Elucidating the nature of mantle heterogeneity

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Abstract. The primary source of information on heterogeneity within the Earth comes from seismic tomography. A powerful tool for examining the character of heterogeneity comes from the comparison of images of bulk-sound and shear wavespeed extracted in a single inversion. However particularly in such multi-parameter inversions there are many hidden facets which can have a strong influence on the results, such as the weightings between parameters and in the misfit functions. Joint inversion with restricted data sets giving comparable cover for P and S waves provides useful checks on more inclusive studies, and can provide relatively high resolution in some areas. The relative behaviour of bulk-sound and shear wavespeed can provide a useful guide to the origins of heterogeneity both in the deep mantle and in subduction zone studies.

1 General Considerations

Although substantial progress has been made in the delineation of three-dimensional structure within the Earth, we are still some way from being able to understand the provenance of the heterogeneity.

Tomographic inversions for a single wavetype can help to provide control on the spectrum of heterogeneity but do not give any direct information on the underlying causes. The current generation of images of S wave structure provide a good definition of low order heterogeneity across the globe and for both P and S there are indications of relatively rapid variations in seismic wavespeed for parts of the mantle. However the disposition of natural sources and available receivers does not provide good sampling for body waves for nearly half the mantle.

Each of the main sources of information to be used in seismic tomography have a clear bias towards one of the major wave types:

(a) For longer periods where seismograms are represented in terms of a superposition of normal modes, the main information is for S wavespeed structure derived from free oscillation splitting, waveform matching or global surface wave tomography. There is a limited dependence on P wavespeed structure available through waveform analysis including some P phases. The PREM model (Dziewonski & Anderson, 1981) is the common reference model for this work.

(b) At intermediate periods, body wave travel times have been measured using cross-correlation techniques to produce both absolute S times and relative times e.g. SS-S. The comparable P wave data set is somewhat smaller. There are some outstanding issues about the baseline for this class of data, since PREM is used in to create necessary synthetic seismograms but other corrections are made.

(c) A short periods, using arrival time information from bulletins, P wave data dominate both in quantity and quality. There is structural information in the reported S wave arrivals but the quality of the picks are significantly lower, and are likely to have been made on lower frequency onsets. In recent work the AK135 model of Kennett el al (1995) has often been used as a reference.

The differences in both the quantity and the frequency ranges for the two wave types poses significant problems for utilising a wide range of data at one time. We become heavily reliant on corrections such as that for the velocity dispersion due to attenuation. This 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, since there is real potential for artifacts especially for higher order expansions.

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

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

depending on the shear modulus and density, and the bulk sound speed ϕ derived from both P wavespeed α and S wave speed β

$$\phi = (\alpha^2 - \tfrac{4}{3}\beta^2)^{1/2} = (\kappa/\rho)^{1/2}, \tag{2}$$

which isolates the bulk modulus κ. This style of parameterisation has been employed by Su & Dziewonski (1998), Kennett, Widiyantoro & van der Hilst (1999) and Masters et al (1999). Ideally in the future it may also be possible to obtain independent estimates of the 3-D variation of density which is a topic of active investigation (Ishii & Tromp, 1999; Kuo & Romanowicz, 1999; Masters et al 2000)

Since any construction of the bulk-sound and shear wavespeed distributions will involve and 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, Widiyantoro and van der Hilst (1998) who only used arrival times for paths with common source and receiver for P and S. The size of the data set is reduced substantially but there is comparable resolution in the P and S datasets (and by implication the bulk-sound speed information).

When standard methods of linearised inversion are used to extract multi-parameter models care needs to be taken with the relative weighting of the different aspects of the model. It is for example possible to down weight one set of parameters such as the bulk-sound speed so that most of the data fit is taken up by shear wavespeed; in which case the reliability of a bulk-sound image will be significantly reduced. Iterative approaches are available to put different parameter classes on a similar footing (Kennett & Sambridge, 1998) and the two parameter class version was used by Kennett et al (1999). A similar issue arises with the relative weight placed on different data-sources when assessing misfit. The resulting model can depend quite noticeably on the the choices for the misfit function and parameter weights and also on the nature of the regularisation term applied.

The use of some classes of data brings with it implicit assumptions about the nature of the underlying model. For example the use of SKS arrival times or S-SKS times assumes homogeneous properties at the top of the outer core and a knowledge of P velocity structure in that region, which cannot be obtained from P data alone because of the caustic in PKP.

Another source of influence in linearised inversion comes from the nature of the reference model used for partial derivative calculation. The 220 km discontinuity in the PREM model is a major feature; yet continuity of wavespeed is normally assumed across the boundary so that no change in the parameter jump at 200 km is allowed. When inversion is carried out for bulk-sound speed we need also to recognise that the reference values are themselves a derived quantity, susceptible to minor differences in the representation of P and S models. For example, just below the 660 km discontinuity in the AK135 model, the P and S models appear to have similar properties but there is sufficient difference in the gradients that ϕ is almost constant rather than having similar gradients to P or S wavespeed.

We also need to beware of the influence of reference models in display. Subduction zones are certainly recognisable in images because they are fast compared with their surroundings but this does not mean that they are automatically fast compared to the refence model. Both the Caribbean and New Caledonia slabs show little difference from the P wavespeeds of the AK135 model but are still fast compared to local structure.

2 Joint Inversions

When information is available for two classes of wavespeed we are in a position to ask very different questions than when interpreting images for a single wavespeed. We can for example ask how much of the variation in P wavespeed can be explained solely by variations in shear?

When we work with the bulk-sound speed we are closer to experimental information since diamond-anvil work provides direct constraints on the properties of the bulk modulus. By contrast our knowledge of the properties of shear modulus at high pressures is very limited. For conditions at the base of the mantle *ab initio* calculations can be attempted for mineral assemblages, but the thermal properties represent a challenge to computational techniques.

Despite the limited knowledge of the details of the properties of the shear modulus we would anticipate a broadly similar response to that for bulk-modulus. Thus if both bulk sound speed and shear wavespeed show a common variation we can anticipate a common cause (mostly likely thermal). However when there is little correlation between bulk-sound speed variation and shear wavespeed or even negative correlation we would expect effects other than thermal to be at work. Just above the core-mantle boundary the variations in shear wavespeed and bulk-sound speed in a number of different studies are anti-correlated (Su & Dziewonski 1998, Kennett et al, 1998; Masters et al, 1999) and it is likely that this arises from chemical heterogeneity. at shallower depths

Joint inversions have been carried out using a wide assortment of seismic phases (Su & Dziewonski, 1997; Masters et al, 1999), and as we have noted above it is difficult to judge how the selection of data may influence the inversion. Whereas, if inversions are carried out with restricted data sets with common P and S coverage, we can be confident of comparable resolution. The restricted inversions can then have an important dual role, both in providing checks on the more inclusive inversions and in yielding locally higher resolution. The variance reduction achieved in the restricted inversions is comparable to that in an S inversion alone.

The global study of Kennett et al (1998) has shown that the variations in bulk-sound speed near 2000 km depth are rather weak confirming the results of earlier work by Robertson & Woodhouse (1996) obtained by independent inversion of P and S data. Between 2100 km and the core-mantle boundary the amplitude of variation of both bulk-sound speed and shear wavespeed increase with little correlation between the two. This change in the nature of the relative behaviour of the two wavespeeds was one of the lines of evidence invoked by Kellogg, Hager & van der Hilst (1999) in their model of a dynamic, hot zone at the bas of the mantle with an intrinsic density increase almost balanced by thermal effects.

The orogenic belts of southeastern Asia and the western USA show substantial differences between the bulk-sound speed variation and shear wavespeed properties. The strong low velocity anomalies in the shear wavespeed images may indicate the presence of volatiles in addition to elevated temperatures. However the apparent wavespeeds could be influenced by the low Q in these tectonic regions, which would both make the the S arrivals more difficult to pick and increase the frequency differential between P and S waves. If the frequency differences are too large, the assumption in the joint inversion that the P and S wave arrival time data can be treated on an equal footing is suspect.

Joint inversions can also provide useful information in a more local environment as in the work of Widiyantoro, Kennett & van der Hilst (1999) on the subduction zones of the northwest Pacific. Substantial difference between P and S wave tomographic images for the portions of subducted slabs lying horizontally on top of the 600 km discontinuity suggest that the bulk modulus may have have an important role in the control of the deformation of subduction zones. The anomalies occur in northern Izu-Bonin and the Tonga regions where there is evidence of trench retreat, which has perhaps modified the conditions of slab emplacement. Nevertheless there is some indication of direct slab penetration in the S wave images. Such results raise interesting questions and suggest benefits in a closer attention to S wave arrival time data across a range of frequencies.

3 References

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