Lithospheric discontinuities beneath Australia: interaction of large-scale and fine-scale structure

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Abstract

Understanding the complex heterogeneity of the continental lithosphere involves a wide variety of spatial scales and the synthesis of multiple classes of information. Seismic surface waves and multiply reflected body waves provide the main constraints on broad-scale structure, and bounds on the extent of the lithosphere-asthenosphere transition (LAT) can be found from the vertical gradients of the S wavespeed. Information on finer scale structures comes through body wave studies, including detailed seismic tomography and P wave reflectivity extracted from stacked autocorrelograms of continuous component records. With the inclusion of deterministic large-scale structure and realistic medium-scale stochastic features there is not a need for strong fine-scale variations. The resulting multi-scale heterogeneity model for the Australian region gives a good representation of the character of observed seismograms and their geographic variations and matches the observations of P wave reflectivity. There are some indications of a change of reflection character in the lower part of the lithosphere in the transition to the asthenosphere. In some parts of central Australia there is a reasonable tie between a change in reflectivity and other information on mid-lithospheric discontinuities.

Keywords: continental lithosphere, discontinuities, heterogeneity

1. INTRODUCTION

A variety of types of evidence derived from recent seismological observations have revealed the nature of large-scale and fine-scale heterogeneities in the continental lithosphere. Large-scale 3-D images of the continental lithosphere have been constrained primarily from surface waves, and indicate fast wavespeed anomalies for cratonic lithosphere, with typical lithospheric thickness of about 200 km. Surface wave observations in Australia also provide evidence for strong radial anisotropy with faster SH wavespeed than SV, particularly at shallower depths above 90 km as well as in the asthenosphere, while the strength of radial anisotropy tends to be weak in the middle to lower lithosphere (Yoshizawa 2014).

Discontinuities in the lithosphere are well constrained by body-wave receiver functions that indicate the wave conversions and reflections underneath seismic stations. One of the striking features in S-wave receiver function analysis for the Australian cratons is the presence of clear signals of discontinuities in the mid-lithosphere at around 70-90 km (Ford et al., 2010), which may indicate arapid drop in seismic velocity or a change in the character of radial anisotropy in the middle part of the continental lithosphere where the wavespeed is generally at its fastest. The estimated depth of the enigmatic mid-lithosphere discontinuity (MLD) from receiver functions corresponds well with a rapid change in the strength of radial anisotropy derived from surface waves (Yoshizawa & Kennett, 2015).

An additional constraint on the nature of lithospheric heterogeneity comes from observations of high-frequency P-wave reflectivity profiles derived from the autocorrelograms of vertical component records at seismic stations across Australia (Kennett, 2015). These P reflectivity profiles suggest vertical changes in the character of the fine-scale structures in the Australian continent, indicating stronger reflectivity in the crust and upper lithosphere underneath the cratons. These observations support the existence of fine-scale laminated heterogeneity in the lithosphere superimposed on broader-scale wavespeed variations. Such behaviour was suggested from numerical simulations of high-frequency scattering of seismic waves for the paths in the cratonic areas (Kennett & Furumura, 2008). Recently Kennett & Furumura (2016) have undertaken a further suite of numerical studies covering the full range of tectonic environments across the Australian continent and have been able to demonstrate good correspondence between the numerical simulations and the properties of both high-frequency refracted waves and P wave reflectivity.

The presence of such quasi-laminar fine-scale heterogeneity in the lithosphere has equivalent effects to shape-preferred orientation of crystals, and so vertical variations in the character of the heterogeneity can produce changes in the effective radial anisotropy for long-wavelength surface waves as well as apparent discontinuities in the mid-lithosphere region for higher frequency body waves.

2. THE AUSTRALIAN LITHOSPHERE

The exposed geology of the Australian continent is composed of an assemblage of crustal blocks that can be broadly grouped into the Precambrian western and central cratonic zones and the Phanerozoic eastern province. The Australian continental crust was accreted in three major episodes, each comprising about one third of the continental area from the Archean cratons in the west to Phanerozoic provinces in the east. Disparate Archean crustal elements were assembled into three major cratonic zones in the Proterozoic; West Australia, the North Australian Craton and the South

Australian Craton were formed by 1830 Ma, and these cratonic elements were joined to the Rodinian supercontinent by 1300--1100 Ma (Cawood & Korsch, 2008). The supercontinent broke up around 800 Ma. Subsequently, the fold belt structures of the Phanerozoic Tasman Orogen of the eastern third of Australia were accreted onto the eastern margin of the Precambrian cratons in the late Palaeozoic in a series of stages (Direen & Crawford, 2003).

2.1 Large Scale structure

Yoshizawa (2014) has recently developed a new radially anisotropic 3-D shear wave model for Australia from a large number of multi-mode surface wave paths across Australia, based on multi-mode phase speed measurements, with the incorporation of finite-frequency effects. He has proposed a way to estimate the plausible depth range of the lithosphere-asthenosphere transition (LAT) by exploiting the character of the wavespeed gradients on local vertical profiles through the 3-D shear wavespeed model. The shallower bound is taken where the negative vertical gradient in isotropic wavespeed is largest. The deeper bound is placed at the minimum absolute wavespeed beneath the lithosphere, and thus the minimum of the S wave low velocity zone (Yoshizawa, 2014). With this definition, the LAT lies in a low-velocity-zone created by the high shear wavespeeds in the shallower part of the lithosphere. The shallower bound generally lies just below the highest S wavespeeds.

Vertical wavespeed profiles are extracted on a 0.5^{o} grid and the shallower and deeper LAT bounds are estimated at each of these grid positions. The bounds on the LAT are particularly effective in zones of thick lithosphere, though they will tend to exaggerate the thickness of the transition when it is very sharp (Yoshizawa, 2014). For thinner lithosphere the shallower bound tends to lie closer to alternative estimates of lithospheric thickness; whereas the deeper bound marks the lowest wavespeed encountered in the asthenospheric low velocity zone beneath.

A map view at 125 km depth and cross sections of the isotropic S wave speed in the continental lithosphere of Australia is displayed in Figure 1. West-to-east sections are displayed for constant latitude at 4^{o} intervals. These sections cross the full range of tectonic provinces in Australia. The shallower bound on the LAT indicated with a dashed red lines in Figure 1 appears flat across the Archean and Proterozoic regions of the continent, confined to the depth range between 120 and 150 km.

In the east of Australia the bounds on the LAT tend to diverge with the shallow bound marking the top of the strong gradient associated with a relatively sharp transition as seen in the Sp receiver function results (Ford et al., 2010). In contrast, the deeper bound on the LAT indicated by the dashed blue line in Figure1 clearly displays large regional variations from 160 to 250 km. The deepest locations are associated with the rather thick lithosphere beneath the Yilgarn Archean craton in western Australia, as well as in the centre of northern Australia. In the cross-sections from 24-32^{o}S we clearly see the thick cratonic lithosphere beneath the West Australian craton, accompanied by a thick transition zone from lithosphere to asthenosphere. Similar features are visible for the North Australian craton (16-20^{o}S). The LAT is somewhat thinner in the Mesoproterozoic suture zone in central Australia and the South Australian Craton (24-32^{o}S).

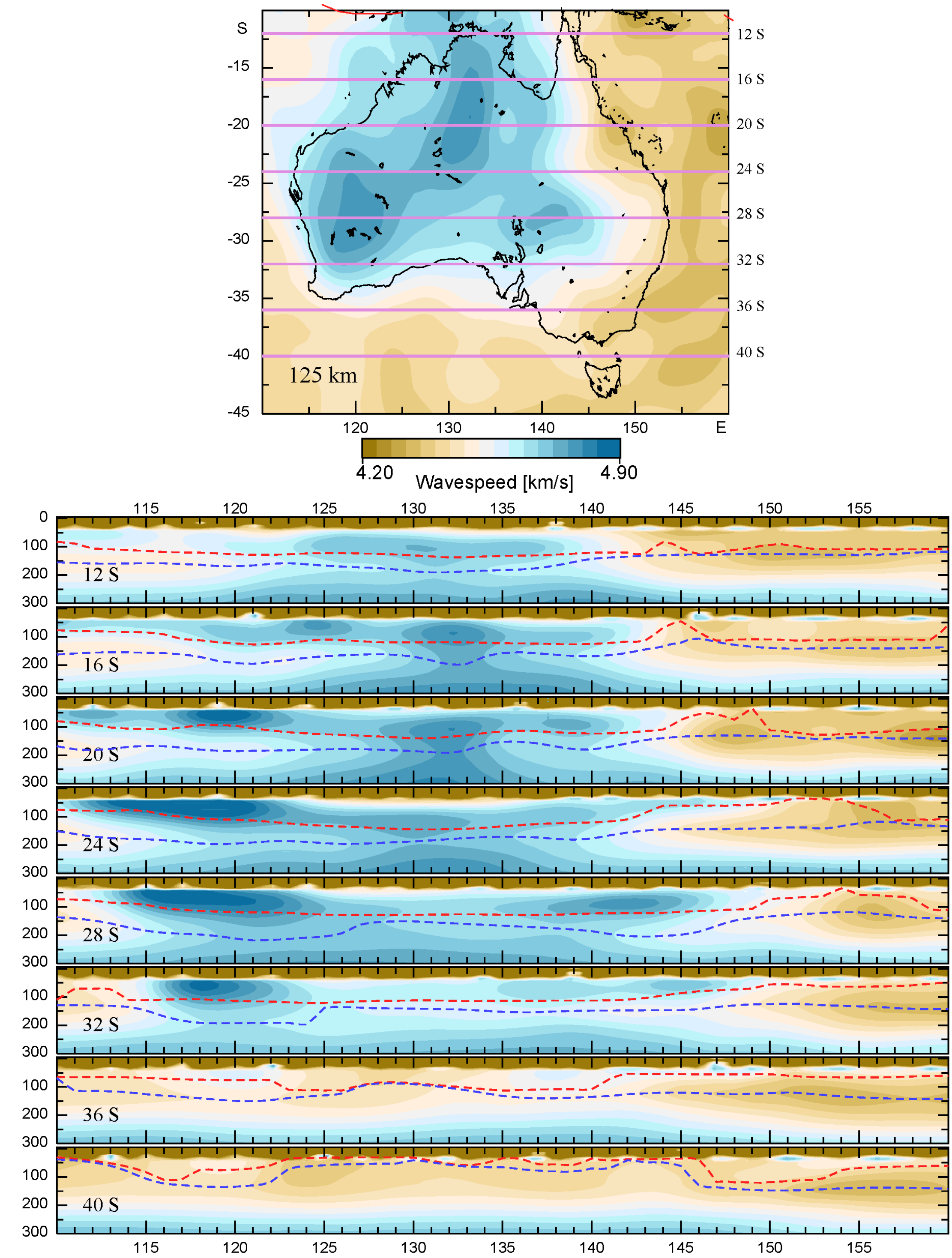

Figure 1: Cross-sections at constant latitude through the isotropic S wavespeed model of Yoshizawa (2014) with the upper and lower bounds on the lithosphere-asthenosphere transition (LAT) indicated.}

It should be noted that in the oceanic regions to the south and east of Australia the requisite velocity gradients are difficult to estimate. As a result, the apparent sharpness of the lithosphere to asthenosphere transition might be exaggerated on the sections at 36°S and 40°S between 125°E and 135°E.

In the cratonic blocks, particularly beneath the Pilbara and Yilgarn cratons in western Australia and the centre of the North Australian craton, the apparent LAT thickness exceeds 80 km (Figure 1). However, the Gawler craton in South Australia shows distinctly thinner lithosphere and a LAT with rather subtle differences from the suture zone in central Australia. Furthermore, the isotropic shear wave speed at the bounds of the LAT beneath this region is apparently slower than for the other cratons. These differences may be associated with basal erosion during the continental breakup of Australia and Antarctica.

2.2 Finer-scale structure

Kennett (1985) drew attention to the characteristics of high-frequency body waves from events in the Indonesian subduction zone recorded at the Warramunga array in the middle of the North Austraian craton. From shallow sources, the seismograms show very little difference in frequency content between P and S and extended complex coda, so that S arrives before the P coda has subsided. These features suggest that the arriving waves have travelled through a complex scattering environment with very low intrinsic attenuation. Gudmundson et al. (1994) demonstrated the major difference between such high-frequency waves trapped in the lithosphere and body wave phases returned from the upper mantle transition zone which showed much lower frequencies indicating passage through significant attenuation beneath the lithosphere.

Observations of seismic phases refracted back from the lithosphere include the integrated effect of the entire path, including any multiples and so it is hard to disentangle the influence of different aspects of the structure. Fortunately, it has recently become possible to obtain a more direct view of fine-scale structure in the lithosphere from estimates of high-frequency P-wave reflectivity beneath seismic stations extracted from stacked autocorrelograms of vertical component records (Kennett, 2015). The P-wave reflectivity results include full free surface effects. For these steeply travelling P waves the reflection coefficients are small, so surface multiple trains rapidly diminish in amplitude. This is contrast to the situation for P receiver functions where shallower angle reflections can give strong multiple trains for complex near-surface structure. In consequence, good P-reflectivity results can be obtained for stations such as FORT, in southern Australia, where the P-receiver function does not even reveal the Moho (Ford et al., 2010).

In Figure 2 we illustrate results for a profile across Australia at approximately latitude 20^{o}S) displaying the P reflectivity as a function of time, with an approximate conversion to depth using the *ak135* model (Kennett et al, 1995). The crustal age for each station is indicated with a coloured background. For each profile we show a cross-section through the Yoshizawa (2014) S wavespeed model passing through the group of stations, the position of each station is projected to the cross-section. For each station we also indicate the Moho estimate from the AuSREM model (Kennett & Salmon, 2012) and the LAT bounds from the Yoshizawa (2014) model.

The P reflectivity shown in Figure 2 is for the frequency band from 0.6-3.0 Hz and indicates the presence of variability in physical properties on scales from a few hundred meters to tens of kilometres. There are significant differences in the character between stations but a general consistency in style between tectonic regions. In particular the Proterozoic of the North Australian craton shows strong variability to considerable depth, some component of which may arise from localized scattering (Kennett, 2015). Such reflectivity estimates are available for more than 200 broad-band portable or permanent stations across the continent, and taken overall there is a tendency for a slight change in the style of reflection response to be associated with the zone of the lithosphere-asthenosphere transition. This change would be consistent with the suggestion of Thybo (2008) of a different heterogeneity regime in the low velocity zone beneath the highest lithospheric wavespeeds.

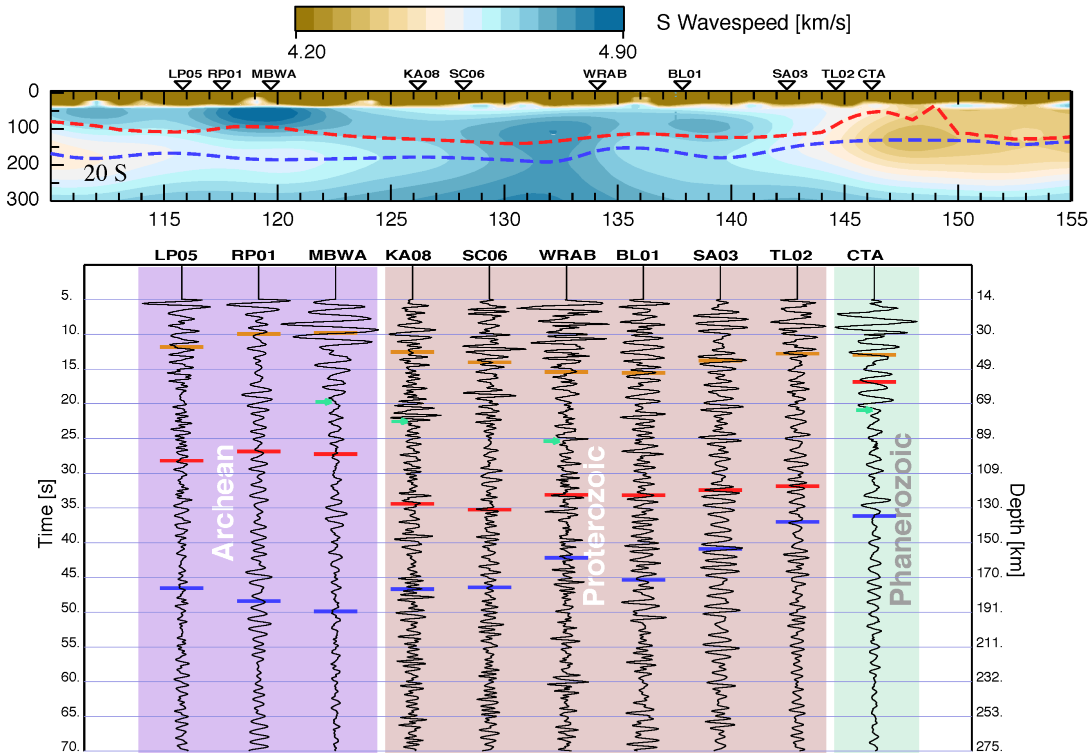

Figure 2: Estimates of P-wave reflectivity for stations along a profile approximately at 20°S, for the frequency range 0.6-3.0 Hz extracted from stacked station autocorrelograms. The representative section through the isotropic S wavespeed model of Yoshizawa (2014) is shown on which the upper and lower bounds on the lithosphere-asthenosphere transition (LAT) are indicated, along with the projection of the station locations. The P wave reflectivity to 70 s two-way-time is shown, with the expected time for the Moho and the mapping of the upper and lower bounds on the LAT are marked in red and blue. Where available, green arrow markers indicate the discontinuities determined by Ford et al. (2010) using S wave receiver functions. The time to depth conversions are made with the ak135 model of Kennett et al.(1995), and the depth scale is indicated at the right side of each profile. The coloured backgrounds indicate the broad age provinces.

2.3 Multi-scale lithospheric heterogeneity

In Figures 1 and 2 we have shown the large scale structures in the upper mantle determined from surface-wave tomography, and the presence of fine-scale features from analysis of higher frequency body waves. Where dense observations are available, as in southeastern Australia, body wave tomography demonstrates the presence of considerable complexity beneath the crust (e.g., Rawlinson et al., 2014) with variations down to the available sampling of 50 km, and such intermediate heterogeneity needs also to be included.

Kennett & Furumura (2016) have built up a composite model for the lithosphere incorporating the full range of scales. Large scale structure in the mantle is taken from the AuSREM model (Kennett et al., 2013), and superimposed on this are both medium- and fine-scale stochastic features. This multi-scale model includes significant variation in the crust with larger amplitudes between 15 km depth and the Moho. The lithospheric mantle is mildly heterogeneous with a longer horizontal correlation length, which is needed to produce the minutes of coda duration for both P and S waves for passage through the Precambrian zones. Between the lithosphere-asthenosphere transition (LAT) bounds extracted from the model of Yoshizawa (2014) a change in heterogeneity regime is imposed with larger amplitude and shorter horizontal correlation length (cf. Thybo, 2008). In the asthenosphere beneath the deeper LAT bound the same style of heterogeneity is sustained.

This composite model with many different scales of heterogeneity in various depth ranges gives rise to a rich structure with a slow decline in the wavelength spectrum (Kennett & Furumura, 2016). In 2-D simulations it is able to produce a good representation of the character of high-frequency wave propagation out to 1500 km across the continent, and also the correlation properties of seismic waves at the PSAR array in northwestern Australia from an event in central Australia (Kennett & Furumura, 2016). Further the character of P wave reflectivity seen in te observations such as Figure 2 can be well reproduced.

3. DISCUSSION

Multi-scale heterogeneity in the continental lithosphere is required to represent the character of the seismic wavefield in Australia, both with regard to long-distance propagation and to near vertically travelling waves. Superimposed on the broad-scale variations extracted from seismic tomography, including radial anisotropy, there are modest levels of medium- and fine-scale features that can currently only be represented stochastically. Horizontal correlation lengths are longer than those in the vertical direction, and such effects lead to contribution to radial anisotropy when sampled by longer wavelength waves. In the presence of 3-D variations, there is the potential for an azimuthal anisotropic component as well.

The main framework of the lithosphere-asthenosphere transition can be extracted from the surface wave results, with shallower and deeper bounds derived from the vertical gradients of seismic wavespeed. Radial anisotropy tends to be weak in the mid-lower lithosphere, but more pronounced in the upper part of the lithosphere and in the LAT and asthenosphere beneath. The lower zone is likely to be influenced by mantle flow.

Only high frequency probes can reveal the presence of the finer scale structures directly, but they can have a profound role in shaping seismic observations at lower frequencies. Quite subtle changes in the style of velocity variation can induce reflections and conversions. With lower frequency probes interference occurs between waves generated from nearby features, and an apparent discontinuity can appear as the aggregate of fine scale changes. A change of heterogeneity style into the top of the lithosphere-asthenosphere transition, with both increased amplitude of fine-scale variation and a more squat planform of correlation, changes local anisotropic properties and modifies the interference between waves sampling the fine structure. Wave interference can thus contribute to the creation of an apparent mid-lithosphere discontinuity without there ever having been a major change in seismic wavespeeds.

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