Review

On seismological reference models and the perceived nature of heterogeneity

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Abstract

A key ingredient in understanding Earth structure is the integration of seismological information with results from mineral physics for both the dominant radial dependence of material properties and the 3D structure revealed by seismic tomography. In each case an important role is played by reference models for the internal structure of the Earth originally constructed to meet seismological needs. Representations of the travel times of seismic phases are required for the location of seismic events and these have been supplemented by models that match the frequencies of the free oscillation of the Earth, which have played a major role in characterising seismic sources through the centroid moment tensor derived from long-period records. Parameterised models were introduced to combat the computational demands of inversion and have been extensively used; however, in such models (e.g. PREM) the form of the seismic parameters is prescribed to have a functional behaviour, such as a cubic, based on mathematical convenience rather than physical requirements. Any 1D models face the challenge of the significant lateral heterogeneity at the top and bottom of the mantle, as well as the more subtle variations in between. It may well be possible to capture the long wavelength components of 3D heterogeneity, but the nature of available data sources means that it will be difficult to achieve comparable P and S definition for the whole mantle.

In many circumstances reference models are used for comparison with models constructed for different data sets. It is then best that, e.g., a cratonic reference model is used to judge results from cratons. Regionalisation of travel-time observations provides a means of constructing such reference models for a broad range of tectonic environments. When coupled with suitable path corrections it is possible to make a good account of regional 2D variations.

It is desirable that reference models used for interpretation of seismic tomography are tied as clearly as possible to mineral physics results, with a representation based on the bulk modulus $K$, shear modulus $G$ and density rather than just the P and S wavespeeds. Comparator models for different mineral compositions and temperature regimes have the potential to aid the interpretation of tomographic images, particularly in the separation of the influences of temperature and composition.

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1. Understanding Earth structure

Seismic waves provide the major probes for the internal structure of the Earth. The specific trajectories of the different types of seismic waves are controlled by the distribution of natural earthquake sources and the locations of seismic stations, dominantly in continental regions, with high concentrations in regions subject to earthquakes. In consequence about half of the Earth’s mantle is well sampled by direct body waves between source and receiver for P and S, but additional probing is provided by seismic phases multiply reflected at the
Earth’s surface and globe-circling S and surface waves from large earthquakes. The result is strong constraints on the radial distribution of seismic properties in the range between 800 and 2500 km depth, which exclude the zones of strongest horizontal variability. In addition much of the large wavelength variation of shear wavespeed in the mantle is well mapped, but higher resolution is restricted in geographic coverage.

The seismological observations are summarised through reference models, currently dominantly 1D, i.e., specifying seismic wavespeeds as a function of radius. These reference models play a direct role in the location and characterisation of seismic sources, but increasingly are called upon to provide constraints on the internal constitution of the Earth through the reconciliation of mineral physics results derived from laboratory experiments and mechanical modelling.

Thus Mattern et al. (2005) have attempted to infer the composition and temperature profile of the lower mantle by comparison of mineral systems with the radial distribution bulk-sound velocity and density taken from seismic reference models. They have used a five component system (MgO–FeO–CaO–Al2O3–SiO2 with three phases: (Mg, Fe, Al)(Si, Al)O3 perovskite, (Mg, Fe)O magnesiowustite and CaSiO3 perovskite, and find that the inferred conditions depend heavily on the a priori models, pyrolite, a chondrite model and a model based on cosmic element abundance. A somewhat similar approach was adopted by Deschamps and Trampert (2004) to try to constrain lower mantle temperatures.

Although Cammarano et al. (2005a) endeavoured to match certain classes of seismic data (free oscillation periods and some travel times) by direct calculations from mineral physics results, there is still an implicit dependence on seismological reference models through the actual data sets employed. Thus, e.g., the seismic travel times depend on the estimate of the hypocentre of the events that is extracted using a reference model.

In addition to the dominant radial variation in properties, there is pervasive 3D heterogeneity in the mantle and this is almost universally represented as deviations from 1D seismic reference models (see, e.g., Kennett et al., 1998; Megnin and Romanowicz, 2000; Montelli et al., 2004). The use of perturbations from a reference model can provide strong conditioning on perceptions of behaviour. However, some features such as the anti-correlations of bulk-sound and shear wavespeed variations at the base of the mantle (e.g. Masters et al., 2000) are robust and not dependent on the choice of reference.

Nevertheless interpretation of 3D perturbations has been attempted (Deschamps et al., 2002; Deschamps and Trampert, 2003; Karato and Karki, 2001) particularly with a view to separating the influences of composition and temperature. The choice of reference can be influential on assessments of, for example, ratios of perturbations. The changes in seismic wavespeed expected from chemistry and temperature are different and can even work against each other to diminish wavespeed anomalies (Kellogg et al., 1999).

Efforts to work on the temperature distribution in the upper mantle (Cammarano et al., 2003, 2005b) are limited by the representative role of 1D reference models in this region with strong horizontal variability.

2. Seismological reference models

The first class of seismological reference models was developed in the context of interpreting the arrival times of seismic phases. A variety of different travel-time tables were developed, with increasing sophistication, culminating in the tables of Jeffreys and Bullen (1940). These results were presented as a set of travel time for many different classes of seismic phases at a limited number of depths. Only the P and S times were derived directly from observations and the remainder were computed, by hand-cranked calculator, from a summary earth model. The observed travel times were assembled from a number of disparate sets of well-constrained data; crustal propagation was taken from Europe, data for the upper mantle from Japan and only deeper in the mantle was there any global coverage. Despite their known deficiencies, in particular in the times of core phases, the Jeffreys–Bullen tables have been the mainstay of earthquake location procedures for over 50 years.

Once a significant number of observations had been made of the free oscillations of the Earth, a new class of models for P, S wavespeeds and density were developed to provide a match to observations. The 1066A, 1066B models (Gilbert and Dziewonski, 1975) invoke different styles of representation of the upper mantle (without or with wavespeed discontinuities), since this region is only moderately constrained by the normal mode data.

The next step was to develop models to explain both travel-time and free-oscillation data; the challenge of the computational demands of the inverse problem led to the introduction of parametric models (Dziewonski et al., 1975). With a representation of seismic wavespeeds and density in terms of polynomials in normalised radius, the spherically averaged Earth could be defined by a limited number of polynomial coefficients. The highest order of polynomial used was cubic and single polynomials were employed for substantial regions, e.g., the entire outer core.
This class of representation was carried further by Dziewonski and Anderson (1981) in the preliminary reference earth model (PREM), in which transverse isotropy of seismic wavespeeds is introduced in the top 220 km of the mantle to reconcile Love and Rayleigh wave observations. The PREM model is based on normal mode, travel time and differential travel time data, with an allowance for the frequency dependent wavespeeds induced by anelastic attenuation. For travel times, the velocity model needs to be used in conjunction with the tabulated corrections for different seismic phases.

A similar parametric representation was also used in the IASP91 model of Kennett and Engdahl (1991) that was designed for the direct representation of high-frequency (1 Hz) travel times. Rather than use an auxiliary table, with interpolation, direct computation provides phase times for any depth of event. The procedure is made very efficient by using the intermediary of the tau-spline representation (Buland and Chapman, 1983), which allows rapid extraction of times for a specified epicentral distance.

The IASP91 model has greater compatibility between the main seismic phases, such as P, and their associated surface reflections (pP, SP) than the Jeffreys–Bullen tables, and so the depth of events can be improved in the location process. With a relocation of events from the Bulletin of the International Seismological Centre, a new set of empirical travel-time tables was developed and then inverted to produce an updated model (AK135, Kennett et al., 1995). The AK135 model is not parametric but represented instead as a sequence of linear gradients in radius. A difficulty faced when trying to produce such a model is the balancing act between not fully consistent information. Any 1D reference model such as AK135 is thus a compromise and will reflect the geographical biases of the original set of observations. The AK135 model has, however, proved to be very effective for event location and the identification of later seismic phases. Engdahl et al. (1998) have used an iterative process of successive event location and phase identification for both P and S phases, using the AK135 model, to produce a comprehensive catalogue of well-located events that has since been regularly updated.

Morelli and Dziewonski (1993) in their travel-time model SP6 took a somewhat different approach and tried to compensate for geographical bias to produce a truly spherically averaged structure. This means that the velocity model needs to be accompanied by a systematic set of travel time corrections to provide the passage times for particular source-receiver paths.

3. Construction and use of seismological reference models

Reference models permeate seismological usage, they are invoked explicitly or implicitly when an event is located, when seismograms are interpreted and in the construction of tomographic models. It is therefore important for the mode of representation of such a model to take into account the ways in which it is likely to be employed:

- **Source characterisation.** Travel time or derivative computations for a reference model lie at the core of location procedures for seismic events, and source mechanism inversions depend on Green’s function calculated for a specific model, the model used should be representative of the actual structures encountered for the data employed.

- **Phase interpretation.** Seismic phase information needs to be identified so that it can be employed in a location scheme and this will normally be done with an approximate hypocentre and arrival time calculations for likely candidate phases in the reference model.

- **Model comparison.** A common question is whether a model extracted from new data shows any unusual features, comparison with a suitable reference model can help answer this question.

- **Migration and inversion.** Reference models are frequently used as a basis from which 3D heterogeneity is estimated, e.g., by some class of iterative linearised inversion in tomography or by migration of paths as in studies of upper-mantle discontinuities using receiver functions.

- **Display of information.** An important role for reference models comes in the display of 3D structure; variations and properties are often more easily recognised through deviations from a 1D model than from absolute seismic velocities.

3.1. Nature of reference models

It is highly desirable that any reference model is conservative in the introduction of distinctive structure, since any prominent feature will be carried into comparisons, inversions and displays as with the large velocity jump at 220 km in the PREM model (as can be seen in the velocity profiles (Ekström and Dziewonski, 1998) derived in analysis of anisotropic structure in the northern Pacific).

Although 1D models provide the convenience of rapid evaluation of travel times and theoretical seismograms, they are inevitably limited by the 3D nature of the real Earth. Global 1D models, such as PREM, AK135 cannot
represent the significant lateral heterogeneity at the top and bottom of the mantle, or the more subtle variations in between (Fig. 1). They will therefore have a summary value in the regions of greatest complexity and need supplementation to account for 3D effects. It may well be possible to capture the long wavelength components of 3D heterogeneity in a more sophisticated 3D reference model that is yet to be developed, but still corrections will be needed for the shorter wavelength components of mantle heterogeneity.

For location purposes at regional distances the variations in crustal and uppermost mantle structure can be largely compensated by the inclusion of appropriate path corrections (see, e.g., Yang et al., 2001, 2004; Bondář et al., 2004). However, the influence of such structure on amplitudes cannot be handled so easily. A significant component of the variability for teleseismic events can be suppressed by introducing station corrections in arrival time to compensate for upper mantle structure. For seismic arrays, further corrections can be made for the deviations of the propagation paths from that expected for the reference model by modifying the slowness and azimuth of the arrivals (Bondář et al., 1999).

A significant problem for the construction of any class of global reference model is that it is difficult to achieve comparable definition of the P and S wavespeed distributions. In 1D models, e.g., the P wave structure in the outer core is dependent on knowledge of the S wave structure in the mantle since only the phase SKS provides full sampling up to the underside of the core–mantle boundary. The large drop in seismic velocity for P waves between the mantle and core means that the AB branch that has the shallowest paths only has turning points in the mid outer-core or below.

In 3D studies the differences between P and S wave studies are more marked in the mantle (see, e.g., Antolik et al., 2003). The primary source of P wave data comes from arrival time data form bulletins whose sampling of the Earth is limited by the distribution of natural sources and stations. A certain amount of moderate frequency data has been measured using cross-correlation techniques, but this data set is much smaller than the bulletin data. As a result extensive P wave sampling is only available for about half the mantle. For S waves, data is available from a variety of sources at longer periods. Thus constraints on the S wavespeed distribution come from the splitting of normal modes, waveform matching and global surface wave tomography. The matching of long-period waveforms also provides a limited control on P wavespeed. The long-period S information is supplemented by body wave travel times measured using cross-correlation techniques to produce both absolute S times and relative times, e.g., SS-S. There is also structural information in the reported S wave arrivals from bulletin data, but the quality of the picks are significantly lower than for P, and are likely to have been made on lower frequency onsets.
The differences in both the quantity and the frequency ranges for P and S waves pose significant problems for utilising a wide range of data at one time. There is immediately a heavy reliance on corrections, such as that for the velocity dispersion due to attenuation. This dispersion correction must be viewed as having an effective direction from low to high frequency, at least with regard to the use of a $Q$ model. At 1 Hz, $Q$ measurements will include both intrinsic and scattering $Q$, but the dispersion applies only to the intrinsic component.

A further complication comes from the uneven geographic distribution of data. Whereas S wave information is available from globe circling paths; P wave information, dominantly from travel times, is dictated by location of seismic sources and receivers. It is not appropriate to compare full global coverage from S in a spherical harmonic expansion with results derived from much more limited geographic coverage for P, since there is real potential for artefacts especially for higher order expansions.

In principle we can derive a significant increase in understanding of Earth structure if we can use both P and S information. It is convenient to work in terms of S wavespeed

$$
\beta = (G/\rho)^{1/2},
$$

(1)

depending on the shear modulus $G$ and density, and the bulk-sound speed $\phi$ derived from both P wavespeed $\alpha$ and S wavespeed $\beta$,

$$
\phi = (\alpha^2 - 4\beta^2)^{1/2} = (K/\rho)^{1/2},
$$

(2)

which isolates the bulk modulus $K$. Such a style of parameterisation has been employed in a number of tomographic studies (Kennett et al., 1998; Masters et al., 2000; Su and Dziewonski, 1997; Gorbatov and Kennett, 2003), in which inversion has been undertaken directly for the bulk-sound and shear wavespeed; differencing P and S wavespeed images produces many artefacts in the bulk-sound distribution.

Since any construction of the bulk-sound and shear wavespeed distributions will involve an implicit combination of P and S wave data it is very desirable that the data sets used have comparable geographic coverage for P and S, even if this means that only a subset of the information is employed. This was the approach adopted by Kennett et al. (1998) and Gorbatov and Kennett (2003), who employed arrival times for paths with common source and receiver for P and S. The size of the data set is reduced substantially, but the quality of picks is likely to be higher and there is comparable resolution in the P and S datasets.

Hitherto, reference models have been focussed on P and S wavespeeds and secondary properties such as the bulk-sound speed $\phi$ have been derived from these distributions. As a result discrepancies can arise, e.g., in the AK135 model just below 660 km the gradients in P and S velocities are not compatible so that the bulk-sound speed has a different inflection at 760 km to the P and S wavespeeds. Such difficulties can be avoided if the full range of applications is considered at the time the model is constructed.

The structure in the top 200–300 km of the mantle show a strong correlation with surface geology and this has lead to a variety of schemes to try to estimate regionalised structure as a way of extracting the dominant signal of lateral heterogeneity in the lithosphere. Initial efforts were focussed on surface waves (e.g. Knopoff, 1972) but subsequently extended to body waves, e.g. Gudmundsson and Sambridge (1998) used a restricted data set of well-located events in a regionalised tomography scheme, with S tectonic styles and detailed models of subduction zone structure.

The significance of the degree of variability in this region can be seen from Fig. 2, based on a regionalisation exploiting the full phase set from the reanalysis of the ISC data set (Kennett et al., 1995) The group of illustrated models have been derived by analysis of the residuals from the AK135 model used to relocate the events, for sources and receivers within an individual tectonic type. The models are indicative of the deviations from the global reference model and indicate that the linear gradient in radius employed between 210 and 410 km depth in the AK135 model is too simple to represent the behaviour for the real Earth. Such models are of benefit in providing direct representations of continental/oceanic regimes and as a basic for comparison in the analysis of, e.g., cratonic structure.

3.2. Use of reference models

Reference models currently play a major role in the determination and presentation of tomographic images of 3D structure. In simple linearised delay-time tomography, or current work with allowance for finite-frequency effects (Montelli et al., 2004), the analysis is made directly in terms of determining perturbations from a reference model. Even where an iterative non-linear approach is employed for arrival time tomography, including 3D ray tracing (see, e.g., Gorbatov and Kennett, 2003; Widiyantoro et al., 2000) the final model is presented in terms of perturbations from the AK135 reference model. Models for global structure using long-period waveforms or free-oscillation splitting
measurements are also derived as perturbations from the PREM model (e.g., Megnin and Romanowicz, 2000; Masters et al., 2000). Only limited progress has so far been made with direct construction of refinements to an initial 3D model (Hara, 2004).

A commonly used regularisation technique in tomographic inversion is to use model damping to limit excursions from the starting model. In situations where there are strong contrasts in structure, such as the juxtaposition of oceanic and shield structures in surface wave work as in Western Australia (Fishwick et al., 2005), such damping will not match either structure and so tend to underestimate the true wavespeed variations.

Considerable effort has been expended in recent years to exploit the analysis of ratios of wavespeed properties to establish links with mineral physics (see, e.g., Karato and Karki, 2001). What we would like to unravel are the competing influences of temperature and composition, and the ratios of perturbations in P and S wavespeed or bulk-sound and S wavespeed provide important informa-
tion. The theoretical development is based on quantities such as

\[ \frac{\partial \ln \phi}{\partial \ln \beta} = \frac{\delta \phi/\phi}{\delta \beta/\beta}. \]  

(3)

under the influence of variation of a single physical parameter such as temperature. It is tempting (as in the work of Kennett et al. (1998), Masters et al. (2000), and Karato and Karki (2001)) to assume that the relative perturbations can be taken directly from a joint tomographic inversion derived from both P and S wavespeeds. However, these perturbation estimates will carry the imprint of their reference model; the estimate of the ratio is provided by

\[ \frac{\partial \ln \phi}{\partial \ln \beta} = \frac{\phi - \phi_0}{\beta - \beta_0} \cdot \frac{\beta_0}{\phi_0}. \]  

(4)

Only if the mineral physics results refer to the same reference state can we expect direct correspondence. More reliable information is afforded by the ratios of absolute wavespeeds, even though these are not as immediately amenable to theoretical analysis. Further when we seek to extract variations in the elastic moduli for comparison with ab initio calculations at lower mantle conditions (see, e.g., Brodholt et al., 2002) we need to know the relative variations in density, which are very poorly constrained.

The ratios of tomographic quantities are spatially dependent, and so summary properties, such as root-mean-square (r.m.s.) variations are frequently constructed as a function of radius. Such quantities cannot be directly compared to mineral physics estimates because the ratio of averages is not equivalent to the average of ratios, although this was assumed by Karato and Karki (2001).

A substantial effort has been made in recent years to map properties of the upper mantle using receiver function information (e.g., Li et al., 2000; Dahl-Jensen et al., 2003). With closely spaced stations corrections are made for the spatial pattern of sampling that depend on the reference model employed. Further, the interpretation of the depths of discontinuities (both absolute and relative) from receiver function studies depends on the velocities in the reference model. We would expect both a cold transition zone and one with water present to have a larger separation between the depths for the 410 and 660 km discontinuities, but the intervening zone would be characterised by faster seismic wavespeeds for temperature and slower wavespeeds for wet mantle. Without direct constraints on transition zone velocity the “wet” case is likely to be misinterpreted as close to normal.

4. Alternative styles of models

In the previous sections we have discussed the character and use of current reference models, which include applications hardly envisaged when these models were constructed. How might we improve reference models in the light of the many different demands being placed on them?

It is particularly important that the representation used for any reference model should not overly prescriptive, the parameterisation needs to be driven by the likely physics rather than just by mathematical convenience.

A range of attempts have been made to extract temperature and compositional information from regional results and reference models such as PREM or AK135 (Deschamps and Trampert, 2004; Cammarano et al., 2005a,b, 2003). Although it appears that the AK135 model does not lie too far from the 1300 °C adiabat for a pyrolite mantle from 100 to 800 km, the choice of linear gradients in radius for the P and S velocities between knot points in AK135 means that close agreement with a thermal model is unlikely. The present knowledge of mineral physics parameters and derivatives, means that it is difficult to separate compositional and temperature effects in the contrasts in seismic wavespeeds revealed in tomographic images, since these also carry the imprint of reference models. It would be highly desirable if tomographic results were represented in terms of absolute wavespeeds; even though presentation may be through perturbations from a display reference model, which does not have to be the same as that used in construction of the tomographic image.

It is therefore important that we have a class of reference models that refer directly to the information that can be extracted experimentally, and computationally, for the conditions appropriate to the Earth’s mantle that will be suitable for analysis of tomographic results. For such models we need to start afresh from a physical formulation, i.e., from the elastic moduli \( K, G \), and density \( \rho \) rather than the P and S velocities. Polynomial representations of the moduli and density with radius can be justified as a reasonable approximation to the behaviour expected from finite strain theory. The squared seismic wavespeeds are then obtained from the ratio of two polynomials; such a Padé approximant provides considerable flexibility in representation and avoids the restrictions on radial velocity gradients imposed by polynomial forms for the wavespeeds themselves. A physical representation has the additional merit that the explicit use of the moduli and density requires embedded assumptions to be imposed directly, such as an adiabatic gradient structure, rather than be carried over from previous models.
The range of moduli can also be expanded, as appropriate, to include anisotropy. Such a physical parameterisation of a seismological model would be complementary to the efforts to extract such parameters as composition and temperature from seismic data (Mattern et al., 2005; Deschamps and Trampert, 2004; Cammarano et al., 2005a).

We have already seen that we need to be able to make corrections for the influence of intrinsic attenuation to make simultaneous use of seismic information obtained in different frequency bands. This can readily be achieved in the $K$, $G$, $\rho$ formulation by the use of complex moduli in the frequency domain. In general the intrinsic attenuation associated with bulk compression is small and only a minor correction to $K$ is needed; the exceptions come in multi-phase environments with the presence of melt or free water. The major complex component is therefore associated with the shear modulus $G$. As pointed out by Gribb and Cooper (2000) and reinforced by a more comprehensive analysis (Jackson et al., 2002), the shear modulus $G$, and particularly its associated attenuation, is notably affected by temperature well before solidus melting conditions are reached. The behaviour is strongly non-linear in temperature with a rapid decrease in the modulus $G$ and associated $Q_G$ for higher temperatures. The temperature derivatives for the wavespeeds are therefore strongly temperature dependent. Some allowance has been made for this effect in analysis of tomographic images in terms of temperature (Goes and van der Lee, 2002) based on a mapping of $Q$ behaviour (Karato, 1993), but may well underestimate the strong contribution at near-solidus temperatures.

Even the best of reference models is not the Earth! The summary of behaviour in a 1D model carries with it geographic sampling and averaging issues specific to the parameterisation. For example, the sensitivity of the shear wavespeed to temperature means that the temperature inferred from the average shear wavespeed will be lower than the equivalent averaged temperature. Since P wavespeeds are less temperature sensitive, there is likely to be some difficulty in reconciling P and S wavespeeds simultaneously in regions with large temperature variations (this may well be a cause of the strong anti-correlation of apparent bulk-sound speed and shear wavespeed anomalies in orogenic belts (Kennett et al., 1998)).

Many aspects of what we would like to know about the Earth are not readily summarised in the properties of a reference model where, e.g., the assigned feature at a discontinuity is likely to be very simple. Also, many significant constraints on Earth structure are derived from rather specific class of observations and need to be applied for the frequency ranges where they were determined, e.g., the results (Shearer and Flanagan, 1999) on low contrasts for underside reflection of PP precursors at the 660 km discontinuity apply to long-period waves (see also Kennett, 2002).

5. Discussion—comparator models

Experimental and computational studies have dramatically expanded our knowledge of materials at conditions relevant to Earth’s mantle. There are still uncertainties in the nature of the mineral assemblages (Mattern et al., 2005; Cammarano et al., 2005a), in the role of minor constituents such as calcium and aluminium in the dominantly ferromagnesian silicate lower mantle (Caracas et al., 2005), and in the role that might be played by spin transitions in iron (Li et al., 2005). Knowledge is better for elastic moduli than for their derivative with respect to either pressure or temperature that play an important role in equation of state formulations (Stacey and Davis, 2004).

With current knowledge of mineral physics properties it is difficult to interpret seismological models directly, particularly since potentially significant effects of minor constituents are not well characterised (Mattern et al., 2005; Jackson and Ridgen, 1998). For the lithosphere, the olivine component has been well studied, but the pyroxenes are less well known. In the lower mantle, the influence of calcium and aluminium perovskites could have significant effects on physical properties.

It is therefore worthwhile to develop a range of comparator models, based on well defined mineral compositions subject to different temperature regimes, and examine the level of correspondence with seismological results.

A venture in this direction is the work of Faul and Jackson (2005) based on experimental results for the shear properties of synthetic olivine aggregates as a function of temperature for different grain sizes. Both shear wavespeed and attenuation have been used to develop a representation of the experimental results, based on a Burgers model with a band of relaxation times. This multi-parameter model can then be adjusted to fit a shear wave profile as a function of depth through variation of the temperature profiles, particularly the confluence with the adiabat, and the grain size profile, with an increase in grain size as the adiabat is approached. Fig. 3 illustrates the correspondence that can be achieved between such an olivine model and vertical profiles through a 3D shear wavespeed model for the Australian region, derived from surface-wave tomography (Fishwick et al., 2005). The profiles represent averaged properties for regions with...
Fig. 3. Comparison of vertical profiles through the 3D model of the Australian region derived from surface-wave tomography by Fishwick et al. (2005), with physical models based on the properties of olivine from the work of Faul and Jackson (2005). The black dashed line is the 1300°C adiabat (Courtesy of U. Faul and I. Jackson).

distinct wavespeed character, and the parametric fits suggest that there is substantial variation in upper mantle temperatures through the region. The pure olivine model does not allow for the presence of the pyroxenes that are an undoubted component of the lithosphere, nor does it include any dependence on iron content. Nevertheless, it does provide an estimate of temperature derived from a clear set of assumptions.

If we had several different physical models based on different assumptions or experimental results we could compare the estimates of, e.g., temperature in the lithosphere. The estimates from an ensemble of models would then provide an effective measure of uncertainty.

We can envisage extending the use of such physically based models to derive a new class of regionalised models to supplement those illustrated in Fig. 2. With models parameterised by mineral composition and temperature profiles we would be able to interpret tomographic images in terms of different comparator systems and hence gain further insight into the nature of seismic heterogeneity.

Table 1 provides a summary of the classes of information that are available for generating suitable comparator models for many parts of the mantle. For regions such as the lower mantle where we rely on indirect inference, it is important to test standard hypotheses that may have originally been introduced for reasons such as computational convenience that do not apply today. For example, Kennett (1998) has demonstrated that although the assumption of an adiabatic gradient in density in the lower mantle is compatible with current seismic data on the free oscillation frequencies of the Earth, it is not required by that data. Indeed geodynamic modelling suggests that a purely adiabatic profile in the mantle is somewhat unlikely; and Mattern et al. (2005) infer sub-adiabatic gradients in temperature for a variety of styles of mineralogical models.

The traditional seismological representations of Earth structure have many valuable functions, but are not necessarily the most useful for extracting information on the physical properties of the deep Earth. Mineral physics results still have many ambiguities and detailed knowledge of shear modulus behaviour is scarce. We can recognise these limitations and work with them by developing physically based comparator models, based on different sets of assumptions, to provide measures of the uncertainties in such important quantities as temperature, or the influence of major element chemistry. By linking different ways of interrogating the Earth we will be in a better position to refine our understanding of the geodynamics of our planet.

Acknowledgements

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Table 1
Summary of information sources for relating physical parameters and seismological results

<table>
<thead>
<tr>
<th>Type</th>
<th>Lith–Asth</th>
<th>TZ–UM</th>
<th>TZ–LM</th>
<th>Lower mantle</th>
<th>$D^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Composition</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>2. Thermal</td>
<td></td>
<td></td>
<td>Adiabat?</td>
<td>Adiabat?</td>
<td>Adiabat?</td>
</tr>
<tr>
<td>3. EOS</td>
<td>exp.</td>
<td>exp.</td>
<td>exp.</td>
<td>Ab initio effect of A12O3?</td>
<td>?</td>
</tr>
<tr>
<td>4(a). $G(P,T)$</td>
<td>exp.</td>
<td>exp.</td>
<td>Indirect + ab initio</td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>4(b). $G, Q^{-1}(\omega)$</td>
<td>exp.</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>??</td>
</tr>
</tbody>
</table>

/: models readily constructed from existing information; exp.: topics for which experimental information is developing; Lith–Asth: lithosphere and asthenosphere; TZ–UM: transition zone and upper mantle; TZ–LM: transition zone into upper part of lower mantle.
and sharing of world-wide seismic data, in particular the catalogues of phase arrival times maintained by the International Seismological Centre and the archive of seismic waveforms sustained by the IRIS Data Management Center in Seattle.

References


