Restoring the continent-ocean boundary: constraints from lithospheric stretching grids and tectonic reconstructions

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SUMMARY

We present a revised set of Euler poles describing the relative motion between Australia and Antarctica from the onset of continental rifting at ~160-140 Ma to the reorganisation of the spreading system at ~50 Ma. Our revised reconstruction addresses two key issues that remain unresolved in current plate reconstructions.

Firstly, we present new estimates of the pre-rift plate boundary locations for the conjugate Australian-Antarctic margins. These reconstructions are truly palinspastic, incorporating estimates of crustal thickness along these margins, derived from gravity inversions. Integrating the crustal thickness along tectonic flowlines results in the pre-rift location of the continental plate boundary. This integration relies on defining the present-day extent of stretched continental crust within the margin, which is the subject of the companion paper, Williams et al. [2010]. Once restored, we are then able to use the pre-rift plate boundary positions to compute 'full-fit' poles of rotation for Australia relative to Antarctica. This approach allows us to model a deforming passive margin, with implications for understanding and modelling the formation of basins and deposition of sediments along passive margins.

Secondly, reconstructions for plate motions since ~83 Ma have been revised to obtain a better fit along the entire Australian-Antarctic conjugate margins, which extend from at least the Kerguelen Plateau and Broken Ridge in the west to Tasmania, Australia and Cape Adare, Antarctica in the east. Previously published reconstruction models for the period 83-50 Ma had resulted in a poor fit between the two plates at the extreme ends of the conjugate margins.

Key words: continent-ocean boundary, plate tectonic reconstruction, passive margin

INTRODUCTION

Relative motion between Australia and Antarctic began as early as the Late Jurassic (~160-140 Ma) with the onset of continental rifting [*Totterdell et al.*, 2000]. Subsequently, continental break-up and the commencement of seafloor spreading occurred at ~83 Myr. Continual improvement in resolution of satellite gravity (fracture zones) and magnetic shiptrack datasets (magnetic anomalies) over the past decades have led to increasingly well-constrained plate tectonic reconstructions for the seafloor spreading phase of continental separation, from ~83 Ma to the present. Utilising these new datasets the most recent models addressing the relative motion between Australia and Antarctic have focussed on accurately reconstructing the earliest period of seafloor spreading from ~83-50 Ma when there was extremely slow crustal accretion [*A A Tikku and Cande*, 1999; *A A Tikku and Cande*, 2000; *J M Whittaker et al.*, 2007]. However, even with (or perhaps because of) the increased resolution of the satellite gravity and shiptrack magnetic anomaly data these models are surprisingly different and both result in poor fits for at least one section of the conjugate margin pair. The Tikku and Cande, [1999; 2000] models result in good fits along the western and central sections of the conjugate pair but cause problematic overlaps between Tasmania and Cape Adare, Antarctica for times earlier than ~79 Ma (chron 33o). This model also results in a small amount of improbable motion between Broken Ridge and Kerguelen Plateau. The model of Whittaker et al. [2007] solves the Tasmania-Cape Adare overlap problem but this model also results in a considerable amount of highly improbable motion between the Kerguelen Plateau and Broken Ridge.

In contrast, the pre-83 Ma relative motions between Australia and Antarctica, that reconstruct continental rifting and stretching, have been much more poorly addressed by plate reconstructions. Although global plate models (e.g. Schettino and Scotese, [2005] and Müller et al. [2008] attempt to reconstruct Australia and Antarctica to their relative pre-rift or "full-fit" prior to the onset of continental rifting at ~160-140 Ma [*Totterdell et al.*, 2000], this problem has not been closely addressed at a regional scale. Most more detailed regional models restore the outboard edge of the stretched passive margins, often either the continent-ocean boundary or the seaward edge of the magnetic quiet zone. However, this methodology does not take into account stretching of the continental crust.

In order to palinspastically reconstruct the pre-rift or 'full-fit' position of two continental blocks it is necessary to restore the thinned continental margins to their unstretched, pre-rift configuration. However, this restoration to a pre-rift configuration is notoriously difficult, as it is necessary to know (or estimate) both (1) the present–day width of the stretched continental margin, and (2) the magnitude and distribution of extension along and across the margins.

To estimate the present-day width of a stretched continental margin it is necessary to define the boundary between the stretched continental crust and oceanic crust (commonly known as the continent-ocean boundary) and also the boundary between the stretched continental margin crust and the unstretched continental crust further landward. Delineation of both of these boundaries is, in most cases, not a clear-cut exercise. Indeed, on the oceanward side, observations from many margins around the world indicate that a clean boundary does not always exist; rather there is often a continent-ocean transition zone (COTZ) that can be comprised of severely stretched continental fragments, igneous intrusions, and exhumed continental mantle. This is the case for the Australian and Antarctic continental margins, where a COTZ, up to 120 km in width, is interpreted along much of the conjugate Southern Australian and East Antarctic margins [*Sayers et al.*, 2001] (Figure 1). A detailed discussion regarding the identification of the landward and oceanward boundaries of the Australian and Antarctic passive margins based on potential field data is contained in a companion paper, Williams et al. [2010].

Once the width of the passive margin is established, it is necessary to understand the amount of crustal thinning that has occurred. A number of factors need to be constrained to do this, including present-day crustal thickness, paleo-crustal thickness and direction of stretching. Crustal thinning during passive margin formation is not uniform with thinning factors increasing towards the outboard boundary. Seismic refraction and gravity inversion techniques are particularly useful for estimating the present-day crustal thickness of a passive margin.

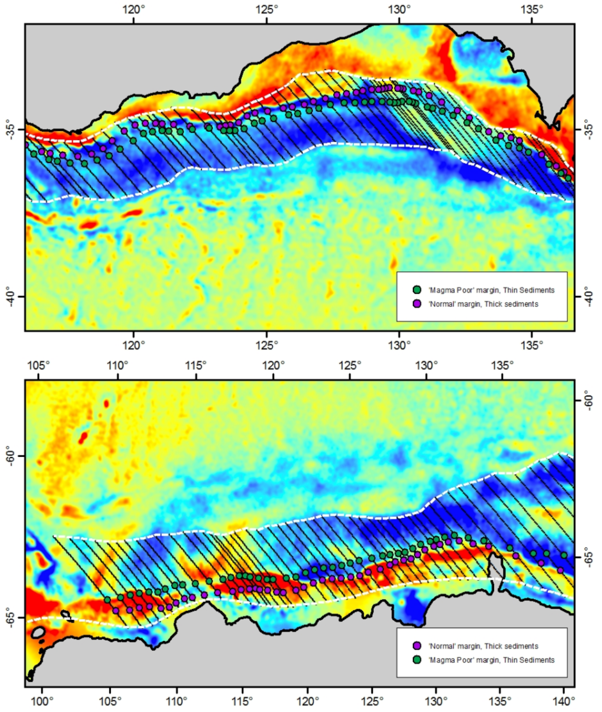

Figure 1. Satellite gravity [*Sandwell and Smith*, 2005], overlain outline of stretched continental crust (white dashed lines), tectonic flowlines (black lines), and locations of restored continental extent based on integrating two alternative gravity inversion models of crustal thickness [*Kusznir*, 2009].

METHODS AND RESULTS

To palinspastically reconstruct the Australian and Antarctic passive margins, i.e. restore the stretched passive margins to their pre-rift configuration, we utilise estimates of crustal thickness, derived from a series of gravity inversions that take sediment thickness and magmatic input into account [*Kusznir*, 2009]. We use the inboard and outboard extent of the stretched passive margin from Williams et al. [2010] to undo thinning of the conjugate Australian-Antarctic passive continental margins. Using these boundaries, we integrate the crustal thickness to obtain the pre-rift location of the continental plate boundary. The integration is undertaken along tectonic flowlines that match the NW-SE striking fabric revealed from satellite gravity [*Sandwell and Smith*, 2005] and are consistent with the oblique direction of motion that affected this margin during continental rifting and early seafloor spreading. The NW-SE trend is consistent with structural trends observable from satellite gravity and interpreted by a number of authors e.g. Willcox and Stagg [1990] and Whittaker et al. [2007].

The gravity inversion results of Kusznir [2009] comprise a series of crustal thickness estimates, derived using different estimates of sediment thickness (‘thick’ and ‘thin’) and magmatic addition (‘magma poor’ and ‘normal’). We performed crustal thickness integrations along the same flowlines for each of these crustal thickness models. The model that assumes the presence of thick sediments and normal volcanic input during rifting results in a minimum width of the pre-rift continental margins. The gravity inversion model that assumes thin sediments and no volcanic addition to the crust results in a maximum width of the pre-rift continental margin.

The restored pre-rift plate boundary positions were then used to constrain Euler poles describing the “full-fit” relative motion between Australia and Antarctica. In the west, the present-day outlines of the Kerguelen Plateau and Broken Ridge were also used as a constraint in the computation of our full-fit pole of rotation. In this paper, all finite rotation poles were computed by a visual fitting technique using GPlates, open-source software.

Chron	Age	Lat	Lon	Angle	Source
20o	43.8	14.91	32.51	24.51	W2007
21y	46.3	13.62	33.59	24.64	W2007
27y	61.0	7.55	37.17	25.39	This paper
31o	68.0	6.45	37.33	25.59	This paper
32y	71.1	5.03	37.42	25.84	This paper
33o	79.0	3.28	37.95	26.27	This paper
34y	83.0	-1.83	38.7	26.91	This paper
OECC	96.0	-4.76	39.16	27.73	This paper
Full-fit	~140	-15.67	43.00	31.95	This paper

Table 1. Finite rotations for East Antarctica – Australia (fixed). OECC – oceanward extent of continental crust; ages are after Cande and Kent [1995] timescale.

We have also revised Euler poles describing the early spreading history for the entire Australian-Antarctic system in order to improve the tectonic fits through time between Broken Ridge and Kerguelen Plateau. To do this, we use magnetic anomaly identifications taken from Whittaker et al. [2007] and Tikku and Cande [1999], fracture zone interpretations from Whittaker et al. [2007], and the outlines of the Kerguelen Plateau and Broken Ridge as constraints when computing our Euler poles. We used the combined fracture zone and magnetic anomaly identifications and crustal boundary constraints to compute well-constrained finite rotations that describe our new plate motion history for Australia and East Antarctica.

DISCUSSION

Delineation of the pre-rift extent of continental crust is a necessary constraint to obtain a meaningful full-fit plate reconstruction. A number of plate tectonic models have used various physical and geophysical markers as proxies for the pre-breakup extent of continental margins, including the 500 fathom (~900 m) contour [*Bullard et al.*, 1965], prominent free-air gravity anomalies [*Lawver et al.*, 1998] and horizontal gradient of gravity anomalies [*Schettino and Scotese*, 2005]. The exact methodology is often poorly described with no clear justification as to why the particular marker should be a good proxy for the pre-rift extent of continental crust. This makes it difficult to make a direct comparison between our restored pre-rift continental crust extent and the approximations made by other authors. Figure 1 shows our calculated location for the pre-rift extent of the stretched continental crust (green and purple circles) overlain on free-air gravity. There is a rough correlation between the locations of our pre-rift continental extents and the trends of the prominent gravity high along the margins. However, there are significant differences, especially along the Antarctic margin that would influence the fit of Australia and Antarctica in a full-fit reconstruction.

Figure 2 shows a comparison between our full-fit plate reconstruction and that of Schettino and Scotese [2005]. There is a considerable difference between the two models, with Antarctica located >500 km further east relative to a fixed Australia in the Schettino and Scotese [2005] model. This more easterly location results in considerable overlap between Tasmania and Cape Adare, and the misfit of the Naturaliste Plateau and the Bruce Rise. A considerable misfit of the restored continental extent also results from using the Schettino and Scotese [2005] poles of rotation. Our reconstruction results in a good fit between both the restored continental extents, and the Naturaliste Plateau-Bruce Rise and Tasmania-Cape Adare sections of the margin. Our reconstruction also conforms to the additional constraints provided by the NW-SE trending structures found on both the Australian and Antarctic continental margins, including the Perth and Vincennes Fracture Zones.

Reconstructions that conform with the orientation of fracture zones and structural trends, the alignment of the transform Tasmanian-Cape Adare margin, and the fit of Broken Ridge and Kerguelen Plateau are just as crucial for reconstructions following continental break-up. Broken Ridge and Kerguelen Plateau are the volcanic products of the Kerguelen hotspot [*Coffin et al.*, 2002]. Broken Ridge and Kerguelen Plateau formed over a period of 25 million years from ~130 Ma to ~95 Ma. The previous reconstruction of Whittaker et al. [2007], who modelled a major reorganisation of the Australian-Antarctic spreading system at ~50 Ma, introduced inconsistencies in the fit between Broken Ridge and Kerguelen Plateau, especially at 71 Ma (chron 32y) [*A Tikku and Direen*, 2008], see Figure 2a. Our new poles of rotation resolve this issue (Figure 2b) and show reveal that the Australian-Antarctic spreading system was characterised by oblique spreading in the east that became progressively steeper towards the west, until turning into essentially a transform boundary between the still forming Kerguelen Plateau and Broken Ridge.

This increase in obliquity is related to the formation of the very rough Diamantina Zone, located at the western end of the Australian southern margin and dissipates further to the east, in the Great Australian Bight section of the margin. The roughness of newly formed oceanic basement is related to spreading rate and spreading obliquity [*J Whittaker and Müller*, 2008]. Early spreading between Australia and Antarctica was extremely slow (< 10 mm/yr) and our new reconstructions show, extremely oblique.

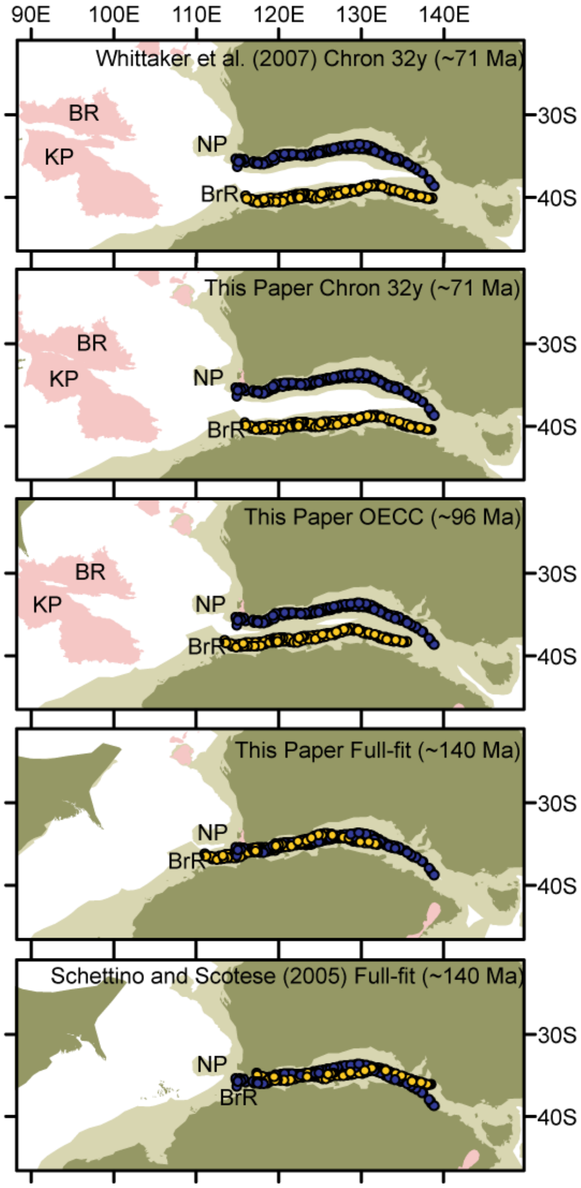

Figure 2. Plate tectonic reconstructions with Australia fixed. Plate reconstructions are, (a) Whittaker et al. (2007) at 71 Ma (chron 32y), (b) this paper at 71 Ma (chron 32y), (c) this paper at 96 Ma, (d) this paper at ~140 Ma (full-fit), and (e) Schettino and Scotese (2005) at full-fit. BR – Broken Ridge, KP – Kerguelen Plateau, NP – Naturalise Plateau, BrR – Bruce Rise. Yellow dots – restored extent of Antarctic margin, Blue dots – restored extent of Australian margin. Light green – continental shelves. Pink – Large Igneous Provinces.

Our development of an accurate plate tectonic model describing the continental rifting and break-up between Australia and Antarctica allows a better understanding of the temporal tectonic and thermal regimes influencing the basins of the southern Australian margin from ~140 Ma to ~50 Ma. Accurate reconstruction of stretched continental crust, as well as transitional and oceanic crust, is crucial for reconstructing accurate paleo-bathymetries, paleo-geographies and paleo-ocean circulation modes as the nature of the crust on the Australian-Antarctic margins may produce considerable differences in the width and depths of gateways for paleo-ocean currents [*Gohl*, 2008].

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