Full-fit reconstructions of the southern Australian margin and Antarctica – implications for correlating geology between Australia and Antarctica

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Keywords: Australia, Antarctica, Gondwana, plate tectonics, full-fit reconstruction, continental rifting, Southern Margin.

Abstract

The sedimentary basins along the southern Australian and conjugate Antarctic margins formed as a result of Mesozoic rifting. A number of alternative models have been proposed for the pre-rift configuration of Australia and Antarctica. They differ both in how tight the fit between these continents is, and in the lateral juxtaposition of the two continents, ie. some reconstructions place Australia further to the east, relative to a fixed Antarctica, than others. The continuity of comparable geological terranes, surface-mapped shear-zones, and geophysical signatures (e.g. magnetic anomalies) between Australia and Antarctica within Gondwana has implications for assessing these different reconstruction models.

To investigate this issue, we tested a range of scenarios for the full-fit configuration of Australia and Antarctica. In the light of palinspastic reconstructions of the extended continental crust within each margin, we investigate how different reconstruction models reconcile geological and geophysical signatures from the conjugate plates. We find that a model that matches the Leeuwin Fracture Zone (in the Australian margin) with the Vincennes Fracture Zone (in the Antarctic margin) reconciles Proterozoic structures previously correlated between the continents based on their geological similarity. These include rocks from the Albany-Fraser orogeny, and the Kalinjala mylonite zone and Mertz shear zones. This model also reconciles the constraints from palinspastic reconstruction of Mesozoic extension better than models that place Australia further east or west relative to Antarctica within Gondwana. This model does not produce a postulated alignment between the Darling Fault in Western Australia and the Denman Glacier in Western Wilkes Land. The preferred full-fit reconstruction model, together with other evidence from the early breakup history between the Australian and Antarctic plates, suggests that the overall opening direction between the two continents was broadly NNW-SSE, but this includes phases of N-S and NW-SE–directed extension.

Introduction

The Australian and Antarctic continents were neighbours in Gondwana, before continental rifting and breakup in the Cretaceous. Many studies of the older geological domains in each of these continents have sought to establish the links between structures bordering the conjugate continental margins on each side of the Southern Ocean (e.g. Stump et al, 1986; Foster and Gleadow, 1992; Fitzsimons, 2003; Goodge and Fanning, 2010; Flottmann and Oliver, 1994; Gibson et al, 2011; Cayley, 2011; Veevers, 2012). Some of these studies draw correlations within the framework of schematic reconstruction sketches. Others consider the configuration of the continents based on Euler poles of rotation from a single chosen model for the full-fit configuration of Australia and Antarctica. However, various alternative models have been proposed for the full-fit configuration and early seafloor spreading history and direction of relative plate motions during continental rifting. These different models lead to large differences in the lateral position of Australia relative to Antarctica within Gondwana. This in turn has major implications for the alignment of the geological and geophysical 'piercing points' identified in each continent.

To investigate this issue, we tested a range different reconstructions for the full-fit configuration of Australia and Antarctica that were constructed on the basis of the evidence from Cretaceous rifting and early seafloor spreading alone (Williams et al, 2011). Here, we examine the correlation of onshore geological and geophysical structures in the context of the alternative reconstruction models.

Full-fit reconstructions of Australia-Antarctica

The pre-rift configuration and early rifting history of 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 began during the Late Jurassic (~160-140 Ma) with an early phase of continental rifting followed by thermal subsidence (Totterdell et al., 2000). Acceleration of continental extension at ~100 Ma (Totterdell et al. 2000) was followed by continental break-up and the commencement of very slow seafloor-spreading (~10 mm/yr half rate) at ~83.5 Ma, though breakup was diachronous and occurred much later to the east.

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 in 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) proposed that pre-breakup continental rifting and extension was oriented NNE-SSW based on the pattern of faulting in the Bass

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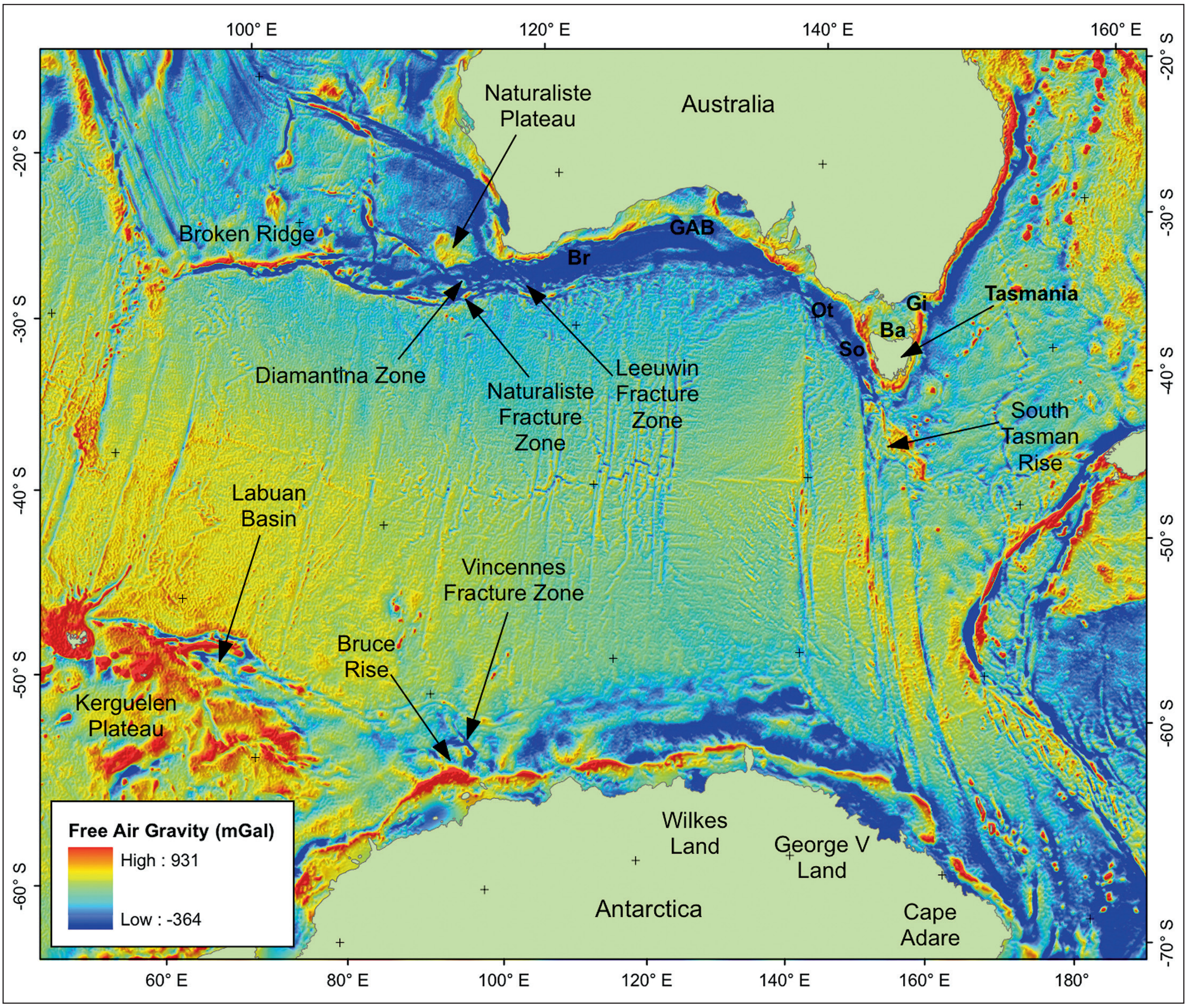

Figure 1. Map of free-air satellite gravity (Andersen et al., 2010) illustrating major tectonic features of the Australian Southern Ocean. Br – Bremer Basin; GAB – Great Australian Bight Basin; Ot – Otway Basin; So – Sorell Basin; Ba – Bass Basin; Gi – Gippsland Basin. Figure reproduced from Williams et al (2011).

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. 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. More recently, Williams et al (2011) used palinspastic restoration of crustal thickness grids for the conjugate extended margins to evaluate various reconstructions and determined a new full-fit pole of rotation that reconciled the restored continent boundaries as well as other available constraints.

Testing Mesozoic reconstructions against older structures

Australian-Antarctic fit reconstructions should result in a realistic juxtaposition of geological terranes across the conjugate margins. Since our reconstructions were derived independently of fitting onshore geological structures, the former provide an independent test of various proposed correlations. The method for deriving a palinspastic full-fit plate configuration described by Williams et al (2011) did not use as a quantitative constraint the proposed correlations between ancient Palaeozoic and older geological terrains in Australia and Antarctica – instead their reconstructions were constrained by structures and variations in crustal thickness within the extended margins. Here, we investigate the implications of our preferred full-fit reconstruction, together with the two end member scenarios for the lateral position of Australia relative to Antarctica, for the proposed correlation of pre-existing geological and geophysical structures within the two continents.

We tested three alternative full-fit and early rifting models for Australia-Antarctica (figure 2) for consistency with various lines of evidence, including (i) the basin-scale extension directions recorded within the conjugate margins, (ii) interpreted correlations between conjugate features within the rifted margins, and (iii) constraints (isochrons, fracture zones) for the earliest phase of seafloor spreading. In this study we consider three scenarios – our preferred reconstruction model based on palinspastic restoration of the extended crust within the conjugate rifted margins, as well as two end-member scenarios, which align the Australia several hundred kilometres to the east or west relative to Antarctica.

(a) *Preferred model*: The Leeuwin and Vincennes Fracture Zones (figure 1) are conjugates; this may be achieved by assuming either (1) that the motion from the onset of continental rifting (~160 Ma) until break-up at ~83.5 Ma is recorded by the NW-SE trend of these structures (cf. Tikku and Cande, 1999) – implying 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; or (2) that motion from the onset of continental rifting (~160 Ma) until break-up at ~83.5 Ma is not recorded by the NW-SE trend of these structures, but rather there is a change in plate motion at some point between the onset of rifting and onset of seafloor spreading (Williams et al, 2011).

(b) *The Naturaliste model*: The basic assumptions underlying this 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 break-up at ~83.5 Ma is recorded by the NW-SE trend of these structures.

(c) *Powell model*: The model of Powell et al. (1988) (1) does not align either the Naturaliste or the Leeuwin Fracture zones with the Vincennes Fracture Zone and (2) predicts a NE-SW direction of motion during continental rifting that is significantly different from that implied by the models described above.

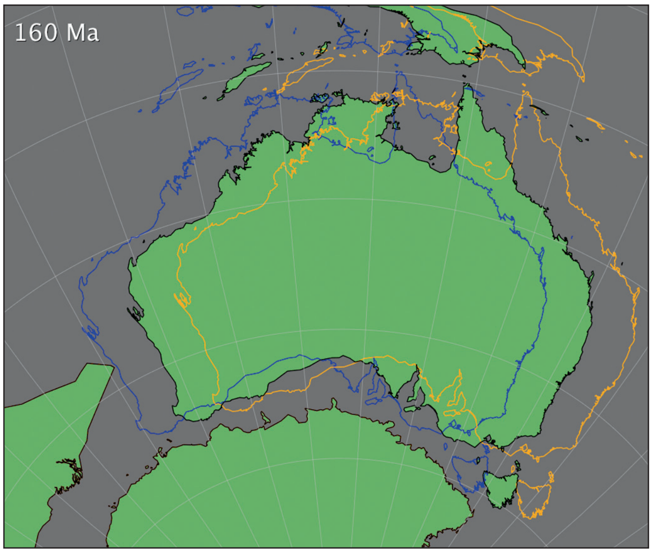

Figure 2. Figure showing three end member full-fit models; Reconstructions show three possible locations of Australia relative to a fixed Antarctica at 160 Ma, prior to the onset of rifting and eventual breakup of these continents. Filled green polygons show palinspastic full-fit reconstruction after Williams et al (2011); Blue polygon (Powell model) shows a westernmost end-member location for Australia based on alignment of the Naturaliste Fracture Zone with the Vincennes Fracture Zone; Orange polygon (Naturaliste model) is an easternmost end member full-fit location for Australia. The graticule shows lines of longitude and latitude at 10° intervals.

Links between Australia and Antarctica

Southwest Australia and Western Wilkes Land

The geology of the southwestern corner of Australia records the Albany-Fraser orogeny, formed as a result of collision between the southern margin of the Yilgarn Craton and the Mawson Craton (Fitzsimons, 2003; Boger, 2011). The orogeny is thought to have occurred in two stages, both during the Mesoproterozoic, and both of which can be identified in units exposed in East Antarctica as well as southwest WA. The geological provinces shown in figure 3 are based on the work of Boger (2011). Various metamorphic complexes within the Bunger Hills area are correlated with the Biranup complex in WA (both with metamorphism ages predominantly within stage 2 of the orogenesis), while the rocks to the east of Bunger Hills are correlated more closely with the Nornalup Complex. Dredge samples from the Naturaliste Plateau (Halpin et al, 2008) suggest that the continental basement of the plateau also has affinity to the Albany-Fraser Orogen.

A further possible line of evidence linking Australia and Antarctica is the Darling Fault, a major N-S structure along the western margin of Australia (Figure 3). Correlation of this feature with its interpreted continuation beneath the Denman Glacier (white dashed line in figure 3) has been used to estimate the relative position of Australia and Antarctica (e.g. Beeson et al, 1995).

Figure 3 shows correlations between southwest Australia and East Australia according to the three reconstructions under consideration. The reconstruction of Powell (1988) satisfies the postulated alignment of the Darling Fault and Denman Glacier, whereas the in the other reconstructions the projection of the Darling Fault into Antarctica lies significantly to the east of the Denman Glacier. The different reconstructions also have implications for the variation of the surface extent of units related to the Albany-Fraser origin. Using the outlines defined by Boger (2011), the Preferred model allows for the mapped width of this belt to be fairly continuous between Australia and Antarctica (the true extent in Antarctica is poorly constrained due to ice cover) and a continuation of the Biranup complex to continue along its observed trend in WA to the Bunger Hills units.

Eyre Peninsula and Eastern Wilkes Land

Correlations between the Eyre Peninsula in South Australia and Eastern Wilkes Land are discussed by Goodge and Fanning (2010) and Veevers (2012). In the Eyre Peninsula, Archean and Paleoproterozoic metamorphic units are juxtaposed against Paleoproterozoic igneous units across the Kalinjala mylonite zone. Archean and Paleoproterozoic units are observed within the Terre Adelie area of Antarctica, with shear fabrics suggesting that the Mertz shear zone forms that eastern boundary of these units (with the caveat that rocks to the east of the shear zone are hidden under ice). On the basis of their similar dextral kinematics, and the correspondence in ages of both of the structures themselves and the units they cut, Goodge and Fanning (2010) correlate the Kalinjala mylonite zone with the Mertz shear zone.

When placed in the candidate full-fit reconstructions (figure 4), the poles of rotation for the preferred model match

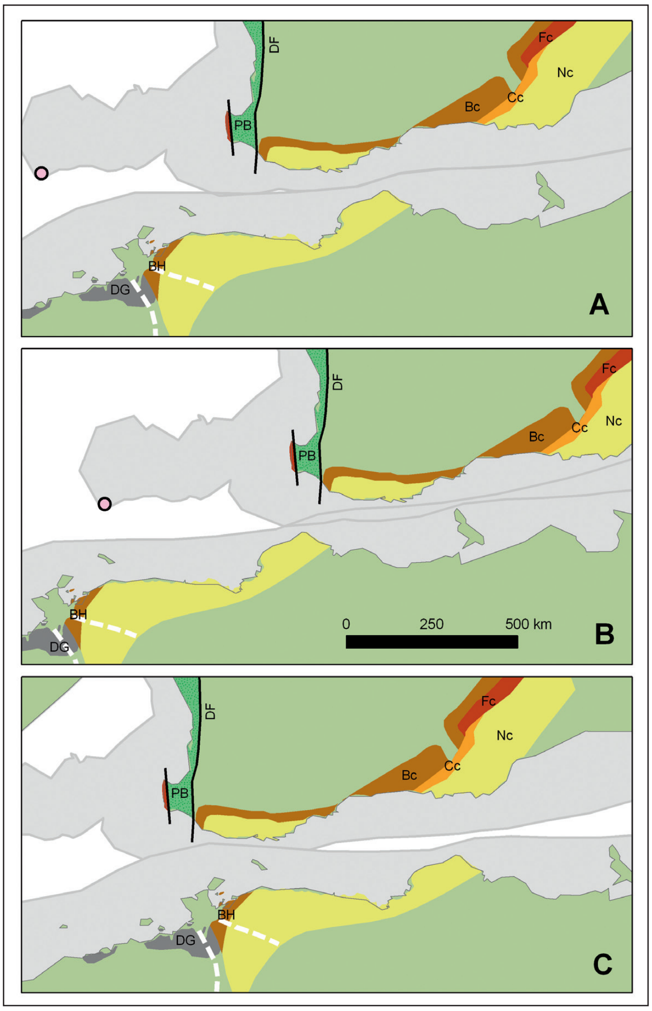

Figure 3. Juxtaposition of geological provinces and structures between southern Western Australia and Western Wilkes Land, according to three different reconstructions for the Australia and Antarctica prior to Mesozoic rifting. (A) Preferred model (b) Naturaliste Model; (c) Powell et al (1988) model. Geological provinces and naming conventions based on Fitzsimons (2003), Halpin et al (2008) and Boger (2011). Pink-filled circle shows site of Naturaliste Plateau dredge samples described by Halpin et al (2008) DG – Denman Glacier; BH – Bunger Hills; Nc – Nornalup Complex; Bc – Biranup Complex; Fc – Fraser Complex; Cc – Corumup Complex; PB – Perth Basin; DF – Darling Fault.

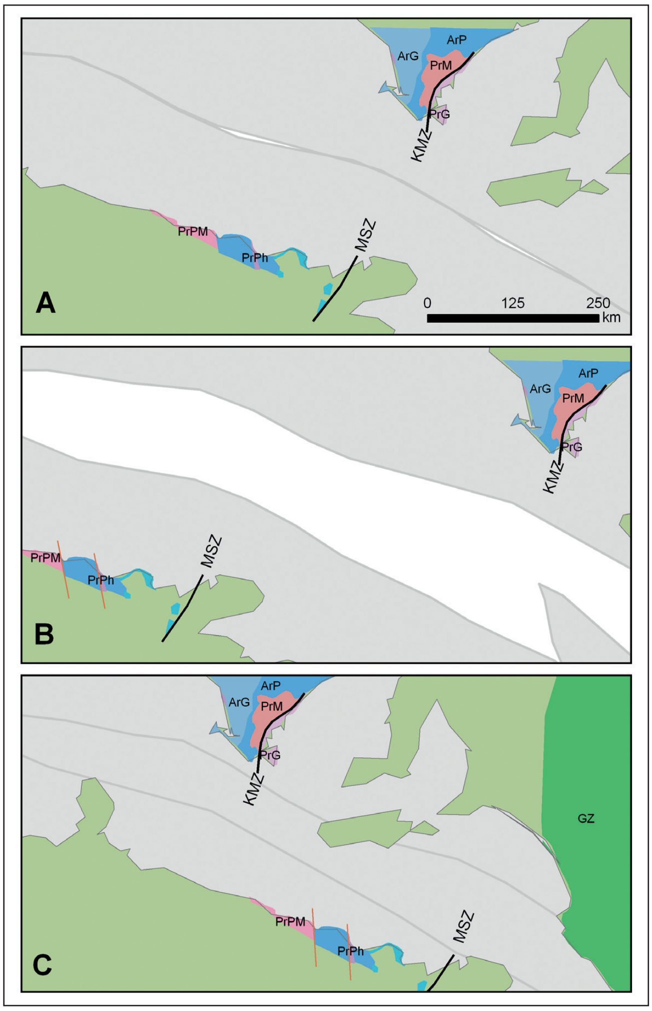

Figure 4. Juxtaposition of geological provinces and structures between the Eyre Peninsula and Eastern Wilkes Land, according to three different reconstructions for the Australia and Antarctica prior to Mesozoic rifting. (A) Preferred model (b) Naturaliste Model; (c) Powell et al (1988) model. Geological provinces and naming conventions based on Goodge and Fanning (2011), Veevers (2012). KMZ – Kalinjala Mylonite Zone; MSZ – Mertz Shear Zone; ArG – Archean granitoid; ArP – Archean paragneiss; PrM – Proterozoic Metasediments; PrG – Proterozoic granitoid; PrPM – Proterozoic paragneiss and migmatite; PrPh – Proterozoic phyllite.

these structures very well, consistent with them forming a single continuous feature prior to Gondwana breakup. The Naturaliste model yields a dextral offset of greater than 300 km between the projections of the two structures, while the Powell model yields a sinistral offset of just less than 300 km.

Tasmania-Victoria and Northern Victoria Land

Geological correlations between Eastern Australia, Tasmania and Northern Victoria Land in Antarctica have been discussed by various authors including Foster and Gleadow (1992), Gibson et al (2010), Cayley (2011) and Moore and Betts (2011). Some of the details of these correlations differ between these authors, but other correlations are less controversial. For example the Moyston Fault (also referred to as the Woorndoo Fault; Foster and Gleadow, 1992) in western Victoria is a likely counterpart of the Leap Year Fault in Northern Victoria Land – Moore and Betts (2011) identify these structures as both being part of a west-dipping Cambrian subduction zone along the eastern margin of Gondwana.

Figure 5 shows a comparison of the three reconstruction models for the Victoria-Tasmania-Northern Victoria Land sector within Gondwana. The figure illustrates the space problems associated with the two end-member scenarios – the Naturaliste model results in a large gap between the palinspatically restored boundaries of Australia and Antarctica (too big to be explained by restoring the South Tasman Rise northwards), while the Powell model results in overlap in the Otway and Sorell Basins. Note that in these reconstructions Tasmania is fixed to Australia. Some, though far from all, of this overlap could be avoided by accounting for extension on the Bass Strait and Gippsland Basin. Large strike-slip motions between mainland Australia and Tasmania have been invoked to completely resolve this overlap (Tikku and Cande, 2000), but aeromagnetic data for the Bass Strait do not appear to support this interpretation (Cayley, 2011).

Of the three different reconstruction models, the correlation of geological provinces is hardest to reconcile within the Naturaliste model (figure 5b). In this reconstruction the projections of the Moyston and Leap Year Faults are offset by over 400 km. Within

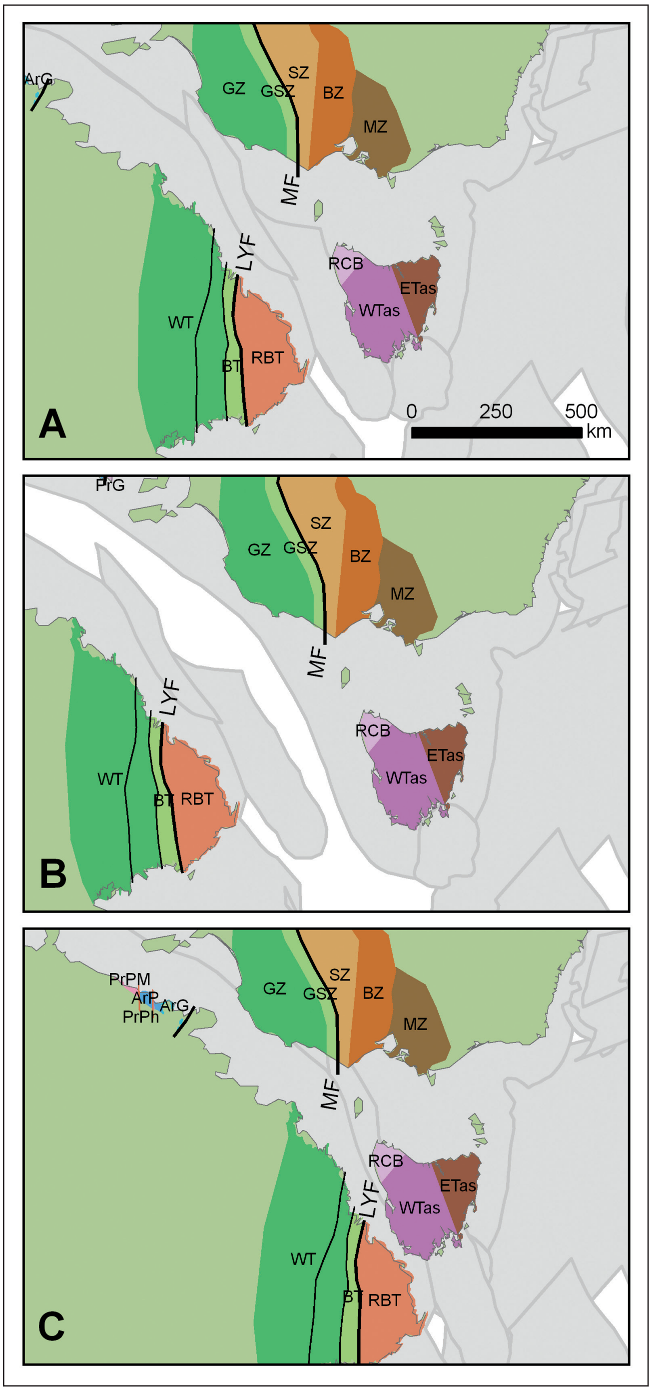

Figure 5. Juxtaposition of geological provinces and structures between eastern Australia and George V Land-Cape Adare, according to three different reconstructions for the Australia and Antarctica prior to Mesozoic rifting. (A) Preferred model (b) Naturaliste Model; (c) Powell et al (1988) model. Geological provinces and naming conventions based on Gibson et al (2011), Cayley (2011), Moore and Betts (2011). GZ – Glenelg Zone; GSZ – Grampians-Stavely Zone; SZ – Stawell Zone; BZ – Bendigo Zone; MZ – Melbourne Zone; Etas – East Tasmania; WTas –West Tasmania; RCB – Rocky Cape Block; WT – Wilson Terrane; BT – Bowers Terrane; RBT – Robertson Bay Terrane; MF – Moyston Fault; LYF – Leap Year Fault.

the Powell model, the two faults are aligned on an almost N-S trend. For the preferred model based on palinspastic restoration of Mesozoic extension, a slight bend is required to link the two structures, but such a bend is consistent with bending already observed in both the Moyston and Leap Year Faults as they approach the respective coastlines.

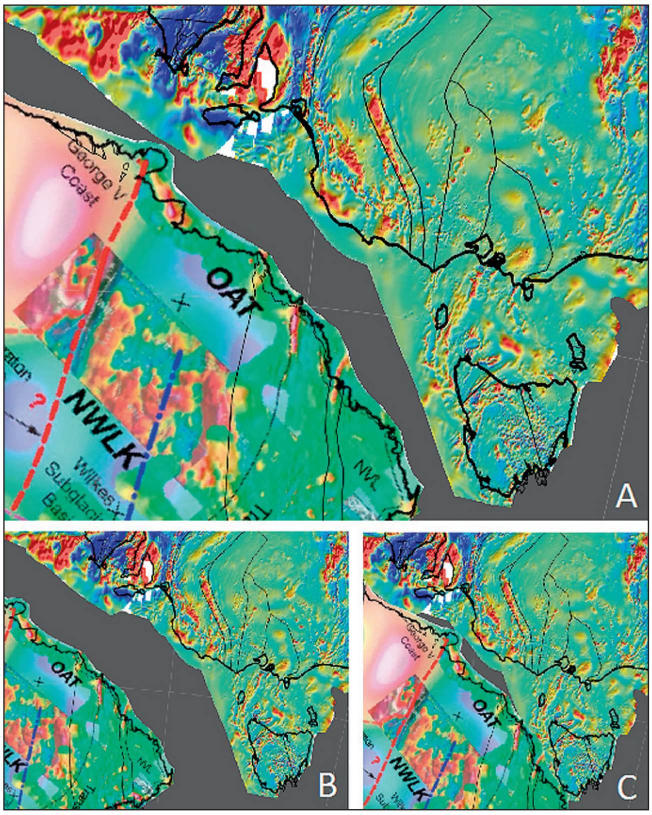

Figure 6. Reconstruction of aeromagnetic anomaly maps for Australia and Antarctica. (A) Preferred model (b) Naturaliste Model; (c) Powell et al (1988) model. Data for Australia are from Milligan et al, (2010), data from Antarctica from Goodge and Finn (2010), Damaske et al (2003).

Aeromagnetic anomaly comparison for Tasmania-Victoria versus Northern Victoria Land

A further means to correlate the geological fabric between Eastern Australia and Antarctica is to use aeromagnetic data. For the part of Antarctica conjugate to Australia, aeromagnetic data are only available east of 145° longitude. The aeromagnetic anomaly image for Antarctica shown in figure 6 is a synthesis of data sets taken directly from the of Finn and Goodge (2010), and importantly incorporates data for the Oates Coast and Northern Victoria Land originally presented by Damaske et al (2003). For Australia, we use data from the fifth edition of the aeromagnetic anomaly map of Australia (Milligan et al, 2011). The data have been reduced to the pole (RTP) using a variable magnetic inclination RTP algorithm to remove the latitude dependence of the induced anomaly shapes (Milligan pers comm., 2011). Although the data from Antarctica are total magnetic intensity (TMI), the data shown for Antarctica mostly lie close to the south magnetic pole at magnetic latitudes greater than 80°, so RTP anomalies would not differ significantly in shape from those plotted.

The aeromagnetic anomaly maps are shown reconstructed in the three candidate full-fit configurations in figure 6. Within Australia, the anomaly field is clearly subdued over Paleozoic crust in eastern Australia compared to the much larger amplitudes observed in the Gawler Craton bounding this crust to the west. Within East Antarctica anomalies are similarly subdued in the area for which aeromagnetic coverage is available. Goodge and Finn (2010) use satellite magnetic anomalies to define the edge of the Terre Adelie Craton (adjacent to the Gawler craton within their reconstruction) as lying just east of the area covered by aeromagnetic data. Within the strip of data along the coast of East Antarctica, several 20-30 km half wavelength, positive anomalies are observed trending broadly N-S within the generally subdued area. Several similar anomalies are observed within eastern Australia. Finn et al (1999) showed that the anomalies within the Bowers Terrane and the Grampians-Stavely Zone could both be explained as resulting from forearc oceanic crust juxtaposed against continental margin crust by thrust faulting, likely as part of the same west dipping subduction regime. The NNW-SSE trend of anomalies in the Grampians-Stavely Zone differs from the more NNE-SSW trend of anomalies to the north and south, suggesting no direct connection between western Victoria and Tasmania (Cayley, 2011). Our preferred reconstruction allows for a continuation of the magnetic sources between the Bowers and Grampians-Stavely Zones that bends around Tasmania parallel to the anomaly trends observed in the western Bass Basin.

Discussion

Comparison of the different candidate reconstructions

Of the models investigated in this study, the Naturaliste model yields the greatest discrepancies between the basement geology of Australian and Antarctica. The preferred model produces a strikingly consistent alignment of the Kalinjala and Mertz shear zones, and is consistent with the interpreted continuation of the Albany-Fraser orogenic belt into Antarctica. One difficulty with this model is the proposed alignment of the Darling Fault with the Denman glacier, an alignment better represented using the poles of rotation of Powell (1988). In the Tasmania-Northern Victoria Land sector, a plate configuration intermediate between these two models (ie figures 5a and 5c) would yield a better match to the onshore geology.

Williams et al. (2011) tested each of these models using palinspastic restoration of the extended continental margins based on crustal thickness grids derived from gravity inversion (Kusznir, 2008), and found that a good fit to the unstretched continent outlines can be achieved within a reconstruction that aligns the Leeuwin and Vincennes Fracture zones at full-fit. The Naturaliste model alignment leaves a significant gap between South Australia and eastern Wilkes Land, while a model with initial NE-SW rifting (Powell et al, 1988) yields significant overlap in the unstretched continent boundaries in this region and further east. A further model proposed by Royer and Sandwell (1989) appears to significantly overestimate the amount of closure between Australia and Antarctica based on restoration of crustal thickness data. In the light of the geological correlations tested here, the full-fit pole of rotation derived by Williams et al (2011) based on palinspastic reconstruction appears also to reconcile the onshore geological structures in each part of the conjugate margin system.

The geological units that have been discussed here, particularly in Western and South Australia, are much older than the age of Gondwana breakup. For these alignments to help us to determine the most robust reconstruction for Australia and Antarctica shortly before Late Jurassic-Early Cretaceous rifting. The boundary along which Australia and Antarctica broke apart in the Mesozoic may have acted as a zone of intraplate tearing during the Paleozoic and earlier (Veevers, 2000). Some authors have argued for lateral motions across this tear during the Paleozoic which could have offset older structures prior to Gondwana breakup. Both sinistral (Flottman and Oliver, 1994) and dextral (Cayley 2011) shear senses have been invoked, and the magnitudes of any such displacements are poorly constrained. For our comparisons we assume that little significant lateral displacement between the two continents has taken place throughout much of the Neoproterozoic and Paleozoic.

Implications for Basins on Australia's Southern Margin

Determining a robust model for the full-fit configuration of Australia and Antarctica has important implications for studying the sedimentary basins that developed within the conjugate continental margins. The candidate reconstruction models here imply significantly different directions for the overall relative motion of the plates during the rifting – the model of Powell (1988) predicts overall NE-SW initial opening (figure 7c), while

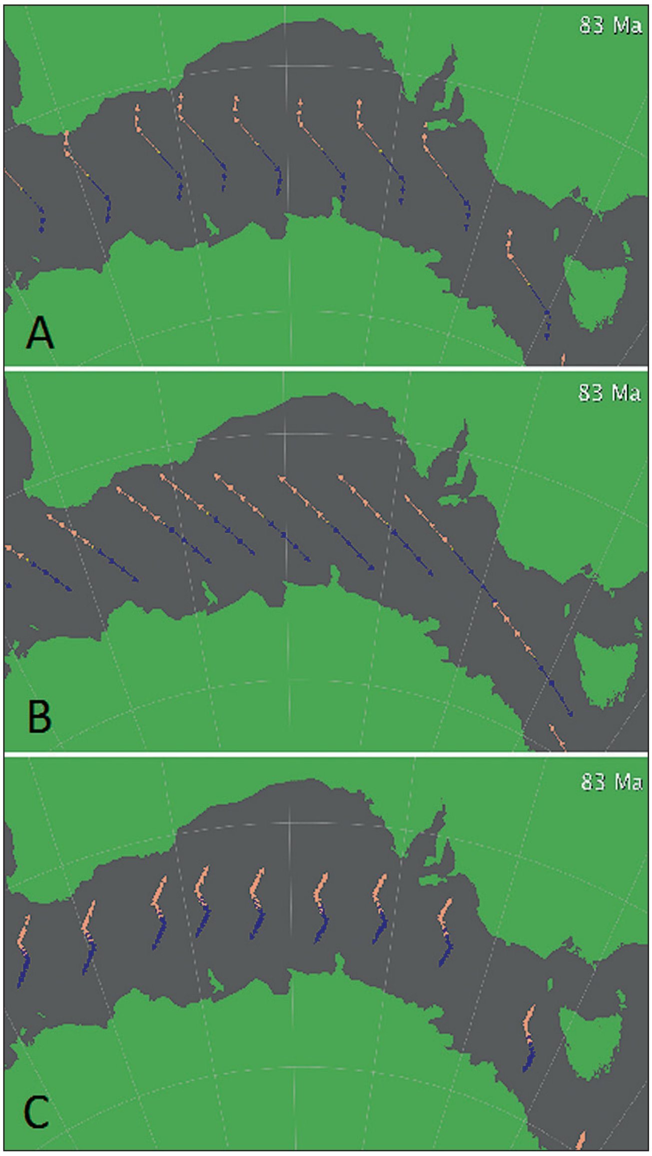

Figure 7. Synthetic flowlines showing the relative plate motions of Australia (pink) and Antarctica (blue) from the onset of rifting to the time of the earliest seafloor spreading isochron in the Bight Basin (~83 Ma), according to three different reconstruction models (A) Preferred model, modified after Whittaker et al (submitted) (b) Naturaliste Model; (c) Powell et al (1988) model.

the Naturaliste model predicts overall NW-SE which is highly oblique to the margins in the Tasmania-Northern Victoria Land sector (figure 7b). The full-fit reconstruction pole of Williams et al (2011) yields an overall NNW-SSE displacement. Such a model avoids a large overlap between Tasmania and Cape Adare that arises if the initial rifting direction is assumed to follow the trend of the Leeuwin and Vincennes Fracture Zones (Tikku and Cande, 1999, 2000).

These opening directions describe the overall plate motions over many tens of millions of years, from the beginning of rifting (~160 Ma) until the earliest seafloor spreading anomalies in the Bight Basin (~83 Ma). Hence, it would not be surprising for there to have been variability in the relative plate motions during this timespan. Whittaker et al (submitted) used the full-fit pole of Williams et al (2011) together with an additional pole of rotation at ~100 Ma, producing a set of reconstructions that better reconciles observations from the Kerguelen-Broken Ridge section of the Australia-Antarctica plate boundary to the west of the continental rift zone. The 100 Ma change in plate motions corresponds to a regional plate reorganization (e.g. Veevers, 2000). In this scenario (figure 7a), the opening direction for basins on the southern margin was initially N-S, followed by a change to more NW-SE motion after 100 Ma that persists until a further acceleration and change to N-S relative motion at ~49 Ma. The 100 Ma change in plate motions corresponds to an increase in subsidence rates (Totterdell et al, 2000) and more oblique relative motions in the Otway and Sorell basins.

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