Seismic reflection and refraction profiling across the Arunta Block and the Ngalia and Amadeus Basins

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In order to investigate the tectonic evolution of the Arunta Block and the Ngalia and Amadeus Basins, a regional north–south seismic reflection line 420 km long from the Northern Arunta Province to the southern part of the Amadeus Basin, and an east-west refraction profile over 400 km within the Arunta Block, were recorded by the Bureau of Mineral Resources in 1985. The most significant basement features observed in the reflection data are prominent bands of northerly dipping reflections originating from beneath the Northern Arunta Province and the Ngalia Basin at times of between 4 and 10 s. In this region, reflected energy with frequencies as high as 100 Hz is present at two-way times of 5–6 s, implying that the rocks have high Q to depths of at least 18 km. The character of the reflections changes markedly with varying frequency, which suggests that they arise by interference phenomena, probably associated with laterally varying lamellar structures. Deep crustal features on the reflection profiles from the Central Arunta Province are less clear, although the refraction data suggest an average crustal thickness of about 55 km. Below the Southern Arunta Province there is a zone of northerly dipping reflectors at depths between 21 and 30 km, which suggests deeply buried rocks of sedimentary origin. Beneath the southern part of the Amadeus Basin, prominent bands of reflections, similar in character to those observed beneath the Southern Arunta Province, occur at times between 6 and 10 s, but have an apparent dip to the south. The reflections from the sediments of the Ngalia and Amadeus Basins are generally weak, except for those below the Missionary Plain in the northern part of the Amadeus Basin where strong, excellent-quality reflections were obtained. Data from an expanding spread recorded in this area give well-constrained velocity estimates throughout the 10 km thick sedimentary sequence, thus enabling the local thickness of the basin to be accurately determined.

Key words: Amadeus Basin, Arunta Block, Ngalia Basin, seismic profiling.

INTRODUCTION

A programme of deep seismic reflection profiling within the Australian continent, initiated by the state Lithospheric Transect Studies of the Australian Continent (LITSAC) groups (McElhinny 1982), is currently being implemented by the Bureau of Mineral Resources (BMR) and cooperating organizations. In 1985, BMR undertook a programme of seismic reflection and refraction profiling, supplemented by aeromagnetic and gravity surveys, across the Arunta Block and the Ngalia and Amadeus Basins in central Australia (Fig. 1). This central Australian project involves the first extensive reflection profiling within a hard-rock area in Australia.

The major purpose of this paper was to present some preliminary interpretations of the geophysical data obtained from the fieldwork undertaken in 1985. At this stage, we can provide detailed interpretations only for sedimentary structures in the northern part of the Amadeus Basin and for basement structures within the Arunta Block. However, ongoing research is concentrating on the more difficult problems of resolving deeper crustal structure beneath the Amadeus Basin and assessing the implications for the tectonic evolution of the region.

PREVIOUS GEOLOGICAL AND GEOPHYSICAL WORK

The Ngalia and Amadeus Basins are separated by a region of exposed Proterozoic crust, the Arunta Block (Fig. 2), part of a major ensialic mobile belt in central Australia (Stewart et al. 1984).
The Arunta Block

The Arunta Block (Shaw et al 1984; Stewart et al 1984) consists mainly of Precambrian metamorphosed sedimentary and igneous rocks. It consists of three tectonic provinces with separate histories of deformation and metamorphism (Fig. 2).

The complex tectonic history of the region involved six cycles of extension and compression that commenced before 1800 Ma and culminated in the Alice Springs Orogeny that took place between 400 and 300 Ma. Deformation of the Ngalia Basin and northern part of the Amadeus Basin at this time was influenced by processes operating in the underlying Arunta Block. An important function of the present seismic profiling is to map faults throughout the crust to determine the extent to which the most recent compressional movements took place along faults or weaknesses generated by previous tectonic episodes.

The Northern Arunta Province (Fig. 2) consists largely of metamorphosed sediments intruded by granites. Rocks of the Central Province (Fig. 2) have generally been metamorphosed to granulite and upper amphibolite facies at depths of about 30 km during an event at 1800–1750 Ma. The Southern Province (Fig. 2) consists of gneiss, unconformably overlain by metasediments. Granites are widespread and dolerite dykes are locally abundant.

The Redbank Deformed Zone (RDZ) (Fig. 2) is a relatively narrow (7–10 km) easterly trending region of complex deformation located along the northern margin of the Southern Province. The zone dips to the north at about 45° and is interpreted as an overthrust towards the Amadeus Basin to the south, but more detailed interpretations in terms of thick- or thin-skinned tectonic styles can only be tested by deep seismic profiling. Many northerly dipping faults have been mapped throughout the Arunta Block.
The Ngalia Basin

The Ngalia Basin (Wells et al. 1972; Wells & Moss 1983a) covers much of the southern part of the Northern Arunta Province. It contains Late Proterozoic and Palaeozoic sediments, of maximum thickness in the west of about 6 km, that can be correlated with sediments in the Amadeus Basin. Thrusting of Arunta rocks from the north over the northern margin of the basin probably took place during the Alice Springs Orogeny. The mapping of both the basement shape and the bounding thrust faults of this basin was a further objective of the seismic reflection work.

The Amadeus Basin

The Amadeus Basin (Wells et al. 1970; Schroder & Gorter 1984; Lindsay & Korsch 1988) is an east–west-trending intracratonic depression, 800 km long, bounded on the north and south by the Arunta and Musgrave Blocks, respectively (Fig. 1). Sedimentation in the basin was interrupted by tectonic episodes at 1050–900 Ma and at about 600 Ma. Late Proterozoic sedimentation ceased at around 600 Ma with uplift and folding associated with the Petermann Ranges Orogeny in the southwest of the basin. Early Palaeozoic deposition was halted in the Late Ordovician to Silurian with folding and peneplanation in the north and east of the basin, followed by further deposition during the Late Devonian. The Alice Springs Orogeny was the last major diastrophism to influence regionally the structure and petrological nature of the basin. Sediments reach thicknesses of about 14 km in the north, and the sub-basins in the north are separated from the platform regions and sub-basins in the south by an east–west-trending ridge that is most probably a basement high.

Lindsay and Korsch (1988) argued that the basin evolved in three stages, the first two involving crustal extension and thermal subsidence, followed by a final stage of overthrusting comprising the Alice Springs Orogeny. An objective of the present seismic profiling was to define accurately the thicknesses of the sedi-
mentary sequence and underlying basement, and to determine any differences in the character of basement reflectors from those observed below the Arunta Block.

Gravity field and models of tectonic evolution

Some of the largest differences in the gravity field on any continent are present in central Australia where the total variation is about 1400 μm/s² (Fig. 1). In general, negative Bouguer anomalies correspond to the basins and positive anomalies correspond to the intervening areas of the Arunta and Musgrave Blocks. Models of the crust to explain features of the gravity field have been given by Anfiloff and Shaw (1973), Mathur (1976) and Wellman (1978), but none of these authors has attempted to explain the tectonic processes that could have resulted in the proposed models. The evolution of the basin and basement regions comprising the Arunta Block and the Ngalia and Amadeus Basins is not satisfactorily explained by conventional models of basin formation involving thermal or stretching mechanisms, because the basins are not in local isostatic equilibrium and the basin margins are characterized by thrust structures.

A generalized mechanical model for the evolution of the central Australian basins (Lambeck 1983, 1984) assumed that the crust has been predominantly in compression for the last 1000 Ma; it gives a simplified description of the evolution of the entire region, and has recently been modified to explain teleseismic travel-time residuals better (Lambeck et al 1988). Sudden decreases in crustal thickness of up to 20 km across the northern and southern margins of the Amadeus Basin due to the relative uplift of the Arunta and Musgrave Blocks, respectively, are predicted, and provide a satisfactory explanation of the gravity field. Features that the seismic work may elucidate are: the amount of crustal thinning associated with the uplift and erosion of the Arunta Block; the location of any sudden changes in crustal thickness; and the possible presence of underthrust upper crustal material producing local thickening of the crust.

SEISMIC REFLECTION PROFILING

The recording parameters used in the routine reflection profiling in central Australia are given in Table 1, together with equivalent COCORP (Brown 1986) and DEKORP (DEKORP Research Group 1985) data. The BMR parameters are similar to those of overseas groups, and produce comparable results. For deep crustal profiling, the low fold does not appear to be a disadvantage, because, both in central Australia and in southeast Queensland (Wake-Dyster et al 1987), stacking generally does not significantly improve the signal to noise ratio of reflected signals from the deep crust.

Figure 2 shows the locations of seismic reflection lines in relation to the main tectonic elements of the region. The main north-south profile (L1), about 420 km long, extends from the Northern Arunta Province to the southern part of the Amadeus Basin; the field procedures used are described by Goleby et al (1986). A short east-west line, about 15 km long, was recorded along L3 in conjunction with the expanding-spread profiling described later. A north-south line (L2), 40 km long, east of L1 and crossing the northern margin of the RDZ (Figs 2, 3), was recorded in order to map dipping fault structures into deeper regions of the crust. Eight additional shots of 80 kg each were detonated on L2 at 1.5 km intervals near the northern end (Fig. 2, Cl) and recorded at offsets between 21 and 25 km. These larger shots were recorded to get additional information on seismic velocities and to try to observe reflections or diffractions from northerly dipping faults extending into the middle and lower crust. Eight portable refraction instruments were also deployed in the northern portion of L2 to record the near-vertical incidence reflection shots and consequently to provide information on lateral velocity variations to depths of 1 km or more. L4 (Fig. 2), 10 km long, was recorded in the northern part of the Amadeus Basin to tie existing industry seismic grids to L1.

Two expanding-spread reflection profiles with maximum offsets of 36 km and common midpoints (Musgrave 1962) were recorded on L1 and L3 (Fig. 4). They were located within the

GEOPHYSICAL FIELD SURVEYS AND PROCEDURES

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Table 1  Recording parameters: COCORP (Mojave Survey 1982: Brown 1986), DEKORP (DEKORP 2-South: DEKORP Research Group 1985) and BMR (central Australia: Goleby et al 1986).

<table>
<thead>
<tr>
<th></th>
<th>COCORP</th>
<th>DEKORP</th>
<th>BMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of recording channels</td>
<td>96</td>
<td>200</td>
<td>48</td>
</tr>
<tr>
<td>Sample rate (ms)</td>
<td>8</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Record lengths (s) (correlated record length for VIBROSEIS)*</td>
<td>20</td>
<td>20</td>
<td>20 or 24, 39 for expanding spreads</td>
</tr>
<tr>
<td>Spread location</td>
<td>—</td>
<td>Off-end</td>
<td>Symmetric or asymmetric split spread</td>
</tr>
<tr>
<td>Group interval (m)</td>
<td>100.6</td>
<td>80.0</td>
<td>83.3</td>
</tr>
<tr>
<td>Geophone arrays</td>
<td>24 geophones, 4.3 m spacing</td>
<td>80 m total length</td>
<td>16 geophones, 5 m spacing</td>
</tr>
<tr>
<td>Source spacing (m)</td>
<td>100.6</td>
<td>320 (NVI)†</td>
<td>1280 (WA) or 333</td>
</tr>
<tr>
<td>Multiplicity (fold)</td>
<td>48</td>
<td>25 (NVI)</td>
<td>6</td>
</tr>
<tr>
<td>Source</td>
<td>VIBROSEIS*</td>
<td>Explosives</td>
<td>Explosives</td>
</tr>
<tr>
<td>Hole depths (m)</td>
<td>—</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Charge size (kg)</td>
<td>—</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>Average</td>
<td>Some 5 (NVI)</td>
<td>Some 5 (NVI)</td>
<td>Some 5 (NVI) or 12, up to 168</td>
</tr>
<tr>
<td></td>
<td>Some 60 (WA)</td>
<td>for expanding spreads</td>
<td></td>
</tr>
<tr>
<td>Vibrators</td>
<td>5 synchronous with upsweep from 8 to 32 Hz over 32 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vibrator spacing (m)</td>
<td>15.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Registered trademark of Conoco Inc.
†NVI, near-vertical incidence; WA, wide-angle.

Table 1 shows the recording parameters for COCORP, DEKORP, and BMR surveys. The table includes details such as the number of recording channels, sample rate, record lengths, spread location, group interval, geophone arrays, source spacing, multiplicity, source type, hole depths, charge size, and vibrator spacing. The experiments were designed to obtain deep crustal reflections to provide information on seismic velocities in the deep crust. During the recording of the expanding-spread shots, 16 portable refraction instruments were deployed along the line on which no shots or recording spread were located, thus giving three-dimensional coverage.

The objective of this experiment was to use refracted P and possibly S wave arrivals to quantify anisotropy or lateral velocity variations in the bedrock velocity variations given in Fig. 10.

Fig. 3 Map of the Milton Park region, showing the location of the reflection line, large offset shots and the inferred positions of four major faults (F). A and B mark the northern and southern limits of the bedrock velocity variations.
Expanding spread shots

Fig. 4 Map of the Central and Southern Arunta Province regions, showing the locations of expanding spreads. One, approximately north-south, lies on L1 and consisted of 20 shots, and the other, on L3, consisted of 19 shots. The maximum shot receiver offset in each case was 36 km. During the recording of each expanding spread, refraction recorders were deployed on the other line to provide three-dimensional coverage.

RESULTS FROM NEAR-VERTICAL INCIDENCE PROFILING

The main basement features have been inferred from examination of both the single-shot records and the stacked sections, and are shown schematically in Fig. 5. Some of these features are discussed from north to south along L1.

Northern and Central Arunta Provinces

The band of northerly dipping reflections at times of between 2 and 10 s beneath the Northern Arunta Province (CD of Fig. 5) is particularly striking. These reflections probably correspond to a series of fault surfaces, the most northerly of which is present just north of the Ngalia Basin. This interpretation is consistent with the pattern of dipping faults within the Arunta Block observed in the surface geology (R. D. Shaw pers. comm. 1987; Goleby et al. 1988), and is the favoured explanation of persistent dipping reflectors, particularly at terrane boundaries, in other areas of Precambrian basement (Gibbs 1986). The reflections die out north of the Ngalia Basin and are replaced by shallower, relatively flat reflections. The persistent character of the dipping reflections suggests that the thrusting of the northern part of the Arunta Block towards the Ngalia Basin involved the entire crust.

Figure 6 shows a preliminary stack from the northern end of L1 (Fig. 1) across the northern estimates of crustal velocities and thickness along the strike of the Arunta Block. The refraction profile was located well away from the margins of the Amadeus or Ngalia Basins to minimize the possible effects of lateral variations in seismic velocities and crustal thickness. Ten explosions at five different shot sites were recorded by 33 portable refraction recorders; these refraction instruments were deployed, depending on shot size and location, at 131 different locations separated on average by 2.5 km. Shot sizes varied between 0.5 and 3.0 t (Bracewell & Collins 1986).

Gravity readings were made at intervals of 333 m (every fourth surveyed seismic recording station) along all reflection lines, and airborne magnetics were recorded at altitudes of 150 m and 1000 m over L1, L2 and L3 of Fig. 1 (Goleby et al. 1986).

using tomographic analysis techniques (Sugiarto 1988).

A third expanding spread was recorded within the northern part of the Amadeus Basin, over a sedimentary sequence about 10 km thick. Its main purpose was to provide accurate estimates of seismic velocities at depths below 4 km, since near-vertical incidence reflection profiles give poor velocity information for the deeper basin sediments because of the short (<2 km) shot-receiver offsets.

Refraction profiling and supplementary geophysical observations

A seismic refraction survey was undertaken within the Central Province of the Arunta Block along an east–west line about 400 km long (R1, Fig. 1) with the major objective of obtaining
margin of the Ngalia Basin covering about 40 km (CD of Fig. 5). It is possible to trace reflections from times of 1.5–1.9 s to the surface, at a point corresponding to the northern margin of the Ngalia Basin. Beneath this is another group of reflections from 3 to 5 s with southerly apparent dips at the northern end. However, the main bands of reflections have an apparent northerly dip and are prominent in the middle of the section. Features of the present section at the northern margin of the Ngalia Basin are somewhat similar to the shallow thrust fault so clearly defined in earlier seismic profiling west of the present line (Wells & Moss 1983b; Moss & Mathur 1986). Superimposed on this stacked section, slightly displaced, is a single-shot record displayed to facilitate comparison of the sixfold stack with unstacked data. The stack preserves the main low-frequency features of the reflected wave field, but much of the high-frequency energy is lost. In the northern part of the Ngalia Basin, there are significant statics problems, which also contribute to the degradation of the stack.

On the northern part of the profile (Fig. 6), reflections have unusually high frequencies; significant energy at a frequency of 100 Hz is returned at times of 5–6 s from single 12 kg explosive charges in shot holes 40 m deep. In addition, the dominant reflected energy occurs in bands of fairly high-frequency arrivals. Examples from a single shot in the Northern Arunta Province are shown in Fig. 7.

Filter panels for the interval 3.5–6.5 s are given for passbands from 20 to 40 Hz (Fig. 7a) and from 40 to 60 Hz (Fig. 7b) to illustrate the rapid change in character of the seismic reflections with frequency. For this time interval, there is little seismic energy below 20 Hz. On Fig. 7a, b, the band of reflections starts at about 4 s, with a particularly strong onset around 5.3 s with an apparent dip to the north. At higher frequencies the correlation distance of reflections is only of the order of five to ten traces (i.e. 416–833 m). This suggests that the signal is corrupted by relatively rapid changes in the near-surface, since reflections from 15 km depth would be expected to show greater continuity. Figure 7c, d illustrate...
a deeper reflection band from 8 to 11 s, where the reflected energy is shifted to lower frequency, resulting in fewer coherent reflections in the 40–60 Hz band but prominent low-frequency events below 20 Hz. The correlation between reflected events from adjacent shots is only moderate. Such features are difficult to model without introducing a stochastic element into the description of the near-surface zone. The variability in the character of the reflections across individual shot gathers and between shot gathers means that these data do not meet the assumptions built into conventional seismic data processing schemes. Nevertheless, reasonable results are obtained from common mid-point stacking (see Fig. 6).

The most southerly band of reflections starting at times of 6 s below the Northern Arunta Province becomes faint within the Central Province, suggesting that the reflection character can be used to define the boundary between the tectonic provinces to considerable depths. However, beneath the Central Province, the linear extension of a prominent segment of seismic

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**Fig. 6** Portion of BMR line L1 across the Arunta Block (CD on Fig. 5). Section is processed to brute stack stage. An enhanced line drawing (a) is shown above. Shot record 96 is superimposed on both parts of the diagram to illustrate the effects of stacking.

**Fig. 7** Portion of shot record 96 (see Fig. 6 for position): (a) 20–40 Hz bandpass filtered; 3.5–6.5 s window; (b) 40–60 Hz bandpass filtered; 3.5–6.5 s window; (c) 20–40 Hz bandpass filtered; 8–11 s window; (d) 40–60 Hz bandpass filtered; 8–11 s window.
arrivals reaches the surface at the RDZ (F of Fig. 5). These events are interpreted as reflections with a dip of about 42° after migration. It appears that this thrust (RDZ) observed at the surface (Shaw et al 1984; Stewart et al 1984) extends through the crust to a depth of at least 30 km (Goleby et al 1988). The deep seismic data thus delineate the boundary between the Central and Southern Tectonic Provinces, and also provide evidence to support a thick-skinned model of tectonic evolution in which old zones of weakness were reactivated during the Alice Springs Orogeny. However, the absence of evidence for a single low-angle thrust on which faults sole out, suggests a different style of evolution from that recently proposed by Teyssier (1985).

Southern Arunta Province and Northern Amadeus Basin

Prominent deep reflections beneath the Southern Province of the Arunta Block are observed from lines L1 and L2 (Fig. 2). Strong reflections at two-way times of 6 s and a prominent band of reflections between 8.5 and 10 s are present at the southern end of L2 beneath the RDZ. However, on L1 the strongest band of reflections has a slight apparent dip to the north and commences later at about 6.8 s (EF of Fig. 5).

Figure 8 gives line diagrams of two short pieces of the seismic section below the northern part of Missionary Plain, northern Amadeus Basin (Fig. 8A), and below the Southern Arunta Province (Fig. 8B). In the Missionary Plain section (Fig. 8A), the sedimentary sequence is about 10 km thick and has reflections dipping gently to the north and rapidly dying out close to where surface geological observations suggest that they are folded upwards (CDP 13850, Fig. 8A). North of this, there is a gap of about 23 km with little reflected energy. Beneath the Southern Arunta Province (Fig. 8B), bands of reflectors extend from depths of roughly 21–30 km (about 7–10 s), again with an apparent dip to the north. The reflections on the seismic sections of Fig. 8B are possibly from sills of mafic rocks or from rocks of sedimentary origin. A reasonable time correlation exists between reflections below the Missionary Plain in the time interval 1.5–3.3 s, and between those below the Southern Arunta Province in the time interval 7.0–8.7 s. The apparent thickness in the time domain of the deep section is about 6% less than its shallow counterpart in the northern part of the Missionary Plain. If the bands of deep reflectors were originally part of the Amadeus Basin sequence, the reflections at times of 7.0 s would correspond to the top of the Ordovician Larapinta Group (Wells et al 1970; Schroder & Gorter 1984). The deep reflectors below the Southern Arunta Province might also be the remnant of another Proterozoic or early Palaeozoic Basin, or may be from westerly plunging metasediments belonging to Division 3 rocks of the Iwupataka Metamorphic Complex (Stewart et al 1984). It is not clear if near-surface heterogeneities make the deep reflections appear less continuous than they really are, or if the rocks are less reflective than the Missionary Plain sedimentary sequence; further processing and numerical modelling may clarify this situation.

Strong reflections from the sedimentary sequence are observed to depths greater than 10 km below the Missionary Plain in the northern part of the Amadeus Basin (G of Fig. 5). Multiples generated from the strong reflectors within the basin sediments have so far prevented identification of deep basement reflections. The Gardiner Fault (Fig. 5), with a vertical uplift of the southern section of more than 3 km, is clearly observed in the sections.

Southern platform region of the Amadeus Basin

Reflections from the sedimentary section together with some multiples remain clear for a distance of 40 km south of the Gardiner Fault (Fig. 5). Within the southern platform region of the Amadeus Basin (Fig. 5), shallow reflections become diffuse, and there are few clear reflections from the deep crust. The absence of strong shallow reflections continues throughout the southern part of the Amadeus Basin where the sedimentary cover appears thinner (generally less than 1.5 km) than earlier geological interpretations have suggested (Wells et al 1970; Lambeck 1984).

Strong reflections, similar in character to those observed beneath the Southern Province of the Arunta Block, are observed below the southern part of the southern platform area at times between 5 and 10 s, but have an apparent dip to the south. The onset of these reflections is sharp.
Fig. 8  Line diagram of short segments of seismic sections below the northern part of the Missionary Plain (GH of Fig. 5) and below the Southern Arunta Province (EF of Fig. 5). The lower part of the figure shows seismic sections below the northern part of the Missionary Plain (A) and the Southern Arunta Province (B). The vertical lines A and B on the line drawing indicate the portion of section displayed below. Spot depths are given for both sections A and B.

over a distance of more than 40 km; this reflected energy starts at 5 s in the north and becomes progressively later towards the south (Fig. 5). A brute stack of part of the southern part of L1 (MN of Fig. 5) shows particularly strong reflected energy between 5.8 and 6.0 s followed by bands of reflections to 10 s (Fig. 9).

Possible improvements to the seismic sections

Attempts at signal enhancement by using improved statics corrections and refined seismic velocity determinations are proving successful in improving the quality of both the shallow and deep seismic sections throughout the survey.
Fig. 9 Section processed to brute stack stage (MN of Fig. 5) from the southern part of the Amadeus Basin, showing strong bands of reflected energy starting at 5.8–6.0 s.

region. In particular, better statics corrections are resulting from the use of the refracted arrivals from the reflection shots to produce velocity models of the zone of variable weathering and overburden thickness. P wave velocities in weathered and unweathered bedrock vary from 3.0 to 6.5 km/s, while the averaged P wave velocities in the overburden of the top 40 m vary between 1.2 and 2.9 km/s over the survey region. The variable overburden thickness within the Arunta Block and parts of the Amadeus Basin is a particularly severe source of problems, because of the large increase in seismic velocity of about 4 km/s from overburden to unweathered bedrock.

RESULTS FROM OTHER SEISMIC PROFILING

Milton Park experimental profile

The early processing and interpretation of the Milton Park line (Fig. 3 and L2 of Fig. 2) has con-
centred on mapping P wave velocity variations in the top 300 m of bedrock by using the refracted arrivals from the reflection shots. This shallow-velocity analysis has been undertaken because of the absence of clear shallow reflections and the complicated variations in signal waveforms and arrival times of the refracted arrivals. Localized measurements of apparent velocity of the refracted arrivals that have penetrated to bedrock depths vary between 4 and 15 km/s. This emphasises the need for special techniques to cope with the near-surface structural complexities that influence both the static and normal moveout corrections. Seismic signals in the first 4 s that may be associated with moderately dipping fault structures could also be a form of signal-generated noise (Key 1967) and will be the subject of a future investigation.

Deep reflections on L2 are faint except at the southern end of the line where strong reflections are observed at times of 5.8–6.0 s followed by a band of fainter reflections ending at 10 s. Farther north on L2, faint reflections are observed from within the Central Arunta Province at times of between 13 and 14 s. If these reflections are from immediately below the reflection spread, they could be interpreted as indicating a crustal thickness of 42–45 km.

Wright (1988) has devised a method for mapping shallow bedrock-velocity variations to define lithological changes and zones of extensive fracturing better by using refracted arrivals from the normal reflection shots; this method has been applied to a 15.4 km section of L2, lying within the Central Arunta Province, and shown as the segment A–B on Fig. 3. Figure 10 shows the results plotted as a contour map of bedrock velocity variations from the base of the weathering (150 m) to depths of about 320 m. The measured velocities lie in the range 5.2–6.5 km/s. The southern end is characterized by relatively low velocities (approximately 5.6 km/s), which increase steadily towards the north. North of location 2095 to about 2190 (~7.9 km), velocities are greater than 6.0 km/s at depths of about 200 m. These relatively high velocities are most probably associated with mafic or felsic granulites (Shaw et al. 1984). The velocities decrease rapidly north of location 2185 from 6.4 to <5.6 km/s. The numerical and statistical techniques used to prepare Fig. 10 will cause some smearing out of relatively abrupt changes

![Fig. 10 Contour map of bedrock velocity variations along a portion (A–B) of L2 of Fig. 1. The location of A–B is given in Fig. 3. V/H denotes vertical to horizontal exaggeration of diagram.](image_url)
in seismic velocity. It is therefore suggested that north of location 2185 a faulted contact between granulites and lower-velocity material is being imaged and the apparent dip to the north is about 15–20°. The more gradual change from high to low velocity in the southern part of Fig. 10 possibly results from an oblique crossing of an irregular granulite boundary (Wright 1988). Because of the complexity of the lithological layering in the Central Province of the Arunta (Shaw et al 1984), an unambiguous petrological explanation of the lower-velocity material is not possible. Granite or granitic gneiss are the most likely candidates.

Arunta Block tomographic experiment

Preliminary results from the refraction tomographic survey (Fig. 4) suggest lateral heterogeneity or anisotropy with P wave velocities in upper basement in the range 5.6–6.2 km/s, and S wave velocities of about 3.3 km/s on average (Sugiharto 1988). Because of the severity of the static correction problems in this region of the Arunta Block, the results from the expanding spreads and coincident near-vertical incidence profiling are being used to remove the effects of near-surface heterogeneity and so enhance the tomographic analysis of the refracted P and S arrivals.

Missionary Plain expanding spread

Figure 11 presents the seismograms from the expanding spread recorded across the Missionary Plain (E3 of Fig. 2) with receiver and least-squares shot statics corrections applied (Wright & Taylor 1986). High-quality reflections are observed in the thick sedimentary section, but there are no clear deep-basement reflections.

The first-break times have been used to determine the velocity structure to a depth of 4.3 km using the Herglotz–Wiechert inversion procedure (Aki & Richards 1980, pp. 643–650). The slowness–distance relationship (Fig. 12) was derived by summary value smoothing (Jeffreys 1961; Bolt 1978), and shows a small increase in

![Missionary Plain expanding spread filtered 12-36 Hz](image)

**Fig. 11** Missionary Plain expanding spread plotted with adjacent shots side by side and not in the alternating manner suggested by Musgrave (1962). The time displacement of the seismograms at the left margin of the figure occurs because it was not possible to locate the recording spread correctly. S denotes refracted shear waves.
Fig. 12 Slowness–distance relationship derived by weighted summary value smoothing for the Missionary Plain expanding spread (Jeffreys 1961; Bolt 1978). The lines surrounding the summary value estimates represent the calculated standard errors. The schematic slowness–distance relationship (continuous lines) in the bottom left plot is for a low-velocity layer that gives rise to a small shadow zone. The broken line with a local maximum indicates the form of a smoothed slowness curve constructed from scattered slowness measurements on the earliest detectable seismic energy.

slowness with increasing distance, which had to be removed in order to evaluate the Herglotz-Wiechert integral. A possible explanation of the small increase is the presence of a low-velocity layer, which results in the earliest observed arrivals over a small distance range being associated with a cusp in the slowness–distance relationship, as illustrated in the inset portion of Fig. 12 (Wright & Cleary 1972). The maximum velocity of 6.02 km/s occurs at a depth of 4.3 km (Fig. 13). The inferred velocity inversion starting

Fig. 13 Velocity profile for the Missionary Plain sediments, derived from refracted arrivals by the Herglotz-Wiechert inversion method. Interval velocities inferred from the reflections from four key horizons are also plotted, together with the seismic stratigraphy (Schroder & Gorter 1984; Lindsay & Korsch 1988).
at depths of below 2 km adds significant uncertainty to the estimated maximum depth reached by the refracted energy, which can only be reduced by additional ray tracing and a study of the fainter reflections on the expanding spread.

Reflection times for the four most prominent reflecting horizons have been picked for the innermost 11 of the expanding-spread shots, and the smoothed velocities with estimated errors are plotted in Fig. 14. The velocities are defined as the square root of the slope of the $T^2 - X^2$ relationship derived for each shot, and then smoothed as a function of receiver location. The velocity terms derived by this approach are very sensitive to reflector dip, and an account of the problems associated with deriving a velocity model for the Missionary Plain sediments has been given by Wright et al. (1988). Estimates of r.m.s. and interval velocities corrected for dip are given in Table 2 and the interval velocities are plotted in Fig. 13. The velocity inversion inferred from the refraction data is attributed mainly to the Mereenie Sandstone (depths 3.0–3.9 km) because of its high porosity. Further velocity inversions at depths below 4.3 and 7.0 km may also be present. The reflections used are from the base of the Mereenie/Carmichael Sandstone, within the Pacoota Sandstone, an intra-Proterozoic boundary and the top of the Bitter Springs Formation.

Table 2 Velocity estimates for sediments below the Missionary Plain, Amadeus Basin.

<table>
<thead>
<tr>
<th>Reflection horizon</th>
<th>$V_{\text{rms}}$ (km/s)</th>
<th>Two-way time at zero offset (s)</th>
<th>$V_{\text{int}}$ (km/s)</th>
<th>Depth (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (base of Mereenie Sandstone?)</td>
<td>5.07</td>
<td>1.544</td>
<td>5.07</td>
<td>3.91</td>
</tr>
<tr>
<td>B (within Pacoota Sandstone)</td>
<td>5.09</td>
<td>1.883</td>
<td>5.18</td>
<td>4.79</td>
</tr>
<tr>
<td>C (Intra-Proterozoic reflector)</td>
<td>5.34</td>
<td>2.632</td>
<td>5.92</td>
<td>7.03</td>
</tr>
<tr>
<td>D (top of Bitter Springs Formation)</td>
<td>5.32</td>
<td>2.997</td>
<td>5.17</td>
<td>8.00</td>
</tr>
</tbody>
</table>
Clear S wave arrivals are observed on the expanding-spread seismograms (Fig. 11); note that a wave that has travelled for the major part of its propagation path as a shear wave is labelled S, but some P to S or S to P conversion may be involved (Wright & Finlayson 1988). The measured apparent velocities of S waves are in the range 3.0-3.5 km/s, indicating P to S wave velocity ratios of between 1.5 and 1.7.

Seismic refraction survey: Central Arunta Province

The seismic refraction survey in the Arunta Block (Rl of Fig. 1) yields P wave velocities near the surface that vary between 4.0 and 5.5 km/s, and increase rapidly to about 6.2 km/s at a depth of about 1 km. A weak refracted arrival with an apparent velocity of 7.2 km/s is present at offsets greater than 220 km, and is attributed to a velocity boundary at a depth of about 31 km (Fig. 15). This boundary may correspond to the base of the reflecting zone that ends at times of about 10 s below parts of the Arunta Block (Fig. 5). No arrivals with velocities greater than 8 km/s are observed. Later arrivals at offsets between 200 and 240 km may be wide-angle reflections; if this is so, the crust-mantle boundary would be at a depth of about 55 km. Good S wave arrivals are observed from most shots and yield apparent velocities of between 3.4 and 3.9 km/s.

CONCLUSIONS

The seismic reflection profiling across the central Australian region has yielded strong deep crustal reflections below much of the Arunta Block and the southern part of the Amadeus Basin. Results from the Amadeus Basin are varied, depending on local surface structure, but more refined statics corrections using information on the first arrival times is resulting in significant improvement in record quality. The base of the Amadeus Basin sediments is still poorly defined south of the Gardiner Fault.

The most interesting results have come from the Arunta Block and the southern platform area of the Amadeus Basin. In the northern part of the Arunta Block, dipping bands of reflected energy may well be generated by thrust faults, with apparent dips to the north of about 40°, some of which may extend to depths greater than 30 km. The reflection character favours a thick-skinned model of tectonic evolution involving lateral and vertical displacements of entire crustal blocks. The presence of bands of reflections below the Southern Arunta Province and the southern part
of the Amadeus Basin at depths greater than 18 km needs to be explained by revised models for the tectonic evolution of the region. Nowhere does the reflection character clearly define the Moho, but this appears to be a characteristic of Precambrian regions (Brown et al 1987).

Many important attributes of the seismic data will help constrain the petrological nature of the deep crust. The variability of the frequency content of the reflection bands must represent an interference phenomenon, possibly associated with laterally variable lamellar structures. In basement rocks of the Arunta Block and below the Amadeus Basin, there is no clear indication of any depth interval being 'non-reflective', even though some reflection bands can be particularly prominent. This is in sharp contrast to the crust beneath the Phanerozoic basins of eastern Australia, which has a distinct non-reflective upper crust (Moss & Mathur 1986; Wake-Dyster et al 1987). The relatively short correlation distances of the high-frequency energy require the development of alternatives to conventional stacking to exploit finer details in the reflections.

The relative weakness of deep crustal reflections in the Central Arunta Province compared with the Northern Province appears to be correlated with the presence of granulites at the surface; faint reflections on L2 (Fig. 2) suggest that the thickness of the crust below the granulites is in the range 42–45 km. The seismic refraction results, mainly applicable to the Central Arunta Province, also suggest a thick crust (approximately 55 km) beneath much of the Arunta Block. This is not easy to reconcile with the physical model for the evolution of the central Australian region of Lambeck (1983, 1984) or with the observed teleseismic travel-time anomalies and gravity data (Lambeck & Penney 1984; Lambeck et al 1988), which suggest a relatively thin crust beneath the Arunta, without introducing some additional complications to models of the crust. The refraction data also suggest that there is little overall increase in seismic velocity within the reflective top 30 km of the crust, and that the less-reflective region below 30 km is not upper mantle material. The expanding-spread reflection profile recorded in the northern part of the Amadeus Basin has enabled seismic velocities to be estimated accurately for the lower part of the sedimentary sequence at depths greater than 4 km. However, for both this expanding spread and the two recorded in the Arunta Block, the interpretation is complicated by the presence of significant lateral variations in seismic velocity below weathering.

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