Teleseismic imaging in southeast Australia using data from multiple high density seismic arrays

N. Rawlinson, B. L. N. Kennett

Research School of Earth Sciences, Australian National University, Canberra ACT 0200

Abstract

The recent proliferation of passive seismic array experiments in southeast Australia has resulted in the dense coverage of Tasmania, Victoria and parts of South Australia and New South Wales by some 260 plus seismometers in less than a decade. In total, six separate temporary deployments have been carried out in order to build this large network of instrumentation. Teleseismic tomography, which exploits relative arrival time residuals from distant earthquakes, is used to image the structure of the lithosphere beneath each array. A new tomographic inversion method, which uses advanced wavefront tracking techniques to solve the forward problem of predicting arrival time residuals through a 3-D heterogeneous model, and an efficient subspace inversion method to iteratively solve the non-linear inverse problem, is applied to data collected from the recent TIGGER and SEAL experiments. Results from both these studies demonstrate the potential of this class of seismic imaging in revealing important structural information beneath regions obscured by young cover sequences. The challenge of combining all passive array datasets from southeast Australia in a single tomographic inversion will also be discussed.

Keywords: Teleseismic tomography, southeast Australia, seismic array

Introduction

The idea of using multiple deployments of seismic arrays to gradually span a large region with a useful density of seismometers was first put into practice with the SKIPPY experiment in the early 1990s. By exploiting surface waveforms from the combined arrays, it is possible to build detailed shear wavespeed images of the Australian continent (e.g. Fishwick et al., 2005). More recently, this idea has been adopted on a grand scale by the USArray, which is currently attempting to progressively cover continental USA with a uniform distribution of seismometers. In southeast Australia, the three year MALT experiment began in 1998 in western Victoria with the deployment of the LF98 array (Graeber et al., 2002), which comprises 40 short period recorders, for a period of approximately four months. This was followed in 1999 and 2000 by the MB99 and AF00 arrays respectively, which have resulted in a dense coverage of stations spanning a region between Melbourne and Adelaide (see Figure 1).

In 2002, the 72 broadband and short period recorders of the TIGGER array were deployed in northern Tasmania for a five month period by the Research School of Earth Sciences, Australian National University (Figure 1). This was followed by 20 short period recorders in southern New South Wales and northern Victoria in 2004-2005, also for a five month period, as part of SEAL. The most recent experiment involved the deployment of 50 short period recorders in western Victoria in September 2005 as part of the EVA experiment (Figure 1). These instruments will be in place until May 2006. As Figure 1 shows, the different arrays are all geographically linked (with the obvious exception of TIGGER), and together with a number of broadband stations from the QUOLL experiment, span a large region of southeast Australia. To date, data from each array has been analysed separately, but there would be definite benefits in simultaneously inverting all available data for a unified tomographic model.

Data reduction

The group of short period seismic arrays shown in Figure 1 record ground motion at a rate of between 20 - 25 samples per second using vertical component seismometers. Over a period of 4-5 months, large volumes of data are recorded. In the case of MALT, each of the three component arrays produced about 30 Gb of continuously recorded data. The total volume of data for all arrays shown in Figure 1 is in excess of 200 Gb. The process of distilling out the information

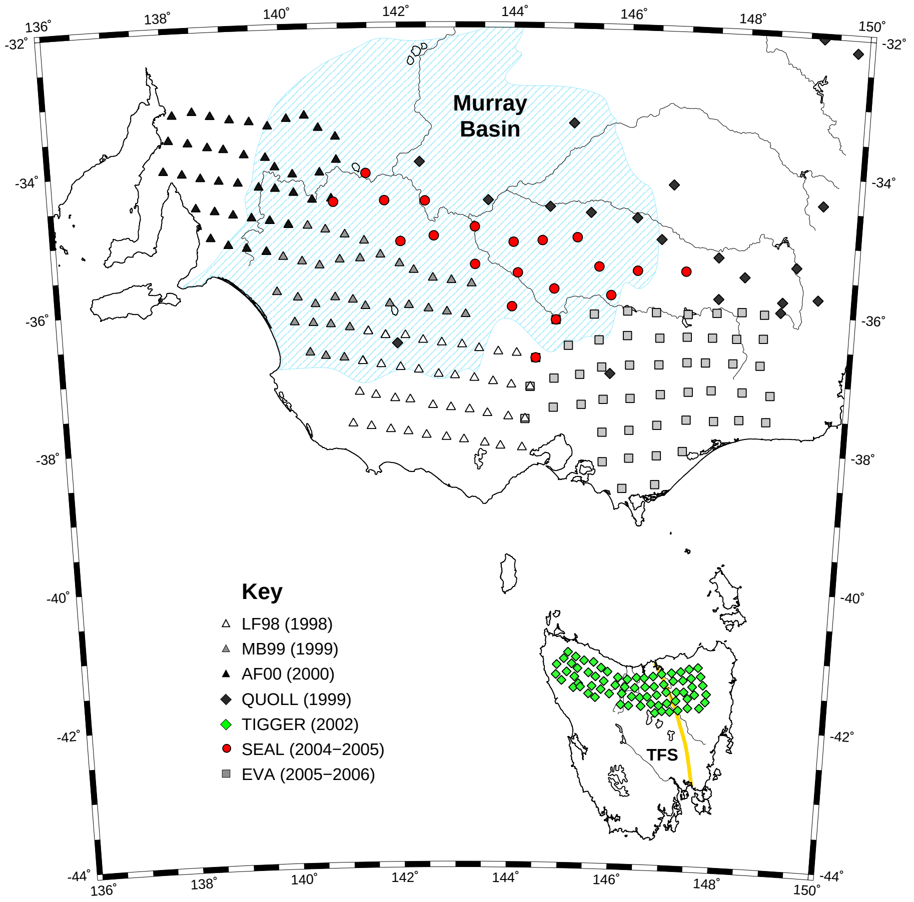

Figure 1: *Location of the TIGGER and SEAL arrays within the framework of other passive array deployments in the region.*

actually used in the inversion process begins by extracting data windows (usually 30 - 60 minutes long) corresponding to expected onset times of large earthquakes, which can be obtained from global catalogues. The next step involves trying to identify the arrival of global seismic phases (e.g. direct transmissions, reflections from the outer core), and then estimating the onset time of the associated wavetrain at each recorder. Both these processes can be done quite efficiently in a semi-automated fashion, and result in 10s of Gb of data being reduced to 10s of Kb. A significant portion of ongoing research efforts in seismic imaging is directed towards trying to exploit more of the seismic record than simply the arrival time of specific phases.

Teleseismic tomography

Teleseismic tomography uses relative arrival time residuals from distant earthquake sources, recorded across an array of seismic stations, to image the seismic structure of the crust and upper mantle (e.g. Aki et al., 1977; Humphreys and Clayton, 1990). Relative arrival time residuals can be extracted from seismic records using cross-correlation type methods (e.g. the adaptive stacking method of Rawlinson and Kennett, 2004) which exploit the relative invariance (or coherence) of the teleseismic coda across a dense local array. The new teleseismic tomography method we have developed to map the extracted arrival time residual patterns as 3-D perturbations in seismic wavespeed uses a non-linear tomographic procedure that combines computational speed and robustness. Structure beneath the array is represented using a mosaic of smoothly varying cubic B-spline volume elements, the values of which are controlled by a mesh of velocity nodes in spherical coordinates. A grid based eikonal solver, known as the Fast Marching Method (FMM,) is used to compute traveltimes from the base of the model to the receiver array on the surface (Rawlinson and Sambridge, 2004). The inverse problem, which requires the velocity node values to be adjusted in order to satisfy the observed traveltime residual patterns, subject to damping and smoothing regularization, is solved using a subspace inversion method. The non-linear nature of the tomographic inverse problem is addressed by iterative application of the forward and inverse steps.

Results from TIGGER and SEAL

A total of 6,520 arrival time residuals are inverted from the TIGGER dataset to produce a 3-D wavespeed perturbation model; for SEAL, this value is 3,085. In both cases, six iterations of the tomographic inversion method are required to achieve convergence. Despite the large number of velocity nodes that are inverted for in both cases (61,380 for TIGGER; 21,645 for SEAL), the computing time on a 1.6 GHz Opteron PC is approximately 20 minutes to solve the complete problem in each case. The reason that the SEAL inversion is no faster than the TIGGER inversion is due to the greater number of teleseismic sources (about 50% more than TIGGER) that are used; in terms of computing time, FMM is insensitive to the number of receivers, but not to the number of sources. Figure 2a shows an E-W cross section through the TIGGER solution model with some of the principal features highlighted. Figure 2b shows a horizontal slice through the SEAL solution model with a schematic map of major regions and boundaries superimposed.

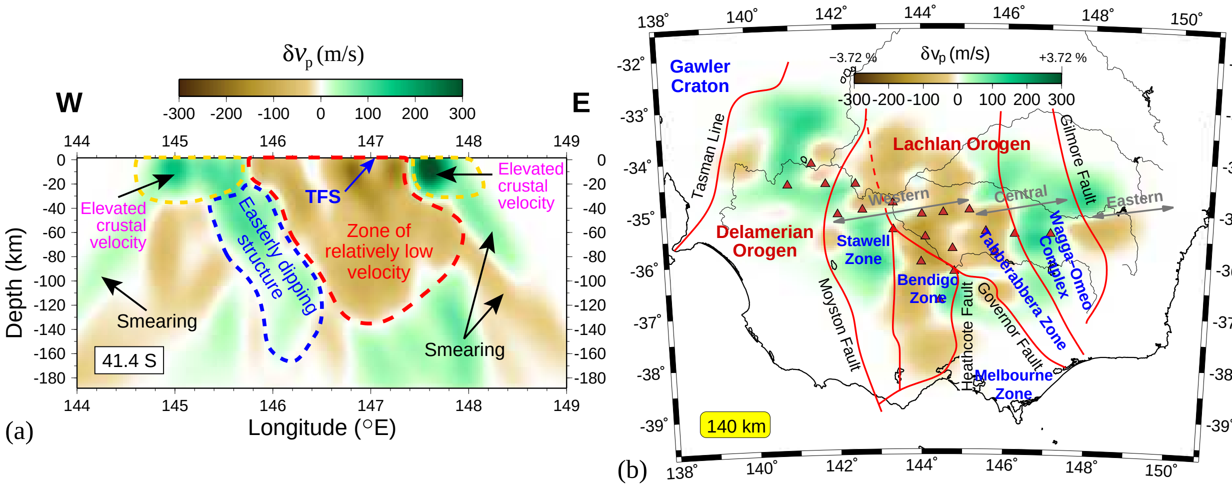

Figure 2: *(a) E-W slice through the TIGGER solution model; (b) horizontal slice through the SEAL solution model.*

The location of southeast Australia relative to surrounding seismogenic zones means that path coverage is relatively dense from the north and east, but quite sparse from the south and west. Checkerboard resolution tests, which attempt to recover a synthetic 3-D pattern of alternating fast and slow anomalies using the same path coverage as the observations, show that this first order variation in path coverage has some affect on the recovery of structure. In particular, fine scale structure (approximately equal to the average station spacing), towards the southern and western ends of both arrays tend to be smeared out, although larger scale features appear to be quite well resolved.

Discussion and conclusions

Many fundamental questions regarding the structure and evolution of the lithosphere beneath south east Australia remain unanswered, including the development of the Palaeozoic Lachlan Orogen, and the relationship between Tasmania and mainland Australia. The results from the TIGGER experiment reveal several interesting features, including a pronounced W-E increase in crustal velocity at about 147.4° E (Figure 2a). This abrupt change in wavespeed supports the idea that eastern Tasmania is underlain by dense rocks with an oceanic crustal affinity, while western Tasmania comprises continentally derived siliciclastic crust. Interestingly, the Tamar Fracture System (TFS) does not overlie the boundary between the two regions, which suggests that it is a shallow feature. The easterly dipping structure further west may represent remnants of an early phase of easterly subduction during the Tyennan Orogeny in the Cambrian.

The horizontal slice through the SEAL solution model (Figure 2b) shows a dominant W-E fast-slow-fast wavespeed variation that can be observed throughout the upper mantle between 70-250 km depth. The transition from faster to slower wavespeeds in the west is indicative of a change from Proterozoic to Phanerozoic lithosphere that has also been observed further south by the LF98 experiment (Graeber et al., 2002). The elevated velocities beneath the Stawell Zone may well be caused by the presence of Precambrian basement extending beneath the western part of the Lachlan Orogen in the vicinity of the Murray Basin. The relatively fast velocities observed beneath the Wagga-Omeo Complex (Figure 2b) point to a significant change in character of the upper mantle between the central and western subprovinces of the Lachlan Orogen, although the precise reason for this change is difficult to identify.

Although all the different seismic arrays on the Australian mainland (Figure 1) form a single large array with no major gaps, it is not a simple exercise to try and relate features imaged beneath one array, with features imaged beneath an adjacent array. There are two reasons for this: (1) edge effects, which cause structure to be smeared out towards the edges of the array due to insufficient angular path coverage, and (2) the use of relative arrival time residuals in the inversion, which means that unless the average wavespeed with depth is identical beneath adjacent arrays, they will not join continuously. Given these limitations, it is far more desirable to simultaneously invert all available data for a unified model of the entire region. Although this will require a very large tomographic inversion problem to be solved, with of the order of 30,000 ray paths and 500,000 unknowns, the new tomographic scheme we have developed has the necessary computational efficiency and robustness.

References

K. Aki, A. Christoffersson, and E. S. Husebye. Determination of the three-dimensional seismic structure of the lithosphere. *J. Geophys. Res.*, 82:277–296, 1977.

S. Fishwick, B. L. N. Kennett, and A. M. Reading. Contrasts in lithospheric structure within the Australian craton - insights from surface wave tomography. *Earth Planet. Sci. Lett.*, 231:163–176, 2005.

F. M. Graeber, G. A. Houseman, and S. A. Greenhalgh. Regional teleseismic tomography of the western Lachlan Orogen and the Newer Volcanic Province, southeast Australia. *Geophys. J. Int.*, 149:249–266, 2002.

E. D. Humphreys and R. W. Clayton. Tomographic image of the Southern California Mantle. *J. Geophys. Res.*, 95: 19,725–19,746, 1990.

N. Rawlinson and B. L. N. Kennett. Rapid estimation of relative and absolute delay times across a network by adaptive stacking. *Geophys. J. Int.*, 157:332–340, 2004.

N. Rawlinson and M. Sambridge. Multiple reflection and transmission phases in complex layered media using a multistage fast marching method. *Geophysics*, 69:1338–1350, 2004.