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Contrasts in mantle structure beneath Australia: relation to Tasman Lines?

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Surface-wave tomography for the Australian region, using data mostly from portable seismic recorders, reveals a very strong contrast in seismic shear-wave speed beneath central and western Australia and the east of the continent. Shear-wave speeds faster than the continental average extend to at least 200 km depth in the cratonic zone to the west of 140°E. Along an approximately north–south line there is then an eastward step to thinner lithosphere (~150 km thick) but still with fast shear-wave speeds. A further more irregular transition to the east marks the transition to lowered shear-wave speeds. The eastern transition at 75 km depth is in close agreement with the original Tasman Line, whereas the two more westerly transitions do not bear a simple relation to the more recent group of Tasman Lines defined from crustal information (outcrop and inferred geophysical trends). The westward transition to the thickest coherent lithosphere (near 140°E) may well mark the edge of the ancient core of the continent, but the current mantle structures must bear the scars of the breakups and reassembly that have created the current Australian continent.

KEY WORDS: craton, lithosphere, seismology, Tasman Line.

INTRODUCTION

Direen and Crawford (2003) have provided a valuable account of the evolution of the concept of the Tasman Line from the work of Hill (1951) '. . . the boundary line between the craton and geosyncline in early Palaeozoic times' with an emphasis on outcrop, through to later boundaries defined on the basis of faults and geophysical lineations (Gunn *et al.* 1997; Scheibner & Veevers 2000). The concept of the Tasman Line has transmuted over time to include alternative viewpoints, from the line of breakup of Rodinia to the westernmost limit of deformation associated with the Palaeozoic fold belts of eastern Australia. The boundary is often represented in terms of rather rectilinear segments inferred to represent strike-slip transforms and edges of rift basins. However, the same segments have been interpreted in different ways, for example the direct contradiction between Li and Powell (2001) and Veevers and Powell (1984).

A selection of these delineations of the Tasman Line is displayed in Figure 1. We note that the original line of Hill (1951) lies further east than the others in Queensland. Although Hill's definition was restricted to the north, we can envisage an extension into the Broken Hill region to link to the later suggestions. Most later 'Tasman Lines' are in general agreement in Queensland because they follow the southern edge of the Mt Isa Block; the differences come in the regions of thick sedimentary cover through the Cooper Basin, where magnetic and gravity signatures are muted.

Direen and Crawford (2003) documented the ages of many of the geophysical anomalies that help to mark the belt. These may represent the edge of the craton and infer a protracted and complex Neoproterozoic to Carboniferous geological history that produces a variety of structures rather than a simple line.

The magnetic and gravity anomalies used in the definition of the various Tasman Lines lie in the upper part of the crust, but geophysical evidence for a contrast associated with the edge of the Australian Shield is not confined to the near-surface. Lilley *et al.* (2003) described the results of electrical conductivity studies that imply strong contrasts extending through the crust, particularly at the edge of the Mt Isa Block. In the mantle the results of a variety of seismological studies demonstrate deep-seated contrasts in seismic-wave speed. There are significant variations in the thickness of the zone of higher wave speeds, marking the seismic lithosphere, between the Precambrian regions of the centre and west of Australia and the Phanerozoic zones to the east. In this paper we review the seismic results and examine how the zone of major contrasts varies with depth and relates to the various 'Tasman Lines' at the surface.

SEISMOLOGICAL CONSTRAINTS

The most direct exploration of mantle structure comes from the use of seismological techniques, particularly that of surface-wave tomography and body-wave analysis, using high-fidelity recordings of ground motion from sensitive seismometers with a broad frequency response. There are few permanent broadband stations within the Australian continent and so coverage has been achieved with the widespread deployment of portable broadband seismic recorders by the Research School of Earth Sciences at the Australian National University in the SKIPPY experiment, and its successors (van der Hilst *et al.* 1994; Kennett 2003). The earthquake belt running along the Indonesian Arc, through New Guinea and the Solomon

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Islands to Vanuatu, and thence through Fiji and Tonga to New Zealand, provides a very useful set of sources for probing upper mantle structure. Occasional earthquakes to the south, mostly associated with the southeast Indian and Southern Ocean ridge system provide additional and valuable coverage.

Seismic recordings of regional earthquakes using broadband seismometers and high-fidelity digital recording provide a wide range of information. A major benefit is the delineation of lithospheric and mantle structure using waveform inversion for the shear-wave and surface-wave portion of the seismogram (Zielhuis & van der Hilst 1996; van der Hilst *et al.* 1998; Debayle & Kennett 2000a, b, 2003; Simons *et al.* 2002; Yoshizawa & Kennett 2004). The body-wave records provide valuable information on upper mantle structure (Gudmundsson *et al.* 1994; Kennett *et al.* 1994; Kennett 2003). Records of distant earthquakes also allow information to be extracted on the crust and uppermost mantle structure using receiver-function analysis (Shibutani *et al.* 1996; Clitheroe *et al.* 2000a, b; Reading & Kennett 2003; Reading *et al.* 2003).

A high density of crossing paths is achieved in eastern Australia, and this allows reliable recovery of the 3-D shear wave-speed structure using the techniques of surface-wave tomography, in which the properties of nearly horizontally propagating waves are tracked (for a summary of seismic tomographic methods, see Kennett 2002). A very strong contrast in mantle structure beneath Australia is found with lowered shear-wave speeds along the eastern margin as compared with raised wave speeds in the centre and west, which extend to at least 200 km depth. The quality of the 3-D model of shear-wave speed has been enhanced in the most recent inversion (S. Fishwick pers. comm. 2004) by the inclusion of a significant volume of data from stations in western Australia, which improves the distribution of path coverage and hence resolution. Additional data have also been included from stations in southeastern Australia. The resulting images differ somewhat from earlier versions, but are now very stable, with only minor changes introduced by the last increment in path constraints. As can be seen from Figure 1c, d the configuration of the transition from slower to faster wave speeds at 150 km depth is relatively rapid and runs close to the positions suggested for the Tasman Line.

The position of the transition in seismic-wave speeds can be independently controlled by using the passage times of *S* body waves from source to receiver. In northern Australia, in particular, we can use refracted *S* waves

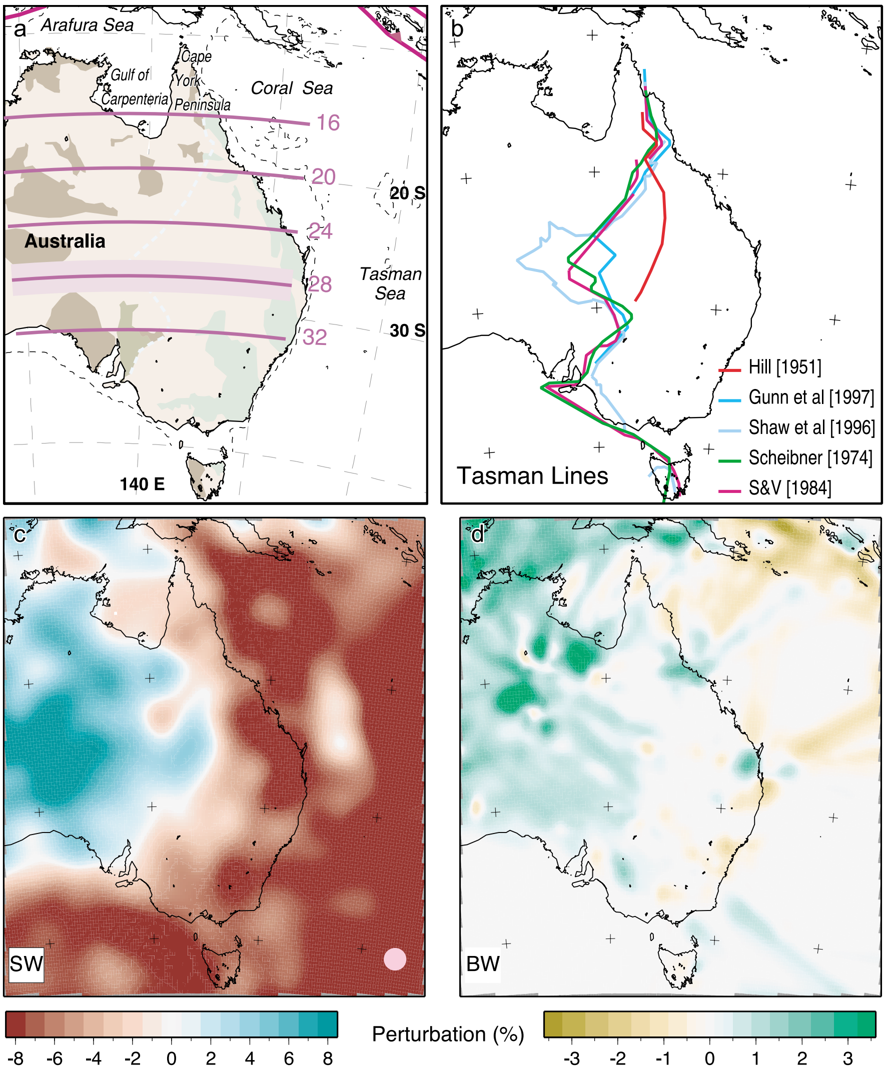

Figure 1 (a) Key map for geological setting and the lines of vertical sections displayed in Figure 3b; brown shading indicates Precambrian outcrop; green shading, Phanerozoic outcrop. The resolution attainable with current surface-wave inversion is indicated by a lilac band about the section line at 28°S. (b) Superimposition of a number of proposed Tasman Lines, for comparison with the mantle structures in later figures (S&V, Scheibner & Veevers). (c, d) Perturbations in shear-wave speed relative to the *ak135* reference model at a nominal depth of 150 km: (c) surface-wave tomography (SW); (d) body-wave tomography (BW). The lilac spot in (c) indicates the resolution of the image.

turning within the lithosphere to map the change from the characteristics of the paths. There has to be a relatively rapid transition between high and low seismic-wave speeds close to the western edge of Cape York in northern Queensland (Figure 1d) and extending in an approximately north–south direction. Because the body-wave tomography relies on waves arriving at steep angles at the stations, the coverage of the continent is more localised than is achieved with the surface waves. In consequence the appearance of the images has both local rapid variations near stations, and streaks where there is limited crossing of ray paths. Many of the arriving rays have similar angles of incidence and so vertical smearing of velocity structure tends to occur. The lower amplitudes of perturbation for the body waves reflect in part the difficulties of reading *S* phases against the background of the coda of *P* waves, so that picking-error can be significant. However, there is some compensation from the strong sensitivity of the *S* wave travel times to variations in *S* wave speed. For the shield regions the passage times for the *S* waves have large departures from the expected values for the reference model and can exceed the bounds allowed in the inversion.

CONTRASTS IN MANTLE STRUCTURE

We use the *ak135* model of Kennett *et al.* (1995) as the reference for both the surface-wave and body-wave studies. This model was constructed to give a representation of global seismic travel times, and has an average continental upper mantle structure. The *S* wave speed increases slowly with depth and the *ak135* model has no zone of lowered seismic-wave speeds. Shear-wave speeds lower than the *ak135* values can readily be produced by the influence of increased temperature, but very fast wave speeds associated with the cratonic elements are likely to require some chemical component.

The path density of surface waves across the eastern portion of the Australian continent is high (Figure 2a, b), with a good distribution of crossing paths, and thus we can achieve a good representation of structure. When we allow for the frequency range that we use to analyse the surface waves (0.008–0.025 Hz), we have to recognise that the potential resolution of structure will be at a horizontal scale of ~200 km and a vertical scale of ~25 km. More localised variations may be detected, but cannot be reliably imaged.

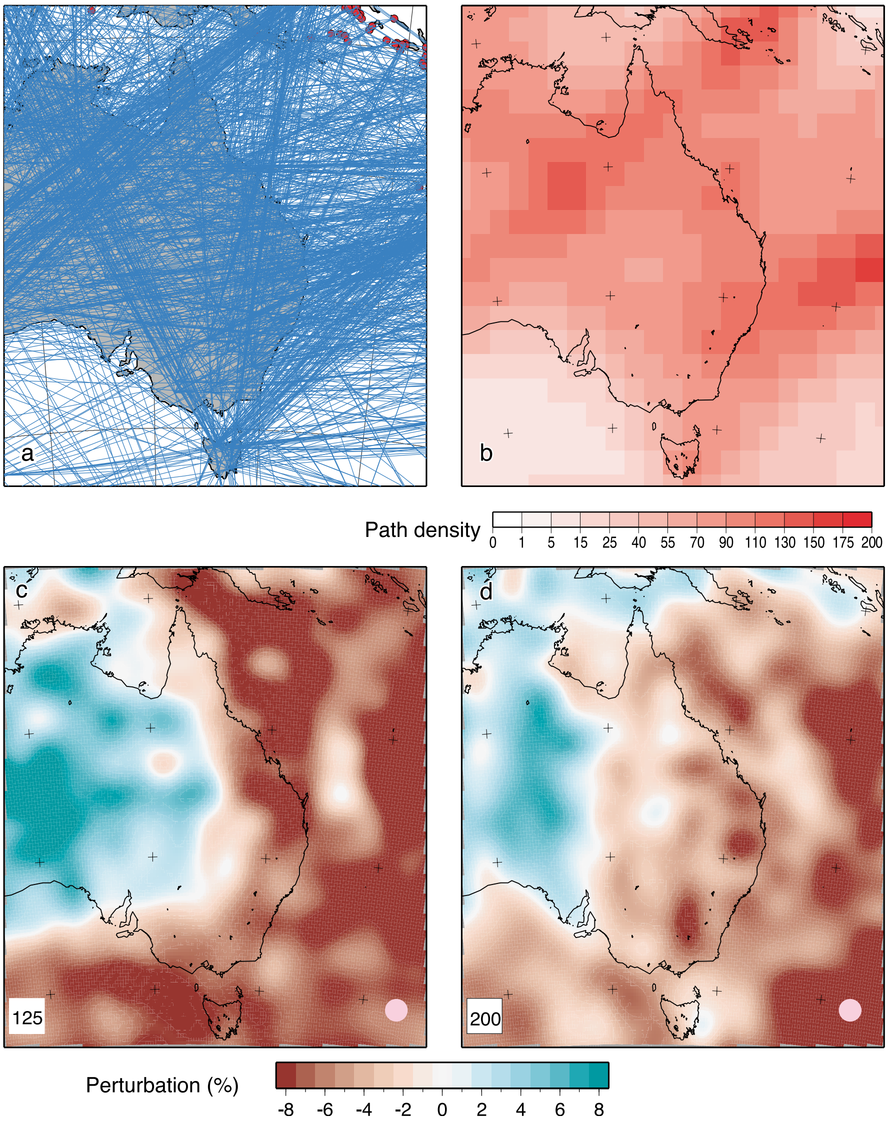

Figure 2 (a, b) Path coverage for surface-wave tomography: (a) paths from event to station for all the events analysed; (b) path density of surface-wave paths. (c, d) Perturbations in shear-wave speed relative to the *ak135* reference model: (c) surface-wave tomography at 125 km; (d) surface-wave tomography at 200 km. Lilac spots in (c, d) indicate the resolution of the image.

The changes in the position of the gradient zone between slower and faster shear-wave speeds with depth are not small, as can be seen in the comparison of the shear-wave speed images from the surface-wave tomography at 125 and 200 km depth (Figure 2c, d). The variations in wave speed across the transition zone are somewhat larger at 125 km, but still exceed 8% at 200 km depth.

The major change in mantle structure occurs on an approximately north–south trend close to 140°E. This is marked by a zone of very high horizontal wave-speed gradient extending southwards from Cape York and central Queensland. To the west of this line the higher velocities extend coherently to 200 km or below while, to the east, although there is an area of elevated wave speed, it does not extend to the same depth.

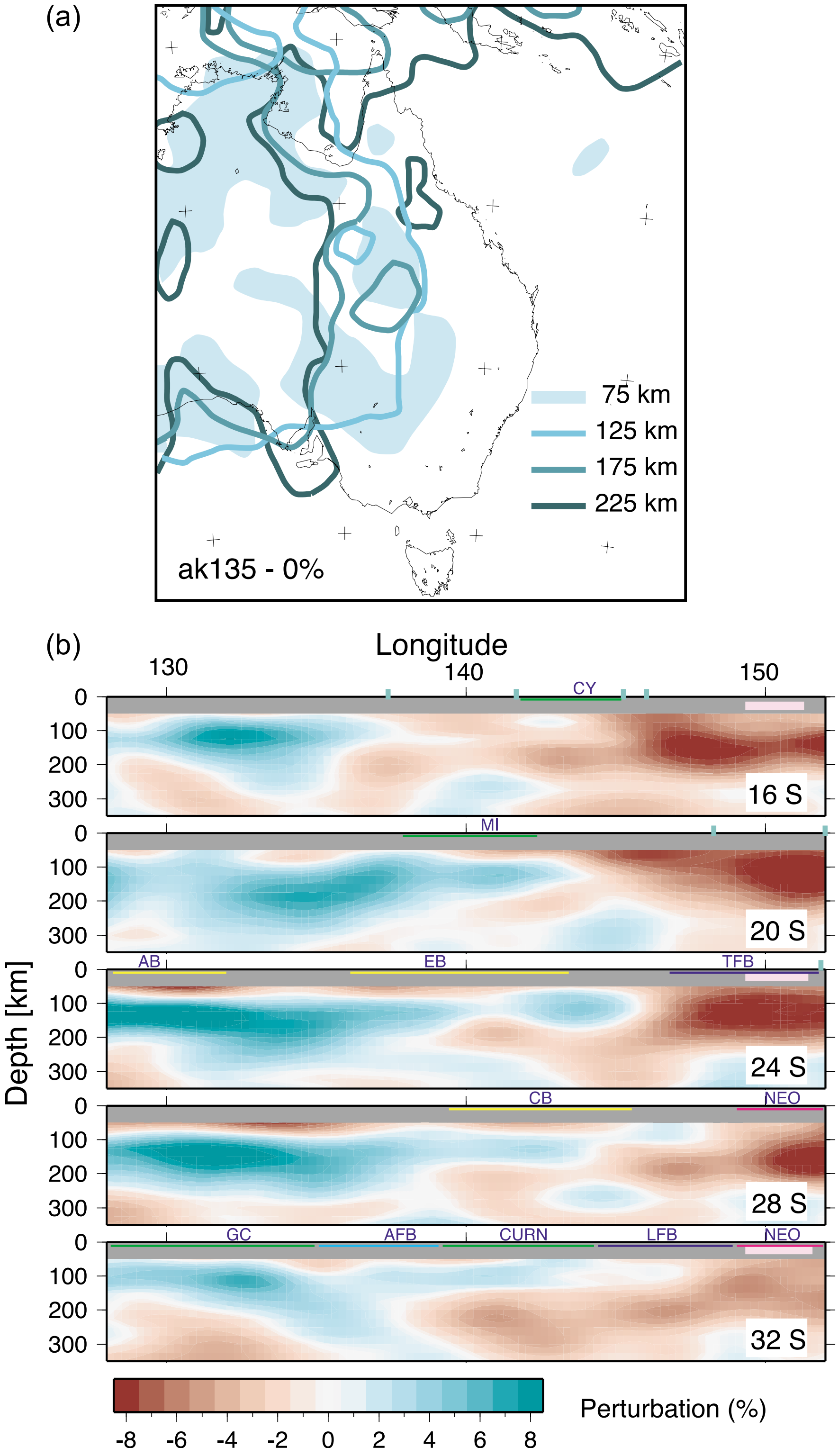

Figure 3 (a) Variation of the neutral line in the perturbation of shear-wave speed relative to the *ak135* reference model as a function of depth, derived from surface-wave tomography. (b) Vertical cross-sections of shear-wave speed model at 4° intervals of latitude from 16 to 32°S. The perturbations in shear-wave speed from surface-wave tomography are displayed relative to the *ak135* reference model. The lilac markers indicate the horizontal and vertical resolution attainable with the surface wave tomography. The positions of major features are marked above the sections: CY, Cape York; MI, Mt Isa Block; AB, Amadeus Basin; EB, Eromanga Basin; TFB, Thompson Fold Belt; CB, Cooper Basin; NEO, New England Orogen; GC, Gawler Craton; AFB, Adelaide Fold Belt (including Stuart Shelf); CURN, Curnamona Province; LFB, Lachlan Fold Belt. The vertical cyan markers indicate the coastline and the edge of the continental shelf.

As can be seen from Figures 1c, d, 2c, d, the neutral values for the *ak135* model in the shear-wave speed image fall within the zone spanned by the various definitions of the Tasman Lines, and the most rapid change of wave speeds occurs in the vicinity of this zone. We can therefore summarise the behaviour of the shear-wave speed patterns with depth by plotting the position of this neutral zone (Figure 3a). Shading is employed to denote the regions of higher wave speed at 75 km depth and darker tones then indicate the neutral contour for greater depths at 50 km intervals. The neutral zones at 175 km and 225 km depth lie quite close together, but there is an offset to the east at 125 km depth. The pattern at 75 km depth is more complex, having a region of lowered shear-wave speed in the regions of central Australia affected by the Alice Springs Orogeny (450–300 Ma: Betts *et al.* 2002). However, this zone has coherent elevated shear-wave speeds below 100 km depth.

Vertical cross-sections across the continent provide an alternative representation of the 3-D structure and allow us to begin to assess the thickness of the seismic lithosphere. Figure 3b displays sections at 4° intervals from 16 to 32°S, for the longitude span from 128 to 152°E. Because of the wavelengths employed, the sections should be regarded as representing an average across a zone ~2° in latitude centred on the nominal line of section. The horizontal and vertical resolution is indicated by a lilac bar on three of the cross-sections. The positions of the coastlines are indicated by vertical cyan bars.

The section at 16°S crosses the North Australian Craton and the southern part of the Gulf of Carpentaria from 136 to 142°E. The craton has a distinctive signature of very high *S* wave speeds extending to beyond 200 km depth near 134°E. There is a rather abrupt edge to the west of Cape York with a rapid transition to lower velocities in the 80–150 km depth range, and an apparent step back to the west below 150 km.

The cross-section at 20°S crosses the North Australian Craton passing through Tennant Creek, slightly to the north of Mt Isa, and the section crosses the coast south of Townsville at 148°E. A distinct and thick zone of high wave-speed material extends below 100 km from 128 to 143°E, with a rapid transition to lowered shear wave speed as the coast is approached, probably indicative of elevated temperatures.

The section at 24°S crosses central Australia beneath the Amadeus and Eromanga Basins. In the west there are high velocities above 200 km. The Amadeus Basin itself appears with relatively slow velocities in the shallower part of the mantle. There are somewhat higher velocities beneath 100 km, which appear to link to a deeper feature near 300 km depth. To the east of the Amadeus Basin, just south of the Mt Isa Block, the shear velocities are high down to 200 km depth to 139°E. Further east, we see a thinner zone of high velocities down to ~150 km with lowered shear-wave speed beneath. At greater depth, near 300 km, beneath western Queensland is a tongue of high-velocity material projecting east between 139 and 143°E, which appears to have a weak connection to the shallower higher velocities to the west. To the east the Thompson Fold Belt is underlain by a zone of much lower wave speeds, which extends to the coast at Rockhampton and beyond. There is a very distinct transition from elevated to lowered wave speed in the top 120 km close to 145°E.

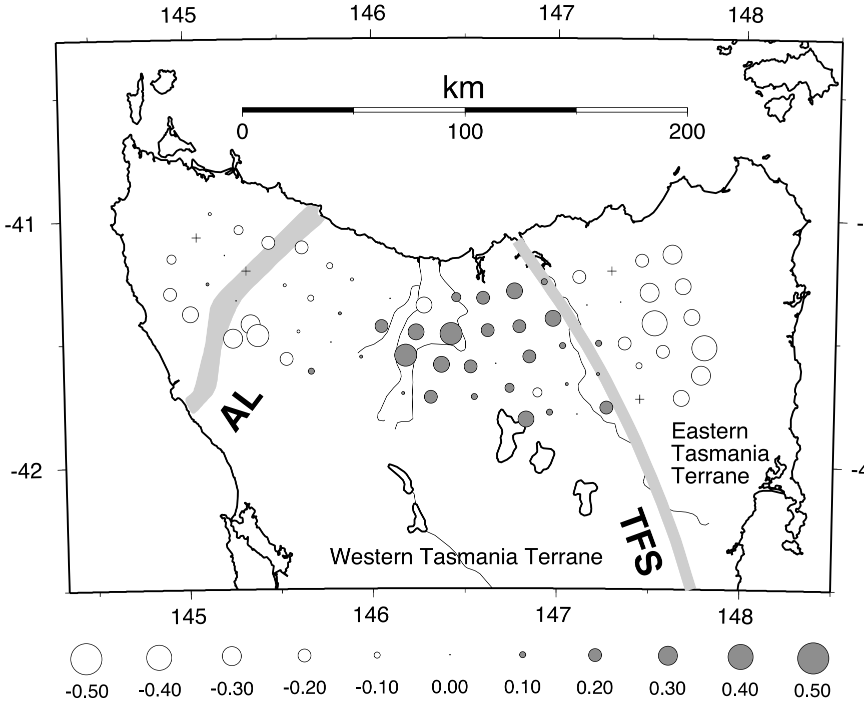

Figure 4 Travel-time residual pattern (in seconds), relative to *ak135*, for an event (mb 6.0) from the Fiji Islands (173.26°E; 16.38°S; 33 km depth) that occurred on 20 April 2002. From west to east, the residuals exhibit a large-scale variation from negative (fast) to positive (slow) and then back to negative (fast). The eastward transition from slow to fast lithosphere coincides with the approximate location of the transition zone between Eastern and Western Tasmania Terranes, as inferred from surface geology, magnetic intensity maps and reflection profiles. The negative residuals of the Eastern Tasmania Terrane, east of the Tamar Fracture System (TFS), suggest that it may be underlain by Proterozoic lithosphere of oceanic origin. The westerly transition from slow to fast lithosphere occurs near the Arthur Lineament (AL), and may be correlated with the northwest limit of deformation (thickening) in Tasmania caused by the Mid–Late Cambrian Tyennan Orogeny.

The cross-section at 28°S passes just south of the Musgrave Ranges and the southern part of the Great Artesian Basin (Lake Eyre), and then across the sedimentary rocks of the Cooper Basin, finishing close to Brisbane. This section displays lowered shear-wave speeds, compared with the *ak135* reference model, down to ~80 km depth across to 144°E. Beneath this are higher shear-wave speeds with a distinct step close to 139°E from more than 200 km thick to ~150 km thick. This feature can be clearly tracked in Figure 3b, through the offset in the neutral contour for the perturbations between 125 and 175 km depth.

The southernmost section, 32°S, passes through the Gawler Craton, Broken Hill and through the southern part of the New England Block. From the west a coherent zone of higher shear velocities extends across to 139°E. There is a tongue of higher shear-wave speed out to 144°E with lowered wave speeds beneath. The striking structure with an apparent dip to the east extending to 140°E ties in with the step in fast wave speeds down to 225 km; the resemblance to a subduction zone may be accidental because this morphology is not sustained over more than our resolution length of 2° in latitude.

Our 3-D model for the shear-wave speed does not provide a direct specification for the seismic lithosphere. A working definition, which allows for differences in resolution in different parts of the model, is to take the level of strongest vertical gradient in elevated shear-wave speed. This gives ~200–250 km thickness beneath Proterozoic outcrop and ~75 km thickness above the lowered wave speeds on the eastern margin. The continuity of structure at 20°S suggests rather thick lithosphere beneath the North Australian Craton. However, it is unclear whether the feature near 300 km depth in the section at 24°S has a direct association with the lithosphere.

Our present images of the shear-wave speed distribution across mainland Australia are sufficient to define the presence of a major transition in lithospheric structure that is related to the presence of the cratonic core of the continent. However, these images do not provide strong constraints on structures within Tasmania, because we cannot achieve resolution at a fine-enough scale using surface waves.

We have therefore undertaken a more detailed experiment in northern Tasmania using a dense array of short-period recorders with delay-time tomography using distant events to investigate the contrasts in crustal and upper mantle structure. The TIGGER experiment involved 72 seismometers in all, with recording over the period from December 2001 to August 2002. The patterns of relative delay across the array show clear indications of changes in structure (Figure 4), and this information is being combined with information from reflection and refraction studies (Rawlinson *et al.* 2001) to build a model of the structure beneath northern Tasmania.

INTERPRETATION AND DISCUSSION

When we compare the location of the neutral marker for the wave-speed transition in the mantle (Figure 3a) with the postulated Tasman Lines (Figure 1b), we find that different aspects of the mantle structures are reflected in the definitions adopted by different authors.

The original Tasman Line of Hill (1951) in Queensland corresponds broadly to the edge of the fast wave-speed anomaly down to 125 km depth, associated with the seismic lithosphere. There is also some relation between the northwest to southeast trend along the edge of the Curnamona Province in most of the more modern suggestions, with the configuration of part of the wave-speed anomaly at 75 km. However, the main north–south boundary below 150 km in our results, with higher seismic-wave speeds to the west, has no correspondence to any of the many proposed Tasman Lines. This boundary of fast and thick seismic lithosphere has a relatively steep dip to the west down to at least 225 km depth. The wave speeds increase rapidly to the west away from the neutral marker, achieving more than a 2% increase within 100 km.

The dividing line at ~140°E marks the edge of a coherent zone of thick lithosphere and so may represent the ancient core of the continent. The progressive accretion of the eastern part of Australia through a sequence of subduction and rifting events could be expected to modify the original boundary, so that what we image today is the result of many different processes over geological time.

However, we note that to the east of the main boundary there is some extension of thicker lithosphere to depths of ~175 km. There is a distinct feature in the west of northern New South Wales and southern Queensland, the characteristics of which suggest that this lithosphere may also have Precambrian affinities. Interestingly, the Broken Hill area, despite the conspicuous Precambrian outcrop, is underlain by fast wave speeds to only ~150 km, rather than more than 225 km further west. This feature is consistent with the delay-time results from the recording of the Cannikin nuclear test in the Aleutians (Cleary *et al.* 1972), where the fastest arrivals occurred to the west of 139°E (see also Kennett 1997).

The models of shear-wave speed structure that we have constructed from the surface-wave tomography are based on the assumption that the mantle structure is smoothly varying. Yet, we find a relatively sharp transition in structure comparable to available resolution. The mantle lithosphere appears to be very long-lived and to have a close association with the crust above, but it is very difficult to envisage how such sharp contrasts in mantle properties can be sustained against thermal erosion over the 500 million years or more since eastern Australia started to be accreted (cf. Direen & Crawford 2003).

A new deployment of 20 broadband seismic recorders was begun in May 2003 surrounding the length of the mantle transition in seismic-wave speeds, to try to improve resolution of details of the structures along the 'Tasman Line', by using higher frequency waves and inter-station measurements. The new stations will also provide additional control on crustal structure.

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