Crustal structure of the east Gondwana margin in southeast Australia revealed by transdimensional ambient seismic noise tomography

M. K. Young,1 R. A. Cayley,2 M. A. McLean,2 N. Rawlinson,1 P. Arroucau,3 and M. Salmon1

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[1] Ambient seismic noise data from the ongoing WOMBAT transportable seismic array in southeast Australia, the largest deployment of its kind in the Southern Hemisphere, are used to produce a high-resolution 3-D shear wave velocity model of the region. We apply a two-stage, transdimensional, hierarchical Bayesian inversion approach to recover phase velocity maps at periods of 1–20 s and then invert phase velocity dispersion for 3-D shear wave velocity structure to the base of the crust. Data uncertainty is propagated through the sequence of inversions, ensuring that model complexity is justified by the quality and quantity of the measurements. The pattern of 3-D velocity variations helps elucidate the geometry and position of key crustal features—such as the Torrens Hinge Zone—associated with the transition from Paleozoic eastern Australia to Precambrian central and western Australia that formed along the proto-Pacific margin of east Gondwana.


1. Introduction

[2] The Proterozoic and Archean terranes that now form the western two-thirds of the Australian continent represent an amalgamation of fragments of the former supercontinent Rodinia [Powell et al., 1994]. The remaining eastern third of the present-day Australian continent, the region east of the locus of the Neoproterozoic Rodinia breakup, comprises the Tasmanides (Figure 1). This orogen, also known as the Tasman Fold Belt System, formed as a result of accretion along the (then) east Gondwana margin throughout the first half of the Phanerozoic [Glen, 2013].

[3] Interpretation of the Tasman Fold Belt System is difficult given the vast Late Paleozoic-Mesozoic-Cainozoic sedimentary and volcanic cover sequences that overlie and obscure basement structures [e.g., Glen, 2013]. Furthermore, the region has a very complicated tectonic history, with competing models advocating multiple subduction zones [Foster and Gray, 2000], predominantly accretionary oceanic systems [Foden et al., 2006], an intraplate setting [Fergusson et al., 1986], or a combination of all of the above [Cayley et al., 2011a]. In southeast Australia, most authors now conclude that the mid-late Cambrian Delamerian Orogen formed as a result of accretion above a west-dipping subduction zone along the proto-Pacific margin of Gondwana [e.g., Foden et al., 2006] followed, nearly 50 million years later [e.g., VandenBerg et al., 2000], by complex accretion of the Lachlan Orogen, thus forming the majority of southeast Australia by the mid-late Devonian [Glen, 2013].

[4] The seam that marks the transition between the Tasman Fold Belt and the older Australian craton to the west, often called the “Tasman Line,” is a lithospheric-scale structure whose inferred location and nature remain largely controversial [Glen, 2013]. Direen and Crawford [2003] contend that the term has been so misused and confused as to now be meaningless. Part of this confusion stems from the complex 3-D nature of this transition, which has led to marked divergences between interpretations of its position. We believe that the Tasman Line concept can still have value when used as a collective term to describe the complex set of structures that mark the Australian signature of the Rodinian rifted margin—akin to interpretations by Gunn et al. [1997].

[5] In southeast Australia, the Torrens Hinge Zone (THZ, Figure 1) is the western-most surface expression of the Tasman Fold Belt System and separates the Archaen-Mesoproterozoic Gawler Craton from the Neoproterozoic-Paleozoic Delamerian Orogen. The THZ is a north-trending belt of tight folds and meridional faults of Late Cambrian age, imposed on Neoproterozoic-Cambrian, predominantly epicontinental, metasedimentary rocks of the Adelaide Rift Complex [Cawood, 2005]. A major crustal-scale feature, the THZ is estimated at between 15 and 60 km wide [Schmidt and Williams, 1995], but its geometry and depth extent are not well understood.

[6] Ambient noise tomography has the potential to increase tomographic resolution for structures such as the THZ, and especially the subsurface orientation of faults, that play a key role in deciphering the tectonic history of a complicated region. This has been demonstrated previously by Arroucau et al. [2010], who produced a model of group velocity for southeast Australia through a linearized inversion of WOMBAT ambient seismic noise data. WOMBAT is the largest transportable seismic array experiment in the Southern Hemisphere and has resulted in dense passive
2. Data and Method

The transportable WOMBAT seismic array project began in 1998 with the goal of spanning the majority of southeast Australia with seismometers at approximately 50 km spacing. To date, over 600 stations have been installed, of which this study utilizes data from 434 of the mainland sites (most of the remaining sites lie to the south on the island of Tasmania, Figure 1). Each subarray ran between 6 and 12 months, and the presence of overlapping array boundaries facilitates a more uniform ray path coverage than might otherwise have been achieved.

The ambient noise cross-correlation procedure we employ is similar to that of Bensen et al. [2008] and Young et al. [2011]. The cross-correlation and stacking of vertical-component data for all simultaneously recording station pairs yields over 8200 usable cross-correlograms (Figure S1a in the supporting information). We measure phase velocity dispersion using the image transformation technique described by Yao et al. [2006] and modified by Young et al. [2011] (Figure S1b), which exploits the negative time derivative of the cross-correlation function’s symmetric component (average of the causal and acausal signals), which can be interpreted as Rayleigh wave Green’s functions [Curtis et al., 2006].

Once phase velocities are measured for central periods of 1–20 s, a series of tomographic inversions are performed using the new transdimensional, hierarchical Bayesian technique described by Young et al. [2013]. The key advantages
of our Bayesian approach [Bernardo and Smith, 1994] are that the number and distribution of model parameters are implicitly controlled by the data and that the standard deviation of the data noise (assumed to have a Gaussian distribution) is treated as an unknown in the inversion. This “noise” includes whatever our model cannot explain [Bodin et al., 2012], which can be attributed to measurement errors, shortcomings of the forward model, and mathematical or theoretical approximations. As a result, the required complexity of the solution is inferred from the data itself [Bodin et al., 2012], rather than from ad hoc uncertainty estimation techniques and arbitrary parameterizations so often utilized by more traditional, linearized inversion techniques (see review by Rawlinson et al. [2010] for more discussion). The recovery of a phase velocity map for a given central period takes approximately 1000 CPU hours. Although this is three to four orders of magnitude greater than the time taken by a more traditional iterative, nonlinear approach [Young et al., 2011], the improved quality of the results and provision of uncertainty estimates fully justify the additional cost (for example, see the synthetic tests of Young et al. [2013]).

10 The final phase velocity maps (Figures S2 and S3) represent the average of a large ensemble of models of varying parameterization. The 2-D maps are sampled over the range of periods at 20 km intervals in latitude and longitude to produce a collection of 1572 dispersion curves. This is the maximum sampling density at which finer grid spacing did not improve results. Uncertainty estimates for every curve at each period come from an assessment of the standard deviation of the ensemble of 2-D models at each grid point. The phase velocity curves are independently inverted for 1-D shear velocity models using the same hierarchical, transdimensional Bayesian approach [Young et al., 2013] as before (Figure S4). Additional details regarding the application of this method can be found in the supporting information. Finally, the 1-D models are joined together to create a pseudo 3-D map of the shear velocity structure of southeast Australia from the surface down to 30 km depth. In order to reduce the visual impact of the velocity pixelization, the resulting grid of velocity pixels is then transformed into a continuous curvature surface using the Generic Mapping Tools package of Wessel and Smith [1995].

3. Results and Discussion

11 Here we present the mean of the ensemble of models produced by the transdimensional inversion procedure via a set of three cross sections (Figures 2 and 3). A more complete illustration of the tomographic results and accompanying uncertainties is provided in the supporting information (Figures S5, S6, and S7).

12 Cross sections through the shear velocity model (Figures 2 and 3) show a variable, but broadly stratified, velocity structure across southeast Australia, with velocities of 3.6–3.7 km/s dominating the upper few kilometers of crust, grading to velocities of up to 4.1–4.2 km/s in parts of the middle and lower crust. There are some places, for example near the southern edge of the Curnamona Craton near the NSW-SA border, where near-surface regions with lower velocities (red in cross section of Figure 3) thicken abruptly towards the mid-crust (~10 km depth), to form a block of low-velocity material. Presumably, this reflects the presence of deeper, steep-sided, sediment-filled basin structures. Low shear velocities of likely similar origin also occur in eastern Victoria, coincident with the surface distribution of igneous rocks, including silicic volcanics and carbonates related to the Early Devonian Buchan Rift [VandenBerg et al., 2000].

13 Because the Torrens Hinge Zone (THZ) marks the eastern edge of the Gawler Craton and the western limit of Tasmanides-related deformation in southeast Australia, distinguishing the subsurface geometry of this boundary is important to understanding the accretion of the Delamerian Orogen to the east. Until now, with few exceptions, the THZ has been studied at the surface, limiting our understanding of this structure at depth. The new 3-D shear velocity model introduces important new data that constrain the geometry and origin of the hinge zone.

14 The singular most striking feature of the 3-D shear velocity model is the subvertical zone of relatively high shear wave velocity in the mid-lower crust (Figure 2) that cleaves from the northwestern edge of the model toward the Gulf of St Vincent (Figure 1) in the southeast, where it is lost at the model’s southern margin. This feature coincides with the surface position of the THZ. It is easily identified from surface down to 30 km and dips slightly to the east with a width of ~50 km. This subsurface constraint is invaluable, for previous studies at depth were often of limited horizontal extent [e.g., Belperio and Flint, 1993] or lower resolution [e.g., Saygin and Kennett, 2012].

15 The THZ is a major crustal feature with a variety of interpretations. The slight eastward dip seen in our model accommodates several theories. Clarke and Powell [1989] interpreted the THZ as a thrust fault boundary, with the Tasman Fold Belt to the east pushing and buckling over the undeformed Gawler Craton to the west. Such an interpretation would likely require the THZ to dip to the east. Prest [2000] advocates discrete episodes of rifting characterized by crustal extension and basin formation. He suggests normal faults along this zone produced a series of half-grabens stepping down into the basin center. If this is the case, faulting would have occurred nearly subvertically, compatible with the very steep east dips indicated in our model. Belperio and Flint [1993] present yet another picture in which the THZ is portrayed as a zone of faulting and monoclinal flexuring that is bounded on the west by the Cygnet-Snelling Fault, which dips slightly to the east. The new shear velocity model makes it clear that the THZ is a linear, steep-sided, crustal-scale structure in marked contrast to the younger and shallower intracratonic rifts and basins that scatter across the surface of the Tasmanides farther east. Below ~8 km depth, shear velocities within the THZ are markedly higher than in the flanking Mesoproterozoic Gawler and Curnamona cratons.

16 Because of its position, steep overall geometry, and deeply penetrating shear velocity structure, we concur with authors who favor an extensional origin for the THZ. Its formation in the Neoproterozoic presumably related to protracted whole-of-crust rifting at the onset of the Rodinia breakup. The THZ extends the full depth of the shear velocity model and therefore represents a major failed branch of this rift event. Although dominated near surface by well documented clastic rocks (with low shear velocities compared to adjacent regions), the velocity character of the THZ below 8 km suggests that mafic, igneous rocks are predominant at depth. The THZ therefore likely began as the locus
of major rift-related magmatism initiated around ~830 Ma, before the rift became progressively bypassed from ~600 to 580 Ma onwards. Younger, subparallel rift branches [Crawford et al., 1997] developed farther east as the locus for final Rodinian separation [Direen and Crawford, 2003].

The Gawler Craton is interpreted to thin east beneath the THZ and the rest of the Delamerian Fold Belt to form a buried “Tasman Toe” [Scheibner, 1998]. To the east, the Escondida Fault [Cayley and Taylor, 1997] could be the surface expression of this eastern limit of Precambrian crust. The presence and east-dipping geometry of this fault have so far been largely inferred from deep seismic data [Korsch et al., 2002; Cayley et al., 2011b] and magnetics [Moore, 1996; Cayley and Taylor, 1997], as there is minimal surface exposure. Farther north, any along-strike extension to the Escondida Fault is buried beneath the Cenozoic Murray Basin, and its location becomes equivocal. In southern Victoria, the east-dipping Moyston Fault lies close to, and subparallel with, the Escondida Fault and appears to extend to the Moho and possibly beyond [Graeber et al., 2002].

Another candidate for the Tasman Toeline [Cayley et al., 2011a], the Moyston fault has been nominated as the boundary between the Delamerian and Lachlan fold belts within the Tasmanides system [Cayley et al., 2011a; Glen, 2013].

Both the Moyston and Escondida faults lie in the vicinity of the east-dipping lateral velocity change that is readily apparent in the shear velocity model (Figure 2). However, the location of the Escondida Fault corresponds much more closely with the abrupt change in mid-lower crustal shear velocities. Therefore, we conclude that it is the most likely surface expression of this velocity anomaly. Additionally, magnetic trends in the Escondida Fault hanging wall in SA continue north, eventually swinging toward the northeast and passing into NSW—a path followed closely by the lateral shear wave velocity change. The eastward dipping orientation of this velocity transition is consistent with the eastward dip of the southern section of the fault [Cayley et al., 2011b]. It is therefore possible that the Escondida Fault represents the surface expression of inverted passive margin basins developed during the Rodinia.
breakup and that the elevated shear velocities to the east of the fault reflect an abundance of high-velocity mafic igneous rift fill.

[19] Linking the Escondida Fault to the lateral change in shear velocity data means that its position and existence can be interpreted with increased confidence farther north, where it becomes progressively more difficult to trace in magnetic data. The shear velocity model gives confidence that the Escondida Fault is persistent and trends northeast towards the southern margin of the Curnamona Craton. It has previously been speculated that this northeast orientation, almost orthogonal to much of the Delamerian Gondwana margin, may represent a transform fault [Finn et al., 1999].

[20] The Bootheragandra Fault is a north-trending terrane boundary between the Stawell, Hay-Booligal, and Tabberabbera zones on the west and the rest of the eastern Lachlan Orogen to the east. A west-east decrease in the shear wave velocity (Figure 2b) coincides with the near-surface trace of the Bootheragandra Fault in NSW as defined by magnetic data [Musgrave and Rawlinson, 2010]. However, our model implies that the Bootheragandra Fault is subvertical to at least the base of the mid-crust. This differs from the interpretation of Musgrave and Rawlinson [2010] and instead suggests that the Bootheragandra Fault is a northward extension beneath the Murray Basin of a large, Late Silurian aged strike-slip structure further south in Victoria [Morand et al., 2003].

4. Conclusions

[21] In this study, we obtain a high-resolution 3-D shear wave velocity model for the southeast Australian crust down to 30 km depth using ambient noise data recorded by the WOMBAT transportable array. The trans-dimensional, hierarchical Bayesian inversion methods applied to the phase dispersion data recover structure to a level of detail that is unmatched by more conventional linearized techniques. Major features of the model are the striking velocity anomalies seen along the Escondida and Bootheragandra faults and the Torrens Hinge Zone (THZ). Furthermore, upper crustal shear velocity variation correlates with the known distribution of intracratonic rift and basin successions within the Tasmanides.

[22] The results confirm the THZ as a major steep-sided, crustal-scale rift structure that likely formed due to protracted Neoproterozoic rifting during the breakup of Rodinia. Intermediate shear velocities consistent with craton-related rocks extend east towards the Escondida Fault, where they abruptly change to higher velocities along this east-dipping structure, possibly forming the Tasman Toeline. The revelation of the precise geometry and location of these structures is important to understanding the tectonic evolution of the east Gondwana margin in southeast Australia.

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