Chapter 2 - A regional tectonic model for the Enderby Basin, East Antarctica, suggests a later breakup between India and Antarctica but an earlier breakup for India and Madagascar
ABSTRACT

Before East Gondwana broke up, the Enderby Basin, off East Antarctica, was the southward continuation of the ocean basin between the West Australia and Greater India. We link the spreading corridors of the Enderby Basin and West Australian abyssal plains, using rigorous regional plate tectonic constraints. These include the minimisation of overlap/compression between Madagascar and India, and between Greater India and Australia along the Wallaby-Zenith Fracture zone, off West Australia. We integrate magnetic and gravity anomaly data from the Enderby Basin within a regional Indian Ocean plate kinematic framework to identify a conjugate series of eastwest-trending magnetic anomalies, M4 to M0 (~126.7-120.4 Ma). The spreading that rifted Greater India away from Australia-Antarctica progressed from north to south, starting ~136 Ma northwest of Australia, and reaching the southern tip of India at ~126 Ma. Seafloor spreading in the Enderby Basin was abandoned at ~115 Ma, when the spreading ridge relocated to the north, transferring the Elan Bank and the continental portions of the South Kerguelen Plateau to the Antarctic plate. Our revised plate kinematic model for the Enderby Basin, including a later onset of opening, helps resolve the problem of successive two-way strike-slip motion between Madagascar and India, inherent in previously published reconstructions. Our reconstructions suggest that seafloor spreading between India and Madagascar progressed from south to north from 94-84 Ma (previous studies date this separation to a maximum of ~91 Ma). This Indian motion is essential to replicate the coeval curved fracture zones of the Wharton Basin, and the West Enderby Basin (ours is the first study to accurately model them). We model the onset of these fracture zones bends at ~98 Ma, as Greater India gradually began to unzip
from Madagascar, initially via slow right-lateral transtensional rifting. This is a good match to the well-documented 100 Ma seafloor spreading reorganisation. The 85°E Ridge and Kerguelen Fracture Zone formed as conjugate flanks of a ‘leaky’ transform fault following the ~98 Ma spreading reorganisation. Our model also identifies the Afanasy Nikitin Seamounts as products of the Conrad Rise hotspot following ~80 Ma.

**INTRODUCTION**

East Gondwana, comprising India, Antarctica, Australia, Madagascar, the Seychelles and other micro-continental blocks, separated from Africa in the Mid Jurassic (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.

The migration of Greater India away from East Gondwana, created the abyssal plains offshore East Antarctica (Fig. 2.1) and West Australia (Fig. 2.2), which was a single margin. Relative motion between Madagascar and Africa around this time also created the Somali basin yet no plate tectonic reconstructions have been published that incorporate all available potential field constraints from the abyssal plains created during this early dispersal. This has left various unresolved issues, including successive left- and right-lateral strike-slip motion between Madagascar and India inherent in many
reconstructions (e.g. Gaina et al., 2007; Ramana et al., 2001), and magnetic anomaly picks that suggest different motions for Greater India against West Australia and East Antarctica, which were a continuous margin (e.g. Williams et al., 2011). Published regional plate models were also unable to accurately reproduce the sharp bend in the Kerguelen and Wharton Basin fracture zones off Antarctica and Australia, respectively (Acharyya, 2000; Besse and Courtillot, 1988; Norton and Sclater, 1979), or account for the geometry of the enigmatic 85-East Ridge off the East Indian coast (85°E Ridge, Fig 2.3), and confirm the source of the Afanasy Nikitin Seamounts further south (ANS, Fig. 2.3), all of which are clearly visible in the 1-minute satellite free-air gravity (Sandwell and Smith, 2009). Fitting Sri Lanka into the pre-breakup configuration has also proven difficult (e.g. Eagles and Konig, 2008; Lawver et al., 1998).

The Enderby Basin (Fig. 2.1) retains vital information to constrain the early motion of India, but no study had yet combined the seafloor spreading record in the Enderby and Perth basins offshore East Antarctica and southwest Australia, respectively. Enderby Basin investigations suffer from limited data with regards to interpreting seafloor-spreading anomalies and the older fracture zones. Volcanic output from the Kerguelen Plume masks nearly half the basin while the Cretaceous Normal Superchron (CNS), which commenced soon after opening, restricts the use of seafloor spreading anomalies.
**Figure 2.1.** The Sandwell and Smith (2009) 1-degree satellite free-air derived gravity 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 is outlined in red. Black stars indicate ODP leg 183 sites 1137 (Elan Bank) and 1136 (South Kerguelen Plateau), with minimum ages indicated.
Figure 2.2. The Sandwell and Smith (2009) 1-degree satellite free-air derived gravity 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.

An accurate model of East Gondwana breakup must satisfy geophysical constraints from all abyssal plains involved. A tectonic model for the relative motion between
Greater India and Australia (Gibbons et al., submitted) incorporates potential data from all the abyssal plains along the West Australian margin. Here we construct a revised motion history for Greater India, which is compatible with data in the Enderby Basin, which was the early continuation of the West Australian abyssal plains and also records Greater India’s early motion history.

**STUDY AREA AND PREVIOUS WORK**

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 (Fig. 2.1). The basin contains several northwest-trending fracture zones originating from the Antarctic margin. Some terminate abruptly at the Kerguelen Fracture Zone (KFZ, Fig. 2.1), 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. Running northwest 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, Fig. 2.1).

The Kerguelen Plateau (Fig. 2.1), 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, and the 132 Ma Bunbury Basalts of southwest Australia (Frey et al., 1996a), 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 LIP (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 concluded that at least the southern portion of the Kerguelen Plateau is underlain by stretched continental crust (Bénard et al., 2010).

The Elan Bank (Fig. 2.1) is a promontory jutting out west from the tip of the South Kerguelen Plateau. ODP and seismic data indicate it is a micro-continental fragment, underlying the Kerguelen volcanic carapace (Borissova et al., 2003). The Elan Bank rifted from Antarctica as part of India before being transferred to the Antarctic plate during a northward ridge jump, which left a conjugate set of seafloor spreading anomalies reflected about an extinct ridge, which was dated to ~124.1 Ma/M2 (Gaina et al., 2007).

Magnetic anomalies in the Enderby Basin have previously been identified as a single flank formed from 134 Ma/M11 to 120.4 Ma/M0, forming at a half-spreading rate of 6.5 to 2.8 cm/yr (Ramana et al., 2001). These were a good match to anomalies identified by the same study in the Bay of Bengal, conjugate to the Enderby Basin, but this reconstruction did not consider constraints from beyond the Antarctic and Indian margins, or include Madagascar. Another study identified a conjugate set of Enderby spreading anomalies 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, implied that Elan Bank was a micro-continent and was transferred to the Antarctic plate ~120.4 Ma via a ridge jump. When coupled with a model for the Somali Basin that featured seafloor spreading until anomaly 120.4 Ma/M0 (Cochran, 1988;
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 disparity between magnetic anomaly interpretations in the Enderby and Perth basins. New aeromagnetic data from east of Gunnerus Ridge 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 has been cited as a full-fit location of Sri Lanka between India and Antarctica prior to breakup (e.g. Lawver et al., 1998; Powell et al., 1988).

We tested the existing models for the Enderby Basin against a recent, regional model for the West Australian margin (Gibbons et al., submitted). The model of Jokat et al. (2010) results in ~200 km of separation between Sri Lanka and India between ~120.4-126 Ma (Fig. 2.3). Sri Lanka would have had to close this gap to arrive at its present-day location relative to India, yet there is no evidence of compression or a subduction zone between them. The Enderby model of Gaina et al. (2007) causes a gap of over 300 km in the Perth abyssal plain (for the same magnetic anomalies) and a ~130 km overlap between Madagascar and India at ~125 Ma (Fig. 2.4). Similar effects result using the model of Ramana et al. (2001). These mismatches necessitate a revision the marine magnetic anomaly identifications in the Enderby Basin.
**Figure 2.3.** 120 Ma reconstruction showing that Sri Lanka’s margin would be ~200 km from Greater India, when combining our West Australian margin model (Gibbons et al., submitted) 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 (SLP, in hollow green), which is not evident. Coastlines are filled in grey, continent-ocean
boundary is filled in yellow and thin red lines indicate location of seafloor spreading magnetic anomalies.

Figure 2.4. 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., submitted). 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 grey, 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 micro-blocks shown that were transferred from Greater India to Gondwana are shown in green.

The western Bay of Bengal, near Sri Lanka (Fig. 2.5), is conjugate seafloor to the western Enderby Basin, but it is mostly obscured by the thick sediments of the Bengal Fan, posing problems for reconstructing the kinematics of these margins. Seafloor spreading magnetic anomalies have been identified off India’s east coast as a single flank of M11 to M0 (Ramana et al., 2001), who also identified the same conjugate anomalies in the Enderby Basin. South of Sri Lanka, seafloor spreading anomalies M11 to M0 were identified (Desa et al., 2006), but their conjugate seafloor would be located just east of the Gunnerus Ridge (Fig. 2.1). This interpretation is incompatible with the most recent interpretations of the western Enderby Basin (Jokat et al., 2010).

Southeast-trending fracture zones are discernible in the marine gravity grid within ~500 km of Sri Lanka, where Bengal Fan sediments are thinner. The fracture zones terminate abruptly along a ridge branching southwest from the 85°E Ridge, leading to the Afanasy Nikitin Seamounts (ANS, Fig. 2.5). Both the 85°E Ridge and the ANS have been linked to the Crozet hotspot, (Curray and Munasinghe, 1991). However, it is unlikely that the Crozet hotspot produced the ANS since isotopic compositions of lavas from the Afanasy-Nikitin Rise are sufficiently differentiated and contain significant amounts of a non-plume source while lavas from the Crozet Archipelago are less varied and similar to shield lavas of the Réunion hotspot (Mahoney et al., 1996).
The Conrad Rise hotspot has been proposed a more likely candidate for the ANS and 85°E Ridge, given relative plate motions over hotspots (Müller et al., 1993), but this needs testing in a regional plate tectonic model. Another major tectonic feature offshore
India is the 90°E Ridge (Fig. 2.5), which is the surface expression of the Kerguelen hotspot while it interacted with the Indo-Antarctic spreading ridge from ~100 to 35 Ma (Müller et al., 1993). The 90°E Ridge likely formed at the western edge of the Kerguelen Plateau but on the Australian plate, which migrated north from Antarctica, as the Kerguelen hotspot remained on the Antarctic side of the Southeast Indian Ridge (Bénard et al., 2010).

**METHODOLOGY AND DATA**

We formulate a new plate tectonic model for the breakup and early spreading history between India and Antarctica using constraints from oceanic crust in the Enderby Basin. Potential field data off East Antarctica are limited in coverage and obscured by the volcanic output of the Kerguelen Plateau, yet this area can still provide valuable evidence from seafloor spreading magnetic anomalies, fracture zones and drill sites (Fig. 2.6). 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 (Williams et al., 2011) and India (Müller et al., 2008). We analyse GEODAS (Geophysical Data System) data from the National Geophysical Data Centre (NGDC). All magnetic anomaly shiptrack data were smoothed by highpass (300 km) and lowpass (10 km) filters to remove electromagnetic field disturbances and noise. We make magnetic anomaly identifications by comparing magnetic anomalies from selected shiptrack profiles (Fig. 2.7) 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 combined timescale of Cande and Kent, (1995), for Cenozoic anomalies and Gradstein (1994), for Mesozoic anomalies.
### Parameters used for Enderby Basin synthetic magnetic model

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<td>Spreading full-rate:</td>
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<tr>
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</tbody>
</table>

**Table 2.1.** Parameters used for Enderby Basin synthetic magnetic model

**MAGNETIC ANOMALY INTERPRETATION**

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 midway between the Elan Bank and the Antarctic continent-ocean boundary (Fig. 2.6 and 2.7). See Fig. 2.7 for the stacked plots of our interpretation of selected tracks compared to our synthetic model. The location of our extinct ridge is a good match to that of Gaina et al. (2007) but our ridge jump occurred later ~115 Ma. Full spreading rates from 126.7 Ma were ~70 mm/yr but reduced to ~40 mm/yr after ~124.1 Ma. We identify the extinct ridge (dashed blue line) as an axis of reflection between the magnetic anomalies (thick lines) and gravity profiles (thin lines, Fig. 2.6 and 2.7).
Figure 2.6. Marine magnetic anomalies projected at 80 degrees for the Enderby Basin, overlain on 1-minute satellite-derived free-air gravity field. Thin black lines show marine magnetic anomalies along ship tracks, thin red lines show the selected, representative magnetic anomaly profiles used for Figure 2.7. Thick dotted blue line shows the extinct ridge, surrounded by our interpreted conjugate isochrons M0 (pink), M2 (blue) and M4 (red), thick dotted black line shows the COB. Identification of
marine magnetic anomalies, picked at the young end of normal polarity, is shown in the map key.

**Figure 2.7.** Selected, representative magnetic anomaly profiles for the Enderby Basin. The location of the profiles is shown in Figure 2.6. The synthetic profile is based on the geomagnetic timescale of Gradstein et al. (1994), using a depth to the top of the magnetised layer of 6 km and a thickness of the magnetised layer of 0.5 km. The oceanic crust was assumed to have been magnetised at 60 degrees south. Potential volcanism that could influence magnetic anomaly interpretation is indicated (v).
TECTONIC CONSTRAINTS

Robust plate tectonic models are built on regional constraints so that excessive misfit and unlikely plate motion is avoided. This is particularly significant for a plate the size of Greater India, which was constrained on three sides by Australia, Antarctica and Madagascar. For Euler poles 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, for Indian-Antarctic motion, and those from the abyssal plains bordering the West Australian margin, for Indian-Australian motion (Gibbons et al., 2011). We compute full-stage rotation poles using GPlates (Boyden et al., 2011), by visually aligning coeval magnetic anomaly and fracture zone picks. We also include and test a recently proposed fit-reconstruction for East Gondwana, which shifts the position of Australia, relative to Antarctica (Williams et al., 2011). This helps resolve Indian Ocean fit problems, particularly around Madagascar, where previous fits were too tight (e.g. Lawver et al., 1998; Marks and Tikku, 2001).

The initial motion of Greater India is tightly constrained to the northeast by the geometry of the Wallaby-Zenith Fracture Zone (WZFZ), which was forming off the West Australian margin while, to the southwest, India was very close to Madagascar. Greater India had to ‘slide out’ between these features without overlapping them. We rejected the older anomalies of Gaina et al. (2007) because an earlier northward migration for Greater India causes compression between it and either the WZFZ or Madagascar. Ours is the first model to comply with all constraints along the West
Australian margin as well as to ensure there is reasonable (~200 km dextral) strike-slip motion between India and Madagascar (Fig. 2.9b and c).

Madagascar’s motion is constrained by magnetic anomalies in the Somali Basin, fixed to Africa, which is moving relative to Antarctica. Of the several models available that describe the initial motion for Africa-Antarctica and Africa-Madagascar we adopt Konig and Jokat (2010) and Müller et al. (2008), respectively. We adopt these models because in both studies, seafloor spreading between Africa and Madagascar, and Africa and Antarctica, started ~M26/155 Ma and ceased ~M0/120.4 Ma, ensuring continuity between the seafloor spreading corridors and minimal relative motion between Madagascar and India. Models where seafloor spreading between Africa and Madagascar ceased ~10N/131 Ma (e.g. Eagles and Konig, 2008; Rabinowitz et al., 1983) cause ~200 km overlap between Madagascar, Sri Lanka and India, and ~400 km overlap between Madagascar and the Gunnerus Ridge on Antarctica (Fig. 2.8) in our model.
Figure 2.8. 131.6 Ma reconstruction depicting cessation of seafloor spreading between Africa and Madagascar ~10N/131 Ma (e.g. Eagles and Konig, 2008; Rabinowitz et al., 1983). Note ~200 km overlap between Madagascar, Sri Lanka (SL) and India (green dashed line), and ~400 km overlap between Madagascar and the Gunnerus Ridge (GR, black dashed line). Coastlines are filled in grey, continent-ocean boundary is filled in yellow, isochrons are thin red lines.
Figure 2.9. Mercator-projected reconstructions of Indian Ocean at (a) 140 Ma, (b) 120.4 Ma, (c) 110 Ma and (d) 90 Ma (e) 80 Ma, (f) 70 Ma, constructed using GPlates exported geometries with Australia fixed in present-day coordinates. Showing pseudofaults (light green lines), extinct ridges (light blue lines), COB (thin black line, filled in yellow), continental micro-fragments (filled in green), isochrons (red lines), spreading centres (thick dark grey lines). Countries are outlined in grey 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) and Sri Lanka (SL). Black 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). For continental micro-fragments affiliated with the West Australian margin, please refer to Gibbons et. al., (submitted).
TECTONIC MODEL AND DISCUSSION

In a full-fit reconstruction, the southeast tip of India and southern tip of Madagascar are aligned and are juxtaposed with the northern tip of the Gunnerus Ridge and Sri Lanka (Fig. 2.9a). There is minimal overlap between them and Antarctica, except further east where the Bruce Rise and Naturaliste Plateau continental overlap reaches ~400 km.

We incorporate the Naturaliste Plateau as a micro-continental 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 western extent of the Albany-Fraser-Wilkes Orogen (Halpin et al., 2008). This study identifies the plateau as a middle-to-lower crustal allochthon, exhumed during hyper-extensional break-up 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 (Fig. 2.1 and 2.2), as conjugate features derived from the opening of India from Australia and Antarctica (Williams et al., 2011), rather than forming via initial sinistral motion between Australia and Antarctica, then separation (Tikku and Cande, 1999). Both the palinspastic and our reconstructions support a model that aligned the Vincennes Fracture zone with the Naturaliste Fracture Zone northwest of the Naturaliste Plateau (Whittaker et al., 2007), such that they formed as a transform-rift feature preceding India’s seafloor spreading from East Gondwana.
Our model features the Naturaliste Plateau and Bruse 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., submitted). This initial motion is necessary to create the Mentelle basin, between the Naturaliste Plateau and southwest Australia, whose western depocentre has been correlated with Late Jurassic to Early Cretaceous extension in the Perth abyssal plain, which shares 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.

*Greater India migration*

Greater India started migrating from East Gondwana following a spreading reorganisation several hundred kilometers off northwest of Australia ~136 Ma. The new spreading ridge progressively unzipped India from northwest Australia to the western Enderby Basin (Fig. 2.9b). This implies an anticlockwise motion for India about a southern pivot, at a stage pole located near Sri Lanka. Seafloor spreading formed the Enderby margin from ~130 Ma, incorporating the Elan Bank and South Kerguelen Plateau (SKP). Geochemical studies of these features indicate their continental contamination (Bénard et al., 2010; Frey et al., 2002) and we assign them as Indian continental fragments, which were transferred to Antarctica via ridge jumps. The extended Elan Bank (extending into SKP) migrated with India until a ridge jump transferred it to the Antarctica ~115 Ma. The ridge jump further continued further west and isolated all the seafloor east of Sri Lanka.
Studies describing the formation of the Enderby Basin, which actually consider their implications in the West Australian abyssal plains (Gaina et al., 2007; Royer and Coffin, 1992), imply far higher spreading rates in the Enderby than those recorded in the Perth Abyssal Plain (e.g. Markl, 1978). Published models also typically do not utilise the tectonic constraints given by relative motions between India and Australia along the WZFZ and between India and Madagascar, resulting in up to 150 km misfits/overlaps (Gaina et al., 2007; Royer and Coffin, 1992). Our reconstruction eliminates such inconsistencies and also accurately reproduces the prominent northwest to northeast bend in the Enderby fracture zones (Fig. 2.1, just northeast of the Gunnerus Ridge). This bend is attributed to India’s change in plate motion, and is also based on constraints from the Wharton Basin, located ~1500 km offshore West Australia (Fig. 2.2), where the coeval curved fracture zones are located (Gibbons et al., submitted). The bend in both sets of fracture zones formed from ~98 Ma, as the India Ocean underwent major spreading reorganisation, previously documented at ~100 Ma (Müller et al., 2000b; Veevers, 2000), when India began to migrate northwards, leaving Madagascar fixed to Africa. The Madagascar-India relative motion initiated with dextral transtensional motion from ~98 Ma but seafloor spreading was diachronous and started from the south at ~94 Ma to reach the north ~84 Ma.
India-Madagascar separation

Several plate kinematic models (Besse and Courtillot, 1988; Morgan, 1981b; Müller et al., 1993; Norton and Sclater, 1979) date the onset of seafloor spreading between India and Madagascar to Cenozoic seafloor spreading anomaly 34 (83.5 Ma). Yatheesh et al. (2006), dated this separation to ~86.5 Ma, by incorporating plate reconstruction models and an improved fit of the ~200 km-wide terrace-like feature near Trivandrum (SW India), shown to be block-faulted basement (Rao and Battaharya, 1975). Seismic stratigraphy studies offshore west coast India do not identify marine sediments earlier than Late Cretaceous-Early Paleocene (Singh et al., 1999). 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). The 90 Ma reconstruction from the latter study shows a ~500 km-wide gap between India and Madagascar’s northern margin just 1.6 Ma after their initial breakup, which they inferred from St Mary magmatism, again suggesting an earlier breakup is needed.

The Laxmi Ridge, located ~300 km offshore West India, has been identified as a continental fragment (Naini and Talwani, 1982; Talwani and Reif, 1998), as has the Seychelles (Besse and Courtillot, 1988; Lawver et al., 1998). Seafloor formed during India-Madagascar breakup is inferred to be contemporaneous either side of the Seychelles-Laxmi continental fragment, forming the Laxmi basin, offshore West India, and Mascarane basin, offshore East Madagascar. The spreading systems then relocated to divide the Seychelles and Laxmi Ridge, creating the conjugate Arabian and Eastern
Somali basins (Rangarajan, 2006). Magnetic data in the Laxmi basin reveals that a ~300 km-wide extinct seafloor spreading sequence existed between the Laxmi Ridge and the West Indian margin, which operated from ~83.5-62.5 Ma (anomalies C33-28) at very slow full-spreading rates <9 mm/yr (Bhattacharya et al., 1994). Magnetic data in the Gop Basin, northwest of the Laxmi basin, reveals an extinct spreading system existed 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 C29n-29r (~64.7-64 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 (~67.7 or 64-56.4 Ma).

The Mascarene Basin, 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, 1974), were revised to ~85 Ma by anomaly 34 with full-spreading rates ~55 mm/yr (Bissessur et al., 2010; Norton and Sclater, 1979). No anomalies have been identified in the northern half of the basin, by the Seychelles plateau. The oldest sediments here are volcanogenic and have also been dated to the Upper Cretaceous/Paleocene (Schlich, 1974).

Our pre-breakup fit between India and Madagascar is similar to Torsvik et al. (2000), where the southeast tip of India is sinistrally offset from the southeast tip of Madagascar by ~250 km and our model features the onset of opening with dextral transtensional motion between India and Madagascar from ~98 Ma, leading to continental breakup in the south at ~94 Ma, and in the north at ~84 Ma. This diachronous breakup created a
wedge of seafloor inboard from the Laxmi Ridge, which narrows to the north, incorporating the Trivandrum terrace of block-faulted basement (Rao and Battacharya, 1975; Yatheesh et al., 2006). Due to the coeval spreading corridors offshore West India and East Madagascar, our model then features a three-plate system operating for up to 25 My. Two mid-ocean ridges, located either side of the Seychelles-Laxmi continental fragment, formed the Laxmi and Mascarene basins, each containing a conjugate sequence of magnetic anomalies, before a new spreading regime formed the Arabian and Eastern Somali basins from ~64 Ma. Two sub-parallel mid-ocean ridges, contemporaneously forming seafloor only ~400 km apart is an unusual tectonic occurrence and should be investigated in more detail but is currently beyond the scope of this study.

Sri Lanka

In its present-day position, Sri Lanka is offset from the southern Indian margin along the Mannar basin, to the west, and Cauvery basin, to the northeast. Seismic data indicate that the Mannar basin contains Late Jurassic-Early Cretaceous to recent sediments (Baillie et al., 2004). Curray (1984), suggested that Sri Lanka became a failed rift (aulacogen), when rifting between India and Antarctica initially separated Sri Lanka from India along the Mannar Gulf (the basin immediately west of Sri Lanka, Fig. 2.5) but was instead replaced by seafloor spreading between Sri Lanka and Antarctica. Desa et al. (2006) suggest that a ~200 km NE-trending feature between India and Sri Lanka could represent the failed rift and that two strong linear gravity lows, one parallel to Indian coast and the other sub-parallel to Sri Lankan coast, could either represent the transform ridges or the margins of India and Sri Lanka, respectively (Fig. 2.5).
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), though it has been positioned further south, requiring sinistral then oblique strike-slip to locate it to its present-day location, relative to India (e.g. Gaina et al., 2007).

Our fit reconstruction for Gondwana places Sri Lanka across the southeastern tips of India and Madagascar, just east of the Gunnerus Ridge (Fig. 2.9a). We cannot match the recently identified CNS age for the seafloor just east of the Gunnerus Ridge (Jokat et al., 2010) because if seafloor spreading here started later than ~124.1 Ma, it would have severed India from Sri Lanka (Fig. 2.3), given India’s relative motion constraints for this time (Gibbons et al., submitted). Instead, we tentatively re-interpret the magnetic anomalies for this part of the Enderby Basin to start from anomaly M2 (124.1 Ma, Fig. 2.10). We apply a Euler pole to Sri Lanka between ~124-116 Ma so that Sri Lanka fully
unraveled from India just before seafloor spreading isolated the Enderby Basin ~115 Ma. This avoids the Sri Lankan margin overlapping with Antarctica or the West Enderby seafloor (Fig. 2.9b). A reason for Sri Lanka detaching from Antarctica, is likely the attempt of seafloor spreading corridors to connect between the Enderby Basin and west of the Gunnerus Ridge, which may be related to the location of the Conrad Rise hotspot, which was located ~300 km east of southern Sri Lanka at ~116 Ma. This hotspot may also have instigated a southward ridge jump that attached Sri Lanka to the India plate.

A recent analysis of litho- and tectono-stratigraphy in the Ariyalur outcrop of the Cauvery basin suggests the onset of rift-related subsidence occurred Barremina-Apatian (~120 Ma), which was followed by the transition from the syn-rift to post-rift during the Turonian (~90 Ma) (Watkinson et al., 2007). Other reconstructions feature Sri Lanka-India opening from 90 Ma (Lawver and Scotese, 1987; Torsvik et al., 2000) but apart from the opening between India and Antarctica, the only time a spreading centre was near Sri Lanka was when India, Madagascar and Antarctica began to rift apart 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. The Cauvery basin Turonian subsidence (Watkinson et al., 2007) could have been from a second phase of rifting or from a long, slow rifting of Sri Lanka from Antarctica, but we also propose that the subsidence could also have followed its proximity to the Marion hotspot, ~100 km at ~106 Ma, so that subsidence followed as the Cauvery Basin was migrated away from the hotspot.

The Gulf of Mannar is considered the southeastern sub-basin offshore to the Cauvery Basin as horst-grabens in both regions share the similar northeast strike and major
sequence boundaries in their stratigraphy (Rao et al., 2010). They also share the presence of pre-Albian planktonic foraminifera in sediments on the Sri Lankan side of the Mannar sub-basin (Rana et al., 2008). This suggests that Lower Cretaceous seafloor spreading between India and Antarctica was at least partly responsible for locating Sri Lanka to its present-day position. 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, though it may not have culminated in more relative motion between India and Sri Lanka.
Figure 2.10. Tentative reinterpretation of seafloor spreading anomalies, modified from Jokat et al. 2010. Their figure shows the aeromagnetic data (flight altitude 250 m) as ‘positive’ (red) and ‘negative’ (blue) wiggles overlain on the ETOPO bathymetry grid, plotted with a contour interval of 200 m (GR indicates the Gunnerus Ridge). Previously identified magnetic anomalies M4 and M9, and an extinct ridge (XR) are shown (Gaina et al., 2007) along with the location of seismic line GA 229/35 (Stagg et al., 2005).
Hotspots

Hotspots have long been implicated in the break up of supercontinents (e.g. Condie, 2004; Morgan, 1983; Richards et al., 1989), including Gondwana (e.g. Storey, 1995; Storey et al., 1995). Plumes can incubate beneath thicker continental crust for a considerable time (Kent et al., 1992) before melting is triggered by their arrival beneath thinner lithosphere. If the Conrad, Crozet, Marion, Réunion and Kerguelen hotspots were long-lived (Fig. 2.9), East Gondwana would have overlain them all during the Late Jurassic, which may have influenced its breakup. Even if the hotspots did not exist before the Upper Cretaceous, they can still account for several of the anomalous tectonic features in the Indian Ocean today.

Outputs of the Kerguelen plume feature most prominently in our study, which Coffin et al. (2002) argue as a multiple/dismembered Kerguelen plume source given the unusually long span of peak production (25 Ma). Kent et al. (1992), propose that the Kerguelen plume could have built up beneath the Indian plate from as early as 260 Ma, which remained over the plume for that time until breakup (Kent et al., 1992). The plume has also been implicated in the break-up between Australia-Antarctica and India on the basis of the Bunbury Basalts in West Australia, which formed from 132 Ma (Frey et al., 1996b). This date is a good match to our modelled opening between India and Australia, though the Kerguelen plume, as the nearest hotspot, was over 1000 km west of the Bunbury basalts when they formed (Müller et al., 1993).

The Kerguelen plume formed the Kerguelen Plateau and its conjugate features: Broken Ridge and 90E Ridge (Fig. 2.1-3), from at least 119 Ma at ODP site 1136 (Coffin et al.,
2002). Our model ensures enough oceanic crust existed to accommodate the earliest surface expression of the plume but extends the ~115 Ma Elan Bank ridge jump further east, to the tectonic boundary for the breakup between Australia and Antarctica, so that the continental crust underlying the South Kerguelen Plateau and any volcanic products at this time were also transferred to Antarctica at ~115 Ma. The younger age of this ridge jump is a better match to the Kerguelen plume’s emergence from India’s eastern margin at ~112 Ma (Fig. 2.9c), as the ridge relocated northwards to overlie the hotspot.

Torsvik et al. (2000), implicate the Marion hotspot and associated rifting and extension as the probable cause of magmatism at St. Mary and East Madagascar’s mafic to felsic dykes. Several studies also attribute Madagascar-India breakup to the Marion hotspot (e.g. Mahoney et al., 1991; Morgan, 1981a; Storey et al., 1995; Torsvik et al., 1998). Our model, featuring fixed hotspots adapted from a moving hotspot reference frame (O’Neill et al., 2005), places the Marion hotspot between the southern tips of India and Madagascar ~105 Ma. This coincides with the emplacement of the Androy and Morondava basalts on Madagascar’s east and west margins from 103 and 94 Ma, respectively (Bardintzeff et al., 2010), but is 13 My too early for the ~91.6 Ma magmatism at East Madagascar (Torsvik et al., 2000). The timing of this magmatism instead coincides with our modelled breakup between Madagascar and India, running south to north, from 94-84 Ma.

The Conrad Rise hotspot, located ~1500 km southwest of the Kerguelen hotspot, can account for the southernmost portion of the 85°E Ridge and its conjugate, the Kerguelen Fracture Zone (KFZ), and then the ANS. Our model shows the southern tip of the 85°E Ridge and Kerguelen Fracture Zone formed as conjugate flanks of a leaky transform
fault from ~99-98 Ma, which was underlain by the Conrad Rise hotspot from ~84 Ma (Fig. 2.9d-e). The 85°E hotspot track veers southwest until it connects with the ANS seamounts, which were located over the Conrad hotspot from ~76 Ma (Fig. 2.9e-f).

Krishna et al. (2009), suggest that the KFZ and 85°E fracture zone are conjugate features and dates their inception to ~100 Ma, which is consistent with our reconstruction. The ~99 Ma major transform fault forming the 85°E Ridge and Kerguelen Fracture zone is a good match to the well-documented 100 Ma spreading reorganization signalling India’s northward migration (Mihut, 1997; Müller et al., 2000b; Müller et al., 1998).

Marion and Crozet hotspots emerged from beneath southeast India and Madagascar at ~106 Ma. We propose that this initiated the sinistral motion between Madagascar and India, as India slowly unwound from Madagascar, initiating a triple junction between the newly-forming Madagascar Rise (Louisade Plateau) and Conrad Rise from ~100 Ma (Fig. 2.9c-d). The faster-spreading arms of the triple junction included the southeast Indian Ridge and extinct Mascarene Ridge. The slower arm of this nascent Rodrigues triple junction was the southwest Indian Ridge.
CONCLUSIONS

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 unzipped from north to south. Seafloor spreading started in the Enderby Basin at ~126.7 Ma/M4, and progressed westwards to towards Sri Lanka to finally create seafloor east of the Gunnerus Ridge from ~124.1 Ma/M2. The spreading ridge, east of Sri Lanka, 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. Our younger opening time for the Enderby Basin, resolves the problem of back and forth strike-slip motion between Madagascar and India modelled in other reconstructions without contradicting evidence from fracture zones in the Somalia basin.

Based on coeval bending fracture zones from the Enderby and Wharton basins we identify dextral transtensional motion between Madagascar and India from ~98 Ma, with the southern margins forming from ~94 Ma and perforating the northern margins by 84 Ma. This scenario fits well with the major spreading reorganization ~100 Ma. This spreading reorganisation then caused the conjugate Kerguelen Fracture zone and 85°E Ridge to form until they were underlain by the Conrad Rise hotspot from ~84 Ma, which produced the ANS from ~76 Ma. The Réunion hotspot did not emerge from beneath the northwest Indian craton until ~65 Ma, a good match to the age of the
Deccan Traps erupted in western India ~66-65 Ma (e.g. Baksi, 1994; Duncan and Richards, 1991).
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