Contrasts in lithospheric structure within the Australian craton—insights from surface wave tomography

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Abstract

Contrasts in the seismic structure of the lithosphere within and between elements of the Australian Craton are imaged using surface wave tomography. New data from the WACRATON and TIGGER experiments are integrated with re-processed data from previous temporary deployments of broad-band seismometers and permanent seismic stations. The much improved path coverage in critical regions allows an interpretation of structures in the west of Australia, and a detailed comparison between different cratonic regions. Improvements to the waveform inversion procedure and a new multi-scale tomographic method increase the reliability of the tomographic images. In the shallowest part of the model (75 km) a region of lowered velocity is imaged beneath central Australia, and confirmed by the delayed arrival times of body waves for short paths. Within the cratonic lithosphere there is clearly structure at scale lengths of a few hundred kilometres; resolution tests indicate that path coverage within the continent is sufficient to reveal features of this size in the upper part of our model. In Western Australia, differences are seen beneath and within the Archaean cratons: at depths greater than 150 km faster velocities are imaged beneath the Yilgarn Craton than beneath the Pilbara Craton. In the complex North Australian Craton a fast wavespeed anomaly continuing to at least 250 km is observed below parts of the craton, suggesting the possibility of Archaean lithosphere underlying areas of dominantly Proterozoic surface geology.

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1. Introduction

The Australian continent provides an excellent platform to investigate the variations in lithospheric structure within a large cratonic region. Global studies [1,2] illustrate large-scale correlations between lithospheric properties and the age of the crust, but acknowledge that the detailed picture of lithospheric structure is more complicated than any simple relationship [1]. Within the Australian continent the large differences in seismic structure beneath the older Precambrian shield regions compared to beneath the

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younger Phanerozoic regions have been seen in seismic data since the 1960s [3]. The craton consists of an amalgamation of blocks of Archaean and Proterozoic age (see Section 1.1), and is bounded to the east by the Phanerozoic region of the continent. A more robust image of the lithospheric structure beneath the craton will enable the formation and evolution of the Australian continent to be discussed in greater detail.

Surface wave tomography, exploiting regional earthquakes, is an ideal tool to develop a more detailed picture of the seismic structure within the continent. A wide distribution of events and recorders is required to produce a reliable tomographic image. The active plate boundaries to the north and east of Australia (through Indonesia, Papua New Guinea, Solomon Islands, Vanuatu, Fiji, Tonga and New Zealand) give a wide distribution of frequent earthquakes. A limited number of additional events to the south of Australia, and events from the 90°E ridge system in the Indian Ocean, allow us to record earthquakes from most azimuthal directions. Although there are only a few permanent seismic stations with broad-band recording in Australia, the stable continental interior and scarcity of large urban areas make much of the continent ideal for the deployment of temporary seismic recorders. This has been exploited to provide continent-wide recording of the adjacent seismicity, and hence the potential for excellent surface wave imaging of the region.

1.1. Tectonic setting

The shield region of central and western Australia consists of three main cratonic blocks (the West, North and South Australian Cratons) separated by either orogenic belts, which may represent the accretionary margins of these terranes, or more recent Phanerozoic sedimentary cover [4] (Fig. 1).

In the northern part of the West Australian Craton is the Pilbara Craton; one of the oldest regions in Australia with tectonic evolution beginning around 3.5 Ga. The Yilgarn Craton covers the majority of the southern part of the West Australian Craton and is one of the largest blocks of Archaean crust that survives today. Located between the Pilbara and Yilgarn

Fig. 1. Overview of the geology of the Australian continent, highlighting the major Archaean and Proterozoic regions. The locations of the broad-band seismometers used in the temporary deployments (SKIPPY, KIMBA, QUOLL, WACRATON, TIGGER) are shown with pentagons and diamonds.
Cratons, the Capricorn Orogen reflects the suturing of the two cratons during the Palaeoproterozoic [5].

The North Australian Craton comprises an amalgamation of blocks of Precambrian age including the Kimberley Craton in the west, Mt Isa Inlier towards the east and Arunta Inlier in the south. The majority of the Kimberley Craton is overlain by ancient sediments with little of the original basement exposed. The Kimberley is thought to have amalgamated with the rest of the North Australian Craton during the Palaeoproterozoic Halls Creek Orogeny. The Mount Isa block contains Late Archaean and Early Proterozoic crust, while the Arunta Inlier in the south of the craton is dominantly Proterozoic in age, and contains remnants of the accretionary margin that existed on the southern edge of the craton at this time [4]. The tectonic evolution of the Arunta continues into the Palaeozoic, through to the Alice Springs Orogeny (400–300 Ma) which uplifted deeper crustal rocks to the surface [6].

The South Australian Craton is dominated by the Gawler Craton in the central region, containing Archaean to Mesoproterozoic basement. To the west basement is covered with recent sediments on the Nullarbor Plain. To the east is the Curnamona province, which, although mainly covered by sediments, is delineated by aeromagnetic data. Where exposures exist, the basement is of late Palaeoproterozoic age.

The amalgamation of the Australian shield occurred during the Proterozoic, and was dominated by the long-lived accretionary margin on the southern edge of the North Australian Craton. To the east of the Precambrian cratons are a number of Phanerozoic units. The nature of the boundary between the ancient shield regions and the relatively younger eastern part of the continent, often referred to as the Tasman Line, is presently under discussion, both in the crustal location and meaning [7], and the mantle extension compatible with the present seismological models [8].

1.2. Previous studies

The contrast in seismic structure beneath the Phanerozoic eastern margins of Australia and the Precambrian shield area was indicated in early work on travel time anomalies within Australia from the Bikini and Eniwetok nuclear explosions in the Marshall Islands and the LONGSHOT explosion at Amchitka Island in the Aleutian’s. Cleary [3] observed early, fast, travel time anomalies within shield areas, and late, or slow, anomalies in southeastern Australia and Tasmania. Surface wave studies by Goncz and Cleary [9] in the 1970s found large differences between the two regions, noticeably a low-velocity zone at approximately 130 km deep in eastern Australia, which is absent beneath the shield area of central and western Australia. Small regions of the continent have been studied in some detail using arrays of short period recorders and body wave tomography (see, e.g., [10]), however the comparison of structure across the whole continent has been made possible through surface wave inversion studies using data from temporary broad-band deployments (e.g., SKIPPY, KIMBA) [11].

Zielhuis and van der Hilst [12], using the partitioned waveform inversion (PWI) method of Nolet [13], first used the early SKIPPY deployments in the east of the continent, and were able to provide a clear image of the low-velocity zone in the east, and also a pronounced increase in the thickness of the high-velocity lid under the Proterozoic continental regions. Simons et al. [14] investigated a possible regionalisation of the model, comparing areas based on geological province. At this stage data were limited in Western Australia, but within central Australia it appeared that there was no obvious relationship between seismic signature and lithospheric age. More recently, Simons and van der Hilst [15] again show that at scale lengths less than 1000 km the relationship between the age of the crust and the thickness of the lithosphere is very complicated.

An alternative method of surface wave tomography has also been applied to the Australasian region. Based on the waveform inversion technique of Cara and Leveque [16] and the continuous regionalisation algorithm of Montagner [17], Debayle [18] created an automated tomographic inversion scheme. The Cara and Leveque inversion scheme uses secondary observables derived from the waveform by cross-correlation, rather than directly inverting the waveform itself. The latest work [19] using this inversion scheme has a dataset of over 2000 paths, and looks at both azimuthal and polarization anisotropy, investigating the change from a complex pattern of
anisotropy in the uppermost layer to a smoother pattern below 150 km deep probably related to the large-scale plate motion.

The various approaches to surface wave tomography yield similar results on a large scale; however the small-scale features of the models are quite different. Choices made for regularisation and parameterisation of the inversion procedure affect the models (see e.g., [20]), while at depth different treatments of the higher modes account for some of the differences. Furthermore, lack of adequate path coverage in western Australia has made interpretations of the intracratonic areas difficult.

New data from Western Australia improve the continental coverage significantly and now allows a comparison of the lithospheric structures between the three main cratonic regions, and an investigation of the relationship between mantle structure and surface geology.

2. Data and methods

The data used for the surface wave tomography consist of recordings from broad-band seismometers throughout the Australian region (Fig. 1). Previous studies (Section 1.2) used data from the SKIPPY, KIMBA and QUOLL experiments (undertaken by the Research School of Earth Sciences, Australian National University) alongside data from permanent seismic recording stations in the Australasian region. The present study benefits greatly from the inclusion of additional data from the most recent temporary deployments of portable broad-band seismometers, WACRATON and TIGGER.

A variety of portable instruments have been deployed during the experiments. A combination of Güralp CMG-3ESP, CMG-40T and Streckeisen STS-2 seismometers have been used. Reftek 72A-07 recorders were used in the older experiments, while a combination of Refteks and Nanometrics Orion recorders have been used since WACRATON. The varying responses of these instruments must be known as well as possible for successful application of the waveform inversion procedure. The majority of the seismometers have flat responses to ground velocity between 30 Hz and 0.033 Hz (30-s period), although some of the CMG-3ESPs have a flat response to 62.5 s, while the STS-2 has the longest flat response extending to approximately 125 s.

Data from the permanent seismic stations in the region, and the Southern Alps Passive Seismic Experiment (SAPSE) in New Zealand [21], have also been used to supplement the path coverage obtained from the temporary deployments. The number of paths into the permanent stations has been limited in an attempt to avoid potential bias in the tomographic models produced by too large a concentration of similar paths into a single station. Instead data from permanent stations are used to improve the azimuthal coverage throughout the region and provide additional data through areas where path coverage is otherwise limited.

2.1. 1D path-specific models

The initial stage of the inversion of the surface wave data is to extract a 1D model characterising a specific path from source to receiver. The procedure of calculating the 1D models is split into two distinct parts: firstly a waveform selection process, and secondly the waveform inversion. The waveform selection process has the goal of submitting only high-quality seismic waveforms to the subsequent inversion. The seismogram must contain the appropriate portion of the data, the fundamental and higher mode Rayleigh wave-train on the vertical component, for an event at sufficient distance (>1000 km) from the recorder to avoid the effects of complications from the source region. The quality of the seismogram is assessed using estimates of the signal ($A_s$) to noise ($A_n$) ratio at four frequency bands within the periods of interest (50 to 140 s). The waveform is used if the signal-to-noise ratio $A_s/A_n>3$ for at least two of the frequency bands.

Having identified suitable seismic waveforms, the inversion process is now controlled by a modified version of the automated procedure of Debayle [18]. We attempt to find the 1D shear velocity model that gives the best fit between the secondary observables for the real seismic waveform and the corresponding quantities for a synthetic seismogram calculated for the current 1D model. In order to create an efficient inversion procedure, the secondary observables are chosen to reduce the non-linearity of the Rayleigh waveform data with respect to the model parameters,
and reduce the dependence on the starting model [16].

In previous work, the starting model for the inversion procedure has been a smoothed version of PREM (preliminary reference Earth model) [22], with a crustal average along the path calculated from 3SMAC [23]. Although the Cara and Leveque inversion scheme improves the domain of recovery to a larger perturbation from the starting model than PWI [24], we now introduce another step to improve our set of 1D models. Rather than calculate the 1D model from only one starting model, we perform inversions from seven different starting models. The new starting models are still based on PREM, but have perturbations of $-4.5, -3, -1.5, +1.5, +3, +4.5\%$ in the upper mantle between 50 and 200 km, before slowly converging back to PREM at 500 km depth.

Using multiple starting models enlarges the domain where we can recover a 1D model. For example, a dominantly oceanic path can be very slow, and hence using starting models with negative perturbations from PREM gives an increased chance of recovering the 1D model. The 1D path-specific model that we use in the tomographic inversion is a weighted average of the group of similar final models that are accepted through the inversion scheme. The consistency of the group of models from the multiple inversions gives an additional means to assess the reliability of the wavespeed profile with depth, this information is used in weighting the information from each path within the tomographic inversion.

For this work, we obtain 1D models for 2116 paths. 1400 Paths are from temporary stations deployed in the Research School of Earth Sciences experiments, with additional 716 paths to the permanent stations and SAPSE deployment. The present data limit the potential bias introduced by concentrations of similar paths into a few permanent stations, and importantly give a more uniform path coverage (Fig. 2) allowing comparisons of structure throughout the Australian continent.

2.2. Tomographic inversion

The 1D models representing a path-average for each source–receiver pair are used within a tomographic inversion to derive a model of the 3D velocity structure for the Australasian region. We here use the parameterisation scheme of Yoshizawa and Kennett [25] where a local basis function, in this case a spherical B-spline, is defined throughout the region with knot points at uniform intervals. This approach provides a smooth representation of wavespeed
variations with scale lengths determined by the choice of knot spacing.

The 1D models can be regarded as an average along the path. The reconstruction of the 3D model can be achieved by a linear inverse problem relating the velocity perturbation at a particular point to the path information at the same depth. The tomographic inversion is solved using a damped least squares inversion scheme [26]. The data are weighted to control the relative contribution on each path based on our estimate of the reliability of the 1D model. Damping is used to control the trade off between model variance and resolution (or prediction error and solution length). If the damping is large we will minimise the under-determined part of the solution, but will not minimise the prediction error. If no damping is applied we minimise the prediction error, but no a priori information will be used to single out under-determined parameters [27].

Originally the a priori reference model used in the damping was a global reference model, where wavespeed only varies with depth, e.g., PREM or AK135 [28]. However, previous tomographic models for the Australian region have revealed sub-continental velocities much faster than the reference model, while beneath the oceans the velocities are far slower than the global model. Tests on synthetic structures suggest that a least squares inversion with model-norm damping towards a homogeneous reference model, will struggle to recover small scale features within the contrasting regions. We therefore take an alternative approach to the inversion using a multi-scale approach (see e.g., [29]) to the tomography (Fig. 3). We first create a broad-scale model using knot points at 8° intervals, to obtain the large-scale structure in the region. The resulting model is then used as the reference model for the final 2° inversion, and we now damp towards the large-scale features within the data, rather than towards a global reference model.

3. Surface wave tomographic images

The tomographic images illustrated in Fig. 4 are from the final models produced from the multi-scale scheme, with knot points at 2° intervals. The models are plotted as perturbations from the 1D global reference model AK135 [28]. At all depths the same colour scale is used, with saturation at perturbations greater than ±7.5%. Models are shown at 50-km depth slices from 100 to 300 km.

By 100 km depth, the fast wavespeeds characteristic of an ancient shield region are seen throughout the cratonic area. Slightly fast velocities are also seen in parts of eastern Australia, with much slower velocities on the very eastern margin of the continent. The largest variations in shear wavespeed are seen at a depth of about 150 km, with variations of slightly more than 15% between the fastest and slowest velocities. The potential causes of the velocity variations are discussed in more detail in Section 4.1. Below 200-km depth the fast velocities become more fragmented and the magnitude of the wavespeed
anomalies starts to decrease. It is apparent that some of the fast wavespeed anomalies at these depths are not associated with the continuation of the lithosphere and have their origin in the sub-lithospheric mantle features.

3.1. Resolution

As an aid to assessing the reliability of the tomographic models, we illustrate results from a selection of synthetic tests. From the previous studies...
of the Australian region it is clear that we expect to see features of different scale lengths, e.g., contrasting velocities of craton against ocean compared to intracratonic variations. As simple checkerboard tests only indicate resolution for a particular scale of anomaly [30] we create a multi-scale input structure (Fig. 5a), for the tomographic inversion step, as an approximation for the type of structure we hope to resolve. A set of 1D models are created from this multi-scale input by averaging along the actual paths and these are then employed to attempt to reconstruct the imposed wavespeed structure. A component of noise has been added relative to the weighting for the path used in the actual inversion as a means of simulating the limitations of the waveform inversion step. As in the actual inversions the path-specific models for the synthetic input are weighted by an estimate of the reliability of the path information.

The results from this synthetic test at 100 km are illustrated in Fig. 5. Comparison of the output model with the input model highlights some important of the tomographic results. The sharp contrast at 148° east is recovered well, this is a similar structure to the contrast associated with the Tasman line in the real data. However, to the west of Australia the same contrast is not recovered nearly as well, due to the relatively poor azimuthal variation in path coverage in this dominantly oceanic region (Fig. 2). Within the Australian continent the pattern of high and lower wavespeed anomalies is recovered, although there is some smearing of the velocities. The small-scale features are not that well resolved to the south and west of the continent, again this is not surprising given the more limited path coverage in these regions. We limit our main discussion to features within the continent, where resolution at this depth is sufficient to resolve structures with horizontal scale lengths of a few hundred kilometres.

The multi-scale models are appropriate for the shallower mantle, but by 250-km depth we are below the lithosphere for most of the continent and expect to see a simpler pattern of anomalies. At such deeper levels standard checkerboard tests should provide useful information on the potential resolution. We illustrate the results of two different resolution tests with different size anomalies (3 and 5°) separated by regions of neutral velocity (Fig. 5b,c). Once again, the influence of error from the waveform inversion is simulated through added noise relative to the weighting for the path in the actual inversion at this depth; paths with good higher mode information will therefore have less noise. The 3° input structure is not recovered particularly well at 250-km depth (Fig. 5b); although we see some recovery of the general pattern the recovered amplitudes are lower and there is significant smearing. Using larger size anomalies (Fig. 5c) we see a better recovery of the amplitudes of the imposed anomalies, although there is still some smearing. The recovery of regions with neutral velocity is poorer, this is partly due to the implicit smoothing of the spline parameterisation used to represent the output model, which is different to that used to create the input. These resolution tests illustrate that at greater depths in our model the amplitudes of the anomalies are likely to be more reliable for larger features.

Our results indicate the recovery of synthetic structures for particular depth slices of the tomographic inversion. While we see reasonable recovery of the structures within the continent for this test, we have to recognise the assumptions used within the tomographic inversion. In this study we assume great circle propagation and only consider the sensitivity to structure on the ray path. In reality the seismic waves are influenced by a zone around the path. Neglecting this influence zone means that the realistic resolution is slightly less than the idealized resolution seen from the synthetic tests [25].

The tests we have performed provide a useful assessment of potential horizontal resolution. However it is more difficult to track resolution in depth through the two-stage surface wave inversion. In the second tomographic step each depth slice of our model is calculated separately, and therefore any vertical smearing arises from the construction of the original 1D path-specific models. It is therefore difficult to provide a simple resolution test because the result will be heavily dependent on the specific form of any anomalies.

The reliability of the deeper part of 1D models is markedly improved when higher mode information is available [31], and so such paths are given higher weighting. The distribution of events in depth to the north and east of Australia is favourable for such higher mode contributions, but the shallow ridge events to the south are dominated by fundamental
Fig. 5. Synthetic tests of the horizontal resolution for the tomographic inversion. Top—input structures (a) 100-km depth: contains multi-scale anomalies, maximum perturbations are ±8%; (b) 250-km depth: simple checkerboard pattern with 3° anomalies, the same size as the smaller scale features used at 100 km, maximum perturbations are now ±5%; (c) 250-km depth: larger checkerboard anomalies, 5°; maximum perturbations are ±5%. Bottom—the recovered structures for each tomographic inversion. The same colour scale is used for all images.
modes. The half width of the resolution kernels for a particular 1D model will be in the order of 30 km between 75 and 200 km depth. This means that the largest wavespeed anomalies have the possibility of a small level of leakage between the sections at 50-km depth intervals as displayed in Fig. 4. The quite distinct geographic patterns in the different images suggest that such leakage is not that significant for regions with good data coverage. In the shallowest part of our models there may be some influence from crustal structures. However, the shortest period used in this study is 50 s and at this period the sensitivity kernels are not strongly sensitive to structure in the crust (as illustrated in [19], Fig. 2).

4. Discussion and conclusions

4.1. Velocity variations

The tomographic images illustrate large velocity variations within the Australian region, with variations of about 15% at 150-km depth. Below we briefly discuss the potential causes of the velocity variations within the upper mantle.

Goes et al. [32] combine results from many mineral physics studies to consider the effect of temperature and composition on seismic velocities, and then estimate temperatures in the mantle from P and S tomographic results within Europe. Considering only the anharmonic temperature effect they calculate changes in shear wave velocity of less than 1% per 100 °C. For the range of shear wavespeeds that we have imaged (Fig. 4) a purely anharmonic interpretation would lead to unreasonably large temperature variations in the upper mantle. However, including the effects of anelasticity increases the influence of temperature on shear wavespeed to between 1 and 4% per 100 °C [32], thus reducing the temperature variations that would be required to explain the imaged wavespeed variations.

The effects of composition are calculated to be much smaller than the effect of temperature [32], and shear wavespeed variations alone are unlikely to be able to resolve chemical variations within the mantle. Deschamps et al. [33] propose a method using tomographic models and gravity data to infer chemical variations within the mantle, which has recently been applied to the Australian continent [34].

Although temperature is likely to be the strongest control on the seismic velocity, other variables such as water and partial melt [35] and grain size [36] will have an effect on the seismic velocities observed within the mantle. Due to the complicated interactions of these variables it is beyond the scope of this paper to perform quantitative calculations to calculate possible mantle temperatures or to estimate chemical variability. However, Faul and Jackson [37] have developed a new formulation for the combined influence of temperature and grain size on shear wavespeed based on recent experimental work at seismic frequencies; their modelling based on the shear velocity distribution in our tomographic images indicates variations in temperature of approximately 600 °C between the oceans and the oldest parts of the Australian craton at a depth of 150 km.

We concentrate here on the location of anomalies, and the potential relationship with surface geology.

4.2. Intracratonic structure

At a depth of 100 km fast velocities, about +4% relative to AK135, are seen throughout much of the continent. The fastest velocities are seen in western Australia beneath the Pilbara Craton and northern parts of the Yilgarn Craton. Previous work has tended to concentrate anomalies in western Australia towards the southern part of the Yilgarn Craton, probably due to the limited path coverage being dominated by paths to the permanent station, Narrogin (NWAO), in the southwest corner of the continent.

To the east of the main cratonic region we also see fast wavespeeds that are related to the depth extent of Phanerozoic lithosphere. On the eastern margins of the continent, as seen in the early work by Zielhuis and van der Hilst [12], the very low velocities near the northeast coast of Australia and around the Bass Strait correspond spatially with areas that have undergone Neogene volcanism.

The fast velocities in western Australia continue to greater depth. Beneath the Yilgarn Craton a large fast wavespeed anomaly is clearly seen to at least 250-km depth. This feature does not appear to be continuous from east to west across the craton, but has slower velocities in the central Yilgarn and faster zones at the
western and eastern edges. In contrast, below 150 km, the large fast velocity perturbations are not seen beneath the Pilbara Craton. The synthetic tests (Fig. 5b) suggest that at 250-km depth due to the small size of the Pilbara Craton it would be difficult to resolve a fast velocity anomaly. We therefore must be cautious with any interpretation in this region, however the rapid change from fast to neutral velocities at shallower depths of between 150 and 200 km suggests that the Pilbara may not have as deep a lithospheric keel as the Yilgarn Craton.

In northern Australia, the Kimberley Block is underlain by fast velocities to a depth of around 250 km, and the region of faster velocities extends further south than is apparent from the surface geology. This deep anomaly may be related to older Archaean lithosphere, as isotopic data from diamondiferous kimberlites suggest that Archaean lithosphere once existed beneath the Kimberley craton [38]. Recent work [39] indicates a possible connection between the edge of this anomaly and the occurrence of diamond deposits in the region. At 200 km a distinct break in the fast anomalies is seen below the Canning Basin, which separates the Kimberley and Pilbara Cratons, and also to the east of the Kimberley Craton. The other dominant region of fast velocities is a predominantly north–south belt that runs from the edge of the McArthur Basin, to the west of Mt Isa, and into the eastern edge of the Arunta. This anomaly continues to at least 250 km, and is very similar in magnitude to that seen in the Yilgarn, suggesting the possibility of an Archaean lithospheric root in this region.

Within the South Australian Craton there appear to be variations in the extent of the lithosphere. Underlying the Curnamona block fast velocities are seen to around 150 km. Below this depth the transition to positive anomalies moves to the west. Beneath the Gawler Craton fast velocities are seen to 250 km, however this is a region where path coverage (Fig. 2) is limited and we see smearing in our resolution tests (Fig. 5). We are therefore less confident in the interpretation for this area. A current deployment of portable broadband seismometers should provide more data for this area, and reduce the uncertainties in future work.

The structure of the lithospheric mantle beneath Australia is quite complicated, the location of the fastest wavespeeds changes with depth, and uncertainties in the original age of the North Australian Craton make a simple relationship with the surface geology unclear. In contrast, tomographic results from P- and S-delay times in South Africa [40] indicate a simple relationship where the highest velocities are confined to the region beneath the Archaean Kaapvaal Craton, with lower velocities in the Proterozoic mobile belt to the south. Images from the Fennoscandian region of the Baltic Shield are more complicated, body wave tomography [41] indicates no obvious feature related to the Archaean–Proterozoic suture, but recent surface wave tomography [42] illustrates a different character of structure beneath the Archaean province in comparison to the Proterozoic, although faster wavespeeds are not observed at all depths within the Archaean region. Work in the Canadian shield [43] also indicates no obvious correlation between the depth of the lithosphere and the age of the overlying geological units.

Some variations in lithospheric structure are likely to be a result of the tectonic history of the continent since formation. Assuming the mantle root beneath the Precambrian shield is related to the formation of lithosphere in the Precambrian, then it is also highly likely that this mantle has been affected by the tectonic processes that occurred since that formation. For example, if a geological reconstruction suggested multiple episodes of subduction, it is unreasonable to think that the lithospheric mantle would be unaffected by this series of events, and this may explain some of the complexity to the lithospheric structure that is imaged in the present tomographic models.

### 4.3. Shallow structure

The image of our shallowest depth slice, at 75 km (Fig. 6a), gives an intriguing picture of the uppermost mantle structure underneath the Australian Craton. The West Australian Craton is quite well defined by the high seismic velocities. The highest velocities are seen beneath parts of the Pilbara, Capricorn Orogen and the northern Yilgarn. Within the North Australian Craton we generally see slightly fast velocities, particularly in the northern parts, the Kimberley, Pine Creek Inlier, McArthur Basin and northern Mt Isa Block. In contrast, in the southern parts of this craton, and within much of central Australia we see lowered velocities that are not expected within a cratonic region.
The cause of these lowered velocities is difficult to explain. At these shallowest depths the tomographic models might be affected by smearing of crustal structure. However the region of low velocity does not relate to any a priori information in 3SMAC, and if the low velocities were simply related to deeper crust we would expect to see the strongest feature in the northern Mt Isa region, and thus better correlation with work [45,46] on patterns of crustal thickness.

The unusual slow velocities are confirmed by body wave data. Fig. 6b illustrates the pattern of arrival times of S waves from less than 20° plotted along the propagation path [44]. In the central region slow velocities are seen along paths from earthquakes near Tennant Creek to stations to the south and southwest. Despite the slow propagation speeds the attenuation along these paths is low and high frequencies are retained. The body wave paths turn well below the crust and the concordance with the surface wave results provides strong support for the reduced wavespeeds to be in the uppermost mantle. Future work will aim to give better constraints on the magnitude and location of this anomaly and possible trade offs between crustal and mantle velocities.

4.4. Conclusions

The inclusion of data from new temporary deployments of broad-band seismometers, particularly in Western Australia, provides improved images of 3D shear wavespeed and thus a comparison of structure within the Australian Craton. The additional data from stations in Western Australia not only improve definition of the Archaean cratons but also markedly increase path coverage in central Australia compared with previous studies. At shallow depths, the mantle beneath the West Australian Craton has fast shear wavespeeds. In contrast, below central Australia we see a zone of lower seismic velocity in both body wave and surface wave results, which is unusual for a cratonic region.

At depths greater than 100 km, we see fast velocities throughout the Australian Craton. There are structures on scale lengths of a few hundred kilometres within the cratonic lithosphere. Fast velocities extend deepest beneath the Yilgarn Craton. Beneath parts of the North Australian Craton, including the Kimberley, fast velocities are also seen to depths of at around 250 km. If we assume a relationship between the age and depth extent of the lithosphere, this would suggest that a large part of the North Australian Craton, to the west of the Mt Isa Block is underlain by Archaean lithosphere.

The pronounced high wavespeed features below the Yilgarn Craton in Western Australia continue to about 250 km and then link to a zone of slightly fast wavespeeds, but with an east–west rather than north–south orientation (Fig. 4—300 km). It is therefore rather difficult to determine a particular depth to which the lithospheric keel continues.
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