

The influence of 3-D structure on seismic wave propagation at regional and teleseismic distances

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Abstract

Three-dimensional heterogeneity is pervasive in the Earth on a wide variety of scales. The aim of this project is to improve understanding of the influence of lateral variations in structure in the upper mantle on wave propagation at regional to far-regional and teleseismic distances.

At regional scales we have investigated how to map the seismic velocity structure of a region exploiting records from natural events as a model for upgrading the knowledge base for verification studies. The primary focus of this aspect of the work is on the use of waveform inversion for surface waves (including higher modes) to determine three-dimensional shear wave structure, but receiver function studies of crustal structure and P wave tomography can be achieved with the same data. A set of deployments of portable broadband instruments in Australia have demonstrated how detailed knowledge of crustal and lithospheric structure can be built up by combining specific experiments (of about 6 months duration) with information available from permanent seismic stations.

For global studies we have parametrized heterogeneous structures using a flexible interpolation scheme based on Delaunay tetrahedra. This approach is being applied to the construction of regionalized models of the upper mantle by inversion of travel times from selected events. The resultant three-dimensional model will be suitable for the prediction of wave propagation characteristics, such as travel time corrections for a wide range of seismic phases.

These studies are designed to contribute to the support of a verification regime for a CTBT by providing improved knowledge of regional structure in different tectonic environments and developing representations of 3-D structure which can be used to aid in, for example, improved event location and characterisation.

Keywords

Regional structure, surface wave inversion, mantle heterogeneity, travel times.

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1 OBJECTIVE

Three-dimensional heterogeneity is pervasive in the Earth on a wide variety of scales. The objective of this project is to understand the influence of lateral variations in structure in the upper mantle on wave propagation at regional to far-regional and teleseismic distances.

There are two main facets to the research. The first is an exploration of how to map the seismic velocity structure of a region exploiting records from natural events. The primary focus of this aspect of the work is on the use of waveform inversion for surface waves (including higher modes) to determine three-dimensional shear wave structure. The second class of work is the construction of regionalized models of the upper mantle which are suitable for the prediction of wave propagation characteristics, for example travel time corrections for a wide range of seismic phases.

These studies are designed to contribute to the support of a verification regime for a CTBT by providing improved knowledge of regional structure in different tectonic environments and developing representations of 3-D structure which can be used to aid in, for example, improved event location and characterisation.

2 RESEARCH ACCOMPLISHED

Although radial earth models provide a good description of the major features of wave propagation through the lower mantle and core, the level of lateral heterogeneity in the upper mantle requires region specific information.

2.1 Determination of regional structure

For natural events recorded on broad-band systems the largest arrivals for distances of 10° or more are the S waves and surface waves. For the frequency band between 0.01 Hz and 0.03 Hz the characteristics of the S portion of waveform (for multiple S waves such as SS, SSS etc and surface waves) can be well matched using a radial model which represents the path average along the great-circle path between source and receiver, once the source mechanism is known. When such one-dimensional models are constructed for many paths it is possible to extract the three-dimensional S wave structure by a linear inversion of the multiple constraints provided by the various path averages. This partitioned waveform scheme (Nolet 1990) has been previously applied to determining structure in Central Asia using data from permanent seismic observatories. This application required careful allowance for the strong variation in crustal thickness across the region.

In this period we have applied the same waveform inversion procedure to record from

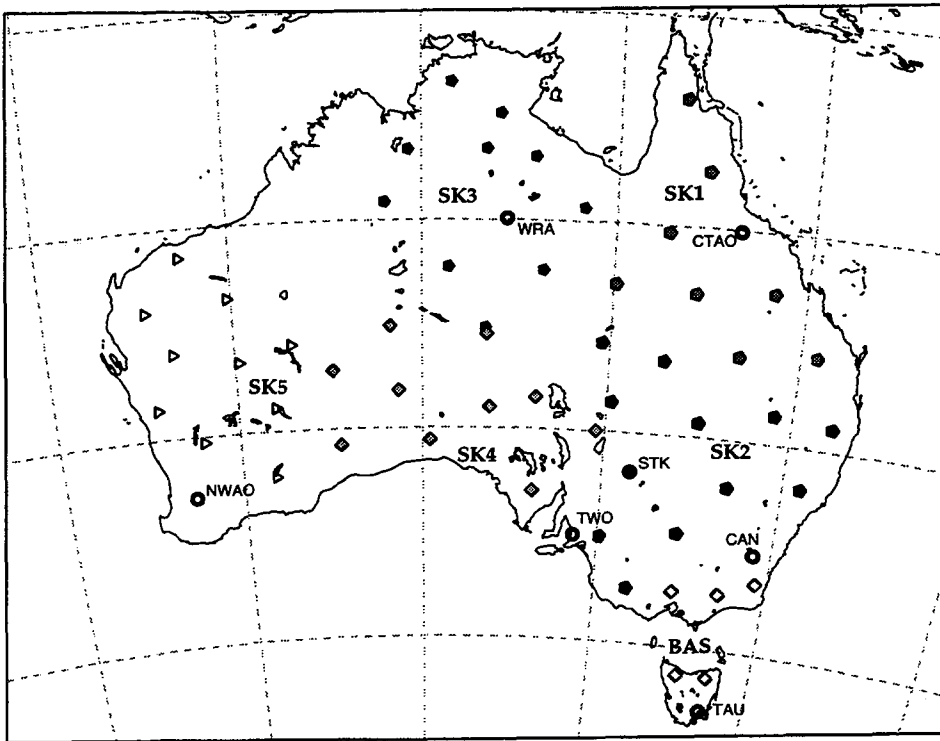


Figure 1. Configuration of array of portable broadband seismic stations and permanent broadband stations in Australia.

an array of portable broadband seismic recorders deployed in northeastern Australia with an inter-station spacing of about 400 km. The array spans the contact between the exposures of Precambrian and Phanerozoic rocks (figure 1). The deployment of the broadband instruments was for 5 months which was long enough to provide sufficient path control to dramatically improve regional coverage compared with the available data for the few permanent broadband stations on the continent. The available path coverage from the experiment is illustrated in figure 2a.

A cross-section through the three-dimensional shear velocity structure determined by partitioned waveform inversion at a depth of 140 km is illustrated in figure 2b. The strong contrast in structure between the high velocities below the craton of central Australia and the lower velocities beneath most of the younger exposure is striking. However, there are unexpected features such as the high shear velocities at depth beneath the New England block. The low velocities along the Queensland coast may be related to the Quaternary volcanism in this area.

This study demonstrates that a limited deployment of broadband instruments in a areal array can provide strong constraints on structure in a region using natural sources. The details of crustal structure can be augmented by the analysis of quarry blasts to provide an improved characterisation of the Pg, Lg propagation at shorter distances. The broadband records obtained in the experiment provide a wealth of other information which can also be used to improve knowledge of regional structure. Thus, P wave residuals at the stations can provide constraints on three-dimensional P wave

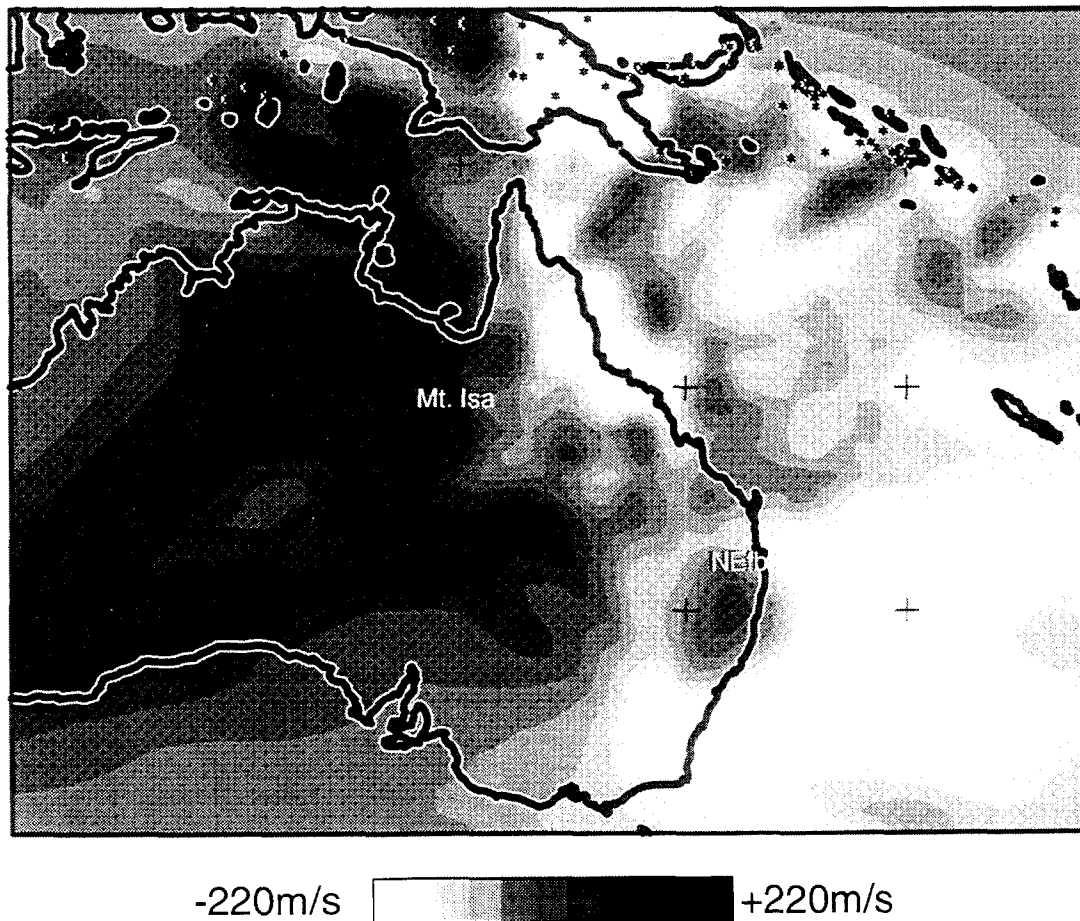
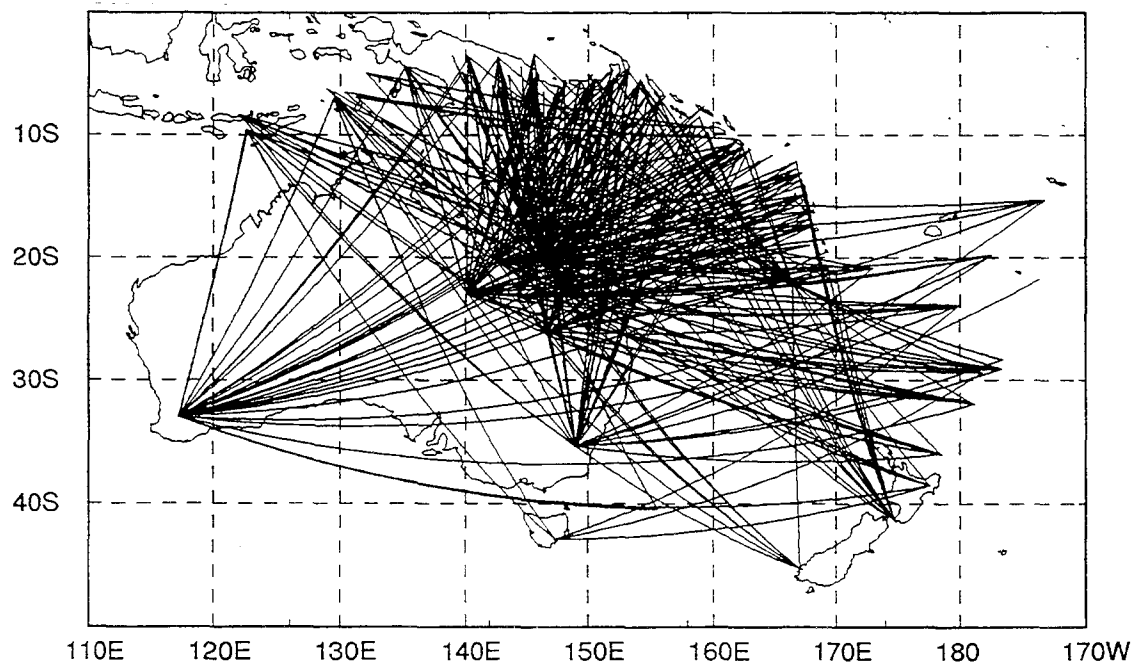


Figure 2. (a) Path coverage for waveform analysis of surface waves from both the portable and broadband station, (b) Section through three-dimensional shear wave model derived by partitioned waveform inversion at 140 km depth.

structure via tomographic inversion. The inclusion of a limited number of additional short-period stations can markedly improve the resolution of P wave structure.

2.2 Regionalisation of Earth structure

Although global coverage of the deep earth is quite good, detailed knowledge of upper mantle structure is rather limited. It is therefore desirable to devise a scheme which can incorporate well-determined structure where this is available, but which can provide a rational extrapolation where structural control is more limited.

2.2.1 *Parametrization of 3-D models*

In inverse problems like seismic tomography a region of the Earth is usually divided into rectangular 'cells' and the value of the (constant) seismic velocity in each cell is an unknown to be found in the inversion. In 3-D this can often lead to a very large number of cells, only a small proportion of which are well sampled by criss-crossing raypaths. Ideally, we would like to avoid using many cells in areas where the data constraint is poor. In global tomography, the scale lengths of seismic structures (e.g. subduction zones) can be small compared to the volume of the Earth sampled by the data (e.g. the whole mantle), and so a regular cellular parametrization would lead to an enormous number of unknowns.

A powerful mechanism has been developed for overcoming these difficulties which retains the advantage of a flexible local parametrization. The new approach uses some sophisticated methods from the field of computational geometry to divide a region into irregularly sized Delaunay triangles in 2-D or tetrahedra in 3-D. This tessellation of the medium may be produced from an arbitrary set of 'nodes' or 'reference points', the distribution of which is completely controlled by the user and can therefore be concentrated in the parts of the model well constrained by the data. An important property of the resulting tessellation is that although the sizes of the triangles (or tetrahedra) are highly irregular, their shapes are regular in the sense that they are 'as least long and thin as possible'. This makes them very useful as an irregular parametrization in inverse problems or numerical modelling methods.

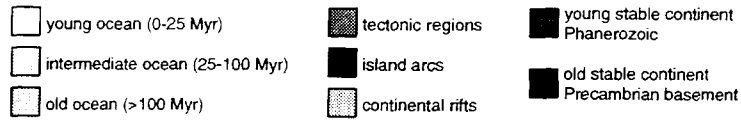
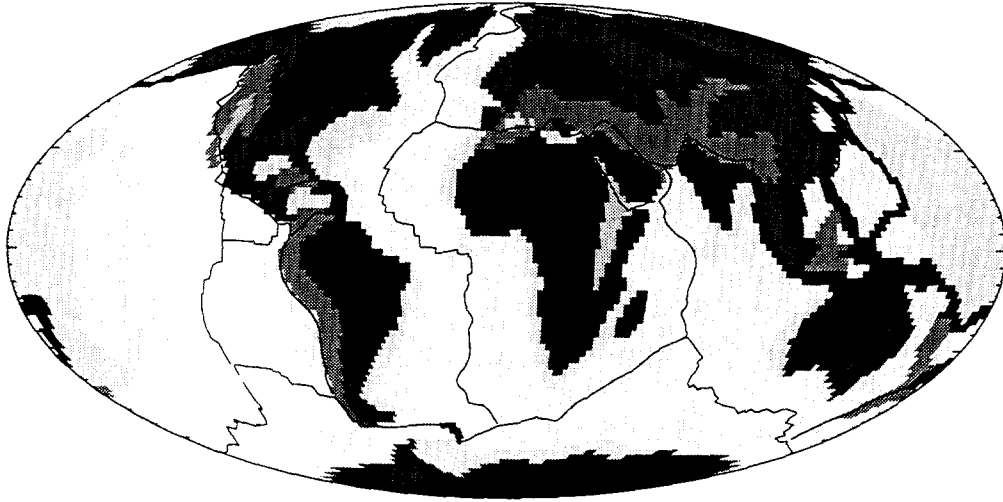
The Delaunay tessellation in 3-D also provides an ideal basis for the local interpolation of irregularly distributed data when combined with another method also derived from the field of computational geometry, known as 'natural neighbour' interpolation. This method is based on the Delaunay tetrahedra and may be applied to any irregular distribution of 3-D data in a procedure which provides smooth, accurate and efficient interpolation of arbitrarily distributed irregular information.

2.2.2 *Building an upper mantle model*

The results of upper-mantle tomography reveal the ancient cores of the continents to have high seismic velocities, while beneath the oceans the seismic wavespeeds become lower with decreasing age of the sea floor. A tectonic subdivision of the globe can therefore be a useful basis for the parametrization of an upper mantle model. Since the tectonic regions of the globe are odd shapes and sizes, the Delaunay tessellation is an ideal tool to handle such an irregular parametrization.

Figure 3(a) shows the Earth's surface divided into regions of 8 tectonic types - as

a)



b)

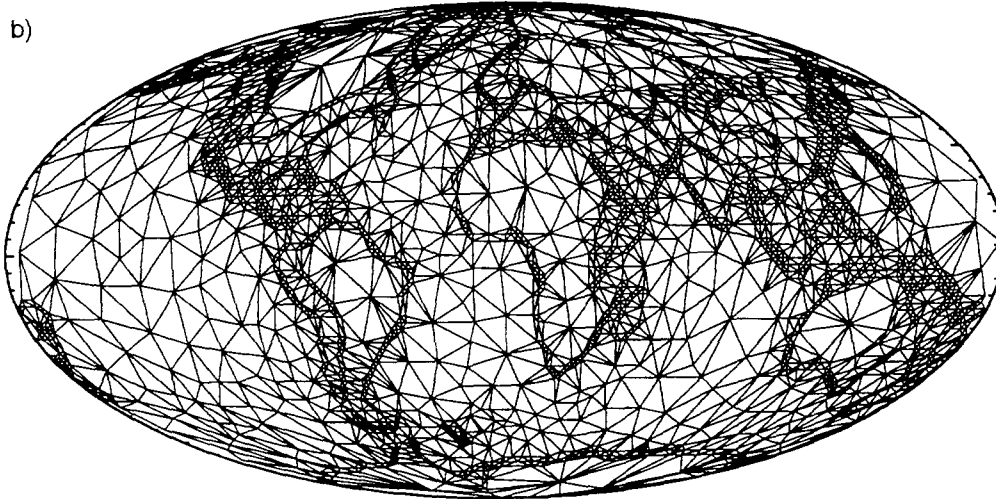


Figure 3. (a) A detailed tectonic regularisation of the surface of the Earth and (b) a Delaunay tessellation between nodes chosen to give a detailed parametrization of the transition from one region to another. This representation is proposed as suitable for a global inversion of travel times for an upper mantle model.

indicated in the legend. These tectonic regions are then subdivided into 97 geographical regions. Nodes are selected in each region so that the boundaries are parametrised in detail (resolution about 200km). A total of 2601 nodes are used to form the Delaunay tessellation on the surface of the globe as shown in figure 3(b). The tessellation can be carried into three dimensions to allow the representation of the rather complex behaviour of subduction zones.

A velocity perturbation at each of these nodes, with all nodes within the same region at a particular level constrained to be equal, represents a highly irregular parametrization of an Earth model. The parametrization allows for detail or sharp transition in structure where we this might be expected. The representation economically avoids over-parametrization in regions of uniform surface signature. At each level the maximum number of degrees of freedom allowed by this parametrization is 97, which is about the same as is resolved in global tomography.

This parametrization is being applied to global inversion on the basis of selected high quality travel times. Such an inversion allows the construction of regionalised one-dimensional velocity models of the upper mantle which can then be used to correct travel times for the effects of 3-D structure in a simple and efficient manner. Such corrections are crucial to removing the biases imposed by heterogeneity within the Earth on the location of seismic events (earthquakes and nuclear tests).

3 FUTURE PRIORITIES

The next stage of building realistic models for the upper mantle is to incorporate the results from detailed tomographic models for subduction zones into the global representation to compensate for strongest lateral heterogeneity. Such detailed models are available for the major subduction zones of the western Pacific margin and the Indonesian region. There is a considerable challenge to convert the tomographic images into suitable velocity models for integration into the Delaunay tessellation scheme.

It is desirable to make an extension of waveform analysis procedures for surface waves to try to exploit a wider frequency band to improve resolution of crustal and uppermost mantle structure - to improve regional representation. Higher frequency surface waves are quite sensitive to three-dimensional structure (Kennett 1995) but once the larger scale structure has been determined it should be possible to introduce path corrections to compensate for such structure.

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