brittle lithologies, such as the Golden Mile Dolerite. Major dilational zones, partly controlled by lithology, cause a reduction of fluid flow rates, and this enhances the extent of fluid - wall-rock interaction, which in turn promotes gold deposition by mechanisms such as fluid de-sulfidation. The most favourable conditions for gold enrichment are thus in areas where competent mafic units such as the Golden Mile Dolerite are deformed by brittle failure between more ductile shears acting as the master conduits (Fig. 9.4).

The source of gold-bearing fluids in this model would lie below the greenstone belt. Evidence of crustal composition from both seismic refraction and reflection surveys (Drummond, 1988) suggests that the material below the greenstones is of felsic gneiss composition. Possible examples of equivalent exposed material includes the Riverina Gneiss to the west of the Eastern Goldfields greenstones (Williams and Whitaker, 1993).

FIGURE 9.1. Main structural features of the crust beneath greenstones

The Bardoc Shear and Ida Fault link at depth. A set of east-dipping shears beneath the Bardoc shear and Scotia-Kanowna Dome may also have an important role in fluid transport from deep level of the crust.

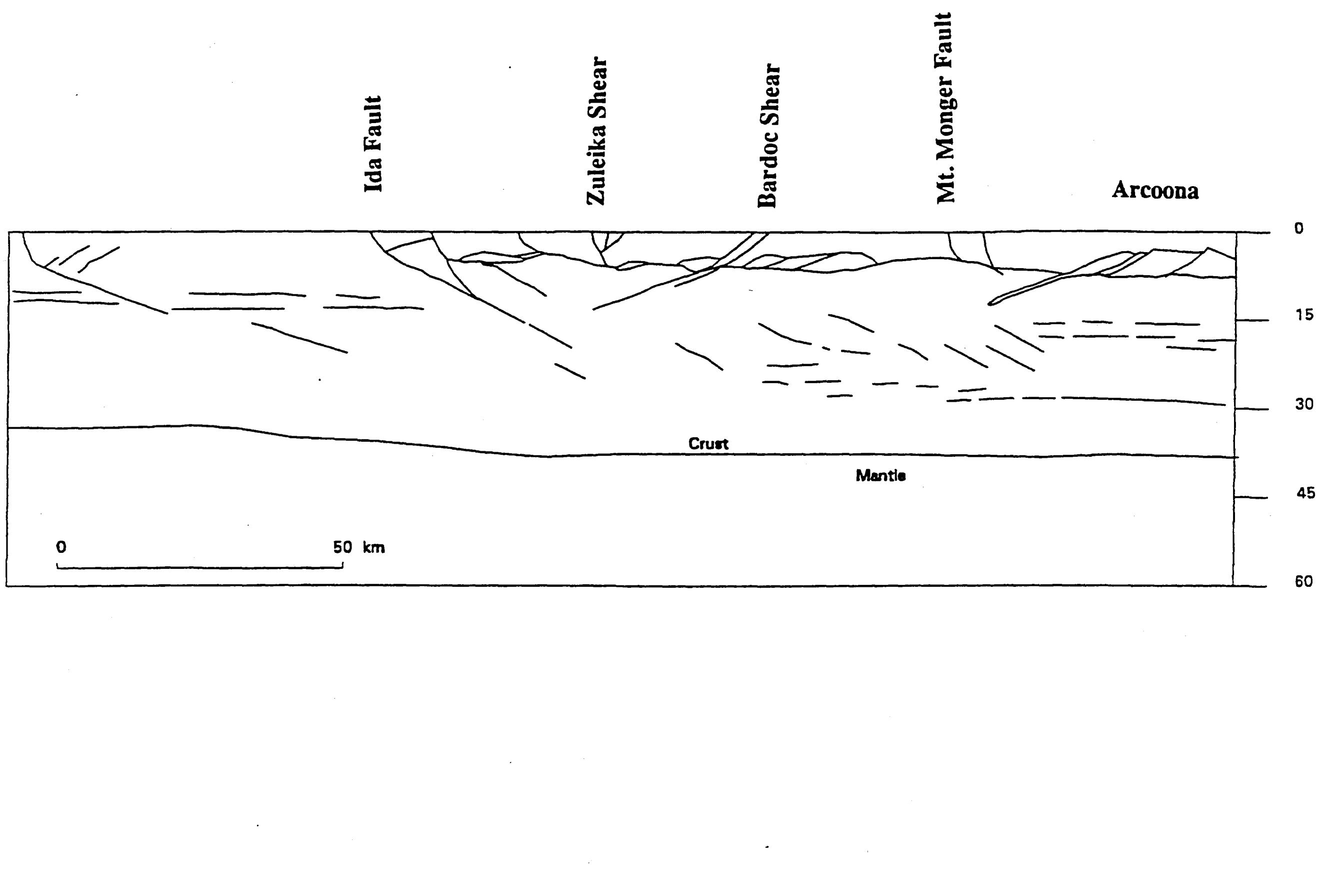


Fig. 9.2 The Bardoc Shear

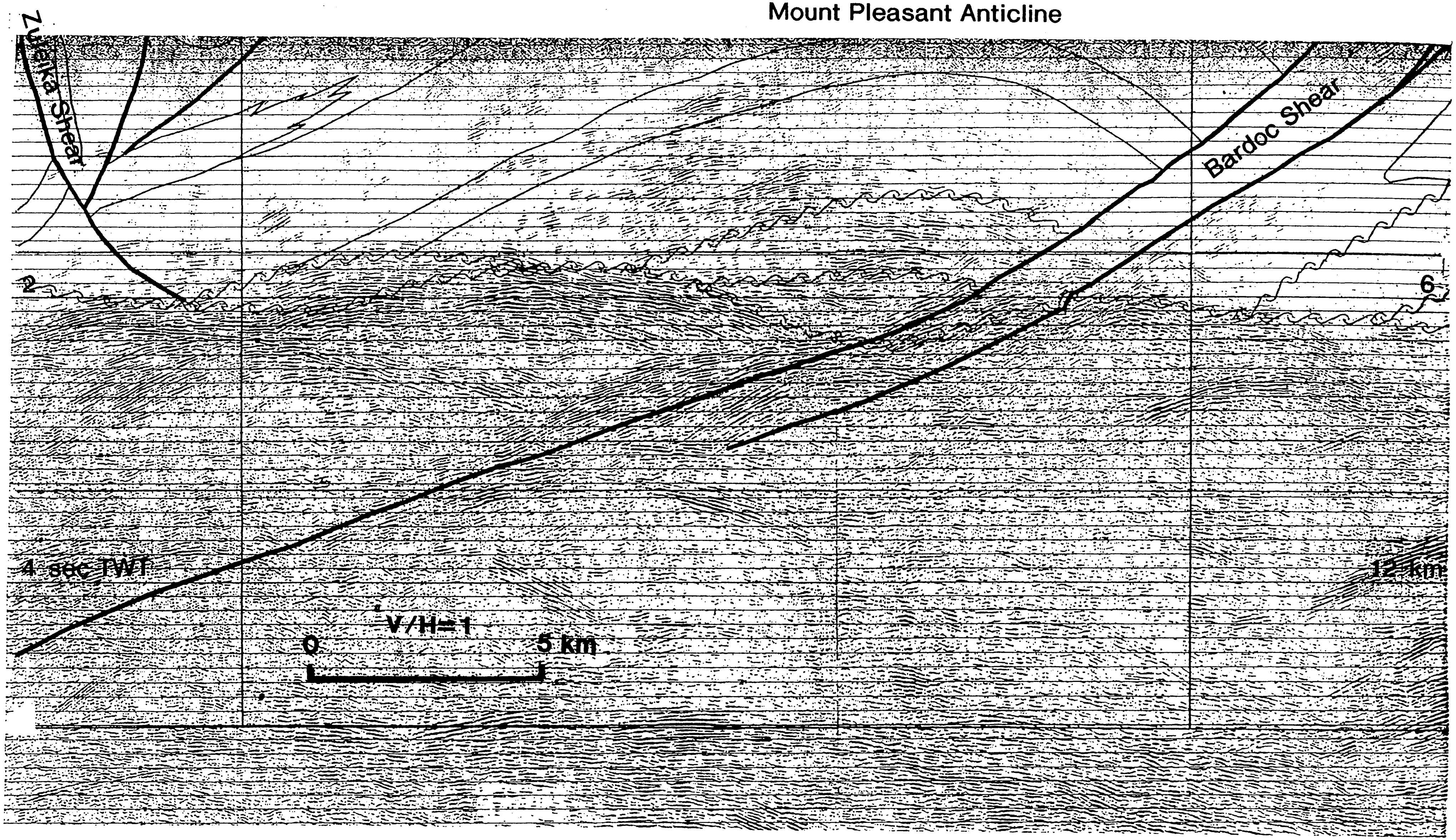


FIGURE 9.3

Geological map of major structures and ore deposits close to the seismic line

Note that the major faults in the Kalgoorlie district are linked to the main Bardoc-Boorara Shear.

Areas with crosses are granites; light shaded areas mafic and ultramafic rocks; areas with dense shade are Golden Mile Dolerite; very light stipling are areas dominated by felsic volcanic rocks.

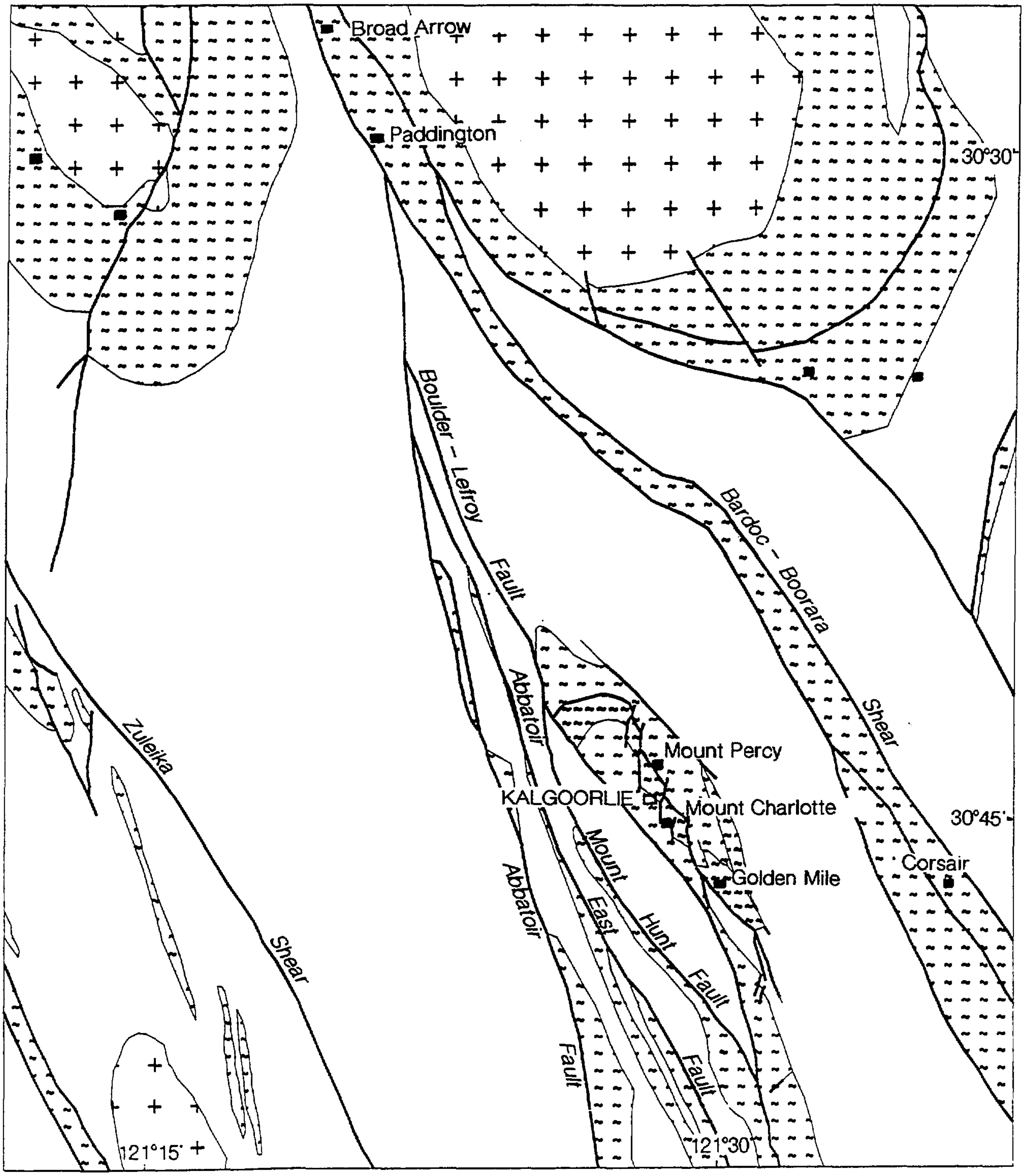
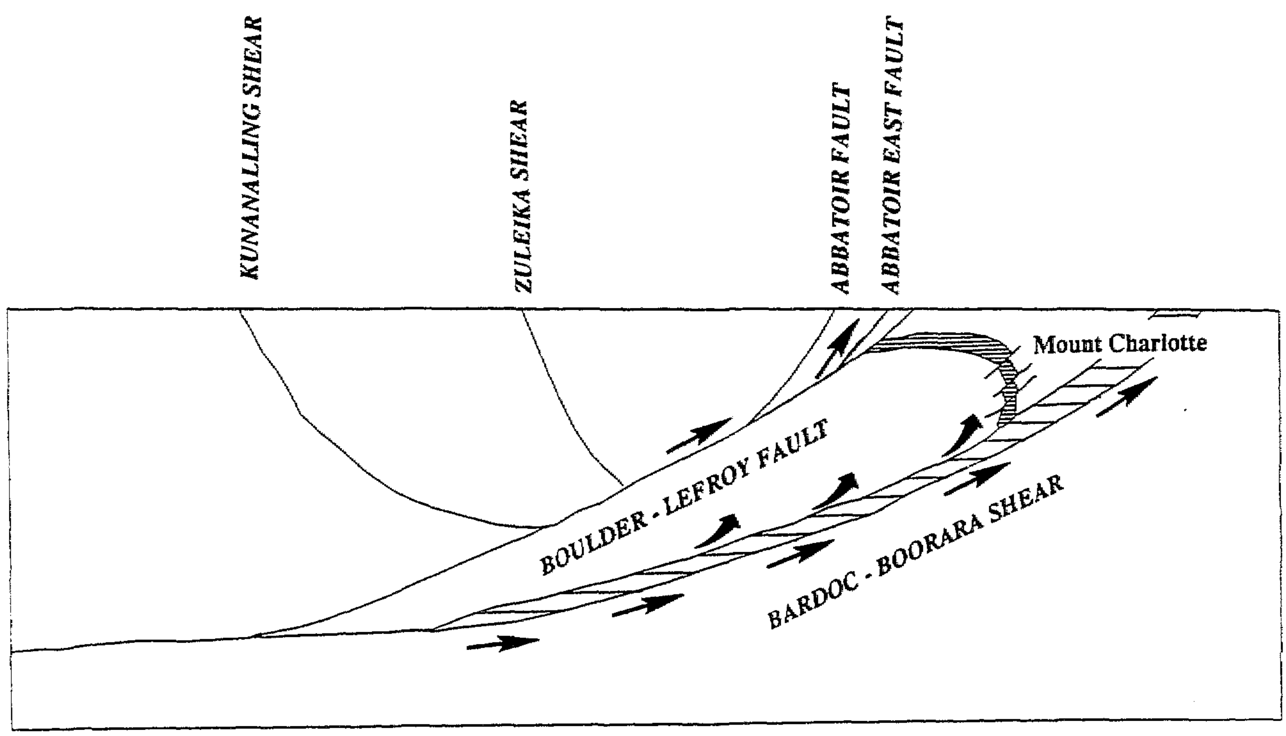


FIGURE 9.4
Schematic view of fluid movement in crustal ductile shears and related brittle structures

1. Boorara-Bardoc Shear is the main fluid conduit
2. Fluid flows through brittle fractures in competent units - eg. Golden Mile Dolerite at Mount Charlotte
3. Continued upward flow means fluids in hanging wall faults, such as th Boulder-Lefroy Fault, will be gold-depleted



Independent geochemical evidence is accumulating suggesting that the gold-bearing fluids have passed through felsic rocks prior to their interaction with the greenstone belt sequence (eg. Sr isotope data; Mueller and others, 1991). The low salinity of ore fluid inclusions and the absence of base metals in most Archaean gold deposits have traditionally been taken as evidence in favour of a 'metamorphic' ore genesis model, and against a magmatic fluid and metal source. However, recent experimental evidence indicates that liquid/vapour immiscibility probably extends to much higher pressures and temperatures than previously thought, and this constrains the possible composition of CO_2-H_2O-rich fluids at lower-crustal conditions to a maximum salinity of 5-10 wt% (consistent with observations from most Archaean gold-related ore fluid inclusions; Ridley, 1993). Independently, recent results from trace element analyses of individual coexisting brine and vapour inclusions of known magmatic origin (using CSIRO's PIXE microprobe; Heinrich and others, 1992) have shown that separation of high-temperature vapour and saline liquid may lead to significant metal separation. This may be a powerful mechanism of preferential enrichment of some heavy metals, including gold, in a deep magmatic vapour phase. Experimental and fluid-analytical data thus suggests that Archaean gold ore fluids could be gold-enriched vapour condensates originating from a mid- to lower-crustal granitoid source: a hypothesis which is consistent with the seismic data and which we are currently trying to test in collaboration with the University of Western Australia.

In summary, the detailed seismic study of the form of the upper crustal shear zones, and the means by which fluid migration occurred into those zones, should provide a powerful exploration tool. The use of the current seismic data has for the first time allowed a definition of the nature of the shears, their direction of dip, and the means by which they may have tapped the sub-greenstone fluid reservoir(s). The current first pass interpretation could be refined considerably, and additional high resolution seismic work in specific target areas could be very rewarding.

10. GEOCHEMISTRY

Eight hundred and eighty-three (883) bottom-hole samples were analysed for 30 minor and trace elements (Ag, As, Ba, Be, Bi, Ce, Cr, Cu, Ga, Ge, Hf, Li, Mn, Mo, Nb, Nd, Ni, Pb, Rb, Sc, Se, Sn, Sr, Ta, Th, U, V, Y, Zn, and Zr), as well as total Fe_2O_3, by X-ray fluorescence, using the method of Norrish and Chappell (1977).

As anticipated, areas underlain by predominantly mafic to ultramafic rocks of greenstone belts have high Fe_2O_3, Cr, Ni Sc, and V; Cu and Zn also tend to be relatively high and some samples have high As (30-100 ppm). Ultramafic units (e.g., peridotite) are characterised by particularly high Cr and Ni, which produce distinctive 'spikes' on the element abundance profiles. In contrast, areas underlain by felsic rocks (felsic gneisses, felsic volcanics, and granites (s.l.)) have much lower Fe_2O_3, Cr, Cu, Ni, Sc, V, and Zn, whereas Ba, Nb, Pb, Rb, Th, U, Zr, and LREE (light rare-earth elements: Ce, La, and Nd) are relatively enriched. Some granites also have relatively high Sr. Samples from deeply-weathered areas (i.e., consisting entirely of regolith material) show relatively wide variations in abundances of most of these elements, and greenstone sequences are compositionally much more heterogeneous than areas of granite. Other elements (Ag, Be, Bi, Ga, Ge, Li, Mo, Se, and Ta) show little or no correlation with the underlying rock type.

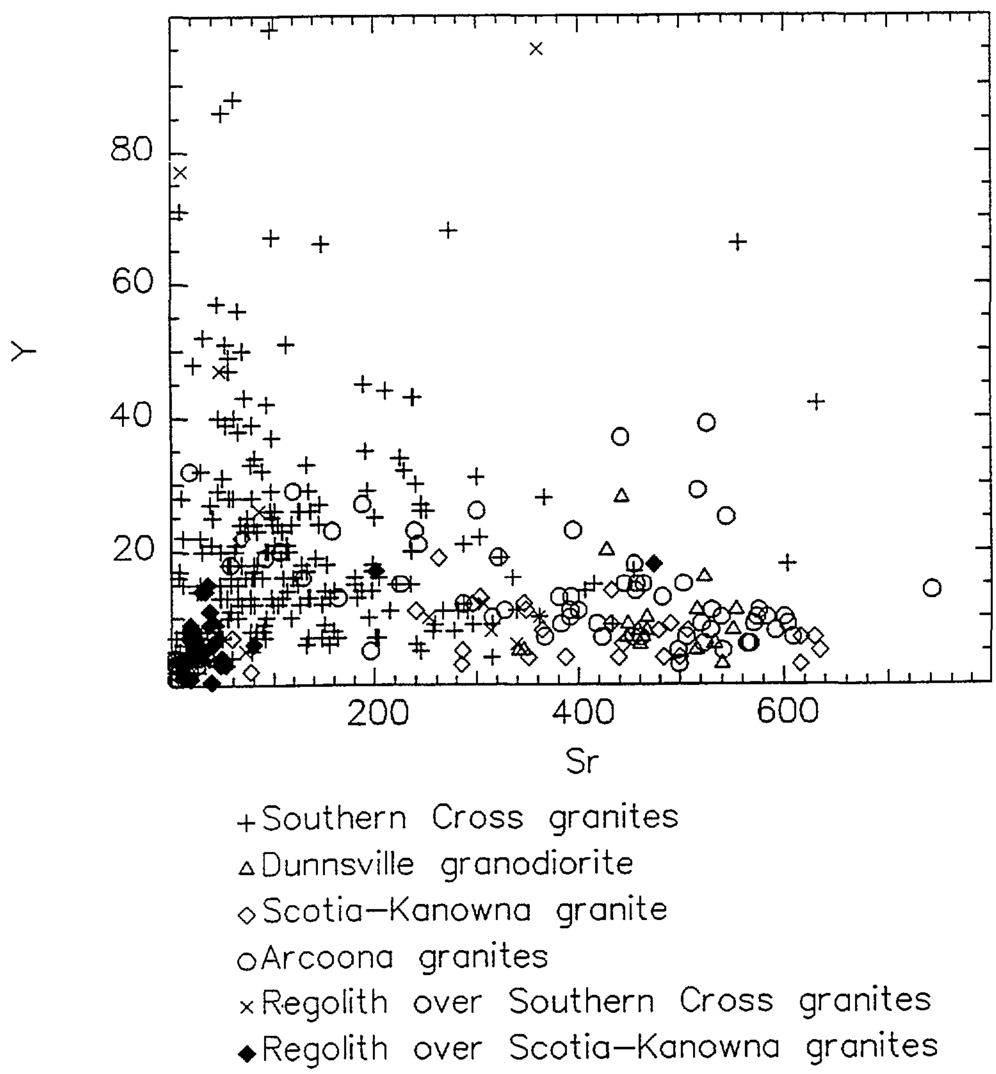
There are systematic differences in the compositions of samples from areas of 'external' and 'internal' (i.e., within greenstone belt) granites. Many external foliated granites of the Southern Cross Province, which make up most of the westernmost 60 km of the line, have relatively high Nb, Pb, Rb, Th, U, Zr, and, to lesser extents, LREE and Y. Internal granites, comprising the Dunnsville, Scotia-Kanowna, and 'Arcoona' intrusions, have higher Sr and lower Y (Figure 10.1), suggesting derivation from a plagioclase-poor, amphibole and/or garnet-rich (i.e., presumably mafic) source. At least some of the latter granites may therefore represent new felsic crust, rather than intracrustal melts.

The (undivided) external granites show considerable compositional heterogeneity, implying the presence of a variety of unrelated components, possibly of different age. It is possible that some of this variation may reflect the deep weathering of this poorly-exposed terrane, although regolith samples do not show any clear systematic trace element compositional differences from the least altered granite samples. Of the internal granites, the Dunnsville granodiorite, westernmost two-thirds of the Scotia-Kanowna granites, and eastern 5 km of the sampled section of the Arcoona granites appear to represent discrete, chemically- coherent plutons, with high Sr and low Y. The western part of the Arcoona granites is compositionally much more heterogeneous than that to the east, suggesting the presence of a variety of different granite units. In contrast, the compositional heterogeneity of the eastern part of the Scotia-Kanowna intrusion appears to be a result of deep weathering, most samples from this area being classified as regolith. The latter are much depleted in Sr (Figure 10.1) and, to lesser extents, LREE, but enriched in Th, compared to the (presumed) underlying granite.

A few elements (Ag, As, Bi, and Mo) which show no clear correlation with rock type show isolated highly anomalous abundances, at least some of which appear to be associated with shear zones or areas of known mineralisation. For example, high Bi contents occur at or near both contacts of the Dunnsville granodiorite and in the Bardoc Shear zone, near the western margin of the Scotia- Kanowna granites. Anomalous As contents are present in samples from near the Ida Fault and Bardoc Shear, as well as the Mayday and ?Broad Dam mines. High Mo contents also occur near the Bardoc Shear, but those from the western part of the Arcoona

Figure 10.1.

Plot of Sr against Y for 'external' (Southern Cross Province) and 'internal' (Eastern Goldfields Province) granites. Most of the latter have relatively high Sr and low Y, although the Arcoona granites are quite heterogeneous. Regolith samples overlying the Scotia-Kanowna granites are markedly depleted in Sr (as well as LREE) compared to little-altered granite samples and so do not apparently reflect the geochemical characteristics of the presumed granitic bedrock.



granites have no obvious structural association. High Ag contents (up to 20 ppm) occur near the Mount Pleasant and Gordons mines, in the Bardoc Shear, and as isolated anomalies in the Southern Cross granites and western Arcoona granites. Sn contents are consistently low, apart from four isolated moderately high values (15-20 ppm) with no obvious explanation (although one may be associated with the Mt Monger Fault). LREEs show wide variations of unknown significance, with some unusually high abundances (>400 ppm Ce) in the Southern Cross granites. Several samples in the eastern part of this terrane (e.g., just west of the Ida Fault) have particularly high Zr and Nb.

The regional geochemical sampling has therefore proved of particular value in showing that the granitic rocks of the Southern Cross Province (west of the Ida Fault) form a geochemically distinct terrane. It has also established that the Bardoc Shear represents a geochemically anomalous zone. Of interest is the presence of a somewhat similar chemical signature (notably high As) in the Ida Fault zone, supporting the contention that the two zones are linked and carried similar fluids at some stage of their history.

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