Geophysical evidence for 'thick-skinned' crustal deformation in central Australia

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Until now, there has been no clear evidence from deep seismic reflection profiles of crustal faults that displace the Moho. New data from central Australia show such a structure in a region characterized by large thrust structures, large gravity anomalies and abrupt changes in teleseismic travel times. Here the principal thrust, the Redbank Deformed Zone, cuts through the crust, and the Moho is significantly displaced across it. The geological and geophysical evidence leads to a model of thick-skinned crustal deformation which occurred in an intra-cratonic environment in late Devonian time.

A CURRENT controversy in the study of continental tectonics is whether deformation initially involves the entire crust and the upper mantle (that is, a 'thick skin') or whether it is controlled by detachment zones within the crust so that much of the folding and imbricate thrusting is restricted to the upper crust alone (a 'thin skin')[1]. This controversy has been introduced recently to attempts to understand the formation of the Pyrenees of Europe, for which both thick- and thin-skinned interpretations have been proposed[2]. Well-known examples of thin-skinned tectonics include the Appalachians and Rocky Mountains of the United States and the Alps of Europe. Thick-skinned models are characterized by major planar crustal faults which cut the entire crust at moderately steep angles. Examples of thick-skinned tectonics include the Wind River Thrust of North America, the Grenville Front region of Canada and the Flannan and Outer Isles Thrusts of Great Britain. The Grenville Front in particular is an excellent example of thick-skinned tectonics[3]. Another example occurs in central Australia, and exhibits clear evidence of a major offset in Moho depth across the structure.

The tectonic setting of central Australia is characterized by a series of late Proterozoic–Palaeozoic basins and an exposed geological basement of middle Proterozoic age[4-7]. The basins include the Amadeus and Ngalia Basins, and the principal region of exposed basement is the Arunta Block (Fig. 1). The region as a whole is characterized by relatively flat topography and by major east-west-trending gravity anomalies (of peak-to-trough amplitudes exceeding 1,400 μm s^{-1} (140 mgal)) (Fig. 1). Teleseismic travel-time anomalies of up to 1.5 s have also been recorded across the region over distances of a few tens of kilometres[8]. Major east-west-trending thrust zones occur within the Arunta Block. These observations, together with the geological evidence that the thrusts were last reactivated in an intra-cratonic environment in late Devonian to early Carboniferous times[9] with little subsequent tectonism, makes this basin-and-block structure quite unusual and raises a number of fundamental questions. What is the deep crustal structure beneath these basins and blocks? What were the driving forces that shaped these and other structures? How has this anomalous structure been supported since the time of the last major thrusting event[10]? Several models have been proposed in response to such questions[9-12], and a 500-km-long north–south deep-seismic-reflection traverse has been recorded by the Bureau of Mineral Resources across the Amadeus Basin and Arunta Block[13]. Only the northern section, extending from north of the Ngalia Basin to a point south of the major thrust zone (the Redbank Thrust or Redbank Deformed Zone), is discussed here (the section A–A′ in Fig. 1). Explosive sources were used throughout and the resulting deep-seismic-reflection data provide excellent resolution of the crustal structure down to an average depth of ~40 km.

Regional geology

The Amadeus Basin[4], bounded to the north by the Arunta Block and to the south by the Musgrave Block, contains up to 14 km of sediments of late Proterozoic (~900 Myr) to late Palaeozoic (~300 Myr) age. The maximum thickness of sediments occurs at the faulted and upturned northern margin, where the Arunta Block has been thrust up and over the basin sediments to form the Amadeus Homocline. Several deformation events have been identified within the basin sediments, with the major and final one having occurred at the time of the Alice Springs orogeny in the late Devonian to early Carboniferous. The northern margin of the Ngalia Basin is also fault-controlled and the last major orogenic event (the Mt Eclipse orogeny) occurred at about the same time as the Alice Springs orogeny[5]. The Ngalia Basin is not an important feature in the seismic-reflection section discussed here because the sediment thickness does not exceed 1 km. Further to the west the sedimentary section exceeds 6 km in thickness.

The Arunta Block can be characterized by three tectonic provinces[6,7], each of which underwent separate histories of deformation and metamorphism during early to middle Proterozoic time (Fig. 1). The Southern Arunta Province, between the Redbank Thrust and the northern margin of the Amadeus Basin, is predominantly an amphibolite-grade granitic gneiss, in contrast to the central province which is characterized by felsic and relatively minor mafic granulite that was metamorphosed at depths of ~25 km at ~1,750–1,800 Myr. The Northern Arunta Province consists of low-grade metasediments of amphibolite and greenschist facies. The southern and central provinces are separated by the Redbank Thrust, a 7–10-km-wide east–west-trending zone of anastomosing mylonites which dips northwards at about 45°. The northern and central provinces are separated by large granitoid intrusions and possibly by moderately to steeply dipping faults. Another major structural feature is the Ormiston Thrust Zone some 13 km south of, and running sub-parallel to, the Redbank Thrust. At the northern end of the line, north of the Ngalia Basin, the tectonics becomes complicated by an oblique lineament known as the Weldon Tectonic Zone[5,6]. Apart from this last feature the tectonic strike is primarily east–west and approximately orthogonal to the seismic reflection line.

Deep seismic reflections

All signal processing was carried out using pseudo-true-amplitude techniques, in which energy loss is assumed to occur only

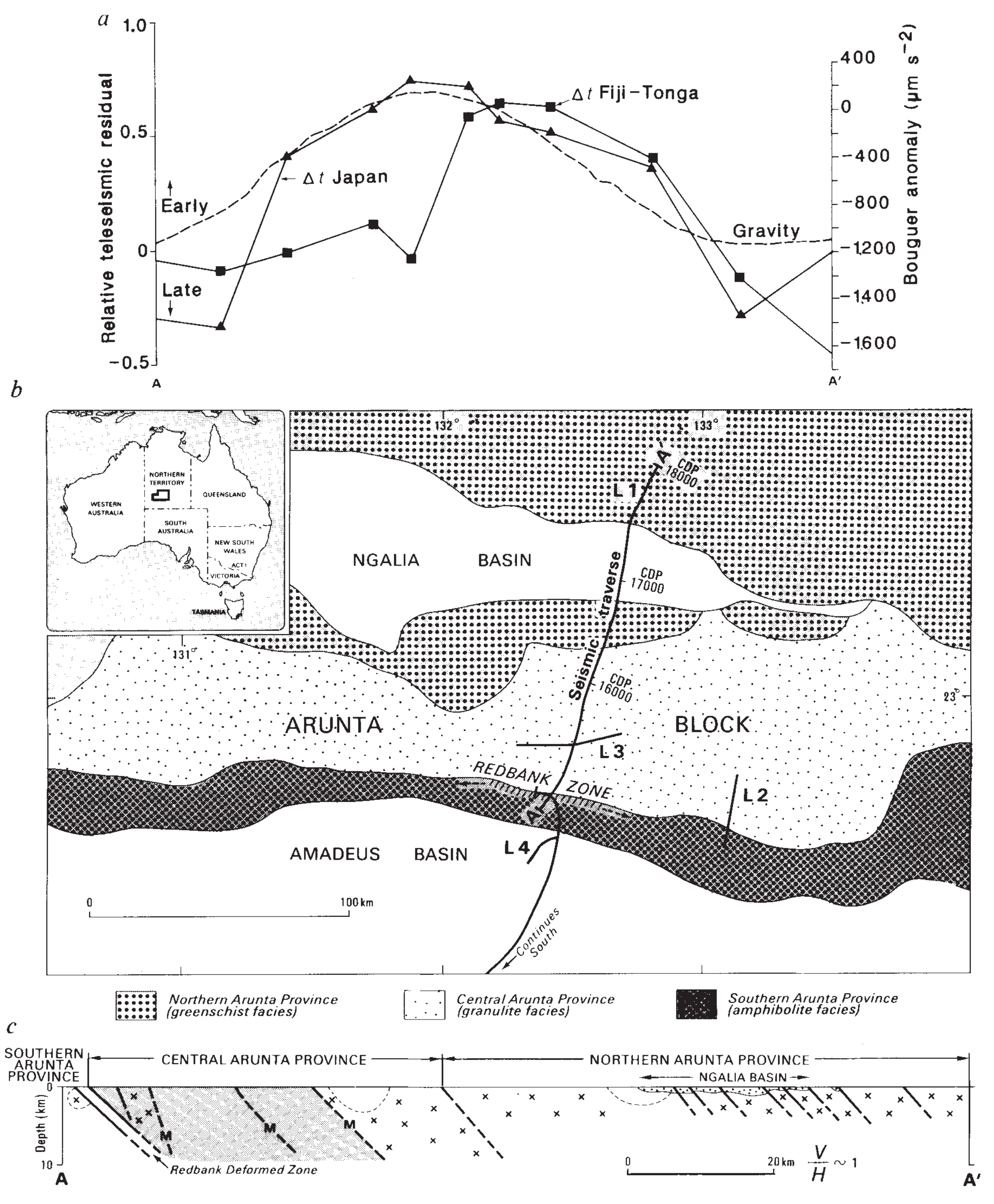

Fig. 1 Location diagram showing the principal tectonic elements of the central Australian region (*b*) and the position of the northern portion of the Central Australian traverse, L1, where it crosses the Arunta Block. Gravity and teleseismic travel-time profiles[1] (*a*) and a schematic geological cross-section (A–A′, shown in *b*) along this traverse are also shown (*c*). The shading schemes used in *b* and *c* are different. The travel-time anomalies are for earthquakes from two different regions: Japan from the north and Fiji–Tonga from the east.

by spherical divergence and losses associated with attenuation are neglected. Major efforts to enhance the deep seismic signal were not required during processing. Figure 2 illustrates the variations in the processed signal throughout the seismic section for a collection of single-shot gathers.

Line drawings of the deep-seismic-reflection section are shown in Fig. 3 and are used here instead of seismic-reflection sections because of the greater clarity of the former and to avoid some of the difficulties of migrating deep seismic data[14]. Each line segment in these drawings represents a coherent seismic reflection seen on the original seismic section. Results obtained with different stacking methods are illustrated for both unmigrated and migrated sections. The migrated sections are produced by migrating each line segment of the line drawing to its time-depth position. The coherency-stacking method (Fig. 3*a*) enhances coherent and continuous dipping and flat reflectors. The corresponding section of migrated line segments is shown in Fig. 3*b*. The energy-stacking method (Fig. 3*c*) emphasizes packets of energy that are not affected by signal polarity, and enables an easier correlation of reflections because they are enhanced above the generally noisy background of the seismic sections[15]. The corresponding line-segment-migrated section is shown in Fig. 3*d*. Both migrations were performed with a velocity-depth function that varied from 5.5 km s^{-1} at shallow depths to 6.2 km s^{-1}.

Other stacking methods have also been used, and they produce the same general features illustrated in Fig. 3. In addition, most of the deep-reflection events seen on these processed sections can also be identified on the single-fold displays (see, for example, Fig. 2).

The principal features of the line drawings are illustrated in Figs 3 and 4. A general feature of the data is that the strength and depth of penetration of the reflected signal is unusually high for deep seismic data; the signal is still strong to reflection times of 14 s with an unusually high frequency content. Frequencies up to 80 Hz at reflection times of 5-6 s and to 60 Hz at 6-10 s are common, particularly within the Northern Arunta Province. Because conditions around the source were similar to those encountered elsewhere in Australia, the high-frequency content implies that the rocks at depths of 15-20 km have a very high quality factor Q (that is, low attenuation)[16].

The Precambrian Arunta Block exhibits reflections of varying strength throughout the section and is not characterized by the marked non-reflective upper-crustal zone that is seen in similar sections of Precambrian regions elsewhere in the world[17]. Instead, the Arunta section is dominated by northerly-dipping reflections throughout the entire crust, which coincide with surface evidence of thrusts and faults. The surface faults and mylonite zones corresponding to the Redbank Thrust correspond to reflections in the seismic section that can be traced to depths of at least 30-35 km and possibly down to 50 km (Figs 3*b* and 4*a*), dipping at an angle of about 35-40°. Three-dimensional modelling has shown that such faults can generate strong reflected signals[18]. A second band of northerly- but shallower-dipping reflections lies below this feature and its extension to the surface suggests that it corresponds to the Ormiston Thrust, which appears to merge with the Redbank Thrust at mid-crustal levels. Beneath the Southern Arunta Province, the reflectors down to 30 km depth are predominantly sub-horizontal, in contrast to the generally northerly-dipping reflectors (~35°) beneath the central and northern Provinces. This transition in dip coincides with the Redbank Thrust. We interpret the Southern Arunta Province as extending to the underthrust foot wall of this thrust, down to a depth of at least 30 km. The crust north of the Redbank Thrust exhibits further moderately dipping (35-40°) reflections which correspond to surface outcrops of mapped faults or of faults inferred from aeromagnetic surveys. These faults and shear zones extend down to a depth of ~35 km and divide the crust into a series of 'blocks', each of which has similar seismic characteristics and which is bounded by the dipping faults. Seismic-reflection sections of Precambrian crust recorded elsewhere in the world have not exhibited such large numbers of dipping faults and inferred tilted blocks. The shallow zone of low reflectivity (<2 s travel time) seen to the north of the Redbank Thrust coincides with mapped outcrops of granitoid and granitic gneiss, and this whole region is interpreted as granitic material. Sub-horizontal reflections occur at the base of this granitic zone, as well as within the crustal blocks (Fig. 3*b*), and are attributed to compositional layering. They can, therefore, be used as marker horizons which indicate the present attitude of the original crustal layering. Within some blocks these sub-horizontal events are truncated against the dipping faults, suggesting that the deformation of the crust occurred by movement along the faults, with little or no rotation of the crustal blocks.

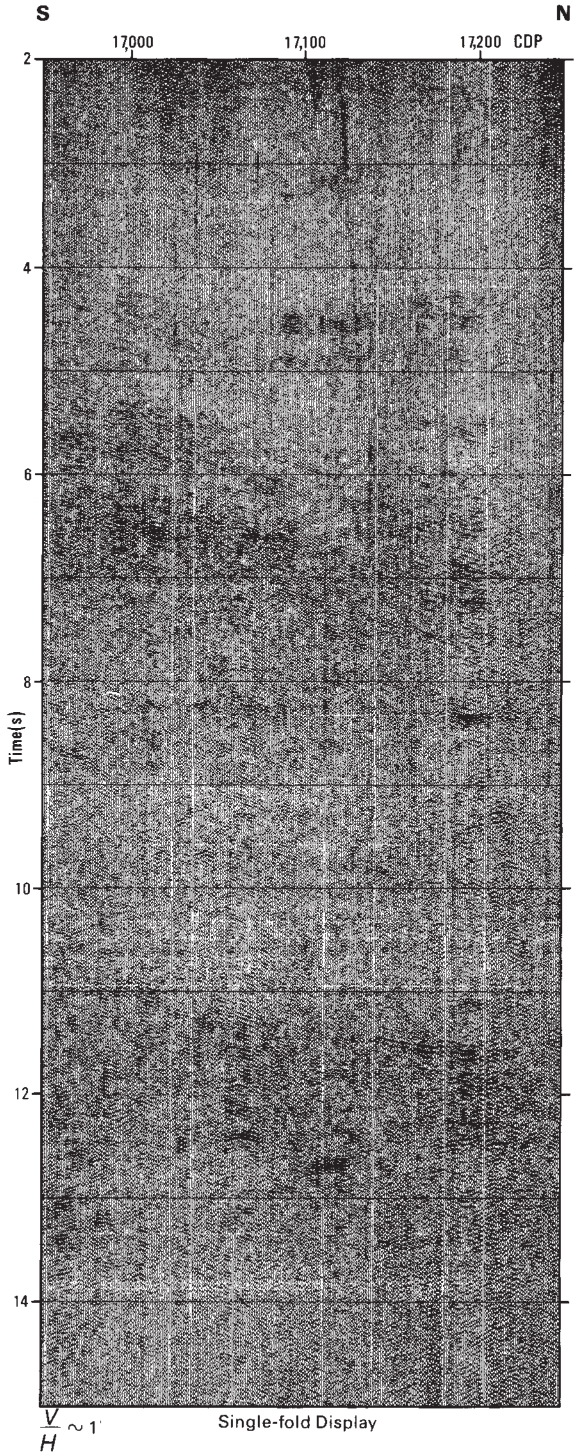

Fig. 2 Portion of a single-fold display, without gain correction, from within the Northern Aunta Province. This is a pseudo-true-amplitude section and illustrates the strength and continuity of the deep signals.

Deep-crustal reflections in the migrated sections are more prominent beneath the northern and southern provinces than beneath the Central Arunta Province (Figs 3*b*, *d* and 4*a*). In particular, the two migrated sections beneath the central province exhibit a relatively transparent zone at about 25-30 km depth, where the density of reflections is comparable to those usually seen in other sections at depths greater than 35-40 km. Energy is received from reflections beneath this transparent zone, indicating that this region is seismically non-reflective rather than being a region of high attenuation. The continental crust-mantle boundary is often defined in seismic-reflection sections as the base of a zone of strong, deep and layered reflections overlying a non-reflective region corresponding to the upper mantle[19,20]. Beneath the northern part of the Arunta Block, the appropriate choice for this boundary would be at about 35-40 km depth but it is less well defined south of the Redbank Thrust. One interpretation is that this boundary occurs at the base of the lowest reflections that are seen at about 50 km depth (Figs 3*b* and 4*a*); this indicates a thicker-than-normal crust and a significant variation in the crustal thickness between the southern and northern provinces. Sediments in the Amadeus

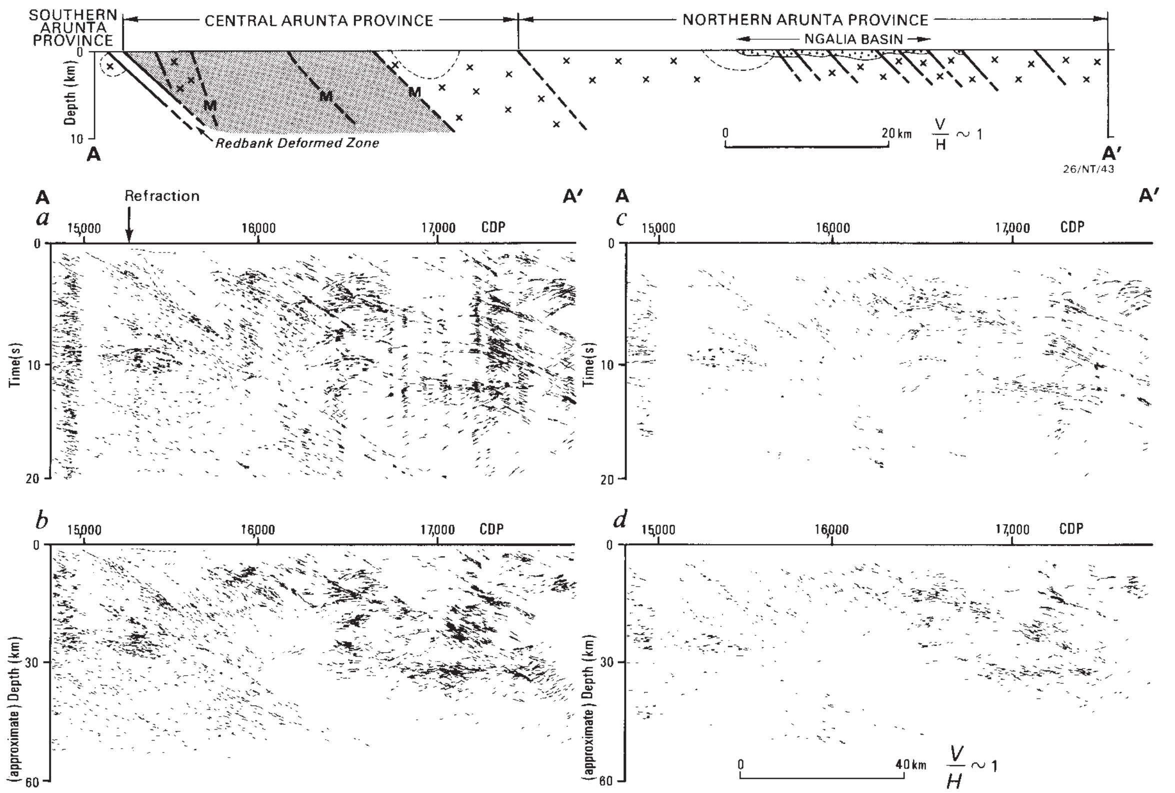

Fig. 3 Unmigrated and migrated line drawings of the seismic-reflection section from the Central Australian traverse. *a*, Unmigrated coherency stack. *b*, Line-migrated version of *a*. *c*, Unmigrated energy stack. *d*, Line-migrated version of *c*.

Basin, south of the Redbank Thrust, have a maximum thickness of 10–14 km and the gravity, teleseismic travel-time anomalies and deep-crustal-reflection data do not indicate any discontinuity in the deep-crustal structure across the basin margin; the interpretation that the base of the crust is at 50 km depth therefore implies that the sediments have been deposited on a crust of approximately normal thickness. This is consistent with a predominantly compressional regime during the later part of the basin formation process. The large negative gravity anomalies, the late teleseismic travel-time arrivals (Fig. 1) across the northern part of the Amadeus Basin and the southern part of the Arunta Block south of the Redbank Zone, and an east-west seismic reflection profile, all favour a crustal thickness of more than 50 km in this region. We therefore interpret the reflection record beneath the footwall of the Redbank Thrust as a broad crust-mantle transition zone of 15–20 km thickness extending down to a depth of at least 50 km. Beneath the Northern Arunta Province this transition zone is considerably thinner and occurs at a shallower depth. The seismically transparent zone immediately north of the Redbank Thrust is interpreted as a region of predominantly mantle material emplaced by major thrusting on the Redbank and Ormiston Thrusts.

Figure 4*b* illustrates the crustal structure derived from the teleseismic travel-time anomalies for the part of the Arunta Block corresponding to the extent of the seismic line. The model has poor resolution north of the Ngalia Basin. The principal requirements of this data set are a zone of relatively high-velocity material dipping steeply northwards such that its continuation to the surface coincides approximately with the Redbank Thrust and the granulite terrain to the north of it, and relatively low-velocity material in the form of a down-thrust wedge to the south of the Redbank Thrust[10]. These features are consistent with the reflection data.

Gravity modelling

The Bouguer gravity anomalies along the seismic line are characterized by a relatively long-wavelength variation of ~1,400 μm s^{-2} peak-to-trough amplitude. The free-air anomalies exhibit a very similar variation, and conventional models of isostatic compensation fail to explain these observations[21]. Near-surface variations in crustal densities of surface outcrop rocks range from 2.5 g cm^{-3} for the Palaeozoic sediments in the basin to 2.95 g cm^{-3} for the high-grade granulite facies rocks north of the Redbank Thrust[10]. If such lateral variations persist down to 10 km depth they would explain about 50% of the observed magnitude of the gravity anomalies. However, the wavelength predicted for these anomalies is considerably less than that observed, and the observed maximum anomaly is offset from the surface exposure of high-density granulites by more than 50 km. Furthermore, there are no significant short-wavelength changes observed across either the Redbank Thrust or the Amadeus Homocline, despite the existence of density contrasts across these surfaces[10]. Overall, these observations suggest a deep origin for the major part of the observed gravity field over the southern part of the Arunta Block. Figure 5 shows the gravity field predicted by the model, using density values based on surface-rock exposure[9,10]. Agreement with the observed field is satisfactory and could be further improved by minor adjustments to the boundaries that separate regions of different densities or by introducing density gradients within the regions. Most importantly, the model makes good predictions of both the amplitude and the wavelength of the observed field.

A tectonic model for the Arunta Block

The deep-seismic-reflection data favour a tectonic model in which the major deformation within the Arunta Block occurred along faults and shear zones that extend from the surface to the crust-mantle boundary (that is, a 'thick-skinned' model). In particular, there is no seismic evidence for mid-crustal ramps branching from a relatively shallow-dipping sole thrust, which is a principal characteristic of the thin-skinned models[22]. In this sense, the Arunta structure is comparable to both the Flannan and Outer Isles Thrusts of Scotland[23], the Pyrenees of Europe[2],

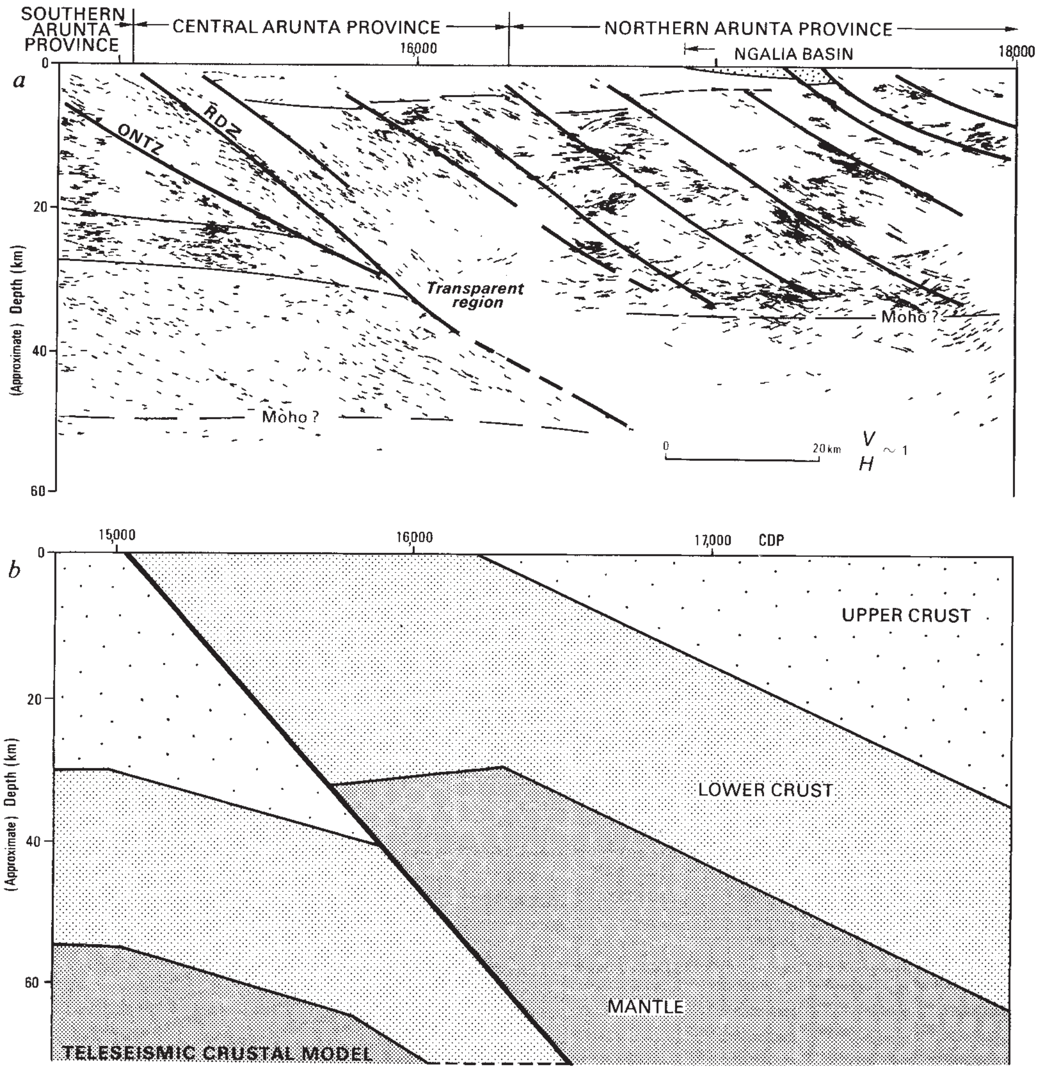

Fig. 4 Interpreted crustal structure of the Arunta Block. RDZ refers to the Redbank Deformed Zone and ONTZ to the Ormiston Nappe and Thrust Zone. *a*, Deep-seismic-reflection model. *b*, Teleseismic crustal model, based on the observed teleseismic travel-time data[1].

the Grenville Front of Canada[3] and, to a lesser degree, the Wind River Thrust of the USA[24], but it differs in that these latter structures do not exhibit the seismically transparent material on the lower part of the hanging wall. None of the Flannan, Outer Isles or Wind River Thrusts are associated with a major gravity anomaly. It is emphasized that the above remarks refer to the central part of the Arunta Block and Amadeus Basin, and that in an intracratonic environment the deformations along the eastern and western limits may differ in significant ways from this model.

Structural, metamorphic, and isotope data reveal that the Arunta Block has had a complex history. In particular, Rb/Sr and ^{40}Ar/^{39}Ar isotope data imply different evolutionary histories for the blocks north and south of the Redbank Thrust before 1,450 Myr and possibly until 1,100 Myr (ref. 9). The overall character of the seismic reflections changes across this thrust and this may be indicative of fundamental differences in crustal composition of the two regions, supporting the interpretation that the Redbank Thrust is a major crustal boundary. Furthermore, the isotope data and the metamorphic grade of the mylonites indicate that the granulites north of the Redbank Thrust were subjected to major uplift (~15 km) during the Alice Springs orogeny, particularly during the last phase of the Amadeus Basin formation which produced the upturned and overthrust northern margin (the Amadeus Homocline). Argon-loss data constrain this uplift at between 300–400 Myr, with the movements on the faults decreasing in age from north to south between the Redbank and Ormiston Thrusts[9].

Teleseismic travel-time residuals[10] favour models in which low-velocity crust is underthrust beneath overriding lower crust and mantle of the Central and Northern Arunta Provinces down to a depth in excess of 50 km (Fig. 4). The isotope evidence shows that a substantial part of this structure developed at a time leading up to and including the Alice Springs orogeny, producing a stacking or imbrication of the crust and the exposure of lower-crustal material north of the Redbank Zone. Displacement of the inferred granitic layer and the deflection of subhorizontal reflectors against the fault or shear zones suggest that the faults north of the Redbank Thrust acted as 'lag' faults during the final stages of movements.

This model generates a number of questions. In particular, one can ask what are the driving forces that have produced this structure, how such a structure, obviously out of isostatic equilibrium, has been maintained for the past 300 Myr, and how these conclusions relate to other thick-skinned regions. The stress differences associated with the present structure are of the order of 100–150 MPa (ref. 10) and the stress fields associated with the forces that produced the structure must have been at least of this magnitude. The isostatic response is anisotropic. The east–west response is consistent with models of local or regional isostatic compensation, whereas the north–south response implies compressional in-plane stresses of the order mentioned[21]. The major movements on the Redbank Thrust before and during the Alice Springs orogeny indicate that compressional forces operated at this time, and the geological setting of central Australia indicates that this occurred within an intracratonic environment rather than at a plate margin. The timing of the Alice Springs orogeny coincides with the Kanimblan

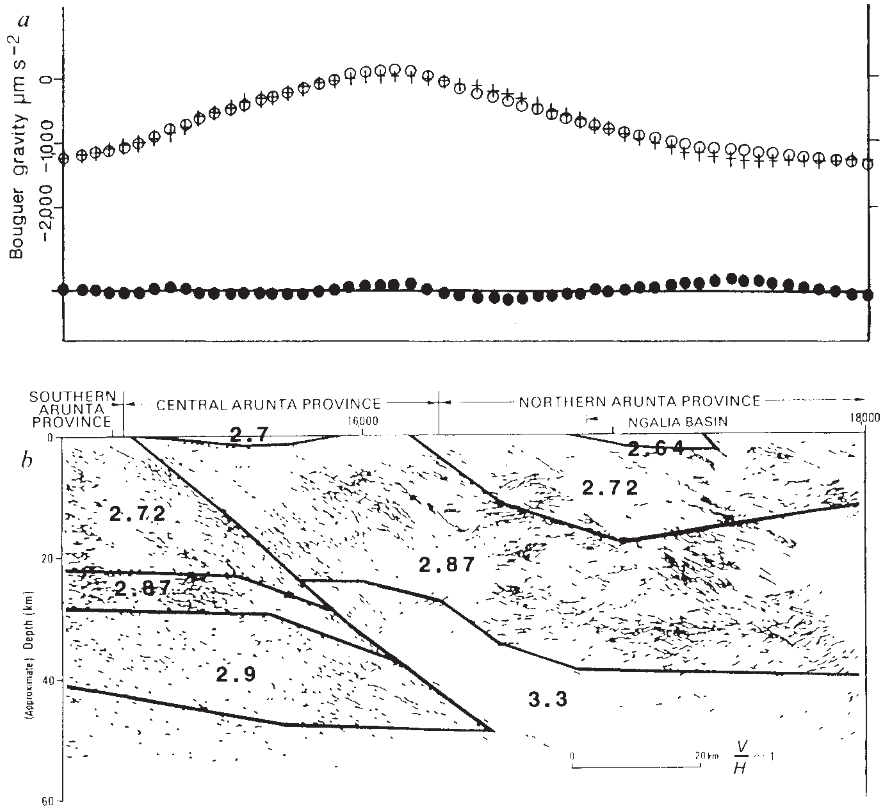

Fig. 5 *a*, Observed and computed gravity profiles along the deep seismic line. The computed profile is based on the interpreted deep-seismic-reflection model (*b*) for the Arunta Block. In *a*, crosses represent the observed profile, open circles represent the computed profile and filled circles represent the residual profile ± 150 $\mu m\ s^{-2}$. Numbers superimposed on *b* are the densities in g cm^{-3} assumed in the gravity calculations.

orogeny of eastern Autralia[25]; this suggests that the intracratonic movement may have been primarily the consequence of the lithosphere acting as a stress guide to forces operating at and shaping the plate margin some 1,000 km or more distant from the Redbank Zone[26]. The implication is that stress differences of 100 MPa and more can be transmitted by the lithosphere over distances equal to the dimensions of tectonic plates and that the evolution of intracratonic tectonic features such as basins may be driven by forces external to the area. Evidence for this can also be seen elsewhere, for example, in the relation between the tectonics of north-west Europe and the latest Cretaceous and Tertiary Alpine orogeny[27].

Once formed, stress relaxation would be expected to lead to isostatic rebound so that the area would reach some state of mechanical equilibrium. There is, however, surprisingly little evidence for major re-adjustment with time. The maximum gravity anomaly is associated with a very mild topographic low and the minimum anomaly is associated with a regional topographic high over the northern part of the basin, suggesting that some rebound has occurred[10]. At the time of the last orogenic event the area would have carried a significant topographic load created by the upthrust crust and by the synorogenic sediment loads deposited on the flanks of the thrust. A study of fission-track ages[28] and isotope evidence[9] points to a removal of up to 4 km of material from both the northern part of the Amadeus Basin and the southern part of the Arunta Block. Thus, immediately after the orogenic event, the region may have been close to isostatic equilibrium, but as erosion occurred the crust did not respond fully to the redistribution of surface loads. The probable explanation is that part of the north-south horizontal compressive force that led to the thrusting was still present after termination of the orogeny, at which time the lithosphere strengthened, locking the sub-surface structure and producing an increasingly regional response to the lateral variations in surface and internal loads[22]. We note that two major earthquake sequences occurred recently in central Australia, one to the south, in the Musgrave Block[29], and the other about 350 km north of the Ngalia Basin[30], both of which indicate that the present lithospheric stress field is one of north-south compression.

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