

# Age-dependent seismic thickness and mechanical strength of the Australian lithosphere

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[1] We present constraints on the regional variations of the seismic and mechanical thickness of the Australian lithosphere. We infer the seismic thickness from a waveform tomographic model of  $S$ -wave speed, and as a proxy for the elastic thickness we use the wavelength at which the coherence of surface topography and Bouguer gravity drops below half of its long-wavelength maximum. Our results show that on scales  $<1000$  km the relationship between the age of the crust and the thickness of the lithosphere is more complicated than longer-wavelength or global averages suggest. Recent geochemical and geodynamical evidence for small-scale secular variations of the composition and stability of continental cratons further illustrates the complexity of the age dependence of seismo-mechanical lithospheric properties on regional scales. *INDEX TERMS*: 1219 Geodesy and Gravity: Local gravity anomalies and crustal structure; 1236 Geodesy and Gravity: Rheology of the lithosphere and mantle (8160); 7218 Seismology: Lithosphere and upper mantle; 7255 Seismology: Surface waves and free oscillations; 8180 Evolution of the Earth: Tomography

## 1. Introduction

[2] The age of continental crust is believed to correlate with its bulk rock composition [Griffin *et al.*, 1999; Pearson, 1999] and elastic thickness [Zuber *et al.*, 1989], and, globally, with surface heat flow [Artemieva and Mooney, 2001] and seismic anomalies down to about 200 km [Polet and Anderson, 1995]. As low temperatures and refractory mantle compositions increase  $S$ -wave speeds, these correlations indicate that the stabilization of the lithosphere over time occurs by progressive depletion of basaltic constituents, forming a seismologically expressed thick and strong thermo-chemical boundary layer or tectosphere [Jordan, 1988].

[3] Recent studies have shown regional departures from the global age correlation of geological, geochemical, and geophysical lithospheric properties. Detailed heat flow analyses manifest the difficulty in representing an entire tectonic province by a single average crustal model [Jaupart and Mareschal, 1999]. Remobilization of cratonic lithosphere [Conrad and Molnar, 1997] is geochemically documented in East China [Menzies *et al.*, 1993], South Africa [Jacob *et al.*, 2000], the Proterozoic Sierra Nevada [Lee *et al.*, 2000], and the Archean Wyoming Province [Egglar *et al.*, 1988]. Thick lithospheres might result from preferential preservation inside orogens [Lenardic *et al.*, 2000] or their initial composition and fertility [Lee *et al.*, 2001]. Furthermore, crust and mantle need not have the same age. Thus, lithospheric thickness may correlate poorly with the age of the overlying crust.

[4] Elastic properties depend on the time scale. Wave speeds reflect the elastic response on short time scales. In contrast, the effective elastic thickness ( $T_e$ ) estimated from the coherence

between gravity anomalies and topography is a measure of long-term mechanical strength.

[5] Recently, our knowledge of the  $S$ -wave structure of Australia has greatly improved [van der Hilst *et al.*, 1994; Simons *et al.*, 1999; Debayle and Kennett, 2000], and advances in coherence analysis now allow robust high-resolution measurements of the mechanical properties of the lithosphere [Simons *et al.*, 2002b]. Resolution and error estimates are discussed by Simons *et al.* [2002a, 2002b]. Here we build on this progress and investigate the relations between crustal age, the seismic thickness, and the long-term elastic strength of the lithosphere. The correlations are more complex than inferred from global analyses, revealing a difference in properties at length scales above and below  $\sim 1000$  km.

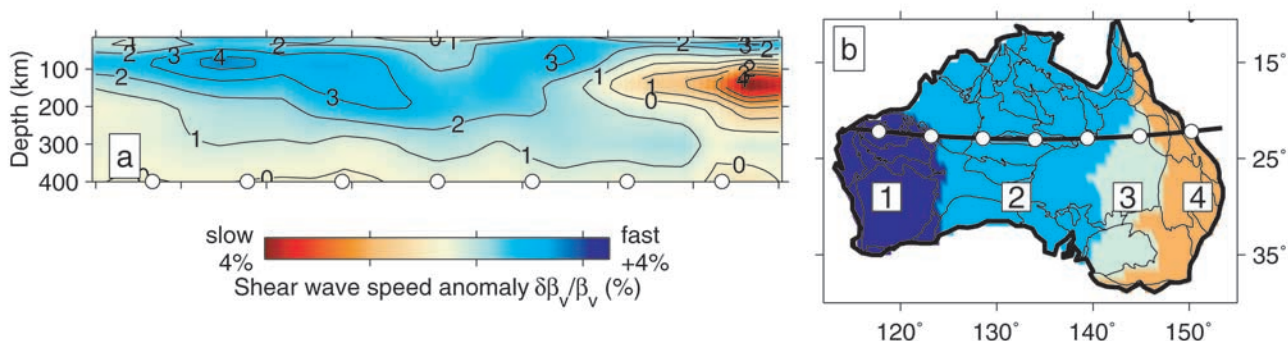
## 2. Seismic Thickness

[6] At length scales  $>1000$  km the propagation speed of seismic waves in the Australian lithosphere correlates with the age of the crust: the eastward decrease in crustal age coincides with a reduction in  $S$ -wave speed (Figure 1), at least to a depth of 200 km. Below 200 km, the realm of deep-penetrating stable continental keels in global models [see, e.g., Masters *et al.*, 1996], this correlation is not borne out by high-resolution seismic modeling which instead reveals significant variations in seismic velocities below crustal domains of similar tectonic age [Simons *et al.*, 1999].

[7] We take the depth to a particular velocity anomaly contour as an estimate of seismic lithospheric thickness [see, e.g., Frederiksen *et al.*, 2001]. Figure 2 shows the depth at which the  $S$ -wave speed deviation from the average continental reference model [Simons *et al.*, 2002a] drops below +1.0%. The choice of contour is arbitrary but we will show that the pattern of seismic thickness variations obtained from the 1.5% and 2.0% contours is consistent with that inferred from the 1.0% contour. The Archean and Proterozoic parts of Australia are marked by thick lithosphere, whereas the Phanerozoic crust overlays a much thinner high velocity lid, or none at all. The transition occurs near the eastern extent of Precambrian outcrop, marked by the Tasman Line [Veevers, 1984]. Some Proterozoic regions of Australia exhibit high velocity keels to greater depth than the Archean portions of the continent. The structure of the mantle beneath easternmost Australia resembles the structure of the adjacent oceanic mantle. In the offshore regions the model shows a large difference in thickness between the old oceanic lithosphere of the Indo-Australian plate northwest and the much younger lithosphere east of Australia.

## 3. Long-term Elastic Strength

[8] The mechanical strength of continents appears to correlate with the time since the last tectonothermal event [Zuber *et al.*, 1989; Bechtel *et al.*, 1990; Poudjom Djomani *et al.*, 1999]. We use the coherence method of Simons *et al.* [2002b] to investigate this correlation in more detail. The relative mechanical strength or  $T_e$  of the lithosphere can be obtained from the coherence ( $\gamma^2$ ) between Bouguer gravity anomalies and surface topography [Forsyth,



**Figure 1.** Wave speed anomalies beneath Australia. (a) Profile (see (b) for location) and (b) map, at 80 km, of average anomalies over crustal age domains. The Phanerozoic ((3–4), <542 Ma) is characterized by a thin lithosphere, whereas in the Proterozoic ((2), 542–2500 Ma) and Archean ((1), >2500 Ma) parts of the continent, lithospheric keels extend to 200–250 km depth.

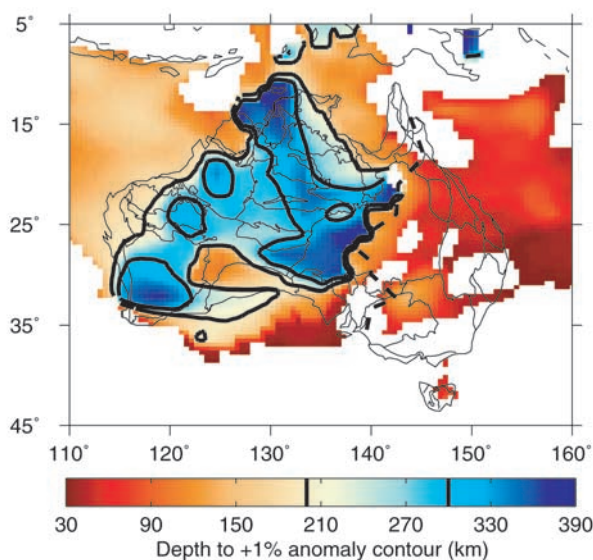
1985]. Theoretically,  $\gamma^2$  evolves from 1 to 0 with decreasing wavelength, and the wavelength at which  $\gamma^2 = 0.5$  varies positively, but nonlinearly, with  $T_e$ .

[9] Numerous factors, such as the unknown ratio of buried to surface loads [Banks *et al.*, 2001], the spectral estimation method [Simons *et al.*, 2000] erosion [Ito and Taira, 2000], and the assumed value of various rheological variables [Lowry and Smith, 1995] influence the estimation of  $T_e$ . Differences in  $T_e$  of up to 100% can result from varying methods and modeling assumptions. Because of these uniqueness concerns we calculate the wavelength ( $\lambda_{1/2}$ ) that marks the transition between wavelengths of loads that are isostatically compensated (high  $\gamma^2$ ) and those of loads that are supported by the strength of the plate (low  $\gamma^2$ ) without converting it into a single  $T_e$  value. We will depict the values of the  $\lambda_{1/2}$  at the

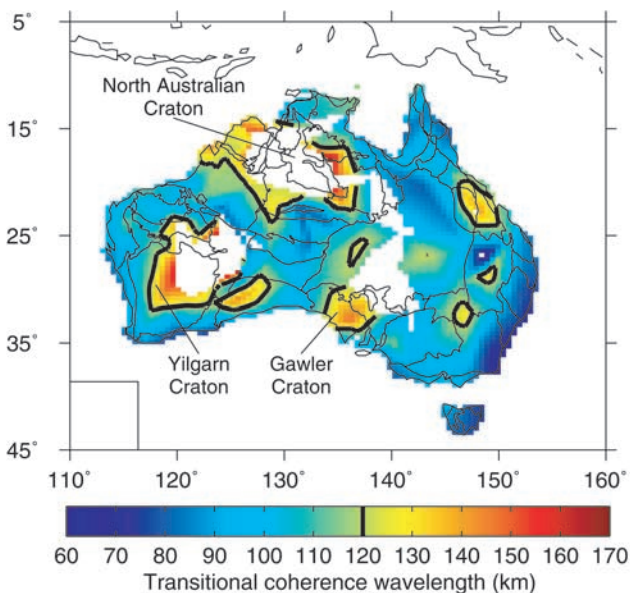
midpoints of the analysis windows, which have a constant dimension of  $\sim 700$  km.

[10] Figure 3 shows the lateral variation of the relative mechanical strength of Australia. Longer  $\lambda_{1/2}$  mostly occur in the western (Archean) and northern (Proterozoic) parts of Australia. In addition, there is a high over the Archean Gawler craton, whereas East Australia encompasses regions of low and high  $\lambda_{1/2}$ . Figure 3 suggests a large-scale trend of  $\lambda_{1/2}$  decreasing eastward with the age of the crust, consistent with the results of Zuber *et al.* [1989].

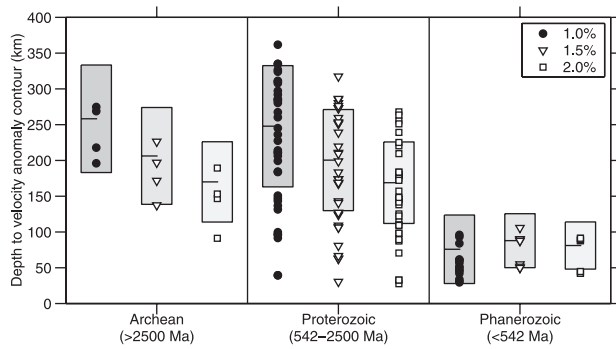
[11] A low value of  $\gamma^2$  at the wavelength corresponding to the window size indicates a failure of the linear isostatic compensation model (for reasons discussed by Simons *et al.* [2000]), and  $\lambda_{1/2}$  is not plotted in regions where  $\gamma^2 < 0.2$ . The blank regions in Figure 3 do not cause a systematic age bias nor do they affect our



**Figure 2.** Depth to the +1.0% velocity anomaly contour, a proxy for seismic thickness. Dashed: Tasman Line [Veevers, 1984].



**Figure 3.** Map of transitional coherence wavelengths  $\lambda_{1/2}$ , an indicator of the mechanical thickness. Bottom left: window size used.



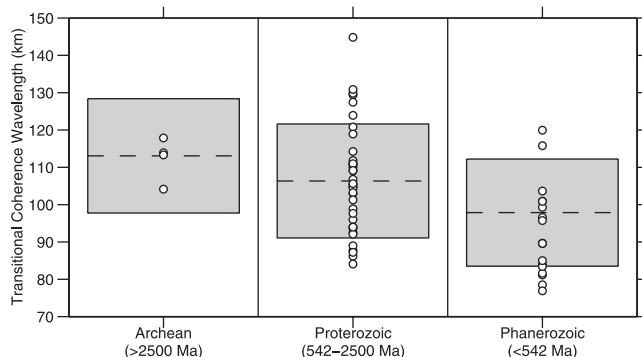
**Figure 4.** Average seismic thickness of tectonic subdomains (symbols), and area-normalized mean (dashed line) and standard deviation (box) over the eon to which they belong. Based on +1.0%, +1.5%, and +2.0% anomaly contours.

interpretation. We assessed the robustness of the trends observed in Figure 3 by varying the window size and using more conservative cut-off values, i.e.  $\gamma^2 > 0.2$ .

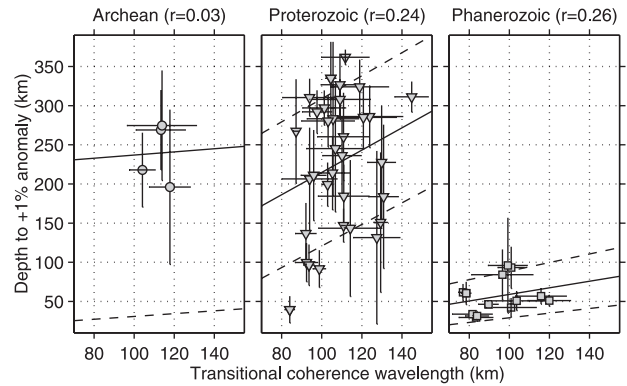
#### 4. Age Dependence

[12] Figure 4 depicts seismic lithospheric thickness as a function of chronometric eon, using the depth to the +1.0%, +1.5%, and +2.0% wave speed anomaly contours. We show average values over the tectonic domains outlined in Figures 2 and 3 (thin solid lines), grouped in function of the eon to which they belong (in more detail than the grouping of Figure 1). The overall decrease in lithospheric thickness with decreasing age, previously seen in longer-wavelength global models, is corroborated by our eon-averaged values, but the improved resolution of our regional surface-wave modeling reveals substantial variation about this long-wavelength trend. Using different wave speed contours leads to qualitatively similar conclusions, but the thickness variation from one contour to another relates to the velocity gradient, which is much steeper in the Phanerozoic than in the Precambrian.

[13] The average of  $\lambda_{1/2}$  per tectonic domain and eon is shown in Figure 5. The mean  $\lambda_{1/2}$  increases slightly with age. Although this indicates a thicker or stronger elastic lithosphere, even in the most favorable of loading scenarios the difference in  $T_e$  calculated from coherence curves with the same range of  $\lambda_{1/2}$  will not exceed 10 km. The variation of mechanical strength within domains formed in the same eon is far greater than the slight thickening of the lithosphere with age. We caution that the absence of large strength variations overall may be as much related to intrinsic properties of the lithosphere as to our inability to detect them in the



**Figure 5.** Average transitional coherence wavelength averaged over tectonic subdomains and grouped per eon.



**Figure 6.** Transition wavelengths, seismic thickness, and their standard deviations, as a function of age. Regression lines (solid) and their 50% confidence intervals (dashed) are shown, but the correlations are not statistically significant.

presence of buried loads and eroded topography [Banks *et al.*, 2001].

#### 5. Discussion

[14] Both the seismic thickness and the mechanical strength of the lithosphere generally correlate with the age of the overlying crust over length scales of thousands of kilometers, but there is significant scatter on scale lengths  $< 1000$  km. Do the seismic and the mechanical thickness covary on these length scales, as assumed in many studies [see Nyblade, 2001]? Figure 6 shows the correlation of seismic with mechanical thickness for the Australian Archean, Proterozoic, and Phanerozoic. Figure 6 also shows the standard deviation of the thickness within the domain under consideration. The (few) Archean regions of Australia cluster within a narrow range of transition wavelengths and show little variation in their seismic thickness. The seismic thickness and mechanical strength of Proterozoic Australia encompass the values for the Archean and scatter around a poorly defined positive linear correlation. The range of thicknesses seen in the Proterozoic is larger than for the Archean or Phanerozoic parts of Australia. Phanerozoic Australia displays small if any high velocity lids that, again, show essentially no correlation with their elastic strength. East Australia is not underlain by a thick tectospheric root, which cautions against making comparisons of the seismic thickness with the elastic strength. We stress that there is no statistical significance to any of the three regression lines shown in Figure 6, as the linear correlation coefficients are low.

[15] There are plausible geodynamical and geochemical mechanisms to preclude a straightforward age relationship of seismic or mechanical thicknesses on regional length scales. The geodynamically sheltered central location of the Australian Proterozoic [Simons *et al.*, 1999] or the geometry of orogens [Lenardic *et al.*, 2000] may be responsible in maintaining a thick tectosphere under Proterozoic Australia, which is locally thicker than under the Archean. Convection processes causing the break-up of Antarctica/Australia from India by 100 Ma [Storey, 1995] may have removed parts or all of the western Archean tectosphere. Furthermore, the breakdown of the correlation between thickness and age occurs at scale lengths compatible with lithospheric instabilities [Conrad and Molnar, 1997]. Alternatively, not all Archean crust may have developed a strong and thick boundary layer due to intrinsic compositional differences such as identified in the southwestern U. S. [Lee *et al.*, 2001].

#### 6. Conclusion

[16] Using the seismic wave speed model of Simons *et al.* [2002a] we have estimated the thickness of the high velocity lid



underlying the Australian continent. We compared this seismic thickness to an estimate of the relative elastic thickness obtained from the isotropic gravity-topography coherence with the method of *Simons et al.* [2002b]. The variations in seismic thickness within broad age divisions of the Australian continent are larger than the differences between the means over the age groups. To first order, the mechanical strength of the lithosphere increases slightly with age, and the (Archean) Yilgarn and Gawler blocks as well as the (Proterozoic) North Australian craton stand out as mechanically strong. There are substantial strength differences within domains of equal crustal age, however. The seismic thickness of the lithosphere, which represents the short-term elastic response, does not seem to be a good proxy for its long-term mechanical properties. Our detailed study of Australia suggests that it is an oversimplification to state that the older a craton, the thicker and stronger it is. Thicker continental keels are not necessarily mechanically stronger, and it is unproven that the shallow mechanical strength controls the preservation of such keels.

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