

The deep seismic structure of Precambrian terranes within the West Australian Craton and implications for crustal formation and evolution

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Abstract

The deep crustal structure across the West Australian Craton has been determined using receiver function analysis of broadband records from temporary seismic stations. These stations were deployed in a series of experiments using both widely-spaced station configurations and denser coverage in the form of lines/groups of stations. Data from the permanent stations, MBWA and NWA0, were also included. The improved coverage that is obtained from the combined deployments allows investigation of deep seismic structure over the whole craton at a resolution greater than the scale of the main terrane groups. We are thus able to investigate the variations in structure across the West Australian Craton in terms of craton assembly and crustal evolution.

We find remarkable consistency of structure within several of the individual Precambrian terranes, most notably the Pilbara, Murchison and Southern Cross. These terranes are underlain by a sharp seismic Moho. We also find significant contrasts in structure between neighbouring terranes, such that several of the major tectonic units have a velocity profile that is a signature of that terrane or terrane group. The structure beneath orogenic belts is often less characteristic and shows a less pronounced seismic Moho. It has been suggested that a very high degree of crustal reworking will produce a felsic lower crust, with a reduced seismic velocity. This increases the velocity contrast across the Moho, producing a very sharp discontinuity. These findings suggest that the seismic structure of Precambrian crust is fixed early in tectonic history, before craton assembly, and preserved through terrane accretion and the subsequent collision of the elements forming the West Australian Craton. We confirm that receiver function methods can be used to delineate the extent of Precambrian terranes in regions where geological exposure of the surface is limited and provide an effective alternative to active source seismic techniques for deep crustal targets.

Keywords: Seismic structure; Receiver function; Yilgarn; Pilbara; Craton; Western Australia

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1. Introduction

For the first time, sufficient coverage of high-fidelity broadband seismic stations exists to undertake a comprehensive survey of crustal thickness and seismic velocity structure across the West Australian Craton at the scale of the main terrane groups. Defining a ‘terrane’ as *a fault-bounded, tectonostratigraphic block with a history distinct from that of adjacent terranes* (Friend et al., 1988), we confine our survey to larger scale crustal architecture and will shorten the terms ‘superterrane’ and ‘terrane group’ to ‘terrane’ with the understanding that allochthonous units may also exist within.

1.1. Tectonic framework of the West Australian Craton

The West Australian Craton is composed of the Pilbara and Yilgarn Cratons. They are themselves made up of allochthonous terranes (Myers and Hocking, 1998; Hickman, 2004; Dentith et al., 2000) and were joined through Paleoproterozoic orogenesis including the Capricorn Orogeny (Cawood and Tyler, 2004) to form the West Australian Craton by 1.8 Ga (Betts et al., 2002).

The Pilbara Craton is a well-exposed block of granitoid-greenstone and metasedimentary rocks of ages from 3.52 Ga (Buick et al., 1995; Barley, 1998). The granite-greenstone terrane (GGT) exhibits a dome-and-basin geometry that is likely to have been caused in part by gravity-driven processes in the Eastern Pilbara (Van Kranendonk et al., 2004) and may have extensively recycled crustal material (Green et al., 2000). The West Pilbara has no dome structures and was arguably formed under a contrasting tectonic regime (Hickman, 2004). By

3.2 Ga, the Pilbara Craton was a coherent block and was modified in a series of subsequent extensional and compressive events that can be correlated across the Pilbara Craton after this time (Blewett, 2002). The Hamersley successions across the southern Pilbara consist of metamorphosed sediments including those of a glaciogenic origin of ages up to 2.45 Ga (Martin, 1999) that overlie Archaean basement.

The Yilgarn Craton is one of the largest areas of Archaean crust on Earth. The Narryer Terrane to the northwest contains the oldest rocks of the craton, gneiss of ages up to 3.7 Ga (Betts et al., 2002). In the central Yilgarn, the Murchison and Southern Cross Terranes are granite-greenstone belts up to 3.0 Ga, bounded by major, linear strike-slip faults. The Eastern Goldfields Terrane (Myers, 1997) contains slightly younger greenstones up to 2.7 Ga while the Southwest Terrane, mostly gneiss of a similar age, is notable for its lack of greenstone. Although a subject of controversy, it is probable that the assembly of these terranes to form a crustal block took place dominantly by a process of accretion in an early plate-tectonic setting (Wilde et al., 1996). Geochemical evidence (Krapez et al., 2000) points to the *tectonic severance* of many of the source terranes for Yilgarn metasedimentary sequences and suggests large-scale recycling of a diverse range of crustal material. It also seems likely that global-scale overturn in the Earth's mantle occurred during the Late Archaean providing a strong intrusive component (Nelson, 1998). There is considerable evidence for regional-scale shortening in an east-west direction and other deformation and metamorphism (Chen et al., 2001, Dalstra et al., 1999). Therefore both plate-tectonic-style and, to a lesser extent, diapiric processes must be considered in forming the crust of the Yilgarn Craton.

The Capricorn Orogen which joins the Pilbara and Yilgarn Cratons is now recognised as deriving from a series of Palaeoproterozoic events (Cawood and Tyler, 2004) with distinct major pulses of deformation taking place from 2.2 Ga, 2.0 Ga (the Glenburgh Orogeny), 1.8 Ga (the Capricorn Orogeny) and 1.6 Ga. The morphology of the Orogen is varied including large-scale shear-zones and thrusts along the margin of the southern Pilbara, indicating an oblique continent-continent collision (Tyler and Thorne, 1990). Along the margin of the northern Yilgarn the surface geology is diverse including high-grade metamorphism and

syntectonic granite emplacement in the Narryer Terrane (Occhipinti et al., 1998). The Glenburgh Terrane to the north of the Narryer, consists of a small allochthonous block which collided with the Yilgarn during the Glenburgh Orogeny (Occhipinti et al., 2004, Kinny et al., 2004). In the centre of the northern Yilgarn margin, a number of basin formations have been identified including the Yerrida, which overlies the Archaean basement and the Bryah, with evidence for back-arc spreading and rifting (Pirajno and Occhipinti, 2000). Deformation on the northern margin of the Yilgarn may have extended well into Mesoproterozoic (Reddy and Occhipinti et al., 2004): much later than previously thought. A large part of the central Capricorn Orogen is overlain by the Mesoproterozoic Bangamall Basin (Cawood and Tyler, 2004).

1.2 Previous investigations of seismic structure

In a summary of early reflection/refraction seismic work across the West Australian Craton, Drummond (1988) characterises the Archaean Cratons as having a two-layered crust, 25-35 km thick, with a distinct Moho. In the Pilbara Craton, the mid-crustal discontinuity is reported at 14 km deep and there is an increase in velocity through the lower crust (Drummond, 1983). Wellman (2000) uses gravity and magnetic anomalies to deduce the 3D geometry of the granite-greenstone terrane finding that the bodies responsible for the anomalies (thought to contain a small proportion of banded-iron formation) are a good match to models of dome-shaped structures with a base at 14 km. Drummond (1988) finds that the crust beneath the Orogens is much thicker at 45-50 km and is multi-layered with a less-distinct Moho. Reflection/refraction seismic work in the Yilgarn Craton (Dentith et al., 2000) finds the southwest Yilgarn to have a crustal thickness of 35 km with a two-layered structure. A short reflection traverse across the north of the Southwest Terrane and just into the Murchison Terrane was carried out in 1992 (Wilde et al., 1996). This showed a nearly 40 km thick crust with a three-layered structure, dipping gently to the east. Further east, in the Eastern Goldfields, a seismic traverse took place in 1991 (Drummond et al., 2000) with a more detailed campaign following in 1999 (Goleby et al., 2000). Both campaigns focussed on

structure in the upper few km. Collins (2003) provides a recent summary of active and earthquake source determinations of crustal structure across Australia showing the variability of structure within the Pilbara and Yilgarn Cratons as a whole.

Earthquake seismological investigations of the structure of Australia moved forward significantly in the 1990s with the deployment of high quality temporary broadband station sets associated with the SKIPPY experiment (Kennett, 2003). Data from these stations and later experiments has been used to construct tomographic models of the deep lithosphere using the (lower frequency, later arriving) surface-waves (Fishwick et al., 2004). The higher frequency, first arriving body-waves may be used to deduce the crustal structure beneath the receiving station using receiver function analysis (described in a later section). Clitheroe et al. (2000) made the first comprehensive determination of receiver function structure across Australia and produced a map of the Moho depth and character across the continent. In the late 1990's, a more detailed set of seismic deployments was carried out in WA including broadband station transects across the Yilgarn (Reading et al., 2003a), and from the Pilbara across the Capricorn to the Yilgarn (Reading and Kennett, 2003 and Reading et al., 2003b). These transects had a much smaller station spacing and allowed the seismic structure of the crust to be related to surface terrane boundaries for the first time. Results from these stations are included in the later synthesis and discussion and are not repeated here.

Earthquake seismic methods of determining the structure of the lithosphere show that there is a broad correlation between continent-scale surface geology and seismic velocity anomalies in the mantle beneath Australia (Kennett, 2003 and Fishwick et al., 2004) however there are many places where there is no obvious relationship between surface tectonic structure and more detailed seismic velocity anomalies within the lithosphere. On a crustal scale, the idea of a correlation between terrane architecture and seismic velocity structure was developed by Reading et al. (2003a). Recordings from more densely spaced stations are now available from across a large part of the West Australian Craton to investigate this correlation more thoroughly.

In this paper, crustal depth and seismic structure are investigated in the context of the surface tectonic boundaries. The consistency of structure within each terrane is examined together with contrasts in structure between terranes; thus providing constraints on the creation and evolution of ancient continental crust.

2. Data and Methods

The WR-deployment used Guralp ESP3 and Streckeisen STS-2 broadband sensors - instruments that show an excellent longer period response. The WP-deployment stations mostly comprised Guralp 40T sensors. These have a slightly more limited broadband response but nevertheless also produce a high-fidelity waveform that is very suitable for receiver function work. Figure 1 shows the locations of all stations discussed in this work. The locations of the new structure determinations are shown in dark grey. Stations of the temporary WT, WS and WV lines (mostly Guralp 40 T sensors) are shown in pale grey while permanent and SKIPPY deployment stations (mostly Guralp ESP3 and Streckeisen STS-2 sensors) are shown in white. Structure beneath these stations has been published in earlier work (Reading et al., 2003a; Reading and Kennett, 2003; Clitheroe et al., 2000) and these findings have also been included in the synthesis of results and following discussion.

The WR deployment took place in two stages. Stations WR01 to 07 were deployed between July 2000 and February 2001 and stations WR08 to 11 were deployed between October 2000 and June 2001. During the whole recording period, approximately 120 earthquakes (magnitude greater than $m_b=5.5$) occurred at a suitable epicentral distance for receiver function analysis ($30^\circ < \Delta < 80^\circ$). Of these, approximately 38 were recorded with a sufficiently good signal-to-noise ratio to be used in the work. Figure 2a shows the source-receiver paths into an example station, WR06. Events occur mainly in the southwest Pacific region, especially the Philippine Islands, Papua New Guinea, Vanuatu, Fiji and the Tonga-Kermadec trench. This represents a spread of azimuths over 180° with only a couple of events occurring to the West of Australia.

The WP deployment took place in four stages. Stations WP01 to 14 were deployed between November 2002 and February 2003; stations WP15 to 18 between March 2003 and July 2003; stations WP25 and WP26 between August 2003 and December 2003; and stations WP27 to 31 between December 2003 and February 2004. During these time intervals, respectively, 8, 19, 9 and 16 events were recorded with suitable magnitudes, epicentral distances and signal-to-noise ratios for receiver function work. Figure 2 shows the source-receiver paths into example stations WP11, WP15, WP 25 and WP 27. As with the events recorded during the WR deployment, the azimuth spread is reasonable over 180° with events from the region around Papua New Guinea dominant.

The principles of the receiver function approach and the methods used to calculate the waveforms used in the modelling of structure were described by Reading et al., 2003a. A more general description is given by Stein and Wysession 2003. In summary, the signal due to the structure beneath the receiving station is extracted from the 3-components of the digital broadband record by deconvolving the vertical component with the horizontal component in the radial (source-to-receiver) direction (Ammon, 1991). Receiver functions were calculated in this way according to the method of Shibutani et al., 1996. The calculated receiver functions are stacked for each station, further reducing noise and enhancing the signal due to the receiver structure. Inherent in this approach is the assumption that the structure beneath the station may be approximated by a 1-D layered structure such that energy from all azimuths produces the same receiver waveform. Small departures from this assumption in the form of gently dipping layers do not strongly affect the analysis (Langston 1977).

The frequency of the incoming signal corresponds to a footprint on the Moho of several km across. The structure obtained are thus unaffected by small intrusive bodies or other structure that are less than a km in extent.

The best-fitting structure is obtained from the stacked receiver function waveforms by searching the solution space using an algorithm that is well-suited to the non-linear relationship between the receiver waveform and Earth structure. As in previous work (Reading et al., 2003a) we use the Neighbourhood Algorithm (Sambridge, 1999) that uses

adaptive techniques to search the solution space in an efficient manner and also provides a means of visualising the best-fit structure against other structures that also fit the observed waveform almost as well.

3. Results

Figures 3 and 4 show the stacked receiver functions from the WR and selected WP stations. After the initial P-pulse at 0 seconds, the highest amplitude arrival (mostly around 5 seconds) is taken to be due to energy converted from P-wave to S-wave propagation at the Moho. An earlier Moho arrival indicates shallower crust or faster seismic velocity in the crust or both. A high amplitude Moho arrival indicates a large contrast in seismic velocity across this discontinuity, i.e. the Moho is a sharp. Lower amplitude arrivals indicate a less-pronounced discontinuity, either a smaller contrast in seismic impedance or a broader zone over which the change in seismic velocity takes place.

The WR stations show discernable Moho arrivals with the exception of WR01, where the signal is very noisy, and WR10 and WR11 where the data is good but the Moho itself is indistinct. No data was returned at station WR03. The amplitude of the Moho arrival is particularly high at station WR02, in the Eastern Pilbara.

The WP stations all show discernable Moho arrivals with consistent Moho returns throughout WP02, 03, 04 and 06 in the Murchison Terrane of the Yilgarn Craton and a particularly high amplitude Moho signal at WR13, in the Southern Cross Terrane of the Yilgarn Craton. WP01 is a very noisy station. The WP stations in the Eastern Goldfields Terrane are the subject of more detailed analysis in separate work in conjunction with reflection seismic results (Goleby et al., 2000).

The best-fit structures determined through inverse modelling using the Neighbourhood Algorithm are shown in figures 5, 6 and 7. The Murchison Terrane is very well covered by the new results of this work and is characterised by a sharp Moho at 34 km (\pm 2 km) depth. In more detail, figure 5a, WR05, shows a well constrained structure beneath the Murchison Terrane of the Northern Yilgarn. In this area there appears to be little in the way of

discontinuities in the upper crust and a velocity gradient between about 22 km and 34 km deep, throughout the lower crust. The structure beneath the Murchison Terrane in the southern part of the Yilgarn Craton, figure 5a, WR08 is very similar, although there may be a small discontinuity in the upper crust, the lower crust is fairly low velocity and the Moho is even more pronounced at 34 km (± 2 km). The line of stations running across the Murchison Terrane (figure 5a, WR06, figure 5b, WP02 and WP04) also show the strong discontinuity at 34 km. WP06 shows a low-velocity lower crust but is otherwise similar to most of the Murchison Terrane stations. WP02 shows very simple upper crustal structure and low velocities in the lower crust, WP04 and WP06 are very similar to WR05. The velocity structures beneath WP01 and WP03 are not shown but they are similar to WP02, fitting the characteristic 34 km deep sharp Moho shown by the other stations of the Murchison Terrane. WP11, across the Youanmi Fault in the Southern Cross Terrane shows a slightly deeper Moho at 36 km and more pronounced structure in the upper crust although this may reflect structure due to the dipping Youanmi and/or Edale Faults at depth. The Moho transition is gradational, probably due to structures associated with the terrane boundary.

The Southern Cross Terrane of the central Yilgarn Craton is characterised by station WT08 with a Moho at 38 km (± 2 km) deep (Reading et al, 2003a). Newly determined structure from beneath WP13, a station which is close to the location of WT08, confirms this result with a similar, very sharp Moho at 36 km (± 2 km). The previously determined structure of the Eastern Goldfields Terrane, characterised by that of WV05, is similar to the closely located WR07 and WP18 shown in figure 6, with a slightly broader Moho at 42 km (± 2 km) deep and upper crustal discontinuities, however this terrane shows more variability than the others.

At the southern edge of the Eastern Goldfields Terrane, station WP17 (figure 7) shows a structure similar to WP18 except that the Moho becomes shallower at this margin of the Craton. WR02 shows a structure typical of the Eastern Pilbara, with a very sharp Moho. In the north, at station MBWA (Reading and Kennett, 2003) however, the Pilbara Craton is shallower at 32 km (± 2 km) deep whereas the best-fit structure beneath WR02 is

significantly deeper at 38 km deep, probably due to the influence of the basins associated with the Capricorn Orogen. Station WR04, over the Capricorn Orogen to the northeast of the Yilgarn Craton, shows structure with a broader Moho.

4. Summary of terrane seismic structures

A characteristic seismic velocity structure for each terrane that is well covered by stations is shown in figure 8. In all cases, there is a ± 2 km uncertainty on all stated depths. In this work, the Moho is taken to be the base of any high velocity gradient zone in the crust. When comparing depth estimates with other work, it is important to keep in mind the possible disparity between the seismic (physical) Moho and the geological (chemical) Moho as well as varying definitions in the case of a gradual transition between crust and mantle properties. Structure determinations from 1) the Murchison Terrane show a very sharp Moho at a depth of 34 km, a two-layer, simple crust with low velocities in the lower crust producing the large Moho velocity discontinuity. In general, the structure is very consistent across the terrane although WP04 and WP06, located towards the eastern edge of the terrane, show a velocity gradient in the lower crust. Previously published determinations of structure for the Yilgarn are based on seismic sections across the central Yilgarn and include very few structure determinations from the Murchison (Drummond, 1988; Collins et al., 2003). In the latter synthesis, the Murchison Terrane structure determined in this work would represent a shallow-crust end member, other locations across the Yilgarn generally showing a crustal depth of 35-40 km. The mid-crust discontinuity at 20 km (e.g. in the record from WR05) is also observed in some sections by Collins et al. (2003).

2) The Southwest terrane is slightly deeper with a characteristic Moho depth of 36km and shows a sharp Moho away from terrane edges (see Reading et al., 2003a). There is a discontinuity in the upper crust at around 10 km deep and a high velocity gradient above the Moho. In comparison with the Murchison Terrane, there is much less consistency in structure across the Southwest. The high-velocity gradient zone thickens markedly towards the western edge of the craton and whether the Moho is assigned to the top or bottom of this zone

is a matter for debate. The crustal depth is consistent, within error, to that obtained using refraction and reflection data methods (35km, Dentith, 2000; 32-40km, Wilde, 1996) but the high-velocity body observed in the refraction data (approximately 60 km south of the WT line) is not seen in this work. The velocity structure of WT04 could be interpreted as three-layer structure although the base of the second layer at WT04 is about 30 km, whereas the base of the second layer observed in reflection data further north is about 25 km (Wilde et al., 1996). Both Dentith et al. (2000) and Wilde et al. (1996) separate the Southwest (super) terrane into Balingup, Boddington and Lake Grace Terranes. Structures at the boundaries of these terranes in particular are probably responsible for the variability in structure within the Southwest.

3) The Southern Cross Terrane exhibits a very characteristic structure with a huge discontinuity at the Moho at a depth of 38 km, a discontinuity in the upper crust at 14 km and a lower crust showing little or no velocity increase with depth (see also Reading et al., 2003a). The structure is consistent across the terrane, with new structure determinations (e.g. from WP13) showing similar characteristics. The majority of the structure determinations shown by Collins et al. (2003) for the Yilgarn would fit this characteristic structure.

4) The Eastern Goldfields Terrane characteristically shows a sharp Moho at 42 km deep and a discontinuity in the upper crust at 7 km. This 7 km discontinuity is interpreted as a detachment surface of variable depth by Drummond et al. (2000) and Goleby et al. (2002). Lower crust discontinuities and velocity gradients are very variable and not possible to generalise for the terrane (see discussion of the Kaapvaal Craton below). The Moho becomes consistently deeper moving eastwards towards central Australia and shallower towards the southeast edge of the craton.

5) The Pilbara shows a very sharp, shallow Moho at 32 km with a discontinuity in the upper crust at 10 km deep and a velocity gradient in the lower crust. The Moho becomes deeper towards the south of the craton. These values compare well with refraction determinations (Drummond, 1988 and Collins et al., 2003).

6) The Capricorn Orogen shows a deep Moho (e.g. WR04 44km) with a low velocity contrast between lower crust and mantle which sometimes manifests as a broad Moho discontinuity or in some cases the Moho can be hard to define at all (Reading et al., 2003b). The structure is variable but there is generally a moderate velocity gradient throughout the lower crust.

5. Discussion

We are now in a position to comment on the variability of structure within the terranes of the West Australian Craton which represents a significant advance on the detail available to Drummond (1988) and Collins (2003). The Murchison and Pilbara blocks show consistent structure, a sharp Moho and a relatively shallow crustal depth. The Murchison seems to be a similar depth throughout while the crustal depth of the Pilbara increases beneath the Hamersley Basin. The Southern Cross Terrane also shows consistent crustal structure although this could be due to its shorter west-east dimension. The variability in character of the Southwest and Eastern Goldfields Terranes is markedly different from the Murchison, Pilbara and Southern Cross. The relatively few stations in the north and south of the Southwest Terrane limits the resolution of the crustal structure. It may be that there is consistent structure within the Boddington and Lake Grace Terranes (Dentith et al., 2000). Since Moho depth is often characteristic of a given terrane (with the exception of craton edges) it follows that the relative crustal thickness of Precambrian blocks is determined early in their tectonic history. This obviously includes the influence of the original crust-forming process, but also early denudation and uplift. We assume that the West Australian Craton has experienced the same (to within 1 km) denudation and uplift across its length and breadth since the end of the Capricorn Orogen but are aware that some of the trends in Moho depth towards the edge of the Craton may be due to later tectonic influences. Later tectonic influences are the most likely explanation for the diffuse Moho observed beneath WR10 and WR11.

Similar observations, although on a less-detailed scale, have been made in the Kaapvaal and Zimbabwe Cratons of southern Africa. Nguuri et al. (2001) report that the Archaean crust is

thin (35-40 km) and shows a sharp Moho and little variability in upper or lower crustal structure. The Moho transition is again shown to be very thin, less than 0.5 km, by Nui and James (2002) who use data from a local, dense array. They also present density determinations that are consistent with a lower crust of felsic to intermediate composition. This implies large-scale crustal reworking between the formation of the crust and the stabilisation of the craton. The shared early history of the Kaapvaal and Pilbara Cratons has been discussed previously (Nelson et al., 1999; Zegers et al., 1998) and raises the possibility that the sharp Moho and simple crustal velocity structure of the Pilbara block (also the Murchison and Southern Cross Terranes) could be due to extensive reworking of the lower crust prior to craton assembly.

Thin crust and a sharp Moho is also observed in Archaean provinces in Canada (e.g. 32-35 km in the Slave Province, Viejo and Clowes, 2003; 34-36 km in the main shield, Darbyshire, 2003). Archaean terranes in Quebec assembled in a similar manner to those forming the Yilgarn Craton (Mueller et al., (1996) suggesting that this style of continental growth was widespread even though few such areas have been preserved throughout geological time. Condie and Chomiak (1996) make the observation that Canadian Archaean terranes existed for a relatively short time, about 20-80 Ma, between formation and collision (compare Mesozoic terranes at mostly 50-200Ma). They also suggest that most early Proterozoic crust evolved 'directly' into continental crust (compare Mesozoic accretion of oceanic terranes and transformation into continental crust).

Although less well studied, the Archaean crust of East Antarctica (e.g. in Wilkes Land, Fitzsimons, 2003) also shows a shallow Moho (32 km near Casey station, Reading, 2004) with a simple crustal structure and a sharp transition to mantle velocities. In India, the East and West parts of the Dharwar craton show a simple crustal structure (Sarkar et al., 2003) with the East also showing thin crust at 34 km. The west is thicker at 41 km with a broad Moho discontinuity.

There has been much discussion regarding the formation of Archaean crust, suggesting mechanisms for crustal formation without subduction (e.g. Zegers and van Keken, 2001),

suggesting mechanisms for primitive subduction (e.g. Smithies et al., 2003), advocating the significance of accretion mechanisms (e.g. a summary by de Wit, 1998) and discussing pulses of continental crust formation and their relation to the evolution of the mantle (e.g. Condie, 2000). With these turbulent processes in mind, we are now be able to discuss the ‘freezing in’ of seismic structure in the various parts of the West Australian Craton.

Wyche (2004) suggests that the Southern Cross and Murchison Terranes (and parts of the Southwest Terrane) may have been more extensively reworked than previously recognised. Very extensive reworking of the crust at, or soon after, the time of formation leads to a more predominantly felsic lower crust and hence a larger, and sharper discontinuity at the Moho. The terranes within the West Australian Craton that show this characteristic correlate well with those that have been subject to more radical ‘vertical’ tectonics (Pilbara) or those which have been reworked by this and other means (Murchison and Southern Cross). Somewhat paradoxically, it seems that if primitive crust is more extensively reworked, the simpler the seismic structure of that crust becomes. The more felsic the lower crust, the lower the velocity, and hence, the sharper the Moho.

Later terranes, such as the Capricorn Orogen, rarely have the comprehensive crustal reworking of the Archaean cratons and hence show more complex crustal structure and broader Moho discontinuities.

This leads to the conclusion that the seismic structure becomes fixed at an early stage, before accretion/terrane assembly (in the case of the Yilgarn). The deep crust of the Eastern Goldfields Terrane is slightly younger and was perhaps less comprehensively reworked, showing a more variable crustal structure and often a higher velocity lower crust (although still a fairly sharp Moho) however the processes responsible for the extensive mineralisation in this terrane may also be significant as a reason for this variability. At the craton edges, there is likely to be some modification of the seismic structure during the emplacement of extensive mobile belts. We see alterations in Moho depth to the west of the Southwest Terrane and in the southeast of the Eastern Goldfields terrane corresponding to the later Pinjara and Albany-Fraser Orogenies respectively (Fitzsimons, 2003).

If the seismic structure is such a long-lived feature of Archaean crust, there must be a mechanism of preserving that structure. O'Reilly et al. (2001) summarise an ongoing body of work which investigates changes to the sub-continental lithospheric mantle over time. Archaean lithosphere is more buoyant (Poudjom Djomani et al., 2001) than that which formed later in geological time. It therefore is less prone to delamination, and better at protecting the crust above from modification. The kind of 'universal metamorphism' Best (2003) which may have acted across the whole Yilgarn Craton is likely to have shifted seismic velocities higher within the crust but it seems not to have brought about structural changes through the deep crust. The terranes retain their own characteristics and have not been overprinted by a homogenising event across the West Australian Craton.

In spite of the close correlations between surface geological terranes and seismic structure in Western Australia, and our insights into the formation and evolution of the lithosphere, the challenge of bridging the gap between crust and upper lithospheric structure (e.g. this work) and mantle seismic tomography (e.g. Fishwick et al., 2004; Kennett 2003) remains.

6. Conclusions

The Precambrian terranes of the West Australian Craton show seismic structures that are characteristic of each of the large terrane groups; Pilbara, Murchison, Southwest, Southern Cross, Eastern Goldfields and Capricorn Orogen. There is notable consistency in structure through the Pilbara, Murchison and Southern Cross Terranes. A proposed mechanism for the formation of an especially sharp Moho is the extensive reworking of crustal rocks such that the lower crust becomes more felsic and lower in seismic velocity, leading to a sharper discontinuity across the seismic Moho. Structure is more variable across the Southwest and Eastern Goldfields terranes. It is likely that the seismic structure was 'frozen in' to each terrane prior to the assembly of the craton. The receiver function method is now established as a tool for mapping crustal units in regions of limited exposure and is a practical and economic alternative to seismic refraction experiments.

ACKNOWLEDGEMENTS

RSES staff / GA staff? / ANSIR / pmdCRC

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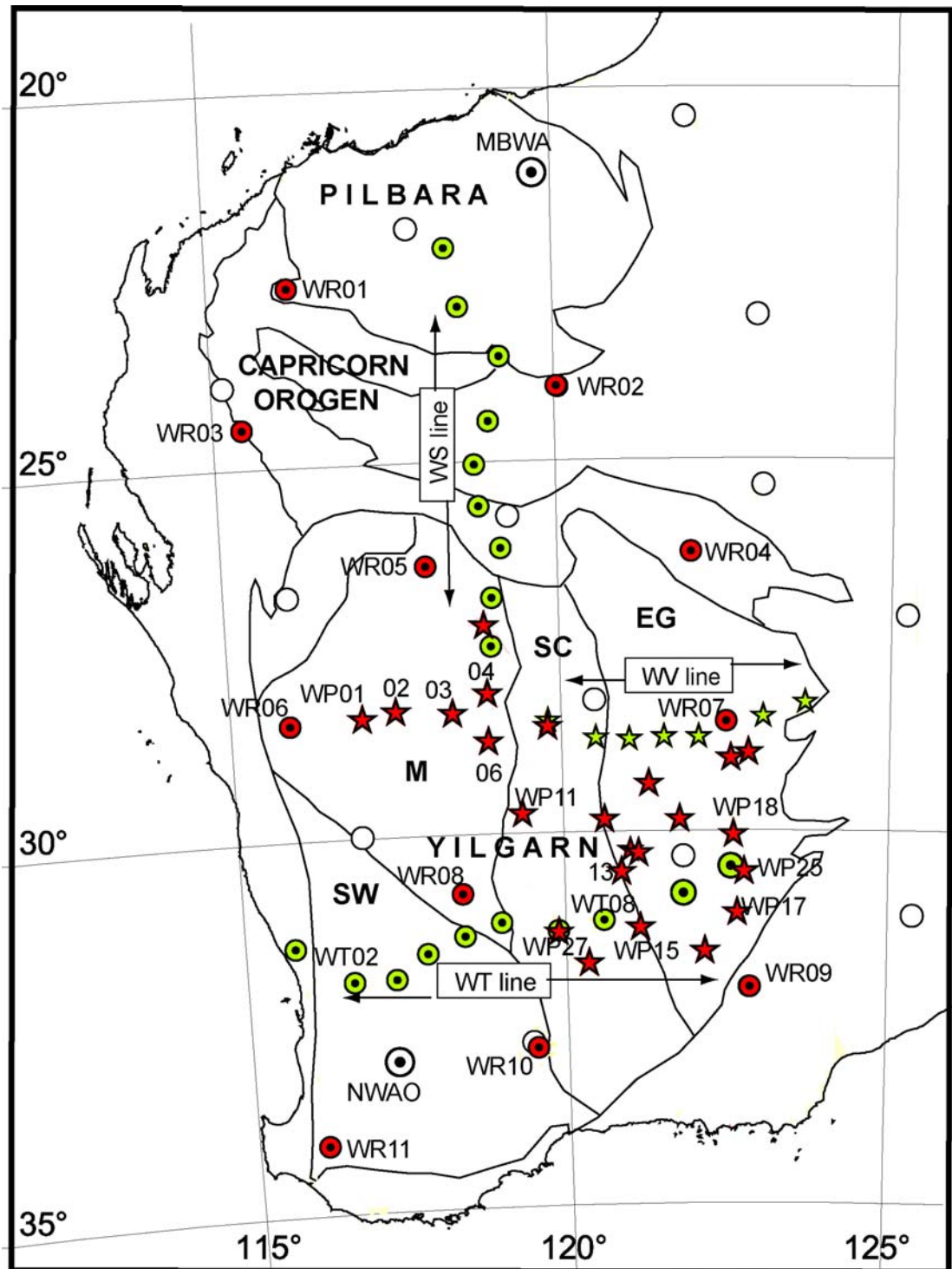
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FIGURES











	WR deployment
	WP deployment
	WT line and WS line
	WV line
	SKIPPY deployments
	Permanent stations
	Stations operated by RSES, ANU
	Stations operated by pmdCRC and RSES, ANU

Figure 1

Station location and geological terrane map for Western Australia including the WR and WP deployment (dark grey symbols). Seismic structures from these stations, determined through receiver function analysis, are presented in this paper for the first time. The WT, WV and WS deployments (Reading et al., 2003a, Reading and Kennet, 2003) are also discussed and structure determinations from the SKIPPY deployments (Clitheroe et al., 2000) and permanent Global Seismic Network stations MBWA and NWA0 are included in the synthesis of results. SW=Southwest Terrane, M=Murchison Terrane, SC=Southern Cross Terrane, EG=Eastern Goldfields Terrane. XXXXmore geog. locations here (as in intro).

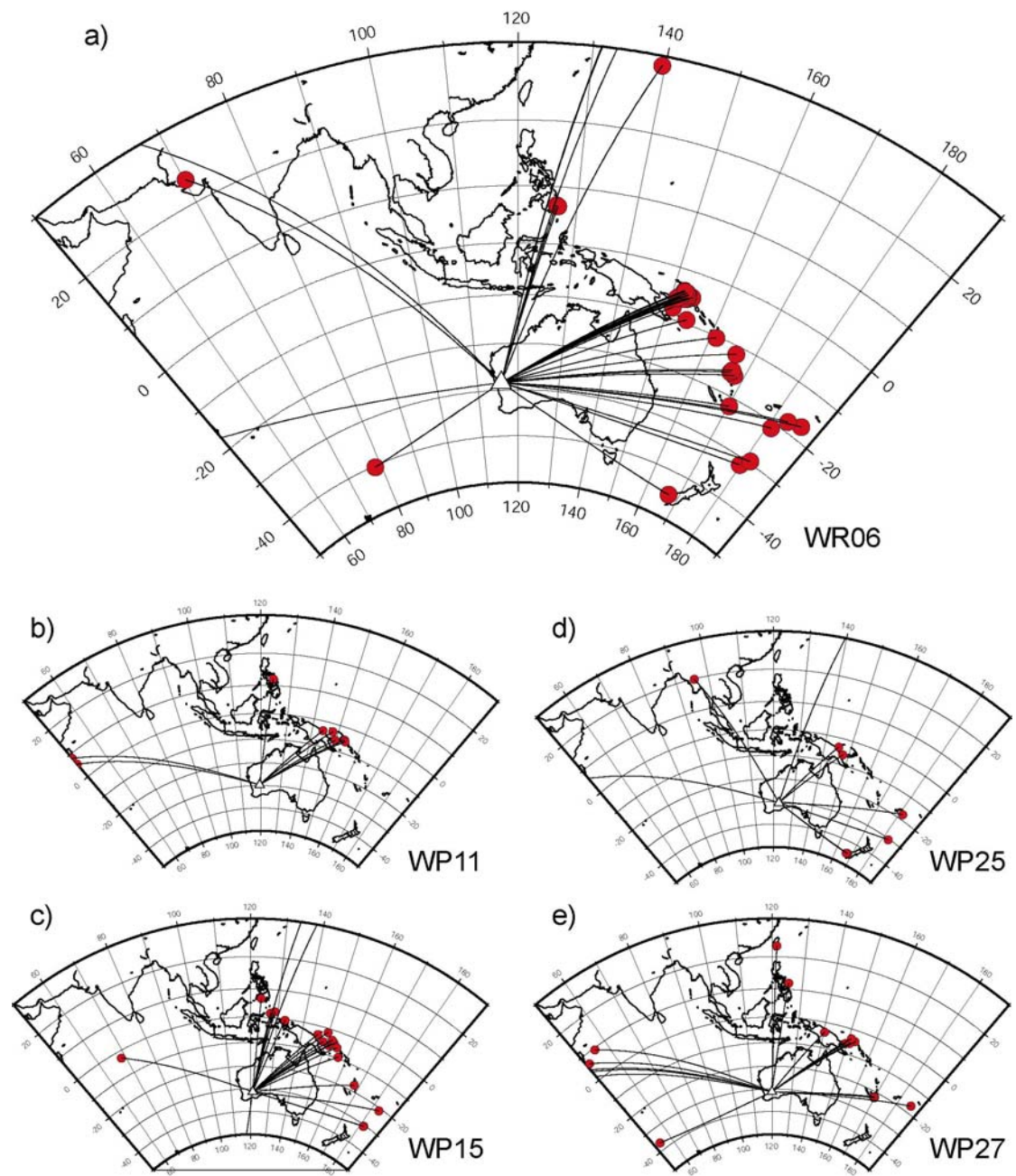


Figure 2

Earthquake locations of events (dark grey circles) available for receiver function analysis for the WR deployment (example station WR06, white triangle) and the WP deployment (example stations WP11, WP15, WP25 and WP27, white triangles).

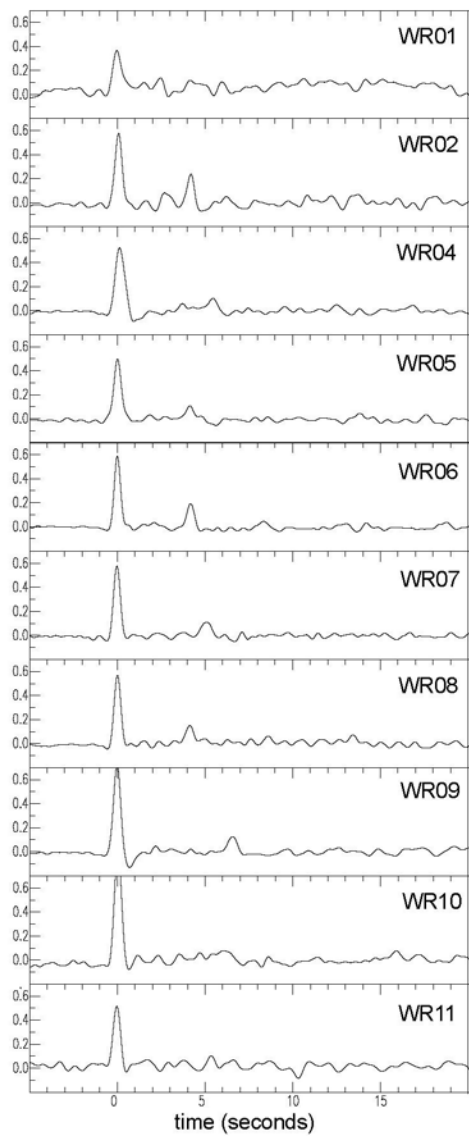


Figure 3

Receiver functions (stacked records for each station) for all stations of the WR deployment.

The signal due to the Moho is the pulse just before 5 seconds on most records.

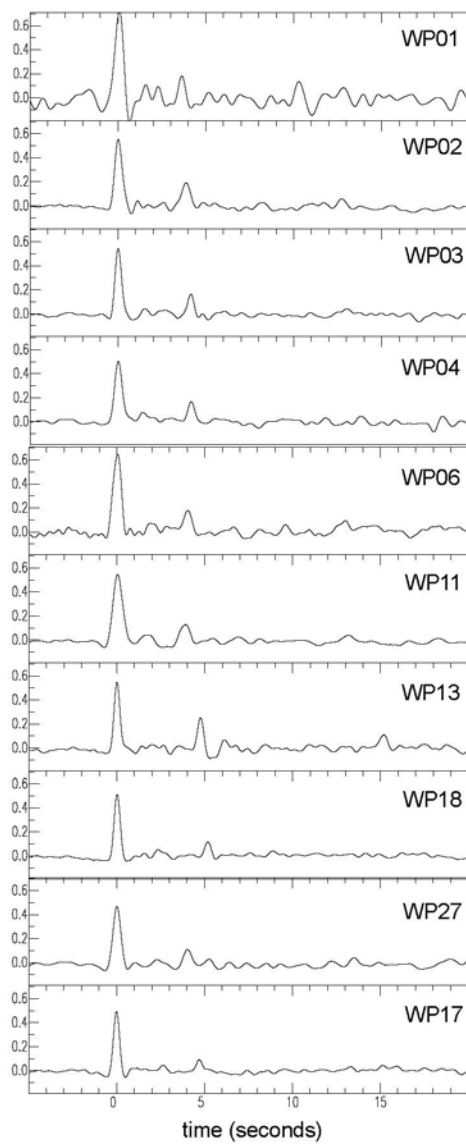


Figure 4

Receiver functions (stacked records for each station) for selected stations of the WP deployment. Again, the signal due to the Moho is the pulse just before 5 seconds on most records.

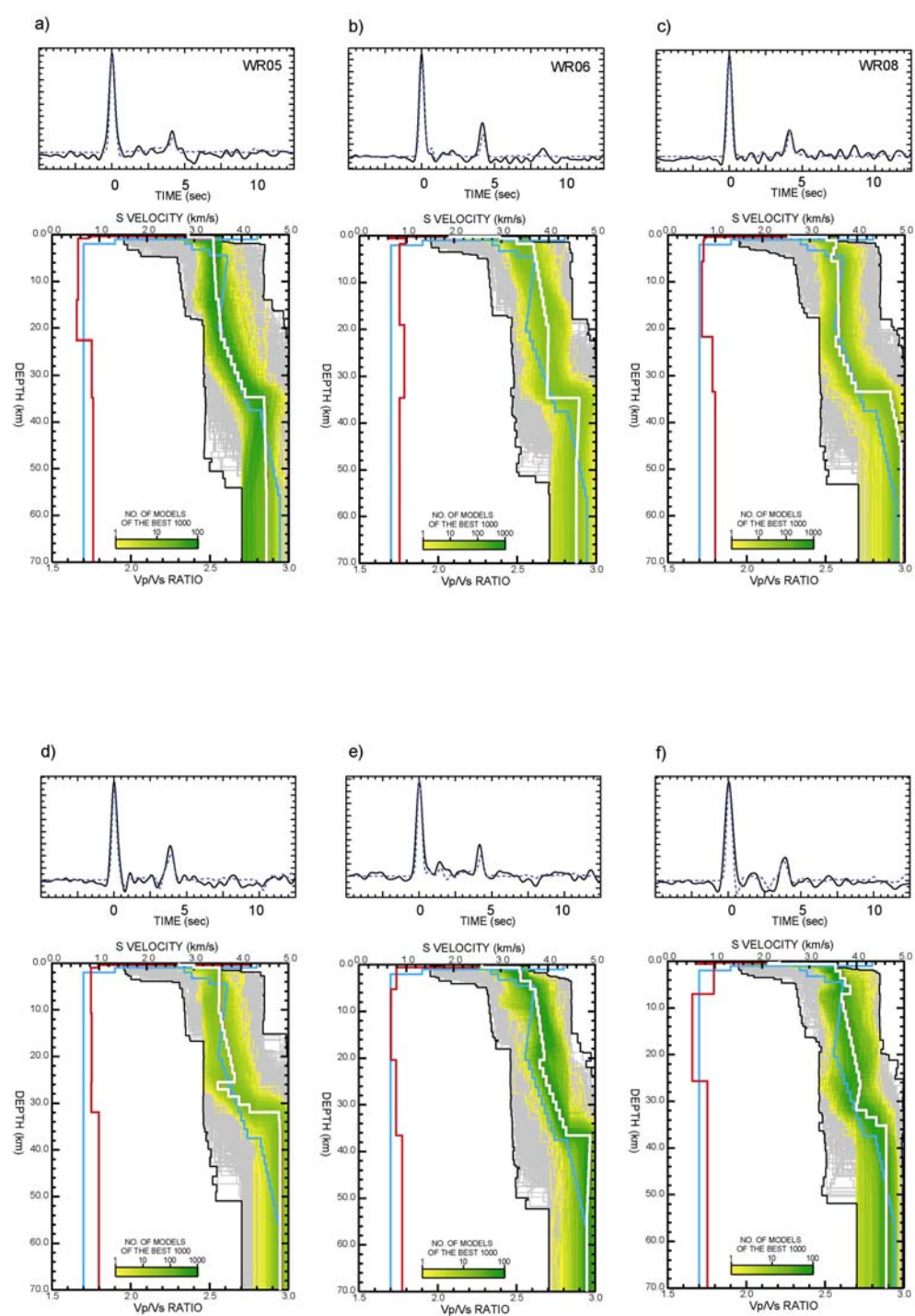


Figure 5

Observed (solid line) and best-fit synthetic (dashed line) receiver functions for selected stations of the Murchison Terrane and WP11 (across the mapped fault with the Southern

Cross Terrane yet shows similarities to the Murchison). The seismic velocity plots below show the best-fit structure (broad white line) corresponding to the best-fit synthetic receiver function. The grey density plots behind the white lines all correspond to the same number of iterations and hence give a comparative indication of the regions of solution space which might also contain a well-fitting structure. The V_p/V_s velocity ratios are shown for completeness since they are variable parameters in the inversion although they are not discussed in the text.

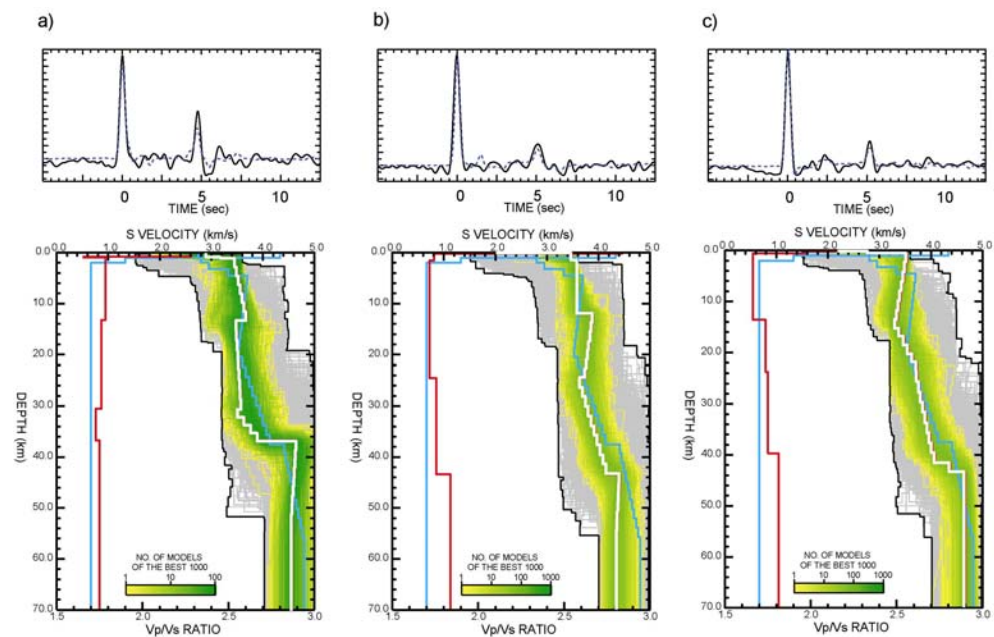


Figure 6

Observed and best-fit synthetic receiver functions, and seismic velocity plots (description as in the caption to Figure 5) for stations of the Southern Cross (WP13) and Eastern Goldfields (WR07 and WP18) Terranes.

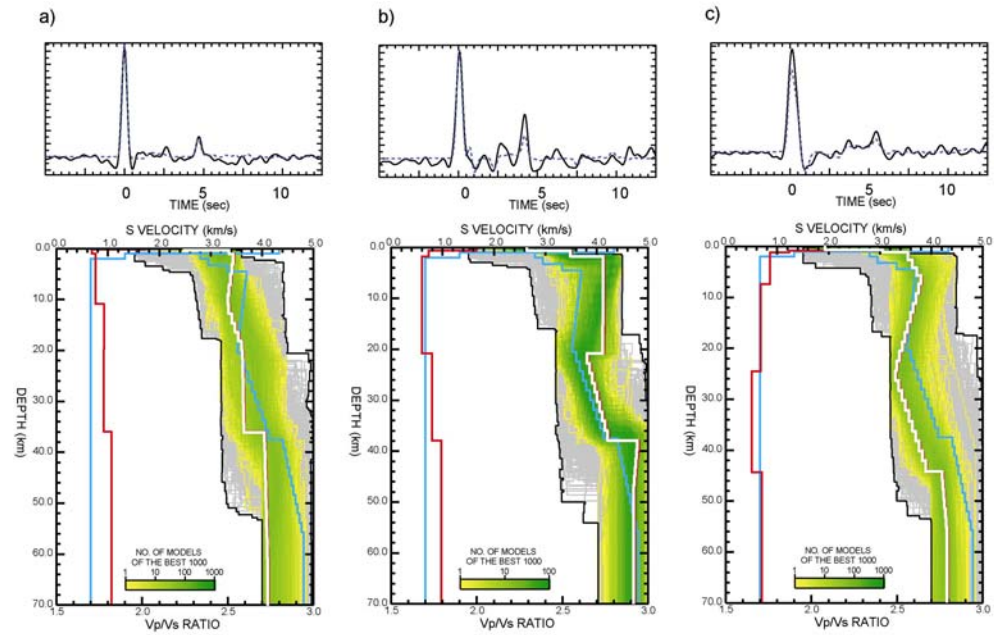


Figure 7

Observed and best-fit synthetic receiver functions, and seismic velocity plots (description as in the caption to Figure 5) for stations on the southeastern edge of the Yilgarn Craton in the Eastern Goldfields Terrane (WP17), the edge of the Pilbara Craton (WR02) and the Capricorn Orogen (WR04).

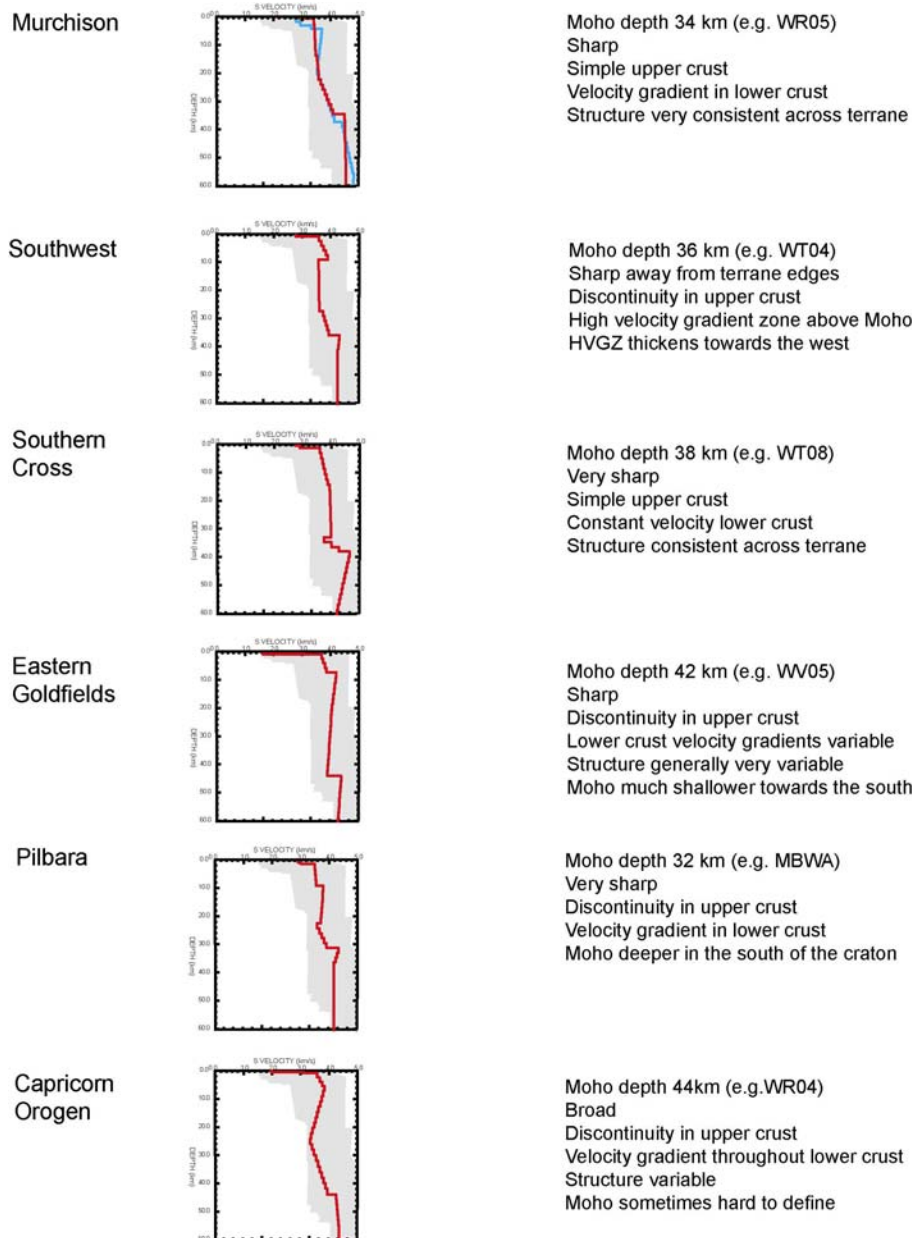


Figure 8

Example seismic velocity profiles that are characteristic of the given terranes. Profiles from WT04, WT08 and WV05 are taken from Reading et al., (2003a) and the profile from MBWA from Reading and Kennett (2003). The light grey regions behind the velocity profiles show the region of solution space which was searched during the inversion.