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New evidence of Tasmania's tectonic history from a novel seismic experiment

N. Rawlinson
Research School of Earth Sciences, Australian National University, Canberra, Australia

G. A. Houseman
School of Earth Sciences, University of Leeds, Leeds, U.K.

C. D. N. Collins and B. J. Drummond
Australian Geological Survey Organisation, Canberra, Australia

Abstract. In March 1995, 44 land-based recorders were deployed throughout Tasmania, SE Australia, to record seismic energy from an encircling array of marine normal-incidence reflection shot lines. We invert refraction and wide-angle reflection traveltimes for crustal structure, with the principal outcome being a map of the Tasmanian Moho. Key tectonic inferences from this map include: (1) the Arthur Lineament metamorphic belt in NW Tasmania overlies a major change in crustal thickness (over 5 km) and probably represents the NW limit of deformation in Tasmania during the Mid-Late Cambrian Tyennan Orogeny, (2) thickening of the crust beneath central northern Tasmania may be associated with the juxtaposition of the Eastern and Western Tasmania Terranes during the Mid-Devonian Tabberabberan Orogeny, and (3) the difference in crustal thickness between the east and west coasts reflects the presence of differing strain regimes during the Cretaceous break-up of Gondwana.

Introduction

Seismic refraction and wide-angle reflection arrivals from seismic experiments that utilize marine air-gun sources and distant receiver locations may be exploited to image subsurface structure. Commonly, this is done using tomographic-style inversion methods which attempt to reconcile observed traveltimes with model velocity and/or interface structure [*Hole,* 1992; *Riahi and Lund,* 1994; *Ye et al.,* 1997; *Zelt et al.,* 1999].

We summarize the results of a 3-D inversion for Moho structure and crustal velocity using seismic refraction and wide-angle reflection traveltime data collected in Tasmania, an island state located off southern mainland Australia. The principal goal of the survey was to collect normal-incidence reflection data during a shot-line circumnavigation of Tasmania [*Hill and Yeates,* 1995]. The placement of seismic recorders throughout Tasmania (Fig. 1a) to collect wide-angle reflection and refraction data was a relatively low-cost addition. This is the first study to attempt the determination of a detailed Moho depth map for an entire island at this scale by inversion of controlled source data.

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Data and method

As part of the TASGO project [*Hill and Yeates,* 1995], the Australian Geological Survey Organisation (AGSO) research vessel *Rig Seismic* fired ~36,000 air-gun shots at a 50 m spacing while circumnavigating Tasmania. In addition to recording normal-incidence reflection data [*Drummond et al.,* 2000], an array of 44 digital and analogue recorders was deployed throughout Tasmania to detect refraction and wide-angle reflection arrivals (Fig. 1a). Despite the limited range at which the airgun sources could be effectively recorded (usually < 200 km), a lack of land-based shots, a number of recorder failures and low signal-to-noise ratios at several sites, sufficient data were obtained to make a tomographic-style inversion for crustal structure feasible.

Reflections from the Moho (P_mP) are generally the most prominent phase type that can be identified in the TASGO wide-angle data set. Moho refractions (P_n) are also evident though not to the same degree as P_mP arrivals. Shallower crustal phases are also identifiable, but generally only for receivers near a shot line. Fig. 1b shows two seismic sections; one in which both P_n and P_mP phases are identified, and one in which only the P_mP phase is visible.

We use the method of *Rawlinson et al.,* [2001] to invert refraction and reflection traveltimes for crustal structure. In this approach, structure is represented by sub-horizontal layers separated by smoothly varying interfaces with a cubic B-spline parameterization. Within a layer, velocity varies linearly with depth but has no lateral variation. A shooting method of ray-tracing is used to solve the two-point problem of finding the first-arrival ray-path and traveltime of a specified phase.

The inverse problem is formulated as a non-linear optimization problem in which an objective function consisting of a data residual term and a regularization term is minimized by adjusting the values of interface node depths, layer velocities, and layer velocity gradients. The regularization term measures the misfit between the initial and re-

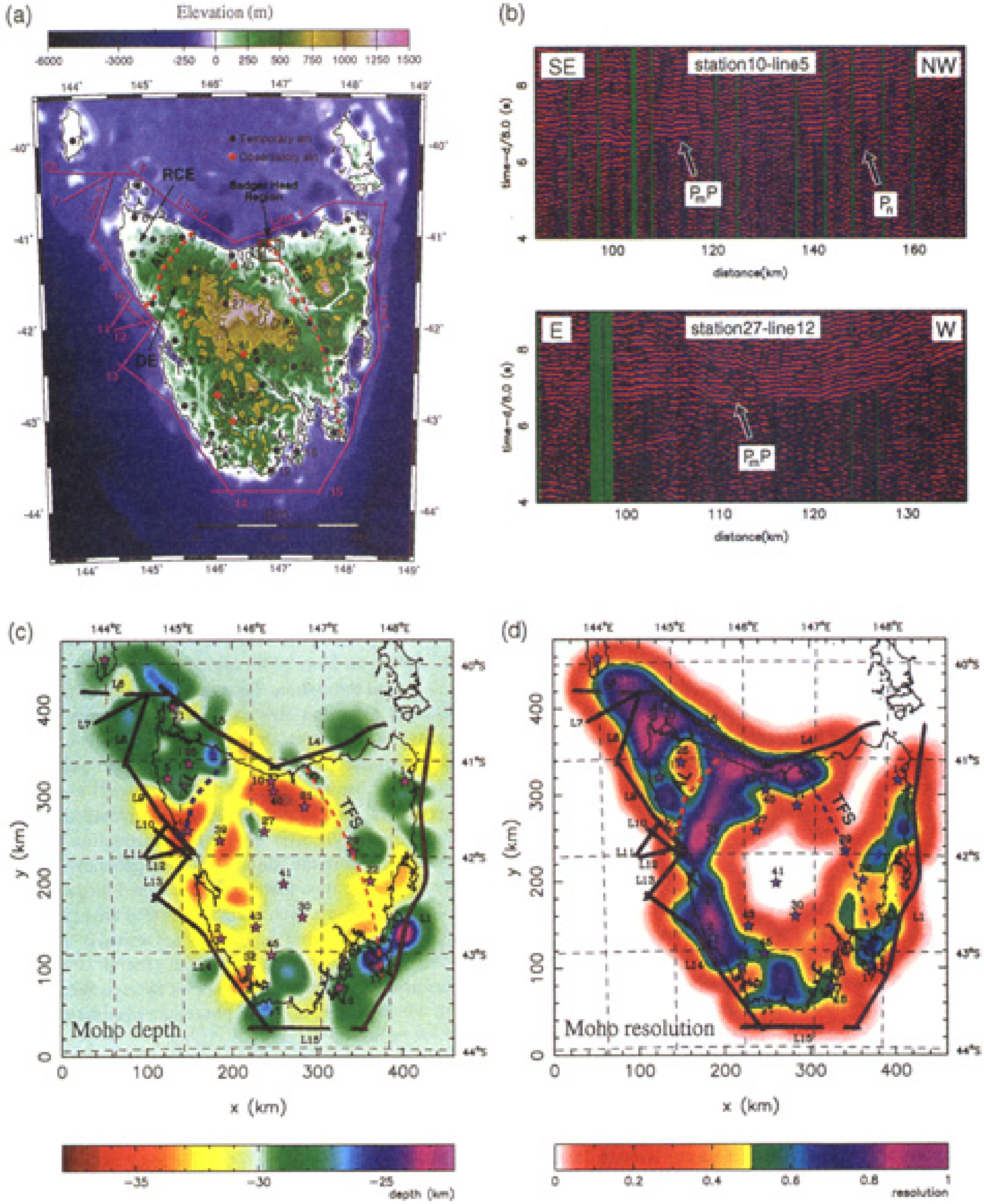

Figure 1. (a) The TASGO wide-angle seismic survey. Solid lines indicate shot lines (50 m shot spacing) and numbered symbols represent land-based stations. The centre of the Rocky Cape Element (RCE) and Dundas Element (DE) are indicated. Thick dashed lines denote tectonic element boundaries: Arthur Lineament (AL) and Tamar Fracture System (TFS). (b) TASGO wide-angle seismic data examples. Bandpass filtering between 4-14 Hz and 9-trace stacking are applied in both examples. (c) Inversion solution after four iterations. (d) Diagonal elements of the resolution matrix for the solution shown in (c). Regions of good resolution have a value ≥ 0.5. In both (c) and (d), stars indicate recorders and small triangles indicate shot points from which data were picked; contiguous triangles form shot lines except where data gaps occur (e.g. lines 4 and 15). P_n and P_mP phases could only be picked from the records of 21 of the 44 recorders shown in (a).

constructed model [*Rawlinson et al.,* 2001]. A subspace inversion technique [*Kennett et al.,* 1988] which naturally deals with multiple parameter classes is used iteratively to perform the function minimization. Rays are re-traced after each model update in order to address the non-linear nature of the inverse problem. To assess the robustness of the solution, resolution estimates obtained from linear theory [*Tarantola,* 1987] are used.

The structural representation assumed by this method lies at one end of a spectrum of possible representations that range from interface-only to velocity-only variation. However, for sparse data sets like the TASGO wide-angle data set, the unlikely prospect of resolving the trade-off between interface depth and lateral velocity variation within a layer does not justify the use of a more complex representation.

Results

The principal inversion result we consider is obtained by using all picked P_mP and P_n traveltimes to constrain a two-layer model of Tasmania, consisting of the crust and upper mantle separated by a Moho of variable depth. The key assumption of this representation is that actual lateral variations of velocity within the crust are not large enough to significantly influence the Moho reconstruction obtained by inversion of P_mP and P_n traveltimes.

A total of 2590 traveltimes (2148 P_mP and 442 P_n) from 13 shot lines to 21 receivers is used in the inversion. The RMS picking uncertainty of these traveltimes is estimated at 143 ms, with each pick uncertainty used in the data covariance matrix of the objective function. A model with 1-D structure, based on the average Moho depth and crustal velocity from nine separate 1-D inversions (each using data recorded at a single station from a single shot line) for interface depth and velocity variation in different regions of Tasmania, is used as a starting model for the 3-D inversion. The Moho depth of the starting model is 30 km and the depth averaged crustal velocity is 6.2 km/s with a velocity gradient of 0.033 s^{-1}. The P_n velocity of the initial model is 7.9 km/s and the velocity gradient in the upper lithospheric mantle is 0.030 s^{-1}. To describe the Moho, a rectangular grid of 600 nodes spaced 20 km apart in x (east) and y (north) is used. The total number of unknowns in the inverse problem is 604.

The RMS traveltime residual associated with the initial model is 371 ms; after four iterations of a 14-D subspace inversion method, this is reduced to 176 ms. Subsequent iterations do not significantly improve the traveltime fit and only result in superficial changes to the solution model. Figs. 1c and 1d show the Moho structure of the solution model and the diagonal elements of the resolution matrix calculated at the solution point respectively. The poor resolution (values <0.5 in Fig. 1d) of the Moho beneath central and NE Tasmania is a result of having no sources near central Tasmania and few receivers in NE Tasmania. Note that resolution estimates are not necessarily zero immediately outside the horizontal bounds of the source-receiver array due to the smooth nature of the interface parameterization [*Rawlinson et al.,* 2001]. The average crustal velocity of the solution model is 6.2 km/s and the average P_n velocity is 8.0 km/s, with resolution estimates suggesting that these values are robust. The velocity gradients within the crust and mantle are reduced to 0.010 s^{-1} and 0.028 s^{-1} respectively, although these values are not well resolved.

To test the validity of assuming a laterally invariant crust, a separate inversion was performed for a model that included a mid-crustal interface (initial depth of 8.5 km) in the Moho-only model. This introduced lateral variability in crustal velocity by allowing the shape of the mid-crustal interface to vary in the inversion. An additional 2156 crustal traveltimes from three different phase types (refractions from the two crustal layers and reflections from the mid-crustal interface) were added to the 2590 P_mP and P_n traveltimes. The inversion result after four iterations reveals a mid-crustal interface that generally varies in depth between 4 km and 16 km with a velocity contrast of ~0.5 km/s. Despite these lateral variations in the crust, the Moho topography and average crustal and P_n velocities are essentially the same as those recovered for the Moho-only model (Fig. 1c). However, the mid-crustal interface is poorly resolved everywhere except for a few patches along the coast, and therefore cannot be very meaningfully associated with geological structure.

Tectonic implications

Tasmania is composed of seven Proterozoic-early Palaeozoic stratotectonic elements overlain by much younger cover sequences [*Brown et al.,* 1998]. Each element is unique in terms of its geological and tectonic history, and its internal structure and composition. The Rocky Cape Element, located in NW Tasmania, is bounded to the SE by the Arthur Lineament (Fig. 1a), a band of metamorphic rock, which separates it from the Dundas Element. There is a strong correlation between the transition from the Rocky Cape Element to the Dundas Element and the steep gradient in crustal thickness SE of stations 5 and 25 (see Fig. 1c), which suggests that the Arthur Lineament is associated with a deeper structure that extends to the Moho and below. The tectonic environment necessary to create these features may have been provided by the Late Cambrian Tyennan Orogeny. During this time, substantial E-W shortening was experienced throughout much of Tasmania [*Elliot et al.,* 1993]. The Rocky Cape Element behaved as a resistant cratonic block during this compressional episode [*Turner et al.,* 1998] and was not substantially thickened; in this scenario, the Arthur Lineament represents the NW limit of the Orogeny.

The Tamar Fracture System (Fig. 1a) marks the boundary between the East and West Tasmania Terranes. The West Tasmania Terrane contains six stratotectonic elements of Proterozoic origin; the East Tasmania Terrane includes the NE Tasmania Element, and contains no evidence of pre-Phanerozoic material. Beneath stations 10, 21 and 40 in central northern Tasmania (Fig. 1c), a significant downwarp of the Moho to a depth of ~37 km occurs. Based on the surface geology of the Badger Head region, which lies above the Tamar Fracture System (Fig. 1a) in northern Tasmania, Elliot et al., [1993] conclude that westward directed thrusting of Early and Mid Palaeozoic strata of the Beaconsfield Block (E) over the Badger Head Block (W) occurred during the juxtaposition of the East and West Tasmania Terranes in the Mid-Devonian, synchronous with the Eastern Australian Tabberabberan Orogeny. Crustal shortening in the Badger Head region as a result of this event has been estimated at 20% [*Elliot et al.,* 1993]. The Moho downwarp observed in central northern Tasmania (Fig. 1c) is consistent with this tectonic model and suggests that shortening has occurred locally throughout the crustal thickness.

During the breakup of Gondwana, seafloor spreading between Australia, Antarctica and New Zealand was initiated in the Cretaceous. The position of Tasmania at the SE tip of Australia and the orientation of the spreading ridge implies that Tasmania's western margin was formed as a result of trans-tensional strike-slip motion along the Tasman Fracture Zone, which lies just west of Tasmania. Severe wrench deformation is the principal feature in this region [*Royer and Rollet,* 1997] and does not require crustal extension and thinning. The Moho model is well resolved along the western coast of Tasmania (Fig. 1d) and the crust is generally quite thick (31-36 km) south of the Rocky Cape Element (Fig. 1c). Crust of this thickness close to the continental slope is more consistent with a margin that has been formed by wrench tectonics as opposed to extension. In contrast, extension during rifting between eastern Tasmania, the East Tasman Plateau and the Lord Howe Rise prior to sea floor spreading in the Tasman Sea [*Royer and Rollet,* 1997] is expected to involve crustal thinning. The crustal thickness beneath the east coast (usually <30 km), although not particularly well resolved (Fig. 1d), tends to decrease towards the continental slope (especially in the SE beneath station 17), consistent with a margin formed by extension-related rifting.

Conclusions

An inversion of P_mP and P_n traveltimes recorded by a land-based receiver array from a series of marine shot lines which circumscribed Tasmania reveals several features in the solution model that support previous interpretations of the tectonic evolution of this region. In particular, the significant Moho depth variations evident in the model are spatially correlated with major surface structures and are consistent with the tectonic styles interpreted from the surface geology.

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C. D. N. Collins and B. J. Drummond, Australian Geological Survey Organisation, Canberra ACT 2609, Australia.

G. A. Houseman, School of Earth Sciences, University of Leeds, Leeds LS2 9JT, U.K.

N. Rawlinson, Research School of Earth Sciences, Australian National University, Canberra ACT 0200, Australia. (e-mail: nick@rses.anu.edu.au)

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