JOURNAL OF GEOPHYSICAL RESEARCH: SOLID EARTH, VOL. 118, 808–822, doi:10.1002/jgrb.50079, 2013

# The breakup of East Gondwana: Assimilating constraints from Cretaceous ocean basins around India into a best-fit tectonic model

Ana D. Gibbons,[1] Joanne M. Whittaker,[1] and R. Dietmar Müller[1]

Received 21 March 2012; revised 26 December 2012; accepted 3 January 2013; published 27 March 2013.

[1] Published models for the Cretaceous seafloor-spreading history of East Gondwana result in unlikely tectonic scenarios for at least one of the plate boundaries involved and/or violate particular constraints from at least one of the associated ocean basins. We link East Gondwana spreading corridors by integrating magnetic and gravity anomaly data from the Enderby Basin off East Antarctica within a regional plate kinematic framework to identify a conjugate series of east-west-trending magnetic anomalies, M4 to M0 (~126.7–120.4 Ma). The mid-ocean ridge that separated Greater India from Australia-Antarctica propagated from north to south, starting at ~136 Ma northwest of Australia, and reached the southern tip of India at ~126 Ma. Seafloor spreading in the Enderby Basin was abandoned at ~115 Ma, when a ridge jump transferred the Elan Bank and South Kerguelen Plateau to the Antarctic plate. Our revised plate kinematic model helps resolve the problem of successive two-way strike-slip motion between Madagascar and India seen in many previously published reconstructions and also suggests that seafloor spreading between them progressed from south to north from 94 to 84 Ma. This timing is essential for tectonic flow lines to match the curved fracture zones of the Wharton and Enderby basins, as Greater India gradually began to unzip from Madagascar from ~100 Ma. In our model, the 85-East Ridge and Kerguelen Fracture Zone formed as conjugate flanks of a "leaky" transform fault following the ~100 Ma spreading reorganization. Our model also identifies the Afanasy Nikitin Seamounts as products of the Conrad Rise hotspot.

**Citation:** Gibbons, A. D., J. M. Whittaker, and R. D. Müller (2013), The breakup of East Gondwana: Assimilating constraints from Cretaceous ocean basins around India into a best-fit tectonic model, *J. Geophys. Res. Solid Earth*, *118*, 808–822, doi:10.1002/jgrb.50079.

## 1. Introduction

[2] East Gondwana, comprising India, East Antarctica, Australia, Madagascar, the Seychelles, and other microcontinental blocks, separated from Africa in the Mid-Jurassic [*Eagles and Konig*, 2008; *Konig and Jokat*, 2010; *Royer and Coffin*, 1992]. Australia and Antarctica were then left behind as the remainder of East Gondwana diverged from the Early Cretaceous [e.g., *Johnson et al.*, 1980; *Li et al.*, 1996; *Mihut*, 1998]. The complexity of East Gondwana breakup, volcanic overprinting from the Kerguelen plume, and a lack of geophysical data particularly offshore southwest Australia and East Antarctica, leaves the early Indian Ocean opening history as a source of controversy in Mesozoic plate tectonic models.

[3] In the Early Cretaceous, the separation between Greater India (referring to the original extent of continental India, including the part now deformed in the Eurasia-India collision) and East Gondwana created the seafloor offshore East Antarctica (Figure 1) and West Australia (Figure 2), which were then a continuous continental block undergoing slow continental rifting (possibly initiating as early as ~160 Ma). Australia and Antarctica remained as such until the latest Cretaceous-Paleocene (~100 Ma), when renewed rifting culminated in the formation of ~50–120 km of transitional crust on the Australian flank (Great Australian Bight and Eucla Basin) and finally seafloor spreading from ~83–79 Ma, as per the interpretation of seafloor-spreading magnetic anomaly 33 [*Sayers et al.*, 2001].

[4] The Enderby Basin (Figure 1) formed between East India and East Antarctica and retains vital information to constrain the early motion of India, but it suffers from "noisy" data and a lesser amount of studies due to its location. Magnetic anomalies and older fracture zones are particularly difficult to interpret due to the masking effects of volcanic output from the Kerguelen Plume and the onset of the Cretaceous Normal Superchron (CNS) soon after opening, which restricts the interpretation of magnetic anomalies. An accurate model for the formation of the West Australian margin can help

---

All supporting information may be found in the online version of this article.

[1] EarthByte Group, School of Geosciences, University of Sydney, Sydney, NSW 2006, Australia.

Corresponding author: A. Gibbons, EarthByte Group, School of Geosciences, University of Sydney, Sydney, NSW 2006, Australia. (ana.ekgibbons@sydney.edu.au)

2169-9313/13/10.1002/jgrb.50079

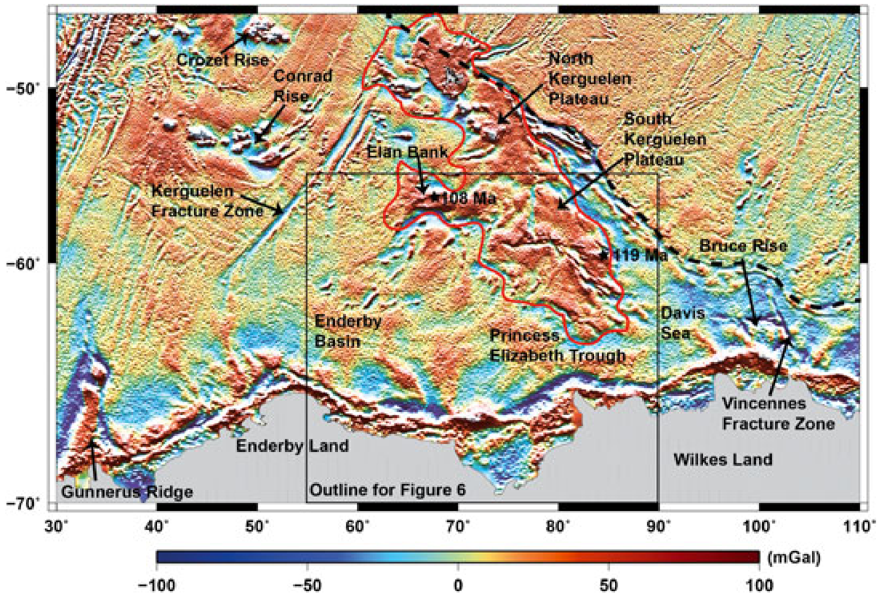

**Figure 1.** The *Sandwell and Smith* (2009) 1° free-air satellite-derived gravity anomalies along the East Antarctic margin. Black dashed line represents the onset of rapid seafloor spreading at ~43.8 Ma [*Müller et al.*, 2000a]. The Kerguelen Plateau outline [*Coffin and Eldholm*, 1994] is shown in red. Black stars indicate ODP leg 183 sites 1137 (Elan Bank) and 1136 (South Kerguelen Plateau), with minimum ages indicated.

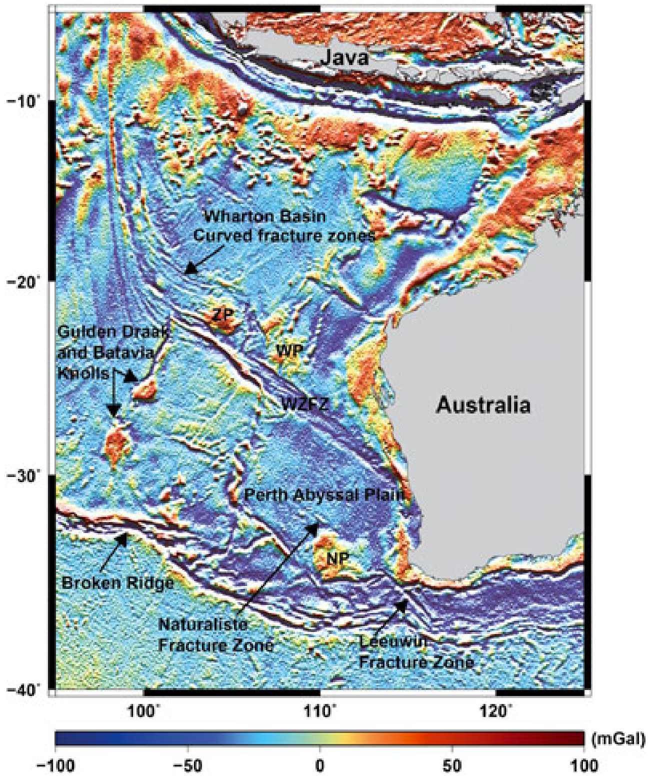

**Figure 2.** The *Sandwell and Smith* [2009] 1° free-air satellite-derived gravity anomalies of the West Australian margin. Seafloor along the West Australian margin was the northward continuation of Enderby Basin seafloor, prior to Australia-Antarctica rifting. ZP is the Zenith Plateau, WP is the Wallaby Plateau, NP is the Naturaliste Plateau, WZFZ is the Wallaby-Zenith Fracture Zone.

constrain the formation of the Enderby Basin because Greater India rifted from their once-continuous margin. The West Australian offshore basins contain a larger and more robust swath of evidence than the Enderby basin, including mostly unaltered seafloor-spreading magnetic anomalies of the Perth, Cuvier, and Gascoyne abyssal plains, and prominent geometrical constraints, such as the Wallaby-Zenith (WZFZ) and curving Wharton Basin fracture zones (Figure 2).

[5] An accurate model of East Gondwana breakup must satisfy geophysical constraints from all abyssal plains created during this breakup. This has recently been attempted for the West Australian margin [*Gibbons et al.*, 2012]. Here, we extend the West Australian margin study to East Antarctica to investigate whether the seafloor-spreading history, interpreted between India and Antarctica, can (1) be compatible with available geophysical data in the Enderby Basin, as well as offshore West Australia, (2) feature motion for Greater India that re-creates the major tectonic features in the Enderby Basin, as well as those offshore West Australia, and (3) adhere to the rules of plate tectonics by minimizing gaps, overlaps, or unusual (e.g., two-way) motion between the tectonic plates: Madagascar, Antarctica, Australia; microplates: Sri Lanka and Naturaliste Plateau; and "potential" microplates: Elan Bank, South Kerguelen Plateau, plus several more offshore West Australia [*Gibbons et al.*, 2012].

## 2. Study Area and Previous Work

[6] The Enderby Basin is situated along East Antarctica's margin between Gunnerus Ridge in the west, Princess Elizabeth Trough in the east, and the Kerguelen Plateau in the northeast (Figure 1). The basin contains several north to NNE trending fracture zones originating from the Antarctic margin. Some terminate abruptly at the Kerguelen Fracture Zone (KFZ, Figure 1), while others terminate ~500 km south

of the Conrad Rise. The only discernible fracture zone further east is the Vincennes Fracture Zone located at the eastern edge of the Bruce Rise (Figure 1). Running northeast of the Bruce Rise and Kerguelen Plateau is a tectonic boundary marking the onset of rapid seafloor spreading between Australia and Antarctica (thick dashed line, Figure 1).

[7] The Kerguelen Plateau (Figure 1), at the northeast extent of the Enderby Basin, is identified as a plume-related igneous province active from ~120 Ma [*Coffin et al.*, 2002]. Mantle plumes are associated with continental breakup [*Richards et al.*, 1989] and the Kerguelen Plume has been linked to the breakup of East Gondwana, the formation of the 132 Ma Bunbury Basalts of southwest Australia [*Frey et al.*, 1996], the 118 Ma Rajmahal Traps in northeast India [*Kent et al.*, 2002], and the ~115 Ma ultramafic lamprophyres from the East Antarctic margin [*Coffin et al.*, 2002]. The Kerguelen Plateau was initially identified as a large igneous province [*Duncan*, 2002; *Watkins et al.*, 1974], but there is also evidence of geochemical contamination by continental material [*Frey et al.*, 2002]. A recent study summarizing all available data for the Kerguelen area, including initially subaerial sedimentary deposition along the southern part of the plateau, concluded that at least the southern portion of the Kerguelen Plateau contains stretched continental fragments [*Bénard et al.*, 2010]. The Elan Bank (Figure 1) is a promontory jutting out west from the tip of the South Kerguelen Plateau. The Ocean Drilling Program (ODP) and seismic data indicate it may be a microcontinental fragment, underlying the Kerguelen volcanic carapace, and the absence of older sediment on its shallower parts suggests that it remained above sea level until at least Maastrichtian time [*Borissova et al.*, 2003].

[8] Magnetic anomalies in the Enderby Basin have previously been identified as a single flank formed from 134 Ma/M11 to 120.4 Ma/M0, at a half-spreading rate of 6.5 to 2.8 cm/yr [*Ramana et al.*, 2001], the same anomalies were also identified by the same study in the Bay of Bengal, conjugate to the western Enderby Basin. Another study identified a conjugate set of seafloor-spreading anomalies in the eastern Enderby Basin from 130 Ma/M9 to 120.4 Ma/M0, at half-spreading rates of 3.9 to 0.8 cm/yr [*Gaina et al.*, 2007]. This conjugate sequence of anomalies, reflected about an extinct ridge, supports the ODP and seismic interpretation that Elan Bank was a microcontinent, in this case transferred to the Antarctic plate ~120.4 Ma via a ridge jump. When combined with a model for the West Somali Basin (Figure 3) that featured seafloor spreading until 120.4 Ma/M0 [*Cochran*, 1988; *Gaina et al.*, 2003], the tectonic reconstruction by *Gaina et al.* [2007] introduced over 600 km of sinistral followed by over 500 km dextral (two-way) strike-slip motion between India and Madagascar. This two-way strike-slip motion is due to the coeval seafloor spreading in the Enderby and West Somali basins, moving India against Madagascar. New aeromagnetic data from east of Gunnerus Ridge (Figure 1) suggests that the western Enderby Basin seafloor formed during the CNS [*Jokat et al.*, 2010], but the study did not provide a tectonic reconstruction. This area, between India and Antarctica, has been cited as the full-fit location of Sri Lanka prior to breakup [e.g., *Lawver et al.*, 1998; *Powell et al.*, 1988]. If combined with the West Australian margin model [*Gibbons et al.*, 2012], the interpretation of *Jokat et al.* [2010] results in ~200 km of extension between Sri Lanka and India between ~120.4 and 126 Ma (Figure 4), with

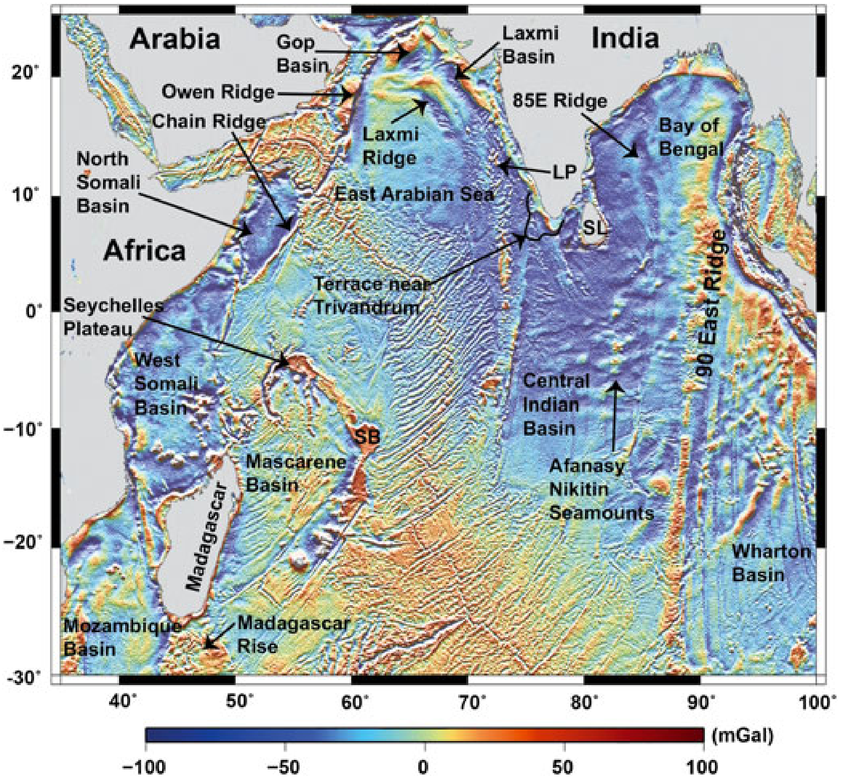

**Figure 3.** The *Sandwell and Smith* [2009] 1° free-air satellite-derived gravity anomalies showing the anomalous tectonic features in the North and West Indian Ocean; seafloor along the East Indian margin was conjugate to the Enderby Basin (LP is Laccadive Plateau, SL is Sri Lanka and SB is Saya de Malha Bank).

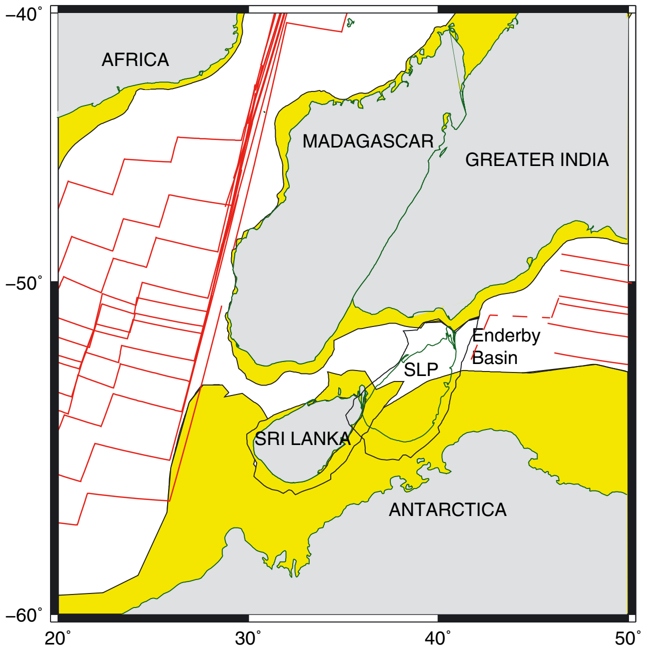

**Figure 4.** 120 Ma reconstruction showing that Sri Lanka, as located in our study's pre-breakup configuration, would be ~200 km southwest of its present-day position by India (SLP, in hollow green) when combining the West Australian margin model [*Gibbons et al.*, 2012], for rotations between Greater India and West Australia [featuring rotations between Antarctica and Australia from *Whittaker et al.*, 2007], with the post-CNS West Enderby Basin interpretation [*Jokat et al.*, 2010]. This reconstruction would necessitate compression or a subduction zone at India's southern margin for Sri Lanka to come to its present-day location relative to India, which is not evident. Coastlines are filled in gray, continent-ocean boundary is filled in yellow, and thin red lines indicate location of isochrons from this study, east of Madagascar.

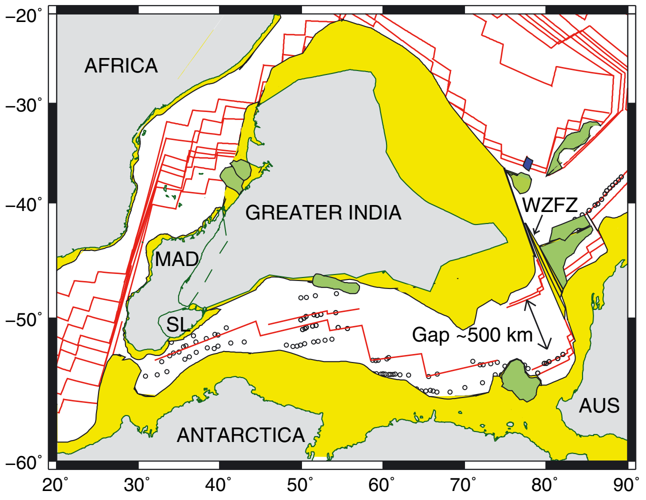

**Figure 5.** 125 Ma reconstruction showing Greater India's location with the Enderby Basin model of *Gaina et al.* [2007] incorporated into our tectonic model for the West Australian margin [*Gibbons et al.*, 2012], describing rotations between Greater India and West Australia (also encompassing rotations between Antarctica and Australia from *Whittaker et al.* [2007]). Note that a ~150 km overlap (green dashed line) exists between Madagascar and India in order to preserve the Wallaby-Zenith Fracture Zone (WZFZ) off West Australia. Coastlines are filled in gray, continent-ocean boundary is filled in yellow, thin red lines indicate location of seafloor-spreading magnetic anomalies (we have attempted to draw the best fit for Enderby isochrons), M4 (126.7 Ma) magnetic anomaly picks are indicated by small black circles, while pale black circles indicate the older Enderby anomalies M9 (130.2 Ma). Continental microblocks that were transferred from Greater India to Gondwana are shown in green.

Sri Lanka remaining fixed to India for that time, demonstrating the difficulties of combining seafloor-spreading models from different oceanic basins (Figure 5).

[9] The western Bay of Bengal, near Sri Lanka (Figure 3), is conjugate to the East Antarctic seafloor, but it is mostly obscured by the thick sediments of the Bengal Fan. Seafloor-spreading anomalies M11 to M0 were also identified south of Sri Lanka [*Desa et al.*, 2006], but their conjugate seafloor would be located just east of the Gunnerus Ridge (Figure 1). Southeast-trending fracture zones are discernible in the marine gravity grid within ~500 km of Sri Lanka, where the Bengal Fan sediments are thinner. The fracture zones terminate abruptly along a ridge branching southwest from the southern part of the 85°E Ridge (~6°N/86°E), leading to the Afanasy Nikitin Seamounts (Figure 3).

## 3. Data and Methodology

[10] We apply the West Australian margin model to the breakup and early spreading history between India and Antarctica in order to reinterpret a set of constraints from the Enderby Basin with increased confidence. We use the satellite-derived free-air gravity anomaly grid [*Sandwell and Smith*, 2009] to interpret fracture zones. We adopt recent studies that outline the continent-ocean boundary (COB) for Antarctica east of the Bruce Rise [*Williams et al.*, 2011] and west of the Bruce Rise [*Gaina et al.*, 2007]. We analyze GEODAS (Geophysical Data System) data from the National Geophysical Data Centre. All magnetic anomaly ship track data were smoothed by high-pass (300 km) and low-pass (10 km) filters to remove electromagnetic field disturbances and noise. We make magnetic anomaly identifications by comparing magnetic anomalies from selected ship track profiles (Figure 7) against a synthetic model of seafloor spreading created using Modmag [*Mendel et al.*, 2005]. Table 1 outlines the parameters used for the synthetic models. We use the time scale of *Gradstein et al.* [1994] for Mesozoic anomalies. Sea floor spreading rates and plate motion is constrained by the rotations

**Table 1.** Parameters used for Enderby Basin Synthetic Magnetic Model

| Parameters | Values |
|---|---|
| Seafloor-spreading direction | 0° |
| Spreading full-rate | 61 mm/yr |
| Depth of magnetized layer (below sea level) | 5 km |
| Thickness of magnetized layer | 0.5 km |
| Magnetization on axis | 10 A/m |
| Magnetic field declination | −55° |
| Magnetic field inclination | −65° |

derived from the West Australian margin study [*Gibbons et al.*, 2012]. Full-spreading rates were ~61 mm/yr, which is near the slow end of intermediate, yet no median valley can be observed in the almost-smooth axial gravity character of the Enderby Basin.

## 4. Magnetic Anomaly Interpretation

[11] We pick the young end of normal polarity intervals and identify magnetic anomalies M4 (126.7 Ma), M2 (124.1 Ma), and M0 (120.4 Ma) about an extinct ridge running parallel to and midway between the Elan Bank and the Antarctic continent-ocean boundary (Figure 6). Figure 7 shows the stacked plots of our interpretation of selected tracks compared to our synthetic model. Seafloor near the southern margin of the Elan Bank, where high-amplitude magnetic anomalies and abnormal seafloor topography and gravimetry indicate that off-axis volcanism took place (Figures 6 and 7), is identified as CNS.

[12] We identify an extinct ridge (dashed black line) between Elan Bank and the Antarctic margin as an axis of reflection between the magnetic anomalies (thick line), gravity profiles (thin line), and ship track bathymetry profiles (dashed line). We outline a pseudofault/northwest Elan Bank boundary, according to the faint lineation visible in the marine gravity grid off East Antarctica and the Bay of Bengal (Figures 6 and 8). This pseudofault corresponds to the ENE propagation of a ridge segment from the western Enderby Basin into the Indian continental margin, transferring the Elan Bank tectonic block from India to Antarctica, as spreading between Elan Bank and Antarctica ceased. Our extinct ridge is located ~40 km further north to that of *Gaina et al.* [2007], and also became extinct later, ~115 Ma. Not all of the oldest Indian seafloor was transferred to Antarctica during the reorganization, such as the seafloor <1000 km NE of Sri Lanka.

## 5. Constraints from Margin Geometries and Seafloor Fabric

[13] Robust plate tectonic models are built on regional constraints so that excessive misfit and unlikely plate motion is avoided. This is particularly significant for Greater India, which was constrained to depart East Gondwana by navigating a corridor surrounded on three sides by Antarctica, Australia, and Madagascar. Our magnetic anomaly interpretations are formulated to avoid overlaps or gaps between the Indian and Antarctic plates when combined with the rotation poles from a recent West Australian margin study

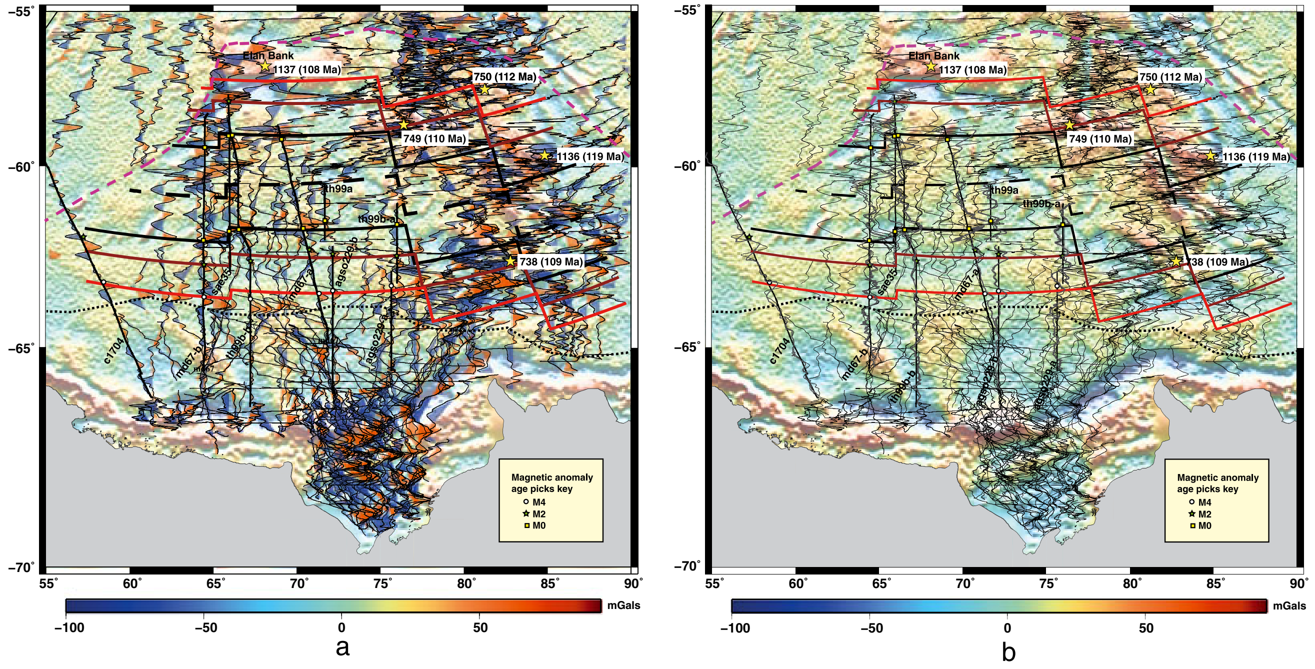

**Figure 6.** (a) Mercator-projected map for the Enderby Basin showing marine magnetic anomalies (thin light gray lines), projected at 90° from North, overlain on 1 min satellite-derived free-air gravity field. Thin dark gray lines show the selected, representative magnetic anomaly profiles and tracks (thin black lines, as labeled) used for Figure 7. Dashed black line shows the extinct ridge, surrounded by our interpreted conjugate isochrons M0 (black), M2 (brown), and M4 (red), black dotted line shows the COB. Identification of marine magnetic anomalies, picked at the young end of normal polarity, is shown in the map key. Yellow stars indicate the location of drill sites, shown with minimal ages. (b) Mercator-projected map for the Enderby Basin showing marine magnetic anomalies projected at 90° from North, overlain on 1 min satellite-derived free-air gravity field. Thin black lines show the selected, representative magnetic anomaly profiles used for Figure 7. Thick dotted black line shows the extinct ridge surrounded by our interpreted conjugate isochrons M0 (thick black line), M2 (thick brown line) and M4 (thick red line), black dotted line shows the COB. Identification of marine magnetic anomalies, picked at the young end of normal polarity, is shown in the map key. Yellow stars indicate the location of drill sites, shown with minimal ages.

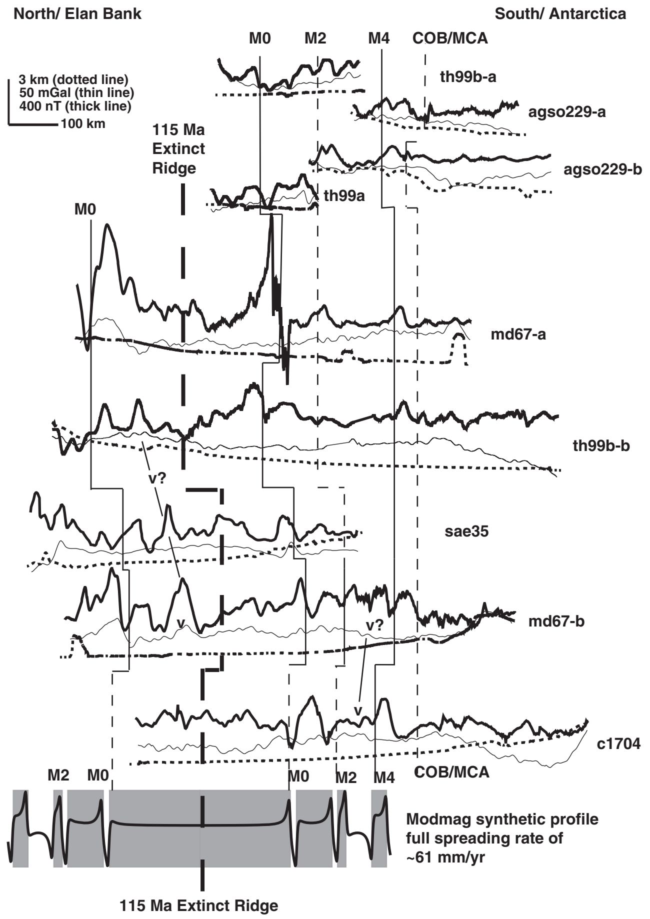

**Figure 7.** Selected, representative magnetic anomaly profiles for the Enderby Basin. The location of the profiles is shown in Figure 6. The synthetic profile is based on the geomagnetic time scale of *Gradstein et al.* [1994], using a depth to the top of the magnetized layer of 6 km and a thickness of the magnetized layer of 0.5 km. The oceanic crust was assumed to have been magnetized at 60° south. Where gravity (thin line)/bathymetric (dotted line) highs coincide with unusual or indistinguishable magnetic anomalies, we tentatively interpret potential off-axis volcanism (v).

[*Gibbons et al.*, 2012]. Having tested several magnetic anomaly interpretations, we are confident that this outcome provides the best solution for seafloor spreading between Greater India and East Gondwana (Australia and Antarctica) when combined with the West Australian margin study. This model incorporates minor motion between these plates prior to 136 Ma to accommodate NW-directed rifting within East Gondwana in a direction roughly orthogonal to the future East Indian and West Australian margins but focused about a western pivot near Sri Lanka. The rifting began sometime in the Mid-Jurassic to Early Cretaceous, as indicated by deposition in the ~60 km-wide western Mentelle Basin, east of the Naturaliste Plateau off southwest Australia [*Borissova et al.*, 2010].

[14] For rotations describing the motion of Greater India relative to adjacent Antarctic and Australian plates, we simultaneously fit magnetic anomaly picks and fracture zones from conjugate flanks in the Enderby Basin, in line with the prescribed Indian-Australian motion [*Gibbons et al.*, 2012]. We visually align coeval magnetic anomaly and fracture zone picks to compute full-stage rotation poles using GPlates [*Boyden et al.*, 2011]. In order to best fit the Enderby Basin potential field data to the West Australian margin model, we incorporate <50 km motion between Elan Bank and India from 116–115 Ma, which we suggest prefaces the NE ridge propagation from the West Enderby Basin, isolating the Elan Bank ~115 Ma. We also include and test a recently proposed fit reconstruction for East Gondwana, which shifts the position of Australia, relative to Antarctica, ~500 km further east [*Whittaker et al.*, 2007; *Williams et al.*, 2011]. This initial Australia-Antarctic fit is based on a deforming plate model for the conjugate margins, which integrates crustal thickness along tectonic flow lines to give an estimate of the prerift location of the margins. The margins are regionally defined using potential field data as are their “full-fit” poles of rotation, which also incorporate geological structures and large igneous provinces within the Australian-Antarctic plate system. The preferred model implies that the Vincennes and Leeuwin Fracture Zones (Figures 1 and 2, respectively) are conjugate features within Gondwana and are likely related to the earlier rifting of India away from Australia-Antarctica rather than the initial opening between Australia and Antarctica. The *Gibbons et al.* [2012] model can replicate these conjugate features via the motion of the Naturaliste Plateau, which rifted along with Greater India from ~136 Ma, while Australia-Antarctica also underwent rifting [*Williams et al.*, 2011].

[15] The initial motion of Greater India is constrained to the northeast by the northern limit of the Wallaby-Zenith Fracture Zone (WZFZ, Figure 2), while, to the southwest, India’s motion is constrained by Madagascar. Greater India’s motion followed the Wallaby-Zenith Fracture Zone and East Madagascan margins, so any reconstruction of India’s motion must be able to recreate their present-day geometries. We rejected the interpretation of older magnetic anomalies (e.g., chron M9) by *Gaina et al.* [2007] because an earlier northward migration for Greater India causes compression between it and either the WZFZ or Madagascar (Figure 5), whose opposing margins either side of Greater India converge toward the north (this effect is exaggerated by the Mercator projection used in Figure 9b).

## 6. Tectonic Model and Discussion

[16] In a full-fit reconstruction, the southeast tip of India and southern tip of Madagascar are aligned and juxtaposed with the northern tip of the Gunnerus Ridge and Sri Lanka (Figure 9a). There is up to ~120 km overlap between their COB’s until further east, where the combined crustal extension between India, Australia and Antarctica, and their respective microblocks: Batavia and Gulden Draak knolls (respectively north(east) and south(west) of the Naturaliste Plateau, NP, Figure 9a), Naturaliste Plateau and Bruce Rise, reached ~400 km. This amount of overlap might be thought of as reasonable given the presence of three extended passive continental margins and the existence of numerous, smaller, highly extended microcontinents. Minimal continental overlap in the neighboring area, between the future South Kerguelen and Antarctic margins, might hint that

some continental crust does underlie the South Kerguelen Plateau (SKP). We incorporate the Naturaliste Plateau as a microcontinental fragment in our model because evidence of reworked Mesoproterozoic continental crust suggests the Naturaliste Plateau was a Gondwanan fragment that can be linked to Antarctica as a westerm extent of the Albany-Fraser-Wilkes Orogen [*Halpin et al*., 2008]. *Halpin et al.* [2008] identify the plateau as a middle-to-lower crustal allochthon, exhumed during hyper-extensional breakup between Australia and Antarctica. A recent palinspastic reconstruction of the Australian-Antarctic margins aligns the Leeuwin and Vincennes Fracture Zones, branching east of the Naturaliste Plateau and Bruce Rise, respectively (Figures 1 and 2), as conjugate features derived from the opening of India from Australia and Antarctica [*Williams et al*., 2011]. This is in contrast to a previous study, which identified them as fracture zone counterparts, formed during Australia and Antarctica separation [*Tikku and Cande*, 1999]. Both the palinspastic and our reconstructions support a model that aligned the Vincennes Fracture Zone with the Leeuwin Fracture Zone, such that they formed as a transform-rift feature at the triple plate junction where India migrated from Australia and Antarctica, and then as conjugate features where the Bruce Rise (Antarctica) and Naturaliste Plateau (India then Australia after ~127 Ma; *Gibbons et al.* [2012]) separated.

[17] Our model features the Naturaliste Plateau and Bruce Rise as composite Gondwanan continental crust that initially rifted along with Greater India until seafloor spreading was established to their west ~127 Ma [*Gibbons et al*., 2012]. This initial motion is necessary to create the Mentelle Basin, between the Naturaliste Plateau and southwest Australia, whose western depocenter has been correlated with Late Jurassic to Early Cretaceous extension in the Perth Abyssal Plain, sharing similar NS structural trends [*Borissova et al*., 2010]. After this initial rifting, the Bruce Rise and Naturaliste Plateau remained composite within East Gondwana until Australia and Antarctica rifted apart in the Mid Cretaceous. This timing coincides with the formation of the Central Enderby margin, including the portion that was conjugate to the Elan Bank, which we test as a continental fragment using the previously proposed outline based on [*Gaina et al*., 2003]. Our model requires up to 50 km of overlap between the Elan bank and Indian COB's before the 115 Ma ridge jump, while the earliest seafloor-spreading anomalies identified in our study formed very close

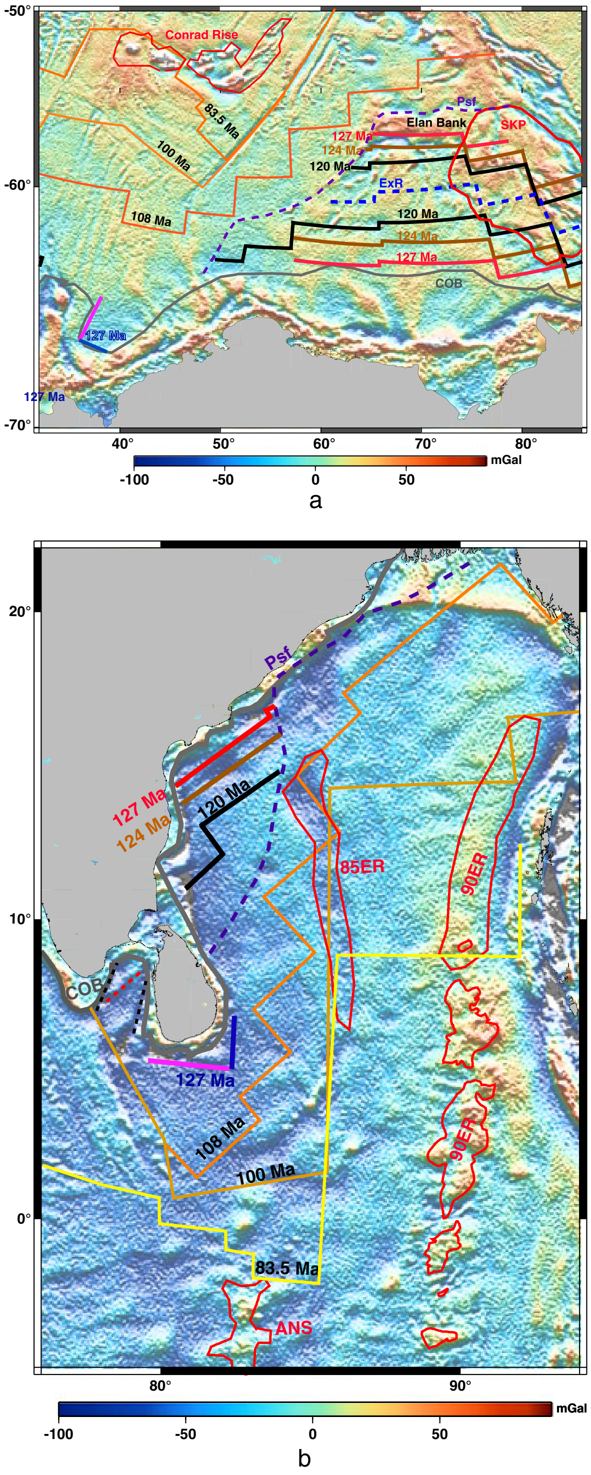

**Figure 8.** (a) Mercator-projected 1 min satellite-derived free-air gravity field map for the Enderby Basin. Thick dashed purple line indicates the pseudofault, which isolated conjugate isochrons M0 (thick black line), M2 (thick brown line), and M4 (thick red line), and the ~115 Ma extinct ridge (thick blue dashed line). Younger synthetic isochrons are shown to highlight the change in direction of seafloor spreading ~100 Ma. Dark gray line shows the COB, while the "corner" features conjugate to Sri Lanka are indicated in mauve and navy, southeast of the Gunnerus Ridge. (b) Mercator-projected 1 min satellite-derived free-air gravity field map for the East Indian margin. Thick dashed purple line indicates the pseudofault, which isolated isochrons M0 (thick black line), M2 (thick brown line), and M4 (thick red line). Younger synthetic isochrons are shown to highlight the change in direction of seafloor spreading ~100 Ma. Dark gray line shows the COB, while the "corner" features conjugate to the Gunnerus Ridge in East Antarctica are indicated in mauve and navy, southeast of Sri Lanka. The failed rift (thin, dashed red line) and transform ridges or margins of India and Sri Lanka (thin, dashed black lines) as described by *Desa et al.* [2006] are also shown. Approximate outlines for seamounts and LIPs (thin red lines) were digitized from the marine gravity grid.

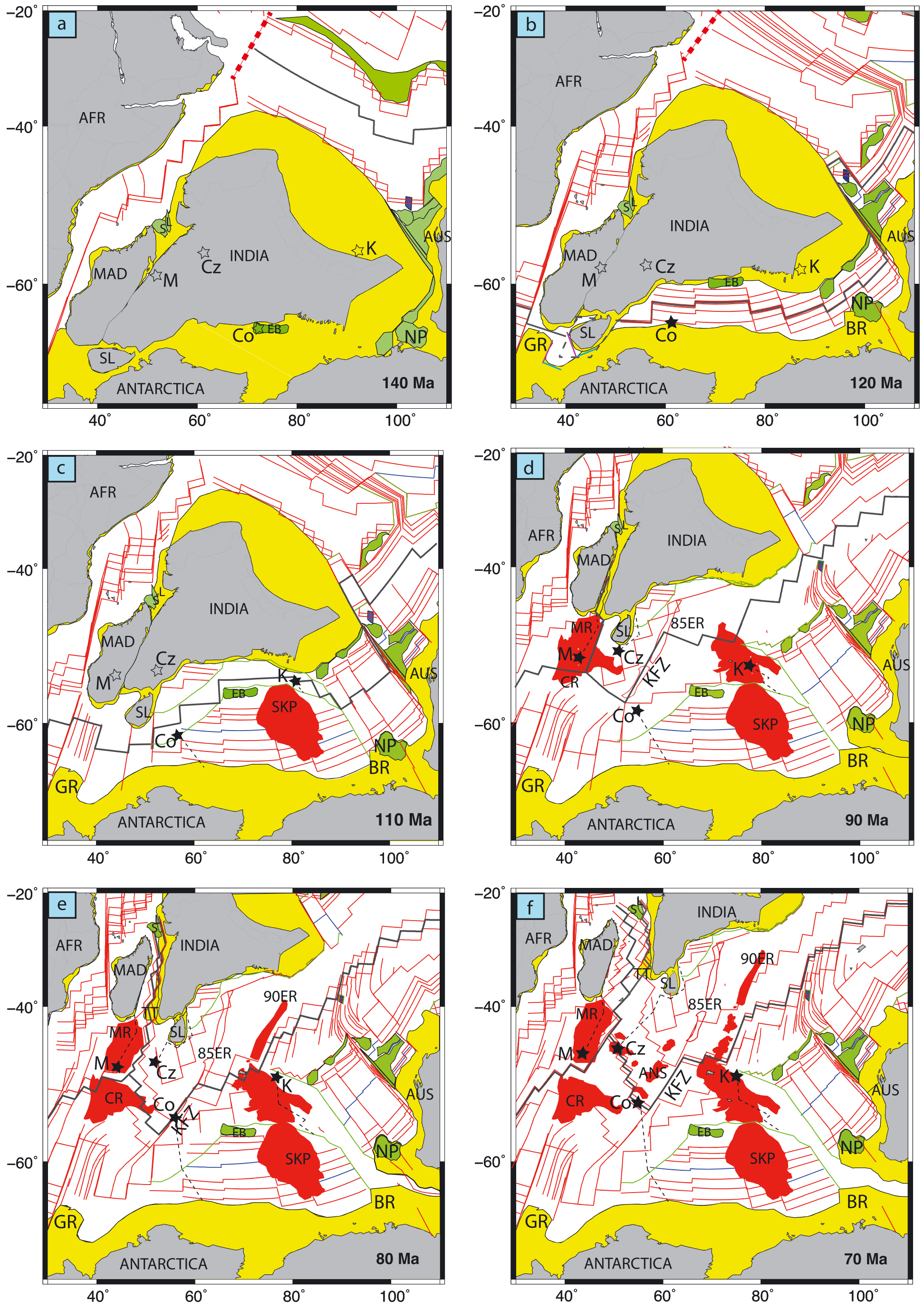

**Figure 9.** Mercator-projected reconstructions of the southern Indian Ocean at (a) 140 Ma, (b) 120 Ma, (c) 110 Ma, (d) 90 Ma, (e) 80 Ma, and (f) 70 Ma, constructed using GPlates exported geometries with Antarctica fixed in present-day coordinates. Showing pseudofaults (light green lines), extinct ridges (light blue lines), COB (thin black line, filled in yellow), continental microfragments (filled in green), isochrons (red lines), East African-Tethyan transform fault (thick red dashed line), spreading centers (thick dark gray lines), and hotspot tracks (thin black dashed lines). Continental material above sea level is outlined in gray, and large igneous provinces are shown in red. Showing the 85°E Ridge (85°ER), 90E Ridge (90ER), Africa (AFR), Australia (AUS), Bruce Rise (BR), Conrad Rise 4000 m isobath (CR), Crozet Hotspot (Cr), Elan Bank (EB), Kerguelen Plateau (KP), Kerguelen Fracture Zone (KFZ), Laxmi Ridge (L), Madagascar (MAD), Madagascar Ridge 3500 m isobath (MR), Naturaliste Plateau (NP), Seychelles (S), Sri Lanka (SL), and Terrace near Trivandrum (TT). Black/hollow stars show the locations of hotspots featured in this study fixed in their present-day locations, including Conrad (Co), Crozet (Cr), Marion (M) and Kerguelen (K).

(<20 km) to the Elan and Enderby COB's, as opposed to the earliest seafloor-spreading anomalies ~50 km from the West Australian COB, for example. If the Elan Bank is underlain by ~14 km of thinned continental crust, and the crustal thickness of East Antarctica is ~35 km [*Block et al.*, 2009], assuming that Elan Bank had an initial crustal thickness similar to that of East Antarctica, it must have been stretched by a factor >2.5, which could help ease our initially tight seafloor spreading/continental overlap between the India, Elan Bank, and Antarctica.

## 7. Greater India Migration

[18] Greater India started migrating from East Gondwana following a spreading reorganization starting several hundred kilometers off northwest of Australia ~136 Ma [*Gibbons et al.*, 2012]. The new spreading ridge progressively unzipped India from northwest Australia to the western Enderby Basin (Figure 9b). This implies an anticlockwise motion for India about a southern pivot, at a stage pole located near Sri Lanka, but culminates in minor (up to 30 km) overlap between India and Madagascar ~120 Ma (Figure 9b) following breakup, which is unavoidable given constraints from the West Australian margin model, WZFZ geometry and position of Madagascar, although it could be eased with an even later onset of spreading in the Enderby Basin. This anticlockwise motion forced the seafloor surrounding NW Greater India to form a transform boundary off East Africa (thick red dashed line, Figure 9a and b), reaching north into the Meso- and NeoTethys, while seafloor spreading between Africa and Antarctica/Madagascar continued until ~120 Ma, providing space for Greater India's motion. The Owen and Chain ridges (Figure 3) could be a remnant of this East African-Tethyan transform fault. Deep sea drilling suggests the Owen Ridge was part of a fracture zone, tilted and uplifted under transpression in the early Miocene from Africa-Arabia rifting [*Weissel et al.*, 1992]. The marine gravity grid highlights the relationship between fracture zones off NE Africa, confirming that the Arabian seafloor spreading occurred after the North Somali and Owen basins formed inboard of Chain and Owen ridges, respectively, causing their separation. Strike-slip motion along the Owen Transform, east of the Owen Ridge, has been underway since the Pliocene [*Fournier et al.*, 2011; *Rodriguez et al.*, 2011], but the Owen Ridge itself may be older because of the age discontinuity between seafloor in the Cenozoic Arabian Basin [*Cande et al.*, 2010] and older Owen Basin. The Error and Sharbithat Ridges, north and south of the North Somali and Owen basins, respectively, are separated via the Sheba Ridge seafloor spreading [*Stein and Cochran*, 1985], and fracture zones to their east appear to link the Owen and Chain ridges. A gabbro dredged from Chain Ridge was dated to a minimum age of ~90 Ma [*Bunce et al.*, 1967], while thermal and gravity modeling of Jurassic (west) versus Cretaceous (east) lithospheric flexure match the geoid step and gravity anomalies [*Cochran*, 1988]. Africa and East Gondwana breakup has been dated to the Kimmeridgian via magnetic anomalies in the Mozambique and Somali basins [e.g., *Konig and Jokat*, 2010].

[19] Seafloor spreading continued to progress southwest, and the Central Enderby margin, conjugate to the Elan Bank, formed from ~129 Ma while the eastern Indian and Antarctic COB's, forming the Enderby margin south of the South Kerguelen Plateau (SKP), may have separated earlier, in the Late Jurassic. Geochemical studies indicate that the SKP contains some continental contamination [*Bénard et al.*, 2010; *Frey et al.*, 2002]. There is no available data to outline the extent, if any, of stretched continental material in the SKP so we do not include it in our reconstructions. If it existed, it would have been located southeast of the Elan Bank and may have measured up to 100 km north-south and 600 km east-west, given the margin geometries/space available according to the *Gibbons et al.* [2012] model at ~130 Ma (Figure 9b), which is similar to the maximum east-west extent of the SKP. If they do both contain continental material, the SKP may have been an extent of the Elan Bank, migrating with India until a ridge jump transferred it to the Antarctica ~115 Ma. The location of our extinct ridge corresponds to the axis of symmetry between the M0 isochrons in the magnetic anomaly profiles and is also visible to a lesser extent in the gravity anomaly profiles (Figure 7).

[20] Our reconstruction accurately reproduces the prominent north to northeast bend in the Enderby fracture zones, such as at the Kerguelen Fracture Zone (KFZ, Figure 1). This bend is attributed to India's plate motion changing from NW to NE, relative to Australia and Antarctica, and is also based on constraints from the Wharton Basin, located ~1500 km offshore West Australia (Figure 2), where the coeval curved fracture zones are located [*Gibbons et al.*, 2012]. The bend in both sets of fracture zones formed from ~100 Ma, as the Indian Ocean underwent a major spreading reorganization, also documented at ~100 Ma [*Müller et al.*, 2000b; *Veevers*, 2000]. The ~100 Ma onset of relative motion between India and Madagascar best replicates the fracture zones in the marine gravity grid, particularly the KFZ and its Indian conjugate, the 85°E Ridge, as India began to migrate north instead of west. *Krishna et al.* [2009] suggest that the KFZ and 85°E Ridge are conjugate features and date their inception to ~100 Ma, which is consistent with our reconstruction.

## 8. India-Madagascar Separation

[21] To match the curved fracture zone trajectories, we initiate dextral-transtensional motion between Madagascar and India following the ~100 Ma reorganization, to culminate in diachronous rifting between Madagascar and India, breaching the south at ~94 Ma and the north ~83.5 Ma. Several plate kinematic models [*Besse and Courtillot*, 1988; *Morgan*, 1981; *Müller et al.*, 1993; *Norton and Sclater*, 1979] date the onset of seafloor spreading between India and Madagascar to chron C34 (83.5 Ma). Seismic stratigraphic studies offshore west coast India do not identify marine sediments earlier than Late Cretaceous-Early Paleocene [*Singh et al.*, 1999]. The extra ~10 million years seafloor spreading between southern Madagascar and India implied by our model may have been incorporated into an as-yet unsampled 200 km-wide terrace-like feature adjacent to the southwest Indian margin. *Yatheesh et al.* [2006] constructed plate reconstruction models to provide an improved fit of the ~200 km-wide terrace-like feature near Trivandrum (Figure 3), SW India, and subsequently dated India-Madagascar separation to 86.5 Ma. The Trivandrum terrace-like feature was identified as block-faulted continental basement [*Rao and Battacharya*,

1975] and proposed a conjugate to the northern Madagascar Ridge [*Dyment*, 1991], specifically between southern Madagascar and the Madagascar Rise (Figure 3). Seismic studies show that the northern section of the Madagascar Ridge (north of 32°) appears structurally complex, yet there are fracture zones penetrating its eastern part [e.g., *Goslin et al.*, 1980].

[22] *Yatheesh et al.* [2006] suggest the Trivandrum terrace-like feature could contain thinned continental crust overprinted by the Marion hotspot but point out that this would cause an overlap if the feature existed before the India-Madagascar separation, obscuring evidence for preceding strike-slip motion. They suggest that the crustal thinning occurred later, under the influence of the Marion hotspot, which our model locates beneath the future location of the terrace from ~112–105 Ma. Our reconstruction at 86.5 Ma fit (Figure 9d and e), being similar to that proposed by *Yatheesh et al.* [2006], could fit the Trivandrum terrace-like feature, but we suggest that it may have formed between ~100–86.5 Ma as southern Madagascar and India began to rift, stretching the continental crust that would have gradually passed over the Marion hotspot, had it existed between ~135–105 Ma. Breakup between India and Madagascar has also been dated to 92–84 Ma by Ar-Ar ages of the rapidly emplaced volcanic rocks and dikes along Madagascar's eastern margin and the U-Pb age of zircons from St Mary Islands off West India [*Storey et al.*, 1995; *Torsvik et al.*, 2000].

[23] The Seychelles Plateau has been identified as a continental fragment [*Besse and Courtillot*, 1988; *Lawver et al.*, 1998]. The Mascarene Basin (Figure 3), between Madagascar and the Seychelles, formed during 83.5–61 Ma, before a ridge jump transferred the Seychelles to the Madagascan-African plate [*Bernard and Munschy*, 2000; *Ganerød et al.*, 2011; *Plummer and Belle*, 1995]. The oldest magnetic anomalies, initially dated ~79 Ma [*Schlich et al.*, 1974], were revised to ~83.5 Ma by anomaly 34 with full-spreading rates ~55 mm/yr [*Bissessur et al.*, 2010; *Norton and Sclater*, 1979]. The oldest anomalies are up to 50 km northeast of and subparallel to the East Madagascar margin [*Bernard and Munschy*, 2000], which suggests that there may have been some transtensional extension or even seafloor spreading, prior to ~83.5 Ma. No anomalies have been identified in the northern half of the basin, by the Amirante Trench and Seychelles Plateau, although the southern half of the basin does contain magnetic anomalies with a conjugate series apparent further east [*Bernard and Munschy*, 2000]. Magnetic anomalies in the northern half of the basin may have been obscured by volcanic activity associated with volcanogenic sediments, the oldest of which have been dated to the Upper Cretaceous/Paleocene [*Schlich et al.*, 1974].

[24] The Laxmi Ridge (Figure 3), located ~300 km offshore West India, has been identified as continental material [*Naini and Talwani*, 1982; *Talwani and Reif*, 1998]. Multibeam swath mapping of the Laxmi Basin, inboard of the Laxmi Ridge, revealed several seamounts overlying a ridge, located subparallel to and roughly midway between the Laxmi Ridge and West Indian margin [*Bhattacharya et al.*, 1994b]. The former study identified relatively flat summits and dendritic drainage patterns, suggesting the seamounts may have been sub-aerially exposed for a time. The elliptical seamounts and ridge were collinear with the extinct spreading center identified from a magnetic anomaly study of the basin, suggesting that it formed from ~83.5–62.5 Ma (anomalies C33-28) with spreading rates that only reached 18 mm/yr for both flanks [*Bhattacharya et al.*, 1994a]. The slowest spreading ridge documented today is the Arctic's magma-starved Gakkel Ridge, with full-spreading rates ~12 mm/yr [*DeMets et al.*, 2010].

[25] *Krishna et al.* [2006] undertook an integrated geophysical study of the Laxmi Basin, finding a highly irregular topography, shallow basement depth (~2 km) with crustal thickness ~14 km, while their magnetic and gravity modeling could match intrusive structures with significant magnetic anomalies, interpreted as seafloors spreading anomalies [*Bhattacharya et al.*, 1994a]. However, the RE-11 profile used by *Krishna et al.* [2006] to match the symmetric seafloor-spreading anomaly profile SK 79-15 of *Bhattacharya et al.* [1994a] was not at the exact same location but rather located ~1° further south. More recent seismic data in the Laxmi basin indicates a crustal thickness of 6–7 km, and basinward (seaward) dipping reflectors were clearly imaged [*Corfield et al.*, 2010].

[26] *Rangarajan* [2006] analyzed gravity and composite magnetic anomaly data offshore West India and identified seafloor-spreading anomalies all along the West Indian COB starting at Chron C34 but with a single-sided set of anomalies C30-33 corresponding to the C33-28 conjugate sequence of *Bhattacharya et al.* [1994a], finding there was no necessity to invoke a ridge jump. If seafloor spreading did isolate the Laxmi continental fragment, a ridge jump or propagation would have been required to transfer it from the Seychelles to Indian plate, leaving a conjugate set of anomalies between it and the Indian margin. We therefore tentatively adopt the seafloor-spreading model of *Bhattacharya et al.* [1994a]. *Rangarajan* [2006] also noted a westerly turn in the magnetic lineations north of 19°N, which we suggest may have been caused by initially oblique seafloor spreading between India and Madagascar, as per our model where seafloor spreading cleaved the margins from SE to NW.

[27] *Minshull et al.* [2008] assessed wide-angle seismic data from a profile across the Gop Basin (Figure 3, also known as the Gop Rift), northwest of the Laxmi Ridge, to delineate offshore igneous bodies associated with the Deccan magmatism, and inferred there were two periods of extension. The first extension period formed the Gop Basin, as characterized by thick oceanic crust and underplated adjacent continental margins, and accompanied Pre-Deccan (75–65.5 Ma) volcanism offshore NW India [*Calves et al.*, 2011]. Geodynamic modeling indicates this took place ~71–66 Ma above a hot (200°C) mantle layer, which incubated the Deccan material, but the thermal anomaly had subsided before the second extension event, between the Seychelles and Laxmi Ridge, ~63 Ma [*Armitage et al.*, 2011]. We suggest that our model can reconcile the initial seafloor spreading offshore west India with the crustal extension further northwest in the Gop Basin because, as oblique dextral-transtensional spreading separated India and Madagascar (possibly via two subparallel close-set spreading ridges, forming the Mascarene and Laxmi basins ~83.5–64 Ma), the intervening Seychelles-Laxmi microplate remained close to the NW Indian margin (Figures 9e and f).

[28] Magnetic data in the Gop Basin suggests that an extinct spreading system exists between the Laxmi Ridge

and the India/Pakistan margin [*Malod et al.*, 1997; *Yatheesh et al.*, 2009]. *Malod et al.* [1997] identified the lineations as C29r-29n (~64.7–63.9 Ma), while *Yatheesh et al.* [2009] found the anomalies could not be assigned a unique interpretation and accordingly ascribed the lineations to either C31r-25r or as C29r-25r (~68.7 or 64.7–56.4 Ma). The latter study determined full seafloor-spreading rates of <12 mm/yr for the C31r-25r model, which is reasonably comparable to the <18 mm/yr full-spreading rates in the Laxmi Basin, although the latter spreading became extinct later, ~62.5 Ma [*Bhattacharya et al.*, 1994a]. The Gop Basin may have been the younger, NW extension of the Laxmi spreading center, where crustal extension preceded seafloor spreading between NW India and the West Somali Basin. More recent magnetic anomaly modeling and Ar-Ar geochronology from the conjugate north Seychelles and Laxmi/Gop margins indicates that spreading along the Carsberg Ridge initiated diachronously, from west to east between ~63.4–62 Ma, following the Deccan Traps emplacement ~65.5 Ma [*Collier et al.*, 2008].

[29] Our pre-breakup fit between India and Madagascar is similar to *Torsvik et al.* [2000], where the southeast tip of India lies ~250 km north of the southern edge of Madagascar (Figure 9c). The south-to-north diachronous breakup between India and Madagascar created a wedge of seafloor inboard from the Laxmi Ridge, narrowing to the north, incorporating the Trivandrum terrace of block-faulted continental basement [*Rao and Battacharya*, 1975; *Yatheesh et al.*, 2006]. The Saya de Malha Bank and Laccadive Plateau (Figure 3, SB and LP, respectively), as potential continental material [*Francis and Shor*, 1966], may also need to be accommodated in our initial fit between the Seychelles/Laxmi microblocks and Trivandrum terrace [*Yatheesh et al.*, 2006], and we hope to tackle this problem using new "deforming" plate tectonic models, which are currently under construction.

[30] If the seafloor-spreading models proposed for the Laxmi [*Bhattacharya et al.*, 1994a] and Mascarene [*Bernard and Munschy*, 2000; *Ganerød et al.*, 2011; *Plummer and Belle*, 1995] basins are correct, then two coeval seafloor-spreading ridges created seafloor offshore West India and East Madagascar in a parallel, three-plate system separating India, Seychelles-Laxmi and Madagascar from at least ~83.5–64 Ma. After this time, the two mid-ocean ridges, located either side of the Seychelles-Laxmi continental fragment, relocated to form one spreading center (the Carlsberg Ridge) to break up the Laxmi and Seychelles microplates, forming the East Arabian Sea. Such coeval, close-set seafloor-spreading ridges exist in the North Fiji Basin, an anomalously hot mature back-arc basin where a pair of subparallel active spreading centers, ~200 km apart, are fuelled by upper mantle convection [*Lagabrielle et al.*, 1997].

## 9. Sri Lanka

[31] Our fit reconstruction for Gondwana places Sri Lanka across the southeastern tips of India and Madagascar, just east of the Gunnerus Ridge (Figure 9a), where their total COB overlap reaches ~50 km between Madagascar and Sri Lanka, ~150 km between Sri Lanka and Antarctica, and ~100 km between India and Madagascar. This is a reasonable match to the juxtaposition presented by a study which suggests that a distinct high-grade, metamorphic mineralization belt (containing gem minerals and graphite), representing a Neo-Proterozoic geosuture linked to the Mozambique Belt, can be traced through southern India, SW Sri Lanka, SE Madagascar, and the Lützow-Holm Bay area, east of the Gunnerus Ridge [*Dissanayake and Chandrajith*, 1999]. Previous Gondwana fit reconstructions have featured Sri Lanka in various positions, mainly based on the best geometrical fit between India, Madagascar, and Antarctica [e.g., *Crawford*, 1974; *Du Toit*, 1937; *Eagles and Konig*, 2008; *Gaina et al.*, 2007; *Smith and Hallam*, 1970]. *Katz* [1978] fitted Sri Lanka onto the southeast tip of India juxtaposing the Sri Lankan and Southern Indian boundary faults separating the Precambrian from the Cretaceous-Tertiary coastal sediments [*Grady*, 1971; *Vitanage*, 1972]. *Kriegsman* [1994] arrived at a similar fit, positioning Sri Lanka by southwest India and the Gunnerus Ridge, according to the respective Late Proterozoic Mozambique and Lutzow-Rayner orogenic belts. *Eagles and Konig* [2008] position Sri Lanka much further east, almost reaching the Elan Bank, but this would require over 500 km of dextral strike-slip to transfer Sri Lanka back to its present-day position, and there is no evidence of such strike-slip motion between India and Sri Lanka. Most reconstructions fit Sri Lanka by the southeast tip of India [e.g., *Acharyya*, 2000], although it has been positioned further south, requiring sinistral then oblique strike-slip to locate it to its present-day location [e.g., *Gaina et al.*, 2007].

[32] Our model cannot match the recently identified CNS age for the seafloor just east of the Gunnerus Ridge [*Jokat et al.*, 2010]. If seafloor spreading here started later than ~124.1 Ma, it would have caused ~200 km of extension between India and Sri Lanka (Figure 4), when combined with the regional tectonic model for India's relative motion to Antarctica [*Gibbons et al.*, 2012]. This would result in subsequent convergence to place Sri Lanka into its present position relative to India, a scenario that can clearly be ruled out. Instead, we apply a Euler rotation to Sri Lanka between ~126 and 116 Ma so that Sri Lanka fully unzipped from India just before seafloor spreading isolated the Enderby Basin ~115 Ma. The coherence of seafloor-spreading magnetic anomalies can be reduced if they formed near over-sedimented spreading ridges [*Levi and Riddihough*, 1986]. We argue this could be applied to the basin east of the Gunnerus Ridge, which was initially proximal to several continental margins, including the strike-slip margin between India and Madagascar, and the post-rift sediments off west Enderby Land reach up to 6–8 km in thickness [*Stagg et al.*, 2004]. The Sri Lankan plate motion is hinged at Jaffna (northernmost Sri Lanka) and is designed to avoid more overlap between Sri Lanka and Antarctia or the West Enderby seafloor (Figure 9b) because India was moving away from Antaractica roughly as fast as Sri Lanka was separating from India.

[33] We also use the marine gravity grid to tentatively identify the bend in the continent-ocean boundary around southeast Sri Lanka to be conjugate to the bend in the continent-ocean boundary southeast of the Gunnerus Ridge. We propose that these shapes formed by extensional (mauve line, Figure 8a) and oblique (navy line, Figure 8a) motion, as Sri Lanka separated from the Gunnerus Ridge at ~126 Ma and then rotated 45° anticlockwise until ~116 Ma (Figure 9b). Our rotations for Sri Lanka avoid gaps and overlaps between

the Sri Lankan and Madagascan COB during sinistral strike-slip motion between India and Madagascar ~130–120 Ma. A reason for Sri Lanka detaching from Antarctica could reflect an attempt of seafloor-spreading corridors to connect between the Enderby Basin and further west of the Gunnerus Ridge, where the Mozambique Basin (Figure 3) and conjugate Riiser-Larsen Sea were forming since Jurassic time [e.g., *Eagles and Konig*, 2008; *Konig and Jokat*, 2010].

[34] In its present-day position, Sri Lanka is offset from the southern Indian margin by the Mannar Basin to the west and by the Cauvery Basin/rift zone to the northeast. Seismic and gravity modeling show that the East Indian margin is composed of six tectonic segments—the Cauvery rift zone, as the southwesternmost segment, formed via orthogonal faulting and is offset from the remainder of the East Indian margin via the Coromondal dextral transfer fault, which runs north to meet another NE-trending orthogonal rift zone at Krishna-Godavari [*Sinha et al*., 2010]. A recent analysis of litho- and tectono-stratigraphy in the Ariyalur outcrop of the Cauvery Basin suggests that the onset of rift-related subsidence occurred during the Barremian-Aptian and that rift-related extension ceased in the Cenomanian or Turonian [*Watkinson et al*., 2007]. Apart from the opening between India and Antarctica, the only time a spreading center was near Sri Lanka was when India, Madagascar, and Antarctica began to separate from ~94 Ma. Spreading between India and Sri Lanka ~94 Ma would entail a rather complicated seafloor-spreading scenario involving a quadruple junction between India, Sri Lanka, Madagascar, and Antarctica. Cenomanian or Turonian subsidence in the Cauvery Basin [*Watkinson et al*., 2007] could have resulted from a second phase of rifting or from a long, slow rifting of Sri Lanka from India, although this is not implied by our model. We propose that the subsidence could have been related to the basin's interaction with the Marion and Crozet hotspots. At ~106 Ma, the Cauvery Basin was proximal to the Marion hotspot (~500 km) and located directly over the Crozet hotspot. By the Cenomanian (Figure 9d), the Cauvery Basin had migrated ~600 and 300 km away from the Marion and Crozet hotspots, respectively, possibly leading to the thermal subsidence.

[35] *Curray* [1984] suggested that Sri Lanka became isolated by a failed rift, where rifting between India and Antarctica initially separated Sri Lanka from India along the Mannar Gulf, the basin immediately west of Sri Lanka (Figure 3). *Desa et al*. [2006] suggest that a ~200 km long NE-trending linear feature between India and Sri Lanka could represent the failed rift (thin, dashed red line, Figure 8b) and that two strong linear gravity lows, one parallel to Indian coast and the other subparallel to Sri Lankan coast, could either represent the transform ridges or the margins of India and Sri Lanka, respectively (thin, dashed black lines, Figure 8b). The Gulf of Mannar is considered the southeastern sub-basin offshore to the Cauvery Basin/rift zone, as horst-grabens in both regions share the similar northeast strike and major sequence boundaries in their stratigraphy [*Rao et al*., 2010]. Seismic data indicate that the Mannar Basin contains Late Jurassic-Early Cretaceous to recent sediments [*Baillie et al*., 2004]. The Mannar sub-basin also contains pre-Albian planktonic foraminifera in sediments on the Sri Lankan side [*Rana et al*., 2008]. This suggests that Upper Jurassic-Lower Cretaceous continental extension or seafloor spreading between India and Antarctica was at least partly responsible for locating Sri Lanka to its present-day position, while the accumulation of oldest sediments may have been a consequence of Africa and East Gondwana separation, which started in the Late Jurassic [e.g., *Konig and Jokat*, 2006]. Intrusives identified within Turonian sediments in the Mannar sub-basin, recently Ar-Ar dated to ~89 Ma [*Rathore et al*., 2007], match well with the age of volcanics off East Madagascar [*Torsvik et al*., 2000], supporting an impact from that event too, although it may not have culminated in more relative motion between India and Sri Lanka. A recent thermochronological study of Sri Lanka's basement rocks identified at least five episodes of thermal overprinting [*Emmel et al*., 2012]. One episode at ~120 Ma coincides with our modeled diachronous rifting between Sri Lanka and Antarctica, another at ~94 Ma has WNW-extensional kinematic indicators and coincides with our modeled Madagascar-India separation, but the NS-oriented extension of the ~144 Ma event appeared in a reconstruction showing seafloor spreading south of Sri Lanka ~134 Ma [*Desa et al*., 2006], with India and Sri Lanka having already separated.

## 10. Conclusions

[36] Consideration of the regional framework is essential to build accurate plate tectonic models. Within a regional Indian Ocean framework, we re-identify the magnetic anomalies off the East Enderby margin as the conjugate series M4/126.7 to M0/120.4 Ma. When Greater India began migrating from Australia-Antarctica at ~136 Ma about a southern pivot near Sri Lanka, it detached from north/east to south/west. Seafloor spreading started in the Enderby Basin at ~126.7 Ma/M4 and progressed westward to Sri Lanka to create a seafloor east of the Gunnerus Ridge from ~126 Ma. However, overlap between Sri Lanka and the Enderby margin, to within ~600 km east of the Gunnerus Ridge, persisted until ~116 Ma as Sri Lanka separated from SE India, from west to east. The spreading ridge east of Sri Lanka then relocated north at ~115 Ma, transferring the Elan Bank and South Kerguelen Plateau to the Antarctic plate. Much of this conjugate magnetic anomaly sequence is now overlain by the South Kerguelen Plateau, which may include continental basement transferred from India to Antarctica, perhaps along with the Elan Bank ~115 Ma.

[37] Our younger opening time for the Enderby Basin resolves the problem of back-and-forth strike-slip motion between Madagascar and India, modeled in other reconstructions. In the absence of magnetic anomaly or other age date for the CNS seafloor, we fix Greater India to Africa until the former is located in a position where a change in its motion allows India to reach its final destination, creating the bending fracture zones in the Wharton and Enderby basins, based on the assumption that the bends are coeval (otherwise the Indian plate would have deformed). To accurately form the bend/curved fracture zones, we identify dextral-transtensional motion between Madagascar and India from ~100 Ma, with their southern margins forming from ~94 Ma, perforating their northern margins by 84 Ma. Such motion, where Greater India pivots anticlockwise about its western edge, forms a tighter bend to its south, as observed in the Enderby Basin, and an

open curve further east, as observed in the Wharton Basin. This scenario fits well with the major spreading reorganization ~100 Ma. This spreading reorganization then caused the conjugate Kerguelen Fracture Zone and a portion of the 85°E Ridge to form.

[38] **Acknowledgments.** The project was supported by ARC grant FL0992245 and an Australia-India Strategic Research Fund grant. We thank Statoil (Norway), the Petroleum Exploration Society of Australia (PESA), and the School of Geosciences at the University of Sydney for support. We also thank Dr Yatheesh Vadakkeyakath from the National Institute of Oceanography (Goa, India) for a review that considerably improved the tectonic model and manuscript. We are grateful to Jerome Dyment, Roi Granot, and Jensen Jacob from IPGP, France, for initial comments on the tectonic model. All figures were made using GMT [*Wessel and Smith*, 1998], with reconstruction geometries extracted from GPlates [*Boyden et al*., 2011]. The model can be viewed in GPlates (http://www.gplates.org/). The reconstruction files (with instructions for use with GPlates) and movie are available from: ftp://ftp.earthbyte.org/papers/Gibbons_etal_Indian_Ocean/

## References

Acharyya, S. K. (2000), Break up of Australia-India-Madagascar block, opening of the Indian Ocean and continental accretion in Southeast Asia with special reference to the characteristics of the peri-Indian collision zones, *Gondwana Res.*, *3*(4), 425–443.

Armitage, J. J., J. S. Collier, T. A. Minshull, and T. J. Henstock (2011), Thin oceanic crust and flood basalts: India-Seychelles breakup, *Geochem. Geophys. Geosyst.*, *12*. doi:10.1029/2010GC003316.

Baillie, P. W., P. M. Barber, I. Deighton, P. A. Gilleran, W. A. Jindasa, and R. D. Shaw (2004), *Petroleum Systems of the Deepwater Mannar Basin*, pp. 533–545, Indonesian Petroleum Association, Offshore Sri Lanka.

Bénard, F., J. P. Callot, R. Vially, J. Schmitz, W. Roest, M. Patriat, B. Loubrieu, and E. Team (2010), The Kerguelen plateau: Records from a long-living/composite microcontinent, *Mar Petrol Geol*, *27*(3), 633–649.

Bernard, A., and M. Munschy (2000), Were the Mascarene and Laxmi Basins (western Indian Ocean) formed at the same spreading centre? *C R Acad. Sci. II A*, *330*(11), 777–783.

Besse, J., and V. Courtillot (1988), Paleogeographic maps of the continents bordering the Indian Ocean since the Early Jurassic, *J. Geophys. Res.*, *93* (B10), 11791–11808.

Bhattacharya, G. C., A. K. Chaubey, G. P. S. Murty, K. Srinivas, K. Sarma, V. Subrahmanyam, and K. S. Krishna (1994a), Evidence for seafloor spreading in the Laxmi Basin, Northeastern Arabian Sea, *Earth Planet. Sci. Lett.*, *125*(1–4), 211–220.

Bhattacharya, G. C., G. P. S. Murty, K. Srinivas, A. K. Chaubey, T. Sudhakar, and R. R. Nair (1994b), Swath bathymetric investigation of the seamounts located in the Laxmi Basin, eastern Arabian Sea, *Mar. Geodesy*, *17*, 169–182.

Bissessur, D., J. Dyment, C. Deplus, and V. Yatheesh (2010), Evolution of the Mascarene Basin with respect to the Reunion hotspot inception in the Deccan, EGU General Assembly, 2010, Geophysical Research Abstracts, 12.

Block, A. E., R. E. Bell, and M. Studinger (2009), Antarctic crustal thickness from satellite gravity: Implications for the Transantarctic and Gamburtsev Subglacial Mountains, *Earth Planet. Sci. Lett.*, *288*(1–2), 194–203.

Borissova, I., B. Bradshaw, C. Nicholson, D. Payne, and H. Struckmeyer (2010), Mentelle Basin—tectonic evolution controlled by of the combined extensional history of the Southwestern and Southern Australian margins: ASEG—2010.

Borissova, I., M. F. Coffin, P. Charvis, and S. Operto (2003), Structure and development of a microcontinent: Elan Bank in the southern Indian Ocean, *Geochem. Geophys. Geosyst.*, *4*, doi:10.1029/2003GC000535.

Boyden, J. A., R. D. Müller, M. Gurnis, T. H. Torsvik, J. A. Clark, M. Turner, H. Ivey-Law, R. J. Watson, and J. S. Cannon (2011), *Next-generation Plate-tectonic Reconstructions Using GPlates: Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences*, edited by G. R. Keller, and C. Baru, pp. 95–115, Cambridge University Press, Cambridge, U.K.

Bunce, E. T., M. G. Langseth, R. L. Chase, and M. Ewing (1967), Structure of western Somali Basin, *J. Geophys. Res.*, *72*(10), 2547-&.

Calves, G., A. M. Schwab, M. Huuse, P. D. Clift, C. Gaina, D. Jolley, A. R. Tabrez, and A. Inam (2011), Seismic volcanostratigraphy of the western Indian rifted margin: The pre-Deccan igneous province, *J. Geophys. Res.-Solid Earth*, *116*.

Cande, S. C., P. Patriat, and J. Dyment (2010), Motion between the Indian, Antarctic and African plates in the early Cenozoic, *Geophys. J. Int.*, *183*(1), 127–149.

Cochran, J. R. (1988), The Somali Basin, Chain Ridge and the origin of the northern Somali Basin gravity and geoid low, *J. Geophys. Res.*, *93*(B10), 11985–12008.

Coffin, M. F., and O. Eldholm (1994), Large igneous provinces: Crustal structure, dimensions, and external consequences, *Rev. Geophys.*, *32*(1/February), 1–36.

Coffin, M. F., M. S. Pringle, R. A. Duncan, T. P. Gladczenko, M. Storey, R. D. Muller, and L. A. Gahagan (2002), Kerguelen hotspot magma output since 130 Ma, *J. Petrol.*, *43*(7), 1121–1139.

Collier, J. S., V. Sansom, O. Ishizuka, R. N. Taylor, T. A. Minshull, and R. B. Whitmarsh (2008), Age of Seychelles-India break-up, *Earth Planet. Sci. Lett.*, *272*(1–2), 264–277.

Corfield, R. I., S. Carmichael, J. Bennett, S. Akhter, M. Fatimi, and T. Craig (2010), Variability in the crustal structure of the West Indian continental margin in the Northern Arabian Sea, *Petroleum Geosc.*, *16*(3), 257–265.

Crawford, A. R. (1974), Indo-Antarctica, Gondwanaland, and the distortion of a granulite belt, *Tectonophys.*, *22*, 141–157.

Curray, J. R. (1984), Sri Lanka: Is it a mid-plate platelet?, *J. National Aqua. Resources Agency*, *31*, 30–50.

DeMets, C., R. G. Gordon, and D. F. Argus (2010), Geologically current plate motions, *Geophys. J. Int.*, *181*(1), 1–80.

Desa, M., M. V. Ramana, and T. Ramprasad (2006), Seafloor spreading magnetic anomalies south off Sri Lanka, *Mar. Geology*, *229*(3–4), 227–240.

Dissanayake, C. B., and R. Chandrajith (1999), Sri Lanka-Madagascar Gondwana linkage: Evidence for a Pan-African mineral belt, *J. Geology*, *107*(2), 223–235.

Du Toit, A. L. (1937), Our wandering continents, *in* Oliver, and Boyd, eds., Volume Edinburgh.

Duncan, R. A. (2002), A time frame for construction of the Kerguelen Plateau and Broken Ridge, *J. Petrol.*, *43*(7), 1109–1119.

Dyment, J. (1991), Structure et evolution de la lithosphere oceanique dans l'ocean Indien: apport des donnees magnetiques, Doctorate Thesis, Universite Louis Pasteur.

Eagles, G., and M. Konig (2008), A model of plate kinematics in Gondwana breakup, *Geophys. J. Int.*, *173*(2), 703–717.

Emmel, B., F. Lisker, and T. Hewawasam (2012), Thermochronological dating of brittle structures in basement rocks: A case study from the onshore passive margin of SW Sri Lanka, *J. Geophys. Res.*, *117*, doi:10.1029/2012JB009136.

Fournier, M., N. Chamot-Rooke, M. Rodriguez, P. Huchon, C. Petit, M. O. Beslier, and S. Zaragosi (2011), Owen Fracture Zone: The Arabia-India plate boundary unveiled, *Earth Planet. Sci. Lett.*, *302*(1–2), 247–252.

Francis, T., and G. Shor (1966), Seismic refraction measurements in the northwest Indian Ocean, *J. Geophys. Res.*, *71*, 427–449.

Frey, F. A., N. J. McNaughton, D. R. Nelson, J. R. de Laeter, and R. Duncan (1996), Petrogenesis of the Bunbury Basalts, Western Australia: Interaction between the Kerguelen Plume and Gondwana lithosphere?, *Earth Planet. Sci. Lett.*, *144*, 163–183.

Frey, F. A., D. Weis, A. Y. Borisova, and G. Xu (2002), Involvement of continental crust in the formation of the Cretaceous Kerguelen Plateau: New perspectives from ODP Leg 120 sites, *J. Petrol.*, *43*(7), 1207–1239.

Gaina, C., R. D. Müller, B. Brown, and T. Ishihara (2003), Microcontinent formation around Australia, *in Evolution and Dynamics of the Australian Plate*, edited by R. R., Hills and R. D. Müller, pp. 405–416, Geological Society of Australia Special Publication 22 and Geological Society of America Special Paper 372.

Gaina, C., R. D. Müller, B. Brown, T. Ishihara, and S. Ivanov (2007), Breakup and early seafloor spreading between India and Antarctica, *J Geophys. International*, *170*(1), 151–170.

Ganerød, M., T. Torsvik, D. J. J. van Hinsbergen, C. Gaina, F. Corfu, S. Werner, T. M. Owen-Smith, L. D. Ashwal, S. J. Webb, and B. W. H. Henriks (2011), Palaeoposition of the Seychelles microcontinent in relation to the Deccan Traps and the Plume Generation Zone in Late Cretaceous-Early Palaeogene time, *Geol. Soc., London, Special Publ.*, *357*, 229–252.

Gibbons, A. D., U. Barckhausen, van den Bogaard, P., K. Hoernle, R. Werner, J. M. Whittaker, and R. D. Muller (2012), Constraining the Jurassic extent of Greater India: Tectonic evolution of the West Australian margin, *Geochem. Geophys. Geosyst.*, *13*. doi:10.1029/2011GC003919.

Goslin, J., J. Segoufin, R. Schlich, and R. L. Fisher (1980), Submarine topography and shallow structure of the Madagascar Ridge, western Indian Ocean, *Geol. Soc. Amer. Bull.*, *91*, 741–753.

Gradstein, F. M., F. P. Agterberg, J. G. Ogg, S. Hardenbol, P. Vanveen, J. Thierry, and Z. H. Huang (1994), A Mesozoic time scale, *J. Geophys. Res.-Solid Earth*, *99*(B12), 24051–24074.

Grady, J. C. (1971), Deep main faults of South India, *J. Geol. Soc. India*, *12*, 56–62.

Halpin, J. A., A. J. Crawford, N. G. Direen, M. F. Coffin, C. J. Forbes, and I. Borissova (2008), Naturaliste Plateau, offshore Western Australia: A submarine window into Gondwana assembly and breakup, *Geology*, *36*(10), 807–810.

Johnson, B. D., C. M. Powell, and J. J. Veevers (1980), Early spreading history of the Indian Ocean between India and Australia, *Earth Planet. Sci. Lett.*, *47*, 131–143.

Jokat, W., Y. Nogi, and V. Leinweber (2010), New aeromagnetic data from the western Enderby Basin and consequences for Antarctic-India break-up, *Geophys. Res. Lett.*, *37*. doi:10.1029/2010GL045117.

Katz, M. B. (1978), Sri Lanka in Gondwanaland and the evolution of the Indian Ocean, *Geol. Magazine*, *115*(4), 237–244.

Kent, R. W., M. S. Pringle, R. D. Müller, A. D. Saunders, and N. C. Ghose (2002), 40Ar/39Ar geochronology of the Rajmahal basalts, India, and their relationship to the Kerguelen Plateau, *J. Petrol.*, *43*, 1141–1153.

Konig, M., and W. Jokat (2006), The Mesozoic breakup of the Weddell Sea, *J. Geophys. Res.-Solid Earth*, *111*(B12), 12102–12102.

Konig, M., and W. Jokat (2010), Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data, *Geophys. J. Int.*, *180*(1), 158–180.

Kriegsman, L. M. (1994), The Pan-African event in East Antarctica: A view from Sri Lanka and the Mozambique Belt, *Precambrian Res.*, *75*(3–4), 263–277.

Krishna, K. S., L. Michael, R. Bhattacharyya, and T. J. Majumdar (2009), Geoid and gravity anomaly data of conjugate regions of Bay of Bengal and Enderby Basin: New constraints on breakup and early spreading history between India and Antarctica, *J. Geophys. Res.*, *114*.

Krishna, K. S., D. G. Rao, and D. Sar (2006), Nature of the crust in the Laxmi Basin (14 degrees-20 degrees N), western continental margin of India-art. no. TC1006, *Tectonics*, *25*(1), C1006–C1006.

Lagabrielle, Y., Goslin, J., Martin, H., Thirot, J. L., and Auzende, J. M. (1997), Multiple active spreading centres in the hot North Fiji Basin (Southwest Pacific): A possible model for Archaean seafloor dynamics?, *Earth Planet. Sci. Lett.*, *149*(1–4), 1–13.

Lawver, L. A., L. M. Gahagan, and I. W. D. Dalziel (1998), A tight fit—Early Mesozoic Gondwana, a plate reconstruction perspective, *Memoirs National Inst. Polar Res., Special Issue*, *53*, 214–229.

Levi, S., and R. Riddihough (1986), Why are marine magnetic-anomalies suppressed over sedimented spreading centers, *Geology*, *14*(8), 651–654.

Li, Z. X., I. Metcalfe, and C. M. Powell (1996), Breakup of Rodinia and Gondwanaland and assembly of Asia—Introduction, *Aust. J. Earth Sci.*, *43*(6), p. 591–592.

Malod, J. A., L. Droz, B. M. Kemal, and P. Patriat (1997). Early spreading and continental to oceanic basement transition beneath the Indus deep-sea fan: Northeastern Arabian Sea, *Mar. Geology*, *141*(1–4), 221–235.

Mendel, V., M. Munschy, and D. Sauter (2005), MODMAG, a MATLAB program to model marine magnetic anomalies, *Comput. Geosci.*, *31*(5), 589–597.

Mihut, D. (1998), Breakup and Mesozoic seafloor spreading between the Australian and Indian plates, Ph.D.]: The University of Sydney, 223 p.

Minshull, T. A., C. I. Lane, J. Collier, and R. B. Whitmarsh (2008), The relationship between rifting and magmatism in the northeastern Arabian Sea, *Nat. Geosci.*, *1*, 463–467.

Morgan, W. J. (1981), Hotspot tracks and the opening of the Atlantic and Indian Oceans, in *The Oceanic lithosphere, Volume 7*, edited by C. Emiliani, pp. 443–487, Wiley, New York, N.Y.

Müller, R. D., C. Gaina, and S. Clarke (2000a), Seafloor spreading around Australia, in *Billion-Year Earth History of Australia and Neighbours in Gondwanaland-BYEHA*, edited by J. Veevers, pp. 18–28, GEMOC Press, Sydney.

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

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

Naini, B. R., and M. Talwani (1982), Structural framework and the evolutionary history of the continental margin of Western India, in *Studies in Continental Margin Geology*, edited by J. S. Waktins, and C. L. Drake, pp. 167–191, AAPG, Tulsa, OK.

Norton, I. O., and J. G. Sclater (1979), A model for the evolution of the Indian Ocean and the breakup of Gondwanaland, *J. Geophys. Res.*, *84*, 6803–6830.

Plummer, P. S., and E. R. Belle (1995) Mesozoic tectono-stratigraphic evolution of the Seychelles microcontinent, in *Selected Topics Relating to the Indian Ocean Basins and Margins., Volume 96*, edited by T. A. Davies, M. R. Coffin, and S. W. Wise, pp. 73–91, Elsevier, Amsterdam, Netherlands.

Powell, C. M., S. R. Roots, and J. J. Veevers (1988), Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean, *Tectonophys.*, *155*, 261–283.

Ramana, M. V., T. Ramprasad, and M. Desa (2001), Seafloor spreading magnetic anomalies in the Enderby Basin, East Antarctica, *Earth Planet. Sci. Lett.*, *191*(3–4), 241–255.

Rana, M. S., Chakraborty, C., Sharma, R., and Giridhar, M. (2008), Mannar volcanics—Implications for Madagascar breakup, 7th International Conference and Exposition on Petroleum Geophysics, Hyderabad 2008, p. 358.

Rangarajan, S. (2006), Did Madagascar and Seychelles separate simultaneously from India? 6th International Conference & Exposition on Petroleum Geophysics "Kolkata 2006".

Rao, M. V., L. Chidambaram, D. Bharktya, and M. Janardhanan (2010), Integrated analysis of Late Albian to Middle Miocene sediments in Gulf of Mannar shallow waters of the Cauvery Basin, India, A Sequence Stratigraphic Approach: 8th Biennial International Conference & Exposition on Petroleum Geophysics, v. 304–403.

Rao, T. C. S., and G. C. Battacharya (1975), Seismic profiler and magnetic studies off Quilon, south-west India, *Indian J. Mar. Sci.*, *4*, 110–114.

Rathore, S. S., M. Bansal, A. R. Vijan, and P. S. Pangtey (2007), Ar-Ar dating of intrusives from Gulf of Mannar sub-basin of Cauvery Basin.: KDMIPE, ONGC Unpub. Report, p. 17.

Richards, M. A., R. A. Duncan, and V. Courtillot (1989), Flood basalt and hotspot tracks—plume heads and tails, *Science*, *246*, 103–107.

Rodriguez, M., M. Fournier, N. Chamot-Rooke, P. Huchon, J. Bourget, M. Sorbier, S. Zaragosi, and A. Rabaute (2011), Neotectonics of the Owen Fracture Zone (NW Indian Ocean): Structural evolution of an oceanic strike-slip plate boundary, *Geochem. Geophys. Geosyst.*, *12*. doi:10.1029/2011GC003731.

Royer, J.-Y., and M. F. Coffin (1992), Jurassic to Eocene plate tectonic reconstructions in the Kerguelen Plateau region, *in Proceedings of the Ocean Drilling Program, Scientific Results, Volume 120*, edited by R. Schlich, S. W. Wise, et al., pp. 917–930, College Station, TX, Ocean Drilling Program, Texas A&M University.

Sandwell, D. T., and W. H. F. Smith (2009), Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate, *J. Geophys. Res.-Solid Earth*, *114*, doi:10.1029/2008JB006008.

Sayers, J., P. A. Symonds, N. G. Direen, and G. Bernadel (2001), Nature of the continent-ocean transition on the non-volcanic rifted margin in the central Great Australian Bight, *in Non-volcanic Rifting of Continental Margins: A Comparison of Evidence from Land and Sea*, edited by R. C. L. Wilson, R. B. Whitmarsh, B. Taylor, and N. Froitzheim, pp. 51–76, Volume Special Publication, Geological Society of London.

Schlich, R., E. S. W. Simpson, and T. L. Vallier (1974), Introduction, *in Initial Reports of the Deep Sea Drilling Program, Volume 25*, edited by R. Schlich, E. S. W. Simpson, et al., pp. 5–24U.S. Government Printing Office, Washington D.C.

Singh, R. P., S. Rawat, and K. Candra (1999), Hydrocarbon potential in Indian deep waters, *Exploration Geophys.*, *30*, 83–95.

Sinha, S. T., M. Nemcok, M. Choudhuri, A. A. Misra, S. P. Sharma, N. Sinha, and S. Venkatraman (2010), The crustal architecture and continental break up of East India passive margin: An integrated study of deep reflection seismic interpretation and gravity modeling: Science and discovery article #40611, v. Adapted from an oral presentation at AAPG Annual Convention and Exhibition, New Orleans, Louisiana, USA, April 11–14, 2010.

Smith, A. G., and A. Hallam (1970), The fit of the southern continents, *Nature*, *225*, 139–144.

Stagg, H. M. J., J. B. Colwel, N. G. Direen, P. E. O'Brien, G. Bernardel, I. Borissova, B. J. Brown, and T. Ishirara (2004), Geology of the continental margin of Enderby and Mac. Robertson Lands, East Antarctica: Insights from a regional data set, *Mar. Geophys. Res.*, *25*(3–4), 183–219.

Stein, C. A., and J. R. Cochran (1985), The transition between the Sheba Ridge and Owen Basin—Rifting of old oceanic lithosphere, *Geophys. J. R. Astronomical Soc.*, *81*(1), 47–74.

Storey, M., J. J. Mahoney, A. D. Saunders, R. A. Duncan, S. P. Kelley, and M. F. Coffin (1995), Timing of hot spot-related volcanism and the breakup of Madagascar and India, *Science*, *267*, 852–855.

Talwani, M., and C. Reif (1998), Laxmi Ridge—A continental sliver in the Arabian Sea, *Mar. Geophys. Res.*, *20*(4), 259–271.

Tikku, A. A., and S. C. Cande (1999), The oldest magnetic anomalies in the Australian-Antarctic Basin: Are they isochrons? *J. Gephys. Res.*, *104*, 661–677.

Torsvik, T. H., R. D. Tucker, L. D. Ashwal, L. M. Carter, B. Jamtveit, K. T. Vidyadharan, and P. Venkataramana (2000), Late Cretaceous India-Madagascar fit and timing of break-up related magmatism, *Terra Nova*, *12*(5), 220–224.

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*(1), 47–50.

Vitanage, P. W. (1972), Post Precambrian uplifts and regional neotectonic movements in Ceylon, 24th Int. Geol. Congress, Section 3, p. 642–652.

Watkins, N. D., B. M. Gunn, J. Nougier, and A. K. Baksi (1974), Kerguelen: Continental fragment or oceanic island, *Geol. Soc. Am. Bull.*, *85*, 201–212.

Watkinson, M. P., M. B. Hart, and A. Joshi (2007), Cretaceous tectonostratigraphy and the development of the Cauvery Basin, southeast India, *Petroleum Geosci.*, *13*, 181–191.

Weissel, J. K., V. A. Childers, and G. D. Karner (1992), Extensional and compressional deformation of the lithosphere in the light of ODP drilling in the Indian Ocean, in *Synthesis of Results From Scientific Drilling in the Indian Ocean, Geophys. Monogr. Ser*., vol. 70, edited by R. A. Duncan, et al., pp. 127–156, AGU, Washington, D. C., doi:10.1029/GM070p0127.

Wessel, P., and W. H. F. Smith (1998), New, improved version of Generic Mapping Tools released, *EOS Transact., AGU*, (79), 579.

Whittaker, J. M., R. D. Muller, G. Leitchenkov, H. Stagg, M. Sdrolias, C. Gaina, and A. Goncharov (2007), Major Australian-Antarctic plate reorganization at Hawaiian-Emperor bend time, *Science*, *318*(5847), 83–86.

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

Yatheesh, V., G. C. Bhattacharya, and J. Dyment (2009), Early oceanic opening off Western India-Pakistan margin: The Gop Basin revisited, *Earth Planet. Sci. Lett.*, *284*(3–4), 399–408.

Yatheesh, V., G. C. Bhattacharya, and K. Mahender (2006), The terrace like feature in the mid-continental slope region off Trivandrum and a plausible model for India-Madagascar juxtaposition in immediate pre-drift scenario, *Gondwana Res.*, *10*( 1–2), 179–185.