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Middle Cretaceous geomagnetic field anomalies in the Eastern Indian Ocean and their implication to the tectonic evolution of the Bay of Bengal

Maria Ana Desa[1]*, Mangipudi V. Ramana[2]

[1]National Institute of Oceanography (CSIR), Dona Paula, Goa, 403 004 India

[2]Sagarika Apartments, Nagali Hills, Dona Paula, Goa, 403 004, India

Email: mdesa@nio.org

Abstract

The Middle Cretaceous period is largely known for its stable normal polarity in the Earth's magnetic field. A few reversals (ISEA, M-3r; M-2r and M-1r) have been postulated during this period but are yet to be accepted in total. Recently, two anomalies Q1 (92 Ma) and Q2 (108 Ma) have been identified globally and proposed as internal time markers useful to trace the evolution of the world oceans. While the evolutionary history of the Indian Ocean from Late Cretaceous to present is well-established, the older (Middle to Early Cretaceous) record is still ambiguous. The occurrence of a major plate reorganization during the Middle Cretaceous period has added to the dilemma in understanding the early evolution of the Eastern Indian Ocean. The detailed evolution of the Bay of Bengal and its conjugate Enderby Basin has remained speculative to date due to various constraints such as lack of good geophysical dataset and drill sites, and the presence of thick sedimentary load.

In the present study, an attempt is made to validate the occurrence of the Middle Cretaceous internal time markers in the Eastern Indian Ocean. These time markers are used to provide additional constraints for tracing the evolution of the Eastern Indian Ocean since Late Jurassic. Identification of these markers aided to confirm the timing of spreading ridge extinction in the Perth Basin as 102 Ma. In the Bay of Bengal, these markers facilitated to infer the evolution of the Middle Cretaceous crust east of the buried 85°E Ridge. The age of the oceanic crust increases from south to 115 Ma at the northern tip of the Bay of Bengal. Seafloor spreading occurred in ~NNE-SSW direction between 115 Ma and 102 Ma, and thereafter it changed its direction to ~N-S. Half spreading rates ranging from 4.0 to 4.2 cm/yr between 108 Ma and 84 Ma in the Bay of Bengal are higher than its conjugate Enderby Basin. This spreading system belongs to the second rifting episode between Antarctica and India, and was caused by the Kerguelen mantle plume activity. The 85°E Ridge south of 12°N is emplaced on a transform fault that constitutes the northern extension of the 86°E Fracture Zone and active since 102 Ma. The study suggests that excess crustal accretion occurred on the Indian plate since the Middle Cretaceous.

Keywords
Middle Cretaceous; Bay of Bengal; magnetic anomalies; Enderby Basin; seafloor spreading; ridge jump

1. Introduction

The Middle Cretaceous period referred as the Cretaceous Magnetic Quiet Zone period is bounded by chrons M0 and A34. This period is also considered as the Cretaceous Normal Superchron with high geomagnetic field strength and low reversal frequency (Larson, 1991; Tarduno et al., 2001; Tarduno and Cottrell, 2005; Aubert et al., 2010). Though this period has been associated with smooth positive geomagnetic field, chaotic magnetic signatures have been reported. Despite the disorderly pattern in the magnetic anomalies, several polarity reversals have now been speculated. The first reversal was inferred at 115 Ma and named as ISEA (Tarduno, 1990). Later, additional reversals such as the M-3r (ending at 102 Ma) and M-2r (ending at 108 Ma) have been inferred, while the M-1r at 118.5 Ma was suspected to be ISEA (Gradstein et al., 2012).

The geomagnetic field depicted high variability in the beginning of this superchron while the magnetic signal was subdued in the last nine million years (Granot et al., 2012). Further, Granot et al. (2012) identified two internal time markers Q1 and Q2 at 92 and 108 Ma respectively in different oceans and proposed their application to date the oceanic crust. The long-wavelength anomaly Q2 and the short-wavelength anomaly Q1 were used to trace the early evolution of the South Atlantic Ocean (Granot and Dyment, 2015). The occurrence of global-scale plate reorganization characterized with major changes in seafloor spreading direction and rates, has been postulated between 105 and 100 Ma (Matthews et al., 2012).

The present work is based on the study by Granot et al. (2012), wherein profiles from different oceans were used to infer magnetic anomalies Q1 and Q2 during the Middle Cretaceous Magnetic Quiet Zone period. Here, an attempt is made to identify the internal time markers (Q1, Q2, M-3r, M-2r, M-1r and ISEA) of the Middle Cretaceous period in the Eastern Indian Ocean. This exercise would validate the occurrences of these anomalies globally and help in dating some of the events which have taken place during the Middle Cretaceous period in the Eastern Indian Ocean. Further, these markers would serve as constraints to understand the evolution and map the extent of the Middle Cretaceous crust in the Bay of Bengal.

The oceanic crust generated in the Eastern Indian Ocean during the Middle Cretaceous period constitutes the study areas (Figure 1). Correlation of the magnetic anomalies and identification of the internal time markers validate the existence of these anomalies in the Eastern Indian Ocean. Several tectonic events that occurred during the Middle Cretaceous

crust in the Eastern Indian Ocean have been dated. Detailed analysis of the magnetic data in the Bay of Bengal facilitates in demarcating the extent of the Middle Cretaceous crust and tracing its evolution.

2. Background of the study areas

The breakup of Eastern Gondwanaland and subsequent seafloor spreading between Greater India, Antarctica, Australia and Madagascar resulted in the present-day configuration of the Indian Ocean (Figure 1). Since the Late Jurassic, seafloor spreading is known to have occurred in three phases separated by two major plate reorganizations (Mckenzie and Sclater, 1971; Norton and Sclater, 1979; Schlich, 1982; Powell et al., 1988).

The identification of magnetic anomalies as old as M25 in the Argo and northern Gascoyne Basins suggests the initiation of seafloor spreading in a ~NW-SE direction since the Late Jurassic (Larson, 1975). This spreading center propagated southwestward (Johnson et al., 1980) to the Cuvier Basin by M14 time (Veevers et al., 1985; Mihut and Muller, 1998). Initiation of seafloor spreading in the Perth Basin occurred by M9 (Markl, 1978; Gibbons et al., 2012) or M10 (Williams et al., 2013; Watson et al., 2016). Further, this spreading center resulted in the breakup of Antarctica from India and formation of the Bay of Bengal and the Enderby Basin, East Antarctica (Powell et al., 1988; Royer and Sandwell, 1989). Mesozoic magnetic anomaly sequence M11 through M0 identified in the Central Bay of Bengal (Ramana et al., 1994) suggests this breakup occurred in the Early Cretaceous. Whereas, Banerjee et al. (1995) and Gopala Rao et al. (1997) suggested that the entire Bay of Bengal was formed during the Middle Cretaceous period. South of Sri Lanka, magnetic anomalies in an arcuate shape and offset by NNW-SSE trending fracture zones were identified as M11 to M0 (Desa et al., 2006) and M9 to M0 (Gaina et al., 2007).

Different Mesozoic magnetic anomaly identifications have been made in the Enderby Basin. These include single set of Mesozoic magnetic anomalies (Joshima et al., 2001; Rotstein et al., 2001; Ramana et al., 2001) as well as two-sided anomalies (Gaina et al., 2003; Stagg et al., 2004). A northward spreading ridge jump around M2 time which transferred Elan Bank along with all the Mesozoic oceanic crust to the Antarctica plate has been postulated by Gaina et al. (2003). Later, the ridge jump has been restricted to the eastern Enderby Basin only (Gaina et al., 2007). South of Conrad Rise, the disappearance of the NNE-SSW trending lineations due to cross trends is related to a ridge jump (Rotstein et al., 2001). An extinct spreading ridge is inferred between the Conrad Rise and Gunnerus Ridge based on vector magnetic data (Nogi et al., 2004).

Krishna et al. (2009) suggested that during the India-Antarctica separation, the ongoing rifting process between the southern Eastern Continental margin of India and western Enderby Basin got reorganized due to the northward ridge jump after M2 time to establish a new spreading system between the entire Bay of Bengal and Enderby Basin. Jokat et al. (2010) using aeromagnetic data suggested the presence of oceanic crust no older than Middle Cretaceous, east of Gunnerus Ridge in the Lutzow-Holm Bay, western Enderby Basin. Desa et al. (2013) revealed that the oceanic crust west of the northern segment of the 85°E Ridge is Early Cretaceous in age, while the crust east of the ridge is of Middle Cretaceous age. Recently, Gibbons et al. (2013) suggested that seafloor spreading between India and Antarctica initiated by 127 Ma (M4), and that the northward ridge jump separating Elan Bank from India occurred during the Middle Cretaceous period. The identification of anomalies M10n to M0 in the Western Basin of the Bay of Bengal (Talwani et al., 2016) suggests that the initial opening between India and Antarctica was in ~NW-SE direction, and was contemporaneous with that off Western Australia.

Complex tectonics during the Middle Cretaceous throughout the Eastern Indian Ocean terminated this first phase of seafloor spreading. Major ridge propagation events accreted large segments of the Indian Plate to the Australian Plate (Muller et al., 2000; Williams et al., 2013) resulting in the formation of several stretched and subsided continental platforms such as the Exmouth, Wallaby, Zenith and Naturaliste Plateaus off Western Australia. About 50 to 55° bend in the fracture zones is observed in the Wharton Basin west of the Zenith Plateau (Muller et al., 2000; Veevers, 2000). Based on conjugate fracture zone bends in the Enderby Basin and Bay of Bengal, rapid change in spreading direction has been inferred in the Antarctica-India spreading system (Rotstein et al., 2001). The occurrence of several ridge jumps (Gaina et al., 2003; Nogi et al., 2004; Gibbons et al., 2012; 2013) has been associated with spreading ridge-hotspot interaction. These complex tectonics belong to the first major plate reorganization proposed in the Indian Ocean during the Middle Cretaceous. This reorganization was assigned at various ages due to lack of identifiable reversals in the geomagnetic field. The ages range from 90 Ma (Johnson et al., 1980), 96 Ma (Powell et al., 1988), 99 Ma (Muller et al., 1998) and around 100 Ma (Veevers, 2000). More recently, an age of 98 Ma was assigned for the onset of reorganization between India and Antarctica (Matthews et al., 2012).

2. Data and methodology

The profile v3621 off the North American shelf traversing the Middle Cretaceous crust in the Atlantic Ocean has been used as a representative profile in the present study (Figure 2). Several anomalies are seen along this profile indicating that the Middle Cretaceous period is not magnetically quiet as it is presumed to be. Despite these undulations in the magnetic field, two prominent anomalies, a short-wavelength low (Q1-92 Ma) and a long-wavelength high (Q2-108 Ma) have been recognized (Granot et al., 2012).

Further, the anomalies Q1 and Q2 are used to identify the signatures due to the proposed reversals (M-3r, M-2r and M-1r) (Gradstein et al., 2012) and ISEA (Tarduno, 1990). It is noteworthy that Q2 marks the end of M-2r, while Q1 was not reported by Gradstein et al. (2012). These anomalies and reversal signatures are then considered as key anomalies or internal time markers to infer the Middle Cretaceous crust across the Eastern Indian Ocean.

The age of the start of the Middle Cretaceous period i.e. M0 isochron is assigned as 120.95 Ma (He et al., 2008; Malinverno et al, 2012) and 125.93 Ma (Gradstein et al., 2012). This 5 million year difference does not alter the identifications and the tectonic inferences but affects only the calculated spreading rates. In the present study, the age of M0 is considered as 121 Ma (He et al., 2008; Malinverno et al., 2012) as done by Granot and Dyment (2015). The age of the end of the Middle Cretaceous period i.e. A34 is unanimous at 84 Ma (Gradstein et al., 2012).

Magnetic profiles from various sources are scanned to choose the transects (Table 1) best matching the fracture zone trends of the Middle Cretaceous crust in the study areas on the three plates (Australia, Antarctica and India; Figure 1). Two profiles, v3308 and inmd06mv have been used in the Cuvier and Perth Basins off Western Australia respectively (Figure 3). Off East Antarctica, profiles from the eastern Enderby Basin are not considered as this region may be lacking in Middle Cretaceous crust (Gaina et al., 2003; 2007; Talwani et al., 2016). South of Conrad Rise in the western Enderby Basin, no profile is available running in the direction of the NNE-SSW lineations. Nevertheless, four profiles (a2093 lying west of Gunnerus Ridge, and ant1, ant3 and rc1704-b between the Kerguelen Fracture Zone (FZ) and Elan Bank) are used in the Enderby Basin to identify the key anomalies (Figure 4). The profile rc1704-b runs parallel to the NNE-SSW trends and is useful to trace the magnetic signatures till it crosses the Kerguelen FZ. The ant1 and ant3 profiles are nearly parallel to the Kerguelen FZ and appear ideal for tracing the evolution of the Middle Cretaceous crust.

In the Bay of Bengal (Figure 5), the Western Basin, west of the 85°E Ridge is inferred to be of Early Cretaceous age (Desa et al., 2013; Talwani et al., 2016). Towards east, the emplacement of the Ninetyeast Ridge along the 90°E meridian has resulted in distorted magnetic signature (Maus et al., 2009). Hence, magnetic analysis in the Bay of Bengal has to be restricted to a narrow zone between the 85°E and the Ninetyeast Ridges. Four N-S running tracks are used in the present study.

All the profiles are visually compared with the representative profile v3621 and the internal time markers are identified (Figure 6). Seafloor spreading models are generated (Table 2), half spreading rates calculated and the ages of the underlying crust are deduced.

Additional magnetic data (Table 1) in the northern Bay of Bengal are used to extend the identification of these internal time markers. Further, a synthetic profile is generated using the EMAG2 grid (Maus et al., 2009) right up to 27°N to understand the evolution of the Bengal Basin, north of Bay of Bengal. These identifications are then superposed onto the track map of the Bay of Bengal (Figure 7).

The identified internal time markers and published results were used to generate plate reconstruction models for different timings using GPlates (Table 3) (Boyden et al., 2011) within the regional plate configuration of Gibbons et al., (2013). These models facilitate to demarcate oceanic crustal zones of different ages (Figure 8), and propose the initial (Early to Middle Cretaceous) evolutionary history of the Eastern Indian Ocean and the Bay of Bengal in particular.

3. Results

Detailed analysis of the magnetic data suggests a good correlation of the major magnetic anomalies along all the profiles in the Eastern Indian Ocean with that on the representative profile v3621 in the Atlantic Ocean. This correlation aided the identification of the internal time markers Q1 (92 Ma), Q2 (108 Ma), M-3r (102 Ma), M-2r (108 Ma), ISEA (115 Ma) and M-1r (118.5 Ma) on most of the profiles (Figure 6). Off Western Australia, the profile v3308 in the Cuvier Basin depicts clearly the anomalies and helps trace the evolution of the Middle Cretaceous crust from 121 to 92 Ma (Figures 3 & 6a). Half-spreading rates range from 2.2 to 4.0 cm/yr during this period. Along the profile inmd06mv in the Perth Basin, symmetric magnetic anomalies about a central anomaly were observed suggesting the presence of double limb crust. Seafloor spreading model suggests that these anomalies are due to oceanic crust of 121 to 102 Ma age with a ridge jump occurring at 102 Ma. Relatively higher spreading rates can be inferred in this basin.

The profiles in the Enderby Basin also show good correlation with the representative profile v3621 (Figures 4 & 6a). The profile a2093 west of Gunnerus Ridge clearly depicts the internal time markers till 92 Ma, while large distorted magnetic anomalies are seen between 84 and 92 Ma. The profile ant3 reveals all the time markers of the Middle Cretaceous period, while the profile ant1 lends support to the identifications. The profile rc1704-b traces the magnetic signatures between M0 and 108 Ma (Q2) only as it crosses the Kerguelen FZ at this location. Half spreading rates of 2.9 to 3.9 cm/yr similar to that off Western Australia are inferred.

Detailed analysis of the four N-S oriented magnetic profiles in the Bay of Bengal helped in identifying the time markers of the Middle Cretaceous period (Figures 5 & 6b). Anomaly 34 is seen confidently on three profiles while Q1 (92 Ma) is clearly identified on all the profiles based on its typical shape. The M-3r (102 Ma) is marked on three profiles, but Q2 (108 Ma) and ISEA (115 Ma) can be inferred only on profile sk100-06 due to limited length of the other profiles. Synthetic seafloor spreading model studies (Table 2) suggest that the oceanic crust between 84 and 108 Ma evolved with half spreading rates of 4 to 4.2 cm/yr.

In order to infer the extent of the Middle Cretaceous crust in the Bay of Bengal, additional magnetic data was examined in the northern region (Table 1; Figure 7). This exercise suggested that the internal time markers can be identified along several profiles east of the 85°E Ridge, thereby endorsing the presence of the Middle Cretaceous crust in the Eastern Basin of the Bay of Bengal. The reversal M-1r (115 Ma) is the oldest anomaly identified with an approximately ENE-WSW trend in the northern Bay of Bengal. The offsets in the magnetic anomalies between 115 and 102 Ma suggest the presence of fracture zones and prevalence of seafloor spreading in a NNW-SSE direction. Between 102 and 100 Ma, the spreading direction changes to N-S and this spreading continues into the Late Cretaceous. The synthetic profile generated in the Bengal Basin depicts low amplitude magnetic anomalies up to a line between the Rajmahal and Sylhet Traps where sudden high amplitude anomalies are seen.

3.1 Plate reconstruction models

The plate reconstruction models generated using GPlates (Boyden et al., 2011) illustrate the movement of the plates in the Middle Cretaceous period (Figure 8). The extent of the oceanic crust generated and the various tectonics involved are also clearly depicted. The M0 (121 Ma) reconstruction (Figure 8a) illustrates the oceanic crust generated between India and the contiguous Australia-Antarctica in an ~NW-SE direction at the start of the

Middle Cretaceous period. The model indicates that the spreading corridors south of Sri Lanka (zone 1) and the Western Basin of the Bay of Bengal (zones 2 & 3) are conjugate to those in the western Enderby Basin. A northward ridge jump to the line joining the Rajmahal and Sylhet Traps around M2 time resulted in an extinct spreading ridge with extra oceanic crust in the Eastern Enderby Basin (zones 4, 5, 6). This major change in the plate boundary caused long transform faults on either side of the isolated microcontinents (Elan Bank, Central and Southern Kerguelen Plateau). Similar long transform fault (WZFZ) is seen between zones 7 and 8.

The Q2 (108 Ma) reconstruction depicts continuation of ~NW-SE spreading in all the corridors (Figure 8b). Oceanic crust is generated north of Elan Bank, Central and Southern Kerguelen Plateau, and in its conjugate Bengal Basin (corridors 4, 5 & 6). Continued Kerguelen mantle plume activity resulting in the emplacement of volcanic material over these microcontinents can be inferred. The Q1 (92 Ma) reconstruction (Figure 8c) illustrates that the spreading direction has changed to N-S. Disposition of the corridors 1, 2 & 3 suggest that transform motion has begun along the Kerguelen-86°E FZ. Under the influence of the Kerguelen mantle plume, spreading stopped in the Perth Basin and the spreading center jumped north transferring Indian crust to the Antarctic-Australian plate.

The A34 (84 Ma) reconstruction suggests the onset of rapid northward motion of the Indian plate and active transform motion along the Kerguelen-86°E and Investigator FZs (Figure 8d). The separation of the Australian plate from the Antarctica plate is initiated by this time resulting in the formation of a triple junction at the probable location of the Kerguelen hotspot, the source of continued volcanic activity. Further, the A34 isochrons suggest excess crust on the Antarctica plate south of the Conrad Rise. Here too, a northward ridge jump of the spreading center can be inferred.

4. Discussion

The Middle Cretaceous period known for its so-called consistent normal polarity in the geomagnetic field is also associated with a global major plate reorganization (Matthews et al., 2012). The internal time markers provide time constraints for the major events and the extent of the oceanic crust generated during the Middle Cretaceous period in the Eastern Indian Ocean.

4.1 Western Australia scenario

Late Jurassic to Early Cretaceous oceanic crust generated by a ~NW-SE trending and southwestward propagating spreading center lies off the western Australian margin (Larson, 1975; Markl, 1978; Johnson et al., 1980; Veevers et al., 1985; Mihut and Muller, 1998; Gibbons et al., 2012; Williams et al., 2013). Several small scale ridge jumps and/or southward ridge propagating events are inferred during the Early Cretaceous period off Western Australia. The Sonne Ridge and the Sonja pseudofault in the Cuvier Basin accreted Indian crust to the Australian plate (Mihut and Muller, 1998). Recently a small northwestward ridge jump has been postulated at 119 Ma in the Perth Basin (Williams et al., 2013; Watson et al., 2016).

The M0 isochron, is well established off northwestern Australia, its NNE-SSW trend mostly offset left laterally in the Gascoyne Basin (Markl, 1974; Fullerton et al., 1989). In the Cuvier Basin, this isochron lies off the Zenith and Wallaby Plateaus, and is offset by ~900 km along the Wallaby Zenith Fracture Zone with that in the Perth Basin (Gibbons et al., 2012; Figure 3). Prominent NW-SE trending fracture zones offset this isochron in the Perth Basin. A large northwestward ridge jump transferred parts of Greater India (Markl, 1974; Gibbons et al., 2012) including the Batavia and Gulden Draak knolls to the Australian plate (Williams et al., 2013; Watson et al., 2016). The present study indicates no ridge jump occurred in the Cuvier Basin during the Middle Cretaceous period. Further, this study suggests that the ridge jump transferring the entire oceanic crust from the Indian plate to the Australian plate in the Perth Basin (Williams et al., 2013) occurred at 102 Ma as suggested by Watson et al., (2016).

4.2 Bay of Bengal-Enderby Basin

The evolution of the Bay of Bengal has been attributed to two rifting episodes (Krishna et al., 2009; Desa et al., 2013; Talwani et al., 2016). The first rifting episode between India and Antarctica during the Early Cretaceous created the Western Basin, Bay of Bengal and its conjugate, the western Enderby Basin. The second rifting episode generated the Eastern Basin of the Bay of Bengal after a northward ridge jump (Gaina et al., 2003; 2007) transferred the Early Cretaceous crust east of 85°E Ridge along with Elan Bank to the Antarctica plate (Desa et al., 2013; Talwani et al., 2016).

The magnetic anomaly identifications made in the present study suggest the presence of Middle Cretaceous crust younger than 115 Ma in the Eastern Basin of the Bay of Bengal. Seafloor spreading in the NNW-SSE direction occurred till 102 Ma. By 100 Ma, spreading

became N-S which continued into the Late Cretaceous (Royer et al., 1989). Higher spreading rates of 4.0 to 4.2 cm/yr suggest excess crustal accretion on the Indian plate as compared to the conjugate plate during the Middle Cretaceous period.

Different M0 isochrons have been inferred in the Bay of Bengal (Ramana et al., 1994; Gibbons et al., 2013; Talwani et al., 2016), south of Sri Lanka (Desa et al., 2006; Gaina et al. (2007) and Enderby Basin (Gaina et al., 2007; Ramana et al., 2001; Rotstein et al., 2001; Talwani et al., 2016). The M0 isochrons identified in the western Enderby Basin are conjugate to those in the Western Basin of the Bay of Bengal (Talwani et al., 2016).

There is a major discrepancy about the existence of the M0 isochron in the eastern Enderby Basin based on the timing of the proposed northward ridge jump which separated Elan Bank from India. Two timings for the northward ridge jump are postulated, (i) around M2 time (Gaina et al., 2003; Talwani et al., 2016), and (ii) in the Middle Cretaceous period (Gibbons et al., 2013). If the northward ridge jump occurred around M2 time (Gaina et al., 2003; Talwani et al., 2016), no M0 chron is expected in the eastern Enderby Basin, whereas two M0 isochrons can be expected if the ridge jump occurred during the Middle Cretaceous period (Gibbons et al., 2013).

The Rajmahal and Sylhet (R-S) Traps (Baksi et al., 1987) and the large amplitude negative anomaly between them (Figure 7) are evidence to the Kerguelen hotspot activity in northeast India (Kent, 1991). A northward ridge jump to the R-S line occurred along a transform fault due to spreading ridge interaction with the Kerguelen hotspot. This jump resulted in the opening of a volcanic margin at the R-S line generating the oceanic crust in Bangladesh (Talwani et al., 2016). The presence of oceanic crust in Bangladesh and the 115 to 84 Ma anomaly identifications of the Middle Cretaceous period in the eastern Bay of Bengal, indicate that the ridge jump occurred just after M2 time and not during the Middle Cretaceous period. Thus, M0 isochron does not exist in the eastern Enderby Basin, but lies north of Elan Bank.

4.3 Early evolution of the Eastern Indian Ocean

The present study facilitated the tracing of the evolution of the Eastern Indian Ocean using plate reconstruction modeling (Figure 8). Contemporaneous seafloor spreading in an ~NW-SE direction occurred off Western Australia, in the Bay of Bengal and Enderby Basin during the Early Cretaceous. The arrival of the Kerguelen hotspot destabilised the entire region causing reorganization of the spreading centers (Kent, 1991), ridge jumps and emplacement of various volcanic plateaus, e.g. Zenith and Wallaby Plateaus. After M2 time,

the spreading ridge jumped northwards from the eastern Enderby Basin (Gaina et al., 2007) to the R-S line due to spreading ridge-hotspot interaction (Talwani et al., 2016). This ridge jump separated a number of microcontinents including the Elan Bank from the Indian plate (Figure 8a).

The ~NW-SE spreading scenario continued between India and the contiguous Antarctica-Australia (Figure 8b & c) till ~102 Ma. In the eastern Enderby Basin, oceanic crust was generated north of Elan Bank and in its conjugate, the Bangladesh and northern Bay of Bengal region, along with the emplacement of the southern portion of the Kerguelen Plateau (Coffin et al., 2002).

The northwestward ridge jump at 102 Ma transferred a large extent of the Indian crust to the Australian plate in the Perth Basin, facilitated the alignment of the spreading center and minimization of the large offset (~900 km) in the isochrons. A change in spreading direction in the entire Eastern Indian Ocean occurred by 100 Ma. The Kerguelen-86°E Fracture Zone became active terminating the older crust abruptly and offsetting oceanic crust of similar age by a few hundred kilometers. Similar abrupt termination of the NNE-SSW trending gravity lineations in the western Enderby Basin and the ~55°bend in the fracture zones in the Wharton Basin by 98 Ma is reported by Matthews et al. (2012). Mantle plume activity of the Kerguelen hotspot continued on the Kerguelen Plateau with the emplacement of the Central Kerguelen Plateau and Broken Ridge (Coffin et al., 2002).

The northward motion of the Indian plate began by 100 Ma and continued into the Late Cretaceous (Figure 8d). The extra crust (92 to 84 Ma) seen south of Conrad Rise on the Antarctica plate (Figure 8d) can be attributed to complex tectonics such as termination of the NNE-SSW spreading, cross trends formation, Conrad Rise emplacement and northward ridge jumps (Rotstein et al., 2001; Nogi et al., 2004). Further, the model suggests that a triple junction formed at the Kerguelen Plateau with the initial breakup of the Australian-Antarctica plate. Higher half spreading rates of 4 cm/yr in comparison to 2.9 cm/yr on the Antarctica plate (Table 2) suggests excess crustal accretion on the Indian plate in the Middle Cretaceous period. Thus, variable extent of the oceanic crust is seen generated during the Middle Cretaceous period in the Eastern Indian Ocean (Figure 8d).

In the Bay of Bengal, the eastern edge of the entire 85°E Ridge is the boundary between the Early Cretaceous crust on the west and the Middle Cretaceous crust on the east (Figure 7). The northern portion of this boundary is a transform fault along which the ridge jump to the R-S line occurred (Talwani et al., 2016). Its conjugate is the fracture zone west of Elan

Bank (Figure 8b). The southern portion of the boundary is a transform fault after 100 Ma between the Indian and Antarctica plates (Figures 8c & d). Thus the 85°E Ridge south of 12°N is the northward continuation of the 86°E FZ (Figure 7). Hence, the 85°E Ridge has evolved in at least two episodes of transform faulting. The topographic buildup of the 85°E Ridge occurred later and its exact timing is yet not known.

5. Conclusions

The present study validates the existence of the internal time markers of the Middle Cretaceous period in the Eastern Indian Ocean and their presence helped in tracing the Middle Cretaceous crust in the Bay of Bengal. These markers facilitated to infer that the oceanic crust evolved at half-spreading rates of 2.2 to 4.0 cm/yr between 121 and 92 Ma in the Cuvier Basin, Western Australia. Further these markers aided to suggest that the symmetric magnetic anomalies about an extinct axis in the Perth Basin are due to a northwestward ridge jump at 102 Ma. Similar Middle Cretaceous crust could be inferred in the zone between the Kerguelen Fracture Zone and Elan Bank in Enderby Basin, off East Antarctica.

The markers further aided in inferring that the crust east of the 85°E Ridge in the Bay of Bengal has evolved with half spreading rates ranging from 4.0 to 4.2 cm/yr in the Middle Cretaceous. The disposition of the magnetic anomalies facilitated in inferring a change in seafloor spreading direction from ~NNW-SSE to ~N-S at 102 Ma. The presence of oceanic crust of age upto 115 Ma in the eastern Bay of Bengal indicates that the northward ridge jump that separated Elan Bank from India occurred around M2 time and not in the Middle Cretaceous.

Seafloor spreading in the ~NW-SE direction between India and contiguous Antarctica-Australia occurred till 102 Ma. By 100 Ma, the spreading direction between India and Antarctica-Australia changed to N-S, with the Kerguelen-86°E and Investigator FZs acting as major transform faults. The study suggests that excess crustal accretion occurred on the Indian plate indicating the initiation of the northward flight of the Indian plate in the Middle Cretaceous itself.

The Conrad Rise and Kerguelen Plateaus were emplaced during the Middle Cretaceous period and are associated with asymmetric crustal accretion and plate boundary reorganization. Both these plateaus are also palaeo locations/birth places of triple junctions.

The 85°E Ridge has evolved in at least two episodes of transform faulting. The northern portion formed during the ridge jump to the R-S line, while the southern portion is the northward continuation of the 86°E FZ.

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Figure Captions

Figure 1: Predicted bathymetry of the Indian Ocean and the adjoining Southern Ocean depicting various topographic features (Smith and Sandwell, 1997). Large igneous provinces are marked in blue (Eldholm and Coffin, 2000). The present-day Indian Ocean mid-oceanic ridge system is traced in black. The three study areas are enclosed in dashed rectangles. AB: Argo Basin; AS: Arabian Sea; BR: Broken Ridge; CB: Cuvier Basin; CbR: Carlsberg Ridge; CIOB: Central Indian Ocean Basin; CIR: Central Indian Ridge; CKP: Central Kerguelen Plateau; CR: Conrad Rise; E: Exmouth Plateau; EB: Elan Bank; GB: Gascoyne Basin; GR: Gunnerus Ridge; LHB: Lutzow-Holm Bay; MB: Mascarene Basin; Mad: Madagascar; NER: Ninetyeast Ridge; NKP: Northern Kerguelen Plateau; NP: Naturaliste Plateau; PB: Perth Basin; PET: Princess Elizabeth Trough; PyB: Prydz Basin; RLS: Riiser-Larsen Sea; SB: Somali Basin; SEIR: Southeast Indian Ridge; SEY: Seychelles; SKP: Southern Kerguelen Plateau; SWIR: Southwest Indian Ridge; W: Wallaby Plateau; WB: Wharton Basin; Z: Zenith Plateau.

Figure 2: Magnetic profile v3621 running on the North American flank of the Central Atlantic Ocean along which internal time markers Q1 and Q2 have been identified (Granot et al., 2012). Dashed lines indicate fracture zones (Wessel et al., 2015). The M0 and A34 anomalies identified by Cande et al. (1989) are shown as thick black and red lines respectively. In the background is the satellite derived gravity mosaic of the area (Sandwell et al., 2014). Red outlines denote large igneous provinces (Eldholm and Coffin, 2000). The inset depicts the North American flank of the Central Atlantic Ocean.

Figure 3: Magnetic profiles v3308 and inmd06mv running in the Cuvier and Perth Basins respectively off Western Australia superposed on the satellite gravity mosaic (Sandwell et al., 2014). . Thin black lines in addition to the thick black (M0) and red (A34) lines are published magnetic lineations (Royer et al., 1989). Remaining information as in figure 1. WZFZ: Wallaby-Zenith Fracture Zone.

Figure 4: Magnetic profiles a2093, rc1704-b, ant1 and ant3 lying in the Enderby Basin, off East Antarctica superposed on the satellite gravity mosaic (Sandwell et al., 2014). Remaining information as in figures 1 and 3. KFZ: Kerguelen Fracture Zone.

Figure 5: Magnetic profiles sk100-06, sk100-22, sk82-02 and sk101-ns are interpreted in the Bay of Bengal superposed on the satellite gravity mosaic (Sandwell et al., 2014). The A34 (red lines) and the M0 (thick black line) anomalies have been identified by Royer et al. (1989) and Talwani et al. (2016) respectively. Remaining information as in figures 1 and 3. 85ER: 85°E Ridge; CR: Comorin Ridge; SL: Sri Lanka; ST: Sunda Trough.

Figure 6: Magnetic profiles used in the present study compared with the key profile v3621 (a) off Western Australia and Enderby Basin, and (b) Bay of Bengal. Internal time markers Q1 at 92 Ma and Q2 at 108 Ma (Granot et al., 2012), ISEA at 115 Ma (Tarduno, 1990), and M-3r; M-2r and M-1r (Gradstein et al., 2012) inferred in the Middle Cretaceous period have been identified along most of these profiles. Seafloor spreading models have been generated using parameters given in Table 2. Computed half-spreading rates are indicated. Thick black line indicates extinct spreading ridge.

Figure 7: Magnetic anomalies plotted perpendicular to the tracks in the Bay of Bengal along which Middle Cretaceous internal time markers are posted in different colors. Published fracture zones are shown as thin black dashed lines (Wessel et al., 2015), while those inferred based on magnetic anomaly offsets are shown as red dashed lines. The gravity low of the 85°E Ridge is shown in blue shading. The proposed northward ridge jump (thick black dashed line) to the R-S line (green dashed line) and the Mesozoic magnetic anomaly identifications M10n, M2 and M0 (red lines) are from Talwani et al. (2016). The probable continuation of the 86°E FZ is shown as thick blue dashed line. The magnetic track along 88.5°E longitude further north in the Bengal Basin (BB) is obtained from EMAG2 grid (Maus et al., 2009). The Indian plate boundary is shown as thick red outline. NER: Ninetyeast Ridge; RT: Rajmahal Traps; SL: Sri Lanka; SP: Shillong Plateau; ST: Sylhet Traps.

Figure 8: Plate reconstruction models for various timings using GPlates (Boyden et al., 2011) within the regional plate configuration of Gibbons et al. (2013). (a) 121 Ma (b) 108 Ma (c) 92 Ma (d) 84 Ma. Rotation pole parameters are provided in Table 3. Antarctica is kept in its present day position. Fracture zones are shown as thin black dashed lines (Wessel et al., 2015). The active spreading ridge is shown as a thick blue line. Thick black dashed lines denote the extinct spreading ridges. The gravity low of the subsurface 85°E Ridge is shown in gray shade. Color shades as per legend denotes the ages of the underlying oceanic crust. The dashed red lines denote synthetic flow lines that border the inferred spreading corridors/zones and are drawn to understand the evolution of the Early to Middle Cretaceous crust. Large Igneous Provinces and inferred continental slivers are outlined in pink (Eldholm and Coffin, 2000). Red circle denotes the probable location of the Kerguelen hotspot. The numbers represent conjugate spreading corridors. Green dashed lines mark the remnants of the transform fault along which the northward ridge jump took place at around M2 time. B: Batavia knoll; BR: Broken Ridge; CKP: Central Kerguelen Plateau; CR: Conrad Rise; EB: Elan Bank; GD: Gulden Draak knoll K-86° FZ: Kerguelen-86°E Fracture Zone; R: Rajmahal Traps; S: Sylhet Traps; SKP: Southern Kerguelen Plateau; SL: Sri Lanka; WZFZ: Wallaby-Zenith Fracture Zone; Z: Zenith Plateau.

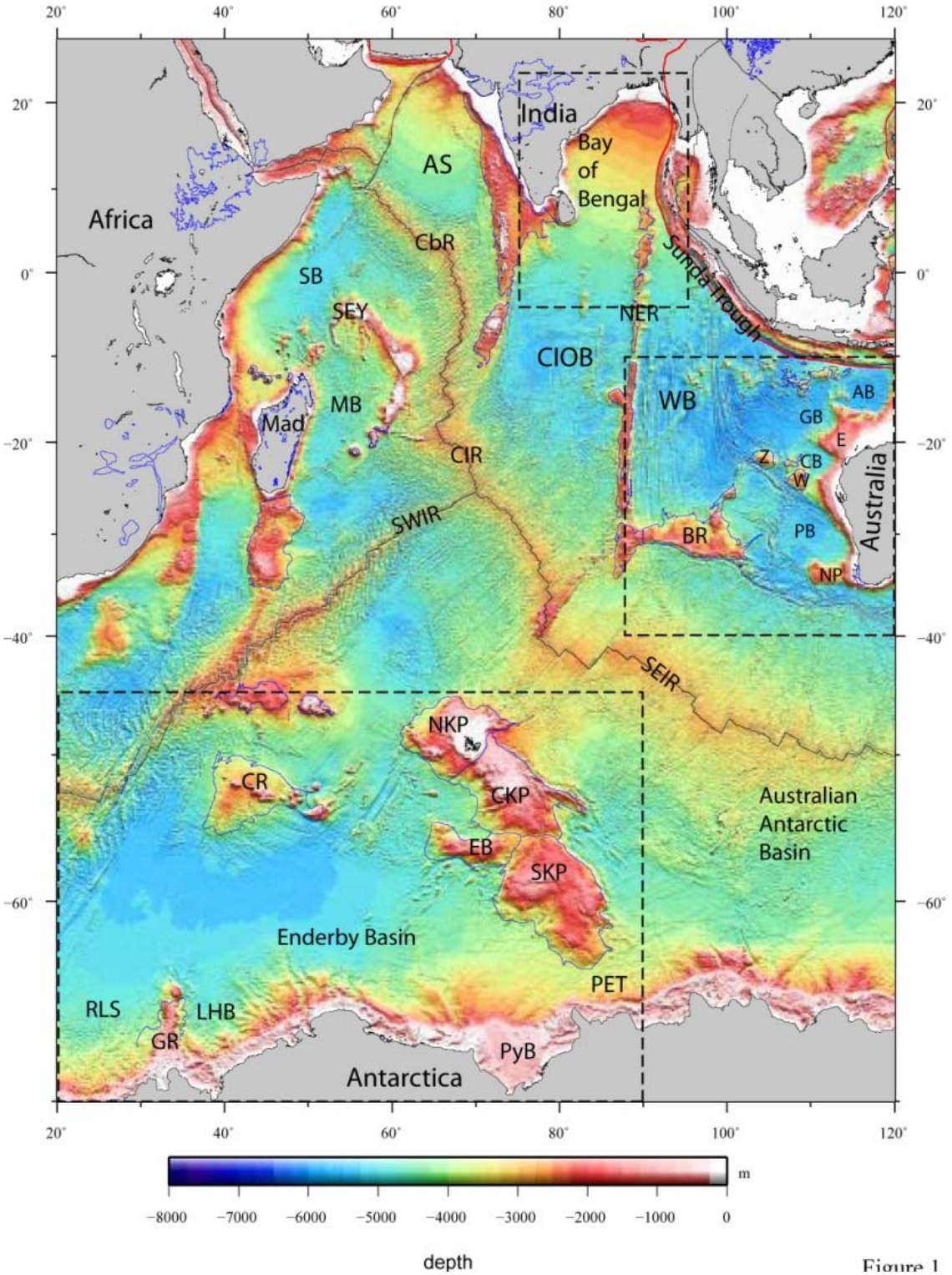
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Figure. 1

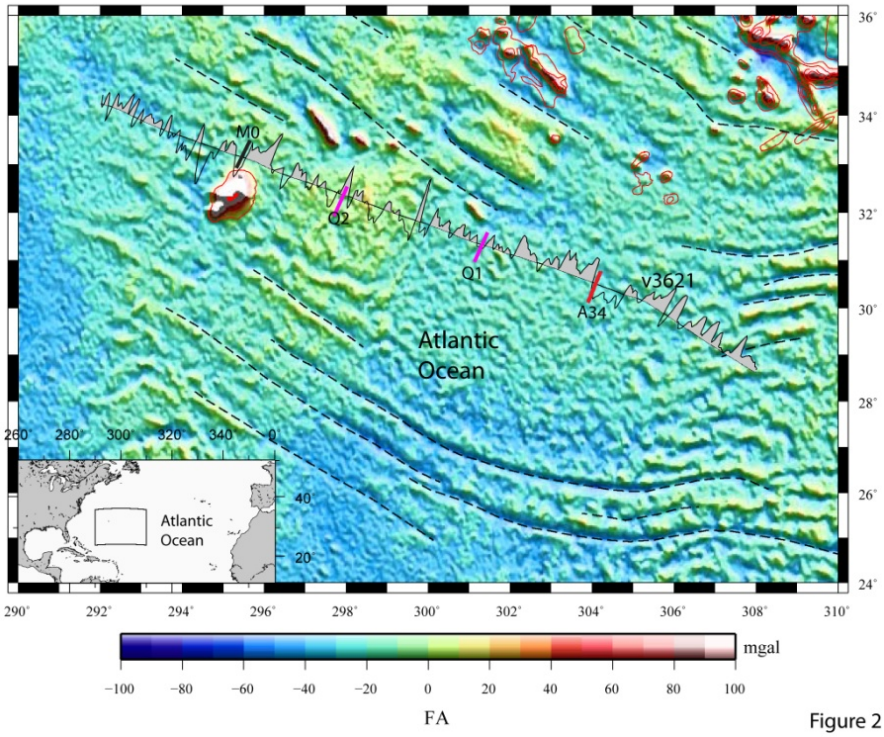


Figure. 2

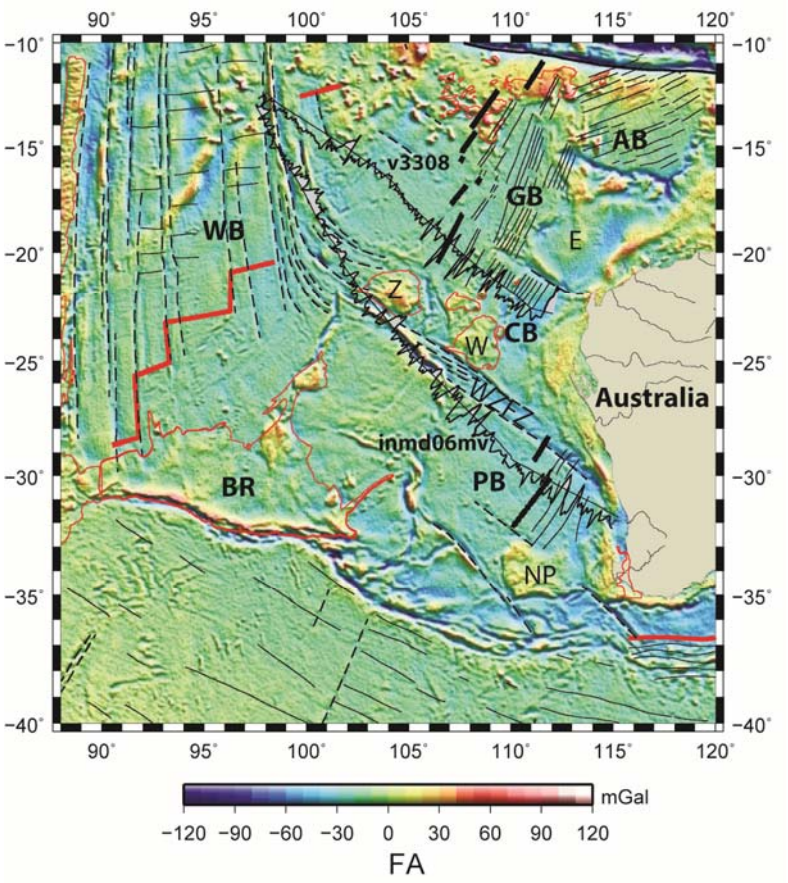


Figure. 3

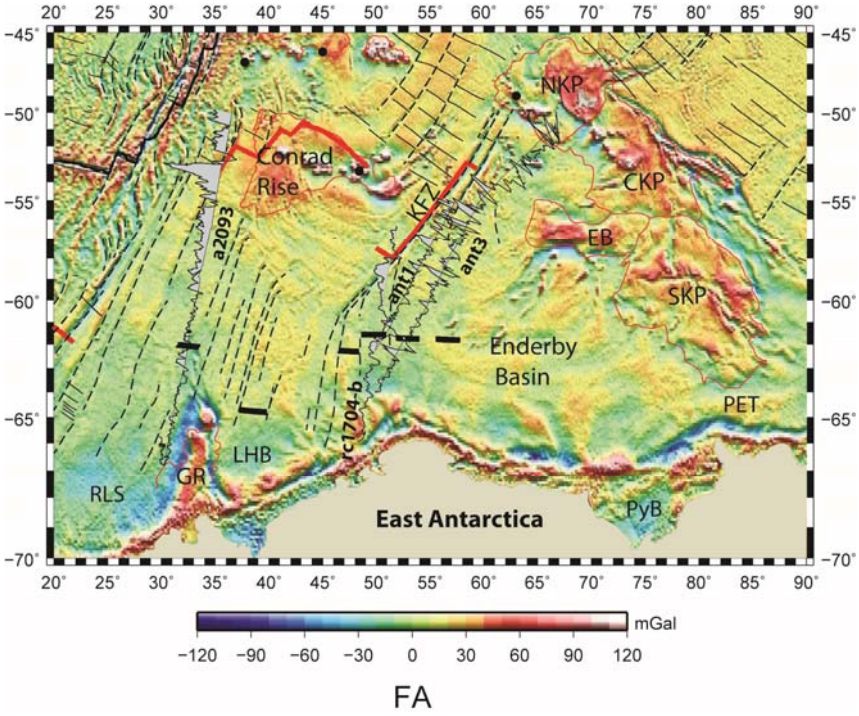


Figure. 4

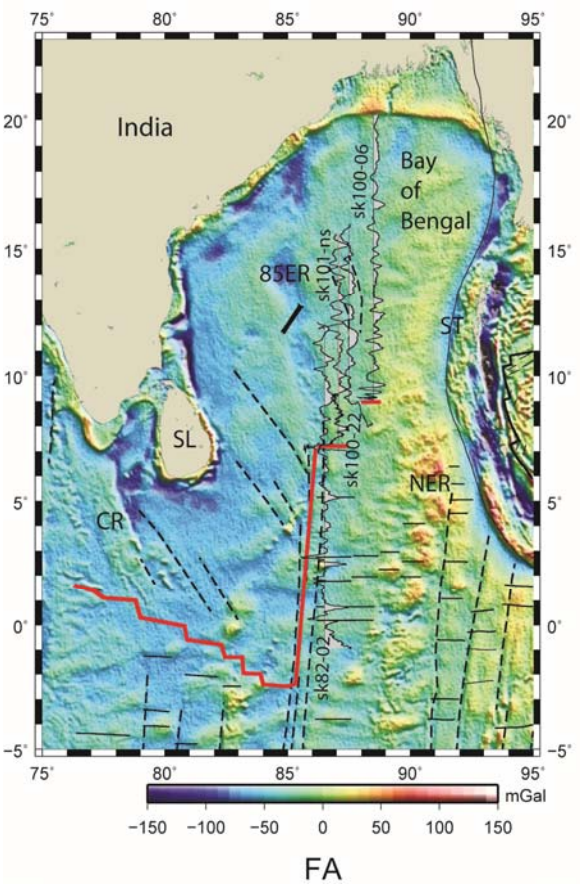
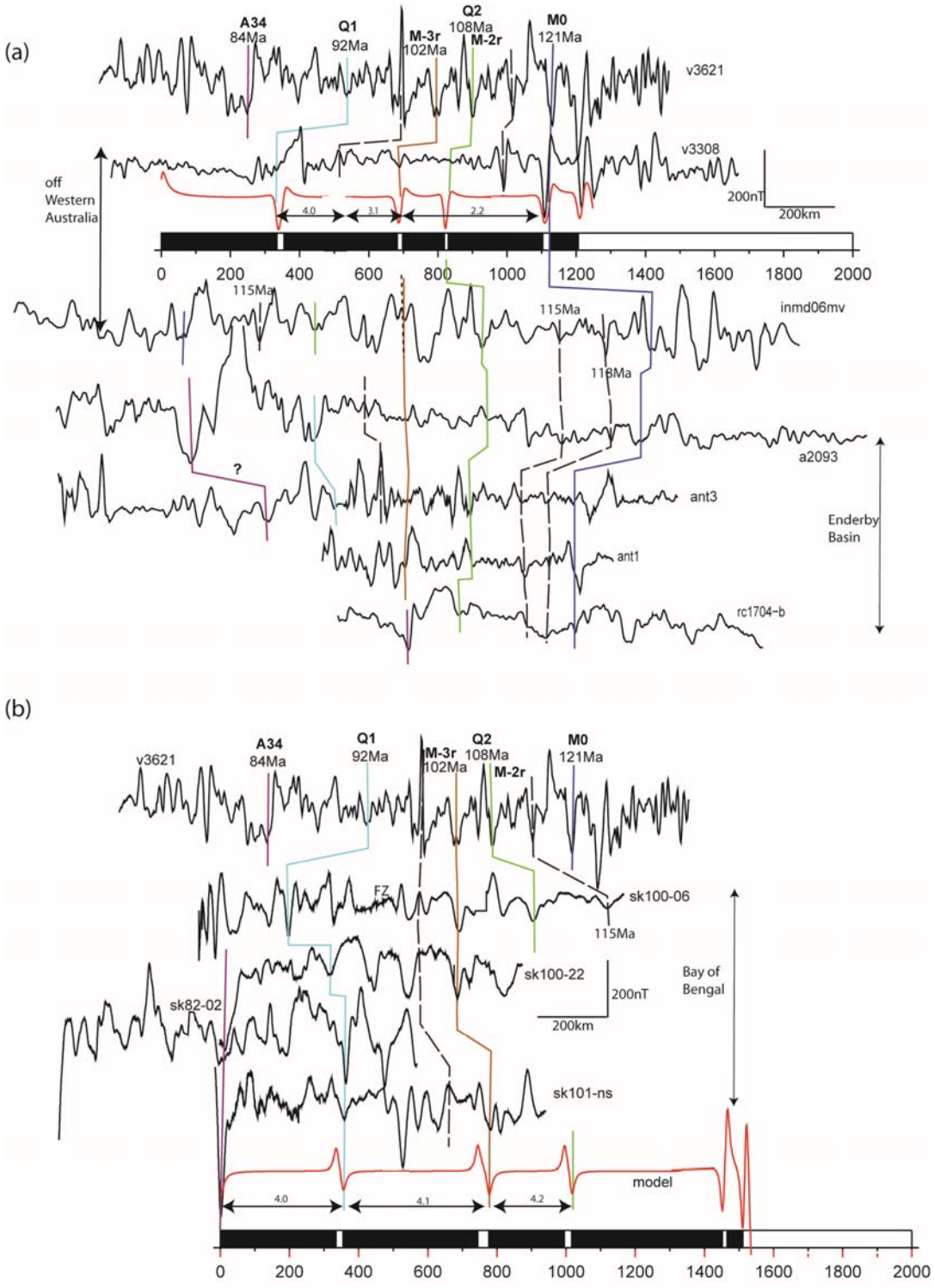


Figure. 5


(a)
A34
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off
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Australia
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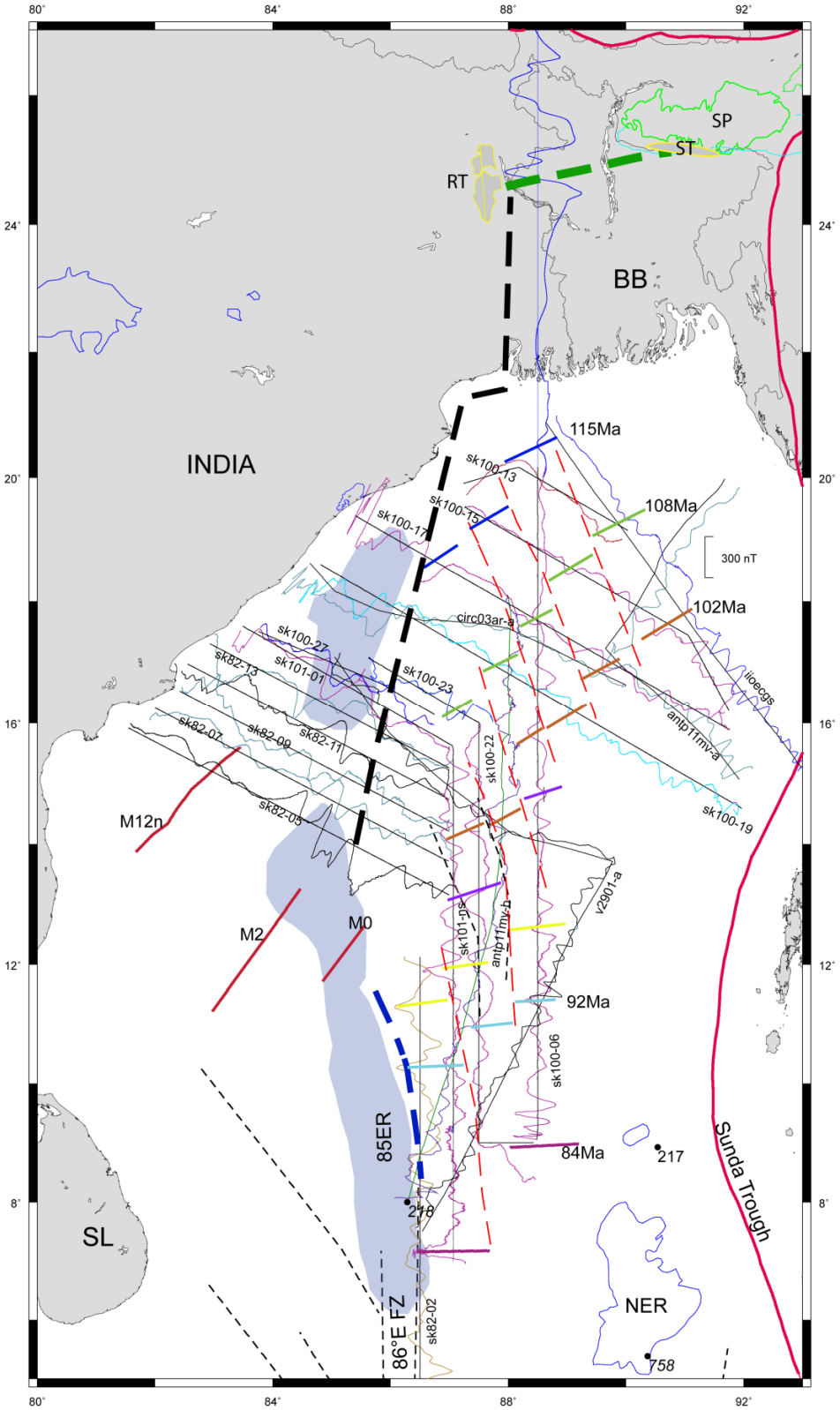
Figure. 6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circ03ar-a
sk100-27
sk82-13
sk101-01
sk100-23
sk82-07
sk82-09
sk82-11
sk82-05
sk100-22
ilioecos
antp11mv-a
sk100-19
M12n
M2
M0
sk101-pos
antp11mv-b
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Figure. 7

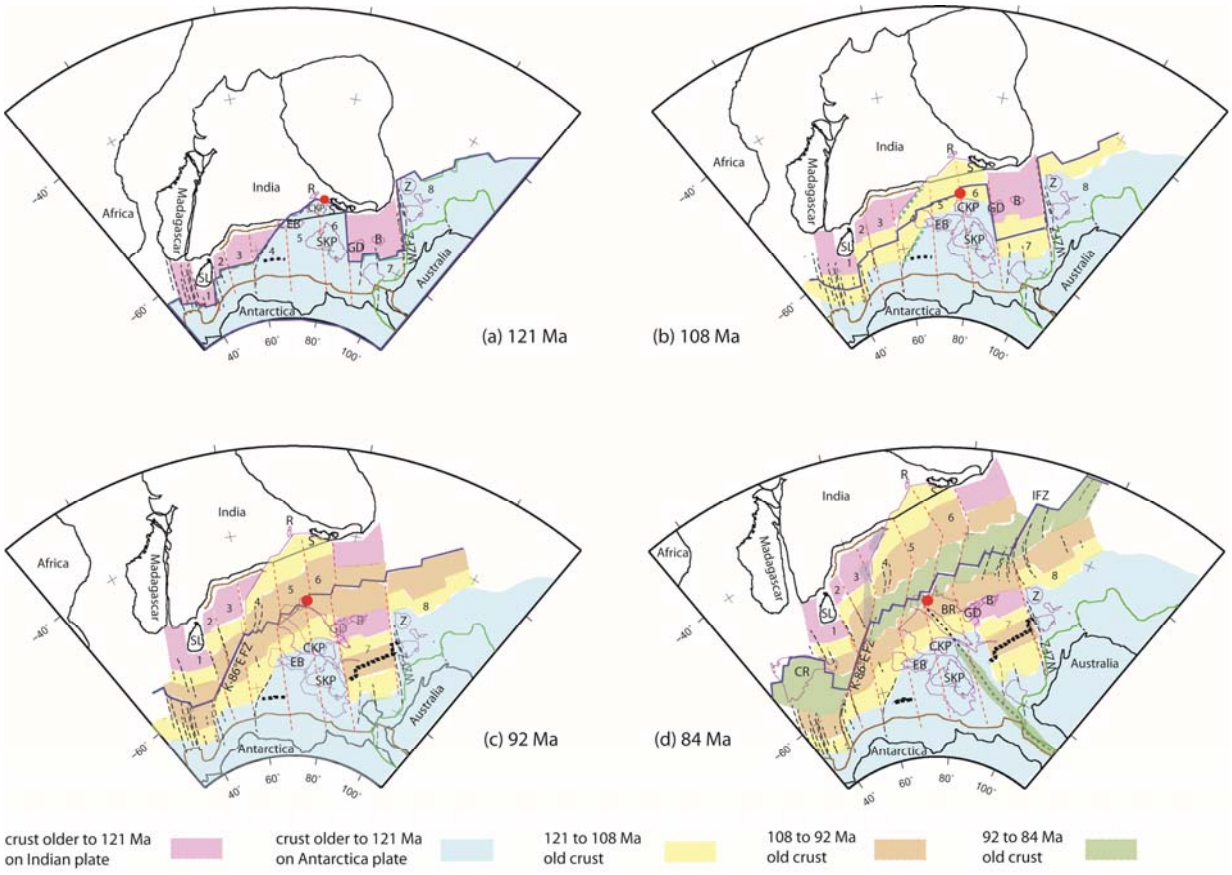

Figure. 8

Table1: Source for the magnetic data used in the present study

Profile name with location in brackets	Source
v3621 (Atlantic ocean)	NGDC
inmd06mv, v3308 (off Western Australia)	NGDC
a2093, rc1704-b (off East Antarctica)	NGDC
ant1, ant3 (off East Antarctica)	Sclater et al., 1976
iioecgs, antp11mv-a, antp11mv-b, circ03ar-a, v2901-a (Bay of Bengal)	NGDC
sk82-02,05,07,09,11,13 (Bay of Bengal)	NIO Database*
sk101-01,-ns (Bay of Bengal)	NIO Database*
sk100-06,-13,-15,-17,-19,-22,-23,-27 (Bay of Bengal)	NIO Database*

* Magnetic data along the segment of the tracks beyond the Indian EEZ extent (Figure S1) have been provided as supplementary information.

Table 2: Parameters used for synthetic seafloor spreading modeling and the computed spreading rates

Parameters	Cuvier Basin, Western Australia	Enderby Basin	Bay of Bengal
Spreading direction	130°	120°	0.0°
Thickness of magnetized layer	0.5 km	0.5 km	0.5 km
Susceptibility (cgs units)	0.015	0.015	0.015
palaeolatitude	-45°	-50°	-50°
Duration and Half Spreading rates (cm/yr)	121 to 102 Ma 2.2 102 to 96 Ma 3.1 96 to 92 Ma 4.0	121 to 115 Ma 3.9 115 to 108 Ma 3.2 108 to 102 Ma 3.0 102 to 84 Ma 2.9	108 to 102 Ma 4.2 102 to 92 Ma 4.1 92 to 84 Ma 4.0

Table 3: Rotation pole parameters used to generate the plate reconstruction models (Figure 8). Antarctica in its present day position. Elan Bank, Central and Southern Kerguelen Plateau were in their present day location by 121 Ma.

Moving plate	Time (Ma)	Latitude	Longitude	Angle
Sri Lanka	121	2.25	12.78	-81.65
	108	5.34	11.93	-77.07
	92	10.61	8.37	-69.16
	84	12.65	5.84	-62.51
India	121	2.13	12.95	-81.78
	108	5.3	11.97	-77.09
	92	10.62	8.37	-69.16
	84	12.66	5.8	-62.48
Australia	121	-0.768	42.58	-31.19
	108	0.239	41.80	-30.93
	92	2.23	40.75	-30.85
	84	5.58	38.79	-27.18
Zenith Plateau	121	-7.29	48.4	-34.21
	108	-5.82	47.18	-33.53
	92	-3.16	45.43	-32.9
	84	-0.05	43.89	-28.85
Batavia & Gulden Draak Knolls	121	-15.93	40.57	-38.41
	108	-10.133	45.234	-35.22
	92	2.23	40.75	-30.85
	84	5.58	38.79	-27.18