Crustal velocity and sediment thickness asymmetries along and between the conjugate Australian-Antarctic margins

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The Australian-Antarctic conjugate margins are remarkably symmetric in comparison to other magma-poor rifted continental margins, particularly in the central Great Australian Bight section. Here, we use two datasets derived from seismic refraction data to investigate the pre-rift crustal structure of the conjugate Australian-Antarctic margins. We analyse two datasets for the conjugate Australian-Antarctic margins, (i) seismic velocity data derived from a synthesis of seismic refraction and sonobuoy data, and (ii) estimates of total sediment thickness from seismic refraction data calibrated against stacking-derived seismic velocities from seismic reflection profiles along each margin. Using a novel approach involving plate reconstruction and 3D visualistion we utilize these datasets to map the 3D lithospheric structure of the Australian-Antarctic margins. Our approach enables accurate juxtaposition of the Australian-Antarctic conjugate margins at the approximate time of breakup (~83 Ma). We find that the distribution of sediment along and across the conjugate Australian-Antarctic margins is highly asymmetric and that observed asymmetries in crustal structure are predominantly due to the patterns of sediment loading. Our results also indicate that total sediment thicknesses have been significantly underestimated from seismic reflection profile data for large sections of both margins. Underestimations of total sediment thickness appear particularly severe on the Antarctic margin. A significant insight this analysis provides is that the velocity information from seismic refraction data has been grossly under-utilised.

Introduction

Understanding the crustal architecture of the Australian and Antarctic continental margins provides an important framework for studying the petroleum systems within basins that developed as a result of continental extension and breakup. Initiation of the sedimentary rift basins along the southern Australian and conjugate Antarctic margins began as early as 160 million years ago (Ma) (Totterdell et al. 2000). Early rifting occurred until ~140 Ma, followed by thermal subsidence until ~100 Ma, when a renewed phase of rifting preceded eventual commencement of continental breakup from ~83 Ma (Totterdell et al. 2000).

The manner in which rifting proceeded and the timing of Australian-Antarctic continental breakup have remained controversial. The extent of continental crust, oceanic crust and the nature of the continent-ocean transition (COT) are unclear in many parts of both margins. Within the Great Australian Bight for example, Sayers et al. (2001) interpreted a zone of transitional crust, up to 120 km in width, containing highly thinned continental crust, mafic intrusions and serpentinized peridotites. In the conjugate Wilkes Land margin a wide COT is also interpreted though opinions vary significantly as to how far this zone extends towards the ocean (Colwell et al. 2006; Close et al. 2009).

A number of authors have examined the crustal architecture of the conjugate Australian-Antarctic margins by juxtaposing single key seismic reflection, refraction and velocity profiles. For example, Stagg and Reading (2007) examined the juxtaposed George V Land and Otway Basin margins and found significant asymmetries in width, thickness and velocity structure of the paired profiles. Direen et al. (2011) used juxtaposed deep seismic reflection profiles from the Ceduna sub-basin and Wilkes Land and potential field data to illustrate the symmetry of features across Australian-Antarctic rift basin immediately prior to breakup. In contrast, Espurt et al. (2012) used juxtaposed deep seismic reflection profiles and balanced cross-sections from further east in the Ceduna sub-basin with Terra Adelie to model the symmetric followed by asymmetric evolution of this section of the margin.

Here, we take a whole margin approach and investigate the spatial variation in the petrophysical properties of the extended crust and overlying sediments. We use seismic velocities, maps of sediment thickness, and estimates of Moho depth derived from gravity inversion. We reconstruct these data based on current plate tectonic models to create maps and a series of vertical profiles of the crustal architecture of the Australian and Antarctic rift basin at the time of continental break-up.

Data and Methods

We present and discuss two datasets from the conjugate Australian-Antarctic margins. Firstly, we co-locate deepest penetrating velocity solutions from refraction and sonobuoy data, and total sediment thickness interpreted in reflection data in two-way time. Figure 1 shows the locations of the seismic refraction and sonobuoy observations. As a result, we obtain velocity-depth functions from sonobuoy/refraction velocity solutions within the areas of the thickest sediments. Access to the refraction data from the recent Russian Antarctic expeditions allowed us to extend these velocity solutions to depth equivalent of 5s TWT below sea floor.

Secondly, we calculate average velocity as a function of TWT below sea floor from these velocity solutions. The purpose of this was to isolate TWT components of (a) water layer and (b) sediments, and to enable a two-step depth conversion: water bottom at constant velocity of 1500 m/s, and basement at average velocity between the seafloor and basement.

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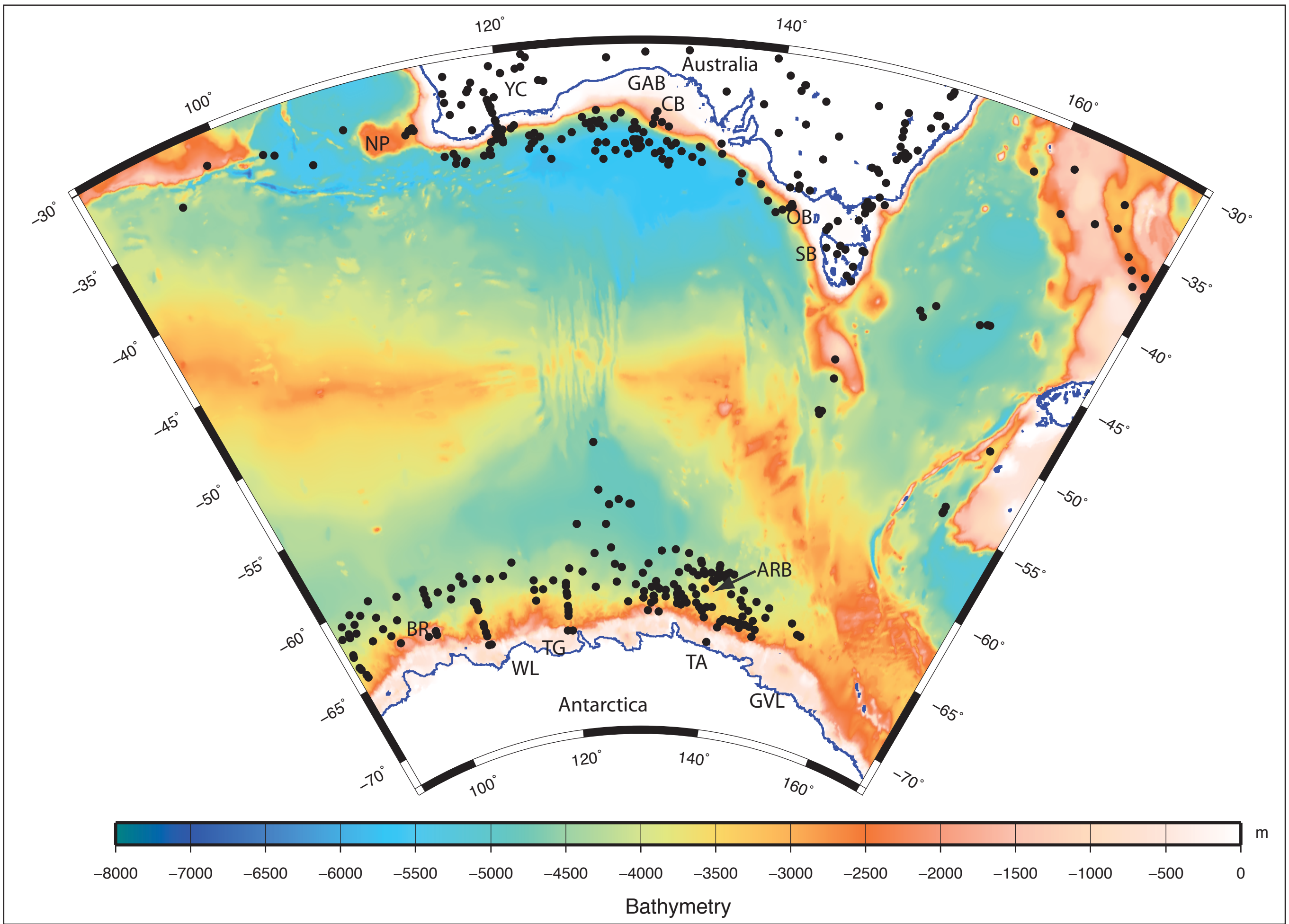

Figure 1. Regional bathymetric map (GEBCO 2008) showing locations of velocity data from seismic refraction and sonobuoy sources (black dots). ARB – Adelie Rift Block; BR – Bruce Rise; CB – Ceduna Basin; GAB – Great Australian Bight; GVL – George V Land; NP – Naturaliste Plateau; OB – Otway Basin; SB – Sorell Basin; TA – Terra Adelie; TG – Totten Glacier; WL – Wilkes Land; YC – Yilgarn Craton.

We then extrapolate the velocity trends in the deepest sediments to provide velocity functions for depth conversion in the areas where reflection basement is interpreted at greater TWT than the extent of available velocity functions from refraction data. Minimum and maximum average velocity functions sub-seafloor are approximated by polynomial functions.

Finally, we estimate the maximum and minimum total sediment thicknesses utilising the maximum and minimum average velocity functions, respectively. We restore the seismic velocity data to their relative positions at 83 Ma (the approximate timing of continental breakup along much of the margin) and then grid the reconstructed data in three dimensions to present both map and profile representations. We reconstruct the velocity data points from the Australian and Antarctic margins to their palaeo-locations at 83 Ma by first excluding data situated on ocean crust younger than 83 Ma. The data points are then rotated back through time using rotation parameters (Williams et al. 2011) that describe the relative motion between Australian and Antarctica. After reconstruction, the velocity grids are created from the data points at 1 km depth intervals from 5 km to 15 km depth (Figure 2). Gridding of the velocity data after reconstruction allows interpolation between points that were adjacent at 83 Ma, but are currently separated by 1000s of kilometers, leading to more accurate calculations of Australian-Antarctic margin crustal architecture.

The spatial distribution of the velocity data varies considerably across the area, with denser coverage achieved in the western portion of the Australian southern margin and the eastern portion of the Antarctic margin (Figures 1 and 2). All data points shown in Figure 1 were gridded using a near neighbor algorithm although the gridded data shown in Figure 2 are limited to longitudes 110°W to 150°E. The resulting grid was masked were there was not either 1 data point within 0.5 degrees or 2 points within 2 degrees.

To visualize this 3-dimensional velocity data set, we present images of (i) velocity grids through the consolidated crust at 1 km intervals down to 15 km depth, and (ii) longitudinal profiles extending from the unstretched Australian continental crust across the restored rift zone to the Antarctic margin.

We construct a series of NNW-SSE oriented vertical profiles spaced at 2 degrees longitudinally (Figure 3) from the 1 km velocity grids (Figure 2). The profiles are oriented NNW-SSE to reflect the overall direction of motion between Australia and Antarctica from the onset of continental rifting to 83 Ma based on the recent model of Williams et al. (2011). Different plate reconstruction models imply significantly different directions for the overall relative motion of the plates during the rifting phase; for example Powell et al. (1988) models overall NE-SW motion, while Royer and Sandwell (1989) model NW-SE overall motion.

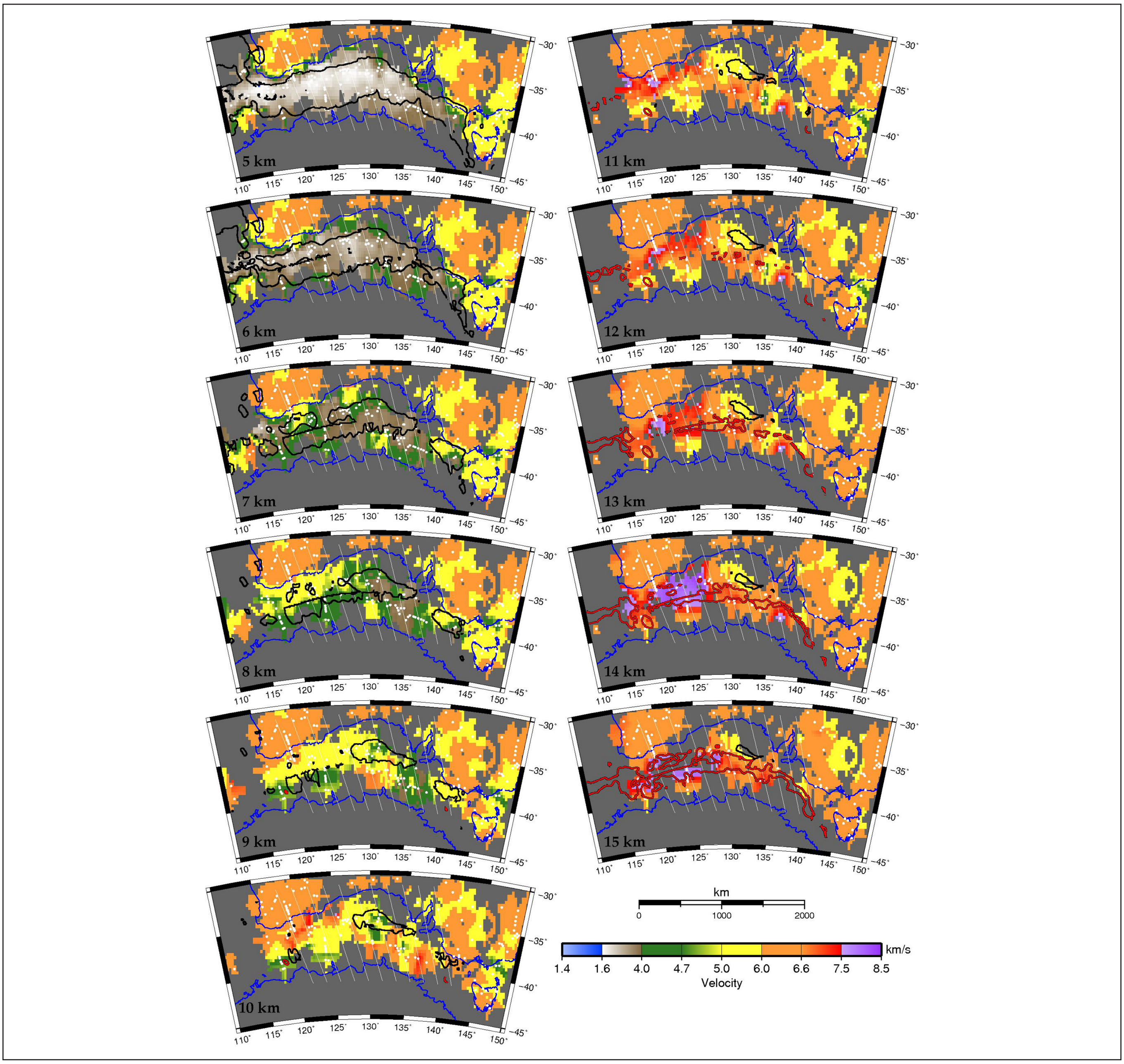

Figure 2. Reconstructed velocity slice data at depths of 5-15 km in 1 km intervals. Blue lines – coastlines; black lines – extent of sediments based on our maximum sediment thickness estimates; red lines – Moho depth (average of the four preferred models from Kusznir (2009)); white dots – data locations; thin white lines – profile locations shown in Figure 2, these profiles are oriented NNW-SSE to match the overall direction of rifting (Williams et al. 2011).

Figures 2 and 3 use a colour palette based on the scheme of Funck et al. (2007; 2012) that relates velocity ranges with crustal elements, see Table 1. For this study key velocity boundaries occur at 4.0 km/sec – between upper and lower sediments, 6.0 km/sec between highly compacted sediments and the upper crust, and at 7.5 km/sec which marks the crust/mantle transition.

On the cross-sections we also plot lines showing the depth of the Moho derived from the gravity inversion results of Kusznir (2009). To simplify the comparison, we took the full set of ‘preferred’ results from Kusznir’s study based on different parameters of margin type and estimated sediment thickness and calculated a mean depth. Note that the original gravity inversion results are grids of depth to Moho that were calibrated against point estimates of Moho depth from sonobuoys.

Velocity range	Possible Lithology
1.4-1.6 km/sec	Water
1.6-4.0 km/sec	Upper sediments
4.0-4.8 km/sec	Lower sediments
4.8-6.0 km/sec	Highly compacted sediments, limestones, basalts?
6.0-6.6 km/sec	Upper crust
6.6-7.5 km/sec	Lower crust
7.5+ km/sec	Crust/mantle transition and upper mantle

Table 1. Guide to the velocity colour palette.

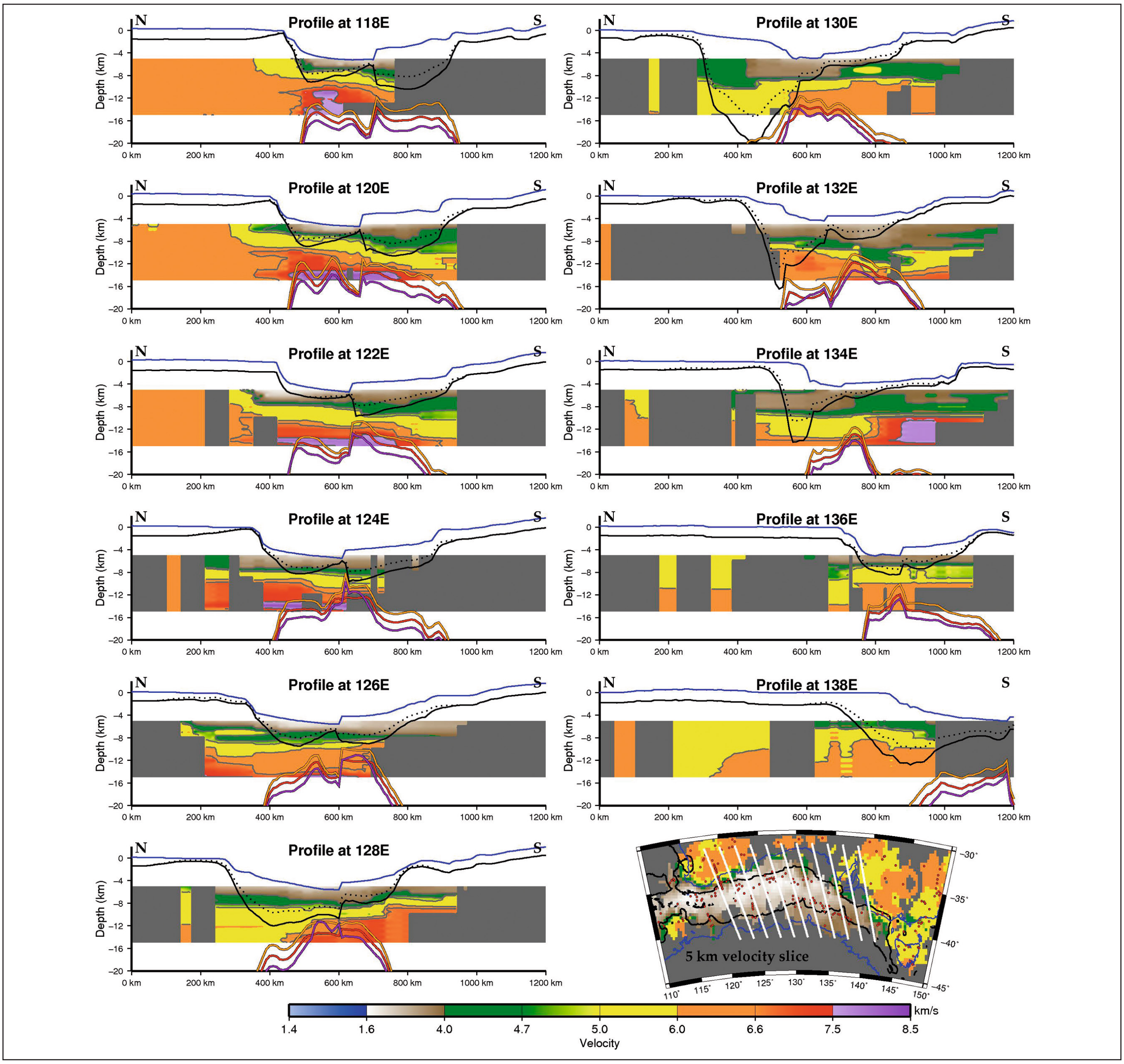

Figure 3. Profiles of the reconstructed velocity data. Blue line – bathymetry (GEBCO 2008); black lines – maximum estimated sediment thickness; dashed black lines - minimum estimated sediment thickness; red lines –moho depth from the average of the four preferred models from Kusznir (2009); orange lines – moho from the 'magma normal/thick sediments' model from Kusznir (2009); purple line – moho from the 'magma poor/thin sediments' model from Kusznir (2009).

Results/Discussion

Figure 2 shows a planar view of the crustal architecture of the Australian-Antarctic margins reconstructed at 83 Ma, the approximate time of break-up for much of the margin. The breakup was likely diachronous, between 94 and 73 Ma for the Naturaliste-Bruce Rise and Bight Basin-Wilkes Land margin sectors, decreasing to ~53-50 Ma in the Sorell Basin-George V Land sector. These ages are based on seismic stratigraphy, dating of dredge samples and breakup volcanics (Totterdell et al. 2000; Beslier et al. 2004; Krassay et al. 2004; Halpin et al. 2007), and are consistent with the most recent plate reconstructions (Whittaker et al. submitted).

The 1 km slices clearly show that there are marked asymmetries in sediment thickness and crustal velocities both along and between the margins. Based on the velocity data, the thickest accumulations of upper sediments (4.0 km/sec boundary) occur to depths of 8 km depths on the Australian margin in the margin distal portion of the Ceduna Basin, and the adjacent portion of the Antarctic margin.

On the Australian margin the Ceduna sub-basin is also the location of the thickest accumulations of total sediment (6.0 km/sec velocity boundary) reaching a maximum depth of 14 km. However, the adjacent portion of the Antarctic margin exhibits a virtual absence of lower and highly compacted sediments, with the thick accumulation of upper sediments sitting almost directly on upper crust in our interpretation. The thickest accumulation of sediments on the Antarctic margin occur west of 126°E reaching a maximum depth of 12-13 km. This sediment accumulation matches the finding of Close et al. (2009) who interpreted sediment thicknesses in excess of 9 km seaward of the Totten Glacier, western Wilkes Land.

A striking result of this analysis is that at shallower depths the velocity patterns (and by implication the sediment distribution) are relatively symmetric. However, at depths greater than ~9 km there is a marked change in the velocity zonation at ~126°E. The asymmetries observed are largely due to the patterns of sediment loading – thick sediments in the Ceduna (east of 126°E) and also offshore the western Wilkes Land margin (west of 126°E). This sediment loading has depressed the crust in these regions making the present day margins asymmetric both along and between the conjugate margins.

Comparison between the key velocity boundaries and our estimated maximum sediment thickness calibrated from seismic reflection data is revealing. For the central part of the conjugate margin system (~126E to 132°E), where the sediment is thicker (i.e. extending to depths in excess of ~10 km) there is a reasonable match between the estimated maximum sediment thickness and the 6.0 km/sec boundary between highly compacted sediments and basement (Figures 2 and 3). However, at both the eastern and western ends of the conjugate margin system, where the total sediment accumulation is thinner, the maximum estimated sediment thickness matches more closely with the 4.0 km/sec boundary between upper and lower sediments. Particularly poor correlation between the maximum estimated sediment thickness and the 6.0 km/sec boundary occur on the Antarctic margin.

The estimated maximum sediment thickness reflects the depth at which basement has been interpreted in the reflection seismic data. It is interesting that a closer match with the corresponding 6.0 km/sec velocity boundary occurs only at larger depths to basement. At shallower depth to basement, the reflection basement corresponds to lower velocities than expected, and the mismatch is particularly pronounced on the Antarctic margin. This leads us to suggest that basement has been underestimated in two-way time interpretation, and consequently even calibration with the velocity model still results in a too shallow position to match velocities. We suggest that the mismatches are likely related to the loss of resolution in the reflection data where basement is shallower. The reason for the underestimation of the basement depth from reflection seismic in regions where there is thinner sediment is somewhat enigmatic. Possibly, it has something to do with specific acoustic properties of thicker sediment, e.g. a higher Q factor translating into a lower rate of attenuation of seismic energy generated by the reflection seismic source.

We also observe asymmetries in the Moho depth. Figures 2 and 3 show that the western portion of the Australian margin and the eastern portion of the Antarctic margin exhibit the shallowest Moho positions at 11 km depth. The Moho position for the Ceduna sub-basin portion of the Australian margin and the adjacent Antarctic margin was deeper than 15 km indicating that deeper velocity data is needed to define the position of the Moho across some sections of the conjugate margin. In general, the Moho asymmetries appear linked to total sediment accumulations, with deeper Moho positions occurring where there are thicker accumulations of sediment. The exception is the Antarctic margin adjacent to the Ceduna sub-basin, which exhibits relatively thin total sediment accumulations but a deep Moho position. This implies thicker continental crust in this region, although deeper velocity data are needed to reveal the actual position of the Moho. The presence of thicker continental crust in this region, and further outboard is consistent with interpretations of the presence of the Adelie Rift Block (Colwell et al. 2006) in this location.

We compare the 7.5 km/sec crust/moho transition from the velocity data with gravity inversion-derived Moho depths modelled by Kusznir (2009). For both margins there is a reasonable match between 118°E and 126°E. East of 126°E the gravity inversion derived Moho depths are shallower than the 7.5 km/sec boundary.

The best match between the gravity inversion derived Moho and the 7.5 km/sec velocity boundary occurs along the portion of the margin adjacent to the Yilgarn Craton, suggesting that the initial crustal thicknesses and crustal densities used in the gravity inversion modelling process are most appropriate for this portion of the conjugate margins. Additionally, the seismic refraction data used to calibrate the gravity inversion process of Kusznir (2009) were predominantly located in the region west of ~135°E, where the better match is observed. Greater mismatch is observed to east, and a likely contributing factor is the difficulty in applying a single set of gravity inversion parameters to the entire length of a conjugate margin pair. The results discussed here were based on a single initial crustal thickness for the entire Australian southern margin, and assume a constant density for the crust. The velocity data investigated here illustrate the variations in seismic velocity of the crust within the extended margins, and hence provide an indication of likely variations in crustal density. Indeed, refraction seismic measurements onshore along the southern Australian margin suggest that the initial crustal thickness varies from ~30 km in the east to 37-40 km in the west and centre. Substantial velocity variation in the lower crust from 6.5 to 7.5 km/s is superimposed on these crustal thickness variation trends. A potential improvement to the gravity inversion process could be to convert the velocities to densities as input for the gravity inversion process.

Conclusions

Analysis of velocity data from seismic refraction and sonobuoy data, in a reconstructed context, clearly shows asymmetries in the thickness distribution of lower and highly compacted sediments along and between the Australian and Antarctic extended continental margins. Additionally, Moho depths vary along and across the margin although in most cases this appears related to the distribution of sediments.

Our analysis reveals that that velocity data for the conjugate Australian-Antarctic margins form an internally consistent picture, even though the individual data points are of different vintages and acquisition schemes, and have been interpreted independently. This indicates that the results from our analysis are robust, and that the seismic refraction velocity information is valuable for constraining crustal structures, particularly depth-to-basement in areas where this is difficult to resolve from seismic reflection data.

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