Transportable seismic array tomography in southeast Australia: Illuminating the transition from Proterozoic to Phanerozoic lithosphere

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The Phanerozoic Tasmanides of eastern Australia is comprised of a series of orogenic belts that developed along the east margin of Gondwana following the breakup of the supercontinent Rodinia and subsequent formation of the Pacific Ocean. The tectonic complexities of this region have been well studied, but most work has been confined to evidence collected from the near surface, where extensive Mesozoic and Cenozoic basin cover masks large tracts of Palaeozoic basement. We apply teleseismic tomography to distant earthquake data recorded by WOMBAT - the largest transportable seismic array experiment in the southern hemisphere - to image P-wavespeed variations in the mantle lithosphere beneath the southern portion of the Tasmanides in detail. In order to seamlessly suture together the teleseismic datasets from each of the 14 sub-arrays of WOMBAT, we use P-wavespeeds from the AuSREM model to construct a laterally heterogeneous starting model that captures the long wavelength structural variations that would otherwise be lost through the use of relative arrival time residuals. Synthetic resolution tests indicate good horizontal resolution of ~50 km within most of the array between depths of 50–350 km. A key feature of the 3-D P-wave model is a pronounced easterly high velocity salient in the mantle lithosphere beneath the northern limit of the New England Orogenic, which may indicate the presence of underpinning Proterozoic lithosphere that was instrumental in its formation. Another pronounced high velocity anomaly underlies the Curnamona Province, a large crustal block with a strong Archean provenance, which is clearly separated from the Gawler Craton to the west at upper mantle depths by a low velocity zone beneath the Adelaide Fold Belt. We also estimate the location of the eastern boundary of Precambrian Australia at depth, and show that it extends eastward further than previously thought.

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1. Introduction

Although less than half of the Palaeozoic basement beneath the southern Tasmanides of eastern Australia is exposed at the surface, a remarkable tectonic history has been progressively revealed over the last century, as more sophisticated techniques and methods of analysis have been brought to bear on an increasingly larger pool of data. Early researchers evidently had a good idea that long timescales and almost unimaginable forces were at work; for instance Schuchert (1916) wrote of the Tasman Sea “It appears that vast land-masses have been fractured, broken up and more or less permanently taken possession of by the oceans”, a statement that by today’s standards would still be considered accurate given what is known of the opening of the Tasman Sea and the emplacement of the Lord Howe Rise as a rifted continental fragment from the eastern margin of Australia (Gaina et al., 1998). However, the notion of continental drift had yet to enter the early 20th century mindset, and large scale deformation was generally attributed to an Earth that periodically shrinks, with parts of the crust either rising or sinking rather than moving horizontally.

Today, great strides have been made in understanding how the Tasmanides evolved into its current state thanks to advances in many different fields of Earth Sciences including geophysical imaging. For instance, high resolution gravity (e.g. Leaman and Richardson, 1989; Murray et al., 1989; Roach et al., 1993; Spencer, 2004), magnetic (e.g. Glen, 2005; Gunn et al., 1997b; Hill et al., 1997; Mackey et al., 1995; Musgrave and Rawlinson, 2010) and reflection/wide-angle seismic studies (Cayley et al., 2011; Drummond et al., 2000; Finlayson et al., 1998; Korsch et al., 2002; Rawlinson et al., 2001) have been instrumental in probing the Palaeozoic crust and defining the main elements of the southern Tasmanides. Passive seismic imaging has also played an important role, particularly in differentiating between lithosphere of Phanerozoic, Proterozoic and Archean origin. For example, surface wave tomography results from continent-wide broadband deployments reveal that the mantle lithosphere beneath cratonic central and western Australia has markedly higher S-wavespeeds in comparison to the Palaeozoic lithosphere beneath the Tasmanides (Debayle, 1999; Debayle and Kennett, 2000, 2003; Fishwick and Rawlinson, 2012; Fishwick et al., 2005, 2008; Simons et al., 1999, 2002; Zielhuis and van der Hilst, 1996), a result also largely mimicked in P-wavespeed and...
as determined from regional body wave tomography (Kennett, 2003; Kennett and Abdullah, 2011). This has allowed constraints to be placed on the boundary between the Tasmanides and cratonic Australia (e.g. Kennett et al., 2004), but there is still considerable uncertainty as to the nature of the transition (Direen and Crawford, 2003b).

A limitation of the Australian continent-wide broadband dataset is that station separation is generally of the order of 200–400 km, which places a restriction on the maximum horizontal resolution to around 200–250 km. Since 1998, a series of targeted experiments – now collectively called WOMBAT – using highly portable short period recorders have been carried out in southeast Australia, with one of the main objectives being to record distant earthquakes for use in teleseismic tomography. With a station spacing of around 50 km or less, a number of studies have revealed detailed patterns of P-wave perturbations in the upper mantle that have allowed the presence of a hot-spot, lithospheric boundaries and continental fragments to be inferred (Clifford et al., 2008; Graeber et al., 2002; Rawlinson and Kennett, 2008; Rawlinson and Urvoy, 2006; Rawlinson et al., 2006a, 2006b, 2010b). Until 2010, these teleseismic datasets were treated separately, but the spatially contiguous nature of the arrays meant that a joint inversion of the datasets would be far more revealing. As such the joint inversion results of Fishwick and Rawlinson (2012), Rawlinson and Fishwick (2012), and Rawlinson et al. (2011) have allowed detailed inferences about the lithosphere beneath Tasmania, Victoria, eastern South Australia and southern New South Wales to be made, including relationships between deep seated anomalies and the distribution of mineral deposits and Cainozoic volcanic centres at the surface.

In this study, we considerably expand on the recent work of Fishwick and Rawlinson (2012), Rawlinson and Fishwick (2012), and Rawlinson et al. (2011) by including data from an additional five arrays in northern NSW and southern South Australia, representing a total of 210 stations or a 53% increase on what was previously available. Furthermore, we also use an improved regional P-wavespeed model (Kennett and Salmon, 2012; Kennett et al., 2013; Salmon et al., 2012) to account for the long wavelength structure that is lost through the use of relative arrival times across multiple arrays. The new P-wavespeed model spans a far greater region of the southern Tasmanides and adjacent cratonic region, and allows new constraints to be placed on the tectonic evolution of Phanerozoic Australia.

2. Tectonic setting

The Tasmanides comprise approximately one-third of the Australian land mass, and is constructed from five Palaeozoic orogenic belts that formed outboard of the Australian section of the east Gondwana — proto-Pacific convergent margin between the Middle Cambrian and the Carboniferous (Cawood, 1982; Glen, 2005). The characterisation and spatial extent of each orogen have been considerably assisted by high resolution gravity and magnetic datasets that have helped overcome the extensive lack of surface outcrop. As a result, rather than showing a map of surface geology, we instead display the distribution of geophysical domains (Fig. 1) as defined by Shaw et al. (1996) based on gravity, magnetic and crustal element boundaries. This has the advantage that major structural variations in the upper crust beneath Mesozoic and Cainozoic cover are revealed, although it is worth noting...
that accuracy will decrease in areas of thick sedimentary cover and sparse data.

In southeast Australia, the Delamerian Orogen abuts the eastern margin of the Gawler Craton and continues south to include western Tasmania where it is commonly referred to as the Tyennan Orogen (Crawford et al., 2003; Direen and Crawford, 2003a, 2003b; Gibson et al., 2011; Reed et al., 2002). East of the Gawler Craton, the Delamerian Orogen incorporates the Adelaide Fold Belt, which was formed by the inversion of the Neoproterozoic–Cambrian Adelaide Rift Complex, a thick sequence of mostly marine sediments that records the formation of the eastern margin of Australia prior to convergent orogenesis in the Palaeozoic (Foden et al., 1999, 2006; Glen, 2005). Outboard of the Adelaide Fold Belt lies the Kanmantoo Fold Belt, an inversion of the marine Kanmantoo Trough, which is composed largely of metamorphic sediments intruded by granitoids (Glen, 2005). Convergence along a west dipping subduction zone against the eastern margin of Gondwana between Mid–Late Cambrian and early Ordovician is thought to have produced the Delamerian Orogen (Foden et al., 2006), The underlying basement is thought to consist mostly of reworked Precambrian continental rocks (Willman et al., 2002). One possible source of continental crust is the supra-subduction zone system that contains an abundance of Copper–Gold deposits (Webster, 1996).

The Lachlan Orogen formed outboard of the Delamerian Orogen between the early Ordovician and early Carboniferous (Kemp et al., 2008). It can be divided into three distinct thrust systems (Foster et al., 2009) that constitute the Western, Central and Eastern subprovinces. The Western subprovince is an east-vergent thrust system with zones of NW–SE and N–S trending structures; the Central subprovince consists of a SW-vergent thrust belt with considerable high temperature/low pressure metamorphism, and is sometimes referred to as the Wagga–Omeo Metamorphic Complex; the Eastern subprovince is characterised by a north–south structural grain and east-directed faults (Foster et al., 2009), and hosts the Ordovician Macquarie Arc, an intra-oceanic supra-subduction zone system that contains an abundance of Copper–Gold deposits (Glen et al., 2009, 2012). Glen (2005) identifies a fourth subprovince – the Southwestern subprovince within the Western subprovince – based on the interpretation of potential field data, which appears to reveal a north–south change in geology.

Of the many important questions that still surround the tectonic evolution of the Lachlan Orogen, there are two which are particularly relevant to this study. The first regards the origin of the lithosphere beneath the orogen, which has variously been argued as either oceanic (Foster and Gray, 2000; Spaggiari et al., 2003, 2004) or mixed oceanic–continental (Taylor and Cayley, 2000; VandenBerg, 1999; Willman et al., 2002). One possible source of continental crust is the supercontinent Rodinia, the break-up of which may have set adrift a number of continental fragments, one or more of which could have become incorporated in the convergent margin setting of the Lachlan Orogeny. The Selwyn Block idea (Cayley, 2011; Cayley et al., 2002), which argues that western Tasmania and the substrate beneath the Melbourne Zone in Victoria are part of the same Proterozoic crustal fragment is one example of how this process may manifest. The second question relates to the location and nature of the Delamerian–Lachlan boundary. The main candidates for the boundary are the Avoca Fault (Glen et al., 1992) and the Moyston Fault (Cayley and Taylor, 1998; Cayley et al., 2002; VandenBerg, 1999), although seismic reflection data (Cayley, 2011; Korsch et al., 2002) appears to show the Moyston Fault as an east-dipping boundary extending into the deep crust, with the West dipping Avoca Fault soling into it at shallower depth. In an alternative model, Miller et al. (2005) argue that the Moyston Fault overlies a reworked orogenic zone that contains elements of both the Delamerian and Lachlan orogens.

The Thomson Orogen lies to the north of the Lachlan Orogen, with the boundary between the two obscured by Palaeozoic–Mesozoic cover (see Fig. 1). Potential field datasets reveal the boundary to be curvilinear, with the centre of curvature lying to the north. Reflection seismic data suggest that the boundary is steeply dipping to the north and separates thick dense crust in the Thomson Orogen from more normal layered crust in the Lachlan Orogen (Glen et al., 2007). As a result of extensive sediment cover, little is known about the Thomson Orogen, although it appears to be underlain by rocks that vary in age from Precambrian to Late Devonian (Glen, 2005).

The New England Orogen lies to the east of both the Thomson and Lachlan orogens, where its boundary is obscured by Permian–Middle Triassic sedimentary basins. Here, we only focus on the southern part of the orogen since it lies within the study area. Although the New England Orogen represents the youngest part of the orogenic system which formed the Tasmanides, it appears to be underlain by both Palaeozoic oceanic and Precambrian rocks, with Re–Os ages, zircon model ages and Sm–Nd isochron ages pointing to the presence of old lithosphere (Glen, 2005). One of the main structural features in the south is the doubly vergent New England Orocline, which developed between 310 and 230 Ma via strong deformation of a pre-Permian arc assemblage (Cawood et al., 2011; Rosenbaum, 2012). Cawood et al. (2011) explain the formation of this feature by invoking a tectonic model in which the arc system is buckled about a vertical axis as the southern part of the arc moves northwards due to oblique sinistral strike-slip motion between the Palaeo-Pacific and Gondwana plates, with the northern part pinned relative to cratonic Gondwana. Rosenbaum et al. (2012) suggest an alternative model in which a west-dipping subduction zone rolls back with variable velocity along-strike, such that the southern end of the arc recedes more quickly and is forced to rotate northwards and eventually fold back on itself, thus forming the orocline.

Following the Palaeozoic formation of the Tasmanides, a number of significant tectonic events took place that considerably altered the nature of the orogen. Of particular relevance to this study is the break-up of Australia and Antarctica and the opening of the Tasman sea between 80 and 90 Ma (Gaina et al., 1998); this event resulted in significant lithospheric thinning near the passive margin of southeast Australia, and the formation of the Bass Basin between Victoria and Tasmania (Gunn et al., 1997a). Another possible result of the rifting process is the formation of the Southern Highlands inboard of eastern Australia in Victoria and NSW, which is consistent with the development of an upper plate passive margin (Lister et al., 1991) in the Cretaceous. However, others (e.g. van der Beek et al., 1999) have suggested that the Southern Highlands are instead an erosional remnant of a large mountain chain formed during late Palaeozoic orogenesis. Even more recently, the Flinders Ranges in South Australia has formed as a result of Neogene intracratonic orogenesis (Sandiford et al., 2004), with some studies indicating that the entire relief (maximum elevation 1200 m) was created in as little as 4 My (Quigley et al., 2007). Although increased coupling between the Australian and Pacific plates during the Miocene may have triggered the event, it is unclear whether thermal or structural anomalies are responsible for the strain focusing observed in this region. Perhaps the most recent event to effect the lithosphere and surface geology of southeast Australia is the emplacement of the Quaternary Newer Volcanics province in western Victoria, which only ceased some five thousand years ago. Evidently arising from hot-spot volcanism (Price et al., 1997), the Newer Volcanics, together with numerous other Cenozoic eruption centres that populate the eastern edge of the Australian mainland, has helped mask older basement, and undoubtedly affected the lithosphere through which it has migrated.

3. Data and method

Teleseismic data for this study comes from the WOMBAT transportable seismic array project which has been operating in southeast
Australia since 1998. It comprises a core array of approximately 50 instruments (although this varies depending on availability) that is progressively moved from one location to the next in order to achieve high-density coverage over a broad area (see Fig. 2). To date, over 600 sites have been deployed as part of 14 separate array movements, with station spacing varying from 15 km in Tasmania to 50 km on the mainland. Recently, a new array called SQEAL1 has been deployed to the north of EAL3, with SQEAL2 planned for deployment north of EAL2 in mid 2013. Over the last 15 years, the instrumentation used for WOMBAT has gradually evolved; the early arrays used recording durations of approximately five months and 1 Hz vertical component seismometers, but since 2006, recording durations of 9–14 months have been achieved using 1 Hz 3-component seismometers. Future deployments are expected to use compact broadband sensors. Passive seismic experiments in southeastern Australia are able to exploit a reasonably good distribution of earthquakes across the globe (Fig. 3). However, events to the north and east are far more frequent and so much more data is available from these directions.

For the first time, we exploit teleseismic P-wave arrival time residuals from all 14 arrays shown in Fig. 2. Previous studies (e.g. Rawlinson et al., 2011; Rawlinson and Fishwick, 2012; Fishwick and Rawlinson, 2012) have only used data up to and including SEAL3 (nine arrays), so the additional dataset that has become available represents a substantial increase in coverage. Distant earthquakes are selected from the NEIC catalogue based on size, depth, angular distance and phase type. In general, all events at an angular distance greater than 27° with a moment magnitude of at least 5.2 are considered; however, any event at a depth in excess of 150 km is also included if it has a moment magnitude greater than 4.6. Large and/or deep focus earthquakes at an angular distance less than 27° are also examined for the presence of core reflection phases. The data processing scheme used to extract relative arrival time residuals is explained in detail in Rawlinson and Kennett (2008), Rawlinson et al. (2006b), and Rawlinson et al. (2011), so it is only briefly summarised here. Traces associated with the arrival of various global phases (e.g. P, ScP, PcP, PKKP, Pdiff, PP) are windowed and aligned using predictions from the global reference model ak135 (Kennett et al., 1995). Any remaining lack of alignment can be largely attributed to lateral variations in structure beneath the array. We use the adaptive stacking procedure of Rawlinson and Kennett (2004) to achieve final alignment, thus producing a set of arrival time residual estimates for each source. The mean is then removed to produce a set of relative arrival time residuals, which are less sensitive to errors in source origin time and long wavelength structure outside the model region.

Unlike the recent studies of Fishwick and Rawlinson (2012), Rawlinson and Fishwick (2012), and Rawlinson et al. (2011), we use a fully automated version of the adaptive stacking code of Rawlinson and Kennett (2004) to produce sets of relative arrival time residuals...
from earthquake and phase listings. One of the benefits of the adaptive stacking approach is that picking uncertainty is estimated, which can be used to discard noisy or incoherent phases. Here, we use a threshold of 65 ms for picking uncertainty, above which phases are rejected. The automated approach has been validated through comparison with those datasets (SEAL3 and earlier) that were picked using adaptive stacking within a more manual framework. The end result of the data processing is a set of 143,850 relative arrival time residuals produced by a total of 3445 earthquake sources (Fig. 3) and 604 stations. Due to the uneven distribution of sources, with most events occurring to the north and east of WOMBAT (Fig. 3), we apply data binning (see Rawlinson et al., 2011, for details on this technique) to help reduce the smearing effect that can be produced by clusters of rays originating from the same source region. The final dataset used in the inversion therefore consists of 54,581 residuals from 1344 sources. An example of the coherence of seismic phases across the individual arrays is shown in Fig. 4, where the arrivals are initially aligned using the ak135 model of Kennett et al. (1995) and then refined using adaptive stacking. The results illustrate the high quality that is typical of much of the WOMBAT dataset.

The inversion method used to map relative arrival time residuals as 3-D perturbations in P-wave velocity has been described in Rawlinson and Kennett (2008, 2011) and Rawlinson et al. (2006b, 2011). Structure is represented by a regular grid of nodes in latitude, longitude and depth, with cubic B-spline functions used to describe a smoothly varying and locally controlled velocity continuum. A grid-based eikonal solver known as the fast marching method or FMM (Rawlinson and Sambridge, 2004) is used to solve the forward problem of traveltime prediction, which involves tracking wavefronts from the bottom of a local 3-D model, where traveltimes are defined by the ak135 model, to the receivers at the surface. Model parameters, which include velocity node values and station terms – the latter used to account for unresolved structure in the receiver neighbourhood – are adjusted to satisfy the data using a subspace inversion technique (Kennett et al., 1988), subject to damping and smoothing regularisation.

One challenge that arises from the simultaneous use of different relative arrival time datasets is that long wavelength structure, equal to or larger than the horizontal dimensions of the component arrays, will be absent from the final model. Rawlinson and Fishwick (2012), and Rawlinson et al. (2011) address this by using a long wavelength initial model based on results from regional surface wave tomography. However, aside from the assumptions that need to be made to convert from S-wave to P-wave velocity, the nature of the regularisation used to constrain the surface wave model will influence the final P-wave model result in a way that is difficult to quantify. Others have used a more direct approach of joint inversion of surface and body waves (Obrebski et al., 2011; West et al., 2004), but in the case of WOMBAT, there is still the problem of S-P-wave velocity conversion. Moreover, it appears to make little sense to try and invert two datasets that differ so markedly in coverage and resolution. Here we make use of the recently released Australian Seismological Reference Model (AuSREM) to provide a robust long wavelength P-wave velocity model as prior information in the body wave inversion. Details of the AuSREM model and how it is constructed are provided in detail in Kennett and Salmon (2012), Kennett et al. (2013), and Salmon et al. (2012). The relevant points for this study are that it contains an isotropic crustal and mantle component and Moho geometry all at a horizontal sampling of 0.5° with both P and S velocities available. The crustal component is based on

![Fig. 4. Three different phase types recorded by three different sub-arrays of WOMBAT that have been aligned using the adaptive stacking method of Rawlinson and Kennett (2004). (a) P arrival recorded by EAL1; (b) ScP arrival recorded by AuScope-CU; (c) PKiKP arrival recorded by EAL2. The top two traces in each case – labelled zssl and zscp – represent the linear and quadratic stack respectively.](image-url)
sediment thickness databases, reflection profiling, refraction and wide-angle reflection experiments, receiver functions and ambient noise tomography. The mantle component is based on surface wave tomography, body wave studies and regional tomography. In addition to using the mantle component of the model, we also include the crustal component to help account for near-surface structural variations that cannot be constrained by the teleseismic dataset. Although these shallow variations are approximate due to the use of a smooth parameterisation which is not capable of explicit representation of the Moho, it is nonetheless an improvement compared to previous work. According to AuSREM, Moho depth varies between 27 km and 52 km beneath the study region. Given that velocity contrasts across the Moho can be up to 2 km/s or more, this variation in crustal thickness may contribute significantly to the measured traveltime residuals. However, the inclusion of a smoothed crustal layer coupled with explicit station terms in the inversion should help minimise any smearing into the underlying mantle.

4. Results

The local 3-D model region used for the inversion of WOMBAT P-wave arrival time residuals spans a latitude range of 18.7°, a longitude range of 23.4° and a depth range of 362 km. The latter value is equal to two-thirds the array aperture (Evans and Achauer, 1993); in this case, the aperture of the largest sub-array within WOMBAT. The node spacing of the velocity grid is approximately 20 km in each dimension, resulting in a total of 209,475 unknowns. An additional 604 unknowns in the form of station terms to absorb localised crustal variations are also constrained during the inversion process. Six iterations of the subspace inversion scheme are used to obtain a solution, with traveltimes and Fréchet derivatives updated after each iteration using FMM. Damping and smoothing regularisation are used to achieve an optimum trade-off between satisfying the data and recovering a model that minimises unwarranted short wavelength features and strong departures from the initial model (Rawlinson and Kennett, 2008; Rawlinson et al., 2006b). Although the initial model is defined by AuSREM, model arrival time residuals are calculated with reference to the laterally homogeneous ak135 model, which means that residual contributions arising from lateral velocity variations in AuSREM are accounted for, i.e. the inversion will only introduce structure that is not already contained in AuSREM. Before presenting the tomographic model from the WOMBAT dataset, we first carry out several synthetic reconstruction tests to provide some insight into the robustness of the inversion results.

4.1. Synthetic tests

Synthetic reconstruction tests are commonly used in seismic tomography to help assess the scale-length of features that the dataset is capable of recovering (Rawlinson and Sambridge, 2003; Rawlinson et al., 2010a). The basic idea is to construct a model that might feature a single or multitude of velocity perturbations and then generate a synthetic dataset by using the same source–receiver combinations and phase types as the observational dataset. Application of the inversion scheme to this dataset with the same initial parameters (initial model, damping, smoothing) as are used with the observational dataset yields a result that can be compared to the true model. The checkerboard reconstruction test, in which an alternating pattern of high and low wavespeeds is used, is by far the most common type of synthetic test found in the published literature. Although the limitations of such tests are well known (Lévêque et al., 1993; Nolet, 2008), their

![Fig. 5](image-url) Horizontal depth sections through the synthetic checkerboard model (top) and recovered model (bottom) at three different depths (a) 90 km, (b) 170 km and (c) 250 km. The smoothly varying background velocities are provided by AuSREM. E–W red and N–S blue lines superimposed onto the synthetic model in (c) denote the locations of the cross-sections shown in Fig. 6.
simplicity, both in implementation and interpretation, has made them a very attractive option. Two synthetic checkerboard tests have been carried out to determine which regions of the model are well controlled by the teleseismic data. In the first test the synthetic dataset is computed in the presence of a checkerboard model which is superimposed on the AuSREM background model. Gaussian noise with a standard deviation of 50 ms is added to the relative arrival times to simulate the picking uncertainty associated with the real data. Figs. 5 and 6 show a comparison between the synthetic model and the reconstructed model after six iterations of the tomographic scheme. The checkerboard pattern has been chosen such that the interface between the individual blocks is represented by a sharp velocity gradient, which is difficult to recover. As shown in both Figs. 5 and 6, the tendency is to both smooth out the sharp velocity gradient and underestimate the amplitude of the velocity perturbations, which is typical of regularised iterative non-linear schemes. None-the-less, the checkerboard pattern is generally well recovered within the bounds of the receiver array. As is most easily seen in Fig. 5, where path coverage is absent, the recovered or output model is unchanged from the starting model, which is defined by AuSREM. Due to the nature of the incident paths, which converge to the receivers, the horizontal extent of the zone of good resolution tends to increase with depth (cf. Fig. 5a and c).

When raypaths have a dominant direction, there is a tendency to smear out velocity anomalies in this direction. This can be easily seen near the edges of the cross-sections in Fig. 6. Furthermore, the heavy concentration of sources to the north of WOMBAT has resulted in a tendency to smear structure at approximately 45° to the vertical in the northerly direction (see Fig. 6b, right). The lack of stations beneath Bass Strait, which separates Tasmania and Victoria, has resulted in a gap in the recovered checkerboard, that is most easily seen in Fig. 6b, bottom right. Although this gap tends to close up as depth increases, the relatively small apertures of the two Tasmanian arrays mean that resolution is limited below about 200 km depth. Overall, however, the recovery of the synthetic model is sufficient to feel confident that the pattern of anomalies revealed by the inversion of WOMBAT data will be largely correct, although more caution is required in the interpretation of absolute amplitude. It is worth noting that at this point absolute velocities are used in Fig. 5, whereas velocity perturbations relative to a horizontally averaged AuSREM model are used in Fig. 6. The reason for this is that dominant variations in wavespeed occur with depth, but our interest is in departures from this trend, which for vertical slices are best seen by removing the depth-dependent component of the velocity field.

The second test is designed to test the sensitivity of the teleseismic dataset to long-wavelength perturbations in wavespeed. Fig. 7 shows the results of a checkerboard test in which the size of each anomaly is clearly much larger than the aperture of the component arrays of WOMBAT. The result shown in the right hand panel of Fig. 7 ostensibly appears to be quite good, with the boundaries between neighbouring anomalies recovered accurately almost without exception. However, given the data density, one would normally expect that the smooth velocity variation that defines each anomaly (essentially AuSREM with a dc offset) is well recovered, but clearly this is not so, particularly in the case of the anomaly centred at 142° east and 34° south. In this case, the velocity is high in the NW corner, but decreases rapidly to the south (Fig. 7, right). The reason this happens is that several arrays join together within the bounds of this anomaly (see Fig. 7, right), and since the mean is separately removed from the arrival times on a source by source basis for each array, the long wavelength features will only be properly recovered if the average velocity of the starting model is correct beneath each array. Consequently, there is a need for an accurate long wavelength starting model for the inversion of multiple teleseismic datasets, although as we have shown here, sharp velocity gradients may be correctly recovered in the absence of such information.

4.2 Seismic structure of southeast Australia

For the inversion of the WOMBAT dataset, identical velocity grid spacing, initial model and regularisation to the synthetic test is used. After six iterations of subspace inversion and FMM, the RMS arrival time residual is reduced from 260 ms to 147 ms, which corresponds to a variance reduction of 68%. The RMS uncertainty of the WOMBAT dataset has been estimated at around 50 ms by adaptive stacking, although it is generally a better predictor of relative rather than absolute uncertainty. Nevertheless, it is clear that the model could be improved so as to better satisfy the data, but a number of limitations of the method make this difficult. These include the nonlinear-nature of the inverse

![Fig. 6. Vertical slices through the synthetic checkerboard model (left) and recovered model (right). (a) E-W slices taken at constant latitude; (b) N-S slices taken at constant longitude. Slice locations are denoted in Fig. 5c (top). Note that compared to Fig. 5, velocity perturbations are differential with respect to a 1-D background model.](image-url)
problem, which may not be fully addressed by an iterative nonlinear approach; the use of a regular parameterisation and the application of smoothing and damping; and the assumption of high frequency wave propagation. However, it is worth noting that the RMS residual of the synthetic test shown in Figs. 5 and 6 is 172 ms, which is 25 ms greater than the 147 ms residual achieved with the WOMBAT dataset. In this case, much of the misfit is due to the fact that a smooth solution model is required; if the checkerboard pattern is described by a smooth sinusoidal pattern rather than one that approaches a box car function, then the misfit can be reduced to a value much closer to the standard deviation of the added noise.

Figs. 8 and 9 show a series of horizontal and vertical slices through the AuSREM and WOMBAT models, using an identical set of cuts to Figs. 5 and 6, which show the checkerboard reconstruction test results. For each slice, AuSREM is shown in addition to the WOMBAT model in order to provide a measure of the additional structure required by the teleseismic data. Clearly, the general effect of the teleseismic data is to superimpose smaller scale structure on the starting model. The basic first order trend of the AuSREM models is a gradual decrease in velocity to the southeast; the addition of the teleseismic data does nothing to change this, which is entirely expected. However, in addition to the obvious small scale features that are introduced, at least one broad scale structure is enhanced — the high velocity region that protrudes south at about 142° E, 33° south (Fig. 8b) becomes more pronounced with the addition of teleseismic body wave data. The vertical cross-sections (Fig. 9) also show a duality in scale with little evidence that the AuSREM model in any way sum up to the combined results. One obvious exception is the B-B’ cross-section at 36.9° south in Fig. 9a, where a strong contrast from higher to lower velocities is introduced at around 143° E, which is absent from AuSREM.

Although there is some evidence of smearing in the combined solution model, particularly in the N–S sections (Fig. 9b), where the propensity for northerly dipping anomalies should be viewed with caution, most of the small scale structure within the bounds of the array is well constrained according to the synthetic test results of Figs. 5 and 6. It is important, however, to be aware when attempting to interpret Figs. 8 and 9, that a distinct switch in resolving power, from ~50 km to ≥200 km is present near the bounds of the combined arrays. Another factor to be aware of is the limited reliability of the model for depths shallower than about 70 km on the mainland and 40 km in Tasmania. This is because station spacing largely dictates the minimum depth at which rays still cross; above this depth, there is little constraint on structure. The inclusion of a smoothed version of the AuSREM crustal model and the use of station terms will help prevent unresolved shallow structure from being erroneously mapped to greater depths, but tests carried out by Rawlinson and Kennett (2008) indicate that anomalies shallower than 70 km depth on the mainland are not reliable. The presence of the Southern Highlands parallel to the southeast coast of Australia, with maximum elevations exceeding 2 km, means that there is likely to be a substantial root at the base of the crust. Without accounting for this explicitly through the inclusion of a Moho interface, it would be dangerous to interpret velocity variations in the mantle immediately below the crust in this region.

5. Discussion

Previous studies using teleseismic data from various subsets of the WOMBAT array (Clifford et al., 2008; Fishwick and Rawlinson, 2012; Graeber et al., 2002; Rawlinson and Fishwick, 2012; Rawlinson and Kennett, 2008; Rawlinson and Urvoy, 2006; Rawlinson et al., 2006a, 2006b, 2010b, 2011) have focused on velocity structure beneath the southern half of WOMBAT (Fig. 1), including those associated with the Newer Volcanics province in western Victoria, the transition from Proterozoic to Palaeozoic lithosphere in Victoria and southern New South Wales, and the boundary between the Western and Eastern Tasmania terranes. In our interpretation of the new model, we focus primarily on anomalies beneath central and northern New South Wales, southernmost Queensland and southern South Australia, as these have not been previously imaged using WOMBAT data. We also examine how the use of an improved starting model in the form of AuSREM may have influenced the results in comparison to previous studies in the south.

Before discussing the results in detail, it is worth briefly summarising the relationship between seismic velocities and the physical and compositional properties of the Earth. Unfortunately, this relationship is highly non-unique, which means that in addition to the uncertainties in the model that are produced due to variations in data coverage and the limitations inherent to seismic tomography,
our ability to make inferences about the underlying geology faces an additional challenge. Seismic P-wavespeeds are largely dependent on temperature, composition, the presence of melt, grain size, solid phase transformations and anisotropy, although in the upper mantle, temperature appears to be the dominant factor. For example, Cammarano et al. (2003) found that a 100 °C increase in temperature at 200 km depth can produce a velocity perturbation of as much as 1%. The effects of composition are more difficult to quantify, with estimates of variations in wavespeed as a result of realistic changes in composition varying between 1 and 5% (Cammarano et al., 2003; Griffin et al., 1998;)

Fig. 8. Horizontal depth sections through AuSREM (top) and combined model (bottom) obtained by the inversion of teleseismic arrival time residuals. Horizontal red and vertical blue lines superimposed on the synthetic model in (c) denote the locations of the cross-sections shown in Fig. 9.

Fig. 9. Vertical slices through the AuSREM (left) and combined model (right) obtained by the inversion of teleseismic arrival time residuals. Slice orientations are identical to that shown in Fig. 6. See Fig. 8c (top) for location information relative to the horizontal sections. Note that velocity variations between 0 and 50 km depth are not shown.
Sobolev et al., 1996). In a comparison of laboratory study results with seismic shear wave and attenuation models, Faul and Jackson (2005) found that reasonable temperature differences could explain the velocity variations seen within continental interiors. Thus, the strong change from high wavespeeds beneath cratonic Australia to lower speeds beneath the Tasmanides observed in surface wave tomography may be a result of older and colder lithosphere juxtaposed against younger and hotter lithosphere. However, a more recent study (Dalton and Faul, 2010) shows that while seismic velocity variations in the upper mantle appear to be largely controlled by lateral temperature variations in dry melt-free olivine, outliers do occur. Beneath oceanic regions, these outliers can be explained by the presence of partial melt, whereas beneath cratonic regions chemically depleted lithosphere (higher Mg#) appears to play a role in increasing wavespeeds, as reasonable temperature decreases alone cannot explain the high velocities that are sometimes observed above 200 km depth.

Fig. 10 shows a 150 km depth slice through the new WOMBAT teleseismic model with crustal element boundaries and magnetic and gravity lineaments from Fig. 1 superimposed. In addition, a line showing the possible location of the eastern limit of the Precambrian lithosphere is included, based approximately on the 8.1 km/s contour. Although the choice of this value as a proxy for the transition between the lithosphere and underlying mantle is somewhat arbitrary, it does correspond to a zone of elevated horizontal velocity gradient. This can also be seen in the E–W cross-sections shown in Fig. 9a, where a distinct lithospheric scale contrast in velocity is clearly present. In the study of Rawlinson et al. (2011), a similar contrast in velocity is seen in western Victoria and southern NSW, and is interpreted as the presence of Delamerian lithosphere of Proterozoic continental origin underlying the Stawell Zone of the Western Subprovince of the Lachlan Orogen. The extension northward of the transition zone is not a simple N–S lineament, but trends northeast, and has a number of distinct salients and re-entrants.

One of the most distinct salients of the inferred transition zone shown in Fig. 10 is that which extends beneath the New England Orocline in the northeast (see Fig. 1). The New England Orogen is clearly observed near the surface by strongly curved magnetic and gravity lineaments, and appears to be one of the most contorted orogens in the world (Rosenbaum, 2012). In the study of Cawood et al. (2011), the eastern margin of Gondwana is assumed to be relatively linear prior to oroclinal folding; this is based on younging directions identified within individual thrust slices that make up the orocline, which point to a progressive imbricate thrusting of oceanic crust and trench sediments along a linear convergent margin. A key element of the reconstruction put forward by Cawood et al. (2011) to explain the formation of the New England Orocline is that southern elements of the subduction system are able to migrate northwards relative to northern elements, which are effectively pinned in place by the presence of the Gondwana craton. Remarkably, the suggested location of the buried tip point of the Gondwana craton in Fig. 9 of Cawood et al. (2011) corresponds almost exactly with the distinct salient observed in the northeast region of Fig. 10, which appears to underpin the strongly curved gravity and magnetic lineaments which characterise the New England Orocline. One caveat with our results is that the northerly extent of the salient is not well constrained, as resolution drops off rapidly north of about 29° south. Thus, the narrow "finger" that is evident may in fact simply be the southerly tip of a much larger high velocity region that extends northwards. However, even if this is the case, it appears that what is probably Precambrian lithosphere of continental origin lies beneath the northern part of the New England Orocline; this is also supported by geochemical evidence in the form of Neoproterozoic Re–Os ages and Neoproterozoic zircon model ages (Glen, 2005).

The Curnamona Province (Fig. 1) lies within the Delamerian Orogen, and was initially regarded as a piece of craton (Thomson, 1970) owing to its apparent immunity to tectonic alteration since the Neoproterozoic. However, ample evidence for Middle to Late Cambrian deformation and metamorphism associated with the Delamerian Orogeny towards the edges of the crustal block has resulted in the label "Curnamona Craton" being dropped (Conor and Preiss, 2008). Much of the Curnamona Province is buried, with aeromagnetic data revealing its full 50,000 km² extent beneath Mesozoic–Quaternary cover (see Fig. 1). Regional surface wave tomography has hinted at its presence (e.g. Fishwick and Rawlinson, 2012) by way of a high velocity zone that extends to depths of at least 200 km – testament to its Archean origins – but does not show any separation between it and the Gawler Craton to the west. This is also true of the AuSREM mantle model, which exhibits a southerly salient in this region (Fig. 8b, top). In both Figs. 10 and 8b, bottom, a more distinct high velocity region can be observed beneath the Curnamona Province, which terminates to the west at the Adelaide Fold Belt (see Fig. 1). To the north, the high velocity zone appears to bend around the northerly limit of the Adelaide Fold Belt and connect with the main cratonic elements of Precambrian Australia. This is consistent with the idea that the Curnamona Province was once an easterly continuation of the Gawler Craton prior to the Neoproterozoic (Belousova et al., 2006; Hand et al., 2008; Wade et al., 2012).

In a previous study using WOMBAT teleseismic data, Fishwick and Rawlinson (2012) converted a regional S-wave model into a P-wave model – assuming a constant Vp/Vs ratio – and used it as a starting model to invert for P-wave structure south of about 32° S. A comparison of the P-wave model of Fishwick and Rawlinson (2012) with the one produced in this study shows good general agreement where they overlap – for instance the location of the Lachlan–Delamerian boundary and the geometry of the low velocity zone associated with the hot spot beneath the Newer Volcanics province. However, there are some notable differences, such as the magnitude of the velocity decrease towards the passive margin, which is less in Fig. 11 (bottom left) of Fishwick and Rawlinson (2012) than it is in Fig. 10 of this paper. Another difference is that the velocities in the deep lithosphere (150+ km depth) beneath the more cratonic region of Australia are higher in Fishwick and Rawlinson (2012) (~8.6 km/s) than they are here (8.3–8.4 km/s). The higher velocities of the previous model seem
less likely to be correct, and are probably due to the very approximate method of constructing the initial P-wave model. As the WOMBAT dataset gradually expands with the deployment of more arrays and methods of analysis improve, variations in the results such as these are to be expected. The hybrid approach of combining a long wave-length initial model with accurate relative arrival time residuals appears to be robust, with the only real weakness appearing to be a lack of good constraint on absolute velocity; however, this is a problem which afflicts most forms of traveltime tomography due to the reliance on regularised inversion.

6. Conclusions

A new P-wave model of the lithosphere beneath southeast Australia has been constructed by combining long wavelength constraints from the newly constructed Australian Seismological Reference Earth Model (AuSREM) with shorter-wavelength constraints from teleseismic data collected by 14 sub-arrays of the WOMBAT transportable array experiment. In the mantle lithosphere, the first-order pattern of velocity variation sees higher velocities beneath cratonic regions in South Australia, and lower velocities beneath the central and eastern Tasmanides, which likely corresponds to a transition from Precambrian lithosphere of continental origin, to thinner Palaeozoic lithosphere which appears to have a mixed oceanic and continental ancestry. Towards the passive margin of the continent velocities in the uppermost mantle decrease even further, which may be due to the combined effect of a thinner lithosphere and thicker crust beneath the Southern Highlands. On a smaller scale, the main features of interest that differentiate this model from those previously published in the literature are the presence of a high velocity salient beneath the New England Orogen, which may reflect the presence of a piece of cratonic Gondwana that forms the pinning point necessary for the northward buckling of the pre-existing linear arc system; the presence of a distinct high velocity zone in the mantle beneath the Curnamona Province, which demonstrates a separation at depth with the Gawler Craton to the west; and the northeast extension of an apparent boundary between thicker and thinner lithosphere, which suggests that basement of Proterozoic origin may be present beneath much of the Tasmanides, including the Thomson Orogen. Interestingly, the lithosphere beneath western Tasmania, which outcrops at the surface as Proterozoic rocks and appears to have compositional affinities with the mainland Delamerian Orogen, is characterised by relatively low velocities, although this may be a function of limited resolution in AuSREM and a lack of constraints at depth in the teleseismic dataset due to the relatively small apertures of the two Tasmanian arrays.

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References
