# Full-fit, palinspastic reconstruction of the conjugate Australian-Antarctic margins

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[1] Despite decades of study the prerift configuration and early rifting history between Australia and Antarctica is not well established. The plate boundary system during the Cretaceous includes the evolving Kerguelen–Broken Ridge Large Igneous Province in the west as well as the conjugate passive and transform margin segments of the Australian and Antarctic continents. Previous rigid plate reconstruction models have highlighted the difficulty in satisfying all the available observations within a single coherent reconstruction history. We investigate a range of scenarios for the early rifting history of these plates by developing a deforming plate model for this conjugate margin pair. Potential field data are used to define the boundaries of stretched continental crust on a regional scale. Integrating crustal thickness along tectonic flow lines provides an estimate of the prerift location of the continental plate boundary. We then use the prerift plate boundary positions, along with additional constraints from geological structures and large igneous provinces within the same Australian and Antarctic plate system, to compute "full-fit" poles of rotation for Australia relative to Antarctica. Our preferred model implies that the Leeuwin and Vincennes Fracture Zones are conjugate features within Gondwana, but that the direction of initial opening between Australia and Antarctica does not follow the orientation of these features; rather, the geometry of these features is likely related to the earlier rifting of India away from Australia-Antarctica. Previous full-fit reconstructions, based on qualitative estimates of continental margin overlaps, generally yield a tighter fit than our preferred reconstruction based on palinspastic margin restoration.

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## 1. Introduction

[2] The prerift configuration and early rifting history Australia and Antarctica has been debated for decades; the lack of consensus partly reflects the difficulty to reconcile geological and geophysical constraints from the eastern and western end of the plate boundary system using rigid plate models. Relative motion between Australia and Antarctic during the Late Jurassic (~160–140 Ma) with an early phase of continental rifting followed by thermal subsidence [*Totterdell et al.*, 2000]. These authors studied wells and pseudo wells from basins along the Australian southern margin and identified relatively mild thermal subsidence until ~100 Ma, followed by accelerated subsidence until continental breakup. The rapid subsidence phase is tentatively attributed to predominantly lower crustal stretching due to the lack of seismic evidence for upper crustal extension until immediately prior to breakup [*Totterdell et al.*, 2000]. Continental breakup and the commencement of very slow seafloor spreading (~10 mm/yr half rate) occurred at ~83.5 Ma.

[3] Despite clear evidence for the onset and progression of Australian-Antarctic continental rifting, relatively few publications have addressed these earliest plate tectonic motions. Full-fit Euler poles are presented by *Powell et al.* [1988], and *Royer and Sandwell* [1989]. These two models differ predominantly in the direction of motion prescribed to pre-96 Ma motion. *Powell et al.* [1988] and *Veevers* [1987] proposed that prebreakup continental rifting and extension was oriented NNE-SSW based on the pattern of faulting in the Bass and Gippsland Basins (Figure 1) while *Royer and Sandwell* [1989] alternatively proposed a NW-SE azimuth based on transfer faults interpreted from seismic data from the Great Australian Bight. These differences can be seen in the flow lines plotted in Figure 2. *Powell et al.* [1988] restore 360 km of continental stretching across the conjugate margins, estimated using bathymetric, seismic, and magnetic data, along a north-northeast azimuth. *Royer and Sandwell* [1989] use the deflection of the vertical satellite gravity signal to interpret full-fit boundaries to undo Australian-Antarctic prebreakup continental stretching.

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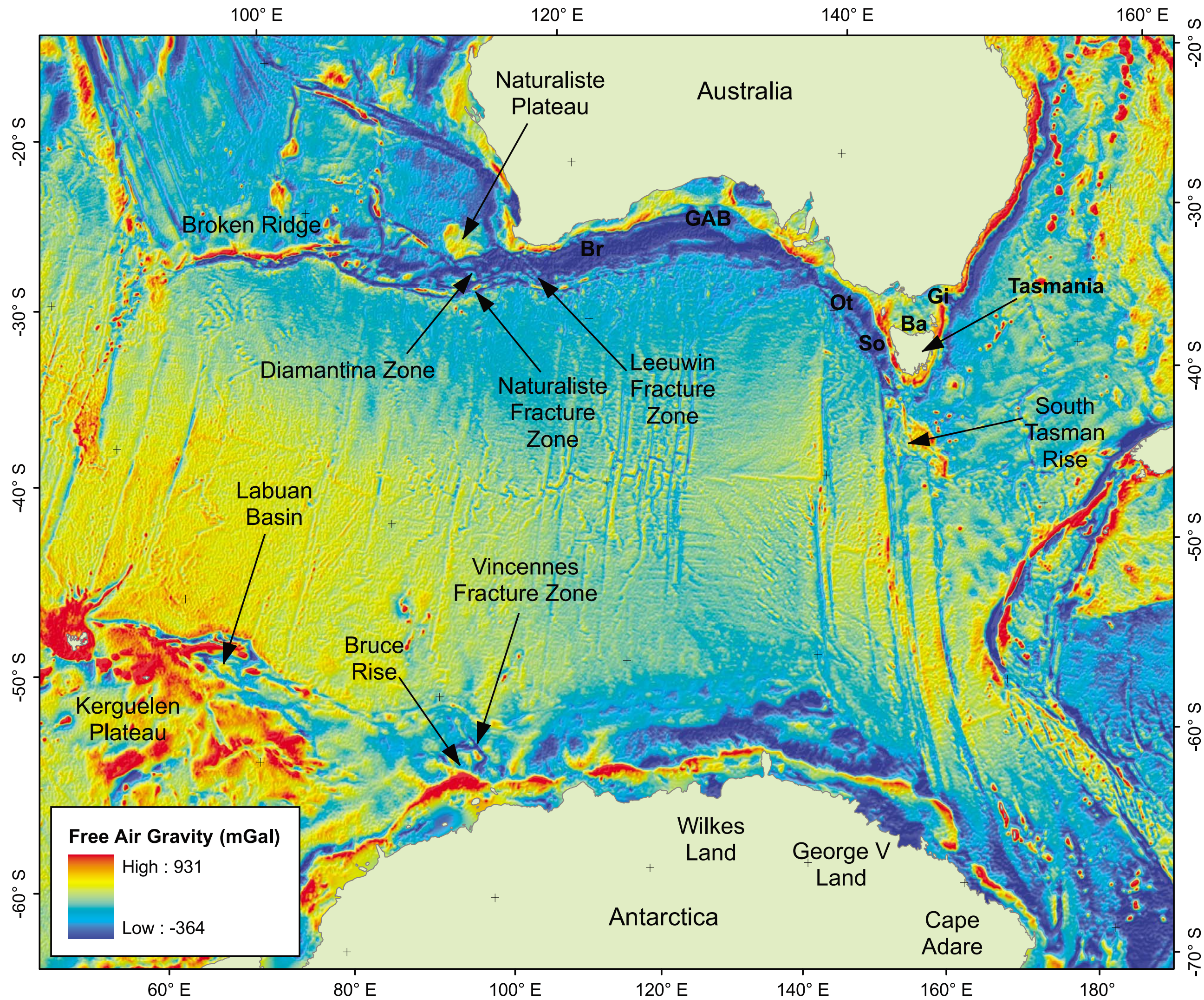


**Figure 1.** Map of free-air satellite gravity [*Andersen et al.*, 2010] illustrating major tectonic features of the Australian Southern Ocean. Br, Bremer Basin; GAB, Great Australian Bight Basin; Ot, Otway Basin; So, Sorell Basin; Ba, Bass Basin; Gi, Gippsland Basin.

[4] More recent studies addressing the early opening between Australia and Antarctica [*Royer and Rollet*, 1997; *Tikku and Cande*, 1999, 2000; *Whittaker et al.*, 2007] use updated magnetic anomaly data sets; however, none of the revised models go back further than ~96 Ma and so do not attempt to compute full-fit reconstructions. Full-fit Australia-Antarctica Euler poles have also been published as part of global compilations including *Schettino and Scotese* [2005], *Müller et al.* [1997, 2008], and *Torsvik et al.* [2008]. Of these global compilations, only *Müller et al.* [1997] use a previously published Euler pole (the full-fit pole of *Royer and Sandwell* [1989]), while all the other compilations use their own poles, but with no methodological explanation. Hence, the question remains as to whether we can improve on previous models for the rifting of Australia and Antarctica in the context of the recently revised reconstructions at the onset of seafloor spreading, and newly available constraints on the crustal structure of the passive margins.

[5] In this paper we investigate full-fit reconstructions for the breakup of Australia and Antarctica (Figure 1). The best fitting model depends on both the amount of closure between the two plates and their lateral configuration prior to and during rifting. To constrain the likely amount of closure, we use estimates of the crustal thickness in the conjugate extended continental margins. We then use palinspastic restoration (where geological features are restored taking into account changes in their geometry) of the extended continental crust within the conjugate margins to derive restored continent ocean boundaries (RCOBs). The estimated location of the RCOBs depend on the direction of initial opening between Australia and Antarctica, which in turn depends on the lateral juxtaposition of the plates during the rifting. To constrain the lateral configuration, we match major geological structures between the conjugate Australian and Antarctic margins.

## 2. Candidate Models for Australia-Antarctica Rifting

[6] A plate-scale model of rifting needs to satisfy several criteria: (1) The implied plate motions should be reasonably

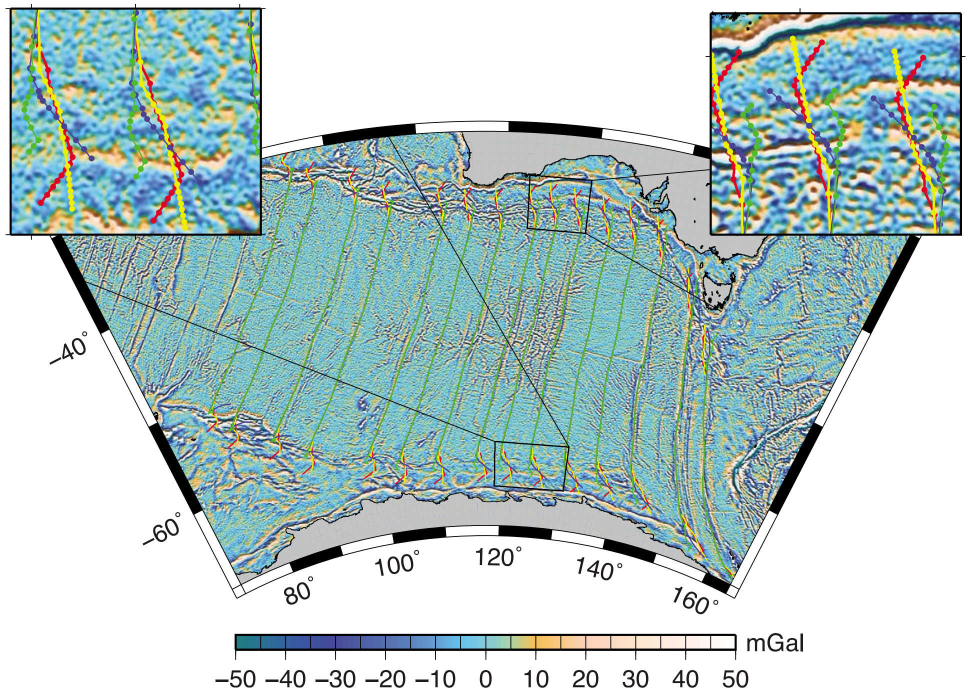


**Figure 2.** Flow lines resulting from the plate tectonic models of *Powell et al.* [1988], red; *Royer and Sandwell* [1989], yellow; *Tikku and Cande* [1999]; and *Whittaker et al.* [2007], blue.

consistent with the basin-scale extension directions recorded within the conjugate margins, (2) the reconstructions should satisfy interpreted correlations between conjugate features on the rifted continents, (3) the reconstruction at the end of rifting needs to be consistent with constraints (isochrons, fracture zones) for the earliest phase of seafloor spreading, and (4) the amount of closure between the plates needs to be consistent with observations from the extended continental crust in the conjugate margins. The restoration of extended continental margins is discussed in detail in section 3. In this section we discuss the first three listed items in the context of the Australia-Antarctica rifting.

[7] The majority of the available structural data comes from the Australian margin, which has been studied in much more detail than the conjugate Antarctic margin. Temporal and spatial variations in basin-scale structural trends make it difficult to reconcile structural information with the extension directions implied from a single Euler pole for a given time interval. At 130°E along the Australian southern margin a well-documented change in the strike of offshore-stepping normal faults occurs, from predominantly NE-SW to the west to predominantly NW-SE to the east [e.g., see *Totterdell and Bradshaw*, 2004, Figure 2]. If taken at face value, explaining the observed Australian margin structural trends from a regional plate tectonic modeling perspective is virtually impossible, as it would imply relative motion between the western and eastern halves of Australia, for which there is no evidence. In fact, many authors have argued that the changing structural trends across the Australian passive margin are the result of preexisting basement trends that controlled the locations and orientations of structures on the extended passive margin [*Totterdell et al.*, 2000; *Totterdell and Bradshaw*, 2004; *Willcox and Stagg*, 1990]. In addition, stress modeling studies [e.g., *Dyksterhuis and Müller*, 2008] show that inherited basement structure can, at basin scales, significantly affect the direction and strength of deformation stresses that at more regional scales are relatively uniform. Nevertheless, we find that even though a wide variety of structural trends are observed along the Australian southern margin, the majority of these structural trends support NW-SE to N-S extension directions during the continental rifting phase of breakup, consistent with our proposed NNW-SSE continental rifting direction.

[8] Along the western half of the Australian passive margin, structural trends are consistent with a NW-SE to NNW-SSE direction. In the Bremer subbasin, E-ENE striking en echelon rift border faults that are offset to the southwest support a NW-SE to NNW-SSE extension direction [*Totterdell and Bradshaw*, 2004]. In the Eyre subbasin, immediately to the west of the 130°E boundary line, NE-ENE striking extensional faults that are offset to the southeast are consistent with interaction between a NW-SW to NNW-SSE extensional direction and E-W trending basement structures [*Totterdell and Bradshaw*, 2004].

[9] At the western end of the Australian and Antarctic margins are three prominent structures, commonly referred to as fracture zones despite the fact that they occur in extended continental crust. The Vincennes Fracture Zone is located at the eastern edge of the Bruce Rise, Antarctica, while the Leeuwin and Naturaliste Fracture Zones are located at the eastern and western edges of the Naturaliste Plateau, Australia (Figure 1). Alternative interpretations exist for the alignment of major features on the Australian margin and Antarctica margins (Figure 1) at ~83.5 Ma. *Tikku and Cande* [1999] align the Vincennes fracture zone on the Antarctic margin with the Leeuwin fracture zone, whereas *Whittaker et al.* [2007] align the Vincennes Fracture zone with the Naturaliste Fracture Zone. These different interpretations

result in the Naturaliste Plateau being reconstructed either to the north, or to the east, of the Bruce Rise. For both alternative alignments, it is possible to interpret additional, though more debatable, conjugate structures on the Antarctic margin, to the west of the Bruce Rise for the Leeuwin alignment and along the Wilkes Land margin for the Naturaliste alignment [e.g., *Whittaker et al.*, 2007].

[10] Using these different scenarios as starting points, we test different candidate models for the direction of relative plate motions during rifting, and examined RCOB locations implied by various stage poles. In each case the stage poles are derived from different finite poles of rotation for Australia relative to Antarctica at both the assumed onset of rifting (160 Ma [*Totterdell et al.*, 2000]) and around the time that seafloor spreading began between the Bight Basin and Wilkes Land (83.5 Ma).

[11] The basic assumptions underlying the Leeuwin model are that (1) the Leeuwin and Vincennes Fracture Zones are conjugates, and that (2) motion from the onset of continental rifting (~160 Ma) until breakup at ~83.5 Ma is recorded by the trend of these structures. This model implies that the major change in direction of relative motion between Australia and Antarctica occurred at ~chron 34 time (83.5 Ma), roughly coinciding with the onset of seafloor spreading.

[12] The basic assumptions underlying the Naturaliste model are that (1) the Naturaliste and Vincennes Fracture Zones are conjugates, and that (2) motion from the onset of continental rifting (~160 Ma) until breakup at ~83.5 Ma is recorded by the trend of these structures.

[13] The basic assumptions underlying the hybrid model are that (1) the Naturaliste and Vincennes Fracture Zones are conjugate features, and that (2) motion from the onset of continental rifting (~160 Ma) until breakup at ~83.5 Ma is *not* recorded by the trend of these structures.

[14] As a comparison to these three candidate models, we tested the model of *Powell et al.* [1988], which predicts a NE-SW opening direction that is significantly different from that implied by the three models described above.

## 3. Methods

### 3.1. Previous Work on Full-Fit Reconstructions

[15] *Bullard et al.* [1965] presented an early attempt to derive quantitative full-fit reconstructions of the conjugate Atlantic margins, testing different bathymetric contours and finding the 500 fm contour to yield the best fit. Many subsequent plate tectonic studies have used potential field data to approximate the position of the unstretched, prerift plate boundaries. *Lawver et al.* [1998] used the "major free-air gravity anomalies," while *Schettino and Scotese* [2005] used the "horizontal gradient of gravity anomalies." Although these authors describe these features as mapping palinspastically restored continent-ocean boundaries, the precise rationale for their approaches and their methods are unclear. A quantitative approach to deriving "nonrigid" plate reconstructions is described by *Dunbar and Sawyer* [1987, 1989] who used total tectonic subsidence analysis to estimate crustal thickness from sediment thickness maps of the Gulf of Mexico and North Atlantic, and so derive more robust plate reconstructions for phases of continental rifting. *Dunbar and Sawyer* [1989] used the results of palinspastic restoration of continental margins to reassess the amount of closure required to fit the prerift configuration of two conjugate plates, thus modifying the angle of rotation about an existing Euler pole. While the analysis presented here shares some similarities with these authors, we adopt an approach that allows us to derive new, statistically robust fits using a combination of constraints from both restoration of stretched continental crust and other structural features.

### 3.2. Prerequisites for Regional Palinspastic Restoration

[16] To properly account for the deformation along continental margins during rifting, the spatial extent of the extended passive margin must be delineated, and the thickness of the extended crust across these continental margins estimated. As illustrated in Figure 3, we need to define (1) the boundary between stretched and unstretched continental crust, which we refer to throughout the rest of this text as the Unstretched Continental Crust Limit (UCCL); (2) the boundary between the stretched continental and oceanic crust (commonly known as the continent-ocean boundary, COB); and (3) the spatial variation in thickness of the extended continental crust between these two boundaries.

[17] A variety of geophysical data sets are available to assist in this process. We have used potential field data, combined with insights from seismic profiles where available, as a primary means to define the crustal configuration in a way that extends continuously along the full length of the conjugate Australian and Antarctic continental margins.

#### 3.2.1. Magnetics

[18] Magnetic anomaly data are taken from the NGDC World magnetic anomaly map [*Maus et al.*, 2009]. The most recent version, referred to as EMAG2, describes the total magnetic intensity of the crustal field on a 2 arc min grid at 4 km above the geoid. Our reconstructions use chron 34y magnetic anomaly picks for the southern ocean from *Tikku and Cande* [1999] and *Whittaker et al.* [2007], in conjunction with additional data described in the text, to constrain the relative position of Australia and Antarctica at the end of continental rifting. The chron 34y magnetic anomalies are located on a basement ridge complex, interpreted to be composed of exhumed continental mantle within the continent-ocean transition. For this reason their interpretation is somewhat controversial [*Tikku and Direen*, 2008; *Whittaker et al.*, 2008a]. However, recent studies have shown that conjugate linear magnetic anomalies within the exhumed mantle are generated by reversals in the Earth's magnetic field in a similar way to those observed in oceanic crust, and so are related to the temporal evolution of this material and can be used to reconstruct relative plate motions [*Sauter et al.*, 2008; *Sibuet et al.*, 2007].

#### 3.2.2. Gravity

[19] We generate gravity derivative maps using the DNSC08GRA model derived from satellite altimetry for marine areas [*Andersen et al.*, 2010]. We calculated a Bouguer correction [e.g., *Blakely*, 1995] using the GEBCO global bathymetry compilation grid [*General Bathymetric Chart of the Oceans*, 2008]. To study the gravity effect of the sediments along the Australian and Antarctic margins we require gridded total sediment thickness. The NGDC global sediment thickness map for the oceans [*Divins*, 2004] provides minimum thickness estimates for these areas, but seismic data indicate large areas where the actual sediment thickness on these margins is much greater than that shown by the global

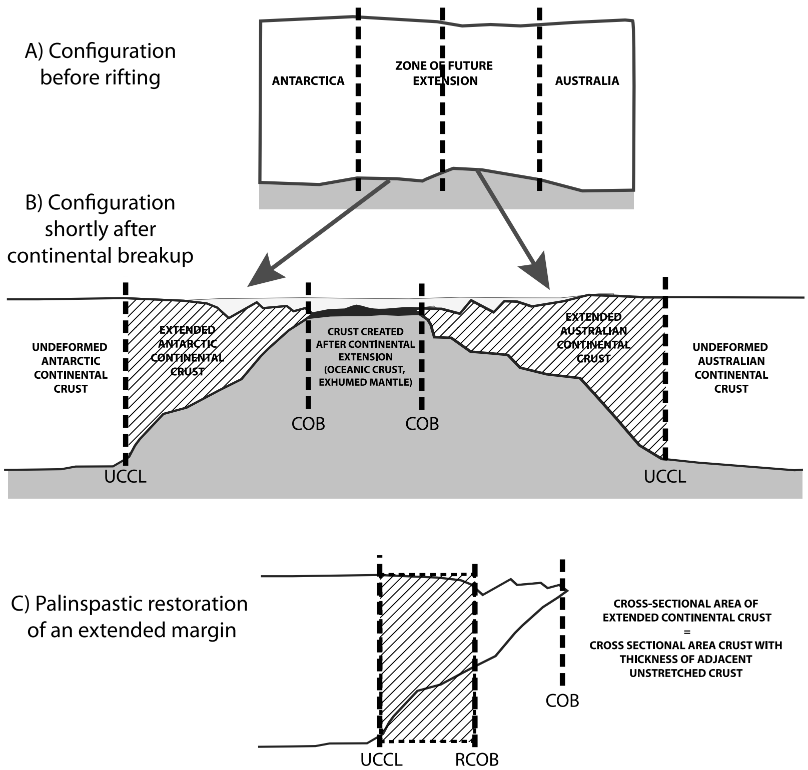


**Figure 3.** Schematic cartoon of rifted margins, illustrating the concepts of UCCL, COB, and RCOB (see text for definitions).

minimum thickness grid. We compute a new regional 5 min resolution sediment thickness grid for the Australian Southern Ocean (Figure 4b) using sonobuoy-derived sediment thicknesses for the Great Australian Bight and Wilkes Land margins (generated by Geoscience Australia and described by *Kusznir* [2009]), merged with sediment thickness data from *Géli et al.* [2007] for the deep ocean basin areas. Values from the NGDC global sediment thickness grid [*Divins*, 2004] were used for areas not covered by the other data sets.

[20] To map the discrete, regionally pervasive changes in crustal thickness and/or density we upward continued the Bouguer gravity data and calculated the total horizontal gradient. We calculated an additional gravity map in which we attempted to strip away the effect of large sediment thickness variations. Using the grids of sediment thickness generated for the Australian and Antarctic conjugate margins, we estimated the gravity effect of the sediments with the aim of more clearly isolating the gravity signal due to variations in thickness and/or density of the crust underlying the sediments. We estimated the gravity effect of the sediments using Fourier domain forward modeling methods [*Blakely*, 1995; *Parker*, 1973] and assuming densities of 2.4 g/cc for the sediments and 2.8 g/cc for the underlying basement rocks. The gravity effect of the sediments was then used as a correction to the Bouguer gravity, and new derivative maps generated from the sediment-corrected gravity anomaly to assist in qualitative interpretation.

### 3.2.3. Crustal Thickness

[21] Our primary constraints on crustal thickness across the conjugate Australian-Antarctic margins are crustal thickness grids derived from gravity inversion by *Kusznir* [2009]. The data are freely available to download at https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=68656. The methodology used to compute these grids involves stripping away the estimated gravity effect of bathymetry and the sedimentary section across each margin, and estimating the long-wavelength gravity signature due to temperature changes within the lithosphere. The remaining gravity signal is assumed to be due to variations in the depth to Moho, and a grid of this depth is determined using an iterative inversion scheme.

[22] The gravity inversion results of *Kusznir* [2009] include assumptions of crustal density, initial crustal thickness, the ages for the onset of rifting and oldest reliable isochron, and the type of margin ("volcanic," "normal," or "magma poor," in each case implying different parameters for modeling of the melt addition within the stretched crust [see *Kusznir*, 2009]). A further uncertainty is the sediment thickness across the conjugate Australian-Antarctic margins. *Kusznir* [2009] used both minimum and maximum estimates for the sediment thickness for each margin and generated a range of crustal thickness grids based on different values for the parameters described above used in different combinations for the gravity inversion. This array of possible output models is narrowed down based on criteria such as the correlation of the estimated Moho depth with Moho depths determined from seismic refraction experiments. The final array of crustal models presented by *Kusznir* [2009] comprises four models of crustal thickness for both the Australian and Antarctic margins. These grids form the starting point for our own analysis.

[23] The gravity inversion method includes an analysis of the crustal thickness in the unstretched crust adjacent to

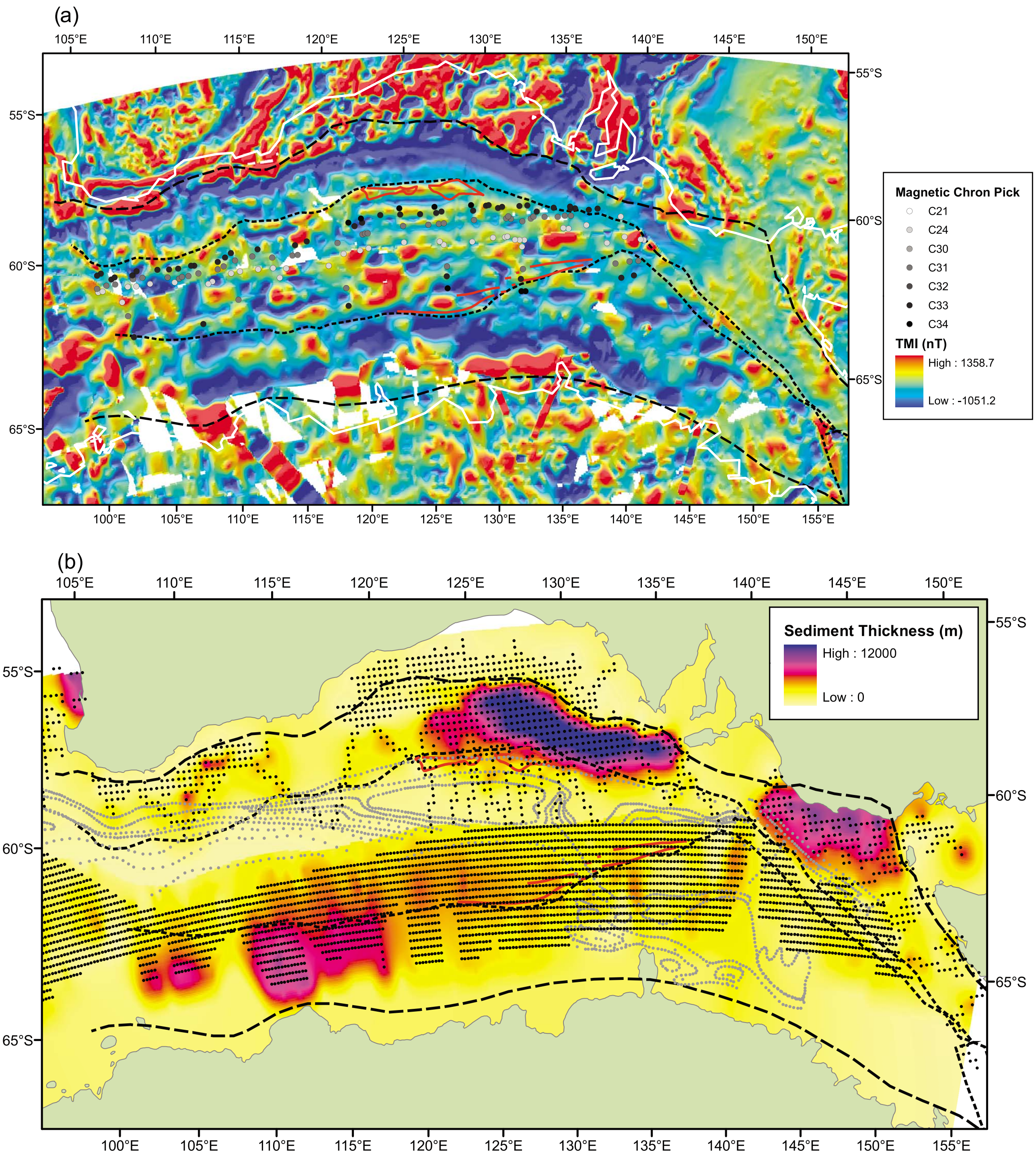


**Figure 4.** Reconstructions of the conjugate Australian-Antarctica margins at ~47.9 Ma, in a fixed-Antarctica reference frame. (a) Total magnetic intensity (EMAG3 [*Maus et al.*, 2009]); (b) estimated sediment thickness, with dots showing locations of data used to derive the regional grid; (c) crustal thickness derived by gravity inversion, with estimates of the prerift plate boundary location; (d) total horizontal gradient of the 1 km upward continued Bouguer gravity; and (e) same as Figure 4d but calculated for a gravity anomaly with the estimated gravity effect of the sediments removed. Locations of peridotite ridges [*O'Brien and Stagg*, 2007; *Sayers et al.*, 2001] are shown by red lines in Figures 4a–4c and white lines in Figures 4d and 4e. Dashed lines show landward and oceanward limits of "certain" stretched continental crust used to derive prerift plate boundary locations.

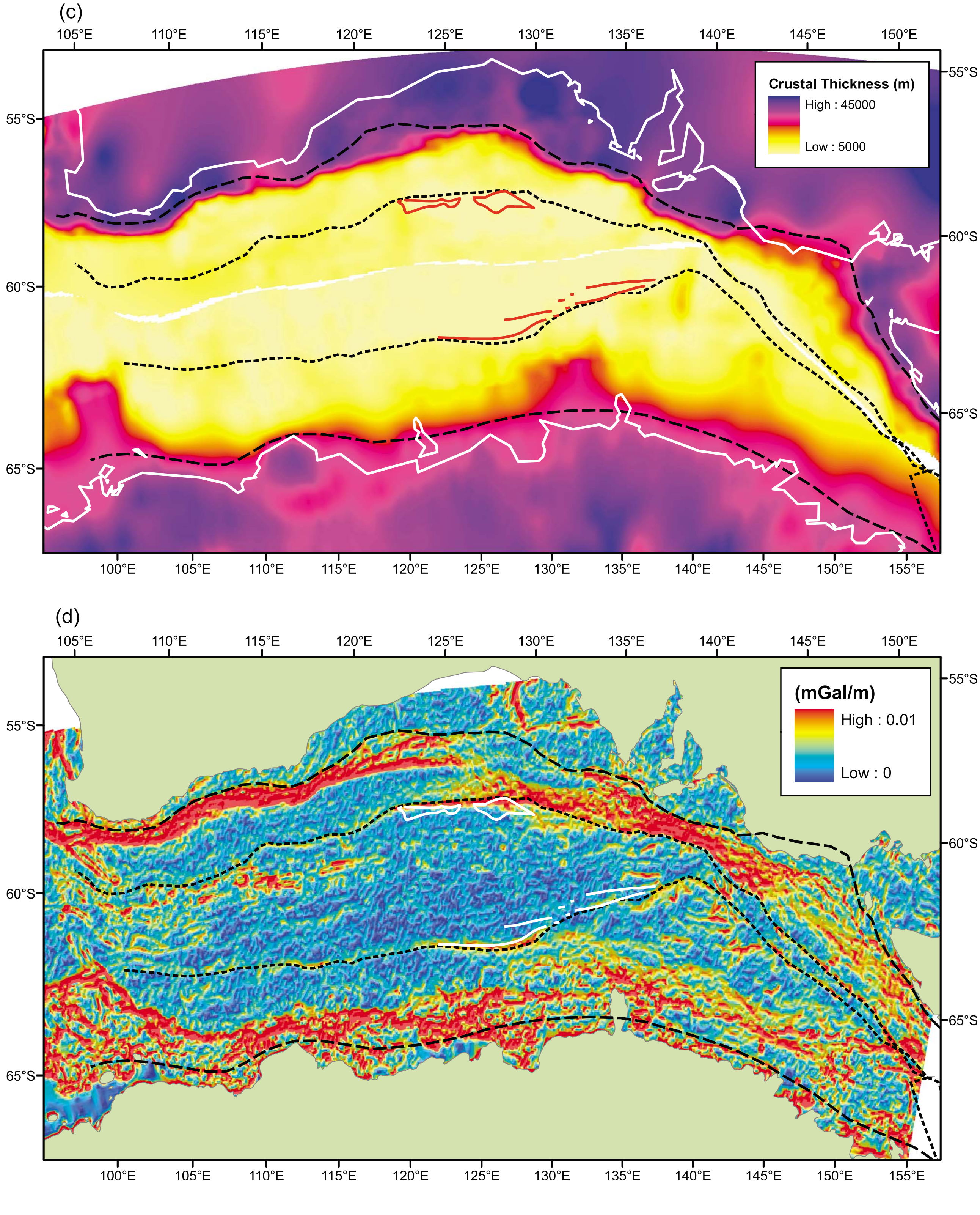


**Figure 4.** (continued)

each margin, with the results tied to available seismic refraction data. The preferred values for the crustal thickness beneath Australia and Antarctica adjacent to the conjugate margins were 42.5 km and 37.5 km, respectively [*Kusznir*, 2009]. We have used these values as the thickness of unstretched crust when calculating the length of restored crust after the crustal thickness integration. The beta factors implied by these crustal thickness are given by $\beta = tc_0/tc_{now}$

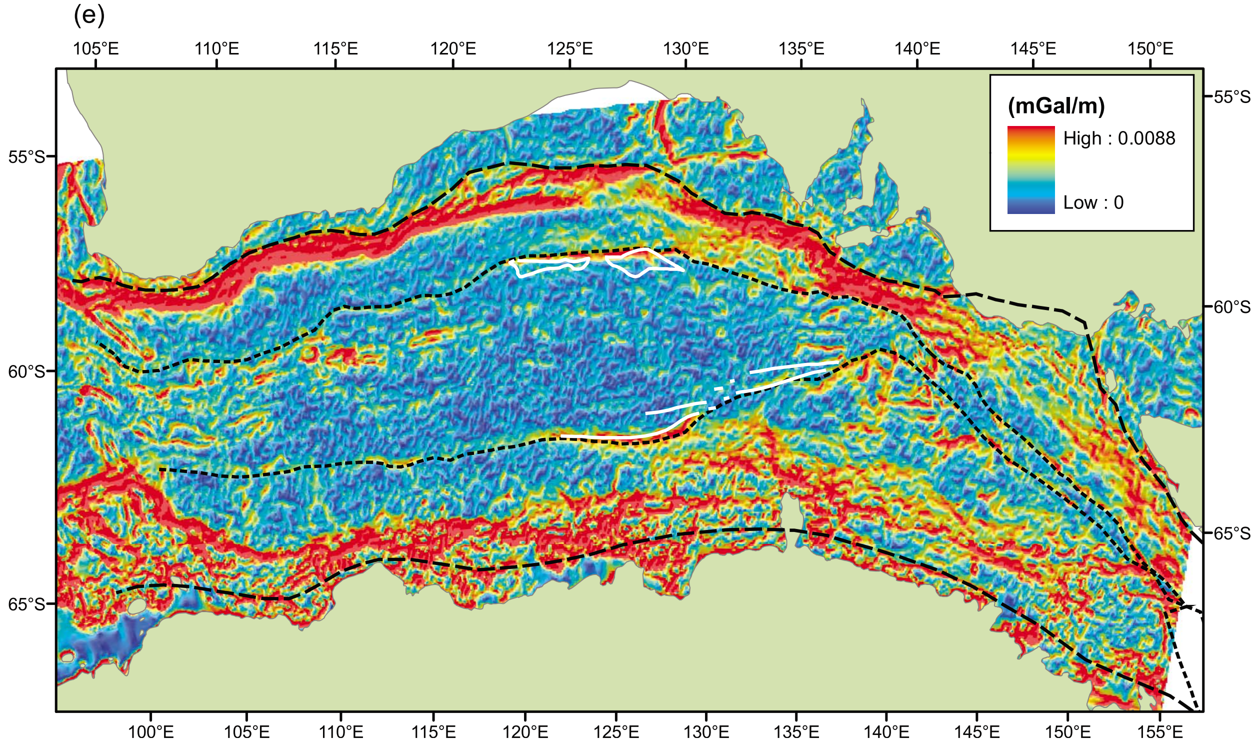


**Figure 4.** (continued)

where $tc_0$ is the thickness of unstretched crust and $tc_{now}$ is the present-day crustal thickness.

[24] *Kusznir*'s [2009] crustal thickness grids do not extend across the full extent of the stretched margin, in particular on the Antarctic margin. To fill the gaps we have merged these grids with the crustal thickness for the Antarctic margin from the CRUST2 model [*Bassin et al.*, 2000]. On the Australian margin, the crustal thickness grids were extrapolated using the scattered crustal thickness estimates from seismic refraction from *Brown et al.* [2003]. In the case of a "normal" type margin, *Kusznir* [2009] assumes that melt is added to crust thinned beyond a certain critical thinning factor (in this case 0.7). We recalculated the extent of melt addition to the crust for these expanded grids. An example of the resulting set of crustal thickness grids is shown in Figure 4c.

#### 3.2.4. Interpretation of COB and UCCL

[25] For both the Australian and Antarctic margins the Bouguer gravity anomaly shows a regional transition from low values over the continents to high values over the oceans, mirroring the deepening of the Moho beneath the continents. The total horizontal gradient of the Bouguer gravity anomalies (Figure 4d) shows a ~100 km wide zone of high gradient that extends along the south Australian margin. When a correction for the gravity effect of the sediments is incorporated, the resulting gradient map (Figure 4e) is broadly similar with the exception of the areas around the thick sediment accumulations in the Bight Basin, where the strong gravity gradient lies significantly further landward of the high-gradient zone across the same part of the margin in Figure 4d. Grids of crustal thickness derived from gravity inversion (e.g., Figure 4c) suggest that the majority of crustal thinning takes place within the same >100 km wide zone of high-gravity gradient (as we would expect since the inversion result is based on the same gravity data). On this basis, we define the landward limit of stretched crust to lie at the landward margin of the regional gravity gradient shown in Figure 4e. The total horizontal gradient maps show a distinct linear trend along the location of the peridotite ridge. Oceanward of this, there is little evidence for major, laterally continuous changes in crustal type and/or thickness. Hence we define our oceanward limit of the "certain" stretched continental crust to follow the gravity and magnetic trends delineating the peridotite ridge.

[26] The analysis of the conjugate Antarctic margin is less certain than for the Australian margin. The difficulty in acquiring geophysical data close to the Antarctic coast means that the data sets needed to constrain the Bouguer and sediment thickness corrections are less complete for this margin. For this reason, our landward limit of stretched continental crust for this margin is based largely on that presented by *O'Brien and Stagg* [2007]. In common with the Australian margin, the total horizontal gradient of Bouguer gravity maps show a linear trend following the peridotite ridge (Figures 4d and 4e). We use this trend to define the oceanward boundary of "certain" stretched continental crust for our plate reconstruction calculations, although other authors have interpreted some continental crust oceanward of the ridge [*Colwell et al.*, 2006].

### 3.3. Palinspastic Restoration of the COB

[27] We assume that the regional-scale direction of extension should match that defined by stage rotations, which differ for different candidate plate motion models. Candidate stage poles for the relative motion between Antarctica and Australia during the period of continental rifting define small

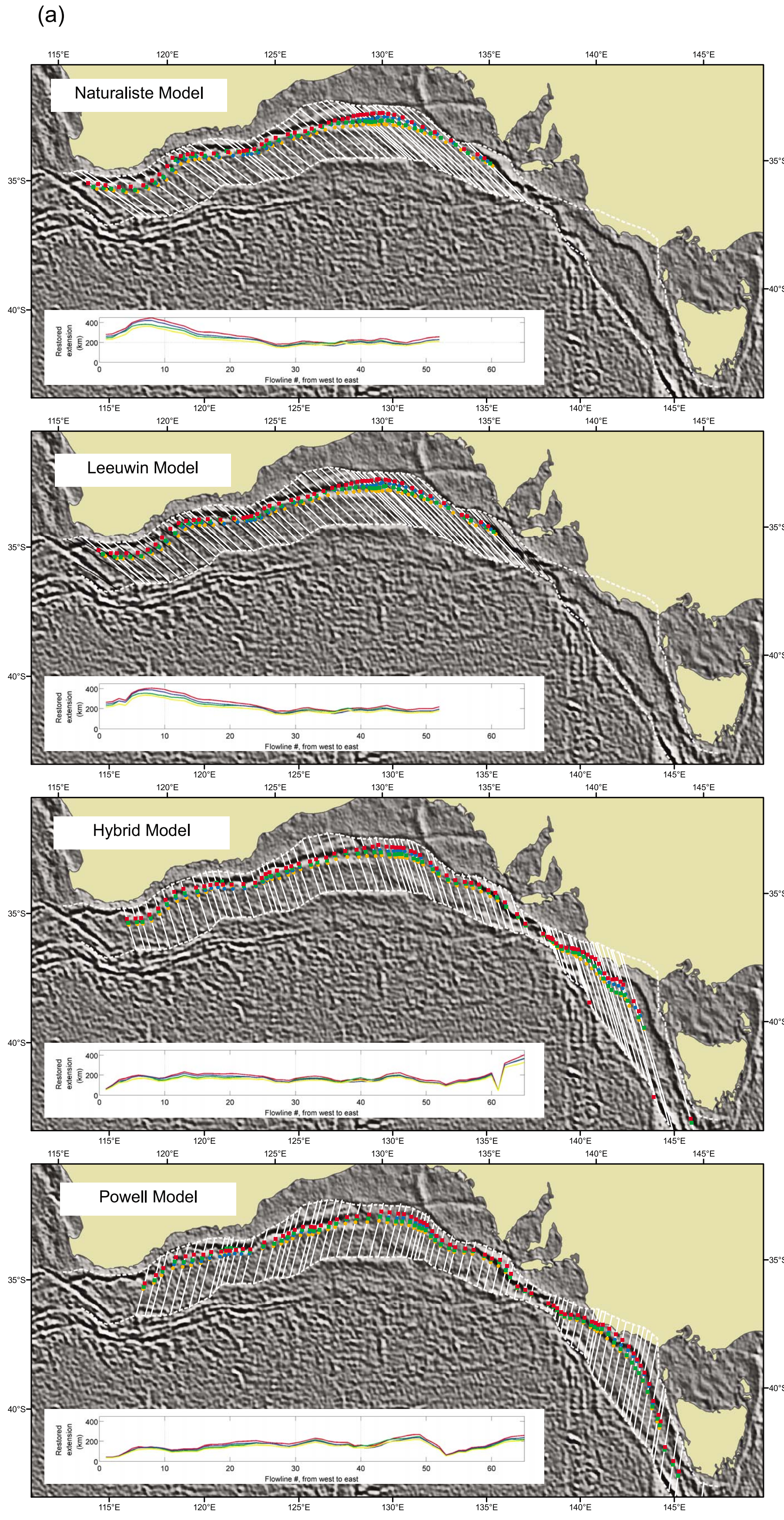
(a)
Naturaliste Model
Leeuwin Model
Hybrid Model
Powell Model
Restored extension (km)
Flowline #, from west to east
115°E
120°E
125°E
130°E
135°E
140°E
145°E
35°S
40°S

**Figure 5**

circle paths across either margin, which we take to represent the direction of motion of crust within the extending regions relative to the parent plate. For a given stage pole we generate a series of small circle paths across the extended continental crust between the present-day COB and the present-day UCCL (Figure 5). These paths are then treated as profiles along which a two-dimensional palinspastic restoration is performed (Figure 3c). For each path, we extract the crustal thickness along each profile, then integrate the crustal thickness along the profile and calculate the length of this crust prior to extension assuming conservation of cross-sectional area and uniform crustal thickness prior to rifting. The point that lies at the same distance from the UCCL along the small circle path as the restored profile length is taken as the RCOB location for that profile. Applying this process to a series of paths along the margin yields a RCOB line.

[28] The workflow in section 3.3 has much in common with the work of *Dunbar and Sawyer* [1989]. The process relies on having poles of rotation to define the stage pole paths during the continental rifting and hence the position of the RCOBs. For their analysis of the North Atlantic and Labrador Sea, *Dunbar and Sawyer* [1987, 1989] used existing poles of rotation for the period of continental rifting (well constrained by transform margin segments) to derive their small circles, then modified the angle of closure between the conjugate plates. The difference here is that we do not rely on existing models of the relative plate motions, but rather test different scenarios and examine their consequences for the full-fit reconstruction.

[29] For Australia-Antarctica, we used the procedure described above to generate results for different candidate plate reconstruction model using the COB and UCCL lines defined earlier. We used the small circle paths for different models to derive RCOBs for each of the four “preferred” crustal thickness grids presented by *Kusznir* [2009]. These grids comprise crustal thickness estimates derived using different estimates of sediment thickness (“thick” and “thin”) and magmatic addition (“magma poor” and “normal”). Of these four possibilities, the model that assumes the presence of thick sediments and normal volcanic input during rifting results in a minimum width of the prerift continental margins. The gravity inversion model that assumes thin sediments and no volcanic addition to the crust results in a maximum width of the prerift continental margin. We then determined the mean RCOB location of the innermost and outermost estimates generated along each small circle. These points are then used as input data for the Euler pole computation procedure, along with additional constraints, discussed in section 3.5.

### 3.4. Computation of Euler Poles

[30] Euler poles are computed using two different methods. The first is a visual-fitting technique where all the available data, RCOB locations and structural trends, are fit interactively using GPlates software [*Boyden et al.*, 2011]. Models used in this paper are provided as GPlates-compatible files from http://www.earthbyte.org/people/simon. This approach was used for the computation of Euler poles for the Naturaliste and Leeuwin models. Due to the poor fits at least one section of the conjugate plate pair we did not compute 95% confidence errors for either the Naturaliste and Leeuwin models.

[31] For our preferred hybrid model we compute all finite rotation poles using the least squares fitting method of *Hellinger* [1981] and *Royer and Chang* [1991]. Constraints on the relative lateral positions of the plates come from matching of the Vincennes Fracture Zone with either the Leeuwin and Naturaliste fracture zones (this varies for the different candidate models), trend of fracture zones in the Labuan Basin and conjugate features in Broken Ridge.

[32] For the 83.5 Ma reconstructions, we assign less weight (see Table 2) to the chron 34y identifications of *Tikku and Cande* [1999] and *Whittaker et al.* [2007] when computing both the visual-fit and least squares derived Euler poles for the 83.5 Ma reconstructions. For the least squares methodology we assign a higher degree of uncertainty to the chron 34y identifications in our statistical calculations. Continental rifting in the conjugate Tasmania–Cape Adare margins was predominantly complete by ~90 Ma prior to the onset of spreading in the Tasman Sea [*Gaina et al.*, 1998; *Hegarty et al.*, 1988], so our reconstructions treat these conjugate COBs approximately as a transform margin until final separation some 40–60 million years later, The Euler poles, and their errors, resulting from our analysis are presented in Tables 1 and 2.

[33] For the full-fit reconstructions the RCOB lines for each margin are used as inputs to the geometric fitting, in a way that is analogous to how magnetic isochrons picks are used to reconstruct periods of seafloor spreading. The use of differing RCOB locations, based on different gravity inversions, resulted in better fits for the alternative models. We used RCOBs computed using the gravity inversion grids of *Kusznir* [2009], (1) the Normal, Thick gravity inversion for the Naturaliste model, (2) the Poor, Thin gravity inversion for the Leeuwin model, and (3) the midpoint between the Normal Thick and Poor, Thin gravity inversions for the hybrid model. Use of the midpoint between the two extreme estimated RCOB locations allowed us to compute individual errors for the location of the COB for the least squares Euler pole computation, in the hybrid case.

## 4. Results

[34] Figure 5 shows RCOBs derived for the Australian and Antarctic margins. The results are presented for three candidate plate reconstruction models and for the poles of rotation presented by *Powell et al.* [1988]. For each of the plate tectonic models tested four sets of RCOBs are derived

**Figure 5.** Satellite gravity [*Sandwell and Smith*, 2005] downward continued to the seafloor [*Whittaker et al.*, 2008b] overlain with the outline of stretched continental crust (white dashed lines), small circle paths showing relative plate motions (white solid lines), and locations of restored continental extent based on integrating alternative gravity inversion models of crustal thickness [*Kusznir*, 2009]. Each plot shows results for one of the alternative models of the plate reconstruction history described in the text for the conjugate (a) Australian and (b) Antarctic margins. Insets show the amount of restored extension along each plotted small circle path.

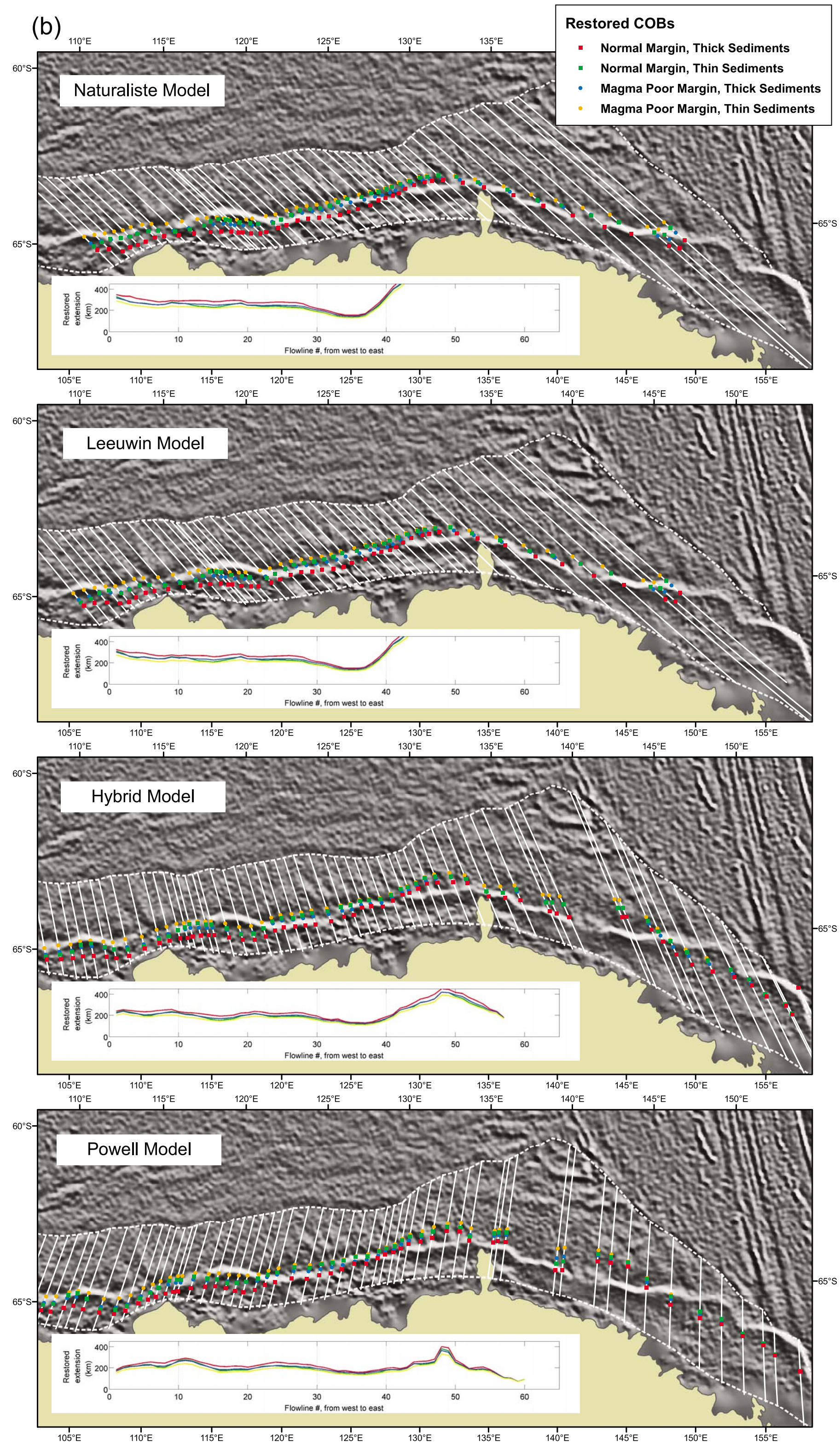


**Figure 5.** (continued)

from the alternative crustal thickness grids of *Kusznir* [2009]. The underlying image in Figure 5 is the free air gravity downward continued to the seafloor [*Whittaker et al.*, 2008b], which should help to identify the regional structural grain in bathymetric or crustal features in the extended crust of the margin. Note for example how the small circles for different rotation models compare to the orientation of the Leeuwin fracture zone.

**Table 1.** Euler Poles for the Naturaliste and Leeuwin Models

| Model | Chron | Age (Ma) | Latitude (deg) | Longitude (deg) | Angle (deg) |
|---|---|---|---|---|---|
| Naturaliste | c34y | 83.0 | −0.49 | 36.76 | −26.98 |
| Naturaliste | full fit | 160.0 | −13.71 | 38.88 | −31.57 |
| Leeuwin | c34y | 83.0 | 6.49 | 39.58 | −27.11 |
| Leeuwin | full fit | 160.0 | −3.33 | 38.99 | −30.51 |

[35] For the COBs along the margins of the Otway Basin and the George V Land section of the Antarctic margin, results are only shown for the hybrid model. The Naturaliste and Leeuwin models both imply plate motions at a highly oblique angle to the margins in this area during the time period during which the majority of extension in the Otway Basin occurred [*Hegarty et al.*, 1988]. Hence, small circle paths beginning from seed points on the present-day COB along the Otway margin run almost parallel to the margin itself and so it is impossible to derive meaningful values for the integrated crustal thickness between the COB and UCCL. The insets in Figure 5 illustrate the amount of extension restored along each small circle path for each candidate reconstruction model and crustal thickness grid. The amount of restored extension on each margin typically lies in the 150–250 km range. The hybrid and Powell models produce less along-strike variability than in the restored extension than the Naturaliste and Leeewin models, which yield restored extension values increasing to the west for both margins.

[36] Our alternative configurations of Australia and Antarctica at 83.5 Ma and full fit are shown in Figures 6 and 7, respectively. The Euler poles computed using the visual fitting are shown in Table 1, while the Euler poles and their associated errors are shown in Tables 2 and 3.

[37] The Leeuwin model achieves a very good fit for the RCOBs from crustal thicknesses derived using gravity inversion [*Kusznir*, 2009] (Figure 7). By design, the model results in NW-SE relative motion from onset of continental rifting (~160 Ma) until ~83.5 Ma that matches the trend of Leeuwin and Vincennes fracture zones and the trend of the strike-slip boundary marking the edges of western Tasmania and Cape Adare (Figure 6). Much further to the west, the NW-SE motion is also roughly parallel with the NW-SE trends observed in the oceanic Labuan Basin. The correlation can be observed through comparison of flow lines computed using this model's Euler poles and the fracture zone traces interpreted from satellite gravity (Figure 8). There is a good fit between the flow lines and the Naturaliste, Leeuwin and Vincennes fracture zones.

[38] The Naturaliste model results in a reasonable fit for the RCOBs from the gravity inversion–derived crustal thickness. The model results in NW-SE relative motion from onset of continental rifting (~160 Ma) until ~50 Ma that matches the trend of the Naturaliste and Vincennes fracture zones and the trend of the strike-slip boundary marking the edges of western Tasmania and Cape Adare (Figure 8). Similar to the Vincennes model, the NW-SE relative motion implied for the Labuan Basin is roughly parallel with the NW-SE basement trends observed in this basin—again illustrated by the correlation between computed flow lines and signatures observed in satellite gravity data (Figure 8). The model gives a good fit between flow lines and fracture zones along the western Tasmanian margin and the Cape Adare margin. There is also good fit between flow lines and fracture zones for the Naturaliste and Leeuwin fracture zones, while a slight angular difference is observed between computed flow lines and the Vincennes fracture zone.

[39] The *Powell et al.* [1988] model is based on the poles of rotation published by *Powell et al.* [1988], the estimates of RCOB locations are used only to modify the angle of closure between the Australian and Antarctica plates in an way that minimizes the misfit between the conjugate RCOB lines. This approach results in a reasonable fit in the area of the Bight Basin (Figure 7) but large overlaps are produced between the western margin of Tasmania and Cape Adare. The full-fit configuration implies that the Naturaliste fracture zone is conjugate with the western margin of the Bruce Rise—the Leeuwin and Vincennes fracture zones have no obvious features.

[40] The hybrid model restores Australia-Antarctica to the Leeuwin full-fit position that results in the best fit of the RCOB locations. Then, rather than force NW-SE relative motion following the prominent fracture zone trends, this model invokes N-S to NNW-SSE relative motion from full-fit to chron 34y time that allows a good fit to be obtained for the Tasmanian–Cape Adare conjugate margins. This model results in two major changes in the direction of relative motion, first at ~83.5 Ma and then again at ~50 Ma. Flow lines computed for this model show a good correlation with structural trends in both the Labuan Basin and the eastern segment of the plate pair (Tasmania–Cape Adare).

## 5. Discussion

### 5.1. Uncertainties in Restoring the Continental Margins

[41] The RCOBs shown in Figure 5 illustrate that the results for different candidate plate reconstruction models are very similar. The different plate models imply different small circle paths for the crustal thickness integration, but the results for each margin are relatively insensitive to even significant changes in these paths (e.g., compare the oblique small circles from the Naturaliste and Leeuwin models with the broadly margin perpendicular small circles implied by the hybrid model). The crustal thickness grids derived from gravity inversion are relatively smooth, so small circles starting from the same point on the COB aren't likely to sample significantly different crustal thickness profiles.

**Table 2.** Hybrid Model Euler Poles for Australia–East Antarctica (Antarctica Fixed)[a]

| Chron | Age (Ma) | Latitude | Longitude | Angle | r (km) | $\hat{\kappa}$ | dF | N | s |
|---|---|---|---|---|---|---|---|---|---|
| 34y | 83.0 | 0.89 | 36.69 | −26.64 | 540.50 | 0.17 | 92 | 103 | 4 |
| Full fit | ~160 | −3.91 | 37.90 | −30.86 | 131.75 | 1.04 | 137 | 148 | 4 |

[a]Finite rotations were computed following the methods of *Hellinger* [1981] and *Royer and Chang* [1991]. Parameters are r, misfit; $\hat{\kappa}$, estimated quality factor; dF, degrees of freedom; N, number of data points; s, number of great circle segments. The uncertainty assigned to fracture zone identifications are $\sigma$ = 5.0 km following *Müller et al.* [1991], and magnetic anomaly identifications is $\sigma$ = 5–10 km for chrons 20–33 and $\sigma$ = 15.0 km for chron 34. The uncertainty assigned to the full-fit identifications are half the total distance between our minimum and maximum. Ages are after *Cande and Kent* [1995] timescale.

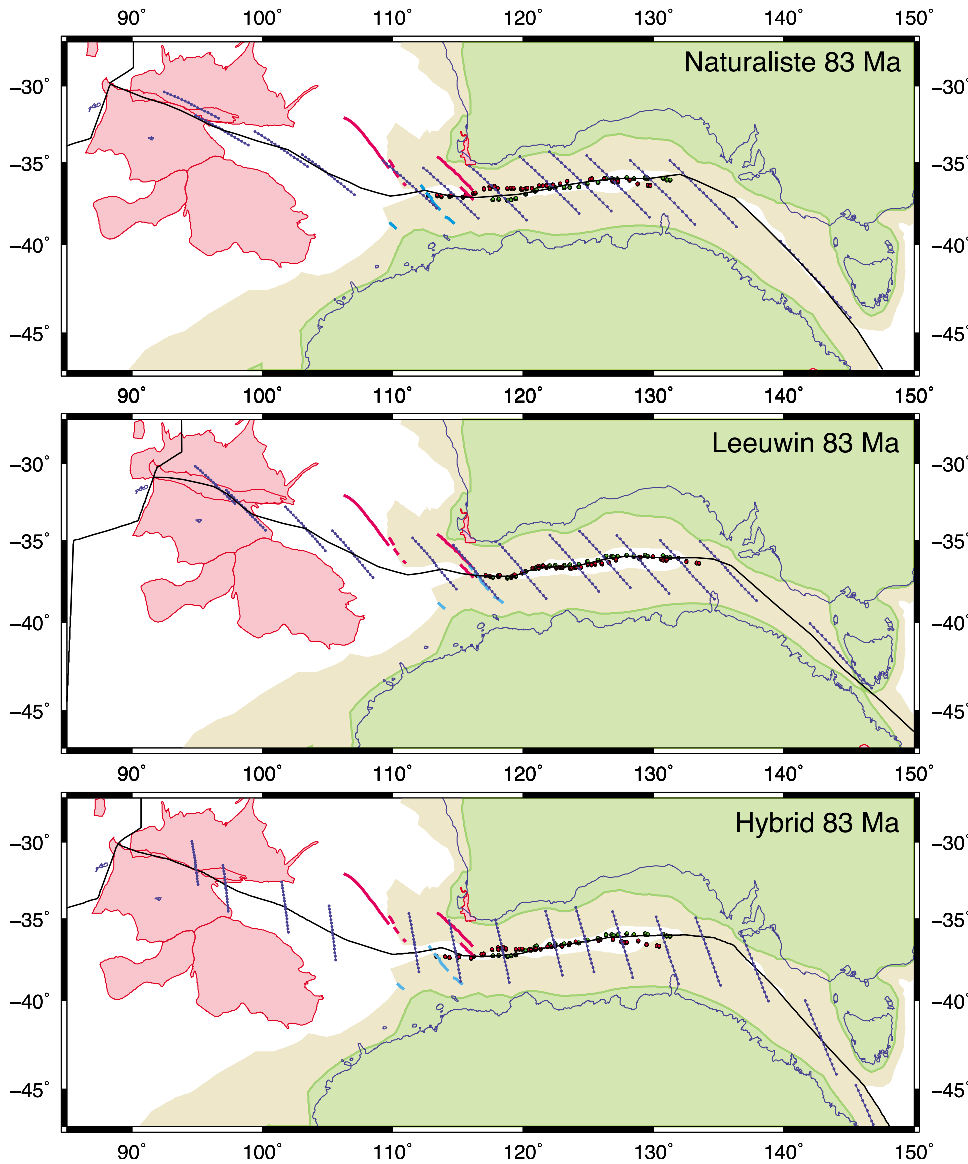


**Figure 6.** Alternative plate tectonic reconstructions for Australia-Antarctica at 83 Ma. (top) Naturaliste model, (middle) Leeuwin model, and (bottom) hybrid model. Colored dots show chron 34y picks (red, Antarctic plate; green, Australian plate); solid black lines represent plate boundaries; solid pink and blue lines show major fracture zones on Australian and Antarctic margins; pink polygons show the extent of large igneous provinces [*Coffin and Eldholm*, 1994]; pale brown shows extent of extended continental crust; and dotted lines show flow lines for the relative plate motions from 160 to 83.5 Ma implied by each model.

A more detailed crustal thickness grid with more sudden variations could give a larger disparity between the results for different small circles. However, the main consequence of the different models is not in the location of the RCOB locations calculated for each individual margin—rather, the difference between the models is the quality of the fit achieved when we try to fit the conjugate RCOB lines together. The results described above are dependent on our interpretation of the landward and seaward limits of extended continental crust in the conjugate margins. Other interpretations of these boundaries are possible. Likewise, other crustal thickness grids could be used. We now investigate the how these factors affect the RCOB locations.

[42] To test the influence of COB and UCCL interpretations, we have collated these alternative interpretations, together with other constraints such as bathymetry and onshore surface geology maps, to derive lines representing the most landward and most oceanward locations of the crustal boundaries for both margins (Figure 9). We then used these boundaries to derive alternative RCOB locations to understand how sensitive our results are to the interpreted locations of the boundaries.

[43] On the Australian margin, the most oceanward previous interpretation for the extent of continental crust comes primarily from seismic reflection profiles and forward modeling of potential field data [*Borissova*, 2002; *Direen*

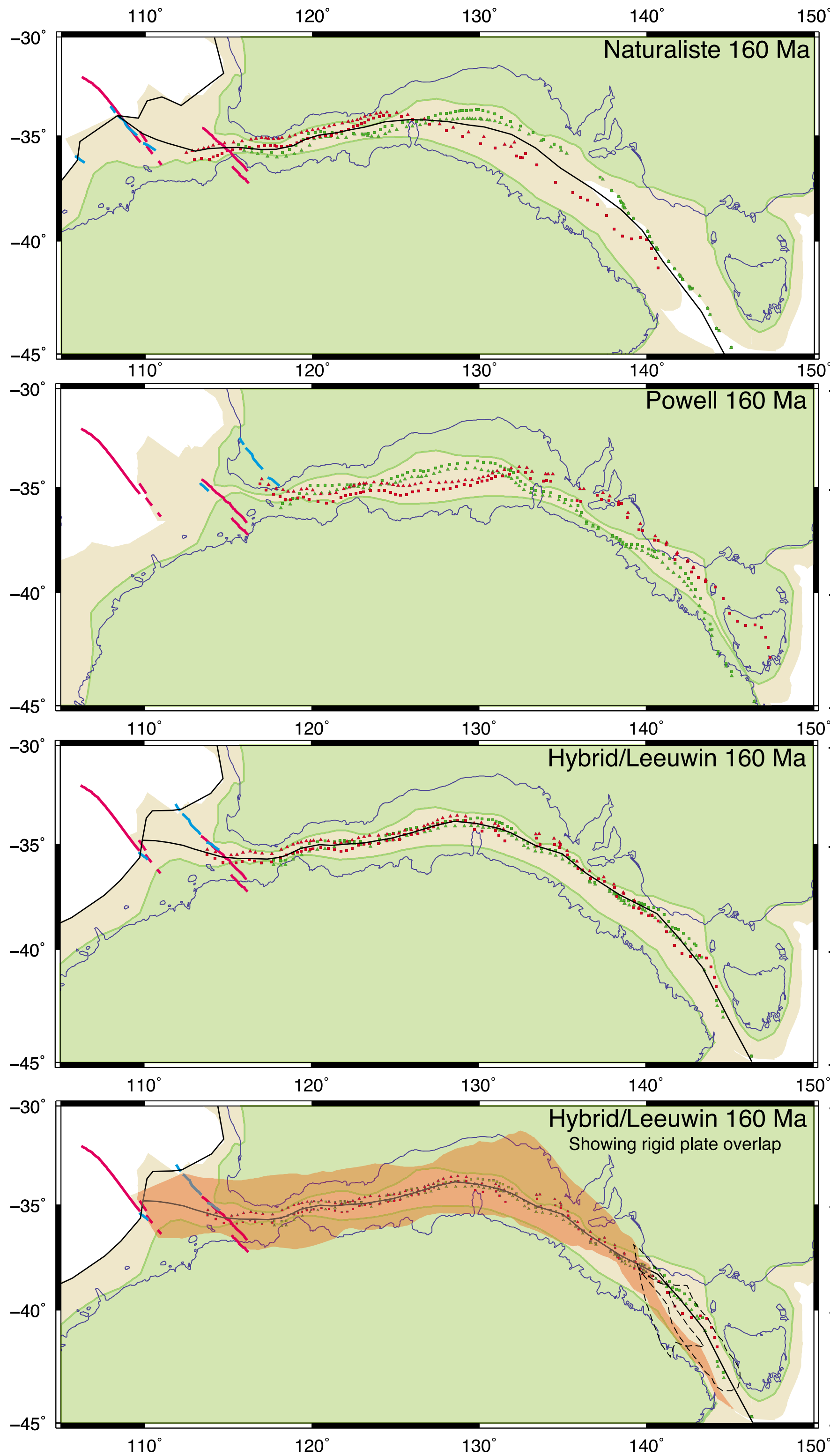


**Figure 7.** Alternative plate tectonic reconstructions at full fit (~160 Ma). (top to bottom) Naturaliste model, full-fit model implied by modifying the amount of closure about the pole of rotation of *Powell et al.* [1988], Leeuwin and hybrid models (the full-fit configuration is the same for both these models), and alternative illustration of the preferred hybrid model at full fit as a traditional "rigid" reconstruction, with continental blocks represented with their present-day extents, resulting in significant overlaps in the areas of subsequent extension. Symbology as in Figure 6 except that colored dots represent innermost and outermost RCOB locations (see Figure 5) for the Australian (green) and Antarctic (red) margins. Reconstructed positions of East and South Tasman Rise, modified from *Gaina et al.* [1998], shown by dashed black outlines.

**Table 3.** Covariance Matrices for Finite Rotations in Table 2[a]

| Chron | K | *a* | *b* | *c* | *d* | *e* | *f* | *g* |
|---|---|---|---|---|---|---|---|---|
| 34y | 0.17 | 6.65 | −2.31 | −5.81 | 9.11 | −9.03 | 22.7 | 7 |
| Full fit | 1.04 | 2.85 | −2.69 | 3.77 | 4.01 | −6.93 | 13.8 | 6 |

[a]The covariance matrix is given by the formula $\frac{1}{\kappa}*\begin{pmatrix} a & b & c \\ b & d & e \\ c & e & f \end{pmatrix} \times 10^{-g}$, where the values of a–f are given in radians squared.

*et al.*, 2007; *Espurt et al.*, 2009; *Sayers et al.*, 2001; *Totterdell and Bradshaw*, 2004]. Similarly on the Antarctica margin, interpretations of the COB based on seismic data [*Stagg et al.*, 2005] place the COB more oceanward than our interpretation. At the other extreme, we defined most landward COB locations based on the stretching factors (beta, derived from the gravity inversion results). We used the contour for beta = 3.5 as a rough estimate of the stretching factor that corresponds to significant melt generation and the onset of seafloor spreading [cf. *McKenzie and Bickle*, 1988]—put another way, we are assuming that where the crustal thickness is greater than ~12 km that it is unlikely to be oceanic.

[44] In contrast to COBs, the landward limit of extended continental crust is not something for which other interpretations have been proposed. We use the shelf break determined from bathymetry data as the most oceanward possible extent of unstretched continental crust, while the most landward extent is defined by mapped outcrop of prerift rocks. Basement outcrops on the Australian continent were taken from the UNESCO world geology map [*Bouysse*, 2010], while outcrops on the Wilkes Land margin were taken from images presented by *Stagg et al.* [2005] In the case of the Australian margin, this strategy results in a UCCL line up to several hundred kilometres inboard of the coast over the Madura Shelf since there is no basement outcrop—while this would be an extreme interpretation, it provides a test case for situations where less data is available to constrain this boundary.

[45] To investigate the degree to which RCOBs may be sensitive to the uncertainty in interpreted crustal boundaries, we generated a series of additional results using the alternative crustal boundaries shown in Figure 9. We generated results using crustal thickness from the global 2 degree resolution CRUST2 model [*Laske and Masters*, 1998] in addition to the two gravity inversion grids that give the most landward and oceanward RCOBs from the four grids analyzed previously. Figure 10 summarizes the results of this analysis for the Australian and Antarctic margins. Each polygon defines the envelope of all RCOB locations for the model and crustal thickness grid indicated using the four possible combinations of most oceanward and most landward COB and UCCL. Comparing different crustal thickness models, the distance between innermost and outermost RCOBs is clearly greatest for the CRUST2 model (something which may be related to the inherently lower resolution of this model). The crustal thickness in the region of the various present-day COB interpretations is typically greater for the CRUST2 model. As *Dunbar and Sawyer* [1989] pointed out, the uncertainty in the RCOB derived by integration of crustal thickness is much less than the uncertainty in the present-day COB itself—for example, a 10 km lateral shift in the present-day COB location results in corresponding shift in the RCOB location assuming crust stretched by a factor of 5 is 2 km. Following this logic, the greater the crustal thickness predicted by a given model near

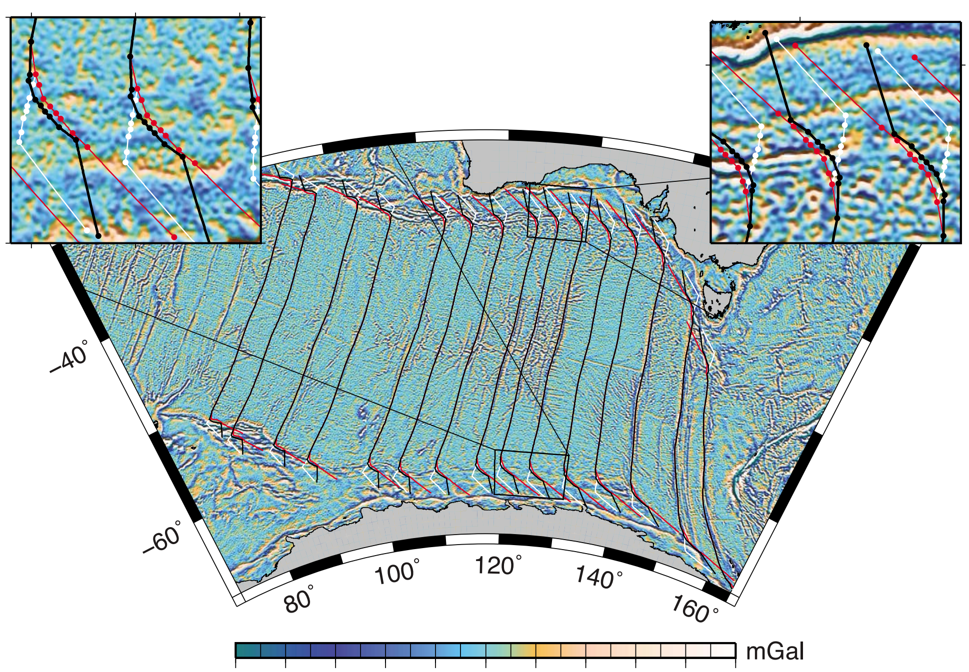


**Figure 8.** Flow lines resulting from our three alternative plate tectonic models: Leeuwin, white; Naturaliste, orange; and hybrid, black.

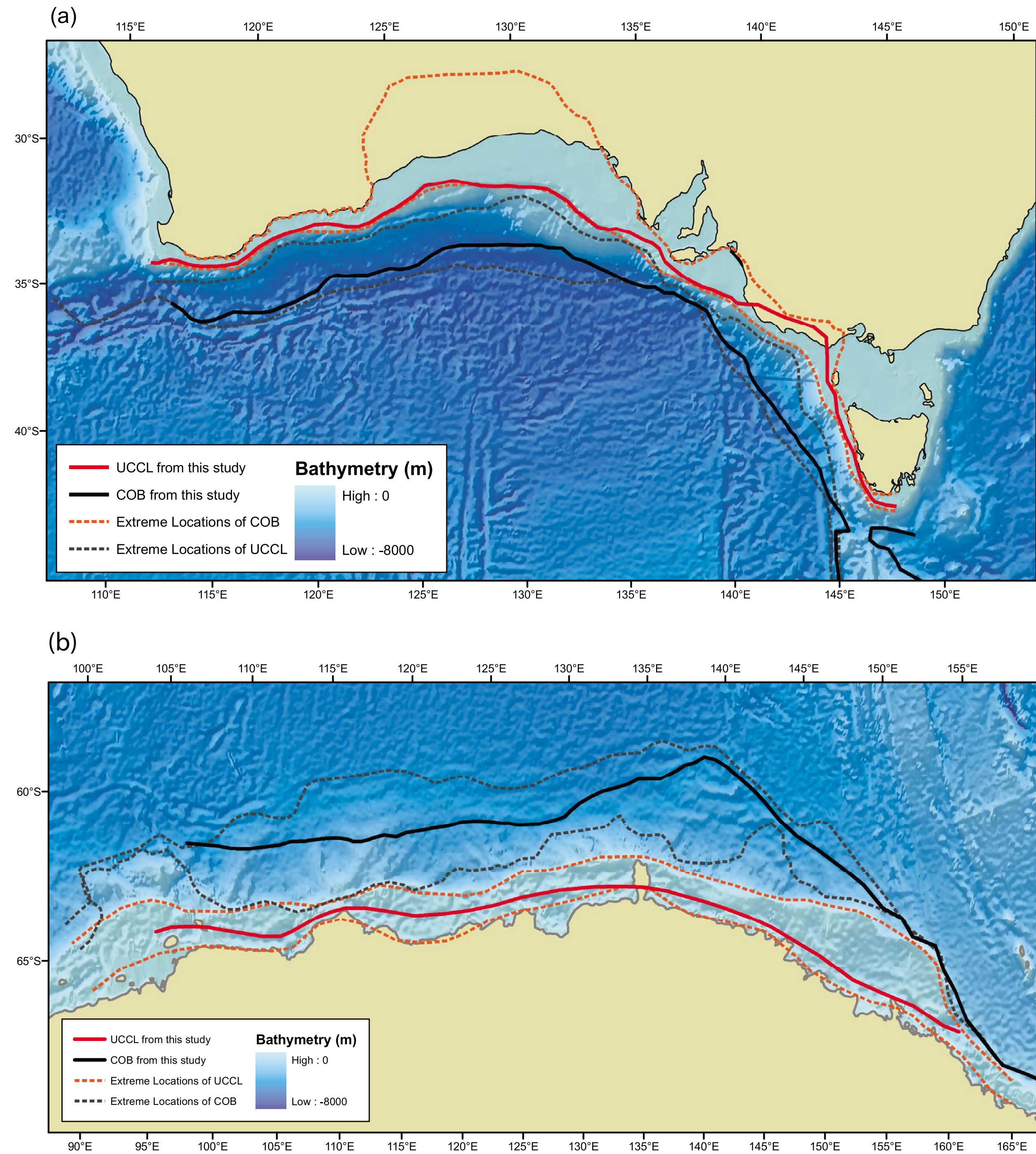


**Figure 9.** Interpreted locations of the COB and UCCL compared with innermost and outermost interpretations of the COB and UCCL from the literature and alternative interpretation approaches. (a) Southern Australian margin and (b) Antarctic Margin.

the COB, the more sensitive the RCOBs derived from this model will be to lateral changes in the present-day COB definition. The gravity inversion method of *Kusznir* [2009] prescribes that, for "normal" margins, crust thinned beyond a thinning factor of 0.7 will include some melt addition. Hence the residual continental thickness is reduced compared to that expected at a "magma poor" margin, crust thinned. As a result, the RCOB results for the "normal" margin grids are less sensitive to the position of crustal boundaries (Figure 10).

[46] It is worth reiterating that the range of results shown in Figure 10 reflects the full range of RCOB locations possible using the most extreme interpretations for the UCCL and present-day COB (Figure 9). Perhaps of greater significance is the sensitivity of the results to the more subtle differences between alternative, published, data-driven

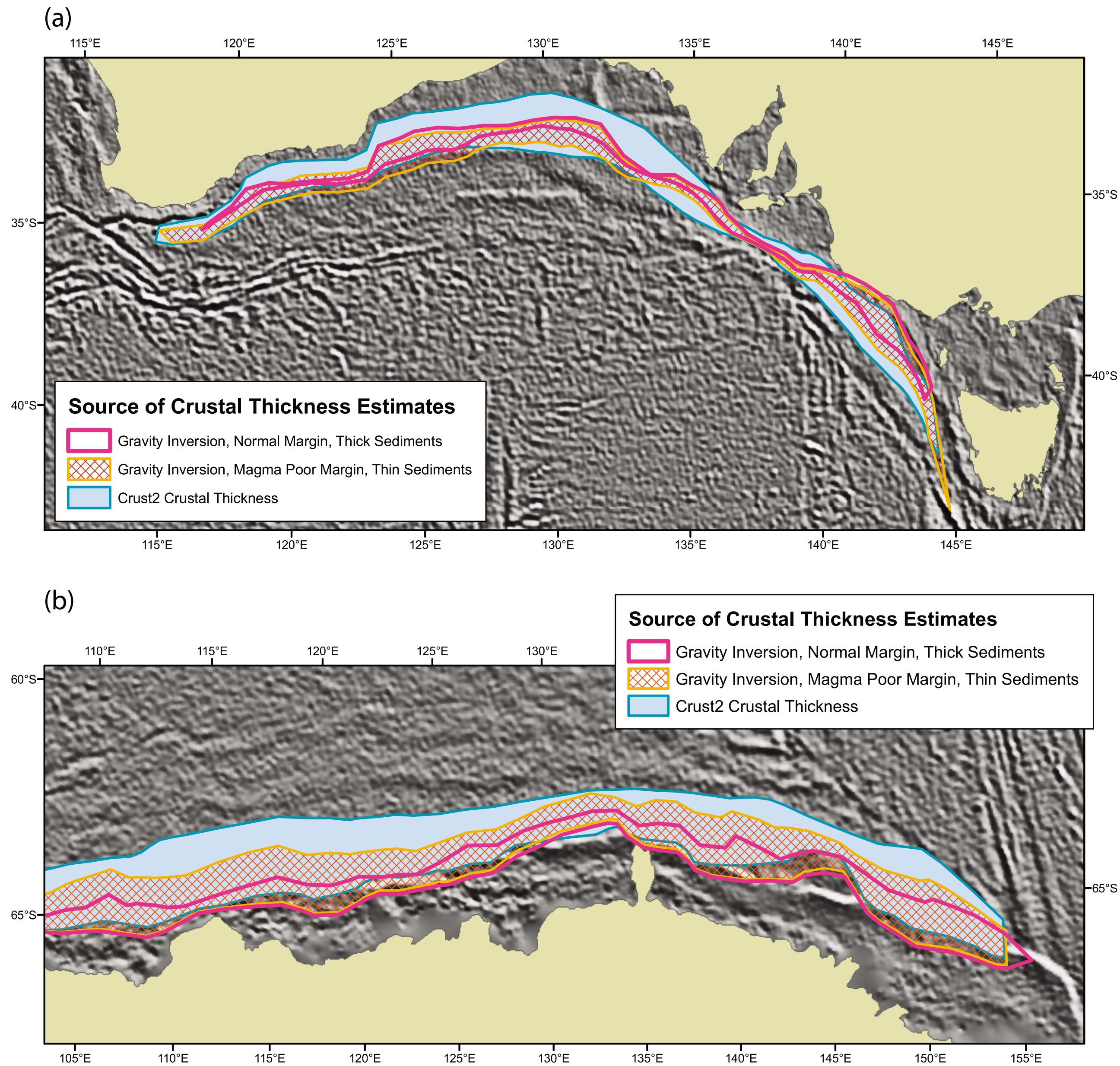


**Figure 10.** Results from sensitivity analysis of how varying the COB, UCCL, and crustal thickness grid used affect the restored position of the continental margin. All RCOBs are calculated using the small circle paths implied by the hybrid model poles of rotation.

interpretations of these boundaries. A major reason for the ambiguity surrounding early Australian-Antarctic relative motions is the lack of a clear boundary between continental and oceanic crust. The transition zones of these margins have been described as continental crust [e.g., *Colwell et al.*, 2006], oceanic crust [e.g., *Tikku and Cande*, 1999; *Whittaker et al.*, 2007] and exhumed continental mantle [e.g., *Beslier et al.*, 2004]. We have chosen to use an interpretation of the COB that is further landward than the limit of continental crust proposed by several of these authors, since we only want to restore crust that we are certain belonged to the continents prior to rifting. In any case, the differences in these interpretations are minor compared to the extreme interpretations shown in Figure 9. Furthermore, cross sections shown by various authors interpreting continental crust to extend further oceanward than our definition in the Bight Basin indicate that the continental thickness is typically <5 km [e.g., *Direen et al.*, 2007; *Espurt et al.*, 2009]. Hence, had we assumed that some continental crust lay oceanward of our COB line for the Bight Basin, the influence on the RCOB line would amount to <10 km lateral difference.

[47] The Naturaliste and Leeuwin models both imply plate motions at a highly oblique angle to the margins when the majority of extension in the Otway Basin occurred (prior to ~90 Ma). The oblique opening direction is an issue for applying our methodology to the Otway Basin. This issue throws up a number of possibilities: (1) The limitation may be the methodology—our small circle paths inherently assume that the rifting can be described a single phase of rifting in the direction implied by the relative plate motions,

whereas in a highly oblique transtensional setting such an approach is inappropriate; (2) the Otway Basin could be incorporated into a Tasmania Block that is allowed to move relative to Australia, thus implying a different net direction of rifting; (3) the extension in the Otway Basin could be allowed to end at a much later time, in which case the Leeuwin model would imply N-S extension for some of the rifting; and (4) the issue may simply highlight that the Naturaliste and Leeuwin models show important inconsistencies with the available geological evidence.

### 5.2. Discussion of the Models

[48] A drawback of the Leeuwin model is that relative motion following the trend of the Leeuwin and Vincennes FZs, from a full-fit position where the Naturaliste Plateau is located to the north of the Bruce Rise, leads to severe fit problems by chron 34y time (~83.5 Ma), with substantial continental overlap occurring between western Tasmania and Cape Adare. To minimize this overlap, we can implement relative motion that results in continued, albeit very slow, extension in the Central Kerguelen Plateau region from 100 Ma until final separation of Broken Ridge from the Kerguelen Plateau at ~43 Ma [*Tikku and Cande*, 2000]. However, even with the implementation of continued spreading beneath the Central Kerguelen Plateau excess overlap between Cape Adare and Tasmania at 83.5 Ma can only be minimized to ~100 km. For comparison, if a static plate boundary between Kerguelen and Broken Ridge is assumed [e.g., *Tikku and Cande*, 1999, 2000] then the excess overlap problem is resolved. The overlap problem is easily observed through the poor match between the flow lines and the fracture zones that curve around the eastern end of the Wilkes Land margin. *Tikku and Cande* [2000] propose a model in which the overlap problem is avoided by invoking ~85 km of ENE-WSW directed dextral strike-slip motion between Australia and Tasmania. The motion is proposed to postdate chron 33o time (79.1 Ma). This timing would coincide with the final phase of rifting in the Bass Basin described in the tectonostratigraphic synthesis of *Blevin* [2003], who do not describe any evidence for major strike slip motions within the various geophysical data sets they analyzed. *Cayley et al.* [2002] and *Cayley* [2011] emphatically rule out the possibility of any significant lateral motion of Tasmania since the Early Cambrian on the basis of modern magnetic data and exposed Palaeozoic geology in southeast Australia.

[49] Of the models discussed here, the Naturaliste model predicts the greatest obliquity of relative Australian-Antarctic motion toward the western end of the system. This ties in well with the formation of the Diamantina Zone, a section of particularly rough oceanic basement located at the western end of the Australian southern margin and dissipates further to the east, toward the Great Australian Bight section of the margin. The roughness of newly formed oceanic basement is related to spreading rate and spreading obliquity [*Whittaker et al.*, 2008b]. Hence the nature of the Diamantina Zone supports the notion of early spreading in the western section of the Australia-Antarctica system that was extremely slow (<10 mm/yr) and oblique to the axis of rifting.

[50] The Naturaliste model has clear fit problems for the initial stages of the breakup history. If we assume that continental extension between the western margin of Tasmania and Cape Adare occurred between 160 Ma and ~83.5 Ma, then in a “rigid” plate reconstruction we would expect the present-day extent of the stretched continental crust to overlap. Instead, a gap of the order of 50 km exists between these conjugate margins as they slide past each other from 160 Ma to the major change in relative plate motions at (50 Ma). The gap becomes substantial when we consider estimates for the restored boundaries of each plate. Note that our model takes into account the estimated restored extents of both the eastern and western segments of the South Tasman Rise in their reconstructed positions after *Gaina et al.* [1998]. One possibility, albeit remote, to explain this “loose” fit is that an extensional episode affected this margin region prior to the onset of Australian-Antarctic motion. It is not entirely unfeasible that this extensional event also affected the Cape Adare–Tasmania region.

[51] The hybrid model avoids the fit problems of the Leeuwin and Naturaliste models. However, the plate motions during early the early stages of rifting do not (by design) conform with the trend of the Vincennes, Naturaliste and Leeuwin Fracture Zones. Our preferred NNW-SSE continental rifting direction is oblique to the NW-SE trends of the prominent Nautraliste, Leeuwin and Vincennes Fracture Zones. While these structures (that actually occur within continental crust and are therefore not fracture zones) are commonly interpreted to have formed due to relative motion between Australia and Antarctica, we instead interpret that they formed due to the NW-SE motion of India away from Australia and Antarctica. Evidence supporting this interpretation includes the observation that these prominent structural trends, that match the trend of true fracture zones observed in the Perth Abyssal Plain, only occur at the very western extent of the Australian-Antarctic conjugate pair, in the only portion of the system directly affected by Indian rifting. Similar prominent structural trends are not observed anywhere further east along either the Australian or Antarctic passive margins. Additionally, Early Cretaceous volcanics cap both the Bruce Rise [*Guseva et al.*, 2007] and the Naturaliste Plateau [*Coffin et al.*, 2002] indicating a shared history related to the rifting of India and early Kerguelen volcanism.

[52] In Figure 11 we analyze the along-strike variation in restored crustal thickness implied by our candidate models and also other previously published models for the full-fit reconstruction of Australia and Antarctica [*Powell et al.*, 1988; *Royer and Sandwell*, 1989]. In each case we used our interpretation of the UCCL and present-day COB, and plotted the envelope of results for different gravity inversion crustal thickness estimates. The paths of the small circle paths vary depending on the poles of rotation for each model, the inset of Figure 11 shows small circle paths for the hybrid model as an example. Note that to generate Figure 11 we use the full-fit pole of rotation exactly as given by *Powell et al.* [1988], in contrast to the additional analysis below where we attempt to modify this pole of rotation to better match the constraints from restored crustal thickness. The plot illustrates that the Leeuwin and hybrid models imply a relatively smooth distribution of crustal thickness along the Australia-Antarctica boundary zone prior to rifting. The Naturaliste model, as well as other previously published models [*Powell et al.*, 1988; *Royer and Sandwell*, 1989] imply much thicker restored crust and with greater along-strike variability in this thickness. This indicates that these models imply an excess of closure between the two

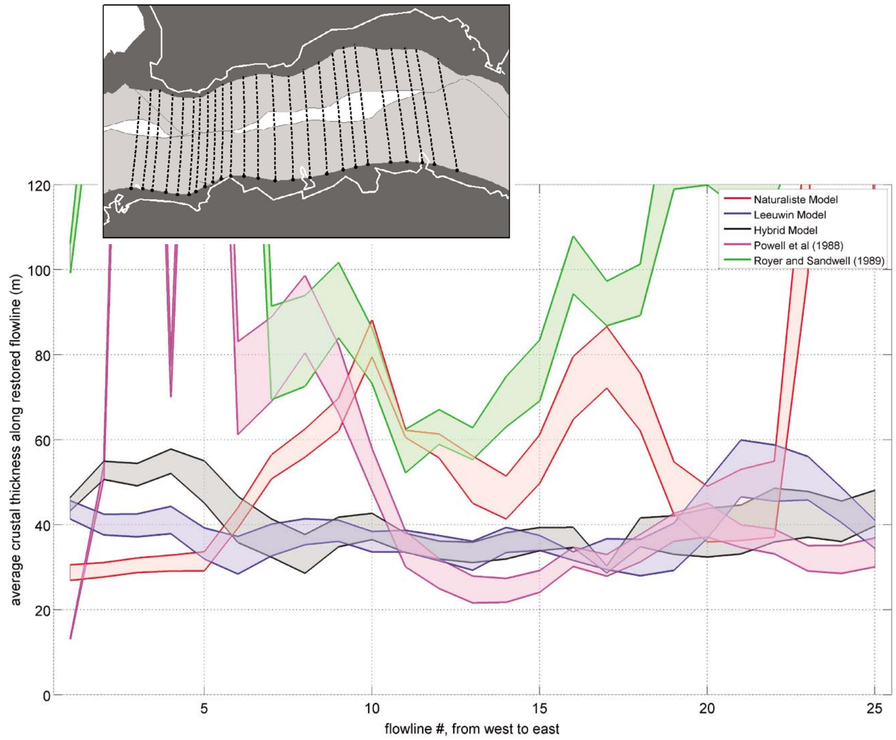


**Figure 11.** Along-strike variation in the average restored crustal thickness implied by different models for the full-fit configuration of Australia and Antarctica. Values are calculated along a series of small circle paths that share the same seed point along the Antarctic hinge line between the Bruce Rise and George V Land. The paths of the small circle paths vary depending on the poles of rotation used. The inset shows small circle paths for the hybrid model as an example.

plates not supported by observations. Another possibility is that we have included too much crust as continental in each of the margins resulting in overly thick crust after it has been restored. However, as discussed previously, our interpretations of the present-day COB are actually landward of the alternative interpretations based on recent seismic data so this possibility is unlikely.

### 5.3. Comparison of the Hybrid Model With Structural Data From the Australian Margin

[53] Our proposed NNW-SSE direction of motion during continental rifting may be more consistent with the observed structural trends in Australian margin basins to the east of 130°E than the previously favored NW-SE direction of motion. Immediately to the east of the 130°E boundary line, in the Ceduna Subbasin, a N-S to NNW-SSE extension direction interacted with NW-SE trending structural basement fabrics to result in half-grabens with E-ENE trending bounding faults. Further east, the Otway and Sorell Basins are characterized by prominent N-S basement faults intersected by NW-SE faults [*Nayak et al.*, 2010]. A wide variety of inferred directions have been proposed for the Otway basin, ranging from NW-SE [*Boreham et al.*, 2002; *O'Brien et al.*, 1994; *Willcox and Stagg*, 1990], NE-SW [*Perincek et al.*, 1994] and N-S [*Hill et al.*, 1994]. *Hill et al.* [1995] found the large range was due to a number of factors including overprinting, limited seismic control and interpretive bias.

[54] We have not attempted to address the causes for individual basinal structural variation as it is clear that much of the localized variation is due to structural inheritance. A clear limitation of using crustal thickness data to restore the extended continental crust is that we can only use these data to make inferences about the plate configurations prior to the onset of crustal extension. A more detailed model of the rifting history describing changes in the rate and orientation of plate motions prior to the onset of seafloor spreading would require more detailed data sets and analysis. Our results provide a single pole of rotation that describes the overall plate motion for the rifting phase; since the RCOBs are relatively insensitive to changes in the overall plate motions, we can be confident that palinspastic restoration incorporating multiple changes in the directions plate motion over time would not imply significantly different RCOB geometries. Hence, the regional Euler poles computed here provide a starting point for more detailed analysis of the rift phase and would be a useful input to stress modeling of the Australian-Antarctic continental margins.

## 6. Conclusions

[55] We have used geophysical data to estimate the extent of stretched continental crust along the conjugate continental margins of Australia and Antarctica. The interpreted crustal boundaries, together with estimates of crustal thickness from gravity inversion, form the basis for the calculation of prerift plate boundary geometries along these margins. We then introduce a new methodology to derive full-fit plate reconstructions that combines the palinspastically restored

continental margins with other geological constraints. We explore a range of possible tectonic models for the breakup history of Australia and Antarctica in the context of these new constraints together the other available geological evidence and so generate more robust full-fit reconstructions of Australia and Antarctica. Our development of an accurate plate tectonic model describing the continental rifting and breakup between Australia and Antarctica provides a framework to develop a better understanding of the temporal tectonic and thermal regimes influencing the basins of the southern Australian margin from ~160 Ma to ~83.5 Ma. The methodology developed here is broadly generic and can potentially be applied for the reconstruction of any passive margin pair, although adaptations are needed to accurately model margins with multiphase rift histories and microblocks.

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