AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL063845

Key Points:
- Anomalous radial anisotropy is found in the suture zone between three cratons
- Thick cratonic lithosphere and gradational base is found in western Australia
- Strong anisotropy beneath the lithosphere may reflect asthenospheric flow

Supporting Information:
- Text S1 and Figures S1–S3

Correspondence to:
K. Yoshizawa,
kazu.yoshizawa@mail.sci.hokudai.ac.jp

Citation:
Yoshizawa, K., and B. L. N. Kennett (2015), The lithosphere-asthenosphere transition and radial anisotropy beneath the Australian continent, *Geophys. Res. Lett.*, *42*, 3839–3846, doi:10.1002/2015GL063845.

Received 13 MAR 2015
Accepted 30 APR 2015
Accepted article online 6 MAY 2015
Published online 26 MAY 2015

The lithosphere-asthenosphere transition and radial anisotropy beneath the Australian continent

K. Yoshizawa[1] and B. L. N. Kennett[2]

[1]Department of Earth and Planetary Sciences, Faculty of Science, Hokkaido University, Sapporo, Japan, [2]Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia

Abstract A new 3-D *S* wave speed model for the Australian region derived from multimode surface waves allows us to examine the nature of the lithosphere-asthenosphere transition (LAT) and its relation to radial anisotropy. In eastern Phanerozoic Australia the estimated depths of the LAT tie well with those from receiver functions. However, in the Archean and Proterozoic lithosphere in western and central Australia, the LAT derived from the surface wave model is generally much deeper than the discontinuities recognized from receiver functions and shows a smooth transition. There is significant radial anisotropy ($SH > SV$) in the upper lithosphere as well as in the LAT and the underlying asthenosphere. Strong anisotropy in the asthenosphere reflects the effects of present shear flow in the mantle beneath the continent. The lateral variation of lithospheric anisotropy correlates well with the suture zones between cratonic blocks, representing frozen anisotropy associated with the ancient tectonics of Australia.

1. Introduction

The nature of the transition from the lithosphere to the asthenosphere (LAT) provides a key to understanding the interactions of continents and plate tectonics. Since the LAT is fundamentally associated with a change in rheology rather than elastic properties, it represents a mechanical or thermal boundary layer rather than a simple interface, which makes it difficult to detect it with reflection or transmission of seismic waves. Nevertheless, physical properties that are responsible for a change in rheological properties often result in a change in wave speeds, which allows us to unravel this elusive boundary layer by combining a variety of seismological observations.

Recent studies of the LAT using body wave receiver functions have revealed evidence for clear converted signals at the bottom of lithosphere in oceanic regions [e.g., *Kawakatsu et al.*, 2009] and in some Phanerozoic continental regions [*Abt et al.*, 2010; *Ford et al.*, 2010]. In each case the depth is consistent with the thickness of the fast velocity lid inferred from surface wave studies. However, this is not always the case for Archean and Proterozoic cratonic regions [*Fischer et al.*, 2010]. The most prominent apparent zones of seismic wave conversion beneath cratons in North America and Australia occur within the zone of elevated seismic wave speeds above 100 km depth [*Abt et al.*, 2010; *Ford et al.*, 2010], which is recognized as the midlithosphere discontinuity (MLD), while the *S* wave speed profiles from surface waves indicate thicker cratonic lithosphere with fast anomalies in the top 200 km [e.g., *Simons and van der Hilst*, 2002; *Fishwick et al.*, 2008]. The cause of the MLD detected by receiver functions is still largely unknown, despite a number of observations in many cratonic regions [e.g., *Selway et al.*, 2015].

The LAT is often discussed in relation to seismic anisotropy. For the Pacific plate, *Nettles and Dziewonski* [2008] reported anomalous radial anisotropy with $SH > SV$ in the asthenosphere beneath. *Burgos et al.* [2014] studied the association of changes in both azimuthal and radial anisotropy in the oceanic domain with the LAT depth, and *Beghein et al.* [2014] used vertical changes in azimuthal anisotropy to relate the LAT and the Gutenberg discontinuity. The association of depth variation of anisotropic properties with lithospheric layering has been discussed for the North American Craton [e.g., *Yuan and Romanowicz*, 2010; *Yuan and Levin*, 2014]. In continental areas, not only the LAT but also the MLD may be related to the vertical changes of anisotropic properties [*Selway et al.*, 2015].

The Australian continent is comprised of Archean and Proterozoic cratonic blocks in the west and center whose assembly was largely completed by 1.3 Ga [*Cawood and Korsch*, 2008], with later Phanerozoic accretion in the east. Currently, Australia is the fastest moving continent in the framework of present plate

motion, with a northward drift speed of about 7 cm yr^{-1}. *Simons and van der Hilst* [2003] and *Debayle et al.* [2005] have shown that seismic anisotropy at the lithospheric depth of Australia represents frozen past deformation, while the azimuthal anisotropy at the base of seismic lithosphere reflects preferentially oriented rapid plate motion, suggesting deformation by basal drag. The change in alignment of azimuthal anisotropy with depth is confirmed in the regional study by *Fishwick et al.* [2008]. Evidence for significant radial anisotropy with faster *SH* wave speed anomalies than for *SV* waves beneath Australia was provided by *Debayle and Kennett* [2000] with very limited path coverage and confirmed in a global context by *Gung et al.* [2003] and in a regional study by *Fichtner et al.* [2010].

Yoshizawa [2014] has recently developed a new radially anisotropic 3-D shear wave model for Australia from a large number of multimode surface wave paths across Australia, based on the multimode phase speed measurements [*Yoshizawa and Kennett*, 2002a; *Yoshizawa and Ekström*, 2010] incorporating finite-frequency effects [*Yoshizawa and Kennett*, 2002b, 2004]. He has proposed a way to estimate the plausible depth range of the lithosphere-asthenosphere transition from velocity profiles by exploiting the character of the wave speed gradients. A brief summary of the approach is provided in the supporting information.

We exploit this new 3-D model for the Australian upper mantle, to examine the details of the nature of the lithosphere-asthenosphere transition across the age provinces of Australia, and its relation to radial anisotropy.

2. The Lithosphere-Asthenosphere Transition and Radial Anisotropy

We can place upper and lower depth bounds on the lithosphere-asthenosphere transition (LAT) by examining local vertical profiles through the 3-D shear wave speed model. The shallower bound is taken where the negative vertical gradient in isotropic wave speed is largest and the deeper bound at the minimum absolute wave speed beneath the lithosphere [*Yoshizawa*, 2014]. Thus, by this definition, the LAT lies in a low-velocity zone created by the high shear wave speeds in the lithosphere. The bounds allow us to examine the lateral variations of the LAT and its relation with alternative lithospheric properties. We consider both the radial anisotropy of the *Yoshizawa* [2014] model, and the discontinuities extracted from the analysis of receiver functions (RFs) across Australia [*Ford et al.*, 2010].

2.1. LAT From Surface Waves and Receiver Functions

There are only a limited number of seismic stations in Australia with long-term recording suitable for *S* wave receiver function analysis. The stations in the Global Seismographic Network supplemented by stations from the Australian National Network, operated by Geoscience Australia, have been exploited by *Ford et al.* [2010] to map out depths of discontinuities associated with a drop in *S* wave speed. In Figure 1 we compare the 1-D isotropic shear wave speed ($V_{\mathrm{iso}} = \sqrt{(2/3)V_{sv}^2 + (1/3)V_{sh}^2}$) and a measure of radial anisotropy ($\xi = V_{sh}^2/V_{sv}^2$) depth distributions extracted from the *Yoshizawa* [2014] wave speed model, with the corresponding estimates of the discontinuity depths at the stations in the *Ford et al.* [2010] receiver function study.

We consider two east-west profiles A-A′ and B-B′ cutting from the Archean in the west across the Proterozoic to the Phanerozoic on the east coast, and a roughly north-south profile C-C′ lying within the Phanerozoic domains. For each station in Figure 1, we plot the estimates for the shallower and deeper bounds of the LAT (red and blue dots, respectively) on the *S* wave speed and radial anisotropy distributions, together with the discontinuity depths from the receiver function analysis (green and purple arrows). Where these discontinuities can be linked to a distinct feature in the *S* wave speed, we have interpreted them as marking a representation of the LAT. Otherwise, where the discontinuities lie in zones of high absolute wave speed, we infer a midlithosphere discontinuity (MLD).

The stations in the west of Australia show a strongly developed low-velocity zone in the LAT due to very high *S* wave speeds in the top 100 km. The low-velocity feature is much more subdued in central Australia where absolute velocities stay high to greater depth, and the top of the LAT moves deeper. In eastern Australia, the *S* wave receiver function results of *Ford et al.* [2010] show a clear drop in *S* wave speed over a depth interval not exceeding 40 km, whose depth is fairly consistent with our estimates of the upper bound of LAT. As can be seen from Figure 1 the surface wave results tend to imply a thicker transition, but this is mainly due to the limited resolving power of surface waves when the true transition is less than 40 km [*Yoshizawa*, 2014]. In this region the *S* wave speed gradient in the LAT (Figure S3d in the supporting information) provides a useful indicator of the relative sharpness of the transition.

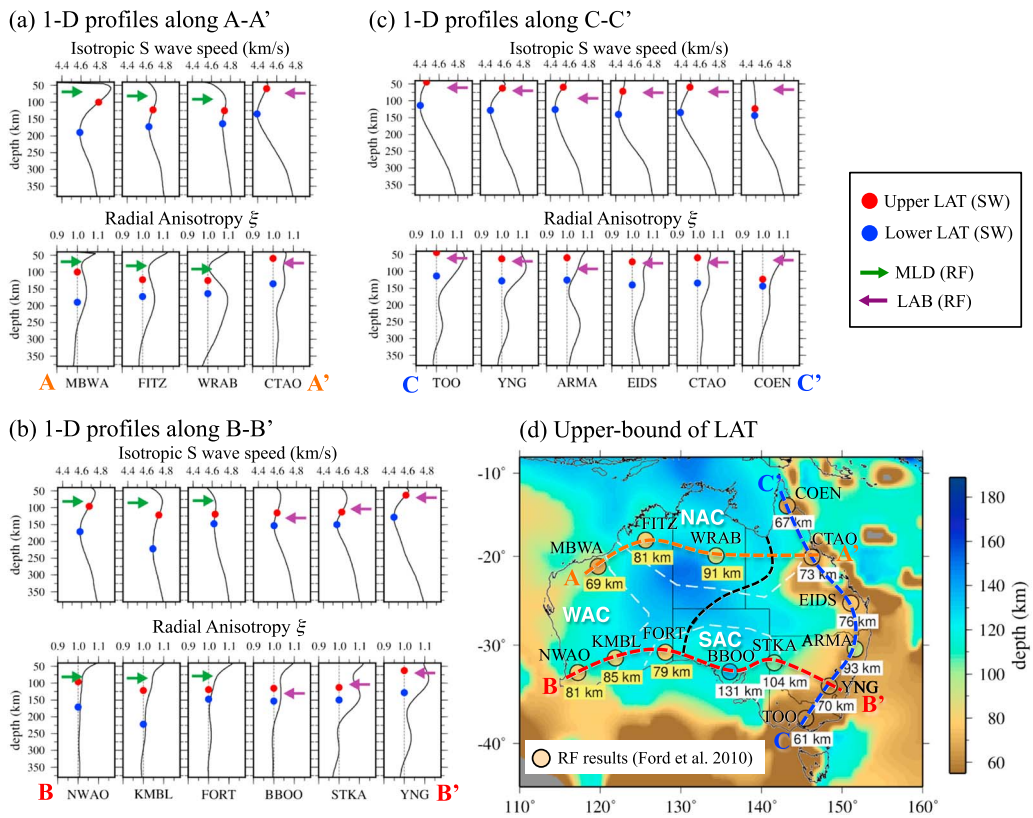

Figure 1. (a–c) One-dimensional vertical profiles of isotropic *S* wave speed (top) and radial anisotropy (bottom) along lines A-A′, B-B′, and C-C′ shown in Figure 1d. Red and blue circles represent the upper and lower bounds of LAT from our surface wave study. Green and purple arrows represent, respectively, the midlithospheric discontinuity and the lithosphere-asthenosphere boundary (LAB) derived from the receiver function study by *Ford et al.* [2010]. (d) The upper bound of LAT (background contour) by *Yoshizawa* [2014] and the depth of LAB estimated from receiver function analysis (circles) by *Ford et al.* [2010]. The black dashed curve dividing eastern and western Australia is taken from the receiver function analysis of *Ford et al.* [2010], indicating the region where *S*- to *P*-converted signal from the bottom of the lithosphere can be found (eastern side) or not (western side). White dashed lines are cratonic boundaries. NAC: North Australian Craton, WAC: West Australian Craton, SAC: South Australian Craton.

For stations in the West and North Australian Cratons, the receiver function results indicate a relatively shallow MLD in *S* wave speed well above any definition for the base of the lithosphere (Figures 1). At these locations we find a gradual transition from lithosphere to asthenosphere sufficiently broad to be resolved well by the surface waves. The conversions between *S* and *P* wave speeds associated with the true LAT will be weak at best and so not detectable from receiver functions [*Ford et al.*, 2010].

Only beneath the southern edge of the Gawler Craton in South Australia (station BBOO) do we find both a moderate thickness for the LAT and a discontinuity in the receiver function studies that might represent the upper side of the LAT. This region shows lower shear wave speeds and shallower LAT than the other parts of the cratons (Figures S2 and S3), which may reflect the influence of basal erosion during the breakup between Australia and Antarctica.

2.2. LAT and Radial Anisotropy

The 1-D profiles in Figure 1 also allow us to examine the relation of the LAT with radial anisotropy. The 3-D *S* wave model is characterized by a dominance of fast *SH* wave speeds compared to *SV* (see also Figure S2b), but this is manifested in different ways at the various stations.

In the West and North Australian Cratons ξ is high (~1.08) just below the base of the crust but drops with depth, typically reaching a minimum or an inflection point very close to the discontinuity depths inferred from the *S* wave RF analysis. On the northern group of stations (Profile A-A′) ξ rises again from the minimum and remains above unity to below the deeper bound on the LAT. In contrast, on profile B-B′, there is little change below the inflection point and radial anisotropy remains weak through the full thickness of the LAT.

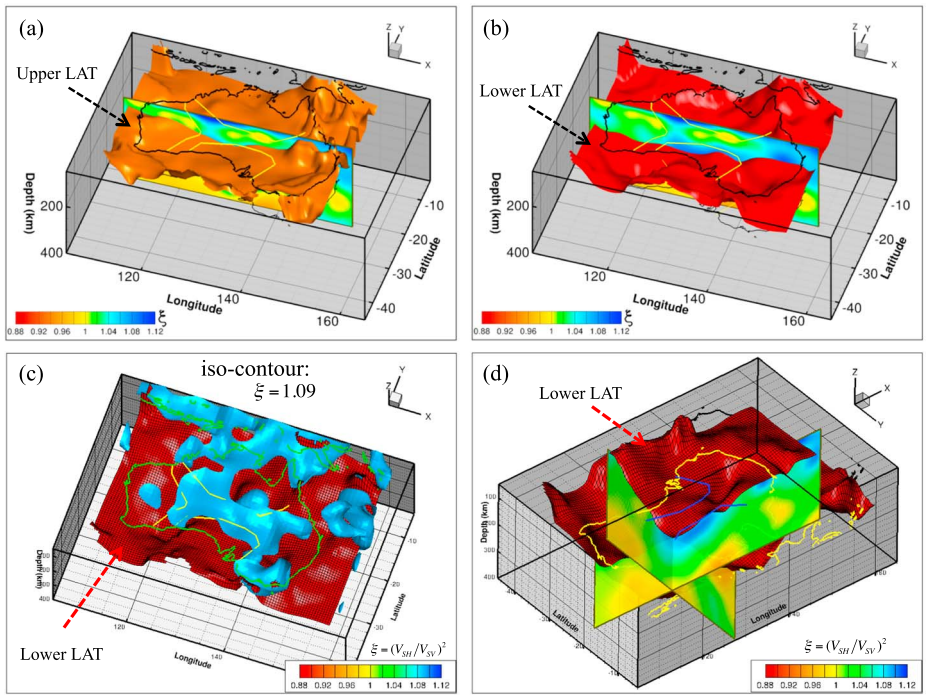

Figure 2. Three-dimensional views of the lithosphere-asthenosphere transition (brown and red membranes) together with an east-west cross section across the center of Australia at 22°S showing the radial anisotropy: (a) the upper bounds and (b) the lower bounds of LAT with coastlines plotted at 50 km depth; (c) isocontour of radial anisotropy above the LAT for $\xi = 1.09$ with coastlines at 60 km depth; (d) cross sections at 127°E and 22°S with coast lines at 200 km depth, seen from below.

At the station STKA on the edge of the South Australian Craton and the other east Australian stations, higher ξ (>1.04) is sustained to below the lower bound of the LAT.

In Figure 2 we present 3-D representations of the relationship between the LAT and radial anisotropy. The sharp rise in the base of the lithosphere between western and central Australia and the younger east is very clear in Figures 2a and 2b. Significant radial anisotropy ($SH > SV$) is present in the upper lithosphere, as well as in the LAT and the underlying asthenosphere. The strongest radial anisotropy ($\xi > 1.09$) above the shallower bound on the LAT is mostly to be found in the ancient suture zones between the cratons (Figure 2c). Radial anisotropy with $\xi > 1.05$ in the asthenosphere (below the deeper bound on the LAT) is concentrated beneath central Australia and the eastern edge of the continent and adjacent Tasman Sea (Figure 2d looking from beneath).

At midlithospheric depth above the upper bound of LAT in central and western Australia (Figures 2 and 3), the strength of radial anisotropy (with faster *SH*) becomes moderate or weak. This rapid change in the anisotropic properties coincides well with the expected depth of the midlithospheric discontinuity (MLD) suggested from the receiver functions in this region (Figures 1a and 1b).

As can be seen from Figures 2a and 2b, the LAT in central Australia starts at greater depth than elsewhere beneath the continent. The presence of strong radial anisotropy with enhanced *SH* wave speed in the LAT and underlying asthenosphere could well be linked to strong shear flow beneath the continent. These results are consistent with the lower resolution global study by *Gung et al.* [2003], who noted that the apparent thickness of the continental lithosphere could be linked to flow patterns in the asthenosphere. In the global study of *Debayle et al.* [2005] and regional model of *Fishwick et al.* [2008], the central Australian region is also marked by the presence of strong azimuthal anisotropy in the zone we identify as the LAT. The fast direction is broadly aligned with absolute plate motion, a result again suggesting the influence of basal shear.

The complex configuration of the base of the lithosphere in the east of Australia sees rapid change in the depth to the LAT, with suggestions of distinct steps [*Fishwick et al.*, 2008]. The relative motion between lithosphere and asthenosphere enhances the radial anisotropy and also induces subsidiary flow patterns

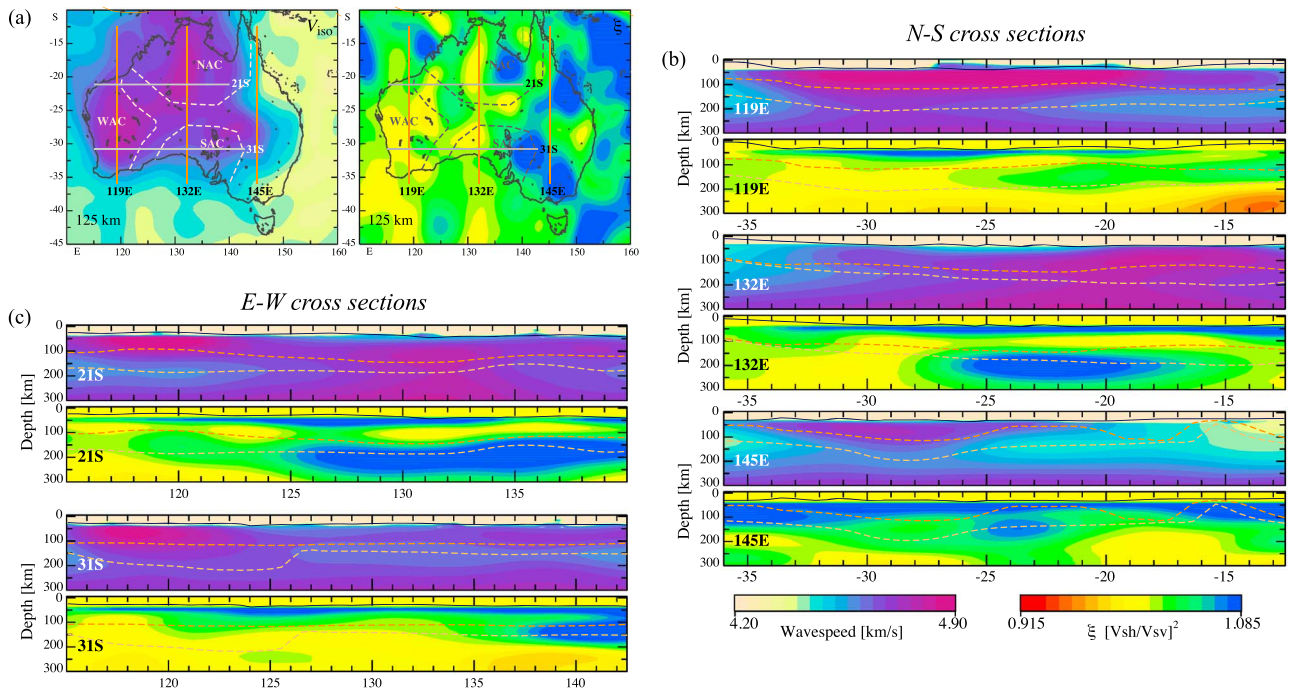

Figure 3. (a) Isotropic *S* wave speed and radial anisotropy maps at 125 km with the outline of the major cratonic elements and the locations of the cross sections. Cross sections through the 3-D radially anisotropic model at (b) constant longitude: 119°E, 132°E, and 145°E and (c) constant latitude: 21°S and 31°S, with a common horizontal scale. In each case the top panel shows the isotropic *S* wave speed with the estimates of the shallower and deeper bounds on the LAT superimposed, the bottom panel shows the pattern of radial anisotropy ξ with again the bounds on the LAT indicated.

around the complex configuration of the lithosphere with surface expression through volcanism [*Davies and Rawlinson*, 2014].

The character of the complex coda of *P* and *S* waves from events in Australia and in the Indonesian subduction zone at cratonic stations is compatible with quasi-laminate heterogeneity with much longer horizontal than vertical correlation length [*Kennett and Furumura*, 2008]. Such structures can make a significant contribution to apparent radial anisotropy [*Fichtner et al.*, 2013].

2.3. Comparative Cross Sections in Different Age Provinces

The different classes of behavior in the character of the lithosphere, the LAT, and radial anisotropy can be well illustrated by cuts through the 3-D model (Figure 3). For each profile, we display the absolute shear wave speed and the radial anisotropy with little vertical exaggeration and superimpose the estimates for the upper and lower bounds on the LAT.

The profile at 119°E (Figure 3b) cuts through the full western Australian Craton; starting in the north on the thinned continental margin, it passes into the Archean Pilbara craton close to 21°S then continues through the Proterozoic Capricorn orogen finally reaching the Archean Yilgarn Craton to the south of 26°S. The LAT is thinnest beneath the thinned continental margin and thickens beneath the Pilbara Craton reaching about 60 km thickness. The LAT thickens beneath the Yilgarn Craton and thins again as it passes into the Proterozoic Albany-Fraser belt at the southern coastline. The northern component of the LAT shows definite radial anisotropy extending through the Pilbara and Capricorn zones, but this becomes less distinct under the Yilgarn (26° – 35°S). The character of the LAT beneath the Yilgarn fits well with the general model of *Thybo* [2006] with a well-developed, heterogeneous low-velocity zone beneath cratons invoked at around 100 km depth. The upper lithosphere in Thybo's model has little, if any, fine-scale heterogeneity; but some is needed to match the character of high-frequency *P* and *S* waves observed in Australia [*Kennett and Furumura*, 2008]. The MLD would then be linked to a change to a stronger heterogeneity with shorter horizontal correlation length, which sets in once the seismic wave speeds start to decrease.

The central profile at 132°E links the North and South Australian Cratons, passing through the suture zone in central Australia whose last deformation was in the Alice Springs orogeny between 400 and 300 Ma

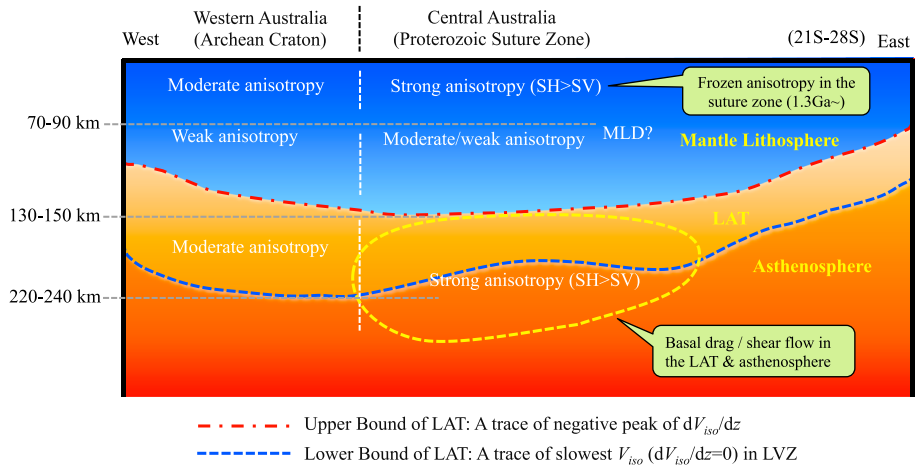

Figure 4. A schematic east-west cross section across the center of the Australian continent at around 21–28°S indicating the major character of the LAT and radial anisotropy.

[e.g., *Haines et al.*, 2001]. The northern Archean core of the North Australian Craton shows a character somewhat similar to the Yilgarn Craton with rather high *S* wave speeds underlain by a thick LAT. In the Proterozoic region in the south of the North Australian Craton the shallower bound of the LAT starts to deepen and the transition thins. The deeper upper limit of the LAT and thin transition is sustained through the central Australian suture zone. Strong radial anisotropy appears in the asthenosphere beneath both the North Australian Craton and the central Australian zones, where *S* wave speeds still remain higher than in their surroundings. The LAT remains quite thin beneath the South Australian Craton, whose lithospheric wave speeds diminish toward the south where the craton was formerly joined to Antarctica.

The eastern profile at 145°E starts in the north at the edge of the Proterozoic domains of northeast Australia and then crosses the Thomson and Lachlan orogens with Phanerozoic outcrop. This profile lies just off the edge of the main zone of high seismic wave speeds, though we see an incursion between 27° and 32°S. The LAT is thin and shallow in the north and then deepens as it passes the edge of the Proterozoic Georgetown Inlier at 16–20°S. The LAT thickens and deepens again beneath the zone of higher wave speeds at 27–30°, finally shallowing and thinning at the southern end of the profile. A major feature with pronounced radial anisotropy lies in the asthenosphere slightly to the north of the zone of higher wave speeds. To the south of the higher wave speeds significant radial anisotropy sits in the LAT, that may well be related to edge-driven convective flow induced by the thicker lithosphere [e.g., *Davies and Rawlinson*, 2014], associated with the steady motion of Australia northward.

In Figure 3c we show two slices at constant latitude (21°S and 31°S) which traverse approximately the same latitudes as those displayed in Figure 1, and in each case span both the Archean and Proterozoic crustal ages. These sections display the strong contrast between the nature of the LAT beneath regions with different tectonic history prior to the amalgamation of cratonic blocks. The edges of these elements can give sharp contrasts in the LAT and ξ, as, for example, the sharp contrast in LAT character at 31°S, 126°E and the ξ variations east of 125°E at 21°S. The extraction process for the most ancient subcontinental lithosphere may have left a distinctive signature that persists to the present day.

3. Discussion and Conclusions

The very fast shear wave speeds in western and central Australia and anomalous anisotropy beneath the continent have long been recognized in global studies [e.g., *Gung et al.*, 2003; *Debayle et al.*, 2005]. Yet when analyzed at the regional-scale exploiting the portable instrument deployments across the continent, there are clear indications of substructure and distinctiveness between the cratonic blocks [e.g., *Kennett et al.*, 2013]. Here we have been able to link the broader-scale features across the continent in terms of the nature of the LAT and the variations of radial anisotropy. The general nature of the interrelations is presented in a schematic cross section through central Australia in Figure 4.

The ancient Archean cratons of western Australia show a gradual transition from lithosphere to asthenosphere with modest anisotropy, while the surrounding Proterozoic belts indicate a thinner transition with a smaller velocity drop, accompanied by anomalously strong radial anisotropy in the upper lithosphere and asthenosphere (Figure 3c).

The radial anisotropy in the western Australian Cratons is somewhat weaker than most other areas of Australian lithosphere. The radial anisotropy model of *Fichtner et al.* [2010] shows similar results of weaker radial anisotropy in western Australia, though the horizontal resolution is weak in the west, due to the limited number of paths used in the full-waveform modeling.

As we move to the east there is a dramatic change. Thinning and deepening of the LAT is accompanied by strong radial anisotropy ($SH > SV$), particularly in the upper lithosphere above 90 km and in the LAT and the underlying asthenosphere. These features are most strongly developed in the suture zone between the cratons and their Proterozoic borders. This region has been repeatedly deformed [*Cawood and Korsch*, 2008], most recently in the Alice Springs Orogeny (circa 400 Ma), yet displays the high shear wave speeds in the lithosphere expected for a cratonic region. *Kennett and Iaffaldano* [2013] estimate that at least 300 Ma would be required for full reestablishment of the lithosphere in central Australia after the orogeny, which would allow the retention of distinctive local properties. The strong radial anisotropy in the upper lithosphere correlates well with the geographical extent of lower crust extrusion during the Alice Spring Orogeny proposed by *Klootwijk* [2013].

A number of lines of evidence suggest that there may be a change in the character of lithospheric heterogeneity at MLD depths [*Kennett*, 1987; *Thybo*, 2006; *Kennett and Furumura*, 2008]. The presence of fine-scale heterogeneity would enhance the apparent strength of radial anisotropy [*Fichtner et al.*, 2013], and changes in the style of heterogeneity with depth can lead to rapid variation of lithospheric anisotropy. Recent work by *Selway et al.* [2015] suggests that a vertical change in the character of radial anisotropy can produce a negative peak in the *S* receiver function. This is consistent with our model, where the MLD depth from RF coincides well with the depth of rapid change in radial anisotropy.

One of the most striking features across Australia is anomalously strong anisotropy immediately beneath the estimate of the deeper bound on the LAT, with the peak strength of anisotropy coinciding with the depth of the deeper bound in central Australia. This peak anisotropy primarily arises from a rather slow *SV* wave speed, which has a strong influence on the estimated depth of the LAT from the velocity gradient, while the fast *SH* wave speeds extend even below this transition.

Such strong anisotropy in the asthenosphere seems to be absent beneath the Archean cratons in western Australia. In central Australia, the absolute isotropic shear wave speed is faster than the average even below the estimated LAT (Figure 3b), suggesting a mechanically more resistive and diffusive lithospheric root in central Australia, which may be a cause of the anomalously strong anisotropy associated with basal drag or shear flow in the asthenosphere.

Acknowledgments
We thank the IRIS Data Management Center for access to a broad range of seismic waveform data, and the members of RSES, ANU who have deployed the extensive set of portable broadband seismic recorders across the Australian continent. Constructive and critical reviews by anonymous reviewers and Stewart Fishwick were helpful for improving the manuscript. The data of the 3-D model used in this study are available upon request to the authors. This study was partly supported by Grant-in-Aid for Scientific Research (24740298 and 26400443) to K.Y. from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Abt, D. L., K. M. Fischer, S. W. French, H. A. Ford, H. Yuan, and B. Romanowicz (2010), North American lithospheric discontinuity structure imaged by Ps and Sp receiver functions, *J. Geophys. Res.*, *115*, B09301, doi:10.1029/2009JB006914.

Beghein, C., K. Yuan, N. Schmerr, and Z. Xing (2014), Changes in seismic anisotropy shed light on the nature of the Gutenberg discontinuity, *Science*, *343*(6176), 1237–1240, doi:10.1126/science.1246724.

Burgos, G., J. -P. Montagner, E. Beucler, Y. Capdeville, A. Mocquet, and M. Drilleau (2014), Oceanic lithosphere-asthenosphere boundary from surface wave dispersion data, *J. Geophys. Res. Solid Earth*, *119*, 1079–1093, doi:10.1002/2013JB010528.

Cawood, P. A., and R. J. Korsch (2008), Assembling Australia: Proterozoic building of a continent, *Precambrian Res.*, *166*(1–4), 1–35, doi:10.1016/j.precamres.2008.08.006.

Davies, D. R., and N. Rawlinson (2014), On the origin of recent intraplate volcanism in Australia, *Geology*, *42*(12), 1031–1034, doi:10.1130/G36093.1.

Debayle, E., and B. L. N. Kennett (2000), Anisotropy in the Australasian upper mantle from Love and Rayleigh waveform inversion, *Earth Planet. Sci. Lett.*, *184*(1), 339–351, doi:10.1016/S0012-821X(00)00314-9.

Debayle, E., B. Kennett, and K. Priestley (2005), Global azimuthal seismic anisotropy and the unique plate-motion deformation of Australia, *Nature*, *433*(7025), 509–512, doi:10.1038/nature03247.

Fichtner, A., B. L. N. Kennett, H. Igel, and H.-P. Bunge (2010), Full waveform tomography for radially anisotropic structure: New insights into present and past states of the Australasian upper mantle, *Earth Planet. Sci. Lett.*, *290*(3–4), 270–280, doi:10.1016/j.epsl.2009.12.003.

Fichtner, A., B. L. N. Kennett, and J. Trampert (2013), Separating intrinsic and apparent anisotropy, *Phys. Earth Planet. Inter.*, *219*, 11–20, doi:10.1016/j.pepi.2013.03.006.

Fischer, K. M., H. A. Ford, D. L. Abt, and C. A. Rychert (2010), The lithosphere-asthenosphere boundary, *Annu. Rev. Earth Planet. Sci.*, *38*(1), 551–575, doi:10.1146/annurev-earth-040809-152438.

Fishwick, S., M. Heintz, B. L. N. Kennett, A. M. Reading, and K. Yoshizawa (2008), Steps in lithospheric thickness within eastern Australia, evidence from surface wave tomography, *Tectonics*, *27*, TC4009, doi:10.1029/2007TC002116.

Ford, H. A., K. M. Fischer, D. L. Abt, C. A. Rychert, and L. T. Elkins-Tanton (2010), The lithosphere–boundary and cratonic lithospheric layering beneath Australia from Sp wave imaging, *Earth Planet. Sci. Lett.*, *300*(3–4), 299–310, doi:10.1016/j.epsl.2010.10.007.

Gung, Y., M. Panning, and B. Romanowicz (2003), Global anisotropy and the thickness of continents, *Nature*, *422*(6933), 707–711, doi:10.1038/nature01559.

Haines, P. W., M. Hand, and M. Sandiford (2001), Palaeozoic synorogenic sedimentation in central and northern Australia: A review of distribution and timing with implications for the evolution of intracontinental orogens, *Aust. J. Earth Sci.*, *48*(6), 911–928, doi:10.1046/j.1440-0952.2001.00909.x.

Kawakatsu, H., P. Kumar, Y. Takei, M. Shinohara, T. Kanazawa, E. Araki, and K. Suyehiro (2009), Seismic evidence for sharp lithosphere-asthenosphere boundaries of oceanic plates, *Science*, *324*(5926), 499–502.

Kennett, B. L. N. (1987), Observational and theoretical constraints on crustal and upper mantle heterogeneity, *Phys. Earth Planet. Inter.*, *47*, 319–332, doi:10.1016/0031-9201(87)90084-7.

Kennett, B. L. N., and T. Furumura (2008), Stochastic waveguide in the lithosphere: Indonesian subduction zone to Australian Craton, *Geophys. J. Int.*, *172*(1), 363–382, doi:10.1111/j.1365-246X.2007.03647.x.

Kennett, B. L. N., and G. laffaldano (2013), Role of lithosphere in intra-continental deformation: Central Australia, *Gondwana Res.*, *24*(3–4), 958–968, doi:10.1016/j.gr.2012.10.010.

Kennett, B. L. N., A. Fichtner, S. Fishwick, and K. Yoshizawa (2013), Australian Seismological Reference Model (AuSREM): Mantle component, *Geophys. J. Int.*, *192*(2), 871–887, doi:10.1093/gji/ggs065.

Klootwijk, C. (2013), Middle-Paleozoic Australia-Asia convergence and tectonic extrusion of Australia, *Gondwana Res.*, *24*(1), 5–54, doi:10.1016/j.gr.2012.10.007.

Nettles, M., and A. M. Dziewonski (2008), Radially anisotropic shear velocity structure of the upper mantle globally and beneath North America, *J. Geophys. Res.*, *113*, B02303, doi:10.1029/2006JB004819.

Selway, K., H. Ford, and P. Kelemen (2015), The seismic mid-lithosphere discontinuity, *Earth Planet. Sci. Lett.*, *414*, 45–57, doi:10.1016/j.epsl.2014.12.029.

Simons, F. J., and R. D. van der Hilst (2002), Age-dependent seismic thickness and mechanical strength of the Australian lithosphere, *Geophys. Res. Lett.*, *29*(11), 24–1–24-4, doi:10.1029/2002GL014962.

Simons, F. J., and R. D. van der Hilst (2003), Seismic and mechanical anisotropy and the past and present deformation of the Australian lithosphere, *Earth Planet. Sci. Lett.*, *211*(3–4), 271–286, doi:10.1016/S0012-821X(03)00198-5.

Thybo, H. (2006), The heterogeneous upper mantle low velocity zone, *Tectonophysics*, *416*(1–4), 53–79, doi:10.1016/j.tecto.2005.11.021.

Yoshizawa, K. (2014), Radially anisotropic 3-D shear wave structure of the Australian lithosphere and asthenosphere from multi-mode surface waves, *Phys. Earth Planet. Inter.*, *235*, 33–48, doi:10.1016/j.pepi.2014.07.008.

Yoshizawa, K., and G. Ekström (2010), Automated multimode phase speed measurements for high-resolution regional-scale tomography: Application to North America, *Geophys. J. Int.*, *183*(3), 1538–1558, doi:10.1111/j.1365-246X.2010.04814.x.

Yoshizawa, K., and B. L. N. Kennett (2002a), Non-linear waveform inversion for surface waves with a neighbourhood algorithm–to multimode dispersion measurements, *Geophys. J. Int.*, *149*(1), 118–133, doi:10.1046/j.1365-246X.2002.01634.x.

Yoshizawa, K., and B. L. N. Kennett (2002b), Determination of the influence zone for surface wave paths, *Geophys. J. Int.*, *149*(2), 440–453, doi:10.1046/j.1365-246X.2002.01659.x.

Yoshizawa, K., and B. L. N. Kennett (2004), Multimode surface wave tomography for the Australian region using a three-stage approach incorporating finite frequency effects, *J. Geophys. Res.*, *109*, B02310, doi:10.1029/2002JB002254.

Yuan, H., and V. Levin (2014), Stratified seismic anisotropy and the lithosphere-asthenosphere boundary beneath eastern North America, *J. Geophys. Res. Solid Earth*, *119*, 3096–3114, doi:10.1002/2013JB010785.

Yuan, H., and B. Romanowicz (2010), Lithospheric layering in the North American Craton, *Nature*, *466*(7310), 1063–1068, doi:10.1038/nature09332.