Seismic structure of the Yilgarn Craton, Western Australia

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The deep crustal and upper mantle structure of the Yilgarn Craton is investigated in this study using receiver-function analysis of teleseismic earthquake records from temporary stations. Two lines of stations were deployed, the main transect ran between Perth and Kalgoorlie, and a second line of stations ran across the east Yilgarn Craton 200 km to the north of Kalgoorlie. The broadband instrumentation records high-fidelity waveform data allowing the signal from the near-receiver structure to be separated from the influence of the earthquake source. The nature of the crust and upper mantle structure under each station is determined from seismic-velocity models that match the observed receiver-function waveforms and the resulting coarse-scale transect provides new, independent controls on the structure of the lithosphere. Mechanisms for the evolution of the Yilgarn Craton, previously put forward to explain surface geological and geochemical observations, and seismic velocity structure from reflection and refraction studies, may be classified as favouring: (i) predominantly accretionary lithospheric evolution; (ii) mixed accretion and other influences; or (iii) no accretionary-style influence. Characteristics of the deep seismic structure enable the evolutionary mechanism to be inferred. From the teleseismic data, we find that the seismic Moho is sharp in character under stations in the middle of the proposed terranes and more gradational near the proposed terrane boundaries. The Moho dips gently eastward and the seismic velocity of the upper mantle increases moving from west to east across the whole craton. An anomalous region exists under the Southwest terrane that shows a thick high-velocity gradient zone at the base of the crust and a Moho dipping to the west. The nature of the lateral heterogeneity in structure and its correspondence with proposed terrane boundaries suggest that accretionary processes are significant in the evolution of the Yilgarn Craton.

KEY WORDS: receiver function, seismic structure, tectonics, Yilgarn Craton.

INTRODUCTION

The evolution of the Yilgarn Craton is significant not only in the geological history of Western Australia, but also as an indicator of the processes operating near the Earth’s surface and throughout the whole mantle during the Archaean. The tectonic evolution of the craton is increasingly being described in terms of terranes (Myers & Hocking 1998), fault-bounded blocks of the Earth’s crust characterised by a geological history distinct from that of adjacent blocks (definition after Friend et al. 1988). In this work we use the word terrane to include superterrane, composite terrane and terrane group because we focus on bulk structure and not detailed stratigraphy. Thus, we examine the main tectonic elements within the craton, but acknowledge that allochthonous blocks can and do exist between the most significant bounding faults. We recognise that the interpretation of the Yilgarn Craton in terms of terranes is not universally accepted, but retain the contemporary nomenclature used by Myers and Hocking (1998) and many other authors on regional tectonic structure while also discussing alternative interpretations of observed Yilgarn Craton geological structure. Description in terms of terranes usually implies that adjacent blocks have been brought together by plate-tectonic processes, yet the significance of such mechanisms of Archaean lithospheric evolution is still a subject of debate.

In this paper, we use receiver-function methods to find the seismic-velocity structure in the crust and upper mantle between Perth and Kalgoorlie and across the Yilgarn Craton near Laverton. These observations provide an independent appraisal of the mechanisms of lithospheric evolution consistent with the broad-scale structure of the Yilgarn Craton.

Precambrian tectonics and the Yilgarn Craton

The Yilgarn Craton (Figure 1), a large body of Archaean crust comprising rocks of 3.7-2.6 Ga in age (Myers 1993) and containing important mineral reserves, has been the focus of much geological and geochemical study. The diverse literature on the structure and evolution of the Yilgarn Craton, and of Archaean provinces in general, is summarised here as favouring: (i) accretionary lithospheric evolution; (ii) mixed accretion and other influences; or (iii) no accretionary-style influence. Also included is work addressing how the Archaean lithosphere has survived so long in an environment of tectonic crustal recycling that, again, has implications for the structure of the craton.

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In a general review of Archaean geology, de Wit (1998) cited preserved relics of oceanic lithosphere, ophiolites and greenstone belts as evidence for plate-tectonic crustal evolution. In general, linear structures and lateral heterogeneity across strike should be characteristic of crust accreted at continental margins. Linear structures, however, can be the result of a sustained extensional regime and only provide an indication of an accretionary mechanism of crustal evolution if blocks with distinct geological histories are juxtaposed. Nonetheless, the inferred style of early Archaean tectonic processes differs from modern tectonic processes in that recycling of oceanic material was not the most significant contributor to the growth of continental crust. It appears from experimental work on komatiitic magma that the upper mantle, although not much hotter than the present day, was wetter and less viscous, and the dominant crustal processes were accretion and hydrothermal cooling (de Wit 1998 and references therein). Condie (2000) interpreted Archaean continental growth in terms of episodic mantle overturn and crust formation and Leitch (2001) suggested that fluctuating upper mantle temperatures, mantle overturn and oblique subduction would facilitate crustal evolution by plate-tectonic-style processes that would have given rise to reported terrane-style settings and structures (van der Pluijm et al. 1994).

The geology of the Yilgarn Craton has been interpreted in terms of terranes (Myers 1993, 1997; Myers & Hocking 1998), which is consistent with a global framework of plate-tectonic-style evolution. Figure 1 shows the terrane boundaries: the Southwest terrane, which consists mainly of granite and gneiss; the Southern Cross terrane, with surface outcrops of granite and greenstone; and the Eastern Goldfields terrane, mainly greenstone in the Kalgoorlie region. We use this work (Myers 1997) to examine the terrane model of the Yilgarn Craton at depth. Additional evidence was provided by Brown (2001) and Krapez et al. (2000) who interpreted volcaniclastic rocks in the Yilgarn Craton as related to plate-tectonic convergent margins and Barley et al. (2001) who also favoured terrane accretion in the Yilgarn Craton by plate-tectonic processes.

Nelson (1998) described the continental growth of the Yilgarn Craton in terms of a combination of processes: episodic mantle overturn with the mantle influence superimposed on the plate-tectonic processes. Some consensus exists that mantle dynamics were different in the Archaean from the present day resulting in bursts of continental-lithosphere formation. There may have been layering resulting from mineral phase changes and there may have been episodic foundering of mafic material with the descending flow driven by the conversion of mafic crust to eclogite (Davies 1995). It is likely in this case that the continents would have linear elements to their structure, but also very considerable bodies of more equal-sided geometry forming the building blocks of the lithosphere. This is provided, of course, that both styles of continental crust stand an equal chance of being preserved under the action of subsequent plate-tectonic processes.

Although there is a considerable body of evidence suggesting that the processes operating in the mantle did cause plate tectonic or early, analogous, forms of crustal evolution to take place during the Archaean, many workers have argued that plume activity (Bateman 2001; Wyman 2001), the rheology of the Archaean lithosphere and delamination of the lower lithosphere may have been dominant or at least highly significant influences on the Yilgarn and other cratons. In essence, the Yilgarn Craton could be interpreted as layered rather than amalgamated, but including large-scale thrusts and listric extensional faults. Rey et al. (2001) suggested that the Archaean crust would not have supported more than 1000 m of topography, thus, lithospheric deformation across the craton would have been more homogeneous with linear mountain belts

![Figure 1](attachment:image.png)
of minor importance. Modelling the northern edge of the Yilgarn Craton, Weinberg (2001) modelled density-driven diapirism, again suggesting that the Archaean crust was softer than it is today. Chen et al. (2001) favoured east–west shortening and the forcing of granitoid blocks into greenstone, resulting in arcuate structures in plan view and vertical contacts, whereas Qiu and Groves (1999) concluded that continental–continental collision and lithospheric delamination were associated with gold emplacement. Zegers and van Koken (2001) also suggested that delamination (non-plate tectonic) processes, which would result in sudden uplift and magmatism, were significant, whereas Fagan (2001) presented the structures in the Yilgarn Craton as the result of obduction. In most of the above cases, i.e. advocating crustal-evolution methods other than a proto-plate-tectonic mechanism, the dominant seismic structure would be layered and laterally homogeneous with no sense of large-scale linear features, although some lateral heterogeneity could exist in the form of diapiric or block-shaped bodies.

The question of how the remnants of Archaean crust that we observe today have been modified, or indeed how they come to be preserved, is important in interpreting the deep seismic structure. Chen et al. (2001) and Dalstra et al. (1999), and references therein, described deformation in the Yilgarn Craton from a structural and metamorphic geology perspective, respectively. It is clear that any major structures in the Yilgarn Craton could be related to transpression episodes or to differential uplift of different components of the craton lithosphere. O’Reilly et al. (2001) discussed the preservation of lithosphere in several Archaean cratons. Archaean subcontinental lithosphere is buoyant in comparison to the asthenosphere and, thus, less susceptible to delamination than the less buoyant Phanerozoic lithosphere (Poudjom Djomani et al. 2001) and, therefore, preferentially preserved. However, Archaean lithosphere could have been disrupted in extensional situations (O’Reilly et al. 2001). Sylvester (2001) pointed out that the preserved record of Archaean crust is biased to periods when thick komatiite–harzburgite oceanic lithosphere formed and low-density harzburgite was added to the base of the cratons. If there were no harzburgite roots, then the lithosphere has probably been recycled or reworked.

Seismic velocity structure of the Yilgarn Craton

Dentith et al. (2000) interpreted seismic-refraction data from several lines crossing the Yilgarn Craton. They found (in common with earlier work such as Drummond 1988) that the overall structure is similar to shield areas elsewhere, with a two-layer crust at an average thickness of approximately 35 km, but that significant lateral variations in velocity structure exist, including a high-velocity zone in the lower crust corresponding to a suggested terrane boundary. This updates the older interpretation of Drummond (1988), who had concluded that the seismic signature of the crust favours Proterozoic provinces forming across and reworking older crust (and hence did not support tectonic models involving lateral accretion).

Some older seismic-refraction data (Mathur 1974) was also included in the analysis by Dentith et al. (2000). Wilde et al. (1996) also found evidence for structures likely to be related to terrane accretion in a west–east reflection seismic traverse north of Perth, and extrapolated the terrane boundaries through the southwest Yilgarn Craton. A wealth of geophysical data exists for the Kalgoorlie region. For example, Goleby et al. (2000) and Drummond et al. (2000) reported on an experiment investigating detailed crustal structure and fluid flow in the Eastern Goldfields. Of particular note is the clearly defined Ida Fault, the boundary between the Southern Cross and Eastern Goldfields terranes, which dips at a low angle, extending approximately 50 km under the surface expression of the Eastern Goldfields.

Whitaker (2001) identified magnetic domain boundaries in the Western Australian lithosphere and pointed out that some of the geological boundaries show no corresponding feature in the magnetic basement. Comparing the magnetic anomaly map of Western Australia (Mackey et al. 2000) and the detailed magnetic anomaly map of the Yilgarn Craton (Whitaker & Bastrakova 2002) with the summary geological map (Myers & Hocking 1998) allows a critical appraisal of the validity of extrapolating some of the geological lineations. Across the Yilgarn Craton from Perth to Kalgoorlie, the Southwest magnetic domain corresponds approximately to the Southwest terrane, but the region near the boundary between the Southwest and Southern Cross terranes is allocated a magnetic domain of

Figure 2 Origin of a receiver function from a teleseismic earthquake. Rays approach a receiving station and pass through an interface, h, such as the Moho. The direct Pp-wave is the first arrival, followed by Ps, the wave that converts to a slower, S mode propagation at the Moho, and multiples such as PpPhs (simplified from Ammon et al. 1991).
its own, the Toodyay – Lake Grace domain. The eastern boundary of the Southern Cross terrane, the Ida Fault, does not coincide with the eastern boundary of the magnetic domain of the same name. Further differences exist between magnetic domains and terrane boundaries in the Eastern Goldfields region.

A general review of the seismic structure in the mantle beneath Australia, deduced using teleseismic earthquake data, was given by Kennett (in press) and a review of the insights gained through the analysis of surface waves was given by Debayle and Kennett (in press). These papers summarise nearly a decade of experiments carried out using portable broadband seismic instruments to record earthquakes from the active plate margins of the southwest Pacific and further afield. The lithosphere beneath Australia was found to be at least 210 km thick in the cratonic region of Western Australia and characterised by fast seismic wave speeds (in contrast, the lithosphere under the Phanerozoic outcrops on the eastern side of the Australian continent is less than 140 km thick). The surface-wave results suggest heterogeneity in the mantle within the high wave-speed zones. Crust and upper mantle structure was determined on a broad scale across Australia by Clitheroe et al. (2000), who determined receiver functions from earthquakes recorded at widely spaced, portable broadband stations, finding the 1-D crustal velocity structure beneath each station. This allowed the depth and nature of the Moho to be mapped on a very coarse scale across the continent.

**Seismic structure from receiver functions**

A receiver function is the part of the recorded waveform that is generated by the interaction of earthquake energy with layered substation structure. This may be extracted from the digitally recorded 3-component broadband seismic record (Ammon et al. 1991) of earthquakes at a suitable distance 30–90° from the station. At greater than 30° epicentral distance, the earthquake signal arrives at a steep angle under the station and, as far away as 90°, can still have sufficient energy for receiver effects to be seen above expected noise levels. The steep angle of the incoming wave results in direct P-wave energy from the source being recorded predominantly on the vertical component. The next arrival is a Ps-wave, converted to S-wave propagation at the Moho under the receiver (Figure 2), and mostly recorded on the horizontal components. Deconvolving the radial (horizontal) signal with the vertical isolates the effects of the near-receiver structure. It is often possible to see energy from

Figure 3  Stacked receiver functions from the WT line of seismic stations. Records from WT02, WT03, WT04, WT05 and WT06 are composite receiver functions from 11 stacked events, and records from WT08, WT09 and WT10 are stacked receiver functions from 10 events.
multiple, receiver-side reflections such as PpPhs (see Ammon et al. 1991 and Kennett 2002 for a more complete description).

The structure is determined by finding a seismic-velocity model that produces a synthetic waveform that matches the observed receiver function isolated above. The relationship between parameters of the velocity model and receiver waveform can be very non-linear and non-unique (Ammon 1990). Inverse methods, which search the model space without the use of partial derivatives are, therefore, most suitable. Shibutani et al. (1996) and Clitheroe et al. (2000) used a genetic algorithm to invert the receiver function, recovering not only the S-wave velocity but also layer thickness and the $V_p/V_S$ ratio. In this paper, we use an inversion approach, the neighbourhood algorithm (Sambridge 1999), to find the crust and upper mantle velocity structure that fit the observed receiver function waveform. Genetic algorithms and the neighbourhood algorithm used in this study seek to guide the search for models that fit the data by using previous models for which the forward problem has been solved, and the misfit to the data calculated. The more promising regions of the solution space are examined in much greater detail than those which contain solutions with a poor fit to the data. The neighbourhood algorithm searches the parameter space more efficiently than the genetic algorithm and also samples the parameter space more evenly.

The strength of the receiver-function methods lies in the relative ease with which basic parameters, such as Moho depth and 1-D velocity structure, can be found across a wide geographical area. Provided a suitable earthquake source region exists, a coarse-scale crustal structure can be found using a modest number of stations with no need for the effort and expense of active source experiments.

Although further from the seismic activity of the south-west Pacific rim than the north and east of the continent, energy from the larger earthquakes is sufficiently well recorded in Western Australia to use receiver-function techniques. Such techniques can be limited by dipping interfaces between layers of differing seismic velocity (Cassidy 1992) and by velocity and depth trade-offs, discussed later in the context of the structure of the Yilgarn Craton. In the work described in this paper; modelling seismic velocity by fitting receiver functions from new more closely spaced lines of stations allows deep crustal and upper mantle structure to be determined, in a simple and cost-effective manner; across the whole craton.

**DATA AND METHODS**

The WA CRATON experiment in which broadband seismic stations were deployed throughout Western Australia follows on from the SKIPPY deployments (van der Hilst et al. 1998; Kennett in press) with the aim of improving the resolution of seismic structure by several different surface- and body-wave methods. This part of the Australian continent is furthest from the earthquake sources of the Pacific margin, running to the north and east of Australia and was relatively undersampled by source-receiver paths from previous deployments. In addition to the widely spaced stations appropriate for the determination of deep structure, WA CRATON included two lines across the Yilgarn Craton (this paper) and one between the Pilbara and the Yilgarn (Reading & Kennett 2003) Cratons in which the stations were more closely spaced. The station locations across the Yilgarn Craton, the WT and WV lines, are shown in Figure 1.

**Figure 4** Stacked receiver functions from the WV line of seismic stations. Records from WV01 and WV05 are single-event receiver functions and those from WV02, WT03, WT04 and WV06 are stacked receiver functions from five events.
The WT recorders were deployed for approximately 7 months between October 2000 and April 2001. Receiver functions from 10 or 11 selected earthquakes recorded at each station were calculated by deconvolving the radial component with the vertical component (Shibutani et al. 1996) and stacking, which enhanced the signal to noise ratio (Figure 3). Station WT07 malfunctioned and no data are available from this site. Most of the stacked receiver functions from the stations of the WT line show energy, Ps, due to mode-conversion at the Moho at just less than 5 s after the P arrival; some stations (e.g. WT02, WT05, WT10) show the whole-crust multiple, PpPhs, at approximately 11 s after P (Figure 3).

The WV recorders were in place for a shorter time, approximately 3 months between May 2001 and July 2001. Receiver functions from five of the best recorded earthquakes are calculated and stacked for each station (Figure 4), with the exception of WV01 and WV05 where only one event is available at each station. The stacked records are noisier, but a clear Moho arrival is observed at station WV02 and is also discernible at station WV06. It is possible to invert for structure using a receiver function from a single earthquake, but the signal to noise ratio is poorer than from a receiver function derived from stacked records from several earthquakes. At WV01, reverberant structure (discussed later) made the remaining four recorded receiver functions unusable, whereas at WV05, equipment failure led to a reduced number of earthquakes being recorded. Data from WV07 are unavailable at the time of writing because of a technical problem.

The stacked receiver function from each station is matched to a best-fit synthetic receiver function for a 1-D wave-speed model by searching many possible crustal models using the neighbourhood algorithm (Sambridge 1999). For each crustal model searched, a synthetic receiver function and its misfit to the observed receiver function for that station is calculated. The final model is the model that produces the synthetic with the lowest misfit to the observed waveform.

Figure 5 Annotated velocity structure plot for station WT04. (a) The observed (solid) and best-fitting synthetic (dashed) receiver-function waveforms. (b) The seismic-velocity model corresponding to the best-fitting synthetic (black), plotted together with the ensemble of models searched in the course of the neighbourhood algorithm inversion. The white line is a reference model, showing the velocity profile for ‘typical’ continental crust with a Moho at 38 km, and is shown only to aid comparison between models on different plots. The lines to the left of the model plots indicate the ratio between P and S wave velocity through the profile; the dark line indicates the best-fitting model and the light line is a reference profile. The location of the P to S wave conversion at the Moho (P$_{MS}$) is indicated on the receiver-function traces.
RESULTS

By looking at the observed receiver functions (Figures 3, 4), it is possible to make some preliminary remarks about the character of the Moho and deep crustal structure under the Yilgarn Craton. The Moho under stations WT02, WT03 and WT04 becomes increasingly sharp, moving from west to east across the Southwest terrane, but is more gradational or disrupted under stations WT05 and WT06, which are close to major fault boundaries. Data from station WT08, in the middle of the Southern Cross terrane, show a particularly high-amplitude Moho conversion indicating a sharp interface, but those from WT09, in the west of the Eastern Goldfields terrane, reveal a disrupted Moho arrival. Data from WT08, in the central Eastern Goldfields terrane, show a clear Moho conversion. The structure under station WV01 is very reverberant, and only one good receiver function was calculated. The nature of the Moho is unclear because the single record is noisy. At station WV02, in the centre of the Southern Cross terrane, the strong Moho conversion is analogous to that observed at WT08 and the disrupted Moho arrival at WV03 (and WV04) is similarly analogous to WT09, both at the western margin of the Eastern Goldfields terrane and affected by the eastward dipping Ida Fault. There is a suggestion of converted energy from the Moho under station WV05, and the Moho conversion is discernible at WV06, corresponding to that seen at WT010, although smaller in amplitude.

Figures 5–8 present the results of the receiver-function inversions at the different receiver stations. In the left-hand panel for each station the observed receiver functions are displayed as a solid line and the synthetic trace derived from the best-fitting model as a dashed line. The right-hand panel shows the results of the neighbourhood algorithm inversion in velocity space. As in the work of Shibutani et al. (1996) and Clitheroe et al. (2000), the model was parameterised in terms of six zones of velocity gradients with the possibility of discontinuities at the boundaries. The inversion is carried out in terms of 24 parameters, the Vs values at the top and bottom of the gradient zone, the thickness of the gradient zone and the Vp/Vs ratio for the zone. The calculations of receiver functions are made with a stair-step representation of the gradients and these are what are plotted in the figures. The Vs velocity distribution is better constrained by the inversion of the receiver

Figure 6 Best-fit models of the upper lithosphere beneath stations WT03 and WT04 in the Southwest terrane, WT05 at the eastern margin of the Southwest terrane and WT06 in the Murchison terrane. See Figure 5 for a description of the plots.
functions than the Vp/Vs ratio. In the right-hand panel the full set of models tested are displayed and the thin black lines represent the envelope of sampling in Vs. The 1000 models with the best fit to data are indicated by progressively darker tones of grey. The model with the least misfit found is shown in black superimposed on the ensemble of velocity distributions. A constant reference model representing a ‘typical’ continental crust derived from the study of Clitheroe et al. (2000) at the stations in the SKIPPY deployment is shown in white. The Vp/Vs ratio for the best-fitting model is displayed in black and the corresponding reference curve in light grey.

In Figure 5 we show the results for station WT04 where there is a relatively tight constraint on the character of the crustal Vs distribution from the consistency of the better fitting models. The incident P pulse and the P to S conversion at the Moho Ps are marked on the receiver-function traces that show a good match between the synthetic and the observations.

Figures 6–8 group representative WT and WV stations by their relationship to the terranes. Figure 6 includes the stations from the western terranes, Figure 7 shows stations crossing the transition from the Southern Cross terrane to the Eastern Goldfields terrane and Figure 8 the two stations (WT10, WV06) in the west of the Eastern Goldfields terrane. In the following discussion the results are based on a combination of the best-fitting model and the other models with similar levels of fit. Unless otherwise stated, all depths given are determined with an accuracy of ±1 km. In Figure 9 we display all the velocity profiles derived from the modelling, together with their locations with respect to the terrane boundaries.

Beneath station WT02 the Moho is diffuse and the velocity structure only weakly constrained. Moving east to stations WT03 and WT04 (Figure 6), the Moho becomes progressively sharper, accounting for the higher amplitude arrival at WT04. It also becomes shallower, with the base of the high velocity-gradient zone (HVGZ) at around 40 km depth (WT02) in the west and at 36 km further east (WT04). These stations all lie in the Southwest terrane. Station WT05 (Figure 6) also lies in the Southwest terrane, but closer to the mapped boundary (Myers & Hocking 1998) with the Murchison terrane (the Koolanooka Fault). Under station WT05, the Moho is gradational with the base of the

Figure 7 Best-fit models of the upper lithosphere beneath stations WT08 and WT09, located either side of the Ida Fault: WT08 is in the Southern Cross terrane and WT09 in the Eastern Goldfields terrane. Stations WV02 and WV03 are located in a similar position with respect to the Ida Fault: WV02 in the Southern Cross Terrane and WV03 in the Eastern Goldfields terrane and show similar features to WT08 and WT09, respectively. See Figure 5 for a description of the plots.
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HVGZ at a depth of 40 km. Beneath station WT06 (Figure 6), in the Murchison terrane but close to the Kawana Fault, the Moho is similarly gradational, with the depth to the base of the crust at 38 km. The lack of data from station WT07 is unfortunate given the jump to a very sharp Moho discontinuity, at a depth of 37 km, under WT08 (Figure 7). It would appear that for the Southern Cross terrane the Moho tends to become more sharply defined moving from east to west, with only a slight change in depth, as can be seen from comparison of the results at WV01, WT08 and WT02.

The clear contrast between the character of the Moho beneath stations WT06 and WT09 (Figure 7)—with the latter showing a very indistinct Moho and discontinuities

Figure 8 Best-fit models of the upper lithosphere beneath stations WT10 and WV06, located in the Eastern Goldfields terrane. See Figure 5 for a description of the plots.

Figure 9 Synthesis of models derived from teleseismic earthquakes across the Yilgarn Craton lithosphere. The dark lines are the best-fitting models derived in this study and the light lines show a reference velocity profile for ‘typical’ continental crust. The Moho is interpreted to be the base of the high-velocity gradient zone, shown in mid-grey shading. See Figure 1 for the locations of the interpreted sections A–A’ (WT line) and B–B’ (WV line). SW, Southwest terrane; SC, Southern Cross terrane; EG, Eastern Goldfields terrane; Koo, Koolanooka Fault; Kaw, Kawana Fault; Ida, Ida Fault.
throughout the lower and upper crust—is consistent with crossing the Ida Fault into the Eastern Goldfields terrane. A similar contrast is observed further north between stations WV02 and WV03 (Figure 7). It is likely that the Ida Fault dips under the surface expression of the Eastern Goldfields terrane as far as station WT09 (Drummond et al. 2000). The disrupted Moho arrival observed at station WV03 suggests that the deep Ida Fault extends north as far as WV03. The Moho under station WV02, at 41 km, is a little deeper than under WT06. For both stations WT09 and WV03 the character of the observed receiver function requires the presence of a low-velocity layer in the upper crust.

Station WT10 (Figure 8), located within a highly mineralised and complex terrane but well away from the main terrane boundary, lies over a sharp Moho at a depth of 40 km. Further north, station WV06 (Figure 8) is also located in the centre of the Eastern Goldfields terrane and shows a Moho depth of 41 km. Data from station WV06 show a smaller velocity contrast than at WT10; the velocity structure is not well constrained by the inverse process in this case.

There is little variation in the depth to the Moho estimated in the inversions from the Southern Cross and Eastern Goldfields terranes (40 ± 2 km), but the observed receiver functions indicate a noticeable difference in the timing of the Ps conversion that is compensated by changes in the crustal velocities. The Moho arrivals observed at stations WT08 and WV02 (Southern Cross terrane) occur at around 4.5 s, with WT10 (Eastern Goldfield terrane) at just less than 5 s. Moving east across the Eastern Goldfield terrane, the crust becomes slightly deeper, with the Moho arrival observed at station WV05 (Figure 4) at approximately 4.7 s. At station WV06, the trend is continued with the Moho arrival observed at approximately 5.0 s. Some shortcomings are apparent in the fit between the synthetic and observed receiver functions: at stations WT05, WT06, WT08 and WT10 the amplitude of the synthetic Moho arrival is too low; this is discussed in a following section.

In general, the crustal velocities modelled are fairly high (WT02, WT03, WT05, WT06, WT09, WT10) with only WT04 anywhere near the reference model for typical continental crust, and WT08 a little faster than the reference model. Upper mantle S-wave velocities are approximately 4.6 km/s under the Southwest terrane, rising to 4.8 km/s under the Southern Cross terrane and 4.9 km/s under the Eastern Goldfields terrane.

DISCUSSION

In general, our data show that the seismic Moho is sharp away from terrane boundaries and more gradational in character close to terrane boundaries. The presence of a transition zone at the crust–mantle boundary, rather than a sharp Moho, could be due to the inclusion of high-velocity material between the terranes or scattering from deep fault surfaces. Under the Eastern Goldfields (Drummond et al. 2000; Goleby et al. 2000), the gradational Moho under station WT09 corresponds to the shallow angle Ida Fault reaching the Moho beneath WT09. This is also inferred to be the case for the gradational Moho observed under station WV03. A similarly angled, eastward-dipping structure is a feature of the Southern Cross terrane throughout the crust (Goleby et al. 2000).

The gradational Moho under stations WT05 and WT06 corresponds to the Toodyay – Lake Grace magnetic domain (Whitaker & Bastrakova 2002), which consists of regionally aligned, compositionally banded gneiss. Further west in the Southwest terrane, the Southwest magnetic domain has less compositional banding attributable to gneiss (Whitaker 2001; Whitaker & Bastrakova 2002). Although the mapped features from the aeromagnetics are in the shallow crust there is the possibility that the deeper crust may be similarly divided, being subject to some of the same influences on its evolution.

Wilde et al. (1996), including the work of Myers (1993), discussed the implications of terrane assembly in the Yilgarn Craton. They placed a significant terrane boundary running northwest–southeast close to station WT02. The WT line is just too far north to see whether this boundary is observed in the structure of the deep crust. In the same discussion, the juxtaposition of rocks showing high-grade regional metamorphism with those showing little of the same influence is cited as evidence of terrane-style assembly of the craton. The strong positive gravity anomaly (Murray et al. 1997) that exists at the western margin of the Yilgarn Craton corresponds to the deeper Moho suggested in the results of Clitheroe et al. (2000) and seen clearly in the crustal models determined from the receiver functions under stations WT02 and WT03. In this vicinity, the upper mantle has a lower seismic velocity than further east. In comparison with the results of Dentith et al. (2000) we find the Moho, defined as the base of the high-velocity gradient zone, to be slightly deeper at 38–40 km, except in the southwest. The high-velocity zone reported by Dentith et al. (2000) in the Corrigin region falls south of the WT line, and adds to the sense of lateral heterogeneity in the deep crust.

If accretion is seen as the physical juxtaposition of regions of crust, colliding by movement across the Earth’s surface, the lateral variation in Moho character across the Yilgarn Craton adds to the body of evidence suggesting that accretionary processes have had an important role in the evolution of the craton. Crust-building processes, such as large-scale diapirism (Weinberg 2001), could also produce marked lateral variations in Moho character, but would be associated with widespread regional metamorphism and vertical contacts in the place of terrane boundaries. While a more easily deformed crust would be subject to considerable gravity-driven influences, accretion appears to be the dominant structural control.

The variations in upper mantle seismic velocity found from the receiver-function analysis are consistent with the accretion mechanism of crustal evolution. O’Reilly et al. (2001) remarked that, in general, steeply dipping terrane boundaries exist and that crustal terranes carry their own lithospheric keel into the amalgamation of the craton, which is supportive of our findings. The higher buoyancy of lithosphere with harzburgite roots provides a mechanism by which Archean lithosphere, or at least a small proportion of it, may be preferentially preserved. Western Australia shows a strong, fast, shear-wave-speed anomaly in the mantle down to at least 200 km, the root of the craton,
distinct from the Proterozoic basement of central Australia (Kennett 2003).

One shortcoming in the process of inverting the receiver function for seismic velocity structure is the influence of the initial P pulse on the fit of the waveform. Although the Moho region is well modelled, the relatively subtle waveforms defining the shallow crust (just after the P arrival) and the upper mantle (just after the Moho arrival) can be ignored by the inversion routine in favour of matching the much larger P arrival. Some of the structure that is discernable by a practised eye from the receiver functions themselves is not always reflected in the modelled velocity profiles, and some of the details of the profiles in Figure 9 are less well constrained. Maximising the information that can be extracted from receiver-function waveforms is also the subject of continued work.

Our results are derived from two lines of stations perpendicular to the main lineations in the craton, one only of which crosses the entire craton. A new deployment of seismometers is directed towards extending the WV line across the whole craton and to provide links between the two east–west lines.

CONCLUSIONS

The variation in seismic structure determined from teleseismic receiver functions, especially the lateral variation in the nature of the seismic Moho, suggests accretion as a significant mechanism for the assembly of the Yilgarn Craton lithosphere. The accretion hypothesis is consistent with evidence from magnetic domains, patterns of metamorphism and recent interpretations of seismic structures found using active source methods. The likely accretionary history is consistent with terrane-style seismic structures found using active source methods. The likely accretionary history is consistent with terrane-style models of Yilgarn Craton structure, although there is still considerable ambiguity in the way in which terrane boundaries at the surface might be reflected in structure deeper in the crust.

Receiver-function methods have here proved a relatively low-cost way of finding the coarse-scale structure of the crust across a large region. Further similar experiments have the potential to address some remaining questions regarding terrane boundaries and deep geological structure and are especially valuable in regions with limited surface exposure. Receiver-function methods may also be considered as a good, economical, preliminary investigation method before major active source seismic experiments.

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