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The mantle beneath Australia

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The configuration of earthquakes around Australia enables these natural events to be used as probes into the seismic structure of the upper mantle. For the region below northern Australia, the combination of short-period and broad-band observations has enabled the construction of radial velocity profiles for P and S velocities and attenuation. There is a range of evidence for lateral variations in seismic velocity in the lithosphere and the upper mantle transition zone. The lateral variations in structure can be investigated directly by a number of techniques, including the analysis of travel-time residuals and waveform inversion, especially for surface waves. Line profiles have revealed strong contrasts in P velocities across the shield edge in southeastern Australia. Broader scale P wave tomography has extended the definition of three-dimensional structure, especially in the northern part of the continent. 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. These results show that some of the contrasts in surface geology between Precambrian and Phanerozoic outcrop are reflected in depth; some structures extend to depths of 200 km or more, e.g. the Mt Isa Block and the New England Block.

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. Structural differences between the Precambrian shield and eastern Australia are inferred from surface wave dispersion (cf. Muirhead & Drummond 1991; Denham 1991), and teleseismic travel-time residuals (Drummond et al. 1989), whose origin is due to structures which certainly extend below 100 km depth.

This paper reports on a variety of studies which have been undertaken to try to constrain seismic structure in the lithosphere, asthenosphere and the transition zone beneath. Most of the studies exploit the extensive seismic activity in the belt which runs through Indonesia, New Guinea and its offshore islands, Vanuatu, Fiji and the Tonga–Kermadec zone. Many of the seismic events enable investigation of the upper mantle structure from their refracted arrival recorded at arrays of portable stations in northern Australia (Fig. 1).

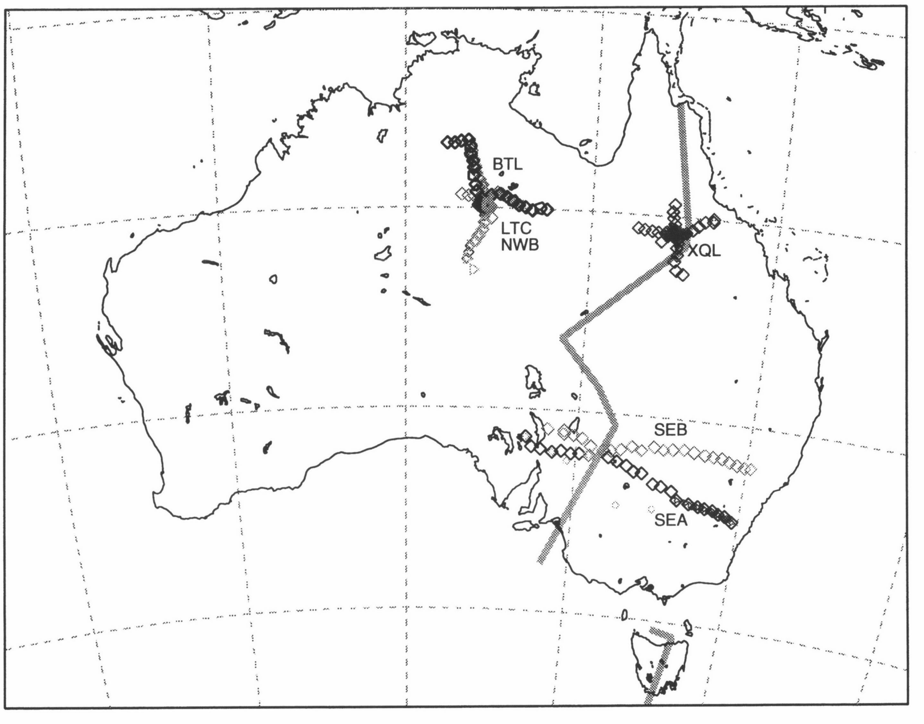

Figure 1. Configuration of short-period seismic array experiments 1985–1992 in relation to the inferred position of the major structural boundary between Precambrian western and central Australia and the Phanerozoic east.

P and S velocity profiles

A number of experiments have been carried out in northern Australia aimed at delineating the major features of the mantle's velocity profile, notably the work of Hales et al. (1980), who used records of Indonesian earthquakes at various of depths from a number of stations in a travel-time analysis. 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 reinterpretation by Leven (1985), using comparisons between observed and synthetic seismograms, led to a somewhat simplified structure, but retained a prominent velocity contrast near 210 km depth.

Muirhead & Drummond (1991) have provided an excellent summary of the results of various experiments, using explosive sources, which have provided constraints on P wave velocity structure in several parts of Australia down to 200 km. Control on lithospheric S velocities is somewhat weaker, even though surface wave dispersion (Denham 1991) provides additional information.

The natural sources to the north of Australia are too far away for refracted wave arrivals (for either P or S) to easily constrain shallower structure and so this is inferred from earlier studies or by using local refraction results. For example, Bowman & Kennett (1991) used the aftershocks of the 1988 Tennant Creek earthquakes to investigate regional S wave propagation in central Australia and were also able to infer the velocity profile in the crust and uppermost mantle. Bowman & Kennett (1993) made further use of these aftershocks 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.

Short-period studies

The Research School of Earth Sciences carried out a sequence of experiments in 1985–1987, using short-period vertical seismometers to record the natural seismicity in the Indone-

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sia/New Guinea region. The LTC experiment in 1985 and the NWB experiment in 1986 were based around the Warramunga seismic array near Tennant Creek. The 1987 XQL experiment in northern Queensland linked into the seismic station at Charters Towers.

Dey et al. (1993) summarised the results from the LTC and NWB experiments, which show significant variation in P wave velocity structure in the upper mantle between paths for events along the Flores arc, studied by Bowman & Kennett (1990), and the paths to events in New Guinea. 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 interpretation confirms the need for a velocity contrast near 210 km depth (see Fig. 3). The event distribution in the NWB and LTC experiments gives rather limited control on the nature of the 660 km discontinuity.

The analysis to determine the velocity profiles was based on composite record sections, using many events recorded at 20–30 portable recorders equipped with vertical component sensors with a dominant period near 1 Hz. Stacking was used to reinforce the coherent arrivals, with all arrivals within 10 km epicentral distance being combined into a single trace. The influence of variable source time functions was minimised by stacking the envelope of the seismograms. This approach works well for P waves, and the branches associated with the main upper mantle discontinuities can be clearly seen in the record sections. However, the corresponding sections for S waves show a clear arrival associated with the lithosphere, which cannot easily be traced beyond 2000 km, and no branches associated with greater depth.

The XQL experiment in Queensland allowed the investigation of deeper structure, and Cummins et al. (1992) showed that in short-period data there is no obvious signature of the postulated discontinuity near 520 km. Consequently, any P velocity transition will have to be spread over at least 25 km, which would still produce an influence on long period records.

Broad-band studies

A broad-band sensor has been operated at the Warramunga array (WRA) in northern Australia since late in 1988, and 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 broad-band stations deployed 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 very little contamination by converted P waves; which is a considerable improvement over previous S wave studies of the upper mantle, which have been restricted to SH waves.

Figure 2 shows a composite record section covering the P and S wave components returned from the upper mantle. This section has been constructed from unfiltered radial components associated with many events, and clearly displays the benefit of broad-band recording. The onset of 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 distance. The loss of higher frequencies is less pronounced for P waves. The travel-time curves for the upper mantle model illustrated in Figure 3 are superimposed on the record section to aid recognition of the phase onsets.

The change in frequency content for the S waves returned from greater depth has been analysed by Gudmundsson et al. (1994) to determine the attenuation structure with depth under northern Australia. They used the slope of the spectral ratio between P and S wave arrivals on the same record to constrain 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 and 410 km. In a parallel analysis, Kennett et al. (1994) 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 (Fig. 3). An advantage of this study is that both P and S velocity profiles are determined for the same events and the P/S velocity ratio can be well determined, which is particularly useful for studies of mantle composition. The depth variation

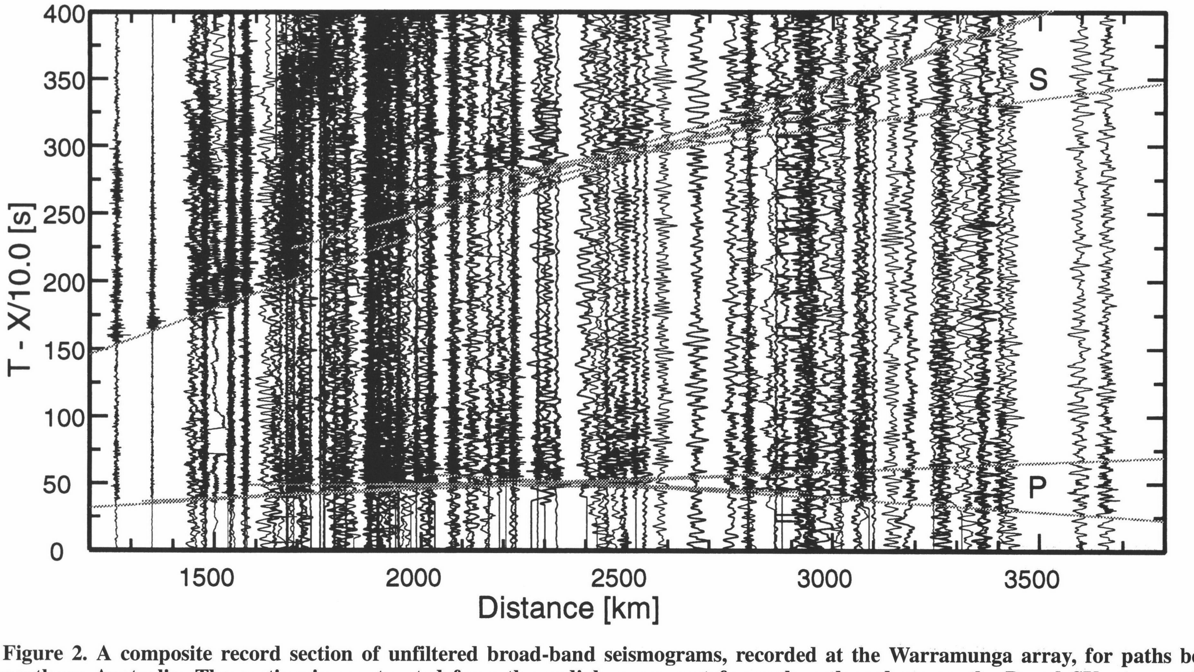

Figure 2. A composite record section of unfiltered broad-band seismograms, recorded at the Warramunga array, for paths beneath northern Australia. The section is constructed from the radial component for each path and covers the P and SV waves returned from the upper mantle. The travel-time curves for the velocity model illustrated in Figure 3 are superimposed on the section.

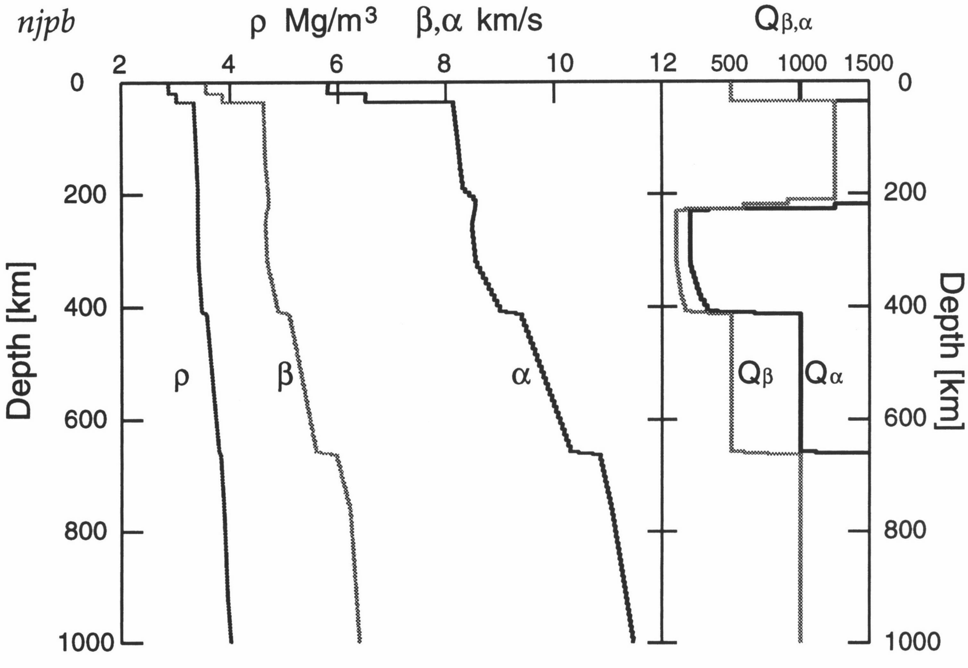

Figure 3. P and S velocity and attenuation structure for the upper mantle beneath northern Australia determined from a combination of short-period and broad-band observations.

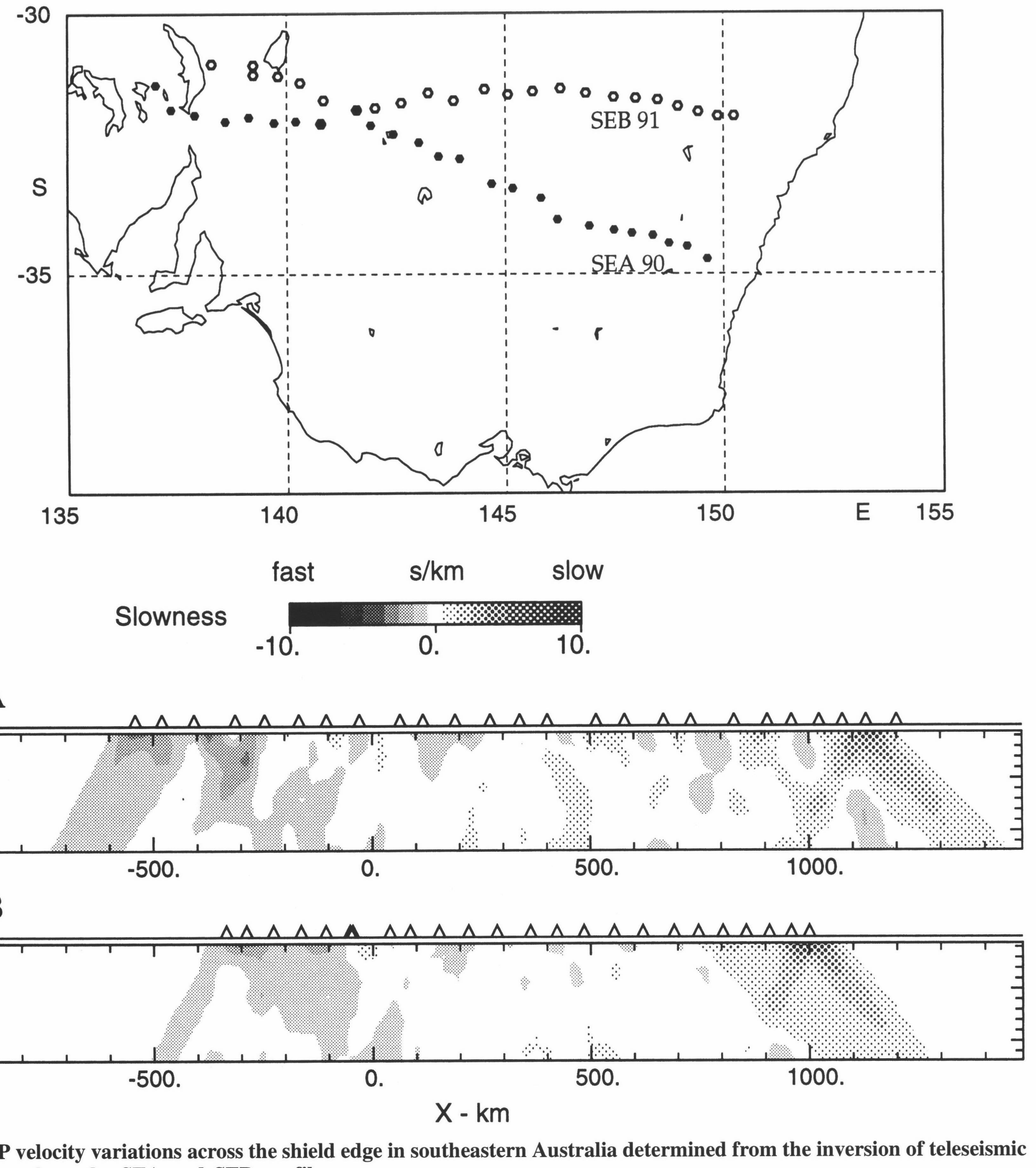

Figure 4. P velocity variations across the shield edge in southeastern Australia determined from the inversion of teleseismic delay times along the SEA and SEB profiles.

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 & Helmberger (1989) with the S wave structure of Grand & Helmberger (1984).

Comparison of the radial and tangential components of the S wavefield indicates that for the arrivals from the upper mantle discontinuities there is a systematically earlier arrival on the SH component of more than a second. These indications of seismic anisotropy for the refracted S wave arrivals have been analysed by Tong et al. (1994), who determined the direction of fast propagation and time shift between the S components by correlation analysis. The nature of the observed anisotropy is such that it cannot be explained by structure local to the receivers. A level of anisotropy of the order of 1% in both the lithosphere and the asthenosphere beneath would explain the data quite well.

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.

Body wave studies

One class of experiment that can provide useful information on seismic structure is to determine the systematic patterns of travel-time residuals across an array of portable stations, and then to invert for the structure along the line. In 1990 and 1991, two arrays, 1500 km long, of short-period recorders were deployed to cross the contact between Phanerozoic and Precambrian rocks in southeastern Australia (Fig. 1). The profiles had two stations in common, near Broken Hill, so that the residual patterns could be tied together. In each case, the residual patterns for teleseismic P waves show a systematic trend to early arrivals to the west on the older Precambrian outcrop with a time differential of 0.6–1.0 s between the ends of the profile, depending on the azimuth of the source. These delay patterns confirm the results of the preliminary survey by Cleary et al. (1972), using the nuclear explosion Longshot in the Aleutians. The interpretation of the residuals requires a substantial contrast in seismic properties in the upper part of the mantle, extending to at least 200 km depth, very close to the edge of the Precambrian outcrop (Vahau & Kennett 1995). The two-dimensional structures inferred along the two profiles are illustrated in Figure 4; there is significant structure beneath the Murray Basin, which may be related to the assemblage of the Lachlan Fold Belt.

A further source of information on velocity structure under northern Australia comes from P wave tomography studies, using the sources in the Indonesian and New Guinea region (Widiyantoro & van der Hilst 1996). This work uses 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, the inversion for P wave velocity follows 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. Figure 5 shows a cross section through the P wave model for the depth interval 160–200 km, which shows very strong contrasts between the high velocities in the lithosphere under northern Australia and the lower velocities behind the subduction zone in Indonesia.

Surface wave studies

The configuration of the seismicity around the Australian continent is very favourable for tomographic methods using surface wave trains. The Research School of Earth Sciences has completed a major field-based program to install some 60 portable broad-band stations across Australia over three and a half years (van der Hilst et al. 1994). The project is using a set of up to 12 portable instruments, which occupy sites for 5 months at a time before being moved to a new location, so that a full continental array can eventually be synthesised. The mobility of the arrays has led to the project being named Skippy.

The deployments commenced in May 1993 with 8 stations

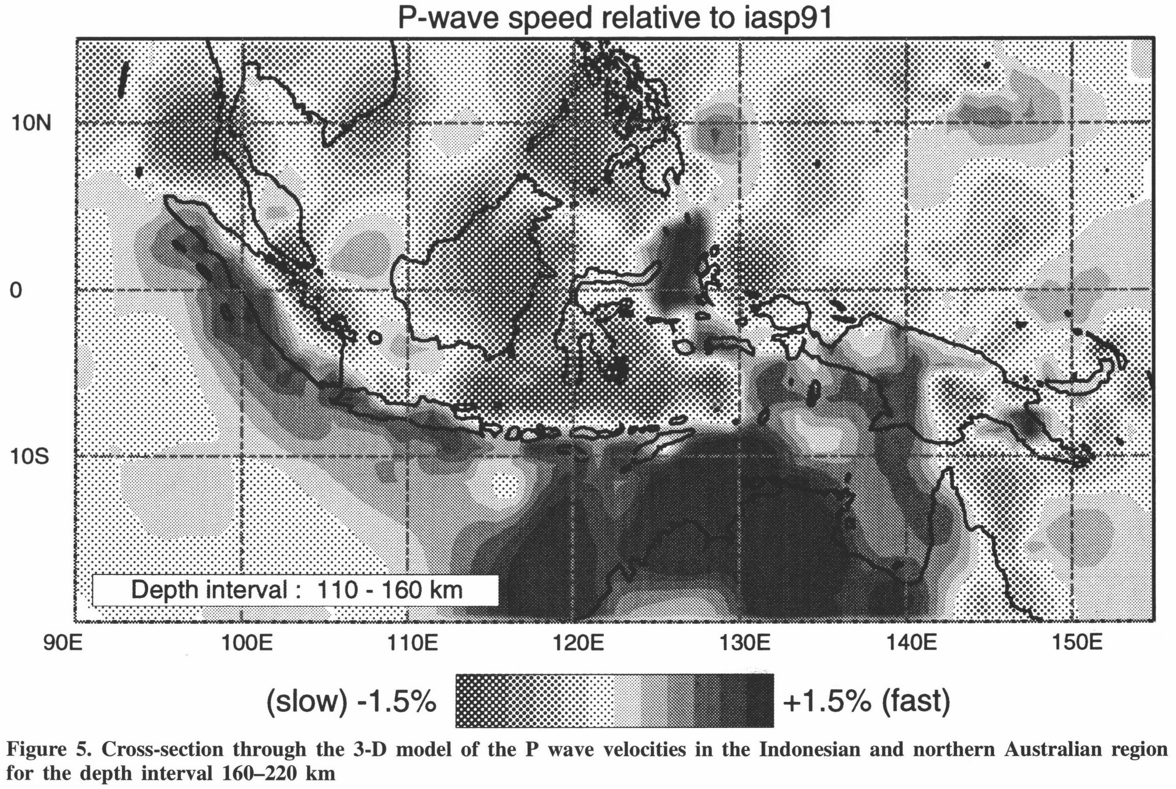

Figure 5. Cross-section through the 3-D model of the P wave velocities in the Indonesian and northern Australian region for the depth interval 160–220 km

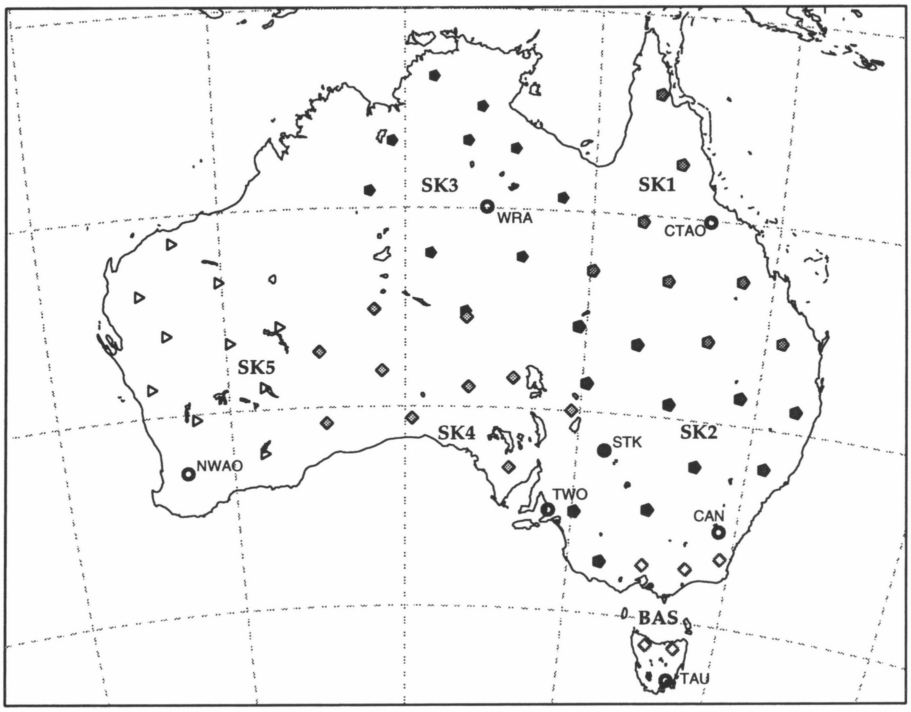

Figure 6. Configuration of broad band surveys. SK1, May–Oct 1993; SK2, Nov 1994–Mar 1995; SK3, May–Oct 1994; BAS, Nov 1994–Feb 1995; SK4, Mar–Aug 1995; SK5, planned Sept 1995–Mar 1996. Permanent stations with high fidelity recording are indicated by a double circle and station name.

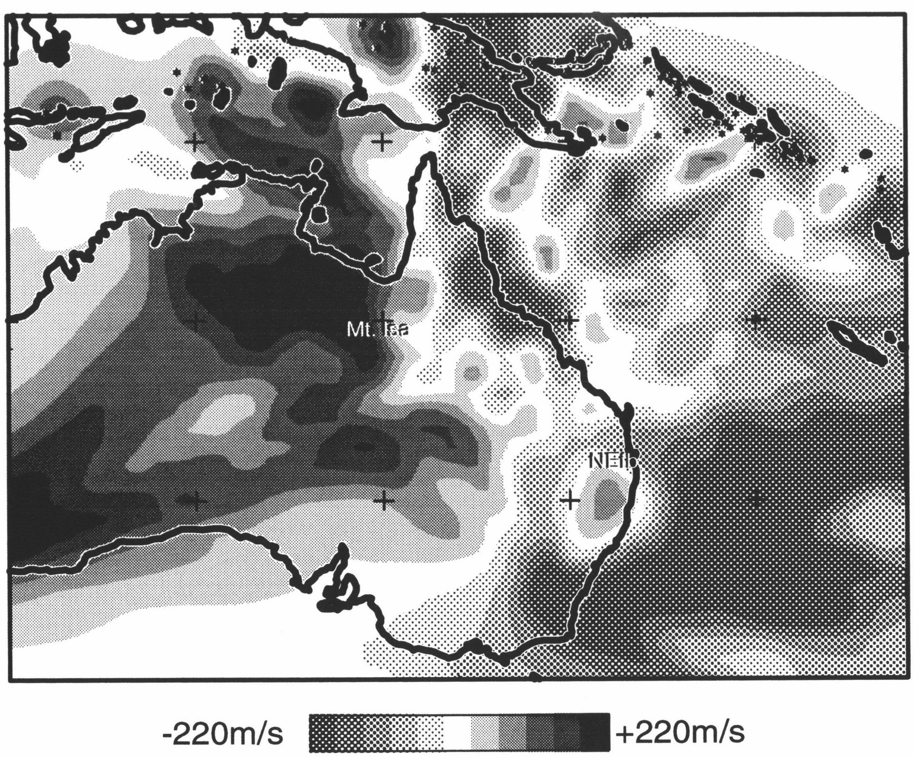

Figure 7. Preliminary three-dimensional shear wave model derived from partitioned waveform inversion, using the permanent stations and the SK1 stations in Queensland, cross-section at 140 km depth.

in Queensland and by the end of August 1995 had covered all the continent except western Australia (Fig. 6). The data set is supplemented by records of suitable events from the permanent broad-band stations. The broad-band records provide a wide range of data, but the primary object is the delineation of lithospheric and mantle structure, using waveform inversion for the shear wave and surface wave portion of the seismogram. The analysis is based on the partitioned waveform inversion technique introduced by Nolet (1990). A nonlinear optimisation is used to find a stratified model which gives the best fit to the observed seismograms, which should represent the average structure along the great circle between source and receiver. The assemblage of path averages is then used in a linear inversion to recover the three-dimensional shear wave structure.

The results of the inversion process for the data from the stations in Queensland (van der Hilst et al. 1995) are presented in Figure 7 for a depth of 140 km. At this level in the lithosphere there are significant contrasts in shear wave velocity. The relatively low shear wave speeds along the Queensland coast may well be associated with Quaternary volcanism. The outline of the higher wave speeds correlates quite well with the surface expression of the Tasman line separating Precambrian and Phanerozoic Australia; though we can note the rather high velocities beneath the Mt Isa Block, which extend to substantial depth (at least 300 km). Another interesting feature is the high shear wave speeds associated with the New England Block. These intriguing results have been derived from the analysis of data from just the first part of the Skippy project. More detail on lithospheric and mantle structure beneath the Australasian region has been revealed as data from the later deployments have been incorporated into the inversion for three-dimensional structure (Zielhuis & van der Hilst 1996, van der Hilst et al. in press).

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, based on the use of both short-period and broad-band seismic information. The current generation of three-dimensional studies based on the use of portable broad-band seismometers has the potential to dramatically increase the level of understanding of structure in the lithosphere and the underlying mantle of the Australian region. In particular, it should be possible to relate the surficial contrasts between eastern and western Australia to the nature of the structures in the mantle beneath.

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