# 8

# Seismic Structure of the Mantle: From Subduction Zone to Craton

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## 8.1. Introduction

Seismological techniques have provided much of the currently available information on the internal structure of the Earth, and in particular on the mantle. Early studies revealed the need for an increase in seismic velocity with depth in the Earth, and by 1915 Gutenberg was able to make a good estimate of the radius of the core. Knowledge of the Earth's internal structure was refined by iterative improvement of earthquake locations and the travel times for seismic phases through the Earth, so that in 1940 Jeffreys and Bullen were able to publish an extensive set of travel-time tables based on a model of both P-wave and S-wave velocities in the mantle. Their velocity profile was intentionally as smooth as possible, but it was not possible to avoid introducing a sharp change in velocity gradient near a depth of 400 km to account for the distinct change in the slope of travel-time curves at a distance of approximately 20° from the source, for both P and S waves. Subsequent studies have refined our conception of mantle structure to reveal the presence of discontinuities in velocity and zones of strong velocity gradients, which have been correlated with mineralogical phase changes (e.g., Jackson and Rigden, Chapter 9, this volume).

The presence of three-dimensional variations in the Earth's structure became apparent in regional differences in seismic travel times, and they became better understood once surface-wave observations demonstrated the significant differences in surface-wave dispersion between oceanic and continental regions (e.g., Knopoff, 1972). Surface-wave studies revealed the presence of a zone of decreased shear-wave velocities at depth and showed significant variations in the thickness of the overlying high-velocity zone ('lid') between different regions. The differences between the characteristics of the upper mantle in oceanic and continental regions led Dziewonski, Hales, and Lapwood (1975) to develop models with allowances for oceanic and continental character as well as an average radial model for the whole Earth.

In recent years, the quality and quantity of seismological data have improved sufficiently that it is possible to begin to resolve the three-dimensional structure within the Earth using a combination of information from the travel times for seismic phases, the free oscillations of the Earth, and long-period seismic waveforms. A consensus is developing on the largest-scale features in the aspherical structure. The ellipticity of the figure of the Earth provides a major component of spherical-harmonic order 2, and this order is also strongly represented in the velocity structure, particularly in the transition zone in the upper mantle (e.g., Masters et al., 1982). There is substantial power in the low-order heterogeneity of the Earth, and some authors (e.g., Su and Dziewonski, 1991) have suggested that the spectrum of heterogeneity is 'red' (i.e., dominated by the large-scale features). However, there is ample evidence for significant heterogeneity on smaller scales than have yet been revealed by global studies.

In particular, the upper mantle is a zone of major variability and relatively strong horizontal gradients in seismic properties. Subducted slabs are associated with large, localized contrasts in velocity. Detailed P-wave tomography based on the inversion of seismic travel times has revealed the complex patterns of subduction in many regions (e.g., van der Hilst et al., 1991). The influence of subduction is largest in the upper mantle, but in many places subducted material appears to have penetrated directly or indirectly into the lower mantle. The high seismic velocities associated with the colder subducted material seem to be the dominant mode of smaller-scale heterogeneity in the lower mantle, which otherwise appears to be characterized by relatively low gradients of heterogeneity. However, the degree of variability increases as the core–mantle boundary is approached, and the D″ layer in the 300-km zone at the base of the mantle shows considerable variability on a wide range of scales revealed by studies with many different types of probes.

### 8.2. The Seismic Structure of the Mantle

The variation of seismic properties within the Earth is inferred from the analysis of seismograms in a variety of ways and is dominated by a radial dependence. However, three-dimensional variations are manifest in the crust and in all parts of the mantle; currently the most effective representation of such three-dimensional structure is as a perturbation to a reference radial model.

For this radial reference model, the major sources of information come from the travel times for seismic phases and from the free oscillations of the Earth. The travel times provide constraints on the seismic wave speeds within the Earth; the frequencies of the normal modes provide additional information on the density distribution and the attenuation profile for seismic waves. A thorough discussion of seismological methods has been provided by Lay and Wallace (1995).

The zones of greatest heterogeneity lie in the uppermost part of the mantle (depths shallower than about 250 km) and near the core–mantle boundary. In such zones, horizontal gradients in velocities can approach the radial gradients, and so it is difficult to define a representation of an 'average' structure in those parts of the Earth.



Various techniques are currently being employed to build up a body of information on the three-dimensional structure of the Earth. To determine the distribution of velocities for compressional (P) waves, the dominant approach is the use of travel-time tomography, primarily based on the impressive collection of arrival-time data for different seismic phases assembled by the International Seismological Centre (ISC). Recently, additional information on travel times has become available from analyses of long-period seismograms by correlation techniques (e.g., Woodward and Masters, 1991; Bolton and Masters, 1994).

In determining the velocity distribution for shear (S) waves, much of the available information has come from techniques based on the fitting of long-period waveform segments to computed seismograms. Such information has been complemented by the use of ISC travel-time data and the long-period S times and differential times between different S phases (Woodward and Masters, 1991).

The techniques of waveform fitting used in the global context are based on summation of the normal modes of the Earth in a perturbation treatment to include the influence of three-dimensional structure. Additional information on such structure comes from analyses of the free oscillations through the local frequencies of modes and the splitting of the modal frequencies produced by interaction with heterogeneity (Masters and Ritzwoller, 1987).

### 8.3. The Dominant Radial Structure in the Mantle

At present, nearly all the techniques designed to assess the three-dimensional structure of the Earth are based on a representation in terms of deviations from a reference model (which normally is a spherically symmetrical model). The nature of the reference model is therefore of considerable importance.

Dziewonski et al. (1975) introduced a new style of representation for such reference models with the PEM model, which was defined in terms of a limited number of radial segments, within each of which the seismic velocities and densities were defined by polynomials (up to cubic) in radius. The advantage of such a form of representation is that the entire model is defined by a relatively small number of parameters. In consequence, the computational labour of retrieving a model from the observations is reduced.

Such parametrized models have been used extensively since 1975, notably in the PREM model of Dziewonski and Anderson (1981), which endeavoured to take account of a very wide range of information from the free oscillations of the Earth, dispersion of surface waves, travel times for the major seismic phases, and differential travel times. The PREM model allowed for the frequency dependence of seismic velocities associated with anelastic attenuation within the Earth, and it also introduced the concept of transverse isotropy in the uppermost mantle to try to reconcile the dispersion characteristics of Rayleigh and Love waves. The PREM model has been extensively used in work involving the normal modes of the Earth, and it is frequently used as a reference model in global studies.

The same style of parametrization has been adopted in the recent models *iasp91* (Kennett and Engdahl, 1991) and *sp6* (Morelli and Dziewonski, 1993) for P and S velocities derived from travel-time information. With these improved velocity models, it is possible to refine the locations of seismic events and thus obtain an updated set of empirical travel times for a wide range of seismic phases. Kennett, Engdahl, and Buland (1995) have constructed a new model, *ak135*, for the seismic velocities using such improved travel times, and in order to fit the observed behaviour they were forced to employ a more complex parametrization in the lower mantle and core.

The merits of improved reference models for seismic velocities have been demonstrated in seismic-tomography studies. Event relocation in such a model can lead to nearly as much reduction in data variance as does direct estimation of three-dimensional structure using raw ISC data, and a further improvement in fit can then be obtained by superimposing three-dimensional structure on the reference model (e.g., Inoue et al., 1990; van der Hilst et al., 1991).

### *8.3.1. The Upper Mantle and Transition Zone*

Such global models for upper-mantle structure represent an average of structures from many regions, even when, as for travel-time studies, the information is dominantly from continental regions. Studies of the three-dimensional structure of the mantle indicate major contrasts, with scale lengths of the order of 3,000 km or so, and within such a zone it is possible to develop a regional representation of the major features of the velocity structure in the upper mantle. Grand and Helmberger (1984a) have used observations of long-period SH waveforms in North America to construct two characteristic models: *sna* for the shield regions, and *tna* for the tectonic regions. Grand and Helmberger (1984b) have made a comparable study for the northwest Atlantic Ocean. These three models differ markedly for depths less than 250 km. For the northern Australian region, Kennett, Gudmundsson, and Tong (1994) have produced both P and S velocity models from the same events using broadband seismograms recorded in northern Australia from the earthquake belt through Indonesia and New Guinea. This study indicated the presence of differences in structure along groups of paths extending into the transition zone, and it confirmed the findings from short-period studies for P waves summarized by Dey et al. (1993). Nolet, Grand, and Kennett (1994) provided a broad survey of heterogeneity and velocity variability in the upper mantle, including results from other areas.

Figure 8.1 shows the shear-wave velocity distributions from the North American and Australian studies, revealing the general concordance of the shield models *sna*



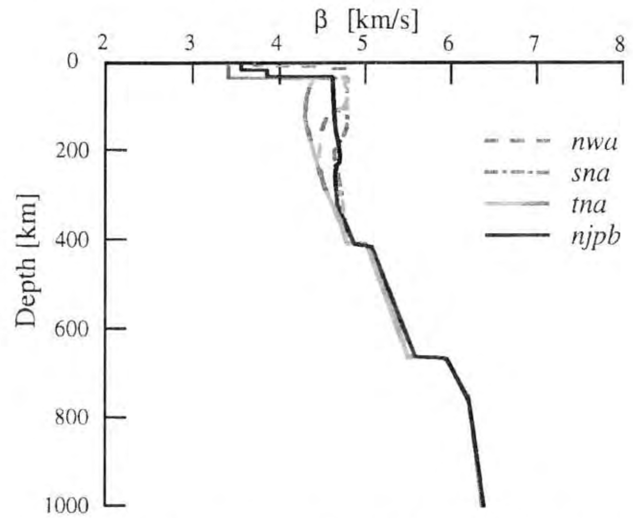


Figure 8.1. Shear-wave velocity distribution from refracted-wave studies: *sna* and *tna* models for shield and tectonic North America (Grand and Helmberger, 1984a), *nwa* for the northwest Atlantic Ocean (Grand and Helmberger 1984b), and *njpb* for the northern Australian shield (Kennett, Gudmundsson, and Tong, 1994).

and *njpb* as compared with the tectonic and oceanic models *tna* and *nwa*. The major differences between the models occur in the shallower structure. We see the major features of upper-mantle structure as revealed by refracted-wave studies displayed in these models. A zone of relatively high velocity just below the crust–mantle boundary is sustained for some depth before the shear velocity decreases (with an increase in shear-wave attenuation) and then recovers as the 410-km transition is approached. This zone of marked velocity change is represented here as a sharp discontinuity, but it may be spread over a few kilometres. The next major transition lies near a depth of 660 km, with a comparable contrast of about 4–6% in seismic velocities. Refracted-wave studies have not produced evidence for an intermediate discontinuity (Jones, Mori, and Helmberger, 1992; Cummins et al., 1992), but techniques based on the stacking of long-period seismograms (Shearer, 1991) and on ScS reverberations for SH waves (Revenaugh and Jordan, 1991) suggest the presence of a transition near 520 km. If this feature were spread over a zone 30 km in depth, or if a component of density change were involved, it would be possible to reconcile the two sets of observations.

The broadband studies in northern Australia have also revealed the presence of significant shear-wave splitting in the horizontally refracted waves used in the analysis (Tong, Gudmundsson, and Kennett, 1994). Such splitting is compatible with the presence of about 1% anisotropy in the low-velocity zone at a depth below 210 km beneath northern Australia, a zone also marked by high attenuation (Gudmundsson, Kennett, and Goody, 1994). Most other observations of shear-wave splitting have come from waves with relatively steep paths through the mantle (e.g., SKS, SKKS), and so it is difficult to localize the anisotropy that gives rise to the splitting. In Australia, there is evidence for a complex regime of anisotropy giving rise to different levels of splitting and different directions of fast polarization at different frequencies (Clitheroe and van der Hilst, 1997).

### 8.3.2. The Lower Mantle

As noted earlier, the upper mantle is a zone with considerable regional variability, but in the lower mantle, beneath about 750 km, there is much greater consistency between the velocities for different reference models. Indeed, the general trends in velocity gradients are very well defined, but there are some differences between models, depending on the different procedures used in their construction.

The structure of the lower mantle is illustrated in Figure 8.2 with the reference model *ak135* for which the P-wave velocity ($\alpha$) and S-wave velocity ($\beta$) have been determined by analysis of travel times for a broad range of seismic phases. The distributions of density ($\rho$) and seismic-wave attenuation ($Q_\alpha$, $Q_\beta$) have then been constructed so that the reference model will be compatible with both travel times and free oscillations (Montagner and Kennett, 1996).

From a mineralogical point of view, the bulk sound velocity $V_\phi$ is of major interest (e.g., Jackson and Rigden, Chapter 9, this volume), but this quantity cannot

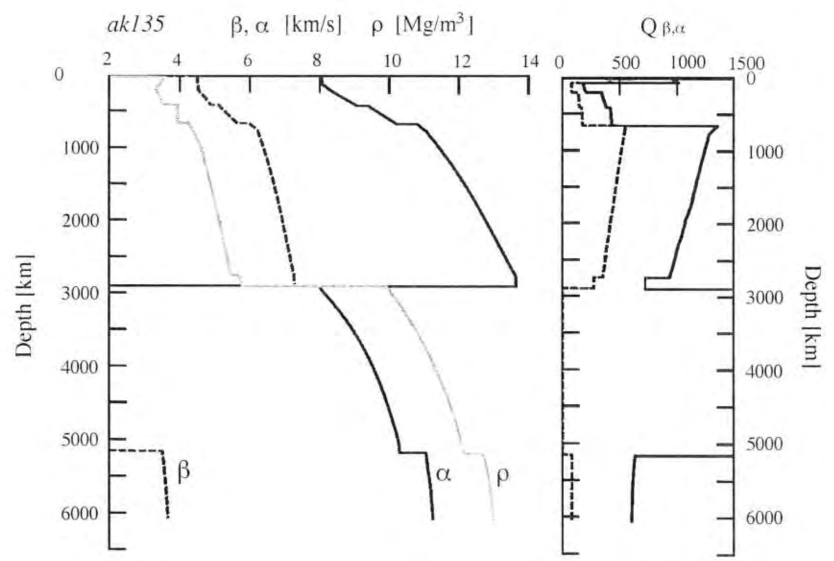


Figure 8.2. The *ak135* Earth model indicating P velocity $\alpha$ and S velocity $\beta$ (Kennett, Engdahl, and Buland, 1995), as well as density $\rho$ and attenuation ($Q_\alpha$, $Q_\beta$) (Montagner and Kennett, 1996). The zone of density inversion in the upper mantle is an artifact of a constraint to monotonically increasing shear velocity in the upper mantle.



be extracted directly from seismic data; instead it has to be calculated by combining the P-wave velocity $\alpha$ and the shear-wave velocity $\beta$:

$$V_\phi = \sqrt{\alpha^2 - \frac{4}{3}\beta^2} \quad (1)$$

It is therefore important that there be consistency between the assumptions underlying the relevant P and S velocities, such as in the *sp6* and *ak135* models.

The bottom 200 km of the lower mantle (the D″ layer) is a zone of relatively strong heterogeneity, as evidenced by a wide range of studies (e.g., Lay, 1994). This zone, just above the core–mantle boundary, may well have heterogeneity comparable to that near the Earth's surface and may serve as a repository for the debris from mantle processes that potentially can be remobilized by the heat emerging from the core.

## 8.4. Detailed Three-Dimensional Structure in the Mantle

Nearly all of the available information on the details of the three-dimensional structure within the Earth comes from the analysis of departures of the observed properties of the seismic wavefield from the predictions made with a reference model. For a majority of studies, the significant quantity is a time shift in the arrival of a phase, measured directly for a short-period body wave, by correlation techniques for long-period body waves and surface waves, or by a waveform inversion where the record contains a number of arrivals, as, for example, the shear-wave field containing both body-wave and surface-wave components. The travel-time residuals for body waves or modified dispersion characteristics for surface waves can then be used as the basis for recovering a three-dimensional model. The essence of seismic tomography is to relate the time differential back to the structure from which it arises. Such a time residual will represent the cumulative effect of all the deviations from the reference model encountered along the propagation path. With multiple crossing paths it is possible to begin to reconstruct the spatial distributions of velocity perturbations, commonly using the assumption that the ray path is unperturbed from that in the reference model. In principle, the results should be improved by an iterative procedure, with recomputation of ray paths in the new three-dimensional model followed by inversion to determine perturbations from the new heterogeneous reference model. Such a procedure is computationally intensive, but is desirable for detailed studies of the shallower regions of the mantle, where there are large variations in seismic velocities.

The resolution of velocity variations and the quality of the resulting images of velocity structure are strongly dependent on the ray-path coverage that can be attained. A number of different procedures have been devised for handling the large systems of linearized equations that must be solved in the tomographic inversion to reconstruct velocity structure; a comprehensive discussion of current techniques has been provided by Iyer and Hirahara (1993).

The amplitudes of seismic waves have been exploited to a lesser degree. However, Romanowicz (1995) has begun to use such amplitude information to define the large-scale variations in seismic attenuation. On a smaller scale, studies of seismic amplitudes have helped to define stochastic models for the velocity variations that lie below the resolution of direct methods (e.g., Kennett and Bowman, 1990).

### *8.4.1. Subduction Zones and Their Environment*

At depths greater than 100 km, slabs of subducted lithosphere are probably the major and best-constrained aspherical structures in the Earth's interior. They play an essential role in the cooling of the Earth's mantle by convection and the consequent recycling of oceanic lithosphere. For various reasons, the structure of subducted slabs is better known than that of plumes, the secondary mode of mantle convection (e.g., Davies, Chapter 5, this volume; Griffiths and Turner, Chapter 4, this volume). The narrow tail of a plume is more difficult to detect by seismological methods, although success in imaging a plume tail has been reported (Nataf and Van Decar, 1993). Moreover, an unambiguous indication of the presence of subducted lithosphere is the occurrence of intermediate-depth earthquakes (focal depth 70–300 km) and deep earthquakes (focal depth >300 km) beneath convergent-plate boundaries.

Thermal models of the subduction process indicate that the temperature difference between the cold core of a slab and the ambient mantle at the same depth is likely to be 500–1,000°C (e.g., Toksöz, Minnear, and Julian, 1971). This thermal anomaly changes the seismic wave speed within the subducted slab, so that its wave speed is several percent higher than that for the surrounding material at the same depth. The effect of the subduction regime is therefore to produce an environment in which seismic waves that propagate within the slab travel faster than would be expected for a global reference model. Surface-reflected phases sampling the region in the back arc above the slab will be delayed, relative to the reference, because of the combination of temperature effects and volatiles released from the slab (e.g., Green and Falloon, Chapter 7, this volume). These differences will be reflected in the arrival times of seismic waves at different stations, depending on the propagation path. The density of earthquake sources in subduction zones aids the delineation of seismic structure by allowing measurements of the deviations in arrival times from those predicted by the reference model.

The first tomographic images of subducted lithosphere were produced in the late 1970s (Hirahara, 1977; Hirahara and Mikumo, 1980) using several thousand P-wave travel times. Since then, the quantity and quality of seismic data have improved, and increased computer power now allows the simultaneous interpretation of many millions of data. In many inversions the heterogeneous structure has been assumed to be confined to the region of interest around the subduction zone. Such an assumption can be very effective for situations where most of the ray paths lie within the structure of interest. For example, tomography has yielded very detailed information about the shallow part of the subduction zone and the relationship between wave-speed anomalies and shallow seismicity and arc volcanism in back-arc regions, such as northern Honshu in Japan (Hasegawa et al., 1991). When information is used from a global distribution of stations, allowance must be made for possible structure outside the zone of interest. This can be done in part by introducing station corrections at teleseismic stations. However, with sufficient computing resources, a preferable approach is to undertake a low-resolution tomographic inversion for the velocity structure of the whole Earth with an embedded high-resolution model for the environs of the subduction zone. That approach was pioneered by Fukao et al. (1992) and taken to higher resolution by Widiyantoro and van der Hilst (1996).



In addition to the representation of the model, an important issue is the nature of the data employed and the reference model. Van der Hilst et al. (1991) have demonstrated that the depth phase pP can commonly be extracted from travel-time observations. Relocation of the earthquake sources using all available phases, with an improved reference model such as *iasp91* (Kennett and Engdahl, 1991), provides a significant improvement in data fit before three-dimensional structure is introduced, and the resulting velocity images show better definition because the path coverage is improved by the inclusion of the surface reflections pP. With well-designed regional tomographic studies, structural variations over distances of about 100 km can be detected (e.g., Spakman, 1991; van der Hilst, 1995), and such studies can provide significant information on the large-scale structure of subducted slabs and their interaction with the mantle transition zone. Global models are just beginning to approach the resolution required for the investigation of slab structure and, in particular, the influence of slabs on the lower mantle (Inoue et al., 1990; Vasco et al., 1994; van der Hilst, Widiyantoro, and Engdahl, 1996).

Slabs of subducted lithosphere, partly delineated by deep seismicity in the Wadati-Benioff zones, represent tangible trajectories of convective flow in the Earth's mantle and have therefore played a central role in attempts to resolve the controversial issue of the depth scale of mantle convection. In addition to geochemical arguments (Anderson and Bass, 1986; Ringwood and Irifune, 1988; Ringwood, 1991), the cessation of seismicity above the 660-km seismic discontinuity has been used as evidence that lower-mantle flow is separate from convection in the upper mantle and transition zone. However, a range of seismological studies, based on analyses of the patterns of travel-time residuals, have provided evidence for aseismic continuation of slabs into the lower mantle (Jordan and Lynn, 1974; Jordan, 1975, 1977; Creager and Jordan, 1984; Fischer, Creager, and Jordan, 1991). These findings have been supported by thermal models (Wortel, 1982) and used as arguments for whole-mantle convection. However, the issue of slab penetration and the style of the convective process in the mantle have remained controversial; for reviews, see Olson, Silver, and Carlson (1990), Silver, Carlson, and Olson (1988), Davies and Richards (1992), Ringwood (1991), Lay (1994), and Davies (Chapter 5, this volume).

Recently, results of numerical modelling of mantle flow (e.g., Machetel and Weber, 1991; Tackley et al., 1993, Davies, Chapter 5, this volume) and improved seismic imaging (van der Hilst et al., 1991; Fukao et al., 1992) have begun to converge to a hybrid-flow model in which neither layered convection nor whole-mantle convection is regarded as a steady-state process. The model of direct slab penetration, as advocated by Jordan and co-workers, provides an oversimplified and incomplete description of the flow pattern associated with subduction. Tomographic imaging has confirmed the conclusions reached in early studies that deep slabs are present in the lower mantle beneath Middle America (Grand, 1987, 1994; van der Hilst and Spakman, 1989) and beneath several western Pacific arcs (van der Hilst et al., 1991; Fukao et al., 1992; van der Hilst, 1995). Indeed, high-resolution global images (van der Hilst, Widiyantoro, and Engdahl, 1996) have revealed relatively narrow regions of high P-wave speed in the lower mantle beneath most major subduction zones, as can be seen in Figure 8.3, which displays a cross section through global structure at a depth of 1,300 km. However, detailed seismic imaging is providing mounting evidence that the interactions of the slabs with the transition zone between the upper mantle and the lower mantle are quite variable: Locally, some slabs penetrate into the lower mantle without much apparent obstruction, whereas elsewhere they are strongly deformed and remain stagnant (at least temporarily) in the transition zone (Zhou and Clayton, 1990; van der Hilst et al., 1991; Fukao et al., 1992).

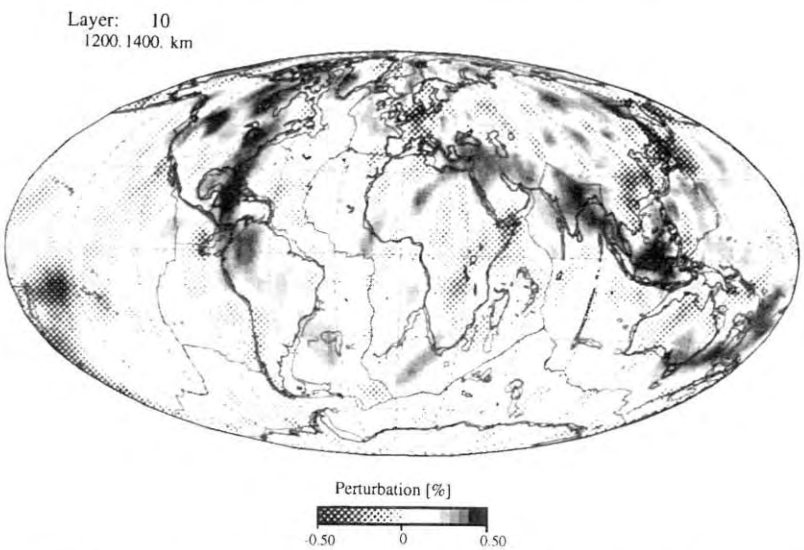


Figure 8.3. Lateral variations of P-wave speed at a depth of approximately 1,300 km determined by a tomographic inversion for the whole globe, with an approximate resolution of 3 × 3° (van der Hilst, Widiyantoro, and Engdahl, 1996).



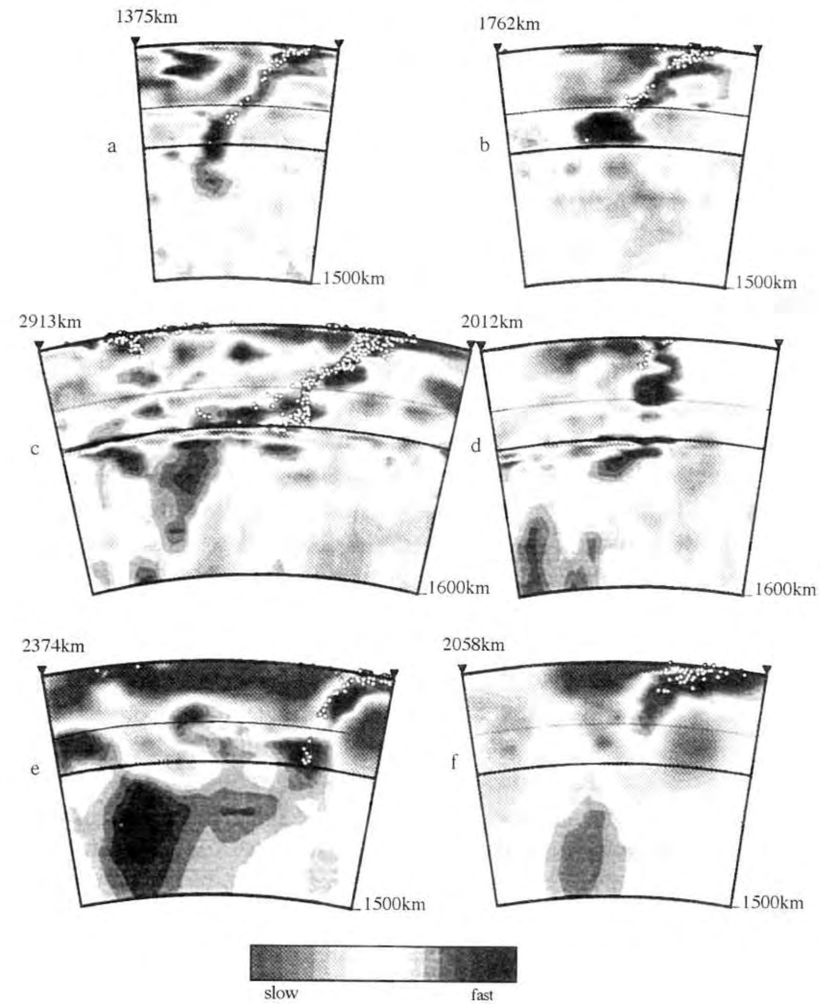


Figure 8.4. Cross sections through tomographic images of P-wave velocity structure for a number of subduction zones, illustrating the variety in styles of subduction: (a) northern Kuriles, (b) southern Kuriles, (c) northern Tonga arc, (d) Kermadec region, (e) Java, (f) Sumatra. The superimposed lines indicate the positions of the 410-km and 660-km discontinuities. Sections a and b are from the work of van der Hilst et al. (1991), c and d from van der Hilst (1995), and e and f from Widiyantoro and van der Hilst (1996).

The following examples of the complex behaviour of slabs in the transition zone beneath individual arc systems have been derived from studies of the structures of deep slabs in the western Pacific (van der Hilst et al., 1991; van der Hilst, 1995) and Indonesia (Widiyantoro and van der Hilst, 1996). Figure 8.4a depicts the trajectory of the Pacific plate subducting beneath the Sea of Okhotsk along the Kurile Trench.

The slab is represented by a steeply dipping structure of higher-than-average wave speed which is partly delineated by seismicity. The zone of high wave speeds can be detected to a depth of about 1,200 km, which suggests that the slab penetrates into the lower mantle. Figure 8.4b depicts the trajectory of the subducting Pacific plate beneath the southern part of the Kurile Trench. In contrast to the situation farther to the north, the slab appears to be deflected in the transition zone; this inference is substantiated by the recent occurrence of a deep earthquake beneath Sakhalin Island that appears to have been located in the sub-horizontal part of the slab. A comparable contrast in subduction behaviour has been detected beneath the Izu Bonin and Mariana arcs: The change from a sub-horizontal slab beneath the Izu Bonin arc to a sub-vertical slab farther to the south is consistent with the pattern of deep seismicity in that region (Okino et al., 1989; Lundgren and Giardini, 1992; van der Hilst and Seno, 1993). Lateral variations in the shape of the deep slab are not restricted to the northwest Pacific subduction systems. Figures 8.4c and 8.4d show the lateral variations in the shape of the Tonga slab (van der Hilst, 1995), and Figures 8.4e and 8.4f show the Sunda slab (Widiyantoro and van der Hilst, 1996). The images of the northern Tonga slab (Figure 8.4c) and the Java slab (Figure 8.4e) are of particular interest because they provide evidence for slab penetration into the lower mantle even though the part of the slab in the transition zone is sub-horizontal.

However, a word of caution is in order. Interpretation of the velocity images to suggest that slabs penetrate into the lower mantle ignores the possibility that the lower-mantle anomaly may be caused by thermal coupling between the transition zone and lower mantle (i.e., the cooling of lower-mantle material by thermal diffusion and the subsequent sinking of that cooled lower-mantle material). The interpretation in terms of slab penetration to a depth of 1,200 km also rejects the possibility that the 660-km discontinuity may be depressed by several hundreds of kilometres. The independent analysis of Shearer and Masters (1992) suggests depression of the depth of this discontinuity by about 50 km beneath subduction zones, and that is concordant with current mineralogical models for the associated phase changes (e.g., Jackson and Rigden, Chapter 9, this volume).

Van der Hilst and Seno (1993) noticed that the sub-horizontal slabs in the transition zone were located beneath regions characterized by recent back-arc spreading due to fast, oceanward migration of the deep-sea trenches. The Kurile slab is laid down in the transition zone beneath the South Kurile Basin, whereas the sub-horizontal slab related to subduction at the Izu Bonin Trench is located beneath the Shikoku Basin. A similar relationship applies to the sub-horizontal part of the northern Tonga slab, which is located beneath the Oligocene South Fiji Basin and the Pliocene–present Lau Basin. Van der Hilst and Seno (1993) and van der Hilst (1995) have used a combination of findings from experimental fluid dynamics (Kincaid and Olson, 1987) and numerical simulations (Christensen and Yuen, 1984; Machetel and Weber, 1991), together with petrological data pertinent to the dynamics of slabs in the transition zone (Ringwood and Irifune, 1988; Ringwood, 1991), to argue that the kinks in the subduction trajectory can be explained by the interaction between the lateral translation of the source of flow and the tendency towards vertical flow in a stratified mantle.



It is generally accepted that slabs in the transition zone encounter resistance against further, unobstructed sinking owing to a combination of increased viscosity in the lower mantle, the dynamical effects of the perovskite-forming phase changes in the subducting slab, and, possibly, a small increase in intrinsic density of material in the ambient mantle due to compositional differences. If the lateral migration of a trench is sufficiently fast relative to the sinking speed in the lower mantle, the slab can be laid down in the transition zone. This model is supported by numerical tests (Zhong and Gurnis, 1995) and fluid dynamical modelling (Griffiths, Hackney, and van der Hilst, 1995) and does not depend critically on the nature of the boundary between the upper mantle and the lower mantle. The boundary slows down radial flow but does not completely eliminate mixing between the upper mantle and the lower mantle.

Such observations can be explained by radial variations in viscosity alone (Griffiths et al., 1995; Griffiths and Turner, Chapter 4, this volume). However, a mechanism of 'megalith' formation representing the cumulation of slab material at the top of the lower mantle, as postulated by Ringwood and co-workers (Ringwood and Irifune, 1988; Ringwood, 1991; Kesson, Fitz Gerald, and Shelley, 1994), would be compatible with the observations if the lifetime of such a structure were about 10–20 million years, rather than the 100 million years suggested by Ringwood and Irifune (1988). Beneath convergent-plate margins, relatively cold material can accumulate in the transition zone and gather sufficient negative buoyancy to accomplish the phase change to a denser assemblage and subsequently be 'flushed' into the lower mantle. Such events, also referred to as 'avalanches', have been simulated in numerical models (Tackley et al., 1993; Davies, Chapter 5, this volume): When a trench is stationary in space, the accumulation of material will occur in a small region in the transition zone, thus facilitating the flushing to greater depths. In contrast, if a trench is migrating sufficiently fast, the subducted material would be laid down on the 660-km discontinuity, thus retarding the flow to greater depths.

The reshaping of Ringwood's megalith is likely to be an important phenomenon on relatively short geological timescales. Episodes of fast trench migration and concurrent back-arc spreading typically last no more than several tens of millions of years; so it is to be expected that the complex behaviour of slabs in the transition zone will have similar timescale. On much longer timescales, relative motions are less important, and the amount of mixing between the upper mantle and the lower mantle will largely depend on differences in intrinsic density. Low-resolution seismic images of lower-mantle structure probably are more representative of flux averaged over a long time period, whereas the high-resolution images of slabs from regional studies represent 'snapshots' of a complex, transient dynamical process. The observation of slab-like structural features in the lower mantle beneath the zones of subduction of old, thermally mature plates (Figure 8.3) suggests that eventually a very substantial amount of subducted material becomes entrained in lower-mantle flow.

### 8.4.2. Structure beneath Continental Regions

The recycling of oceanic lithosphere is very efficient. Indeed, the oldest ocean floor that currently resides at the Earth's surface was created in Jurassic times, some 200 million years ago. In contrast, the oldest parts of continents, the Archaean shields, are almost 4 billion years old. Such continental regions may be stable tectonic provinces at the present day, but the continental lithosphere and mantle can be highly heterogeneous, reflecting a long history of reworking. The imaging of continental regions by means of body-wave information is often complicated owing to the absence of sufficient natural sources. Interpretation of surface-wave data generally provides a more efficient means to study intraplate regions characterized by low levels of seismicity, albeit with somewhat lower resolution owing to the larger wavelengths of the seismic waves considered.

Global images of shear-wave structure in the upper mantle derived principally from waveform matching of long-period seismograms (particularly surface waves) supplemented by differential times between the S and SS phases (e.g., Su, Woodward, and Dziewonski, 1994) show high shear-wave speeds associated with the cratonic regions of the continents, extending to depths of 300 km or more, reminiscent of the 'tectosphere' hypothesis of Jordan (1975, 1988). The horizontal extent of such zones can be quite large, extending 3,000 km or more. However, the vertical resolving power of global studies is somewhat limited, and even in the detailed study by Grand (1994) for SH wave structure in the Western Hemisphere, vertical resolution was limited to about 75 km. As a result, it is difficult to resolve any detail in the transition between different continental regions, particularly the character of the transition at depth between the younger parts of continental assemblages and the older cratons.

#### *8.4.2.1. Body-Wave Studies*

Studies of the seismic structure beneath northern Australia have exploited the active seismicity in the seismic belt extending along the Indonesian arc, through New Guinea, and on to Vanuatu, using arrays of seismic stations. Such arrays have allowed dense sampling of the seismic wave field in a limited time and have revealed regional variations in seismic wave structure of about 1% over a horizontal distance of 1,000 km (Dey et al., 1993). These variations are associated with structure at the base of the lithosphere (which occur near 210 km of depth in this region) and within the transition zone.

The use of arrays of stations not only allows determination of radial structure but also provides constraints on the heterogeneity in seismic wave speeds. Kennett and Bowman (1990) have suggested the presence of heterogeneity with about ±1% fluctuations in P-wave speeds on scales of 200–300 km, superimposed on larger-scale variations. This analysis was based on amplitude and waveform variability for individual events recorded in a number of portable-array experiments with different array dimensions and spacings. The scale length is small enough to be difficult to resolve directly (particularly using refracted waves), and this style of heterogeneity may need to be represented in a stochastic manner. The influence of medium- and small-scale heterogeneity is likely to be particularly important for the regions where radial velocity gradients are small, as, for example, in the uppermost mantle, because horizontal velocity gradients can then dominate the behaviour of the seismic wave field (e.g., Kennett, 1993).

Grand (1994) has endeavoured to extend the analysis of S waves and their multiple reflections SS and SSS to provide coverage of three-dimensional structure from the surface down to the core–mantle boundary. The resulting images confirm the differences in the dominant structures between shields and tectonic regions, as summarized in the *sna* and *tna* models of Grand and Helmberger (1984a,b), with the largest differences in structure occurring above 250 km. There are, however, more subtle but persistent variations throughout the upper mantle, even though the degree of heterogeneity is relatively low in the transition zone.

#### *8.4.2.2. Surface-Wave Imagery*

In order to obtain high-resolution images of the shallower part of the Earth, we need to use seismological probes whose sensitivity is greatest in this region. Fortunately, we are able to exploit the surface-wave portion of the shear-wave field, which commonly represents the largest-amplitude portion of broadband seismograms. The fundamental-mode Love waves and Rayleigh waves are preceded by higher-mode surface waves that represent the superposition of multiply reflected S waves interacting with the free surface. The fundamental-mode energy is concentrated near the surface, but the penetration increases as the frequency is reduced because the S wavelength is longer. The higher modes provide both deeper penetration at comparable frequencies and complementary information on shallow structure, because the pattern of sampling is rather different.

The worldwide network of digital seismic stations has now developed to sufficient coverage of the Earth that over a period of years it is possible to achieve good sampling of most of the surface. Trampert and Woodhouse (1995) have used the full available data set to extract the geographical distribution of the phase velocities of surface waves at different periods. This analysis has concentrated on the dispersion of the fundamental-mode Love and Rayleigh waves at frequencies up to 0.025 Hz (40-s period) and shows features that correlate well with the shear-velocity models from earlier studies, whilst attaining higher resolution in many areas.

Much of the analysis of surface waves has been based on the assumption of direct propagation from source to receiver. However, Snieder (1988) has demonstrated that waveform inversion using scattering theory can be used to image off-path features. Laske (1995) has used the anomalies in the direction of propagation of surface-wave trains to constrain three-dimensional structure.

Although global coverage is quite good, the interstation spacing in many areas exceeds 1,000 km on the continents, and there are only a few stations in oceanic areas. In consequence, if the details of the structure in a region are required, there is a need to incorporate additional information, using, for example, deployments of additional portable broadband stations. This approach was employed by Nolet (1990) in a study of structure beneath Western Europe using a linear array (NARS) of 14 instruments extending from Malaga in southern Spain to Göteborg in Sweden. In order to exploit the full information content of the shear-wave field, Nolet introduced the two-step technique of 'partitioned waveform inversion'. In the first step, a nonlinear waveform inversion is performed on individual seismograms in order to determine the averaged shear-wave structure along the great-circle paths between source and receiver; this requires the matching of observed waveforms with comparable portions of theoretical seismograms, synthesized by mode summation. Separate analysis windows are used for the fundamental mode and the higher modes, to improve the vertical resolution of the structure (see Figure 8.6 for an example). The second step is to combine all of the different constraints on the model structure from the different seismograms in a linear tomographic inversion to construct a laterally varying velocity structure. Nolet (1990) used this approach to determine the large-scale structure in two dimensions under the linear NARS array. Kennett and Nolet (1990) have demonstrated that the method is insensitive to the presence of small-scale heterogeneity provided that analysis is restricted to frequencies below 0.15 Hz.

The partitioned-waveform-inversion approach has been been extended by Zielhuis and Nolet (1994) to determine the three-dimensional variation in shear-wave structure beneath Western Europe and has revealed a very strong contrast between the structures on either side of the Tornquist-Teisseyre zone, extending deeper than 200 km. This boundary marks the junction between Phanerozoic rocks to the southwest and Precambrian material to the northeast. The contrast of several percent in wave speed can be discerned in global velocity images, but the regional study achieves a much more effective localization.

Studies in North America and Europe can build on a good basic network of permanent seismological stations, but a rather different approach must be taken for other continents. In Australia, a sequence of temporary deployments of arrays of up to 12 portable broadband seismometers has been used to synthesize a continentwide array (van der Hilst et al., 1994). This project (SKIPPY) has been designed to exploit the high level of regional seismicity along the active plate boundaries surrounding Australia: the subduction zones to the east and north, with very high seismic activity and many deep earthquakes, and the mid-oceanic ridges to the south and west, with shallow and less frequent seismicity (Figure 8.5, top). The sequence of temporary



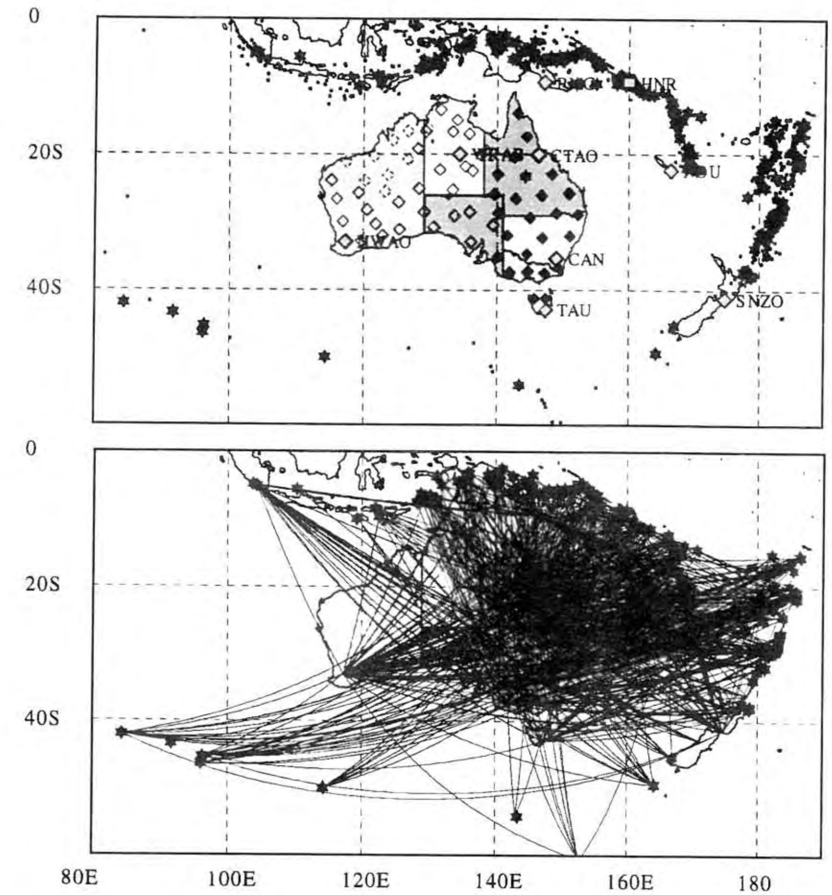


Figure 8.5. Top: Station configuration for the SKIPPY-array deployments relative to the regional seismicity. Bottom: Wave-path coverage for eastern Australia from the SK1, SK2, and BAS deployments.

deployments has led to excellent path coverage (Figure 8.5, bottom), so that it is possible to resolve structural features with horizontal scales of 200 km or more beneath the eastern part of the Australian continent and the oceanic and submerged continental regions between the continent and the convergent-plate boundaries to the north and east. This resolution is substantially better than that of the best current global models (Trampert and Woodhouse, 1995).

The structural analysis has exploited the partitioned-waveform-inversion technique, which is particularly useful for the Australasian region because of the regular occurrence of deep earthquakes beneath the surrounding convergent margins that generate strong higher-mode surface waves. The increased depth resolution that is obtained from the inclusion of higher modes is illustrated by the records of a Vanuatu earthquake at stations in Queensland (Figure 8.6, top). The observed

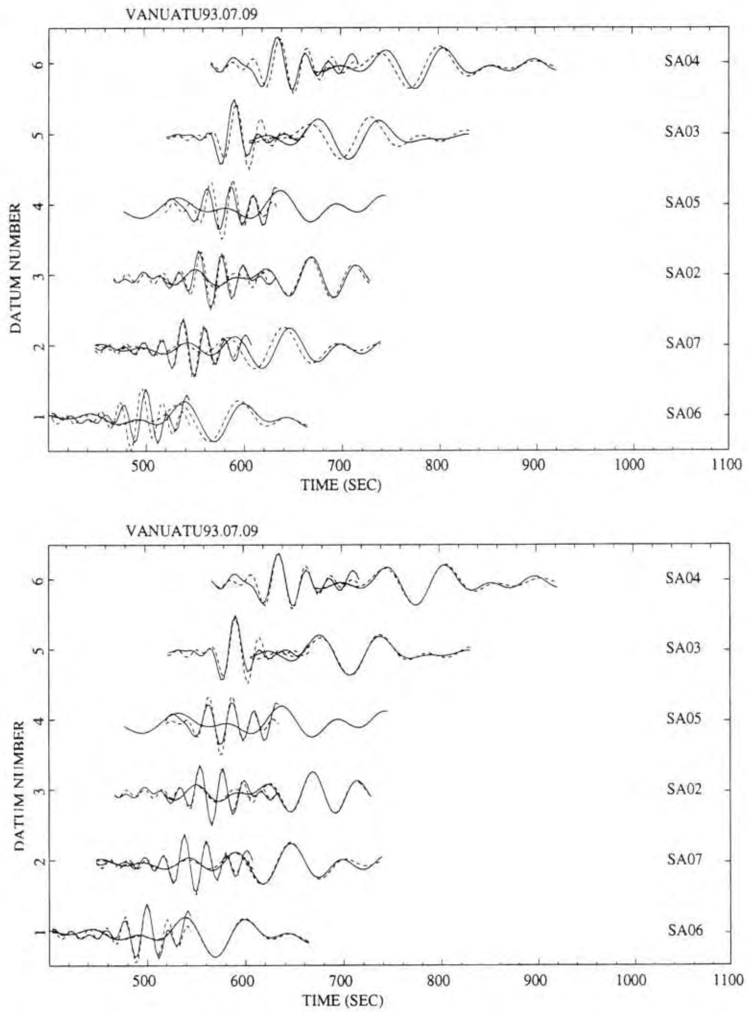


Figure 8.6. Seismogram matching for a Vanuatu event at stations in Queensland, illustrating the advantages of exploiting both fundamental and higher-mode surface waves. The observed seismograms are indicated by solid lines, and those computed from the structural models by dashed lines. Top: Initial fits. Bottom: Waveform matches after adjustment of model (Zielhuis and van der Hilst, 1996).

fundamental mode is slower than predicted, indicating lower wave speeds than in the reference model at shallow depths, but the higher modes are faster, so the wave speeds at depth need to be increased. Once the differences in wave speeds are taken into account to update the velocity model, the observations can be closely matched by theoretical records (Figure 8.6, bottom).

The Australian continent has evolved during a long geological history, with the tectonic processes that have most recently influenced the lithosphere becoming



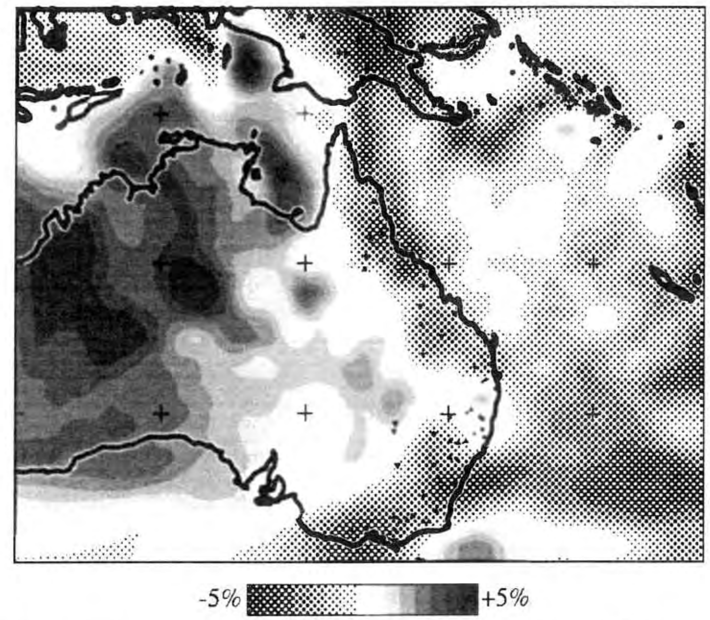


Figure 8.7. Lateral variation of shear-wave speed in the upper mantle beneath eastern Australia and the surrounding region at a depth of 140 km (Zielhuis and van der Hilst, 1996).

younger from west (Archaean) to east (Phanerozoic). Proterozoic cratons form the central part of the continent. The lateral boundaries between the major tectonic divisions are not well constrained, and, in particular, their depth extent is unknown. Waveform inversion reveals large lateral variations in shear-wave speed in the upper mantle beneath the eastern Australian region (Figure 8.7). These findings have been discussed in detail by Zielhuis and van der Hilst (1996) and were obtained by analysis of the waveform data collected at a total of 25 SKIPPY stations in eastern Australia, augmented by data from the permanent observatories operated by IRIS (NWAO, CTAO, SNZO, HNR, PMG, TAU) and Geoscope (CAN, NOU).

The mantle beneath easternmost Australia, and the marginal basins between Australia and the Indo-Australia–Pacific-plate boundary, is marked by a pronounced low-wave-speed anomaly. On the continent, the lateral distribution of these low wave speeds correlates closely with the location of Neogene volcanoes, particularly strongly for seismic structure between 140 and 200 km of depth. This suggests that at least some of the low wave speeds have a thermal origin. Locally, pronounced positive wave-speed anomalies are detected to depths exceeding 200 km, as, for instance, beneath the Paleozoic basement of the New England foldbelt.

Farther to the west, beneath the Lachlan and Adelaide foldbelts, the seismic wave speeds in the upper mantle are significantly higher. The pronounced transition from the low wave speeds in the mantle beneath easternmost Australia to the moderately high wave speeds in the mantle farther to the west is relatively sharp and is well resolved by the data used. Preliminary results indicate that the regions of fast shear-wave propagation related to the central shield in the Northern Territory extend to more than 300 km in depth. However, the precise locations of such anomalies and the boundary between the Proterozoic shields of central Australia and the Phanerozoic basement to the east, the 'Tasman Line', have not been well resolved by the current data coverage (Figure 8.5b). Once additional waveform data from the later deployments covering the rest of the continent (Figure 8.5a) are included, resolution of this boundary and the deep structure of the central Australian cratons will be dramatically enhanced.

## 8.5. Discussion

The rapid development of techniques for estimating three-dimensional structure has changed our perception of the interior of the Earth and has led to a much stronger interaction between seismology and geodynamical studies. However, even the most impressive of the three-dimensional images can explain only part of the available information, and we must be wary in ascribing too detailed an interpretation of structure before the reliability of the images has been fully explored.

As we have noted, most three-dimensional models are derived as perturbations from a spherically symmetrical reference model. In many cases the level of heterogeneity is large enough to suggest that a full three-dimensional analysis is appropriate. The computational tools for simulation of the full seismic wave field in three-dimensional models are just beginning to be developed (e.g., Cummins et al., 1994a,b), and these will be needed to provide direct checks on the models postulated from a simplified analysis.

As the resolution of seismological structure increases, particularly on a regional scale, we will be faced with the problem of interpreting the substantial variations in seismic wave speeds in terms of both the mineralogy and the thermal characteristics of the mantle, because neither alone can provide an explanation for the classes of structures that are beginning to be revealed. Thermal influence may explain much of the large-scale heterogeneity, particularly if the temperature dependence of seismic velocities is greater at seismic frequencies than in the ultrasonic regime, where most laboratory measurements have been made (cf. Jackson and Rigden, Chapter 9, this volume). On smaller spatial scales, the temperature gradients required to match the velocity variations will be difficult to sustain against erosion through thermal conductivity, so that a compositional origin appears more attractive. Previous thermal activity can also leave residual compositional effects. Progress in the understanding of seismic heterogeneity may well depend on resolution of the detail of seismic anisotropy, which, although clearly recognized, is as yet poorly localized (e.g., Tong et al., 1994).



Resolution of many of the outstanding questions about the nature of the structure and related processes in the Earth's mantle will depend on the integration of information from many studies on a wide range of scales, such as, for example, using surface-wave analysis in combination with studies of refracted and reflected S waves to improve resolution of structure in the transition zone to the point where mineralogical questions can be answered directly (cf. Jackson and Rigden, Chapter 9, this volume).

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