Revised Tectonic Evolution of the Eastern Indian Ocean

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Abstract

Published plate tectonic models for the Australian-Antarctic plate pair imply geologically improbable scenarios at either, or both, ends of the Cretaceous rift and spreading system. Controversy also exists around the location of and motion at the plate boundary extending west of Australia-Antarctica, through the Kerguelen Plateau region. We present a plate tectonic model of relative motions among India, Australia and Antarctica from the onset of continental rifting to the establishment of rapid seafloor spreading, at ~43 Ma. The model conforms to a wide range of geological/geophysical evidence and reconstructs the formation of both the western Kerguelen region and the eastern Tasman region. The incorporation of spatio-temporally continuous plate boundaries reveals the presence of a plate boundary beneath the contiguous Central Kerguelen Plateau and Broken Ridge for ~65 million years.

To investigate the relationship between the plate boundary system and the Kerguelen plume we test three alternative absolute reference frames. Using a fixed hotspot reference frame, the Indian Ocean mid-ocean ridge system remains within 500 km of the Kerguelen plume, while the proximity of the plate boundaries and the plume is more variable with a moving hotspot reference frame. Proximity between the plume, plate boundaries, and the Central Kerguelen Plateau/Broken Ridge for ~65Myrs, suggests that these specific features were not formed by a single, short-lived (5–10 Myr) pulse of magmatic activity, but rather by a ~25 Myr period of relatively high magma flux followed by ~40 Myr period of lower volume magmatic activity, an interpretation not excluded by the relatively sparse dredge and drill ages.

1. Introduction

All published plate tectonic models for the Australian-Antarctic plate pair imply improbable plate tectonic scenarios either in the vicinity of the Kerguelen Plateau/Broken Ridge or between Tasmania and Antarctica (Figure 1). Some models result in tectonically improbable and geologically unsupported episodic extension and compression between Broken Ridge and the Kerguelen Plateau (e.g. *Whittaker et al.,* 2007, Supplementary Figure 1a and 5). Others result in unreasonably large continental overlap between Tasmania and Cape Adare for times older than chron 32 (e.g. *Tikku and Cande,* 1999, Supplementary Figure 1b and 5). To resolve the overlap problem unlikely strike-slip motion between Tasmania and Australia has been invoked (e.g. *Tikku and Cande,* 2000). Still others achieve a good fit between the South Tasman Rise and Cape Adare, but lead to misfits of magnetic anomaly identifications in the western Australian-Antarctic Basin (*Royer and Rollet,* 1997).

One reason for these conflicting and problematic plate tectonic models of Australia and Antarctica is that, even with increased resolution of the satellite gravity (*Sandwell and Smith,* 2009) and greater coverage of shiptrack magnetic anomaly data, few clear fracture zones separate magnetic anomalies into discrete spreading corridors in older, margin-proximal oceanic crust. This absence makes it difficult to constrain the relative longitudinal position of Australia and Antarctica prior to ~43 Ma.

Three prominent NW-SE striking structural trends exist at the western end of the Australian-Antarctic conjugate margin pair – the Naturaliste and Leeuwin (Perth) Fracture Zones on either side of the Naturaliste Plateau (Figure 1) and the Vincennes Fracture Zone at the eastern boundary of the Bruce Rise. Although these features are commonly referred to as fracture zones, they may predominantly be located on extended continental or transitional crust rather than oceanic crust.

While these features are prominent in free-air satellite gravity anomalies (e.g. Sandwell and Smith, 2009), it is very difficult to confidently interpret similarly trending features along either the Australian or Antarctic margins further to the east, although some tentative interpretations have been made (*Whittaker et al.,* 2007).

Connecting these prominent NW-SE trending structures with the clear N-S trending fracture zones found in younger oceanic crust of the Australian Southern Ocean is also problematic. For this reason, alternative alignments have been proposed for the conjugate Australian and Antarctic margins during the rifting and early spreading phases of relative motion. At 83 Ma, *Tikku and Cande* (1999, 2000) align the Leeuwin and Vincennes Fracture Zones (Leeuwin fit, Figure 2b), *Whittaker et al.,* (2007) align the Naturaliste and Vincennes Fracture Zones (Naturaliste fit, Figure 2a), and *Williams et al.,* (2011) propose a hybrid alignment (Hybrid fit, Figure 2c).

The relative position between Australia and Antarctica at the onset of rapid seafloor spreading at ~43.8 Ma is well-constrained by the fit of the Broken Ridge and Kerguelen Plateau margins and by magnetic anomaly identifications of Chron 20. If we consider the relative motion between Australia and Antarctica between 83–43 Ma as a single stage rotation, the alternative 83 Ma alignments imply different motions along the length of the Australian-Antarctic plate boundary (Figures 2 and 3). The Naturaliste and Leeuwin models can be considered end member scenarios. The Naturaliste and Hybrid models result in similar Euler pole locations and rotation angles and imply NW-SE motion along the length of the plate boundary. The Leeuwin model results in NE-SW relative motion in the west (Kerguelen end) progressing to N-S relative motion in the east (Tasmanian end).

A further difficulty in reconstructing the plate tectonic evolution of Australia and Antarctica is the absence of a clear paleo-plate boundary through the Central Kerguelen Plateau/Broken Ridge section of the margin prior to ~43 Ma. The conjugate, undulating rifted margins of the Central Kerguelen Plateau and Broken Ridge show no evidence for relative Australian-Antarctic motion prior to ~43 Ma. However, all three scenarios illustrated in Figure 3 imply relative motion between the Australian and Antarctic plates prior to 43 Ma. Figure 3b shows that even the location of a stage rotation pole beneath the Kerguelen Plateau does not result in a complete absence of motion in the Kerguelen and Diamantina Zone sectors. The rules of plate tectonics require that plate boundaries are continuous features. Therefore, on-going relative motion between Australia and Antarctica between 83–43 Ma necessitates the presence of a plate boundary in the Diamantina Zone/Labuan Basin and Central Kerguelen/Broken Ridge sectors to reach the Indo-Australian/Antarctic mid-ocean ridge (*Royer and Sandwell,* 1989) – i.e. within the shaded region shown in Figure 3.

Revising the break-up and early drift history of Australia and Antarctica has important implications for the formation of the volcanic products of the Kerguelen hotspot – Kerguelen Plateau, and Broken Ridge – which form Earth's second largest Large Igneous Province (LIP) by volume. Due to relatively sparse drill and dredge data the exact mechanism(s) causing the formation of these features is controversial. Most plume models support LIP formation through massive eruptions, sourced from the several hundred kilometre wide "head" of a rising mantle plume that undergoes decompression melting when it reaches the base of the lithosphere (*Coffin and Eldholm,* 1994; *Duncan and Richards,* 1991), over short 1–2 Myr periods, followed by more sustained, longer-lived, lower volume magma output (*Duncan and Richards,* 1991; *Richards et al.,* 1989).

Many plume models also expect the massive initial magmatism to be coeval with continental break-up (e.g. *Anderson,* 1995; *White and McKenzie,* 1989).

An interesting problem is how a single plume-head could result in the formation of a LIP such as the Kerguelen Plateau, proposed to have formed in bursts of rapid volcanism (<5–10 million years) but with a ~15 Myr lag between the initial surface manifestation of the Kerguelen plume, and the voluminous volcanism, which then continued episodically for at least 25 Myr (*Coffin et al.,* 2002). Multiple plume sources (e.g. *Coffin et al.,* 2002; *Wilson and Patterson,* 2001) or a single plume source dismembered into several 'diapirs' have been proposed to account for these observations (*Coffin et al.,* 2002; *Olson,* 1990; *Steinberger and O'Connell,* 1998).

The single plume-head model is further challenged by more densely sampled data from onshore LIPs (e.g. *Coble and Mahood,* 2012; *Kent and Fitton,* 2000; *Mahoney et al.,* 2002) that indicate low volumes of magmatism precede the onset of higher volume magmatism. Recent geodynamic models propose that the variations in magma flux may be explained by the development of secondary instabilities in deeply sourced mantle plumes due to the interaction between thermal and compositional buoyancy forces (*Lin and Van Keken,* 2005).

In this paper, we build a new plate tectonic model reconstructing the relative motion between Australia and Antarctica, from the onset of continental rifting (~160 Ma) to the establishment of rapid seafloor spreading (~43 Ma) that conforms to a wide range of geological/geophysical evidence in all three sections of the margin: the Central Kerguelen-Broken Ridge sector, the Great Australian Bight-Wilkes Land sector, and the Tasmanian-Cape Adare sector.

We then use our revised plate tectonic reconstructions, in combination with a new plate tectonic model for evolution of the Eastern Indian Ocean (*Gibbons et al.,* 2012) to examine the relationship between the formation of the Kerguelen Plateau and the tectonics of the Indo-Australian-Antarctic plates, in particular the location of the plate boundaries and triple junction.

2. Methods

We construct a new set of plate tectonic reconstructions for the Indian-Australian-Antarctic plates by computing new poles of rotation for Australia-Antarctica for the early drift phase of relative motion (~83 Ma to 43 Ma) and combining these with published poles of rotation of (i) the continental rifting stage of Australian-Antarctic motion (*Williams et al.,* 2011), and (ii) the motion of India relative to both Australia and Antarctica (*Gibbons et al.,* 2012). Using the combined set of rotation parameters we derive a complete set of Indo-Australian-Antarctic plate boundaries from the onset of continental rifting to the onset of rapid spreading between Australia-Antarctica at ~43 Ma.

2.1 Constraints

We use magnetic anomaly identifications of *Tikku and Cande* (1999) and *Whittaker et al.,* (2007), for magnetic chrons 33o, 32y, 31o, 27y, 24o and 21y. These magnetic anomaly identifications are predominantly located in the central region of the Australian and Antarctic conjugate margins (see Figure 1) and so do not closely constrain the fit of the eastern and western extremities of the conjugate margins.

Both the models of *Whittaker et al.,* [2007], *Tikku and Cande* [1999] imply significant compression between Broken Ridge and Kerguelen Plateau (see Supplementary Figure 5), more than can be reconciled with the available data from the Kerguelen Plateau and the Labuan Basin (*Munschy et al.,* 1993; *Tikku and Direen,* 2008). These two models differ considerably in the relative positions of Australia and Antarctica at 83 Ma, with *Whittaker et al.,* [2007] following the Naturaliste-Vincennes alignment and *Tikku and Cande* [1999] using the Leeuwin-Vincennes alignment (Figure 2). We discount the Leeuwin-Vincennes alignment as it results in unacceptable continental overlap between Tasmania and Antarctica. Left-lateral motion between Tasmania and Australia along the Colac-Rosedale fault has been proposed to resolve this problem however, this motion has been emphatically ruled out based on modern magnetic data, the exposed Palaeozoic geology of southeast Australia (*Cayley,* 2011; *Cayley et al.,* 2002), and the alignment of geological boundaries between southern Australia and northern Victoria Land (*Foster and Gleadow,* 1992).

A major difficulty when constructing these models is the complete lack of constraints (magnetic anomaly or fracture zone identifications) at the western end of the Australian-Antarctic plate boundary system prior to 43 Ma that can be used to constrain the longitudinal relative position of the plates. Instead, we constrain the longitudinal relative position of Australia and Antarctica using two other criteria; small-circle and COB constraints.

Firstly, to ensure the computation of rotation parameters that do not yield significant compression in the Kerguelen Plateau and Labuan Basin, for which there is no evidence, we use a segment of the small circle running through Broken Ridge and the Kerguelen Plateau computed from the Hybrid model 83.5-43.8 Ma stage pole (green line in Figure 2c and 3c).

Secondly, we use continent-ocean boundary (COB) constraints from the western Tasmanian and Cape Adare conjugate margins and palinspastically restored COB constraints for the South Tasman Rise (STR).Motions of the East and West South Tasman Rise blocks have been modified from *Gaina et al.,* [1998]. We assume that the conjugate western Tasmania and Cape Adare COBs formed close to a transform margin between 79 and 43 Ma and use the interpreted COB locations of *Williams et al.,* (2011). The majority of extension in the Otway and Sorell Basins predates this time (e.g. *Gaina et al.,* 1998; *Hegarty et al.,* 1988), and during this period deformation was characterized by late-stage transtension, transform motion and diachronous breakup (*Hegarty et al.,* 1988; *Hill et al.,* 1997). Because the plate motions predict highly oblique relative motion during this time, any continued minor amounts of continental extension would not have led to a significant increase in the distance of the COBs from their respective hinge lines.

Files of all constraints used are provided in GPlates compatible gpml, shapefile, and ascii formats, which are available for download from ftp://ftp.earthbyte.org/earthbyte/WhittakerKerguelenPlateau.

2.2 Computation

To compute rotation parameters that describe the early drift phase of relative motion (~79 Ma to 43 Ma) between Australia and Antarctica we combine oceanic magnetic anomaly identifications, geological boundaries and the small circle segment constraint using the least-squares approach of *Hellinger* (1981) *and Royer and Chang* (1991). We compute finite rotations (Table 1) and 95% uncertainty intervals

(Table 2).

Our Euler poles (Supplementary Figure 2) fall systematically to the west of the previously published poles of *Whittaker et al.,* (2007) *and Tikku and Cande* (2000). The consistent NW-SE elongation of the ellipses reflects the lack of fracture zone constraints in our computations.

The least-squares approach of *Hellinger* (1981) *and Royer and Chang* (1991) is based on computing rotation parameters for ocean basins where there are both magnetic anomaly and fracture zone interpretations to constrain the relative plate motions. However, using this computational approach is problematic where there is an absence of either or both magnetic anomaly and fracture zone constraints, as is the case for the western end of the Australian-Antarctic plate pair for times earlier than ~43 Ma. The problem is particularly acute in the Kerguelen sector, leading us to introduce the small circle constraint. For each time, we use the magnetic anomaly identifications from that time and the small circle and Tasmanian/Cape Adare continent-ocean boundary constraints. Typically, computed uncertainty ellipses represent the errors associated with the interpretation of the input geophysical data. For example, fracture zones are commonly assigned an error of 5 km based on the work of *Müller et al.,* (1991) who found that this is the typical error in interpreted fracture zone location between satellite gravity and shiptrack data. However, the use of the small circle constraint means that the uncertainty ellipses do not only include the errors associated with the interpretation of real data.

The fit of the magnetic anomaly identifications and small circle constraints is shown in Supplementary Figure 3. Good fits are obtained for all modelled time steps with the exception of the easternmost magnetic anomaly identifications at 79.1 Ma (chron 33 old). The poorest fitting chron 33o magnetic anomaly interpretations are proximal to serpentinized peridotite ridges likely formed through mantle exhumation

(*Beslier et al.,* 2004; *Colwell et al.,* 2006). The poor fit of these chron 33 magnetic anomaly identifications may be related to non-seafloor spreading related magnetisation of the ridges, and/or localised deformation related to the ultra-slow seafloor spreading and mantle exhumation,

To extend our model for relative Australian-Antarctic motions to times older than c33o (~79 Ma) we use the full-fit and COB/C34y (83 Ma) reconstruction parameters of *Williams et al.,* [2011], which are based on palinspastic restoration of extended continental crust in the conjugate Australian and Antarctic margins. The Eastern Indian Ocean plate reconstruction of *Gibbons et al.,* (2012) models the onset of relative motion between India and Australia/Antarctica at 136 Ma. Due to the geometry of the India-Australia-Antarctica plates it is unlikely for relative motion between Australia and Antarctica to have initiated prior to any motion of India. For this reason, we model the onset of continental rifting between Australia and Antarctica to 136 Ma.

An artefact of only having two rotation poles (full-fit and earliest seafloor spreading anomaly) describing some 50–80 million years of continental rifting until breakup at 83 Ma is that it results in an apparent change in the relative Australian-Antarctic plate motions at 83 Ma. However, it is more likely that the change in relative motions occurred at ~100 Ma when a major plate reorganization affected the Indo-Australian region (e.g. *Matthews et al.,* 2012; *Müller et al.,* 2000; *Veevers,* 2000). We introduce an additional reconstruction pole at 100 Ma to shift the change in relative motions from 83 Ma to 100 Ma. The introduction of this addition rotation pole also allows us to model the onset of a more rapid Australian-Antarctic continental rifting phase during the Albian (*Totterdell et al.,* 2000).

We compare the reconstructed locations of the continents, plate boundaries, and LIPs with alternative reconstructed locations of the Kerguelen plume. To do this we combine our Australia-East Antarctic relative plate motions with the East Antarctica-Africa relative plate motions from *Seton et al.,* (2012). We combine these relative plate motions with three alternative absolute reference frames a) a fixed hotspot reference frame – Mu93 (*Müller et al.,* 1993), b) a moving Indo-Atlantic hotspot reference frame – ON05 (preferred model of *O'Neill et al.,* 2005), and c) a moving global hotspot reference frame – Do12 (*Doubrovine et al.,* 2012). The moving hotspot absolute reference frames are constructed using numerical models of whole mantle convection and advection where the individual mantle plumes move independently. We incorporate the independent motion of the Kerguelen plume for the moving hotspot models (see Supplementary Table 1 for rotation parameters). It should be noted that the moving hotspot absolute reference frames depend on the plate circuit used, however the errors introduced by using our own plate circuit here are likely to be small due to the short length of the relative plate motion chain (Africa -> East Antarctica -> Australia/India) and the observation that even considerable differences between relative plate motion models have little impact on the resulting absolute reference frame, e.g. the Australia-Antarctic comparison undertaken by *Doubrovine et al.,* [2012].

Attributing a single surface coordinate to the present day location of the Kerguelen Plume is not straightforward. At the present day there are active fumaroles in the Kerguelen Isles (*Bonin et al.,* 2004) and volcanism on Heard Island (*Quilty and Wheller,* 2000) separated by a distance of ~450 km. This ambiguity is perhaps not unexpected considering that seismic tomography models indicate that the Kerguelen plume conduit in the lower mantle has a minimum radius of 400 km, which does not appear to reduce at shallower depths (*Montelli et al.,* 2004). A 400 km radius for the Kerguelen plume can be considered at the upper end of such plume radii estimated from seismic tomography models. Seismic tomography models of Iceland typically estimate plume conduit radii of around 100 km in the upper mantle (*Allen and Tromp,* 2005; *Hung et al.,* 2004), a result supported by the geodynamic mantle model of *Steinberger and Antretter* (2006), which also estimated upper mantle plume radii of around 100 km. *Montelli et al.,* [2004] also estimate a 100 km plume radius for Iceland in the lower mantle.

Plume material is also known to flow laterally beneath oceanic lithosphere, from the location of upwelling, towards ridge axes (*Mittelstaedt and Ito,* 2005; *Sleep,* 2008). This process is an alternative, or additional, explanation for the observed patterns of volcanic activity on the Kerguelen Plateau.

Given the possible large size of plume conduits and lateral flow processes, it is reasonable to expect volcanic activity anywhere within a significant region of the reconstructed hotspot location, and also that the location of surface volcanic activity may vary through time with respect to the conduit. To represent the uncertainty in the surface expression of the Kerguelen plume, a 400 km radius is plotted around the reconstructed plume locations (Figure 4), based on *Montelli et al.,* [2004].

2.3 Plate Boundaries

Based on our revised reconstructions we build a complete set of plate boundaries between India, Australia and Antarctica for break-up through to 43 Ma. We combine our new Australian-Antarctic motions with the plate tectonic model of *Gibbons et al.,* [2012] for the Perth Abyssal Plain and Ender by Basin to help constrain the position of the Kerguelen portion of the Australian-Antarctic plate boundary and the location of the Indian-Australian-Antarctic triple junction.

Our resulting plate tectonic maps (Figure 4) share many similarities with the early work of *Johnson et al.,* (1976) although many of the ages and details are now better constrained with improved data coverage.

We define the plate boundaries of the three arms of the Indian-Australian-Antarctic system from the initiation of continental breakup until the onset of rapid seafloor spreading at ~43.8 Ma. Where available we use magnetic anomaly interpretations to constrain the position of the plate boundary. However, no magnetic anomaly identifications are available during the Cretaceous Quiet Zone, and in the Diamantina/Kerguelen/Broken Ridge sector the oldest available anomaly identifications are C18–20 (43.8 Ma). In these cases, continuous plate boundaries, and the location of the Indian-Australian-Antarctic triple junction were interpolated at key time intervals (120.4 Ma, 115 Ma, 108 Ma, 100 Ma, 83 Ma, 67.7 Ma, 55.9 Ma, 47.9 Ma and 43.8Ma) by sequentially partitioning oceanic crust formed during the preceding time interval. Key boundaries, such as the southern and western edges of the Perth Abyssal Plain, and the final rifted margins of the Central Kerguelen Plateau and Broken Ridge were used to constrain the location of plate boundaries during ridge jumps. This approach allows the mapping of continuous plate boundaries, but the absence of magnetic anomaly interpretations results in lower reliabilities of the interpolated plate boundaries.

Using GPlates (*Boyden et al.,* 2011) we construct a series of topologically correct (no gaps, no overlaps) polygons to assign ages and plate tectonic identities to the seafloor crust. Using the polygons to 'cookie-cut' and reconstruct the free-air gravity (*Sandwell and Smith,* 2009) we iteratively check the interpretations at each time-step. This sequential apportioning of the oceanic crust ensures that the rules of plate tectonics are conformed to at each time-step, with continuous plate boundaries, the preservation of already existing oceanic floor, and the formation of sufficient new ocean floor (or stretching of continental crust) to match the space created by the relative plate motions.

Mapping the spatio-temporal location of the Australian-Antarctic plate boundary through the Kerguelen/Broken Ridge sector is extremely problematic. It is possible that this portion of plate boundary was not a discrete boundary between ~83–43 Ma but rather expressed as a series of short-lived plate boundaries (for example, the 77° E and 75° E rift zones (*Houtz et al.,* 1977) and Southern Kerguelen Rift Zone) (*Royer and Sandwell,* 1989). Instead of short-lived discrete plate boundaries, diffuse deformation across a wider region is possible, the shaded region shown in Figure 3. However, we feel that a rigid plate boundary is more likely in this region. Localisation of extension is observed at the Chagos Bank, a region within the diffusely deforming Capricorn plate boundary that is rheologically weaker due to its thicker crust (*Henstock and Minshull,* 2004). The thick crust of the Kerguelen Plateau/Broken Ridge is also more likely to experience focussed rather than diffuse deformation.

We model jumps in the location of the Indo-Antarctic plate boundary at 115 Ma, the Indo-Australian plate boundary at 108 Ma and the Australian-Antarctic plate boundary at 83.5 Ma, 50 Ma and 43.8 Ma. These ridge jumps result in the transfer of small sections of oceanic crust from one major plate to another. For this reason these micro-plates are assigned their own plate tectonic identity even though at all times they move with one of the major plates (India, Australia or Antarctica) (See Table 3).

3. Plate Model

Our plate tectonic model (Figure 4) reconstructs the rift and early drift phases of relative motion between Australia and Antarctic. Broadly, our new model reconstructs three phases of relative motion punctuated by two reorganizations at 100 Ma and 50 Ma. The main phases are (i) NNE-SSW motion between ~136–100 Ma, (ii) NW-SE motion between 100-50 Ma, and (iii) NNE-SSW motion since 50 Ma.

Full-fit to 100 Ma

In our model, relative motion between Australia, India and Antarctic commenced at 136 Ma, with continental rifting between Australia and Antarctica, and seafloor spreading between both India and Australia (Perth Basin), and India and Antarctica (Enderby Basin). Seafloor spreading spanning the Perth and Enderby Basins occurred as one continuous system (Figure 4 – 120.4 Ma). This simple ridge configuration persisted until ~115 Ma (Figure 4 – 115 Ma) when the MOR in the Enderby Basin jumped northward resulting in the rifting of the Elan Bank from the Indian margin (*Gibbons et al.,* 2012). Continental material is thought to underlie the southern Kerguelen Plateau (*Alibert,* 1991; *Frey et al.,* 2002; *Operto and Charvis,* 1995), which may also have been isolated by this, or a slightly earlier ridge jump. At ~108 Ma seafloor spreading ceased in the Perth Basin when the Perth MOR jumped westward back into alignment with the Enderby MOR (*Gibbons et al.,* 2012), again forming a continuous divergent plate boundary and resulting in the rifting of the continental Batavia Knoll and Gulden Draak Ridge (*Williams,* 2011) from the Indian margin (Figure 4 – 108 Ma).

The plate reconstructions of *Gibbons et al.,* [2012] model the formation of the Perth Abyssal Plain (from 136 Ma to 108 Ma) as a single spreading corridor. In the Enderby Basin, the eastern extent of oceanic crust formed during this spreading phase is unconstrained by available geophysical data due to volcanic overprinting from the Kerguelen plume.

We use the location of the southern boundary of the Perth Abyssal Plain, together with our rotation parameters constraining the relative positions of Australia and Antarctica, to define the eastern extent of the Enderby Basin at this time (Figure 4– 120 Ma and 115 Ma).

Between 115 Ma and 108 Ma the exact location of the plate boundary connecting the Enderby and the Perth MORs is poorly constrained. The Enderby and Perth MORs during this time were likely connected by a transform, or series of transform steps located beneath the developing South Kerguelen Plateau (SKP) (Figure 4 – 115 Ma, 108 Ma).

From 136–100 Ma Australia and Antarctica experienced slow relative motion, with divergence of approximately 140 km in the eastern part of the conjugate margin system increasing to 210 km in the west. Throughout this period we assume that for continental regions of the Australian-Antarctic plate pair relative motion occurred across a continental rift zone (Figure 4). To the west of the continental rifting we speculate that the Australian-Antarctic plate boundary extended from the Bruce Rise/Naturaliste Plateau region through the newly formed oceanic crust at the boundary between the Perth and Enderby Basins to the Perth-Enderby MOR. It is also possible that the small amounts of Australian-Antarctic relative motion (~140–180 km in the region west of Australia over 36 million years) may have manifested as diffuse deformation.

100 to 50 Ma

A major reorganisation is thought to have affected the entire Indian Ocean including Indo-Australian relative plate motions at ~100 Ma, possibly due to the cessation of subduction along the east coast of Australia (*Matthews et al.,* 2012; *Müller et al.,* 2000; *Veevers,* 2000).

This reorganisation event at 100 Ma led to significant changes in the relative plate motions between India [e.g. *Gibbons et al.,* 2012], Australia and Antarctica. For the Australian-Antarctic plate pair the change led to more oblique motion between 50–100 Ma than during earlier periods (Figure 4), with a change in the direction of relative motion from NNE-SSW to NW-SE.

In the Kerguelen sector, the 100 Ma reorganisation resulted in a switch from transtensional motion to almost purely strike-slip at the westernmost extent of the system. Immediately adjacent to the Indian-Australian-Antarctic triple junction ~400 km of left-lateral strike-slip motion is predicted by our model between 100 and 50 Ma. The normal component of motion increases towards the east with ~180 km of seafloor spreading occurring in the Labuan Basin, and ~400 km of seafloor spreading occurring within the Bruce Rise-Naturaliste Plateau sector of the margin.

The reorganisation at 100 Ma also coincides with the onset of a more rapid phase of continental extension between Australia and Antarctica, identified from geological and geophysical data including subsidence curves and seismic reflection profiles [e.g. *Totterdell et al.,* 2000] Slow seafloor spreading in the Central Bight sector of the Australian-Antarctic margins was underway by 83 Ma (*Tikku and Cande,* 1999; *Whittaker et al.,* 2007).

From 100 Ma we model the Australian-Antarctic plate boundary to follow a path from the Naturaliste Plateau/Bruce Rise between the SKP and William Ridge and then through the CKP to meet the Wharton Ridge in the east. Using this plate boundary configuration the William Ridge is modelled as a piece of the SKP that moved northward with Australia and was then transferred to the Antarctic plate following the ridge jump at 43.8 Ma.

From 83 Ma onwards the location of the Australian-Antarctic plate boundary is constrained by magnetic anomaly identifications in the central basin region. Farther west, we continue the plate boundary through the Labuan Basin and the CKP to meet the Wharton Ridge.

Following *Gaina et al.,* (1998) our model incorporates two ridge jumps in the Tasman/Cape Adare section of the margin, which result in the transfer of the eastern and western STR blocks at ~83 Ma and ~50 Ma, respectively (see Table 3 for rotation parameters). Transfer of both blocks occurs earlier compared with previous models. In our model, the eastern STR transfers at 83–80 Ma compared with 65 Ma (*Royer and Rollet,* 1997), or 70 Ma (*Gaina et al.,* 1998), while our western STR transfers at ~50 Ma compared to 43.8 Ma (*Cande and Stock,* 2004), or ~40 Ma (*Gaina et al.,* 1998; *Royer and Rollet,* 1997). The transfer at ~50 Ma coincides with the major change in Australia-Antarctica relative motions linked to a 50 Ma reorganization event.

Prior to breakup we assume that relative motion was accommodated between Australia and Antarctic by a zone of continental rifting. Our model predicts diachronous breakup between 94 and 73 Ma for the Naturaliste-Bruce Rise and Bight Basin-Wilkes Land margin sectors (the breakup age generally decreasing to the east). Some overlap between the COBs of the Otway Basin and the conjugate Antarctic margin persists until ~60 Ma. In the Sorell Basin-George V Land sector, breakup occurs at ~53–50 Ma following a phase of highly oblique transtension. In each case these ages are broadly consistent with observations from seismic stratigraphy, dating of dredge samples and breakup volcanics (*Beslier et al.,* 2004; *Halpin et al.,* 2008; *Krassay et al.,* 2004; *Totterdell et al.,* 2000).

50 Ma to 43 Ma

Our model incorporates a change in direction of relative Australian-Antarctic plate motions from NW-SE prior to 50 Ma, to NNE-SSW after 50 Ma. The change may have been ultimately driven by subduction of the Izanagi Ridge at the northwest Pacific margin causing a reorganisation of the global plate tectonic system (*Whittaker et al.,* 2007).

Our plate reconstructions incorporate a final ridge jump of the Australian-Antarctic MOR at 43.8 Ma. Such a ridge jump is necessary to explain two features that imply that there has not been continuous spreading/relative motion in the Kerguelen sector of the Australian-Antarctic margin (*Rotstein et al.,* 2001): (i) the large step in basement depth between the shallower, younger than C18 crust of the Australian-Antarctic Basin and the deeper crust of both the *Diamantina Zone and Labuan Basin* [*e.g. Rotstein et al.,* 2001], and (ii) the 'wavy' morphology of the Broken Ridge-Central Kerguelen rifted boundary, that is not characteristic of a strike-slip/transtensional boundary required at the western extent of the Australian-Antarctic conjugate margin system for times earlier than ~50 Ma.

Spreading Rates

The spreading rates implied by our model for Australia and Antarctica from the onset of continental rifting through to the transition to faster spreading rates at ~44 Ma are shown in Supplementary Figure 4. Very slow (<10 mm/yr) rates of spreading occur between Australia and Antarctica from the onset of continental rifting to 100 Ma, after which this system experienced a phase of more rapid motion (20–35 mm/yr). The system returned to slow motion (10–20 mm/yr) following continental breakup until the onset of rapid seafloor spreading at ~44 Ma.

There are two spikes in rate of relative motion at 68.7–71.1 Ma and 79.1–83.5 Ma. Finite rotations computed from magnetic anomaly interpretations are known to be affected by substantial noise related to problems with accurately identifying magnetic anomalies from shiptrack data and the calibration accuracy of the geomagnetic reversal timescales (*Iaffaldano et al.,* 2012). The noise related to accurately identifying the location of magnetic reversals is likely exacerbated in the 79.1–83.5 Ma pulse as the chron 34y (and likely the chron 33o) magnetic anomalies are located on or near a basement ridge complex, interpreted to be composed of exhumed continental mantle within the continent ocean transition [*Williams et al.,* 2011]. Although 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), it is likely that there is more error associated with magnetic anomalies identifications of this type.

4. Discussion

4.1 The Kerguelen-Broken Ridge Sector

A plate tectonic reconstruction for the rifting and early spreading between Australia and Antarctic needs to provide a reasonable model for the timing and kinematics of the formation of the basement in the Central Kerguelen-Broken Ridge and Diamantina Zone/Labuan Basin sectors of the margin. Our new rigid plate tectonic reconstruction model (1) does not involve any unlikely tectonic motion, or large-scale deformation of oceanic or continental crust, and (2) provides a detailed model for the formation of the poorly constrained Kerguelen sector of the Australian-Antarctic margin, and in particular the Labuan Basin and the Diamantina Zone.

The southernmost part of the Labuan Basin (also known as the *Shackleton Basin,* Figure 1) is morphologically different to the northern parts of the basin and is characterised by dipping reflectors (Stagg et al., 2004). There is no clear boundary between this basin and the Labuan Basin to the north. The basement and overlying sediments are generally unfaulted, with the basement morphology consistently smooth and flat.

In our model the basement of the Princess Elizabeth Trough and the Shackleton Basin formed between 136–115 Ma due to seafloor spreading between India and Antarctica, with the Antarctic flank underlying the Princess Elizabeth Trough where Mesozoic anomalies have been interpreted (Gaina et al., 2007; Murakami et al., 2000).

Our tectonic reconstruction shows the northern Labuan Basin and the Diamantina Zone formed as one basin between 108–43.8 Ma, in agreement with previous interpretations that these features were once continuous (*Beslier et al.*, 2004; *Chatin et al.*, 1998; *Gladczenko and Coffin,* 2001; *Munschy,* 1998; *Stagg et al.*, 2004). Both the Diamantina Zone and the Labuan Basin exhibit two structurally different provinces: one comprising tilted fault blocks separated by south to southwest dipping faults, and the other characterised by elongated basement highs that are larger and more dome-shaped (*Munschy,* 1998). South to southwest dipping faults separating predominantly northeast oriented basement highs is consistent with the NW-SE oriented transtensional motion in our model.

A number of different models have been proposed for the formation of the ~600 km wide combined Labuan Basin-Diamantina Zone, including: ultra-slow seafloor spreading (*Cande and Mutter,* 1982); diffuse deformation (50–55 Ma, 65–78 Ma) of pre-existing oceanic crust (*Munschy,* 1998); crustal extension between 130–95

Ma and mantle unroofing between 95–84 Ma (*Rotstein et al.*, 1991); amagmatic extension between ~83–43 Ma [*Tikku and Cande,* 2000]; a combination of extended Kerguelen Plateau material and oceanic crust (*Gladczenko and Coffin,* 2001); progressive south to north extension with a central extrusive zone between the pre-Albian and Campanian (*Borissova et al.*, 2002).

Whether the crust within the Labuan Basin and Diamantina Zone is predominantly oceanic (*Gladczenko and Coffin,* 2001) or continental is disputed (*Borissova et al.*, 2002). Our model is more consistent with the oceanic crust formed under slow seafloor spreading conditions. The composition of the alkaline basalts dredged from both the Labuan Basin and the Diamantina Zone indicate small amounts of melting (*Chatin et al.*, 1998) and continental rocks have been sampled from the Labuan Basin, although these were originally interpreted as ice-rafted debris (*Montigny et al.*, 1993).

In our model, the western Labuan Basin/northern Diamantina Zone formed between ~108–83.5 Ma during relative Australian-Antarctic motions that were moderately oblique to the trend of the mid-ocean ridge. During this period, we model the Australian-Antarctic plate boundary to run through the CKP, resulting in the formation of the majority of the crust underlying the CKP. This continuation of the plate boundary from the Labuan Basin to beneath the CKP is supported by the observation that the tilt-block morphology of the Labuan Basin extends onto the Kerguelen Plateau (*Rotstein et al.*, 1991).

We model the formation of the eastern Labuan Basin/southern Diamantina Zone between 83.5 Ma and 43.8 Ma during locally more oblique extensional conditions. During this period relative motion between Australia and Antarctica resulted in ~250 km of extension and 180 km of strike-slip motion in the easternmost

Diamantina Zone, progressing to ~240 km of purely strike-slip motion beneath the northernmost CKP. This phase of motion matches well with the ~120 km width of the eastern Labuan Basin.

For the period between 83.5 Ma and 43.8 Ma our reconstructions model more strike-slip motion than the reconstruction of *Tikku and Cande* [2000] but do not require major strike-slip motion between Tasmania and Australia that seems unlikely in the light of aeromagnetic data over the Bass Basin and onshore geology for southeastern Australia (*Cayley,* 2011; *Cayley et al.*, 2002).A long-standing problem with plate tectonic reconstructions of Australia-Antarctica is the placement of a plate boundary through the Kerguelen region between 95 Ma to ~43 Ma. Magnetic anomaly interpretations from the Bight/Wilkes Land sector of the conjugate Australian-Antarctic margin clearly show continuous, albeit slow, relative motion of these two plates throughout this period. There are structures that can be interpreted as paleo-plate boundaries in the SKP and southern CKP. However, there is a striking absence of evidence for this relative motion, in the form of rifts, strike-slip boundaries etc, in the Central Kerguelen/Broken Ridge sector of the margin. This has lead to the proposal that there simply was no (*Rotstein et al.*, 2001) or minimal (*Tikku and Cande,* 2000) relative motion at this section of the margin. However, as discussed in more detail earlier minimizing/removing relative motion leads to kinematic reconstructions with unlikely plate boundary configurations in the eastern Indian Ocean (*Rotstein et al.*, 2001) or geologically improbable continental deformation in the Tasmanian/Cape Adare region (*Tikku and Cande,* 2000).

Our approach to modelling the formation of crust between Australia and Antarctica explicitly breaks the ocean floor into discrete, rigid blocks and does not take into account the possibility of diffuse deformation. It is likely that the thicker, rheologically weaker Kerguelen Plateau/Broken Ridge regions were not affected by diffuse deformation and rather experienced focussed deformation similar to that observed at the Chagos Bank (*Henstock and Minshull,* 2004). Likely examples of this focussed deformation exist on the SKP, e.g. the 75° E and 77° E Grabens – prominent N-S trending features crossing the Central and Southern Kerguelen Plateaux that formed between 72 Ma and 64 Ma and record small amounts of extensional (~5 km) and strike-slip (~3 km) motion [*Rotstein et al.* 1992]. However, it is possible that diffuse deformation affected the thinner Diamantina Zone/Labuan Basin rather than relative motion being focused at a discrete plate boundary.

Our reconstruction predominantly models the formation of oceanic crust beneath the Kerguelen Plateau prior to, or contemporaneously with the formation of the Kerguelen Plateau. The age of the underlying ocean crust is compatible with igneous basement ages from the Kerguelen Plateau Sites 749 –110 Ma (*Whitechurch et al.*, 1992) and 750 – 112 Ma (*Coffin et al.*, 2002), but not with the 119 Ma basement age from Site 1136 (*Coffin et al.*, 2002; *Duncan,* 2002)which lies on crust we model to have formed between 108–115 Ma (compare the reconstructions in Figure 4 at 115 Ma and 108 Ma). In our model, the Southern Perth spreading corridor forms between 136–115 Ma, followed by the spreading corridor beneath the Southern Kerguelen Plateau at 115–108 Ma. A better match between the age of the underlying ocean floor from the plate tectonic model and the 119 Ma igneous basement age may be achieved, however, if the Southern Kerguelen corridor formed first, prior to 119 Ma and the South Perth corridor second after ~119 Ma. Additional data from the Perth Abyssal Plain are required to test this scenario, which would require a different plate boundary configuration, and possible additional ridge jump.

4.2 Hotspot-Triple Junction Relationship

A possible relationship between volcanic plateaus and triple-junctions has long been observed, for example for the Shatsky Rise (*Nakanishi et al.*, 1999), Agulhas Plateau (*Gohl and Uenzelmann-Neben,* 2001; *Tucholke et al.*, 1981), and Mozambique Ridge (*Gohl and Uenzelmann-Neben,* 2001). Our plate reconstructions allow us to investigate the relationship between the location of the Indian-Australian-Antarctic triple-junction with that of the Kerguelen plume (Figure 4), although we note that the exact location of the reconstructed triple junction remains poorly constrained and may have varied through time. From ~136 Ma to 108 Ma the triple junction between India-Australia-Antarctica moved as a result of India's relative motion away from both Australia and Antarctica at an average rate of ~79 km/My (~1500 km) (Figure 4). During this period, seafloor spreading in the Perth and Enderby Basins resulted in movement of the MOR towards the reconstructed position of the Kerguelen plume for all reference frames considered, although the Mu93 model results in the most consistent proximity between the Kerguelen plume and the mid-ocean ridge system and Indian-Australian-Antarctic triple junction.

The two ridge jumps, at 115 Ma of the Enderby MOR and at 108 Ma of the Perth MOR, were substantial and westward and resulted in fragments of continental crust being rifted from the Indian passive margin (the Elan Bank at 115 Ma (*Gibbons et al.*, 2012), the Gulden Draak Knoll and Batavia Knoll at 108 Ma (*Gibbons et al.*, 2012; *Williams,* 2011) and likely at least some portion of the Southern Kerguelen Plateau (*Operto and Charvis,* 1995). Both these ridge jumps are consistent with the hypothesis of *Müller et al.,* (2001) that plate boundaries jump towards hotspots, resulting in the formation of micro-continents.

At 108 Ma, following the ridge jump the Mu93 modelled location of the Kerguelen hotspot is closest to the Indian-Australian-Antarctic triple junction (also see Supplementary Figure 6). It should be noted that the inferred hotspot tracks all fit poorly with the Ninety East Ridge and the Kerguelen Plateau. The model providing the closest match is the Mu93 fixed hotspot model. This result indicates that individual plume motions coupled with moving hotspot reference frames should be used with some caution when reconstructing individual plumes and interrogating their position relative to reconstructed plate tectonic features. This is particularly applicable for the Kerguelen plume, where considerably different hotspot motions are estimated from models with different buoyancy parameters, for example *Doubrovine et al.* [2012] *and Steinberger and Antretter* [2006].

Between 108 and 43 Ma the Indian-Australian-Antarctic triple-junction progressed much more slowly to the NW (~1000 km) at a rate of 15 km/Myr (Figure 4). This slow motion reduced the distance between the location of the Indian-Australian-Antarctic triple junction and the reconstructed ON05 position of the plume to within ~100 km by 43.8 Ma. Overall, during this period, the triple-junction remains roughly equidistant to the Mu93 and ON05 reconstructed Kerguelen plume locations (Figure 4). The slow progression of the triple-junction location (and by implication the locations of the Indo-Australian-Antarctic plate boundaries) during this period, particularly compared with the rapid motion in the preceding period, suggests a strong preference for the triple-junction to remain near to the Kerguelen plume.

4.3 Triple Junction - Plateau relationship

The Southern Kerguelen Plateau, Central Kerguelen Plateau and Broken Ridge are each proposed to have formed rapidly over short (~5-10 million year) periods, approximately 120–110 Ma, 105–100 Ma and 100–95 Ma, respectively (*Coffin et al.*, 2002). Based on our plate tectonic constraints we propose an alternative scenario for the Central Kerguelen Plateau/Broken Ridge that conforms with the known history for the Eastern Indian Ocean and the Tasmanian/Cape Adare region and implies continued relative transtensional motion in the Central Kerguelen/Broken Ridge sector between ~100 and 43 Ma. To reconcile our model with the absence of rift or strike-slip features in the northern CKP that could have connected the Diamantina Zone/Labuan Basin to the Indian Ocean spreading centres we propose on-going, variable flux magmatism in this region which has overprinted the evidence of much of the paleo-plate boundary. This scenario requires variable magma output rates over extended time periods, a scenario supported by the geodynamic models of *Lin and van Keken* (2005).

We propose that the Central Kerguelen Plateau and Broken Ridge formed as the result of interaction between continued Kerguelen plume-related volcanism, and the Indian-Australian-Antarctic triple junction and Australian-Antarctic plate boundary, over a period of approximately 65 million years, from ~108 Ma to ~43 Ma (Figure 4), with the majority of the joint plateau formed during initial phase of magmatism between 108-83 Ma, followed by lower volume building until ~43 Ma. Episodic magma fluxes exploited this interaction to build the CKP/Broken Ridge volcanic edifice over ~65 Myr, an on-going process that resulted in the masking of rift or strike-slip features formed as a result of Australian-Antarctic relative plate motions. Our model is consistent with the available basement ages available from the CKP (100.4 Ma ODP Site 1138; and 83.7–84.8 Ma ODP Site 747) and Broken Ridge (94.5–95.1 Ma ODP Sites 1141 and 1142).

These relatively sparse data have previously been interpreted to indicate formation of the plateaux over a shorter timespan but do not discount the possibility of more gradual accretion of crust over longer timespans, albeit possibly at lower volumes.

Alternative models have been necessary to explain the formation of the Kerguelen Plateau, and other onshore and marine LIPs, by variable magma output rates over tens of millions of years. Proposed mechanisms have included multiple plume sources, a single, but dismembered plume (*Coffin et al.*, 2002), or the development of secondary instabilities due to the interaction between thermal and compositional variations (*Lin and Van Keken,* 2005).

Our proposed model for the formation of the CKP/Broken Ridge matches variable flux plume models such as *Lin and van Keken* (2005), by requiring variable magma output volumes over longer periods at a relatively stationary location. Continued proximity of the Central Kerguelen Plume to the Indian-Australian-Antarctic triple junction over the ~65 Myr period may also have aided the construction of the extensive CKP/Broken Ridge from lower volume and/or variable rates of magma output. This long period of construction is not inconsistent with the formation of sedimentary basins on the Central Kerguelen Plateau as the slow rates of magmatism would only have affected small regions of the CKP at a time, with other regions quiescent and able to subside and accumulate sediment.

The best-studied example of a LIP formed through the interaction of a plume and a triple-junction is the Shatsky Rise, located in the northwest Pacific (e.g. *Hilde,* 1976; *Larson and Chase,* 1972; *Nakanishi et al.*, 1999). Like the Central Kerguelen Plateau/Broken Ridge, this large oceanic plateau does not appear to have formed rapidly from short-lived ~1–5 Myr episodes of voluminous volcanism.

Subsidence rates observed from DSDP and ODP sediment data on the Shatsky Rise are difficult to reconcile with the rapid emplacement of the plateau by a high-temperature plume (*Ito and Clift,* 1998). *Sager et al.,* (1999), proposed sustained episodic volcanism over approximately 20 million years (chron M20 to M1), with decreasing volumes of magma and plume triple-junction interaction forming the three, spatially separated plateaux of the Shatsky Rise and the volumetrically smaller, linear Papanin Ridge – a model that fits with the variable flux plume model of *Lin and van Keken* (2005). This interpretation is strongly supported by the clear age progression of the Shatsky Rise towards the northeast (*Nakanishi et al.*, 1999). Unfortunately, the basement volcanics of the Central Kerguelen Plateau/Broken Ridge were emplaced during the Cretaceous Quiet Zone, when there was an absence of magnetic reversals, so such a clear age progression is not apparent. In any case, it is unlikely that such a clear age progression would affect the CKP/Broken Ridge due to the nature of the underlying plate boundary. An ultra-slow spreading transtensional plate boundary lay under the CKP/Broken Ridge, in contrast to the normal mid-ocean ridge underlying the Shatsky Rise.

There are significant differences between the morphology of Central Kerguelen Plateau/Broken Ridge and the plateaux of the Shatsky Rise. The Shatsky Rise exhibits a more rugged topography compared to the CKP, and is comprised of three, relatively small, rugged, spatially separated plateaux, while the CKP is a single, very large, relatively smoother, plateau. Nevertheless, both these LIPs exhibit variable magma flux over millions of years, Shatsky over ~20 Myr and the CKP over ~65 Myr.

Although the absolute timescales differ, for both of these LIPs the initial magma flux appears to have been higher, followed by lower volumes, which appear to cease in the Shatsky Rise case but which have continued to the present-day in the case of the Kerguelen plume.

5. Conclusions

We develop a rigid plate tectonic model to reconstruct the history of rifting, breakup and early drifting history between Australia and Antarctica. We incorporate a wide range of constraints from the entire length of the plate boundary system, to present a model that addresses; (1) the formation of the Kerguelen Plateau and adjacent basins including the Labuan Basin and Diamantina Zone, (2) the extension and early seafloor spreading between the Australian and Antarctic continental margins, and (3) the extensional and transform history of the Tasman-Cape Adare conjugate margins, incorporating the formation of the South Tasman Rise.

A major implication of our plate tectonic model is that the Kerguelen LIP, in particular the Central Kerguelen Plateau and Broken Ridge, formed through long-standing interaction between the Kerguelen plume and the Indo-Australian-Antarctic triple junction and Australian-Antarctic plate boundary. Our reconstructions show that the Kerguelen plume remained proximal to the Australian-Antarctic divergent plate boundary and the Indo-Australian-Antarctic triple-junction up until ~43 Ma, indicating at least a ~65 million year interaction between these features. Although there are significant differences in morphology, the Central Kerguelen Plateau/Broken Ridge and the Shatsky Rise appear to share the same formation mechanism, where higher volumes of plume magmatism for ~25 Myr were followed by lower volumes of magmatism are the result of interaction between a triple-junction and adjacent mid-ocean ridge segment and a mantle plume over tens of millions of years.

We tested two moving [*Doubrovine et al.,* 2012; *O'Neill et al.* 2005] and one fixed hotspot reference frame [*Müller et al.,* 1993]. The fixed hotspot reference frame resulted in the best match between the inferred track of the Kerguelen plume and the reconstructed positions of the Ninety east Ridge and Kerguelen Plateau.

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References

Alibert, C., 1991, Mineralogy and geochemistry of a basalt from Site 738: implications for the tectonic history of the southernmost part of the Kerguelen Plateau, *in* Barron, J., Larsen, B., and al., e., eds., *Proceedings ODP, Science Results*, *119*: College Station, TX, Ocean Drilling Program, p. 293–298.

Allen, R.M., and Tromp, J., 2005, Resolution of regional seismic models: Squeezing the Iceland anomaly: *Geophysical Journal International*, *161*, p. 373–386.

Anderson, D.L., 1995, Lithosphere, Asthenosphere, and Perisphere: *Reviews of Geophysics*, *33*, p. 125–149.

Beslier, M.O., Royer, J.Y., Girardeau, J., Hill, P.J., Boeuf, E., Buchanan, C., Chatin, F., Jacovetti, G., Moreau, A., Munschy, M., Partouche, C., Robert, U., and Thomas, S., 2004, A wide ocean-continent transition along the south-west Australian margin: first results of the MARGAU/MD110 cruise: *Bulletin De La Societe Geologique De France*, *175*, p. 629–641.

Bonin, B., Ethien, R., Gerbe, M.C., Cottin, J.Y., Féraud, G., Gagnevin, D., Giret, A., Michon, G., and Moine, B., 2004, The Neogene to Recent Rallier-du-Baty nested ring complex, Kerguelen Archipelago (TAAF, Indian Ocean): stratigraphy revisited, implications for cauldron subsidence mechanisms: *Geological Society, London, Special Publications*, *234*, p. 125–149.

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M.F., and Symonds, P.A., 2002, Geological Framework of the Kerguelen Plateau and adjacent ocean basins, Record 2002/05: Canberra, Geoscience Australia.

Boyden, J.A., Müller, R.D., Gurnis, M., Torsvik, T.H., Clark, J.A., Turner, M., Ivey-Law, H., Watson, R.J., and Cannon, J.S., 2011, Next-generation plate-tectonic reconstructions using GPlates, *in* Keller, G.R., and Baru, C., eds., *Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences*, Cambridge University Press.

Cande, S.C., and Kent, D.V., 1995, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic: *Journal of Geophysical Research*, *100*, p. 6093–6095.

Cande, S.C., and Mutter, J.C., 1982, A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica: *Earth and Planetary Science Letters*, *58*, p. 151–160.

Cande, S.C., and Stock, J.M., 2004, Pacific-Antarctic-Australia motion and the formation of the Macquarie Plate: *Geophysical Journal International*, *157*, p. 399–414.

Cayley, R.A., 2011, Exotic crustal block accretion to the eastern Gondwanaland margin in the Late Cambrian-Tasmania, the Selwyn Block, and implications for the Cambrian-Silurian evolution of hte Ross, Delamerian, and Lachlan orogens: *Gondwana Research*, *19*, p. 628–649.

Cayley, R.A., Taylor, D.H., VandenBerg, A.H.M., and Moore, D.H., 2002, Proterozoic–Early Palaeozoic rocks and the Tyennan Orogeny in central Victoria: the Selwyn Block and its tectonic implications: *Australian Journal of Earth Science*, *49*, p. 225–254.

Chatin, F., Robert, U., Montigny, R., and Whitechurch, H., 1998, The Diamantina rift zone (eastern Indian ocean): petrological and geochemical approach: *C R Academy Science Series II A*, *326*, p. 839–845.

Coble, M.A., and Mahood, G.A., 2012, Initial impingement of the Yellowstone plume located by widespread silicic volcanism contemporaneous with Columbia River flood basalts: *Geology*, *40*, p. 655–658.

Coffin, M.F., and Eldholm, O., 1994, Large Igneous Provinces: Crustal Structure, Dimensions, and External Consequences: *Reviews of Geophysics*, *32*, p. 1–36.

Coffin, M.F., Pringle, M.S., Duncan, R.A., Gladczenko, T.P., Storey, M., Müller, R.D., and Gahagan, L.M., 2002, Kerguelen Hotspot Magma Output Since 130 Ma: *Journal of Petrology*, *43*, p. 1121–1139.

Colwell, J.B., Stagg, H.M.J., Direen, N.G., Bernardel, G., and Borissova, I., 2006, The structure of the continental margin off Wilkes Land and Terre Adélie, East Antarctica, *in* Fütterer, D.K., Damaske, D., Kleinschmidt, G., Miller, H., and Tessensohn, F., eds., *Antarctica: Contributions to Global Earth Sciences*: Berlin, Springer-Verlag, p. 327–340.

Doubrovine, P.V., Steinberger, B., and Torsvik, T.H., 2012, Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans: *Journal of Geophysical Research*, *117*, p. B09101.

Duncan, R.A., 2002, A time frame for construction of the Kerguelen Plateau and Broken Ridge: *J Petrol*, *43*, p. 1109–1119.

Duncan, R.A., and Richards, M.A., 1991, Hotspots, mantle plumes, flood basalts, And true polar wander: *Reviews of Geophysics*, *29*, p. 31–50.

Foster, D.A., and Gleadow, A.J.W., 1992, Reactivated tectonic boundaries and implications for the reconstruction of southeastern Australia and northern Victoria Land, Antarctica: *Geology*, *20*, p. 267–270.

Frey, F.A., Weis, D., Borisova, A.Y., and Xu, G., 2002, Involvement of continental crust in the formation of the Cretaceous Kerguelen Plateau: new perspectives from ODP Leg 120 sites: *Journal of Petrology*, *43*, p. 1207–1239.

Gaina, C., Müller, D.R., Royer, J.Y., Stock, J., Hardebeck, J., and Symonds, P., 1998, The tectonic history of the Tasman Sea: a puzzle with 13 pieces: *Journal of Geophysical Research*, *103*, p. 12413-33.

Gaina, C., Müller, R.D., Brown, B., Ishihara, T., and Ivanov, S., 2007, Breakup and early seafloor spreading between India and Antarctica *Journal of Geophysics International*, *170*, p. 151.

Gibbons, A., Barckhausen, U., van den Bogaard, P., Hoernle, K., Werner, R., Whittaker, J.M., and Müller, R.D., 2012, Constraining the Jurassic extent of Greater India: tectonic evolution of the Australian margin: *Geochemistry, Geophyics, Geosystems*, *13*, p. Q05W13, doi:10.1029/2011GC003919.

Gladczenko, T., and Coffin, M., 2001, Kerguelen Plateau crustal structure and basin formation from seismic and gravity data: *Journal of Geophysical Research*, *106*, p. 16583–16601.

Gohl, K., and Uenzelmann-Neben, G., 2001, The crustal role of the Agulhas Plateau, southwest Indian Ocean: evidence from seismic profiling: *Geophysical Journal International*, *144*, p. 632–646.

Halpin, J.A., Crawford, A.J., Direen, N.G., Coffin, M.F., Forbes, C.J., and Borissova, I., 2008, Naturaliste Plateau, offshore Western Australia: A submarine window into Gondwana assembly and breakup: *Geology*, *36*, p. 807–810.

Hegarty, K.A., Weissel, J.K., and Mutter, J.C., 1988, Subsidence history of Australia's southern margin: constraints on basin models: *American Association of Petroleum Geologists Bulletin*, *74*, p. 615–633.

Hellinger, S.J., 1981, The uncertainties of finite rotations in plate tectonics: *Journal of Geophysical Research*, *86*, p. 9312–9318.

Henstock, T.J., and Minshull, T.A., 2004, Localized rifting at Chagos Bank in the India-Capricorn plate boundary zone: *Geology*, *32*, p. 237–240.

Hilde, T.W.C., N. Isezaki and J.M. Wageman, 1976, Mesozoic Sea Floor Spreading in the North Pacific, *in* al., G.H.S.e., ed., *The Geophysics of the Pacific Ocean Basin and its Margin: A Volume in Honour of George P. Woollard*: Washington D.C., American Geophysics Union, p. 205–226.

Hill, P.J., Meixner, A.J., Moore, A.M.G., and Exon, N.F., 1997, Structure and Development of the West Tasmanian Offshore Sedimentary Basins - Results of Recent Marine and Aeromagnetic Surveys: *Australian Journal of Earth Sciences*, *44*, p. 579–596.

Houtz, R.E., Hayes, D.E., and Markl, R.G., 1977, Kerguelen Plateau bathymetry, sediment distribution, and crustal structure: *Marine Geology*, *25*, p. 95–130.

Hung, S.-H., Shen, Y., and Chiao, L.-Y., 2004, Imaging seismic velocity structure beneath the Iceland hot spot: A finite frequency approach: *Journal of Geophysical Research*, *109*, p. B08305, doi:10.1029/2003JB002889.

Iaffaldano, G., Bodin, T., and Sambridge, M., 2012, Reconstructing plate-motion changes in the presence of finite-rotations noise: *Nature Communications*, *3*, p. 1048.

Ito, G., and Clift, P.D., 1998, Subsidence and growth of Pacific Cretaceous plateaus: *Earth and Planetary Science Letters*, *161*, p. 85–100.

Johnson, B.D., Powell, C.M., and Veevers, J.J., 1976, Spreading history of the eastern Indian Ocean and Greater India's northward flight from Antarctica and Australia: *Geological Society of America Bulletin*, *87*, p. 1560–1566.

Kent, R.W., and Fitton, J.G., 2000, Mantle sources and melting dynamics in the British Palaeogene Igneous Province: *J Petrol*, *41*, p. 1023–1040.

Krassay, A.A., Cathro, D.L., and Ryan, D.R., 2004, A regional tectonostratigraphic framework for the Otway Basin, *in* P. J. Boult, D.R.J., and S. C. Lang, ed., *Eastern Australasian Basins Symposium II,*: Adelaide, South Aust., Pet. Explor. Soc. of Aust., p. 97–116.

Larson, R.L., and Chase, C.G., 1972, Late Mesozoic evolution of the western Pacific Ocean: *Geolocical Society of America Bulletin*, *83*, p. 3627–3644.

Lin, S.-C., and Van Keken, P.E., 2005, Multiple volcanic episodes of flood basalts caused by thermochemical mantle plumes: *Nature*, *436*, p. 250–252.

Mahoney, J., Duncan, R., Khan, W., Gnos, E., and McCormick, G., 2002, Cretaceous volcanic rocks of the South Tethyan suture zone, Pakistan: implications for the Réunion hotspot and Deccan Traps: *Earth Planet Sci Lett*, *203*, p. 295–310.

Matthews, K.J., Seton, M., and Müller, R.D., 2012, A global-scale plate reorganization event at 105-100 Ma: *Earth and Planetary Science Letters*, *355-356*, p. 283–298.

Mittelstaedt, E., and Ito, G., 2005, Plume-ridge interaction, lithospheric stresses, and the origin of near-ridge volcanic lineaments: *Geochemistry, Geophyics, Geosystems*, *6*, p. doi:10.1029/2004GC000860.

Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, E.R., and Hung, S.-H., 2004, Finite-Frequency Tomography Reveals a Variety of Plumes in the Mantle: *Science*, *303*, p. 338–343.

Montigny, R., Karpoff, A.-M., and Hofmann, C., 1993, Résultats d'un dragage par 55°18'S-83°04'E dans le Bassin de Labuan (campagne MD 67, océan Indien méridional): implications géodynamiques, *Géosciences Marines*: Paris, Soc. géol. France, p. 83.

Müller, R.D., Gaina, C., Roest, W., and Hansen, D.L., 2001, A recipe for microcontinent formation: *Geology*, *29*, p. 203–206.

Müller, R.D., Gaina, C., Tikku, A., Mihut, D., Cande, S., and Stock, J.M., 2000, Mesozoic/Cenozoic tectonic events around Australia, *in* Richards, M., and Gordon, R., eds., *The History and Dynamics of Global Plate Motions*, *121*: American Geophysical Union Monograph, American Geophysical Union, p. 161–188.

Müller, R.D., Royer, J.-Y., and Lawver, L.A., 1993, Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks: *Geology*, *16*, p. 275–278.

Müller, R.D., Sandwell, D.T., Tucholke, B.E., Sclater, J.G., and Shaw, P.R., 1991, Depth to basement and geoid expression of the Kane Fracture Zone: a comparison: *Marine Geophysical Researches*, *13*, p. 105–129.

Munschy, M., 1998, La zone de Diamantine, temoin de la separation de l'Australie et de l'Antarctique: arguments geophysiques: *Comptes Rendus de l'Academie des Sciences - Series IIA - Earth and Planetary Science*, *327*, p. 533–540.

Munschy, M., Rotstein, Y., Schlich, R., and Coffin, M., 1993, Structure and tectonic setting of the 77°E and 75°E grabens, Kerguelen Plateau, South Indian Ocean: *Journal of Geophysical Research*, *98*, p. 6367–6382.

Murakami, F., Ishihara, T., Oda, H., Fujimoto, M., Sugiyama, K., and Joshima, M., 2000, Preliminary report of geological and geophysical survey results in the Princess Elizabeth Trough and its vicinity by the R/V Hakurei-maru: *Polar Geoscience*, *13*, p. 165–186.

Nakanishi, M., Sager, W.W., and Klaus, A., 1999, Magnetic lineations within Shatsky Rise, northwest Pacific Ocean: Implications for hot spot-triple junction interaction and oceanic plateau formation: *Journal of Geophysical Research*, *104*, p. 7539–7556.

O'Neill, C., Müller, R.D., and Steinberger, B., 2005, On the Uncertainties in Hotspot Reconstructions, and the Significance of Moving Hotspot Reference Frames: *Geochemistry, Geophysics, Geosystems*, *6*, p. doi:10.1029/2004GC000784, 2005.

Olson, P., 1990, Hot spots, swells and mantle plumes, *in* Ryan, M.P., ed., *Magma Transport and Storage*, John Wiley & Sons Ltd, p. 33-51.

Operto, S., and Charvis, P., 1995, Kerguelen plateau - a volcanic passive margin fragment: *Geology*, *23*, p. 137–140.

Quilty, P.G., and Wheller, G., 2000, Heard Island and the McDonald Islands: a window into the Kerguelen Plateau: *Papers and Proceedings of the Royal Society of Tasmania*, *133*, p. 1–12.

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot spot tracks: plume heads and tails: *Science*, *246*, p. 103–107.

Rotstein, Y., Munschy, M., and Bernard, A., 2001, The Kerguelen Province revisited: additional constraints on the early development of the Southeast Indian Ocean: *Marine Geophysical Research*, *22*, p. 81–100.

Rotstein, Y., Munschy, M., Schlich, R., and Hill, P.J., 1991, Structure and early history of the Labuan Basin South Indian Ocean: *Journal of Geophysical Research*, *96*, p. 3887–3904.

Royer, J.-Y., and Chang, T., 1991, Evidence for relative motions between the Indian and Australian plates during the last 20 m.y. from plate tectonic reconstructions: implications for the deformation of the Indo-Australian plate: *Journal of Geophysical Research*, *96*, p. 11779–11802.

Royer, J.-Y., and Rollet, N., 1997, Plate-tectonic setting of the Tasmanian region: *Australian Journal of Earth Sciences*, *44*, p. 543–560.

Royer, J.-Y., and Sandwell, D.T., 1989, Evolution of the Eastern Indian Ocean since the Late Cretaceous: Constraints from Geosat altimetry: *Journal of Geophysical Research*, *94*, p. 13755–13782.

Sager, W.W., Kim, J., Klaus, A., Nakanishi, M., and Khankishieva, L.M., 1999, Bathymetry of Shatsky Rise, northwest Pacific Ocean: Implications for ocean plateau development at a triple junction: *Journal of Geophysical Research*, *104*, p. 7557–7576.

Sandwell, D.T., and Smith, W.H.F., 2009, Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate: *Journal of Geophysical Research*, *114*, p. B01411.

Sauter, D., Cannat, M., and Mendel, V., 2008, Magnetization of 0-26.5 Ma seafloor at the ultraslow spreading Southwest Indian Ridge, 61°-67° E: *Geochemistry Geophysics Geosystems*, *9*, p. Q04023.

Seton, M., Müller, R., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., and Chandler, M., 2012, Global continental and ocean basin reconstructions since 200 Ma: *Earth-Science Reviews*.

Sibuet, J.-C., Srivastava, S., and Manatschal, G., 2007, Exhumed mantle-forming transitional crust in the Newfoundland-Iberia rift and associated magnetic anomalies: *Journal of Geophysical Research*, *112*.

Sleep, N.H., 2008, Channelling at the base of the lithosphere during the lateral flow of plume material beneath flow line hot spots: *Geochemistry, Geophyics, Geosystems*, *9*, p. DOI: 10.1029/2008GC002090.

Stagg, H.M.J., Colwell, J.B., Direen, N.G., O'Brien, P.E., Brown, B.J., Bernardel, G., Borissova, I., Carson, L., and Close, D.B., 2004, Geological Framework of the Continental Margin in the region of the Australian Antarctic Territory, Volume 2004/25, Geoscience Australia.

Steinberger, B., and Antretter, M., 2006, Conduit diameter and buoyant rising speed of mantle plumes: Implications for the motion of hot spots and shape of plume conduits: *Geochemistry, Geophyics, Geosystems*, *7*, p. doi:10.1029/2006GC001409.

Steinberger, B., and O'Connell, R.J., 1998, Advection of plumes in mantle flow: implications for hotspot motion, mantle viscosity and plume distribution: *Geophysical Journal International*, *132*, p. 412–434.

Tikku, A., and Direen, N.G., 2008, Comment on "Major Australian-Antarctic Plate Reorganization at Hawaiian-Emperor Bend Time": *Science*, *321*.

Tikku, A.A., and Cande, S.C., 1999, The oldest magnetic anomalies in the Australian-Antarctic Basin: Are they isochrons?: *Journal of Geophysical Research*, *104*, p. 661–677.

Tikku, A.A., and Cande, S.C., 2000, On the fit of Broken Ridge and Kerguelen plateau: *Earth and Planetary Science Letters*, *180*, p. 117–132.

Totterdell, J.M., Blevin, J.E., Struckmeyer, H.I.M., Bradshaw, B.E., Colwell, J.B., and Kennard, J.M., 2000, A new sequence framework for the great Australian Bight: starting with a clean slate: *APPEA Journal*, *40*, p. 95–117.

Tucholke, B.E., Houtz, R.E., and Barrett, D.M., 1981, Continental crust beneath the Agulhas Plateau, southwest Indian ocean: *Journal of Geophysical Research*, *86*, p. 3791–806.

Veevers, J.J., 2000, Change of tectono-stratigraphic regime in the Australian plate during the 99 Ma (mid-Cretaceous) and 43 Ma (mid-Eocene) swerves of the Pacific: *Geology*, *28*, p. 47–50.

Wessel, P., and Smith, W.H.F., 1998, New improved version of Generic Mapping Tools Released: *EOS Trans Amer Geophys Union*, *79*, p. 579.

White, R.S., and McKenzie, D., 1989, Magmatism at rift zones: the generation of volcanic continental margins and flood basalts: *Journal of Geophysical Research*, *94*, p. 7685–7729.

Whitechurch, H., Montigny, R., Sevigny, J., Storey, M., and Salters, V., 1992, K-Ar and ^{40}Ar-^{39}Ar ages of central Kerguelen Plateau basalts, *in* Wise, S.W., Jr., Schlich, R., and et al., eds., *Proceedings ODP, Science Results*, *120*: College Station, TX, Ocean Drilling Program, p. 71–77.

Whittaker, J.M., Müller, R.D., Leitchenkov, G., Stagg, H., Sdrolias, M., Gaina, C., and Goncharov, A., 2007, Major Australian-Antarctic Plate Reorganisation at Hawaiian-Emperor Bend Time: *Science*, *318*, p.83–86.

Williams, S., Whittaker, J.M., and Müller, R.D., 2011, Full-fit, palinspastic reconstruction of the conjugate Australian-Antarctic margins: *Tectonics*, *30*, p. doi:10.1029/2011TC002912.

Williams, S.E., 2011, The Perth Abyssal Plain: Understanding Eastern Gondwana Break-up, *RV Southern Surveyor Voyage SS2011_v06 Scientific Highlights*: http://www.marine.csiro.au/nationalfacility/voyagedocs/2011/index.htm, CSIRO.

Wilson, M., and Patterson, R., 2001, Intra-plate magmatism related to hot fingers in the upper mantle: evidence from the Tertiary-Quaternary volcanic province of western and central Europe, *in* Ernst, R., and Buchan, K., eds., *Mantle Plumes: their Identification through Time*, *352*, Geological Society of America Special Paper, p. 37–58.

Table 1. Finite rotations for Australia-East Antarctica (Antarctica fixed). Finite rotations were computed following the methods of *Hellinger* (1981) *and Royer and Chang* (1991), except for the 100 Ma pole which was calculated interactively with GPlates. 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 (i) the synthetic Labuan Basin and William Ridge constraints is σ=5.0 km, (ii) magnetic anomaly identifications is σ=10.0 km, and (iii) the Tasman and Cape Adare margins is σ = 8 km. All ages are after *Cande and Kent* (1995) timescale. [a]Rotation from *Whittaker et al.,* [2007] [b]Rotations from *Williams et al.,* (2011).

Chron	Age	Lat	Long	Angle	r (km)	$\hat{\kappa}$	dF	N	s
20o[a]	43.79	14.92	32.50	-24.51	55.37	0.74	41	58	7
21y	46.26	13.42	33.83	-24.62	5.08	5.32	27	40	5
24o	53.35	10.48	35.17	-25.24	1008.41	0.11	106	115	3
27y	60.92	9.22	35.42	-25.43	577.37	0.17	101	110	3
31o	68.74	7.89	35.75	-25.61	487.43	0.19	95	104	3
32y	71.07	6.67	36.14	-25.75	789.56	0.14	110	119	3
33o	79.08	4.53	36.64	-26.13	885.18	0.13	112	121	3
34y[b]	83.5	1.02	37.28	-26.62	676.21	0.13	92	103	4
100 Ma	100.0	-3.59	36.52	-29.01	-	-	-	-	-
Full-fit[b]	136.0	-3.91	37.90	-30.86	131.75	1.04	137	148	4

Table 2. Covariance matrices for finite rotations in Table 2. The covariance matrix is given by the formula $\frac{1}{\hat{\kappa}} * \begin{pmatrix} a & b & c \\ b & d & e \\ c & e & f \end{pmatrix} \times 10^{-g}$ where the values of a-f are given in radians squared.

Chron	$\hat{\kappa}$	a	b	c	d	e	f	g
20o[a]	0.74	0.63	-0.10	1.68	1.87	-3.10	6.76	6
21y	5.32	13.28	-20.24	0.82	32.03	-2.28	5.76	6
24o	0.11	3.38	-2.17	4.29	4.84	-11.39	42.81	7
27y	0.17	3.09	-1.93	3.60	5.07	-12.06	44.74	7
31o	0.19	3.11	-1.85	3.23	4.95	-11.58	43.03	7
32y	0.14	2.50	-1.82	3.25	4.82	-10.87	39.91	7
33o	0.13	2.52	-1.79	2.97	4.75	-10.31	37.88	7
34y[b]	0.13	5.37	-0.06	-6.56	5.73	-8.19	23.56	7
Full-fit[b]	1.04	2.85	-2.69	3.77	4.01	-6.93	13.8	6

Table 3. Finite rotation parameters for the transfer of the micro-blocks in this model between parent plates. The 83 Ma parameters for the East STR reflect independent motion of the East STR relative to Antarctica. [a]Rotation from *Gibbons et al.,* [2012].

Block	Time (Ma)	Lat (°)	Long (°)	Angle (°)	Fixed Plate From	To
West Perth Abyssal Plain[a]	108	-1.48	-3.7	51.15	India	Australia
Elan Bank[a]	115	2.14	10.54	79.31	India	Antarctica
Diamantina Zone	43.8	14.92	32.5	-24.51	Antarctica	Australia
East Labuan Basin & Bruce Rise	43.8	14.92	32.5	24.51	Australia	Antarctica
William Ridge	43.8	-3.66	36.84	29.42	West PAP	Antarctica
East STR	80	3.68	36.80	-26.24	Antarctica	Australia
	83	3.77	37.23	-26.41	Independent motion relative to Antarctica	
West STR	50	12.00	34.30	-24.91	Antarctica	Australia

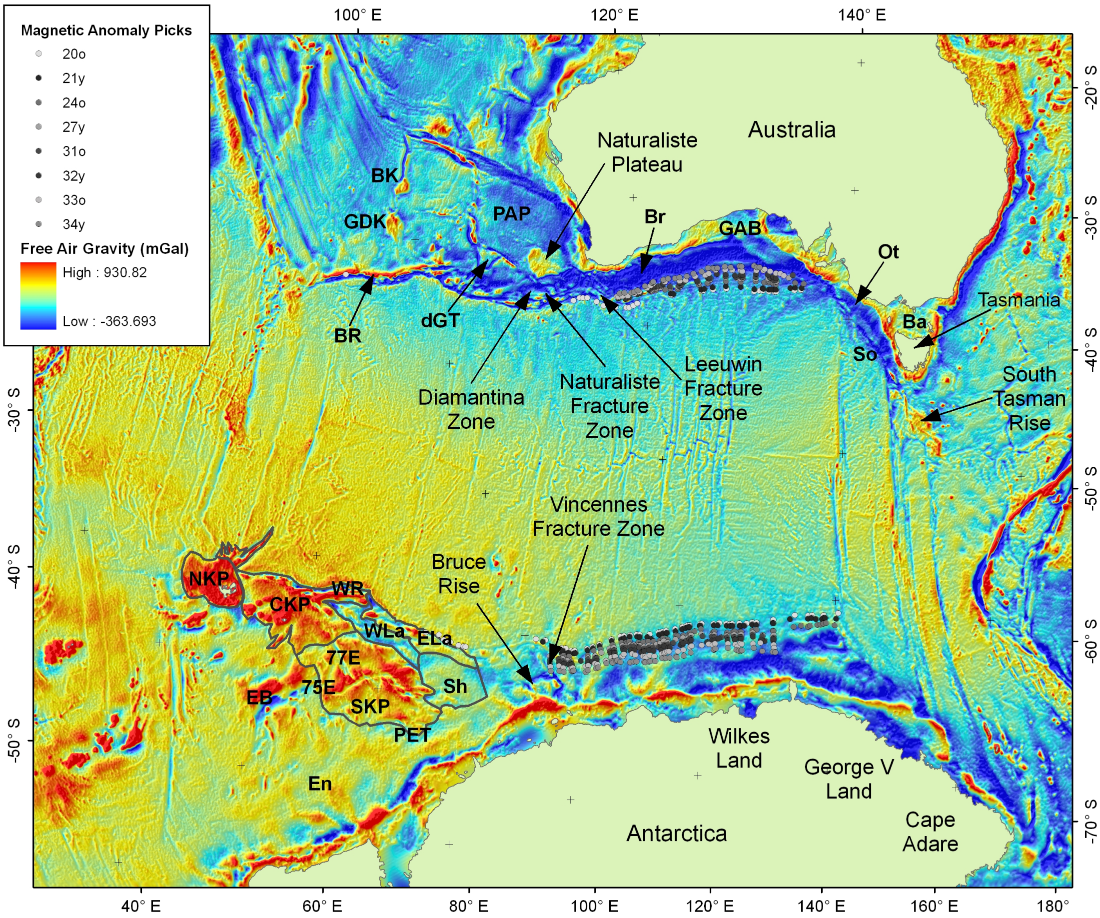

Figure 1. Regional, free-air satellite gravity map of the Australian-Antarctic region, with magnetic anomaly picks from *Tikku and Cande* (1999), *and Whittaker et al.,* (2007). PAP, Perth Abyssal Plain; BK, Batavia Knoll; GDK, Gulden Draak Knoll; dGT de Gonneville Triangle; BR, Broken Ridge; NKP, North Kerguelen Plateau; CKP, Central Kerguelen Plateau; SKP, South Kerguelen Plateau; EB, Elan Bank; WR, William Ridge; WLa, West Labuan Basin; ELa, East Labuan Basin; 75E, 75° E Graben; 77E, 77° E Graben; Sh, Shackleton Basin; PET, Princess Elizabeth Trough; En, Enderby Basin; Br, Bremer Basin; GAB, Great Australian Bight; Ot, Otway Basin; So, Sorell Basin; Ba, Bass Basin.

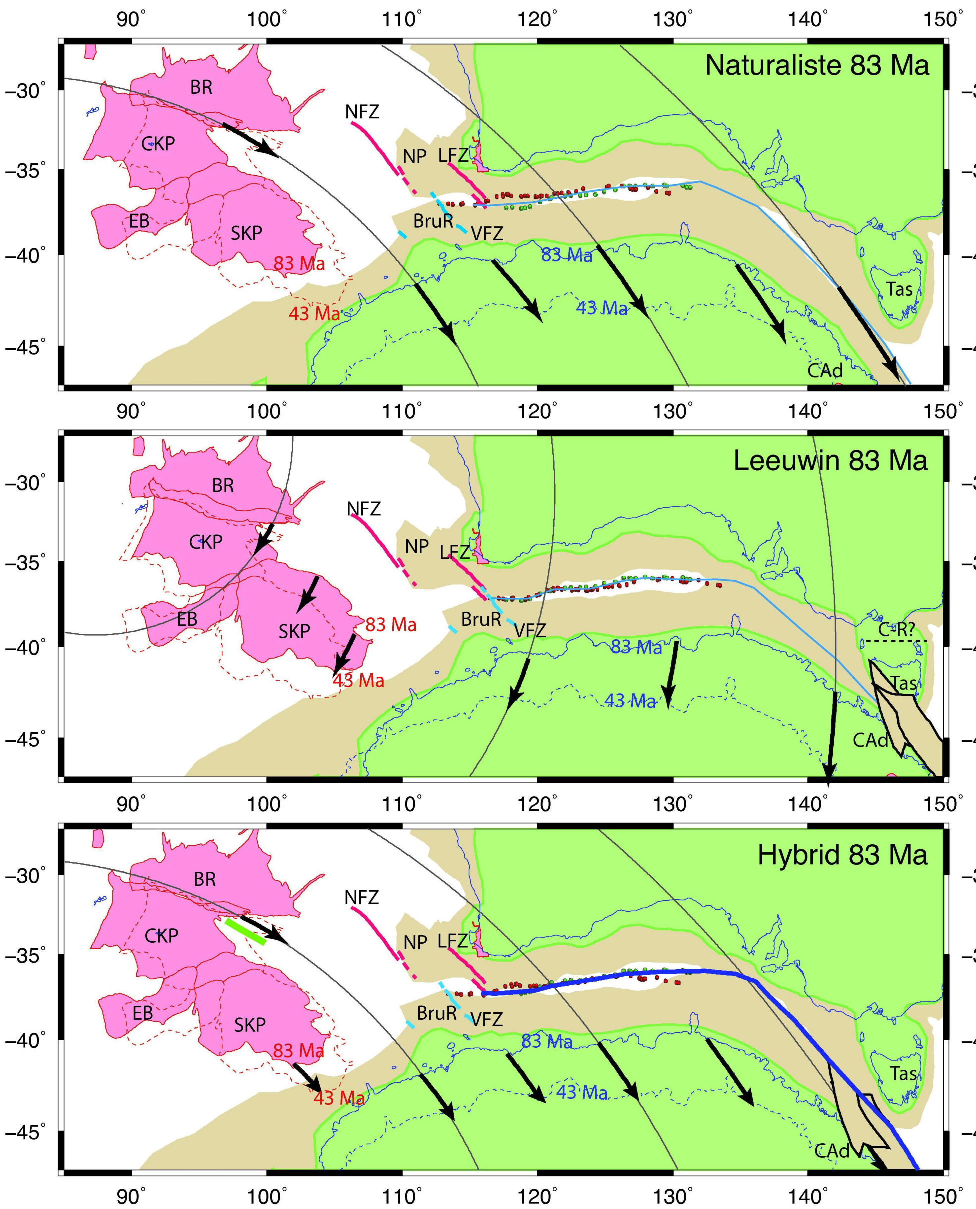

Figure 2. Three alternative reconstructions at 83 Ma for Antarctica relative to a fixed Australia (taken from *Williams et al.,* [2011], **(a)** the Naturaliste model, **(b)** the Leeuwin model, and **(c)** the Hybrid model. Dashed lines show reconstruction at 43 Ma. Grey lines are small circles of the motion across the stage from 83 Ma to 43.8 Ma. Black arrows show small circle motion for the stage 83–43 Ma. Green line in (c) shows small circle constraint used in this paper. C-R is the Colac-Rosedale Fault, invoked by *Tikku and Cande* [2000] to solve the overlap problem between Tasmania and Cape Adare. BR, Broken Ridge; BruR, Bruce Rise; Cad, Cape Adare; CKP, Central Kerguelen Plateau; EB, Elan Bank; Leeuwin Fracture Zone;NFZ, Naturaliste Fracture Zone; NP, Naturaliste Plateau; SKP, South Kerguelen Plateau; Tas, Tasmania; LFZ, Leeuwin Fracture Zone; VFZ, Vincennes Fracture Zone.

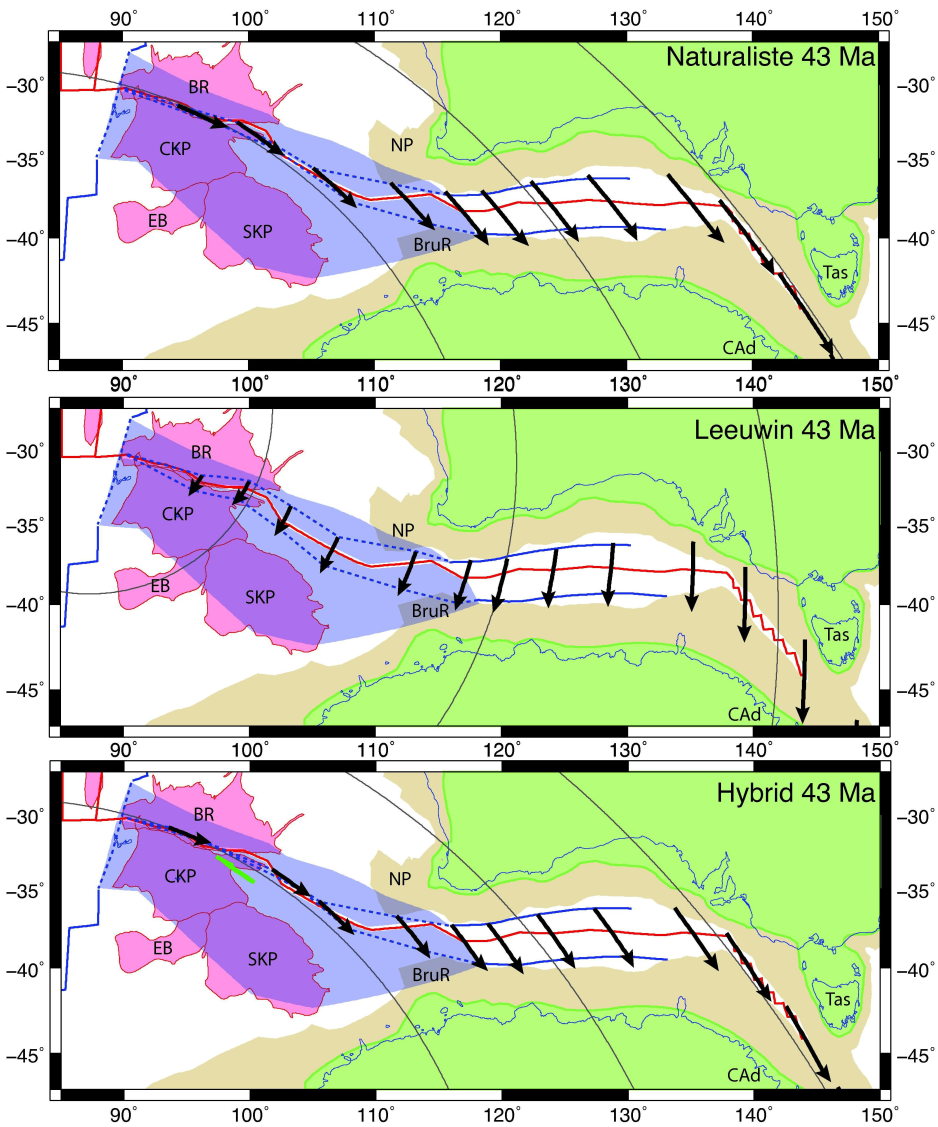

Figure 3. Three alternative reconstructions at 43 Ma for Antarctica relative to a fixed Australia based on the alternative 83 Ma positions shown in Figure 2, **(a)** the Naturaliste model, **(b)** the Leeuwin model, and **(c)** the Hybrid model. Grey lines are small circles of the motion across the stage from 83 Ma to 43.8 Ma. Green line in (c) shows small circle constraint used in this paper. Red lines show mid-ocean ridges at 43 Ma, blue lines show 83 Ma isochron (i.e. paleo-ridge location), dashed line extends the 83 Ma paleo-ridge locations based on the black arrows, which show small circle motion for the stage 83–43 Ma. Grey shaded region shows the area where the plate boundary between Australia and Antarctica could have been located. Labels as for Figure 2.

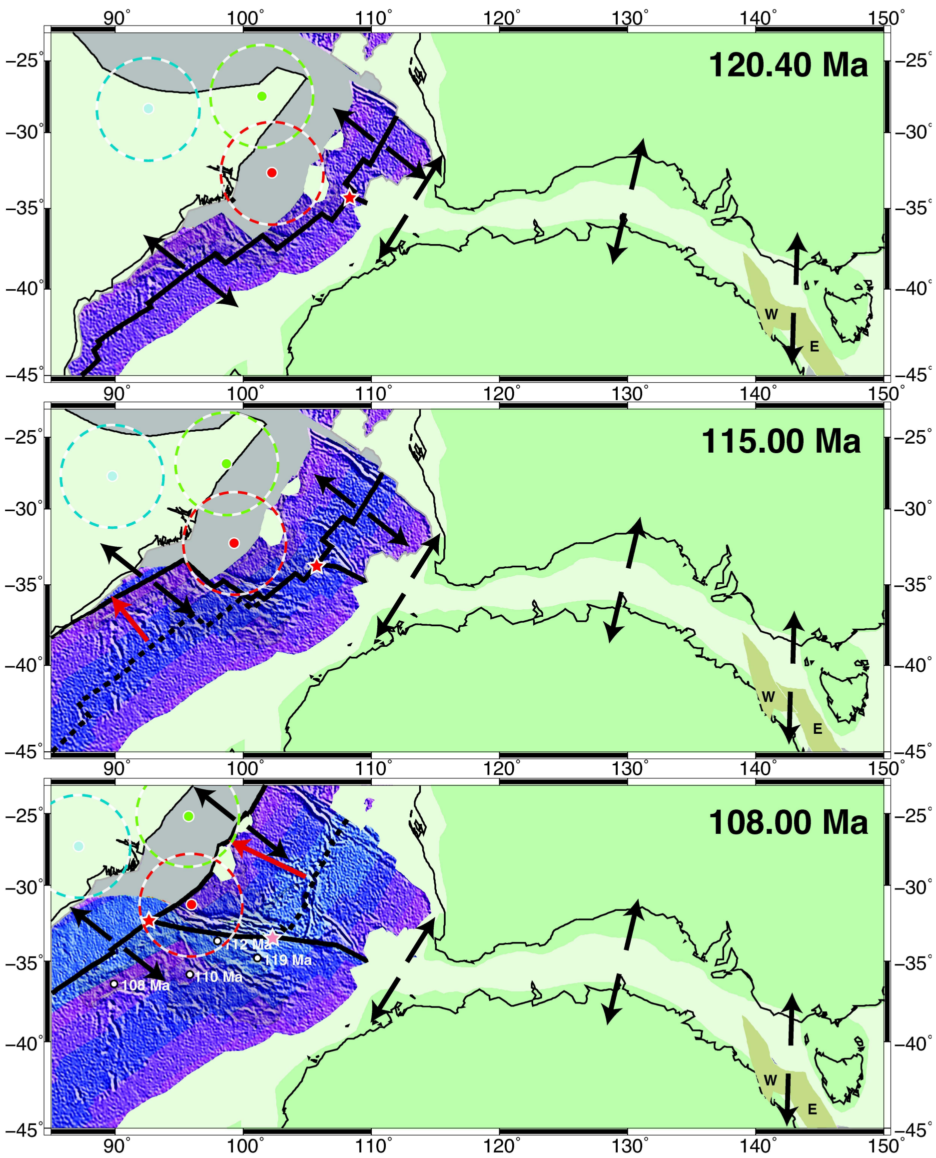

Figure 4. Reconstructions (in a fixed Australian reference frame) using our new rotation parameters combined with those of *Gibbons et al.,* [2012]. Unstretched continental material – green fill; continental margin – beige fill; South Tasman Rise blocks – khaki fill; Kerguelen Plateau and Broken Ridge – shaded regions; plate boundaries – thick black lines; extinct MOR – dashed thick black line; direction of ridge jump – red arrows; direction of relative motion, equal length regardless of speed – black arrows; direction of relative motion prior to 100 Ma reorganisation - grey arrows; ODP/IODP drillsites with basement ages - white circles; India-Australia-Antarctica triple junction location - red star; ancient India-Australia-Antarctica triple junction location - pink star. Modelled Kerguelen plume locations shown as coloured circle and matching 400 km radius plume conduit, Mu93 – red; Do12 – green; ON05 – blue.