

Upper Mantle Structure beneath Australia from Portable Array Deployments

R.D. van der Hilst

*Research School of Earth Sciences, The Australian National University, Canberra ACT 0200, Australia and
Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA 02139, USA*

B.L.N. Kennett

Research School of Earth Sciences, The Australian National University, Canberra ACT 0200, Australia

T. Shibutani

Research Centre for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University, Kyoto 611, Japan

The distribution of earthquakes at regional distances around Australia is particularly favourable for these natural events to be used as probes into the seismic structure of the lithosphere and upper mantle. The distribution of permanent seismic stations is too sparse for detailed continent-wide seismic imaging, and most information used in our studies has come from deployments of portable seismic recorders. These were initially used in northern Australia to define the radial variations in P and S velocity and attenuation, using a combination of short-period and broad-band observations. The whole Australian continent has now been covered in the SKIPPY experiment from 1993-1996, in which a sequence of deployments of up to 12 recorders at a time have been used to synthesize a continental-scale array of broad-band instruments. The major objectives of this project are to delineate the three-dimensional structure of the Australian lithosphere and underlying mantle by tomographic inversions for lateral variations in seismic wave speed and site-specific studies to map crustal thickness (receiver functions) and seismic anisotropy (shear-wave splitting). Surface-wave studies have begun to reveal the three-dimensional variations in shear-wave structure beneath the continent by exploiting the records from portable broad-band stations. Dense data coverage enables the imaging of wave-speed variations on length scales of 250 km, and larger beneath most of central and eastern Australia. Results of the wave-form inversion suggest that the eastern edge of the Proterozoic shields of central Australia is a complex three-dimensional surface, which does not have a simple relation to the conventional Tasman Line marking the separation of Precambrian and Phanerozoic outcrop. In the shallow lithosphere (80 km depth), the most pronounced lateral contrast in seismic wave speed occurs significantly further east than the conventional Tasman Line. However, in northern Australia the eastern boundary of exposed Precambrian basement coincides with a transition from moderately high wave speeds to fast wave propagation that is particularly prominent at a depth of

about 140 km. At larger depth still (200 km), the wave-speed gradient seems to occur significantly further west (near the western margin of the Eromanga Basin). Beneath most of eastern Australia, the fast seismic 'lid' does not extend to depths larger than about 100 km, and there is a pronounced low-velocity zone between about 100 and 200 km depth. The surface-wave data do not indicate a slow wave-speed channel beneath central Australia. Instead, the fast lid extends to a depth of at least 250 km, and locally to depths in excess of 350 km. The North Australian Craton is seismically well defined, but does not seem to continue into the Kimberley Block. In the shallow lithosphere, the region influenced by the Late Palaeozoic Alice Springs Orogeny (Amadeus Basin and Musgrave Block) is marked by significantly slower seismic-wave propagation than the Proterozoic cratons to the north and south. Analysis of data from individual stations has produced a set of shear-velocity profiles for the crust and uppermost mantle beneath SKIPPY stations; these provide a useful complement to the information at depth from the surface-wave studies. The crust-mantle boundary is deep (38-44 km) and mostly transitional in character along the axis of the eastern fold belt, but is relatively sharp and shallower (30-36 km) near the boundary between Precambrian and Phanerozoic outcrop. Shear-wave splitting results from the portable stations are beginning to reveal a complex pattern of seismic anisotropy that requires further analysis of both body and surface wave data.

INTRODUCTION

The surficial 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 1A). Structural differences in the mantle beneath the Precambrian shield and eastern Australia have previously been inferred from limited observations of surface wave dispersion [Muirhead and Drummond, 1991; Denham, 1991] and teleseismic travel-time residuals [Drummond et al., 1989]. These results have been confirmed and extended in recent studies using deployments of portable broad-band instruments across the whole continent [the SKIPPY experiment, van der Hilst et al., 1994], and it is now possible to derive three-dimensional models of the P and S wave speeds beneath the Australasian region to depths of 400 km or more.

The extensive earthquake activity in the seismic belt that runs through Indonesia, New Guinea and its offshore islands, Vanuatu, Fiji, and the Tonga-Kermadec zone provides a wide range of natural sources which can be used to constrain seismic structure in the lithosphere, asthenosphere, and the transition zone beneath. There is a rather limited number of high-quality, permanent seismological stations in Australia, so that high-resolution studies of seismic structure need these observatories to be supplemented by the installation of portable recorders (Figure 1B).

Building on the experience from array deployments in northern Australia, the Research School of Earth Sciences (RSES) started in 1993 a nation-wide observational seismology project, the SKIPPY experiment, which uses a

sequence of array deployments to synthesize a continental-scale array of broad-band instruments. Major objectives of this project are to exploit different classes of seismological data for the delineation of the three-dimensional structure of the Australian lithosphere and underlying mantle, by tomographic inversions for lateral variations in seismic-wave speed and site-specific studies to extract crustal information through the construction of receiver functions, and seismic anisotropy from analysis of shear-wave splitting [van der Hilst et al., 1994; Kennett and van der Hilst, 1996].

For instruments in northern Australia, refracted arrivals for both P and S waves from the upper mantle can be used to determine upper-mantle structure. At greater distances from the sources, multiple S arrivals and surface waves provide a powerful probe for three-dimensional structure using information on many crossing propagation paths. For this class of arrival, the energy is largely directed horizontally and the wave forms are most sensitive to S-wave velocities. The information from regional earthquakes can be supplemented with the arrival times for teleseismic waves in delay-time tomography for P arrivals, where the paths through the mantle are relatively steep. In addition, information from distant events can be used to constrain crustal and upper mantle structure through the analysis of converted waves and reverberations.

The combination of many different classes of seismological information has begun to reveal the complex nature of lithospheric and mantle structure, and sheds light on the way in which the Australian continent may have been assembled. In this paper, we briefly review results of the array experiments in northern Australia, from both short-period and broad-band instruments, and present the

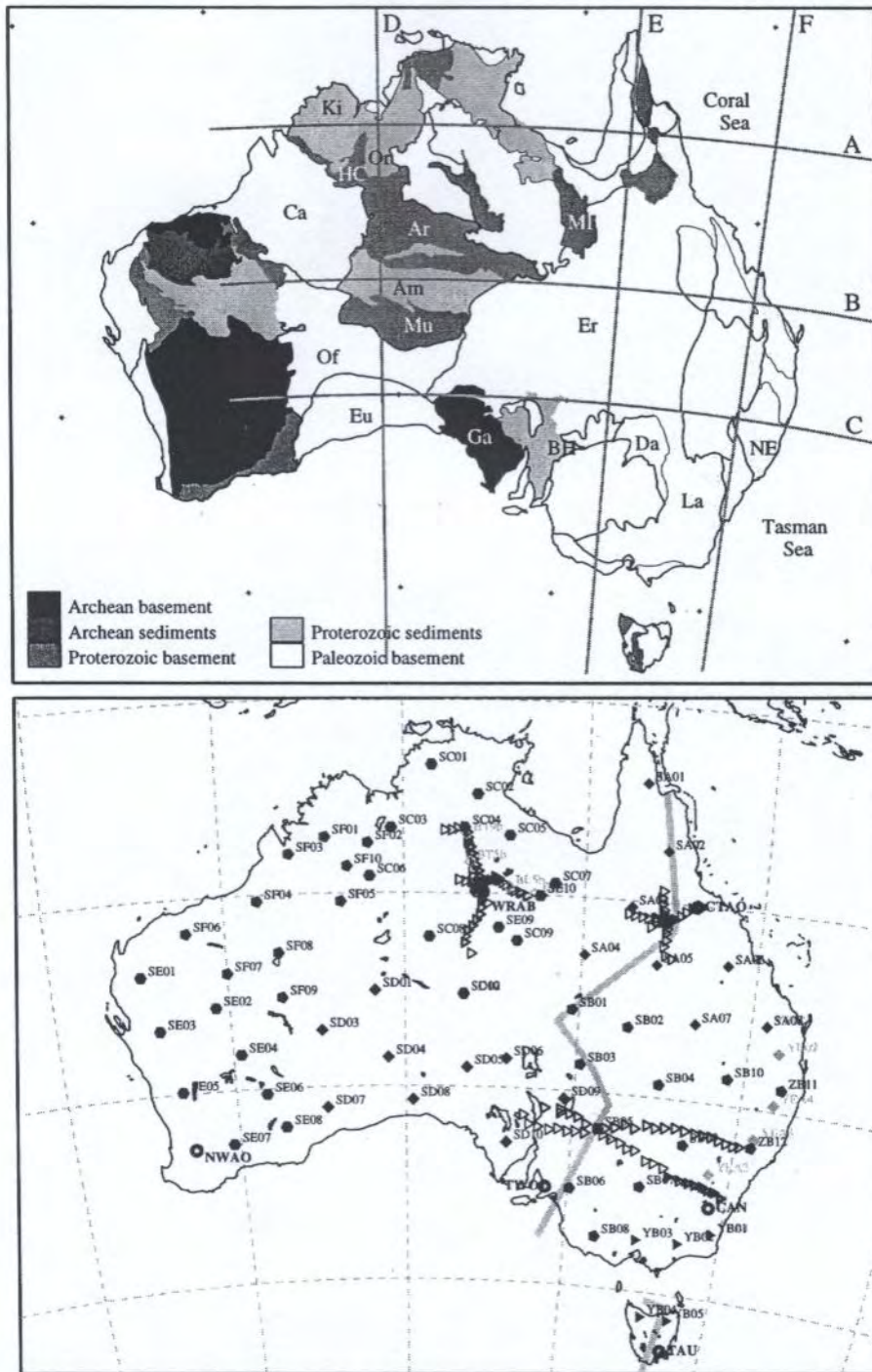


Figure 1: a) Map of the crustal elements and tectonic units referred to in the text, together with the lines of the sections in Figure 6. (Key: Ar - Arunta Block, Am - Amadeus Basin, BH - Broken Hill Block, Ca - Canning Basin, Da - Darling Basin, Er - Eromanga Basin, Eu - Eucla Basin, Ga - Gawler Block, HC - Halls Creek Belt, Ki - Kimberley Block, La - Lachlan Fold Belt, MI - Mt Isa Block, Mu - Musgrave Block, NE - New England Fold Belt, Or - Ord Basin, Of - Officer Basin). b) Configuration of portable seismic recording stations 1985-1996. Short-period stations are indicated by open triangles. Portable broad-band stations are marked by solid symbols. Permanent stations with high fidelity recording are indicated by a double circle and station name. The approximate location of the boundary ('Tasman line'), between Precambrian outcrop in western and central Australia and the Phanerozoic east, is indicated by a shaded line.

latest results from the SKIPPY project for the continent as a whole.

P AND S VELOCITY PROFILES IN THE UPPER MANTLE

The events to the north of Australia provide a convenient set of energy sources for studies of the upper mantle, and it has proved possible to constrain the major features of the mantle velocity profile as well as the attenuation distribution with depth for both P and S waves.

Short-period studies

Much of the information on mantle structure has come from deployments of portable instruments with short-period seismometers. Hales et al. [1980] carried out a travel-time analysis for Indonesian earthquakes that occurred at a variety of depths and were recorded at a number of portable stations in northern Australia. The resulting model is rather complex, with many small discontinuities and low velocity zones, which may reflect the mapping of three-dimensional structure into a one-dimensional profile. A subsequent re-interpretation by Leven [1985], using comparisons between observed and synthetic seismograms, leads to somewhat simplified structure, but retains a prominent velocity contrast near 210 km depth.

In the period 1985-1987, RSES carried out a sequence of experiments using short-period vertical seismometers in northern Australia (Figure 1B) to record the natural seismicity in the Indonesia/New Guinea region. Many of the results were summarised by Dey et al. [1993], who presented composite record sections of upper-mantle arrivals that show significant variation in P-wave velocity structure between paths for events along the Flores arc, studied by Bowman and Kennett [1990], and paths to events in New Guinea. 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 interpretation confirms the need for a P-velocity contrast near 210 km depth. For S waves, the corresponding record sections show a clear arrival associated with the lithosphere which cannot easily be traced beyond 2000 km but no branches associated with greater depth.

Broad-band studies

Modern broad-band seismometers provide a faithful rendition of ground motion over a wide range of frequency, and allow the full exploitation of both P and S body waves. A broad-band sensor has been operated by RSES at the Warramunga array in Northern Australia since late in 1988 (station code WRA); this facility was upgraded in 1994 by IRIS at a nearby site (WRAB). Over a period of years it has been 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. The records from the permanent station have been augmented by portable broadband stations deployed at distances of up to 300 km from WRA. The surface conditions in this region are such that good results can be obtained for SV waves on radial component records after rotation to the great circle path: the high surface velocities lead to little contamination by converted P waves. This represents a considerable benefit over previous S-wave studies of the upper mantle, which have been restricted to SH waves [Gudmundsson et al., 1994].

Additional information on mantle structure is provided by the SKIPPY experiment [van der Hilst et al., 1994] in which portable broad-band instruments were emplaced at a suitable distance range to complement the observations at the Warramunga array. Figure 2 shows a composite record section covering the P and S wave components returned from the upper mantle for events in New Guinea recorded at SKIPPY stations in Queensland (northeastern Australia). This section has been constructed from unfiltered vertical-component records from five shallow events and clearly displays the benefit of broadband recording. The onset of the S waves shows high-frequency behaviour (greater than 1 Hz) out to 2000 km, but beyond this distance the S-wave arrivals have a significantly lower frequency (0.2 Hz at 3000 km), and this is also seen for later arrivals at shorter distances. For P waves, the loss of higher frequencies is less pronounced.

For similar data at WRA, the change in frequency content for S waves returned from greater depth has been analysed by Gudmundsson et al. [1994] to determine the attenuation structure with depth under northern Australia. The slope of the spectral ratio between P and S wave arrivals on the same record has been used to determine the differential attenuation between P and S. This differential information can be interpreted with a knowledge of the velocity structure, and requires strong attenuation of S waves in the asthenosphere between 210 km and 410 km. In a parallel analysis, Kennett et al. [1994] have used the composite record sections, together with the earlier information from the short period studies, to build velocity profiles for P and S. These velocity models have been refined by comparison of observed and synthetic seismograms including the influence of attenuation (Figure 3) and provide a good basis from which to look at three-dimensional structure. By determining the P and S velocity profiles from the same events, the P/S velocity ratio can be well constrained, which is particularly useful for studies of mantle composition. The depth variation of the P/S velocity ratio is in good general agreement with the results for the shield areas of north America obtained by combining the P-velocity profile of LeFevre and Helmberger [1989] with the S-wave structure of Grand and Helmberger [1984].

The broad band studies indicated variations in timing of

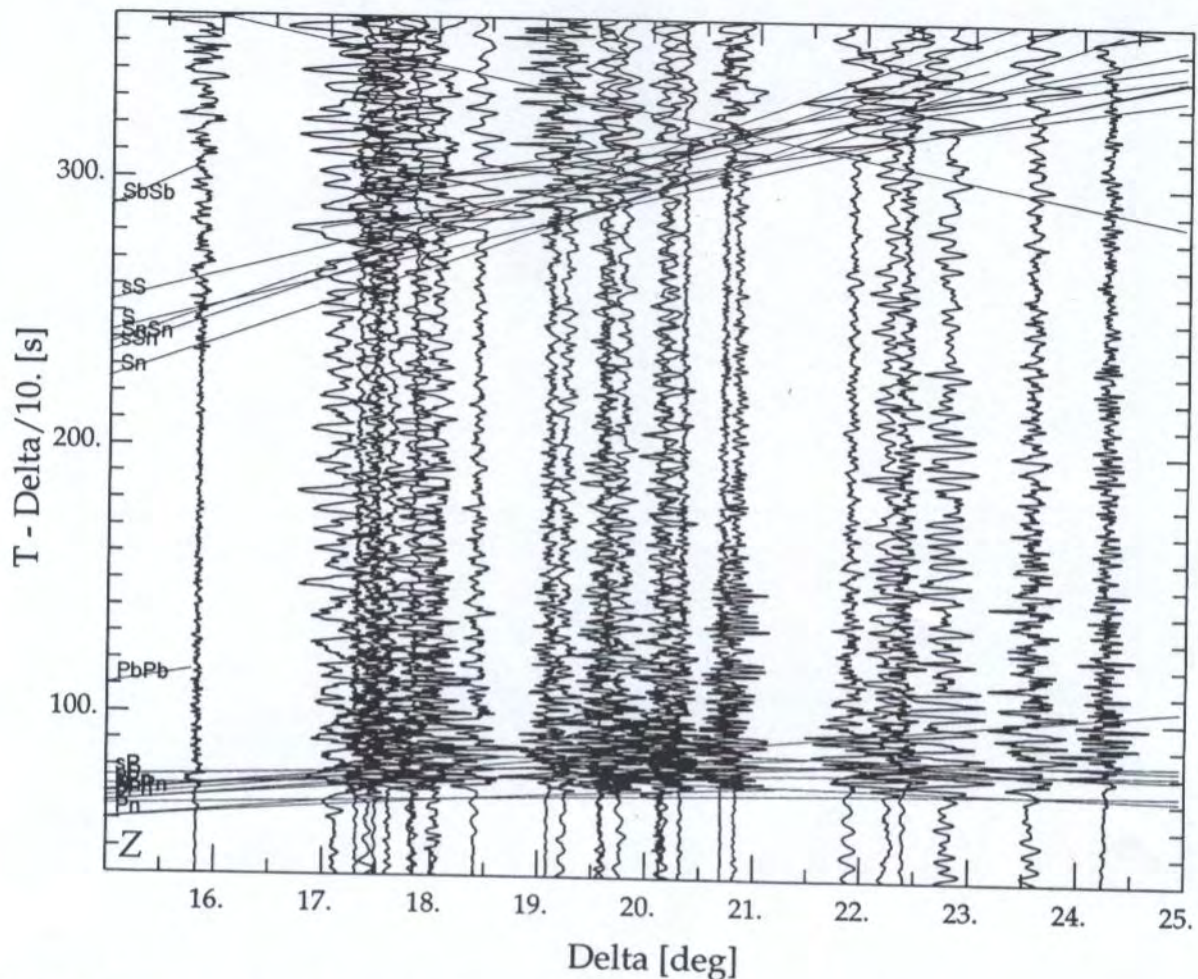


Figure 2: A composite record section of unfiltered broad-band seismograms for five New Guinea events recorded at SKIPPY stations in Queensland. The section is constructed from the vertical component for each path and covers the P and SV waves returned from the upper mantle. The travel-time curves are for an event at 25 km depth in the *ak135* reference model (Kennett et al., 1995)

events at similar distances but different azimuths from WRA, and provided the incentive for more detailed analysis of three-dimensional structure of the continent.

THREE-DIMENSIONAL STRUCTURE

The favourable position of the Australian continent relative to world seismicity can be exploited in a number of ways to obtain information on the three-dimensional seismic structure in the mantle. This can be done by means of tomographic techniques that rely on the number of high-quality crossing paths produced by many source-receiver pairs, or by site-specific studies that aim to define the subsurface structure beneath individual stations by minimizing the influence of structure elsewhere. These applications provide complementary information about

Earth structure, which are being merged to obtain a more complete description of the Australian mantle.

In addition, the configuration of the seismicity around the Australian continent is also ideal for tomographic methods, since with a suitable distribution of receivers a dense and even data coverage of the continent can be achieved. RSES has just completed a three and a half year field program to install some 60 portable broadband stations across the entire Australian continent (see Figure 1B). This project used a set of up to 12 portable instruments, which occupied sites for at least 5 months at a time before being moved to a new location, so that a full continental array could be synthesized [van der Hilst et al., 1994; Kennett and van der Hilst, 1996]. The mobility of the arrays have led to the name SKIPPY (nickname for kangaroo) for the whole project. The deployments commenced in May 1993 with 8

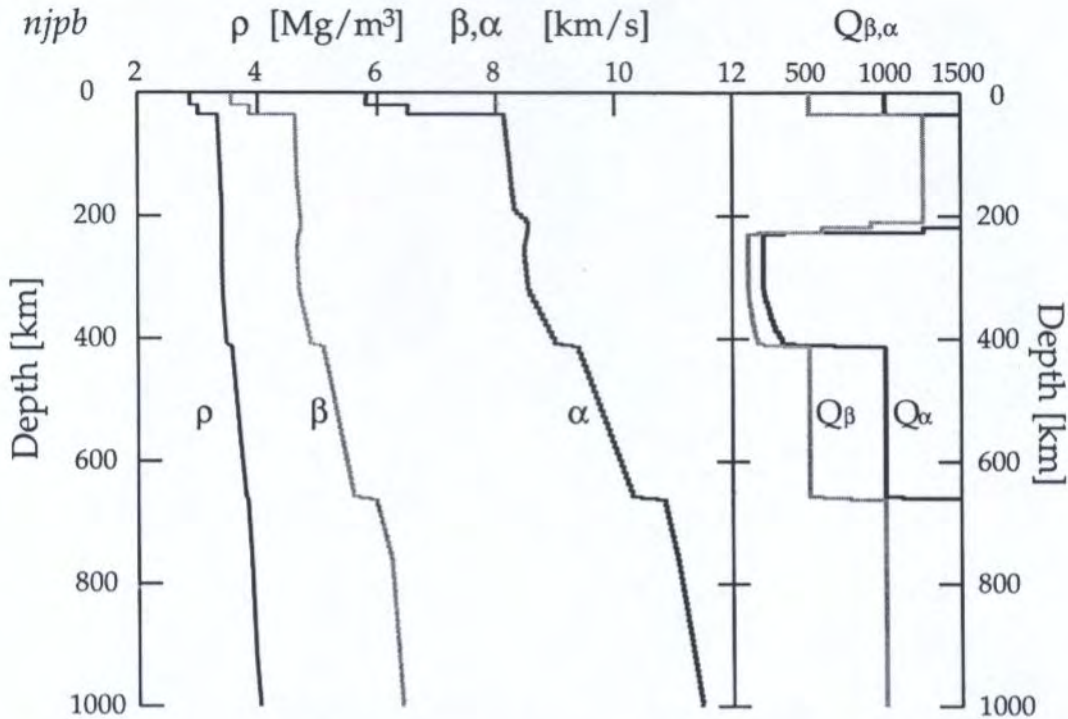


Figure 3: P and S velocity and attenuation structure for the upper mantle beneath northern Australia determined from a combination of short-period and broad-band observations.

stations in Queensland, and the coverage of the whole continent was completed at the end of September 1996. The data set from the SKIPPY stations were supplemented by records of suitable events from the permanent broadband stations. In addition to providing data from sites not occupied by SKIPPY stations, the records from the observatory instruments are important in constraining upper-mantle structure from fundamental-mode surface waves, since at frequencies less than 10 mHz they are often of better quality than the records of the portable stations.

Surface-wave studies

The records from the broad-band stations have been used in a number of different studies. A major objective is the delineation of lithospheric and mantle structure using wave-form tomography for the shear-wave and surface-wave portions of the seismogram. So far the analysis has been based on the partitioned wave-form inversion technique introduced by Nolet [1990]. A nonlinear optimization is used to find a stratified model which gives the best fit to an observed seismogram, which should represent the average structure along the great circle between source and receiver. The assemblage of path averages are then used in a linear inversion to recover the three-dimensional shear-wave structure. The tomographic inversion of the linear

constraints on the three-dimensional velocity structure uses a block structure of approximately equal area in latitude and longitude coupled into a set of mostly triangular basis functions in the vertical direction. Both model norm and gradient damping are used to achieve a balance between data fit and smoothness of the model. The details of the partitioned wave-form inversion method are given by Nolet [1990], and its application to Australian data is presented by Zielhuis and van der Hilst [1996].

The non-linear wave-form technique assumes the independent propagation of individual modes along a great-circle path. The neglect of inter-mode coupling may prevent reliable imaging of deep-mantle structure, and we therefore restrict the present discussion to the upper mantle. Since we do not account for out-of-plane scattering, we do not make use of high-frequency fundamental-mode surface waves, which are sensitive to large wave-speed variations in the shallow lithosphere (such as variations in crustal thickness).

The effective use of the non-linear inversion scheme for the individual paths requires synthetic seismograms that are close to the observed wave forms, and in turn this requires a reference model that is close to the averaged 1D velocity model for the wave path. Care has to be taken to account for the best averaged crustal model for the path in a region which covers both continental and oceanic lithosphere. A

partial compensation for crustal thickness variations is made by using different mode files for source, propagation path, and receiver structure [Zielhuis and Nolet, 1994; Kennett, 1995]. The influence of heterogeneity is rather different for the fundamental and higher modes. For instance, at frequencies higher than about 30 mHz, the fundamental modes are sensitive to variations in crustal structure in general and the ocean-continent transition in particular. The higher modes are more sensitive to structure at larger depth, and are less influenced by scattering due to strong heterogeneity in the shallow lithosphere, and can thus be interpreted to higher frequency. The wave-form matching was, therefore, restricted to frequencies of up to 25 mHz for the fundamental mode, and 50 mHz for a time window covering the range of phase velocities expected for the higher modes. The use of higher modes, which are well excited by the deep earthquakes in the region (Tonga, New Hebrides, Java), improves resolution of structure in depth. However, the influence of the heterogeneity in structure means that it is not always possible to fit both the fundamental-mode and higher-mode windows with the same structure. In future studies, this linearization problem will be remedied by using wave-speed profiles and associated mode files of reference models that are constructed specifically for the region.

Zielhuis and van der Hilst [1996] discussed results of the application of this partitioned wave-form inversion scheme to the data from stations in eastern Australia. This study used arrays SK1 (SA01-SA08), SK2 (SB01-SB10, ZB11, ZB12) and BAS (YB01-YB05); the station locations are illustrated in Figure 1B, and the paths from events to these stations in Figure 4a. The data used in this study are consistent with a pronounced change from slow shear-wave propagation beneath the Coral and Tasman Seas and the coastal regions of continental Australia to very fast wave propagation beneath central Australia. The thickness of the high wave-speed lid increases from about 80-100 km in easternmost Australia to at least 250 km beneath the central shields. The transition is rather sharp in north Queensland but is manifest as a multiple boundary further south. Based on these data, Zielhuis and van der Hilst argued that the conventional Tasman line (Figure 1B) marking the limits of Precambrian outcrop [see e.g. Veevers, 1984], may roughly coincide with a contrast in seismic-wave speed in the north, but that high wave-speed lithosphere extends east of the Precambrian basement further to the south. However, the data used in this earlier study does not constrain the southernmost part of the region around the Tasman Line, nor does it reliably image possible lateral variations in wave speed in the upper mantle beneath central Australia.

The model presented here is based on wave-form data from the permanent observatories in the region and from 45 SKIPPY stations covering the eastern and central parts of the Australian continent. Arrays SK1, SK2 and BAS, which were used in the previous work, are supplemented with data

from the arrays SK3 (SC01-SC10) and SK4 (SD01-SD10). The station locations are indicated in Figure 1B, and the improved path coverage available with the data from the additional stations is shown in Figure 4B. Low-noise records were selected for regional earthquakes for which a Centroid Moment Tensor (CMT) is available from Harvard University. The total number of seismograms used in the construction of the three-dimensional shear velocity mode is approximately 1350, from about 360 earthquakes. Good wave-path coverage is achieved for eastern and central Australia as shown in Figure 4; this enabled the extension of the results for eastern Australia by Zielhuis and van der Hilst [1996].

Results of the inversion for three-dimensional variations in shear-wave speed are presented in Figure 5 for depths of 80, 140, 200 and 300 km. For wavelengths of 1000 km and larger, the observations are in good agreement with inferences from global inversion of Rayleigh-wave phase velocities [e.g., Trampert and Woodhouse, 1995; Ekstrom et al., 1997], but the data coverage provided by the SKIPPY arrays allows the study of continental structure in much more detail. The resolution length is about 300 km for most of the area discussed here.

A striking feature in the images of mantle structure to about 200 km depth is the large difference in shear-wave speed between the part of Australia east of 140°E, and the rest of the continent (Figures 5A,B). The wave-speed gradients are predominantly in west-east direction, and exhibit peak-to-peak amplitude variations of up to 10 per cent relative to the reference model used for the display. The patterns generally match geological trends observed at the surface. Beneath easternmost Australia and the adjacent oceanic regions, the shear-wave speed is relatively low, whereas fast wave propagation marks the central and western part of the continent. The boundary between these regions is well defined at 80 and 140 km depth. The transition from low to high velocities seems to be rather sharp in northern Queensland (near 15°S, 142°E) and lies close to the Tasman Line, the presumed eastern edge of the Precambrian shields based on geological outcrop, gravity and magnetic data (Figure 1B). Further to the south the transition from slower to faster wave speeds appears to be somewhat more complex, and may occur over at least two zones of rapid increase in wave speed. The southern part of the Eromanga Basin, and the region associated with the Lachlan Fold Belt, are characterized by wave speeds that are intermediate to that in the coastal regions and the central shields (Figure 5B). The nature of these wave-speed transitions and, in particular, the complex structure near the Broken Hill Block (32°S, 140°E) will be discussed in more detail in a separate paper [Kennett and van der Hilst, in preparation]. We remark that south of 30°S, the velocity contrast associated with the boundary between Phanerozoic and Proterozoic basement is significantly better constrained than in the study by Zielhuis and van der Hilst [1996].

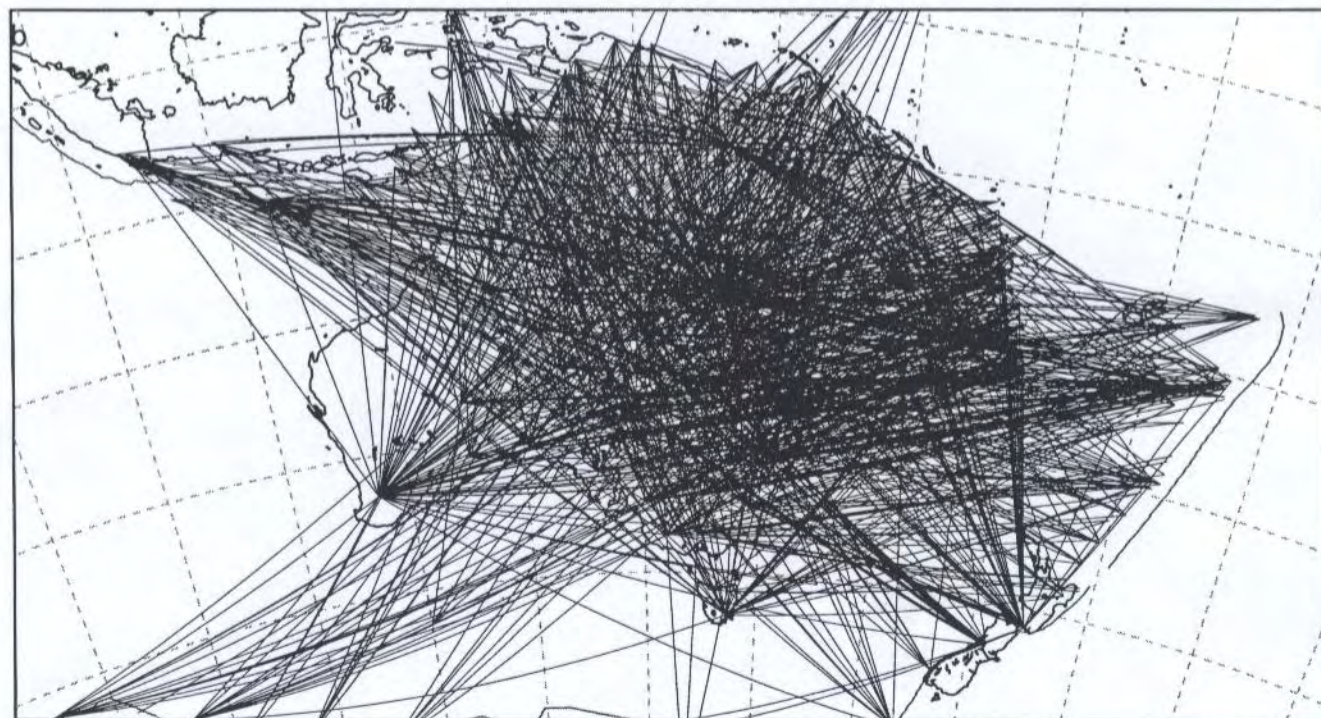


Figure 4: Wave-path coverage available for the SKIPPY experiment in eastern and central Australia. (a) wave paths exploited by Zielhuis and van der Hilst (1996); (b) wave-path coverage used in this study.

Along the eastern seaboard of the Australian continent, there is a pronounced low-velocity zone between 100 and 200 km in depth (Figure 5); the minimum wave speed seems to occur at a depth of 140 km. This low-velocity zone was recognised in earlier surface-wave dispersion studies (see Muirhead and Drummond [1991] for a review), but a striking feature in our 3-D models is the level of lateral variation in the character of the zone. The low-velocity zone is interrupted near 30°S, 150°E beneath the New England Fold Belt and the higher velocities in this region seem to be almost continuous from the surface to the transition zone. The main zones of lower velocities correlate well with recent volcanism and high heat flow. The low-speed anomalies appear to extend to greater depth beneath the Coral Sea and beneath the southeastern corner of Australia. Zielhuis and van der Hilst [1996] discuss the upper-mantle structure beneath easternmost Australia in more detail.

In the upper 200 km beneath central Australia, shear-wave speed is high, but the images suggest significant lateral variations that begin to delineate the major crustal elements. The zone of high wave speed in the central north (Figures 5A-C) coincides with the lateral extent of the North Australian Craton, and the high wave speeds in the central south coincide with the Gawler Craton and the Eucla Block (Figures 5A, B). To approximately 80 km depth, the region associated with the Late Paleozoic Alice Springs Orogeny - in particular the Amadeus Basin and the Musgrave Block - is characterized by slower shear-wave propagation than in the adjacent shields (Figure 5A). The images suggest that the North Australia Craton extends northward into western Papua New Guinea and eastern Indonesia (from Timor to Irian Jaya). Interestingly, the Kimberley Block, near 15°S, 125°E, is delineated by slower wave propagation than the shield further to the east, which suggests that the Kimberley Basin is not underlain by the same basement as the Proterozoic North Australia Craton. The change to slower wave propagation occurs across the Ord Basin and the Halls Creek Shear Zone. The high wave speeds mapped in the southwest may well be related to the Archean cratons, but they are not yet well localized owing to insufficient path coverage.

The amplitude of wave-speed variability is diminished below 200 km depth, but significant contrasts remain. At 200 km depth (Figure 5C) the images reveal again a difference between the wave speeds in eastern and central Australia. The eastern edge of the high wave speeds that characterize the regions of Proterozoic basement seems to coincide with the southeastern margin of the Mt. Isa Inlier (20°S, 140°E) and the western boundary of the Eromanga Basin, and to extend approximately along the 140°E meridian along the eastern side of the Gawler Craton (Figure 1A).

At depths larger than 300 km (Figure 5D), the general trend in the anomalies is markedly different from that in the shallower upper mantle (Figures 5A-C). The predominant

orientation of the gradients is no longer west-east, although even at these large depths the strongest low wave-speed anomalies are located in the east, that is, beneath the Coral Sea and, in particular, the Tasman Sea. Between 300 and 400 km depth, there are prominent high wave speeds beneath the eastern part of the continent, in a broad band extending from 20°S, 143°E, southwards to around 35°S. We have previously noted the high velocities beneath the New England Fold Belt near 30°S, 152°E. These anomalies (discussed in more detail by Zielhuis and van der Hilst [1996]) are robust features of the solution, and are confirmed by a simple differential technique applied to a small number of high-quality Rayleigh-wave data [Passier et al., 1997]. The high wave speeds beneath the western parts of the Musgrave Block and the Officer Basin may be real, but we can not be confident in the mapping of this structure until data from the SKIPPY arrays in West Australia have been analyzed. For the deeper part of the upper mantle, the images display several 'streaks' that may result from a combination of uneven sampling, effects of source mislocation, or from the neglect of inter-mode coupling for the higher-mode packet. This will be subject to further study.

Vertical sections through the three-dimensional shear wave-speed model for the upper mantle (Figure 6) provide further insight into the lateral variation in the character of the lithosphere; in particular, they demonstrate the dramatic differences in upper mantle structure between the Phanerozoic and Precambrian parts of the continent. For the purpose of the present paper, we loosely associate the "lithosphere" with a zone of elevated shear velocity compared with the asthenosphere beneath. The locations of the cross sections are given in Figure 1A.

A section from the Coral Sea across the eastern margin of the Australian continent into the Proterozoic shield (Figure 6a) displays the large contrast in lithosphere thickness between the oceanic and continental shield regions. Beneath the Coral Sea a negative gradient in shear velocity occurs at a depth of about 50 km, beneath the coastal region of easternmost Australia the lithosphere thickness is about 100 km, and beneath the central Proterozoic cratons reduced shear wave speeds do not occur until a depth of about 250 km (Figure 6a). The virtual absence of a high wave-speed lid near 145°E coincides with the region of Neogene volcanism in the Queensland volcanic province, which may suggest that part of the continental lithosphere has been eroded by thermal processes.

The east-west cross section at 24°S (Figure 6b) reveals a similar contrast in lithosphere thickness between eastern Australia and the central shields. The high wave speeds associated with the seismological lithosphere are detected to depths exceeding 300 km beneath West Australia (130°E). The image clearly reveals the low-velocity zone extending beneath eastern Australia (east of 140°E), that separates thin high wave-speed lid from the deeper zone of high wave-speed anomalies between 300 and 400 km depth. This cross

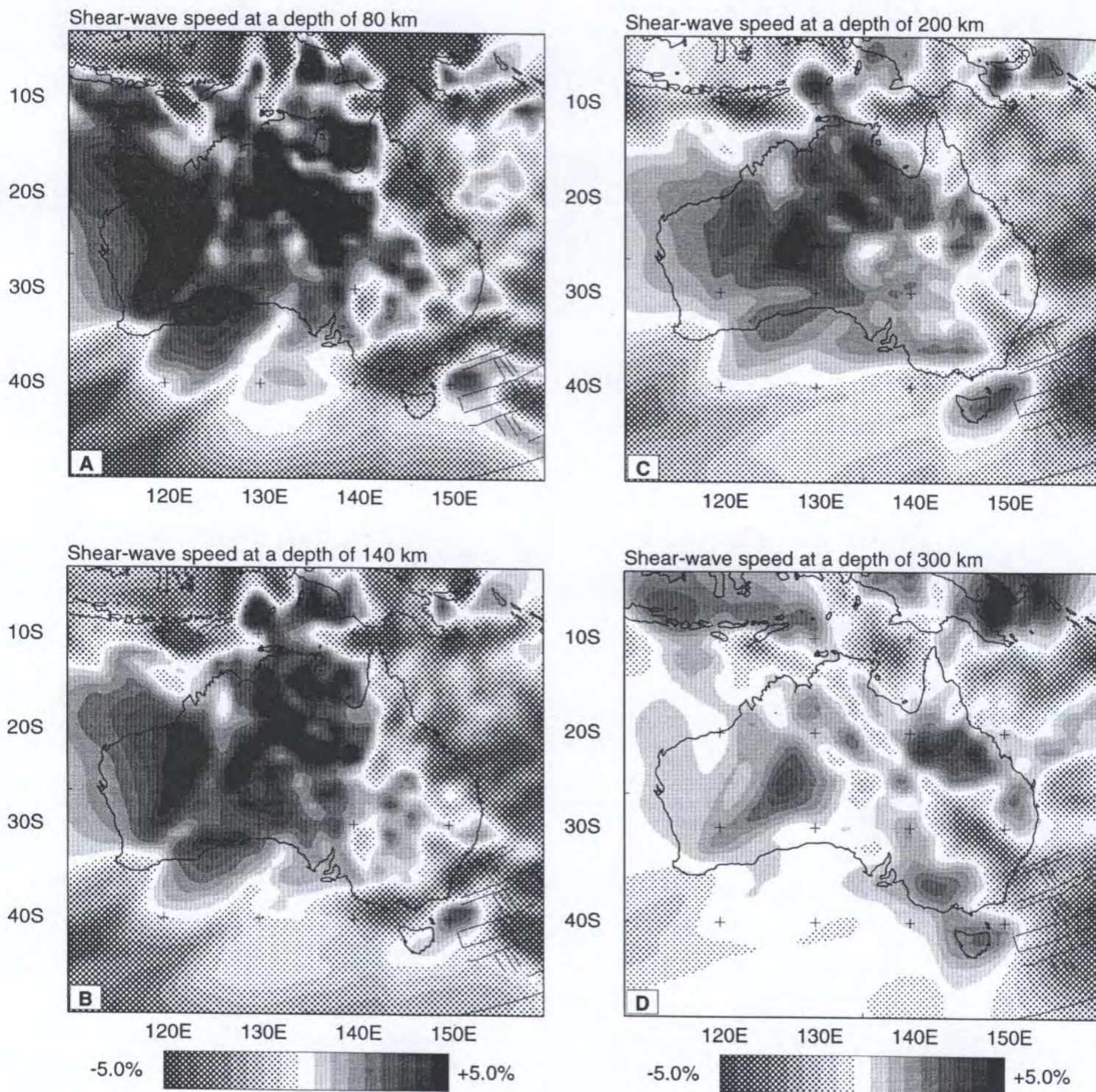


Figure 5: Three-dimensional shear-wave-speed model derived from partitioned wave-form inversion from the SKIPPY experiment in eastern and central Australia. Map views at (a) 80 km, (b) 140 km, (c) 200 km, and (d) 300 km depth. Based on the path coverage (Figure 4B) the wave-speed anomalies are reliable images east of about 125°E.

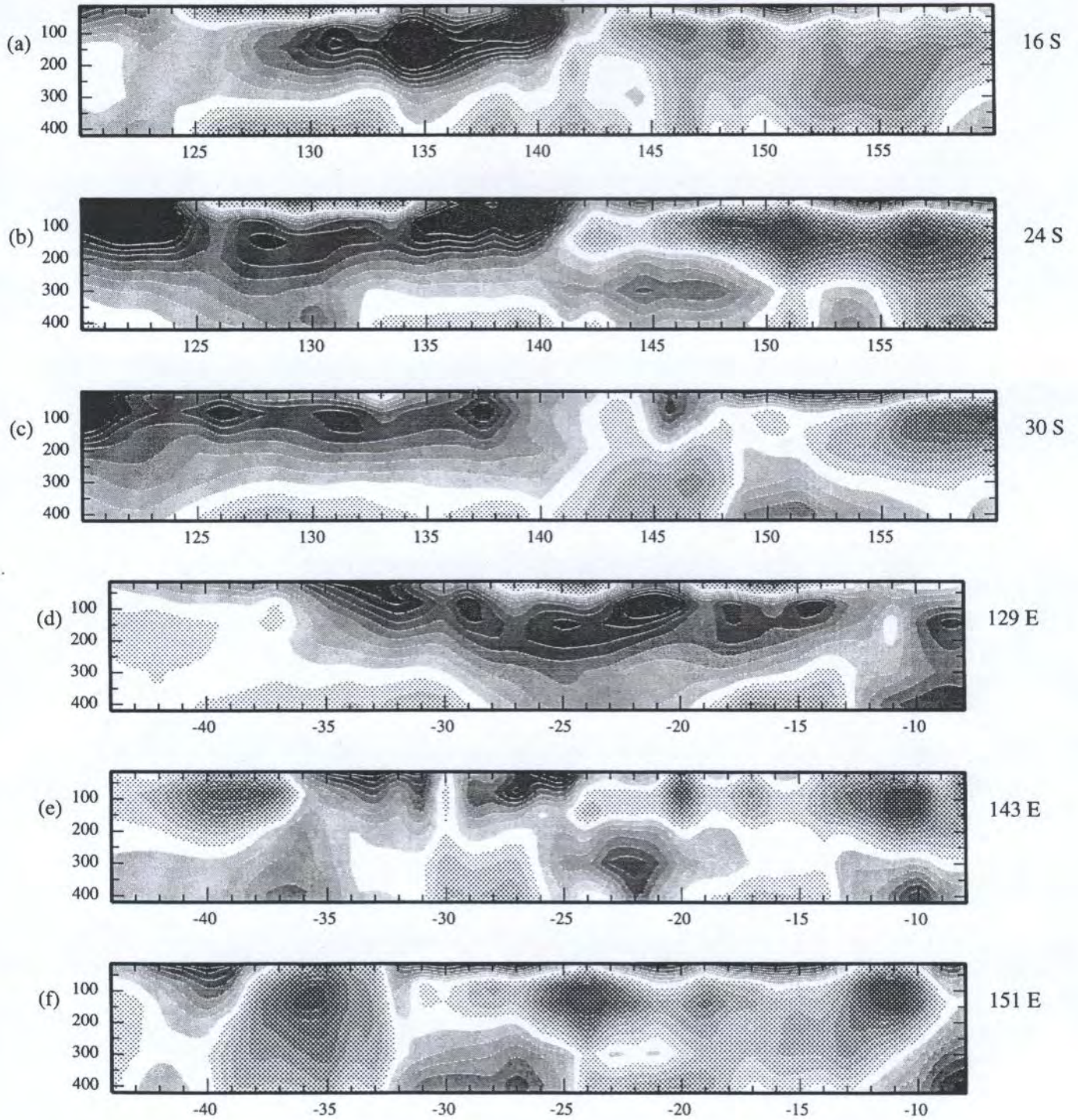


Figure 6: Vertical cross-sections through the three-dimensional shear-wave speed derived from partitioned wave-form inversion from the SKIPPY experiment in eastern and central Australia. Cross sections at (a) 16°S, (b), 24°S, and (c) 30°S, and north-south sections at (d) 129°E, (e) 143°E, and (f) 151°E.

section intersects the volcanic province at approximately 150°E.

The seismic structure shallower than 80 km may be contaminated by variations in crustal structure that are not adequately accounted for by our approach, but the cross sections clearly reveal a pronounced wave-speed anomaly in the region associated with the Alice Springs Orogeny and the eastern part of the Canning Basin (125°–135°E). At 30°S the model reveals the large lateral variations in wave speed near the Broken Hill Block, i.e. across the southern part of the Tasman Line. At this latitude, the seismically defined lithosphere is about 200 to 250 km thick beneath most of the Proterozoic shields (between 125° and 140°E), and possibly even thicker towards the Archean cratons further west. The latter observation is, however, tentative because data coverage is not sufficient to constrain the structures in the southwestern part of the continent.

The map views (Figures 5A–C) and the vertical sections (Figures 6a–c) clearly delineate the transition from thin lithosphere beneath the Phanerozoic of eastern Australia to the thick Proterozoic shields of central Australia. Locally, in particular south of 25°S, the transition is complex and may comprise multiple boundaries and basement types.

The north-south cross sections (Figures 6d–f) further illustrate the pronounced lateral variation in the character of the high wave-speed lid beneath the Australian continent. The thickest lid is located beneath the western part of the Officer Basin, at about 25°S, 129°E (Figure 6d), that is near the boundary of the Proterozoic and Archean shields. The observation of such a thick high wave-speed lid in the western part of the continent, and the absence of a strong negative velocity gradient in shear velocity beneath the lid, are in good agreement with the path average shear-wave profile by Gaherty and Jordan [1995]. At 129°E (Figure 6d), the sudden increase in wave speed at about 35°S marks the ocean-continent transition in the Great Australian Bight, and the deep high wave speeds north of 10°S are probably related to subduction beneath eastern Indonesia. The cross section at 143°E (Figure 6e) displays the intermediate thickness of the lithosphere in the region where the transition from the coastal region to the central shields is gradual. The rapid lateral variations near 30°S coincide with the boundary between the Murray and Eromanga Basins (i.e., parts of the Broken Hill Block, the Lachlan Fold Belt, and the Darling Basin). This section also illustrates the deep anomaly near 22°S in Queensland. Figure 6f displays the deep low wave-speed anomaly beneath the Tasman Sea region, the low-velocity zone beneath easternmost Australia, and the deep high wave-speed anomaly beneath the New England Fold Belt.

These significant results have been derived from the analysis of data from only part of the SKIPPY project. More detail on lithospheric and mantle structure beneath the western part of Australian region will be revealed as the data from the last two SKIPPY deployments are incorporated into the inversion for three-dimensional structure.

P-wave tomography

An additional source of information on three-dimensional structure comes from P-wave tomography using the residuals of observed arrival times of P phases compared with the predictions from a suitable reference model. The residuals reflect the integrated influence of wave-speed variations in the Earth's interior along the propagation path from source to receiver. With sufficient crossing paths, the travel time information can be used to reconstruct the three-dimensional variations in seismic wave speed.

In order to produce a homogeneous set of travel time residuals, the arrival times determined from the SKIPPY records are incorporated in the data processing scheme of the U.S. Geological Survey's National Earthquake Information Center (NEIC). In this way, the SKIPPY data help constrain the hypocenters of earthquakes in the Australasian region, and in return are made to be consistent with the global data set assembled by Engdahl et al. [1997].

Travel-time residuals from the SKIPPY project were first used by Widiyantoro and van der Hilst [1996] in their tomographic study of the complex subduction beneath the Indonesian region. Their three-dimensional mantle model was generated by embedding a high-resolution representation of regional structure in a somewhat lower-resolution cellular model for the rest of the mantle. By this means, contamination of the regional structure by features outside the region of interest can be minimised. The inversions for the Indonesian region incorporated phase data from the SKIPPY records in eastern Australia, along with data from a global distribution of permanent stations, and reveal the thick lithosphere under northern part of central Australia.

With more phase picks now available from later SKIPPY deployments (SK1, SK2, SK3, and BAS), in addition to data from the network of short-period permanent stations, the P-wave tomography has been extended to cover most of the continent, with resolution in the eastern part significantly better than in the west. Figure 7 displays the lateral variation in P-wave speed relative to the *ak135* reference model at a depth of approximately 150 km beneath the Australian region. The image reveals the lateral contrast between high and low wave speeds in northern Queensland, which is prominent in the shear-wave structure inferred from the wave-form analysis described above. The resolution of structure in oceanic regions is, of course, poor because of lack of station coverage.

Much of the information used to construct the P-wave velocity model comes from arrivals travelling rather steeply in the mantle, so that vertical resolution is limited. Nevertheless, the strong contrast in the seismic signature of the lithosphere between western and central Australia and the eastern seaboard are clearly revealed. As in the shear-wave images, the zone of higher wave speeds extends further east than the conventional Tasman Line, but thicker lithosphere lies mostly to the west of 140°E. There are

Depth slice at 150 km

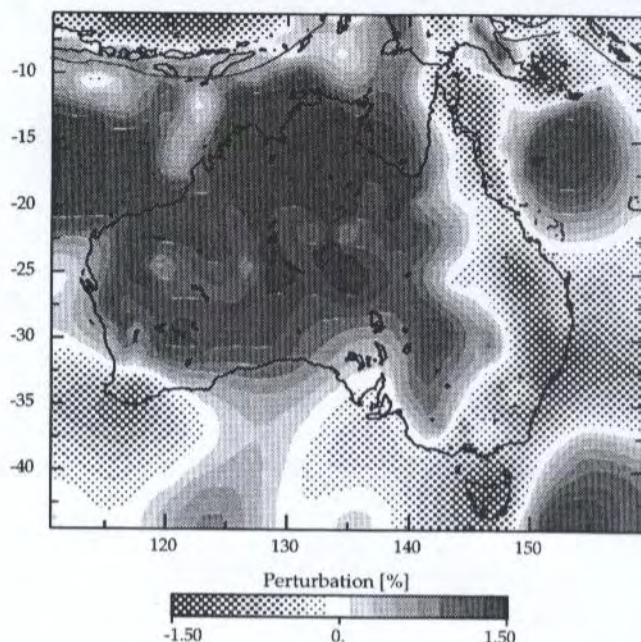


Figure 7: Cross-section through the 3D model of the P-wave velocities in the Australian region for the depth interval from 160–220 km.

some significant differences in the P and S wave-speed models, for instance beneath the New England Fold Belt. These differences may largely be due to variations in data coverage and resolution, but upon further analysis they may also yield new information about the physical nature of the anomalies, as for example whether their origin is thermal or compositional.

Receiver based studies

Along with their use in tomographic studies, the even distribution of portable broad-band stations across Australia can also be exploited to provide a range of information on the structure beneath each of the stations. Here we discuss only the results of receiver-function analyses; measurements and implications of shear-wave splitting are discussed elsewhere in this issue [Clitheroe and van der Hilst, 1997].

For each of the broad-band stations in the SKIPPY deployments, data from distant seismic events are being processed to extract a receiver function which is sensitive to the structure in the crust and uppermost mantle and, in particular, the character of major seismic interfaces such as the Moho. The analysis uses the P-wave onset and its immediate coda. The radial and vertical components of the record share the same source time function, so that the dependence on the radiation from the source can be largely

eliminated by deconvolving the wave-form segment of the radial horizontal component, lying along the great-circle path from the source, with the corresponding segment of the vertical component [Langston, 1979]. The deconvolved radial receiver function then emphasises the influence of near-receiver structure, and can be inverted in the time domain for a 1-D shear wave velocity model of the crust and uppermost mantle [see e.g. Ammon et al., 1990]. A major contribution to the receiver function comes from conversions between P and S waves. The timing and amplitude of such arrivals provide constraints on the properties of major interfaces such as the crust-mantle boundary and internal boundaries within the crust. For example, a sharp crust/mantle boundary produces a converted phase with about 5 s separation from P.

The inversion of the receiver functions to recover crustal and uppermost mantle structure is widely recognised to be sensitive to the starting model if a conventional linearization scheme is employed [see e.g. Ammon et al., 1990]. However, such difficulties can be overcome by employing an inversion scheme based on a Genetic Algorithm [Shibutani et al., 1996]. This approach makes use of a "cloud" or "population" of models to minimise the dependence on a starting model; a set of "biological" analogues are used to produce new generations of models from previous generations, with preferential development of models with a good fit between observed and theoretical receiver functions. The approach provides a good sampling of the model space, and enables the estimation of the shear-wave speed distribution in the crust, along with an indication of the ratio between P and S wave speeds. Many models with an acceptable fit to data are generated during the inversion, and a stable crustal model is produced by employing a weighted average of the best 1000 models encountered in the development of the genetic algorithm. The weighting is based on the inverse of the misfit for each model, so that the best fitting models have the greatest influence.

At each station, a stacked receiver function was constructed from teleseismic observations. For each event, the receiver function was low-pass filtered to eliminate frequencies above 1 Hz in order to minimize the influence of small-scale heterogeneities. Subsequently, the receiver functions from 6–18 teleseismic events at each station were stacked together for a set of ranges of back azimuths. The weighting used in the stacking emphasizes receiver functions with higher signal-to-noise ratios, and those whose back azimuth and incident angle were closer to the mean for the set of events.

The radial component of the stacked receiver function was then inverted for a 1-D velocity model beneath each station. In the Genetic Algorithm inversion, the crust and uppermost mantle down to 60 km were modeled with six major layers: a sediment layer, basement layer, upper crust, middle crust, lower crust and uppermost mantle. The model parameters in each layer are the thickness, the S-wave

velocity at the upper boundary, the S wave velocity at the lower boundary, and the velocity ratio between P and S waves (V_P/V_S). The S-wave velocity for each layer is constructed by linearly connecting the values at the upper and lower boundaries, to give a sequence of constant velocity-gradient segments separated by velocity discontinuities.

The results of the receiver function inversion for the stations SB06 and SA07 are shown in Figure 8. All 10,000 models searched in the Genetic Algorithm inversion for S velocity are shown as the light gray shaded area, and superimposed on this the best 1,000 models are shown with darker gray tones, where the darkness is proportional to the logarithm of the number of the models. The best fitting model for each site is shown as a black line. However a more useful and stable result is provided by the averaged model generated by weighting the best 1,000 models by the inverse of their misfit values. This averaged model is shown in white for S velocity and in a solid line for the V_P/V_S ratio. The lower panel in Figure 8 compares the wave forms of the stacked receiver function to synthetics calculated for the averaged models. The fit to the major phases is good, and this will be true of most of the best 1,000 models. The zone of darker gray in the upper part of Figure 8 can therefore be thought of as an indicator of the constraint on the crust and upper mantle structures. Both SB06 and SA07 have surficial sediment with very low velocities, so that P-to-S converted phases and reverberations (1 - 3 s) originating in the sediment layer are larger than the direct P phase, which arrives at zero time.

The analysis for crustal structure has been completed for all the SKIPPY stations in the SK1 and SK2 arrays in eastern Australia and is in progress for the permanent stations and the later SKIPPY arrays. The parametrization of the model at each station is via a sequence of velocity gradients and discontinuities; sensitivity analysis indicates that the dependence on phase conversions enhances the resolution of boundaries at the expense of the gradients. Nevertheless, all the models have been derived by the same procedure, and we can make direct comparisons and extract a wide range of information on crustal structure and uppermost mantle structure across eastern Australia. In the few places where direct comparisons can be made, e.g. ZB12, there is a very good concordance between the character of the S-velocity structure from the receiver function inversion and the previous P-velocity model from refraction studies.

Figures 9, 10 and 11 summarise the properties of the crustal models at each of the SKIPPY stations in eastern Australia in terms of the major subdivisions of the crust: the upper crust (Figure 9), middle/lower crust (Figure 10) and the crust-mantle boundary and uppermost mantle velocities (Figure 11). In each map we indicate the thickness of the layer, the corresponding crustal velocities,

and the character of the boundary. A sharp boundary is associated with a clear converted phase in the receiver function wave form, whereas the expression of a transitional zone is more subtle. The nature of the boundaries is classified into the categories: SHARP (< 1 km), THIN (< 4 km), TRANSITIONAL or INTERMEDIATE (< 10 km), and BROAD (> 10 km). The depth of the crustal boundaries was estimated at each station; for a transitional zone the lower boundary was selected.

The information from the receiver-function inversion provides a major supplement to the previous results from isolated refraction and reflection experiments. For the construction of the crustal thickness map in Figure 11 the earlier information [Collins, 1991] has been combined with the present results. The crust-mantle boundary is deep (38 - 44 km) and mostly transitional in character along the axis of the fold belt zone in the east (from stations: ZB12, SB09 to SA05, SA03). A relatively sharp Moho is found at a shallower depth (30 - 36 km) at the western edge of the study area, close to the boundary between Phanerozoic and Precambrian exposure.

A major advantage of the receiver-function approach is that it provides good constraints on shear velocities in the crust and uppermost mantle, which are not well resolved by the partitioned wave-form inversion of the S wave and surface-wave portions of the seismogram. The 3-D models are most reliable from 60 km down, whereas the receiver-function analysis is most effective above 60 km. There is a good agreement between the results from the wave-form tomography and the receiver function analysis at 60 km depth.

CONCLUSION

Over the last decade, there has been a significant increase in knowledge of the P and S wave velocities in the mantle, particularly beneath northern Australia. The current generation of three-dimensional studies based on the use of portable seismometers have the potential to increase dramatically the level of understanding of mantle structure beneath the Australian region, in particular the contrast between eastern and western Australia.

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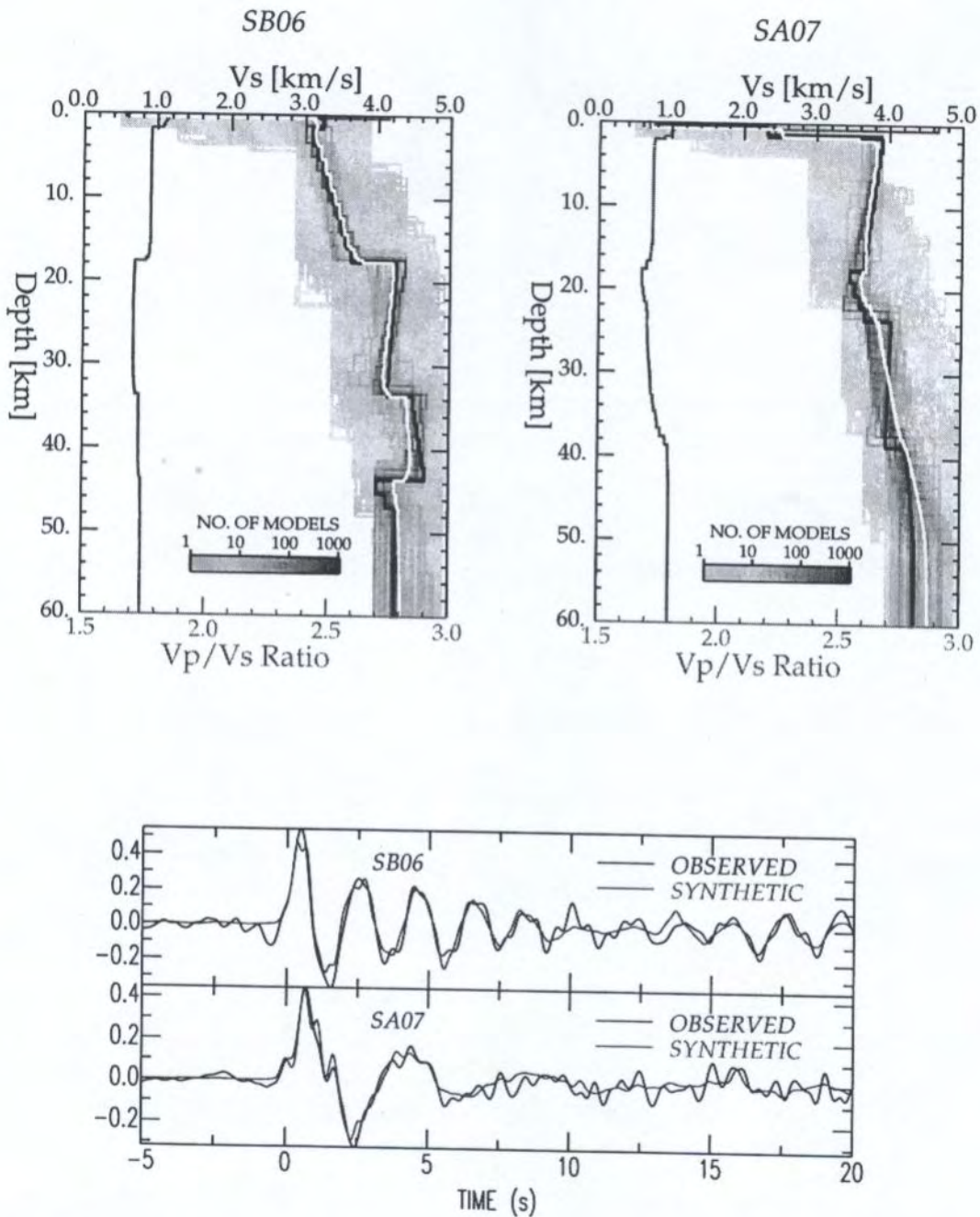


Figure 8: Genetic algorithm inversion of a receiver function to determine S-wave structure and the V_p/V_s ratio. All 10,000 models searched in the GA inversion are shown as the light gray shaded area. The darker gray shaded area shows the best 1,000 models. The darkness is logarithmically proportional to the number of the models as shown by the scale bar. The best model and the averaged model are shown by the black solid line and the white solid line respectively. For the V_p/V_s ratio, the solid line indicates the averaged model.

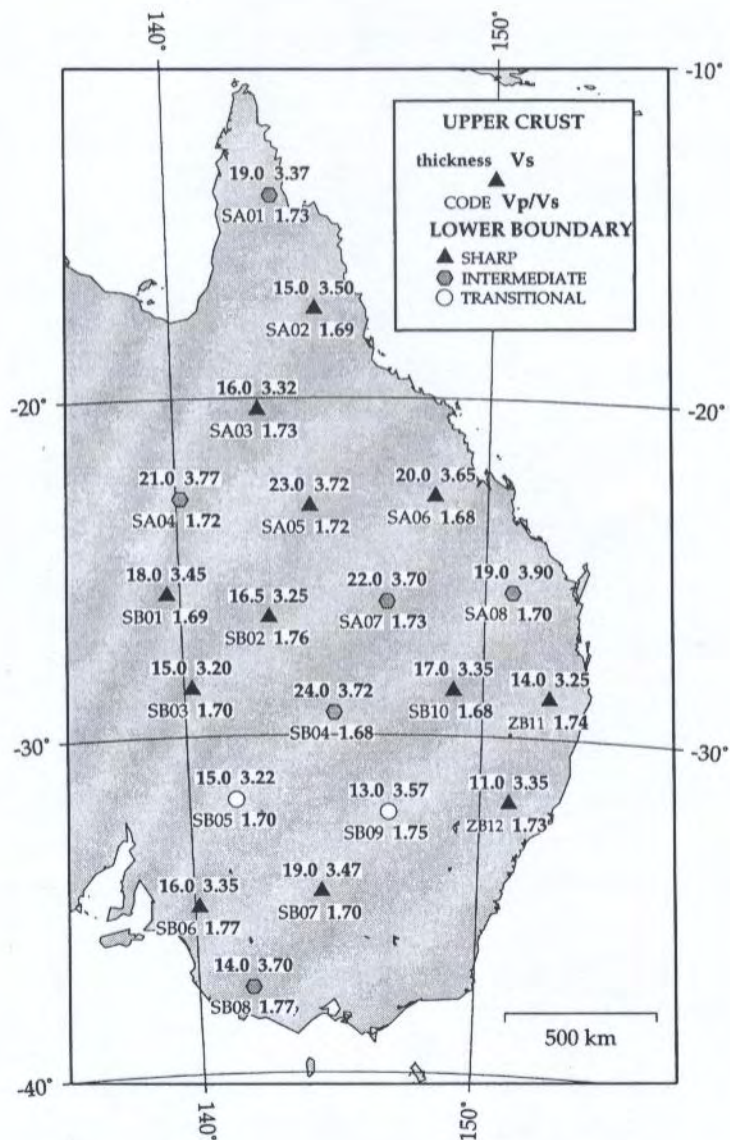


Figure 9: Summary of velocity and thickness information for the upper crust in eastern Australia.

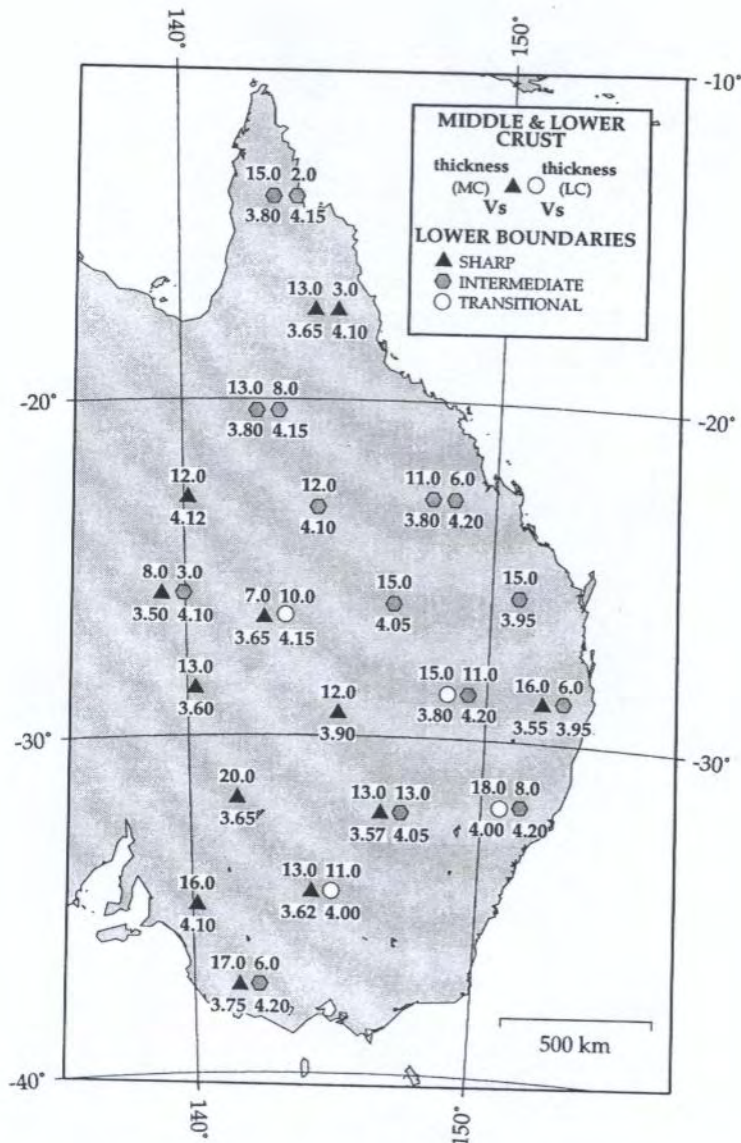


Figure 10: Summary of velocity and thickness information for the middle and lower crust in eastern Australia.

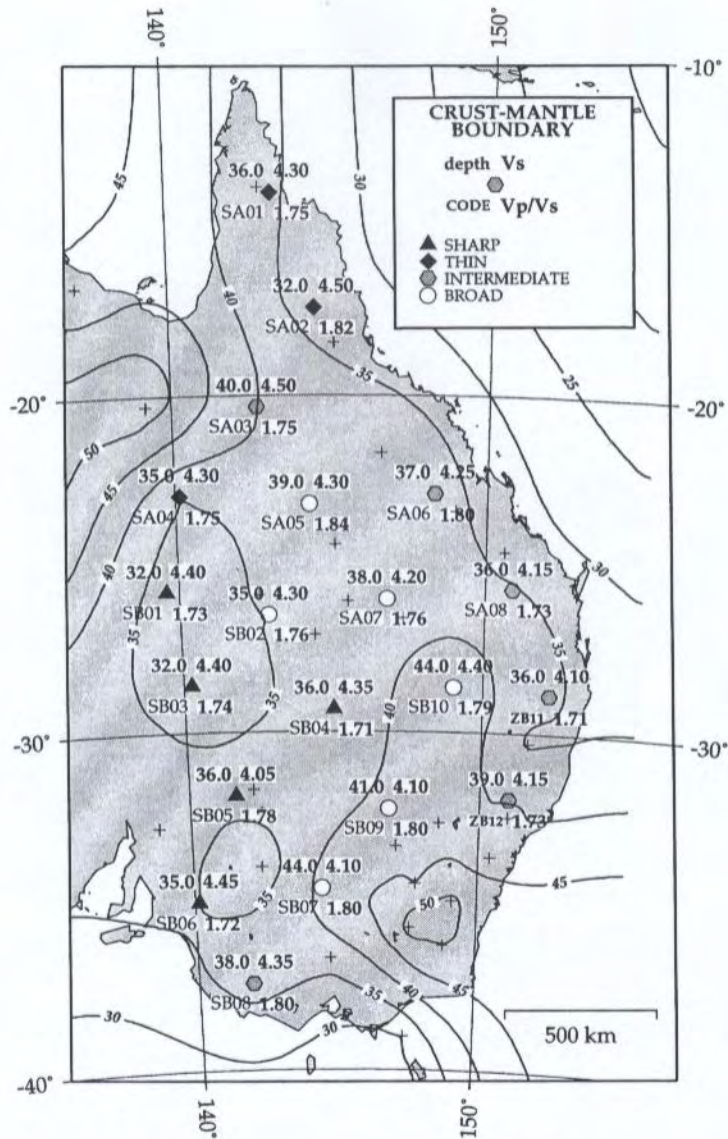


Figure 11: The depth of the crust-mantle boundary beneath eastern Australia, and the S-wave velocity and V_p/V_s ratio at the top of the mantle. The nature of the crust-mantle boundary is classified into four categories: sharp (≤ 1 km), thin (≤ 4 km), intermediate (≤ 10 km), and broad (> 10 km). The crosses indicate the locations for which the crustal structure has been obtained previously from refraction surveys [Collins, 1991]. These data were incorporated into the contouring.

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B. L. N. Kennett, Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia
 T. Shibutani, Research Centre for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University, Kyoto 611, Japan

R. D. van der Hilst, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA