Seismic structure in the mantle beneath Australia

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The configuration of earthquake belts around Australia provides a wealth of events at suitable distances to be used as probes into the seismic structure of the upper mantle. The limited number of permanent high-fidelity seismic stations on the continent has been supplemented with extensive deployments of portable broadband stations for periods of a few months at each site. The combination of a long term of recording at the permanent stations and the broad spatial coverage of the portable stations provides an excellent resource for studies of the mantle. A wide range of techniques can be used to gain information on the three-dimensional structure in the mantle, which exploit different aspects of seismograms. The large-amplitude surface waves in the later part of the seismogram travel nearly horizontally and can be used in a tomographic inversion to determine the 3-D variations in shear-wave speed. This approach relies on matching the waveforms on individual paths and then mapping of the path-specific constraints on shear structure into a 3-D model. In contrast, the higher frequency body-wave arrivals are refracted back from the variations in structure in the mantle and are particularly sensitive to discontinuities in structure. Observations out to 3000 km provide coverage of the structures down through the transition zone and for the region below northern Australia, the combination of short-period and broadband observations has provided detailed information on both P and S wave speeds and attenuation structure. Further information on lateral variations in structure can be extracted from the patterns of travel-time residuals. The combination of the different classes of results reveal a complex pattern of 3-D structure beneath the Australian region. The cratonic region in the centre and west of Australia is underlain by a thick mantle lithosphere extending to around 210 km depth with fast wave speeds (especially for S waves), In the asthenosphere below, the S wave speeds diminish and there is significant attenuation and also some level of seismic anisotropy. Beneath the eastern zone with Phanerozoic outcrop the lithosphere is generally thinner (less than 140 km) and the asthenosphere has a pronounced low-velocity zone for S, again with high attenuation. The variations in seismic-wave speeds extend through the upper mantle with noticeable differences in the transition zone. There is also evidence for pervasive small-scale heterogeneity (scale lengths of 100–200 km) superimposed on the broader scale variations that can be imaged using tomographic methods.

KEY WORDS: asthenosphere, lithosphere, seismic tomography, upper mantle.

INTRODUCTION

The exposed geology of the Australian continent is composed of an assemblage of crustal blocks that can be broadly grouped into the Precambrian western and central cratons and the Phanerozoic eastern province (Figure 1). Structural differences between the Precambrian shield and eastern Australia are inferred from surface-wave dispersion (Muirhead & Drummond 1991; Denham 1991) and teleseismic travel-time residuals (Drummond et al. 1991) whose origin is due to structures that certainly extend below 100 km depth.

The extensive seismic activity in the earthquake belt that runs through Indonesia, New Guinea and its offshore islands, Vanuatu, Fiji and the Tonga–Kermadec zone provides an abundant source of seismic probes for the structure in the lithosphere and the upper mantle beneath. A wide range of studies has exploited the different aspects of the seismic wave train from the P and S body waves refracted back from the velocity structure in the upper mantle through to the large amplitude surface-wave trains which travel nearly horizontally on their path from source to receiver.

The Australian continent itself has a fairly low level of seismicity and only a few high-quality seismographic stations. The study of structure beneath the continent has therefore depended on the deployment of portable seismic instrumentation. Up to 1993 the experiments involved the deployment of vertical-component seismometers (with natural frequency around 1 Hz), with firstly analogue recording, and later low-power digital reel-to-reel tape recorders (Figure 2a). The first portable broadband instruments were used in 1992, and from 1993 the emphasis has been on continent-wide coverage using a mobile network of stations (Figure 2b).

In the SKIPPY experiment from 1993 to 1996 (van der Hilst et al. 1994), stations were deployed across the whole continent at approximately 400 km spacing. Because only a limited number of broadband seismometers and high-fidelity recorders were available, the continental coverage was achieved using between 8 and 12 stations at a time, installed for about 5 months in each location. This period is sufficient to get good coverage of the regional seismicity but is a little short for some classes of studies that depend on less-frequent teleseismic events at specific distance...
ranges. In 1997 and 1998 a denser array of broadband instruments (KIMBA) was deployed in the remote Kimberley region of northwestern Australia to follow up indications of contrasts in cratonic structure. In 1999 additional stations were deployed in southeastern Australia (QUOLL) to provide additional information on the transition between Phanerozoic and Proterozoic structure. Western Australia was revisited in 2000–2001 with a broadly spread array designed to supplement the SKIPPY stations, which had had a number of technical problems. Sets of more closely space instruments are intended to provide more detailed information on the substructure of the Archaean blocks and the links between them.

In less than 10 years therefore there has been a very thorough coverage of the Australian continent with broadband seismic stations. These stations provide information for many different styles of analysis for the 3-D seismic wave-speed distribution, attenuation and anisotropy.

The experiments with the short-period recorders provided valuable information on the nature of the radial distribution of seismic-wave speeds in the mantle, and also indicated the presence of lateral heterogeneity in seismic wave speeds in the upper mantle on a variety of scales. The depth profiles for different azimuthal sectors with sampling regions differing by 1000 km show significant differences. The character of the wavefield variations across the recording arrays indicate pervasive medium-scale heterogeneity with a scale length of 200 km or less. The high-frequency body waves travelling through the cratonic lithosphere have an extended coda indicating very strong scattering due to small-scale variability with very little attenuation.

The impetus for moving to broadband studies using three-component recording came from the disappearance of S waves in the short-period vertical records from northern Australia for epicentral distances beyond 18° (Dey et al. 1993). With a broader range of frequency content it became apparent that once the S waves penetrated below the cratonic lithosphere (about 200 km thick) they encountered a zone of slightly lowered seismic-wave speeds and much higher attenuation. S waves returned from below this asthenospheric layer were of sufficiently low frequency to be poorly recorded on short-period instruments (Gudmundsson et al. 1994).

The broadband seismometers provide good recordings of the surface waves of earthquakes from the neighbouring belts of seismicity with surface-wave magnitude (Ms) greater than 5.5. For these events we can exploit the source mechanisms in the Centroid Moment Tensor catalogue produced by Harvard University (Dziewonski et al. 1999) and use the waveforms in inversion schemes designed to extract 3-D shear-wave structure. The very large number of surface wave paths crossing the continent provide good azimuthal control, particularly in central and eastern Australia, and so it is possible to extract information on azimuthal anisotropy.
Figure 2 Deployments of portable seismic recorders in Australia by the Australian National University. (a) Short-period recorders, 1975–1993. (b) Broadband recorders 1992–2000. The different colours indicate separate instrument deployments.
in seismic-wave speeds. With three-component recording we can study both the Rayleigh waves with polarisation in the vertical plane and Love waves with purely horizontal polarisation. The differences in the structures inferred by analysis of the different wavetypes requires polarisation anisotropy.

SURFACE-WAVE STUDIES

The most prominent feature of seismograms from shallow earthquakes are large-amplitude surface-wave trains. With portable broadband instruments it is possible to achieve good recordings of the surface waves to periods around 100 s, and at typical distances from the source of 2000 km this means that it is possible to sample well the zone down to 400 km.

Much of the analysis of surface waves has concentrated on the Rayleigh waves recorded on the vertical component. The horizontal components of ground motion tend to have higher levels of ambient noise than the vertical component, but for larger events it is possible to exploit the Love waves, with horizontal polarisation, to provide additional information on the upper part of the mantle.

The traditional tool for the analysis of surface waves is the determination of surface-wave dispersion and the mapping of this information into a depth profile of shear-wave speeds. However, the limited number of permanent stations in Australia meant that only a few great-circle paths were available (Denham 1991) and these clearly indicated substantial differences between central and eastern Australia. The dispersion results for the east coast of Australia indicate the presence of a low-velocity zone for shear-wave speed around 150 km depth (Goncz & Cleary 1976), but this is not present in central Australia.

The SKIPPY deployments of broadband instruments were designed to exploit advances in the analysis of surface waves via waveform inversion (Nolet 1990; Zielhuis & Nolet 1994). This ‘Partitioned Waveform Inversion’ (PWI) is a two-stage procedure. The first step generates a shear-wave speed model for each path and the second combines the path-dependent information into a 3-D model.

The first stage of this procedure is based on the matching of observed and calculated seismograms for the surface waves for each source–receiver path, which requires a knowledge of the source mechanism. The inversion for each path generates a radial profile of shear-wave speed which is interpreted as the average structure along the great-circle path between source and receiver. The dependence of the waveforms on shear-wave speed is non-linear and the results are sensitive to the starting shear structure assumed in the inversion. Synthetic tests demonstrate that the influence of fixing the P wave-speed distribution is small. The modelling procedure assumes the independent propagation of individual modes along a great-circle path and thus a smooth change in wave-speed structure.

For Rayleigh waves two different group velocity windows are analysed: for a window around the fundamental mode a bandpass filter from 0.010 to 0.025 Hz is applied and for the earlier window covering higher modes the filter extends from 0.008 to 0.050 Hz. These frequency bands are chosen to minimise the influence of deviations from the great-circle path and to ensure that the seismograms are recorded in the far-field of the source (Kennett 1995). The fundamental Rayleigh mode places the strongest constraints on the region above 250 km, and the higher modes add information at depth. The excitation of higher modes is enhanced as

Figure 3 Coverage from Rayleigh waves for surface-wave tomography. (a) Paths for which both the fundamental mode and overtones could be analysed. (b) Paths for which only the overtones were used (usually from deep events). (c) Paths for which just the fundamental mode was analysed (mostly rather shallow events with poor excitation of the overtones).
the source depth increases, whilst the fundamental mode diminishes. The combination of fundamental mode and higher mode information in the waveform fitting helps to constrain the different aspects of the velocity profile. However, sometimes the effect of heterogeneity in the Earth is such that it is not possible to fit both of the waveform windows with the same wave-speed profile. An example is for paths across the southern Tasman Sea, where there is a very large drop in seismic-wave speed at shallow depth.

The presence of the subduction zones around Australia provides a valuable source of intermediate and deep events, but is concentrated to the north and east. The coverage at depth is therefore somewhat different from that provided by the shallower events which occur to the south as well (Figure 3).

The second stage of the PWI scheme is a linear inversion to generate a 3-D shear-wave speed model. With the interpretation of the models for each path as the average structure, the path information provides linear constraints on the 3-D structure. The second-stage inversion then reconciles the different constraints to produce the 3-D model. Large deviations from the reference model can be accommodated because of the linear dependence of the ‘data’ (the path-averaged models) on the 3-D model parameters. Both model norm and gradient damping are used to achieve a balance between data fit and smoothness of the model. The reliability of the resulting model is highest in those regions where there are multiple crossing paths. At this time the path density is best in central and eastern Australia and the 3-D model is less well constrained to the west of 120°.

The application of the PWI technique to the SKIPPY dataset proceeded as the data were being collected. Zielhuis and van der Hilst (1996) presented the first model based on the analysis of the Rayleigh wave data from the stations in eastern Australia. This already indicated the presence of a very major contrast in the shear-wave speed in the mantle component of the lithosphere between central Australia and eastern Australia. The 3-D model indicated the presence of lowered shear-wave speeds beneath the east coast of Australia at depths around 140 km and confirmed the inferences from surface-wave dispersion. The location of the zones of low wave speed has a strong correlation with Neogene volcanism.

The 3-D models have evolved as more data have been incorporated. Using the PWI technique with vertical-component waveforms, results have been presented by van der Hilst et al. (1998) and Simons et al. (1999) based on a cellular representation of the model with blocks of about 1 x 1°. Figure 4 shows the shear-wave speed distribution for SV waves at 80 and 200 km depth derived from a PWI inversion using approximately 2000 Rayleigh wave paths, and indicates the large deviations in seismic-wave speed from the reference value of 4.5 km/s. The sampling by surface-wave paths is lower in the western part of Australia and features to the west of the 120° meridian should be treated with caution. The areas of exposed Precambrian rocks largely correspond to high seismic-wave speeds but there are zones of enhanced wave speed extending to 150 km or more lying to the east of the conventional Tasman line (Figure 1). The Precambrian regions show the presence of significant internal structure with an indication of the separation of the major cratonic blocks, especially at shallower depths.

The contrasts in shear-wave velocity are more pronounced at 80 km depth, but even at 200 km depth we see variations of the order of 8% in shear-wave speed. The major feature beneath the continent is the lowered wave speeds along the eastern margin as compared with the raised wave speeds in the centre and west. The variations in wave speed are such that a purely thermal interpretation is difficult to sustain (see the Conclusions section).

There is not a simple relation between the structures in the mantle and the conventional Tasman line (which represents the eastern limit of surface exposure of Precambrian material). Rather 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 velocity gradient extending through Cape York and central Queensland to depths below 150 km, which links to slightly weaker features in southern Australia. To the west of this line the higher velocities extend coherently to 200 km or below, whilst to the east although there is an area of elevated wave speed it does not extend to the same depth.

The Phanerozoic belt in eastern Australia has a thin zone of high wave speeds in the lithosphere extending to about 100 km, and beneath this there is a zone of lowered wave speed that extends along most of the east coast of Australia. The low seismic-wave speeds extend to the east beneath the Tasman Sea where sea-floor spreading ceased at about 80 Ma. Subsequently the Tasmanian seamounts have been emplaced with a progression of volcanic edifices as Australia has moved towards the north over a presumed mantle plume: the predicted position of the plume based on current plate motions corresponds to a minor sea-floor feature and is a centre of earthquake activity.

The PWI inversions have provided significant insights into the nature of the mantle lithosphere. The upper part (80 km depth image) shows clear signs of influence from tectonic events: e.g. the lowered wave speeds in the southern part of central Australia in the region affected by the Alice Springs Orogeny at about 300 Ma. Regions such as the Kimberley Block in northwestern Australia appear to maintain a distinct character compared with their surroundings to significant depth. This suggests that the lithosphere is able to retain its character over very long periods of time and that there is the potential for using the ‘geology’ of the mantle revealed in the seismic images to try to track back into the assemblage of the lithosphere. In central and western Australia the high seismic-wave speeds extend to about 200 km depth and the eastern boundary of this high wave-speed zone lies close to 140°E, and does not follow the configuration of the Tasman line.

The abruptness of the transition from high wave speeds to lower values is sufficiently rapid to test the assumptions made in the inversion. The rapid change has the potential of introducing mode coupling and is also such as to produce some deviations of surface-wave propagation paths from the great circle from source to receiver, especially for paths travelling along the transition zone between higher and lower wave speeds. The next generation of inversion schemes will need to take account of such effects and include an iterative development for the construction of the 3-D model. Marquering et al. (1996) have shown how an approximate treatment of mode coupling can improve the
Figure 4  Map views of the 3-D shear-wave model derived from partitioned waveform inversion using the permanent stations and the deployments of broadband stations: (a) 80 km depth; (b) 200 km depth. The red lines indicate the plate boundaries along which the majority of earthquakes used are sited.
treatment of higher modes at shorter periods by providing a better representation of S body-wave propagation.

An alternative approach to the development of 3-D models has been pursued by Debayle (1999) and Debayle and Kennett (2000a, b) again using a two-step inversion, but with a different style of waveform inversion for each path based on the work of Cara and Lévêque (1987) and a second-stage inversion using the continuous regionalisation method of Montagner (1986). The second-stage inversion uses the path information to extract not only the variations in seismic-wave speed but also the azimuthal anisotropy in the SV wave speed using the approach of Lévêque et al. (1998). In a weakly anisotropic medium the variation of Rayleigh wave speed with azimuth θ is expected to have \( \cos \theta \) and \( \sin \theta \) dependence. The local direction of fast shear-wave speed can be extracted in regions where there are sufficient crossing paths. The wave-speed inversion imposes an intrinsic smoothing based on an imposed Gaussian correlation function: a width of 500 km has been found to be satisfactory (for further details see Debayle & Kennett 2002).

Surface-wave analysis requires the passage of seismic waves across and into the region of interest and can be carried out in most parts of the world, but Australia is one of the few places where it is possible to also use body-wave information as a complement and check on the results of surface-wave tomography.

**BODY-WAVE STUDIES**

The configuration of seismic sources around Australia allows the use of body-wave analysis using waves refracted back from the structure in the mantle out to distances of 3000 km from the source. These waves sample through the whole upper mantle and transition zone, and have their maximum sensitivity to velocity structure near their turning point (close to the midpoint of the path from source to receiver for shallow sources). Unfortunately, the separation between the natural sources to the north of Australia and stations on the continent is such that it is difficult to use refracted wave arrivals (for either P or S) to constrain shallower structure and resolution of structure is best below 150 km depth.

The pattern of velocity gradients and discontinuities in the mantle imposes a complex structure on the expected form of seismograms for even a 1-D wave-speed profile (Figure 5). The situation is complicated further by the 3-D structure imaged in the surface-wave work and local small-scale heterogeneity. Earlier studies concentrated on the P wave-speed distribution using arrays of short-period portable instruments on a variety of scales. Subsequently with the advent of high-fidelity broadband recording it became possible to work with S waves as well.

**Short-period studies**

Initial efforts were made to delineate the major features of the mantle velocity profile by using arrays of short-period stations. In a pioneering study Hales et al. (1980) used travel-time analysis of record sections from Indonesian earthquakes at a variety of depths. The span of the recording arrays was such that only part of the wavefield was captured for each earthquake and the velocity profile was pieced together using the information from multiple events. The resulting model, for upper mantle structure under the northwestern part of the Australian margin, is rather complex with many small discontinuities and low-velocity zones, which may reflect the mapping of 3-D structure into a 1-D profile. A subsequent reinterpretation of this data by Leven (1985), using comparisons between observed and synthetic seismograms, leads to a somewhat simplified structure but retains a prominent velocity contrast near 210 km depth.

A number of deployments of short-period vertical seismometers were designed to exploit the natural seismicity in the Indonesia/New Guinea region in studies of mantle structure. The distance span of the deployments covers only a limited portion of the triplications produced by the upper mantle discontinuities. Thus a useful tool in such studies is the assembly of seismograms from many events and stations to produce a composite record section in which the phase branches for the different mantle arrivals can be tracked (Figure 5): all arrivals in a 10 km epicentral distance range are combined into a single trace. The influence of variable source-time functions is reduced by stacking the envelope of the seismograms (Bowman & Kennett 1990). This procedure minimises the influence of local heterogeneity and can produce striking results for P waves with clear delineation of phase branches as illustrated in Figure 5a. The patterns of arrivals can then be in terms of the velocity distribution with depth. The shallow structure has to be inferred, but the P velocity structure is well constrained from above the base of the lithosphere near 210 km down to below the 410 km discontinuity. The short-period results require a P velocity contrast near 210 km depth to explain multiple arrivals with a few seconds separation around 1400 km from the source. However, for S waves the corresponding record sections only show a clear arrival associated with the lithosphere which cannot easily be traced beyond 2000 km, and no branches associated with greater depth. Synthetic seismograms from a reference model for northern Australia are included in Figure 5b as an aid to identifying the arrivals; note that this model is not designed to provide a direct match to the observations. Although the nature of the phase branches in the composite sections can be well summarised by a single 1-D wave-speed profile, there is commonly substantial variability between events. Bowman and Kennett (1990) have presented examples of individual events in the Flores arc with very strong arrivals associated with the 410 km discontinuity, even though other events from nearby locations show much more subdued arrivals. This indicates the presence of significant focussing and defocussing of short-period seismic energy due to heterogeneity. Using a variety of different sources of information, including the nature of signals on arrays of different aperture, Kennett and Bowman (1990) have suggested the presence of pervasive velocity heterogeneity in the upper mantle on scales of 100–200 km with an amplitude of about 1%. This small-scale heterogeneity is superimposed on the larger scale variations that have been imaged in the surface-wave studies and which is also evident in the nature of the body-wave arrivals.

Dey et al. (1993) have summarised much of the short-period work in northern Australia and presented composite record sections of upper mantle arrivals that show marked
variation in P wave velocity structure between paths for events along the Flores arc, and paths to events in New Guinea. The turning points in the mantle for the two profiles differ by nearly 1000 km and indicate larger contrasts at the 410 km discontinuity for the paths to New Guinea and differences in transition zone structure.

Within the Australian continent most of the information on P velocity structure down to 200 km has come from various experiments with large explosive sources (Muirhead & Drummond 1991). The infrequent natural events have also been exploited. Bowman and Kennett (1991) used the aftershocks of the 1988 Tennant Creek earthquakes to

Figure 5 (a) Composite record section of short-period seismograms at stations in the Northern Territory from shallow events in the Flores arc. (b) Synthetic seismogram calculations for a reference model for northern Australia indicating the principal seismic phases which can be seen in the observations. The travel-time branches are denoted by the discontinuity with which they are associated (r, refraction; R, retrograde reflection).
investigate regional S wave propagation in central Australia and were also able to infer the velocity profile in the crust and uppermost mantle. These aftershocks were also used by Bowman and Kennett (1993) to develop a set of travel times for P and S waves travelling in the shield structures of western Australia, and to find a compatible velocity model for the lithosphere.

**Broadband studies**

Modern broadband seismometers provide a faithful rendition of ground motion over a wide range of frequencies and allow the full exploitation of both P and S body waves. Once such broadband data became available, the reason for the absence of S waves at distances beyond 2000 km was clear. The S waves within the lithosphere are high frequency, but once they penetrate into the asthenosphere beneath there is a dramatic drop in frequency content. This effect implies a major contrast in the attenuation properties of S waves. There is very little attenuation of S in the lithosphere, but strong scattering leading to a complex coda. However, the asthenosphere beneath the cratonic lithosphere has both a slightly lower wave speed than the lithosphere above and much higher attenuation.

The initial results were obtained from a broadband sensor operated by the Research School of Earth Sciences (Australian National University) at the Warramunga array in northern Australia since late in 1988 (station code WRA: Figure 2). Over a period of years it was possible to build up record sections covering the range of interest for the upper mantle by using events in the Indonesia/New Guinea earthquake belt for both P and S waves (Gudmundsson et al. 1994; Kennett et al. 1994). The surface conditions in northern Australia make it possible to exploit both horizontal components of S waves after rotation to the great-circle path. Thus both the transverse SH component and the vertically polarised SV waves on the radial component records can be used: the high surface velocities lead to little contamination by converted P waves.

**WAVE-SPEED VARIATION**

The WRA observations have been used to generate composite record sections from many events for P and S waves and, in association with information from the short-period studies, used to build up velocity profiles for both P and S (Kennett et al. 1994). The analysis includes comparison of observed and synthetic seismograms with inclusion of attenuation. Because the P and S wave speeds are determined from the same events, the P/S velocity ratio can be well constrained and is similar to that for the shield areas of North America derived by combining separate P and S models (LeFevre & Helmberger 1989; Grand & Helmberger 1984).

Additional information on upper mantle structure can be obtained from the broadband stations deployed in SKIPPY and later experiments. The 400 km spacing for the SKIPPY stations means that the constraints on mantle structure for an individual event are low, but good coverage can be achieved by suitable combinations of data from many events. Kaiho and Kennett (2000) have exploited such composite record sections to obtain a suite of P and S velocity profiles for 16 azimuthal corridors across the Australian continent. Each 10°-wide corridor includes all source-receiver pairs with path azimuth within ±10° of the orientation of the corridor, and 0.5° bins were used in constructing composite record sections using a variety of stacking techniques.

A similar approach can be used for regional deployments such as the KIMBA experiments, which lie in a convenient position relative to the seismicity to the north. This allows sampling of the continental mantle beneath the northward extension of the Australian Shield with a nearly east–west orientation (Figure 6). A single event can only be observed over a 5° distance span, but coverage of the full upper mantle profile can be achieved by using data from many events.

Composite P and SH record sections for the KIMBA profile for events to the east are displayed in Figure 7, with event stacking in 0.3° bins using an envelope stack. The events were corrected to a common source depth of 25 km before stacking. The travel-time curves for the ak135 reference model (Kennett et al. 1995) for a 25 km-deep source are superimposed on the sections. As can be readily seen, both the P and S arrivals for distances less than 18° arrive before the expected times for the reference model, indicating the need for higher lithospheric wave speeds than for the ak135 model. The discrepancy is greater for S than P. At 13° the onset of S is about 17 s early compared to the ak135 times, requiring an increase in wave speed of about 5% along the path. The P and S sections show complexity in the character of the lithospheric arrivals out to 17–18° suggesting both the need for structure near 200 km depth and some degree of lateral variability in wave speed. The P arrivals remain slightly early compared to the reference times out to 26°. Beyond 20° the S wave onsets are both significantly longer period and quite close to those predicted by ak135. This behaviour can be achieved by introducing a modest reduction in S wave speed below 200 km to create a low-velocity zone, which also has enhanced attenuation.

The record sections in Figure 7 are characteristic of paths sampling the cratonic regions of northern Australia, but very different from paths to stations in eastern Australia from events to the northeast. Kaiho and Kennett (2000 figure 11) presented a summary of travel-time perturbations for epicentral distances out to 20°, which shows clearly the
transition from fast to slower paths across Cape York in the position predicted by the 3-D models derived from surface-wave tomography. As in Figure 7, the relative travel-time anomalies are much larger for $S$ than $P$, implying a relative deviation of about 3 to 1 from the \textit{ak135} reference model.

A selection of $P$ and $S$ wave-speed profiles are plotted in Figure 8 to illustrate the variety of behaviour encountered beneath the Australian region. The shield models (1–4) show a very fast $S$ wave speeds in the lithosphere underlain by a slight low-velocity zone. The corresponding $P$ profiles show only slightly higher wave speeds than the \textit{ak135} reference model (6). For paths in the mantle beneath the Phanerozoic zone (5) the thickness of the lithosphere is substantially reduced, and has lower wave speed.

The velocity models determined from the composite record sections are derived from single-ended profiles and should be interpreted as representing the wave speeds at the position corresponding to the turning point for the arrival rather than as a vertical profile. The model can therefore be associated with the horizontal position of the appropriate turning points. Kaiho and Kennett (2000) have exploited this interpretation to combine the 1-D models for 16 different azimuthal corridors into a pseudo-3D velocity model (Figure 9). Because of the use of the turning-point property there is no mapping of portions of velocity models in low-velocity zones. However, we still see the clear contrasts in lithospheric properties in Figure 9 which match well with the surface-wave results. Considerable variation in seismic-wave speeds are found through the asthenosphere and mantle transition zone (Figure 9 260–310 km, 360–410 km).

**ATTENUATION STRUCTURE**

The relative frequency content of $P$ and $S$ waves provides a visual guide to the relative attenuation of $P$ and $S$. This approach can be quantified by working with the slope of the spectral ratio between $S$ and $P$ windows on the same
seismogram to extract a quantitative estimate of differential attenuation ($\delta t^*$). Gudmundsson et al. (1994) used the broadband observations at WRA to construct the variations of $\delta t^*$ with epicentral distance. With a knowledge of the velocity structure it is possible to invert these $\delta t^*$ observations for a simple layered $Q$ model with depth beneath the shield region. The lithospheric attenuation down to 210 km is very low and $Q_\beta$ for S waves, exceeds 1000. In the asthenosphere beneath, significant attenuation is required with $Q_\beta$ around 120, if the attenuation is spread over the whole zone between 210 and 410 km depth. Even lower $Q_\beta$ values would be needed if the attenuation were concentrated in a thin layer. The $Q_\beta$ value recovers to around 500 in the transition zone and appears to be higher again in the lower mantle below 660 km.

The style of analysis employed by Gudmundsson et al. (1994) for 40 events at WRA has now been extended to nearly 2000 paths covering the continent using the broadband records from the SKIPPY and KIMBA experiments (Cheng & Kennett 2001). Analysis of the spectral ratio between S and P waves for frequencies ($\tilde{f}$) up to 6 Hz yields the differential attenuation ($\delta t^*$) for a low frequency band around 0.6 Hz, and an estimate of the averaged frequency exponent along the path (corresponding to frequency dependence $Q = Q_0\tilde{f}^\gamma$). There is a very substantial geographic variation in $\delta t^*$, with a strong correlation between large differential attenuation and enhanced frequency variation. The cratonic lithosphere with fast wavespeeds has very low $\delta t^*$ with almost no frequency dependence. Whereas the paths sampling the asthenosphere have much

Figure 8 Comparison of 1-D velocity profiles for P and S waves in the Australian region. 1, azns, north–south sampling of mantle below shield (Kaiho & Kennett 2000); 2, kmba, east–west sampling of mantle below shield from KIMBA stations; 3, waus, from travel times for Tennant Creek earthquake aftershocks recorded in western Australia (Bowman & Kennett 1993); 4, njpb, from analysis of records at WRA (Gudmundsson et al. 1994); 5, azne, sampling of mantle beneath eastern Australia (Kaiho & Kennett 2000); 6, ak135, reference model (Kennett et al. 1995)
enhanced $\delta t^*$ and significant frequency dependence ($\gamma$ around 0.5).

With the aid of the 1-D velocity models of Kaiho and Kennett (2000) for the different azimuthal corridors, the differential attenuation as a function of both epicentral distance and frequency has been inverted using the Neighbourhood Algorithm of Sambridge (1999) to produce a set of profiles of $Q$ and the local frequency exponent $\alpha$, as a function of depth. The apparent $Q$ is an integrated property along the path and, with the aid of the vertical and horizontal ray-path density, the results for the different azimuthal corridors have been combined into an estimate of the 3-D structure in both $Q$ and its frequency dependence (Cheng & Kennett 2001). This model is based on a five-layer representation of the attenuation structure. Figure 10 illustrates the geographic variations in attenuation at depths around 150 and 300 km. Beneath the shield the behaviour matches well with the results for WRA. However, here is a profound contrast between the fast lithosphere of west-central Australia and the elevated asthenosphere beneath the eastern part at 150 km, compared with a more modest variation at 300 km depth. As noted above there is a strong correlation between regions of lowered $Q$ and enhanced frequency variation.

REFRACTED-WAVE ANISOTROPY

For many paths sampling the upper mantle transition zone there is an indication of shear-wave splitting in refracted S waves. Tong et al. (1994) have analysed data for events in a broad azimuth range recorded at WRA. For arrivals from the upper mantle discontinuities the S wave is systematically earlier, by more than 1 s, on the tangential (SH) component than the radial (SV) component. This information on the seismic anisotropy for the refracted S wave arrivals has been analysed using correlation analysis for a set of time windows on the seismogram associated with the different phase branches to determine the direction of fast propagation and the time shift between the S components for that branch. The fast directions for groups of events to the west and east of WRA are oriented approximately transverse to each set of paths, so that they are incompatible with material anisotropy confined to the lithosphere.
beneath the WRA station. A level of anisotropy of the order of 1% in both the lithosphere and the asthenosphere beneath would explain the data quite well.

**Travel-time tomography**

A further source of information on velocity structure in the Australian region comes from travel-time tomography studies using sources both in the region and from around the globe. This technique exploits the deviations in travel times from those for a reference model and an inversion is undertaken to determine the 3-D distribution of wave speed compatible with the observations. This approach was pioneered for the Australian region by Widiyantoro and van der Hilst (1996) who used the travel-time residuals for P and pP for teleseismic paths, as well as paths to Australian stations (both permanent and portable) in a tomographic inversion for structure in a zone covering the southern Philippines, Malaysia, Indonesia, Papua New Guinea and northern Australia. In order to minimise the influence of structure external to the region, their inversion for P wave velocity followed the approach introduced by Inoue et al. (1990), in which a detailed grid is used for the region of interest and a coarser grid for the region outside. The resolution attained was of the order of 100 km, both horizontally and in depth, so that the details of the high-velocity subducted slabs can be recognised.

A major effort has been made to relocate seismic events across the globe using the ak135 reference model (Kennett et al. 1995) and then reassociate catalogue readings to provide a comprehensive set of information on the travel times of P, S and many other phases (Engdahl et al. 1998). This provides a high-quality database from which to conduct regional delay-time tomography for both P and S waves. The reading of S arrivals is more difficult than for P, at the onset of the seismogram, and coverage is somewhat less than for P, but still sufficient to provide satisfactory images of structure in the subduction zones (Gorbatov & Kennett 2001).

Figure 10 Map view of sections through (a) 3-D models of Q and (b) its frequency exponent $\alpha$ at depths around 150 and 300 km.
Figure 11 shows map views of the P and S wave structure for Australia and its immediate surroundings at depths around 135 and 240 km. The tomography is carried out using a cellular representation of the wave-speed model with 0.5 x 0.5° cells from the surface to 210 km and 1 x 1° cells beneath. The thickness of each of the layers is around 50 km. Resolution is good in the neighbourhood of the subduction zones because of the concentration of sources. Beneath the continent much of the information is imparted by nearly vertically travelling rays from very distant earthquakes and so sampling is concentrated around the stations.

The P and S wave images are plotted using the same scale of perturbation and we can see the high relative variations associated with S waves. The main subduction zones are clear in both the P and S images at 135 km depth, and the fast wave speeds in the Australian craton show up in patches reflecting the available path distribution. At 245 km the amplitude of heterogeneity is much reduced beneath the continent indicating that the base of the lithosphere has been reached; note that there will inevitably be some level of vertical smearing of anomalies. However, there is a fast S wave-speed structure in the oceanic region in front of the Flores arc in Indonesia which does not have an equivalent in the P wave-speed map at 245 km. This suggest some oceanic–continental dichotomy in the nature of the lithosphere.

CONCLUSIONS

Over the last 15 years extensive progress has been made in understanding of the nature of the distribution of seismic structure in the mantle beneath Australia. The nature of the regional earthquake sources means that it has been possible to undertake a wide range of studies and to produce an integrated result in a way that has not so far been accomplished for any other continent.

Surface-wave studies of the Australasian region have provided broad-scale coverage of 3-D shear-wave speed structure with good resolution currently available to the east of the 120° meridian. Beneath the crustal regions high seismic-wave speeds extend to depths around 220 km and have a relatively abrupt eastern margin that does not correlate simply with the Tasman line marking the eastern extent of current Precambrian outcrop.
results also indicate the presence of substructure in the mantle within the high wave-speed zones at least to depths of 100 km. The eastern seaboard of Australia and the Tasman have markedly lower shear-wave speeds than the centre and west of the continent, with a marked zone of lowered seismic velocities at depths around 140 km.

Body-wave travel times provide an independent check on the nature of lithospheric structure and indicate the need for much larger variability in S wave speed than for P waves. The northern Australian craton shows very high S wave speeds with a rather sharp transition to slower paths occurring in the Cape York peninsula. The full set of refracted body waves from the events in the earthquake belts to the north and east of Australia can be exploited to provide an independent estimate of 3-D wave speed structure for both P and S waves. The results tie well with the surface-wave results for S and the concordance of the different styles of analysis means that we can have considerable confidence in the main features of the structures in the mantle.

The regions of high seismic-wave speed beneath the cratons show very little seismic attenuation, but there needs to be a sharp change at depth since waves which penetrate into the asthenosphere rapidly lose high-frequency energy. The cratonic lithosphere is thus underlain by a zone of slightly lower S wave speeds and significant attenuation. The zones of lower seismic-wave speed in the east of Australia are accompanied by enhanced attenuation with a noticeable frequency dependence.

The levels of variation of S wave speed encountered across the Australian region are large. At 150 km deep the S wave speed varies from about 4.9 km/s in the faster parts of the cratonic lithosphere to close to 4.1 km/s in the southern Tasman Sea. Relative to a reference velocity of 4.5 km/s this represents variations from +8% to -8%. Experiments on shear-wave speeds at seismic frequencies indicate that it is possible to achieve substantial reductions in seismic-wave speed and enhanced attenuation as synthetic materials with mantle compositions approach the solidus (Jackson 2000). The wave-speed variation with temperature is non-linear with rapid variation at high temperatures, and would be enhanced by the presence of volatiles. However, at low temperatures the behaviour is close to linear with only a modest temperature coefficient. It would therefore appear that a substantial fraction of the variations in seismic-wave speed will have a thermal origin, which fits with the association of anomalies in the mantle with the regions which have undergone Neogene volcanism. Goes et al. (2000) have sought an entirely thermal explanation for the somewhat milder variations in

Figure 12 Map view of the 3-D shear-wave speed structure at 140 km plotted with the neutral tone shifted to 4.6 km/s (a +2.5% velocity perturbation from the reference). The darkening red tones indicate the increasing influence of thermal effects and the patterning the portion of the heterogeneity which may well have a chemical component. The red lines indicate the plate boundaries.
shear-wave speed in Europe. The exceptionally fast shear-wave speeds in the mantle beneath the Australian Shield are difficult to explain with any plausible thermal model and suggest that some degree of chemical variability is required.

As an indication of the possible segregation of compositional and thermal effects, the shear-wave speed at 140 km depth (from the study depicted in Figure 4) is plotted in Figure 12, with the neutral tone set at 4.6 km/s (a 2.5% increase on Figure 4). The neutral zone then separates the very high velocities with a potential chemical heterogeneity (indicated by patterning) from the lower velocities (in red tones) for which thermal effects are likely to be the dominant influence. The intensity of tone gives an impression of the influence of temperature.

We can hope to get further constraints on the nature of the seismic structure when we can obtain comparable quality images of P and S wave speed. This is not easy because of the absence of any P wave analogue of surface waves and will be a goal for future studies.

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