Understanding the lithosphere in the vicinity of the Capricorn seismic lines from passive seismic studies

by

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Introduction

The Australian National University has carried out deployments of portable broadband seismic recorders across Australia since 1992. These instruments provide high-fidelity recordings of ground motion, and record both regional and distant earthquakes. The seismograms can then be analysed to generate information on the lithospheric structure beneath the Australian region, using a variety of analysis styles; an early example is provided by van der Hilst et al. (1998). An overview is provided by Kennett (2003).

The principal information obtained from regional earthquakes comes from the analysis of the large-amplitude surface waves late in the seismograms. These surface waves travel almost horizontally through the lithosphere and, with a sufficient density of crossing paths, can be used in a tomographic inversion to determine 3D structure in the lithospheric mantle. Receiver-based studies at individual stations exploit the conversions and reverberations following the onset of the P-wave energy. From distant earthquakes, information can be extracted about the structure in the crust and uppermost mantle.

In recent years, additional information has begun to be extracted from the seismic noise field through the stacked cross-correlation of signals at pairs of stations, which provide an approximation of the signal expected for a source at one station recorded at the other location. This ambient noise tomography approach was pioneered in Australia by Saygin (2007), who used the continuous data recordings at the portable stations in association with data from permanent seismic stations to link different experiments. The main signal comes from high-frequency surface waves that provide imaging of upper crustal structure, and which are particularly sensitive to the presence of sediments (Saygin and Kennett, 2010).

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Surface wave tomography

The earthquake belts north of Australia, along the Indonesian arc into New Guinea, and those to the east in the Tonga–Fiji zone, provide frequent seismic events of suitable magnitude that are well recorded in Australia. There are less common events to the south along the mid-oceanic ridge between Australia and Antarctica, but these are important in providing additional directional control. A number of different techniques have been used to analyse the large-amplitude surface waves that arrive late in the seismogram, and from the combination of these results from many paths, to extract 3D models of the seismic shear wavespeed distribution (e.g. van der Hilst et al., 1998; Debayle and Kennett, 2000, 2003; Kennett et al., 2004a,b; Yoshizawa and Kennett, 2004; Fishwick et al., 2005, 2008; Fichtner et al., 2009, 2010). Most of these methods rely on some approximations to wave propagation in three dimensions, although the work of Fitchner et al. (2009, 2010) uses full seismogram calculations in a 3D model. In consequence, the frequency range used is restricted to prevent excessive computational requirements. Fortunately, the results from this sophisticated analysis indicate that the longer wavelength features obtained with the approximate methods are confirmed.

We can now have considerable confidence in the main lithospheric structures at a horizontal scale of about 200 km and a vertical resolution around 30 km. Figure 1 illustrates the shear wave structure in Western Australia, using a new model developed through collaboration between the authors of different studies (Yoshizawa and Kennett, 2004, Fishwick et al., 2008; Fichtner et al., 2010). This new model benefits from the incorporation of more paths than any individual study, and includes the use of techniques that provide improved resolution at depth. The variations in seismic S-wave velocity are displayed in terms of the absolute shear wavespeed, with a neutral colour chosen to represent typical continental values.

Regions with faster S wavespeeds than the continental reference are indicated by bluish tones, and zones with slower S wavespeeds are shown in brown tones in

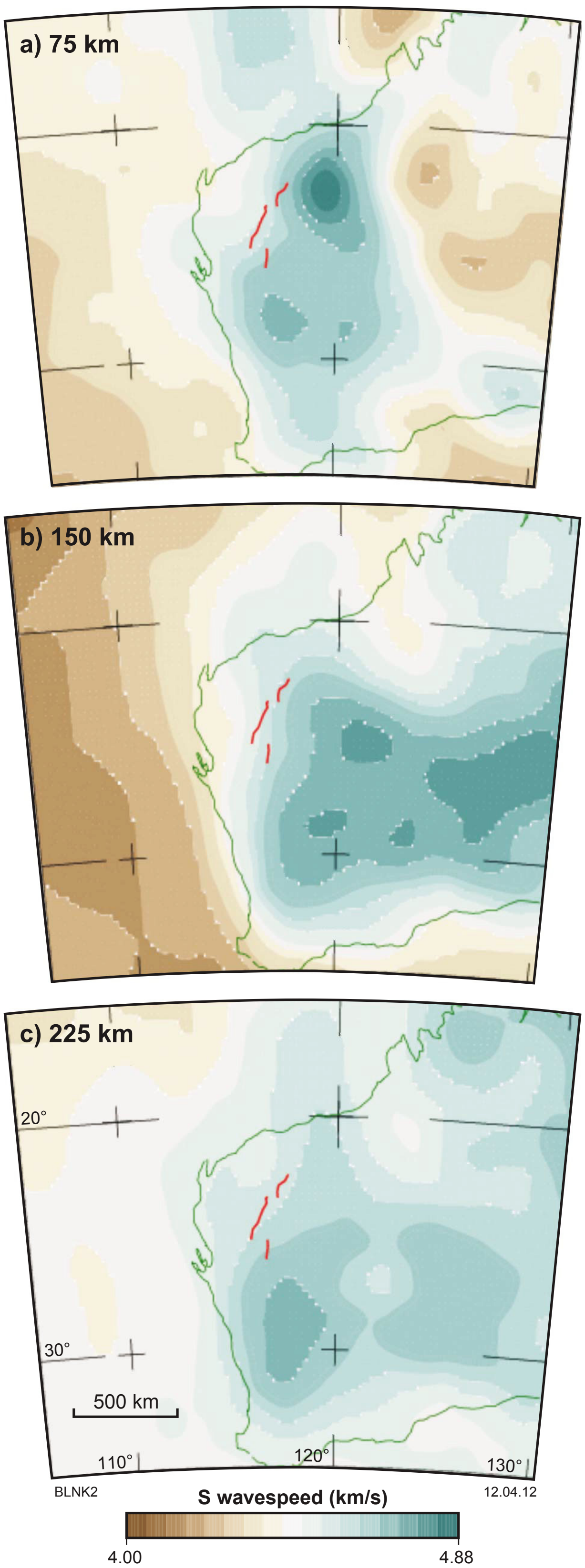

Figure 1. Seismic shear-wavespeed structure in Western Australia, determined from surface wave tomography. Continental scale measurements of seismic wavespeed variation at (a) 75 km; (b) 150 km; and (c) 225 km depth, inferred from the analysis of surface waves. The Capricorn lines are indicated in red in each panel.

Figure 1. Reductions in seismic wavespeed are expected from the influence of temperature, or the presence of volatiles. Faster wavespeeds are produced by cooler temperatures; however, the very fast wavespeeds seen in Figure 1 are very difficult to produce by temperature alone, and suggest the presence of chemical heterogeneity.

The mantle lithosphere below 100 km is marked by distinctly fast seismic wavespeeds, but at about 75 km, there is an indication of somewhat reduced wavespeeds (Fig. 1a) in the east of WA, which may be linked in part to the presence of thickened crust. This feature is not associated with enhanced seismic attenuation, as might be expected if the cause was a concentration of radioactivity in the uppermost mantle.

At 75 km, the Paterson Province is marked by very high seismic wavespeeds, and there is also a distinct, rather fast patch in the northern Yilgarn Craton. There is no distinctive mantle feature associated with the Capricorn Orogen, although we noted that at 225 km the Capicorn Orogen and Pilbara Craton show somewhat lower shear-wavespeeds than in the Yilgarn Craton. The surface wave tomography results are consistent with a situation in which the Capricorn Orogen is more strongly coupled to the Pilbara Craton than the Yilgarn Craton.

Receiver function studies

A powerful method to extract information on crustal structure is to analyse the conversions and reverberations immediately following the onset of the P wave for distant earthquakes using the receiver function technique. The two horizontal components of motion are then combined to produce records with polarization along, (radial) and perpendicular (tangential) to, the great circle back to the source. The rotated components are then deconvolved using the vertical component of motion that represents dominantly P waves. In this way, the influence of the source is largely eliminated, and attention is focused on wave propagation processes close to the receiver. When there is little energy on the tangential receiver function, 3D structural variation is weak and an inversion may then be made using a radial receiver function for an effective 1D structure in the neighbourhood of the receiver (e.g. Shibutani et al., 1996; Sambridge, 1999). Alternative approaches use stacking of receiver functions to emphasise features such as the conversion from the crust–mantle boundary, and hence constrain the depth of the Mohorovičić discontinuity (‘the Moho’). The moveout pattern of conversions and multiples from different source distances can be used to constrain the depth of seismic boundaries and Vp/Vs ratios (Zhu and Kanamori, 2000). It can also be advantageous to make a partial allowance for the influence of the free-surface on the seismograms by a rotation of components in the vertical plane, or a transformation (e.g. Reading et al., 2003a).

The first systematic treatment of receiver function results across Australia was made by Clitheroe et al. (2000a,b), with an emphasis on the thickness of the crust and the base of sediments; a few of these stations lie in the zone near the Capricorn profile.

A particular focus of portable broadband deployments since 2000 has been on Western Australia, with a number of deployments that now provide good coverage of the Archean cratons, and the Proterozoic Capricorn Orogen. Receiver function studies have provided clear evidence for segmentation of the Yilgarn Craton, with characteristic crustal structures for the individual terranes (Reading et al., 2003b, 2007).

In 2005, stations were deployed in association with the University of Western Australia, mostly along the coastal zone of northwestern Australia to monitor seismicity. Subsequently, in 2006–2007, a major deployment of 20 instruments was made throughout the Capricorn Orogen, and along the Telfer Road into the Paterson Province. The locations of many of the stations in this CAPRA project lie close to the reflection profile, and so provide very useful comparisons as to the nature of crustal structure. Reading et al. (2012) presents a detailed analysis of the receiver function responses at these CAPRA stations.

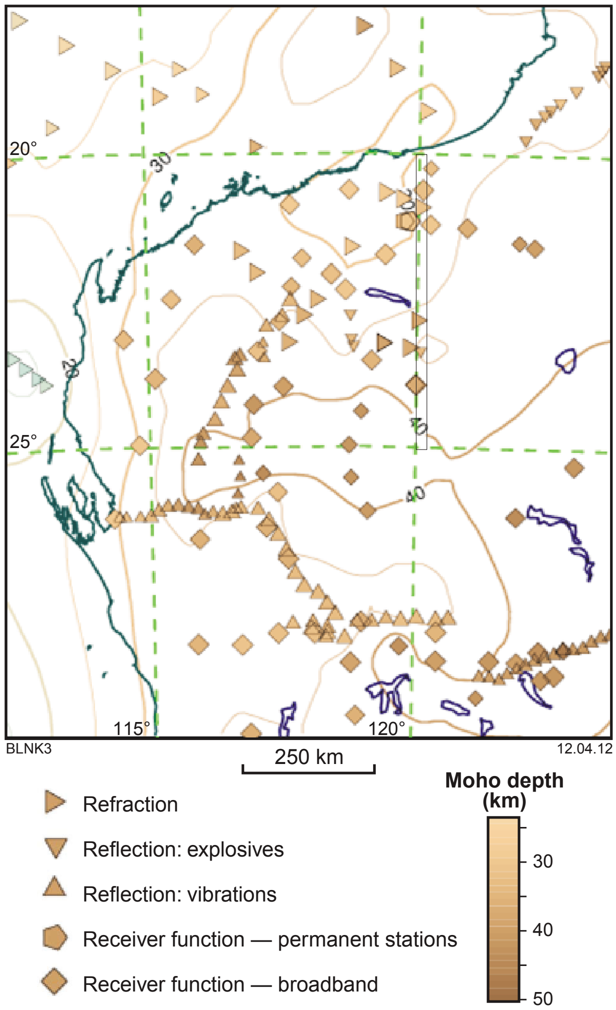

Figure 2. Estimates of crustal thickness derived from refraction experiments (triangles) and receiver function studies (diamonds — broadband stations; squares — short-period stations; less reliable results indicated by smaller symbols). Estimates of the Mohorovičić discontinuity ('the Moho') from reflection work are indicated by the dense lines of triangles. The contours of Moho depth are derived from a continent-wide synthesis (Kennett et al., 2011)

The estimates of crustal thickness derived from the receiver function analysis are summarized in Figure 2, and are plotted alongside results derived from refraction and reflection experiments. In each case, the crust–mantle boundary is taken at the base of the transition to mantle seismic velocities (P wavespeeds above 7.9 km/s, or shear wavespeeds above 4.4 km/s). In addition estimates of the depth to the Moho, derived from the Capricorn line and other reflection lines in the vicinity are included. There is a close correspondence between the estimates obtained from the different techniques and station deployments, even though the methods of analysis differ somewhat. Fortunately, most of the portable seismic stations appear to lie in zones without any dramatic steps in the Moho. The profile of crust thickness along the zone sampled by the recent CAPRA experiment has a similar configuration to that seen on the reflection profile, and in consequence, the receiver function results provide a check on the calibration of the time–depth conversion for these reflection results.

The background contour plot of the Moho in Figure 2 is derived from a continent-wide synthesis of results, using all receiver functions and the refraction data from the compilation of Collins et al. (2003), with additional control from reflection experiments (Kennett et al., 2011).

Discussion and conclusions

Passive seismic methods exploiting natural events provide valuable information on 3D variations in lithospheric structure, which can be helpful in the interpretation of other classes of information, such as reflection seismic profiles. Surface wave tomography provides information on mantle structure, with the most reliable results available below 75 km depth. At shallower depths, there is a strong influence from the crustal structure along the various paths, and the crustal structure can be mapped into the uppermost mantle — especially where the crust is thick. The body-wave portion of the seismograms from distant earthquakes yields additional information on structure in the crust and uppermost mantle from the analysis of receiver functions.

Body wave tomography exploiting the times of arrival of seismic phases from regional and teleseismic events, can provide constraints on crustal structure when stations are sufficiently close together. Abdulah (2007; Fig. 3) shows the results of tomography exploiting all available P-wave readings, from both local events and refraction experiments, and distant earthquakes. The contrasts in P wavespeed show a very high correlation with outcrop of the Pilbara Craton.

The results for the area around the Capricorn Orogen line show a strong distinction in the crust between the Pilbara Craton, with a relative thin crust at 30–33 km, and the Capricorn Orogen, where the crust thickens significantly. There is again a sharp change in crustal thickness into the

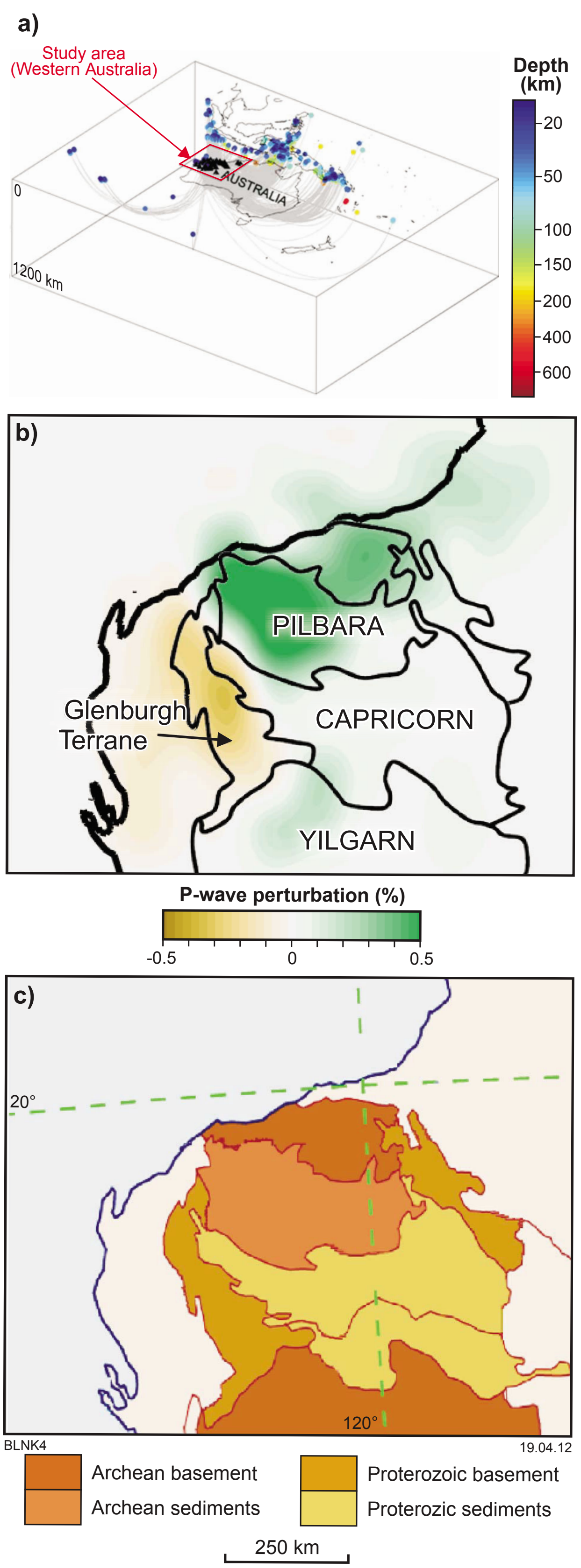

Figure 3. **P-wave tomography for northwestern Australia (Abdulah, 2007) for the crustal depth range of 0–35 km; a) configuration of earthquake sources and ray paths, supplemented by local observations from 1977 refraction experiments; b and c) a number of inversions have been undertaken with slightly offset grids, with the results averaged to give a composite image with improved resolution than any individual grid. The zones of fast wavespeed (green) coincide with the elements of the Pilbara and Yilgarn Cratons. Most of the Capricorn Orogen is neutral, but the Glenburgh Terrane shows as distinctly slower (gold).**

northern Yilgarn Craton. However, the mantle beneath the Capricorn Orogen appears to have greater affinities with the Pilbara Craton, and does not share the rather high-shear wavespeeds seen beneath the Yilgarn Craton.

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