

## Reinterpretation of marine magnetic anomalies in the Bay of Bengal: Implications for plate tectonics during the mid-Cretaceous

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### Abstract

The breakup of India from Antarctica in the Early Cretaceous and subsequent seafloor spreading in the NW-SE direction initiated the formation of the Bay of Bengal and its conjugate Enderby Basin. Two hypotheses are proposed to explain the evolutionary tectonics between India and Antarctica. One involves a single breakup, while the second invokes another breakup episode. Further, a major reorganisation of the plate boundaries in the mid-Cretaceous caused the spreading center to align E-W by Late Cretaceous. The tectonics involved in this spreading direction change is unknown and difficult to understand as it occurred in the mid-Cretaceous, coincident with the Cretaceous Normal Superchron. In the present study, we have generated a revised magnetic isochron map of the Bay of Bengal and used the modulus of its analytic signal to understand the evolutionary tectonics between the two plates, India and Antarctica. Mesozoic magnetic anomalies M12n to M0, and mid-Cretaceous incursion Q2 (108 Ma) are identified in the western basin of the Bay of Bengal, while Q2, Q1 (92 Ma) and Late Cretaceous isochron A34 are inferred in its eastern basin. Gravity grid reconstructions demonstrate asymmetrical crustal accretion in the conjugate corridors. Fan-shaped spreading and a southward ridge jump between 108 and 92 Ma in the eastern basin, aided the ~40° clockwise rotation of the spreading center. The presence of volcanic basement beneath the additional crust suggests on-axis mode of formation for the Ninetyeast Ridge by 100 Ma. The present study favours the two-phase breakup model for the evolution of these plates.

**Key Points:** Clockwise rotation (~40°) of the spreading center between India and Antarctica during the mid-Cretaceous

Fan-shaped spreading and a southward ridge jump facilitated the clockwise rotation of the spreading center

Ninetyeast Ridge formed as on-axis volcanism during the mid-Cretaceous

**Keywords:** Bay of Bengal, mid-Cretaceous, magnetic anomalies, asymmetric crustal accretion, grid reconstruction, Enderby Basin

## 1 Introduction

The Bay of Bengal (BOB) and its conjugate, the Enderby Basin (EB) in East Antarctica formed due to the separation of India from Antarctica-Australia in the Early Cretaceous, and subsequent seafloor spreading in the NW-SE direction (Fig. 1) (Powell et al., 1988; Ramana et al., 1994; Lawver et al., 1998). The mid-Cretaceous is associated with a major plate reorganisation due to the arrival of the Kerguelen plume around 120 Ma beneath eastern India (Kent, 1991; Matthews et al., 2012; Talwani et al., 2016) culminating in steady seafloor spreading in the N-S direction by the Late Cretaceous (Royer and Sandwell, 1989; Royer and Coffin, 1992). The BOB is divided into two basins by the N-S trending 85°E Ridge (85ER): the western and eastern basins (Curry et al., 1982). This ridge buried under thick sediment cover, is inferred using seismic records and its typical gravity low (Curry et al., 1982; Liu et al., 1982). Along the 90°E meridian, the spectacular Ninetyeast Ridge (NER) is considered the trace of the Kerguelen plume (Pierce, 1978; Duncan, 1991; Coffin et al., 2002).

The BOB has been widely studied for its various extraordinary characteristics (Curry et al., 1982; Powell et al., 1988; Talwani et al., 2016). Despite these studies, there is no consensus on its formation with two hypotheses proposed to explain its evolution. The first one is that there was a single phase of breakup between India and Antarctica-Australia (Royer and Coffin, 1992; Ramana et al., 2001; Jokat et al., 2021), while the second one includes another phase of breakup due to plume-ridge interaction (Gaina et al., 2007; Gibbons et al., 2013; Talwani et al., 2016). Further the mechanism of the major plate reorganisation during the mid-Cretaceous is unknown. The development of these different geodynamic models is elaborated in the next section.

In the present study, we are reinterpreting the magnetic anomalies in the BOB and tracing the boundaries of the magnetic bodies using the modulus of the analytic signal. Further, we are using gravity grid reconstruction modelling to move from the well known Late Cretaceous plate configuration through the poorly known mid-Cretaceous arrangement to infer the tectonics that occurred in the BOB and EB.

Detailed reinterpretation of the existing geophysical datasets aided to infer the presence of additional oceanic crust in the eastern BOB that was transferred from the Antarctica plate. Clockwise rotation in the form of fan-shaped spreading and southward ridge jump facilitated the spreading center to align E-W by 92 Ma. The presence of volcanic basement beneath the additional crust indicates that the formation of NER was on-axis by 100 Ma. This integrated analysis supports the two-phase breakup model for the evolution of the conjugate plates.

## 2 Tectonic setting

The geodynamic models proposed for the evolution of the BOB and EB are described below in a chronological manner. Using plate reconstructions, these conjugate basins (Fig. 1) were considered to have formed due to seafloor spreading between India and Antarctica-Australia since the Early Cretaceous (Powell et al., 1988; Royer and Coffin, 1992; Lawver et al., 1998). Mesozoic magnetic anomalies M5 and M1 were first proposed in the BOB by Curray and Munasinghe (1991) (Fig. 2a). The arrival of the Kerguelen plume beneath eastern India by 120 Ma (Kent, 1991) is manifested as the Rajmahal and Sylhet (R-S) Traps (Mahoney et al., 1983; Baksi, 1995). Further, ODP investigations suggested that this plume activity resulted in the formation of several entities such as Bunbury basalts (132 to 122 Ma) of southwest Australia (Frey et al., 1996), the NER (82 to 37 Ma), Broken Ridge (~95 Ma) and the Kerguelen Plateau (KP, 119 to 34 Ma) in Antarctica (Duncan, 1991; Coffin et al., 2002).

Plate reconstructions also revealed that spreading between Greater India and Australia propagated southwest to join the Africa-Antarctica spreading center by M0 time (Royer and Coffin, 1992). Further, their study proposed that the KP complex was emplaced at ~110 Ma in a region between Greater India, Antarctica and Australia. Global relative plate motions indicated that between 118 and 95 Ma, the Kerguelen plume was located on the Antarctica plate forming the KP (Müller et al., 1993). Based on a systematic magnetic dataset of 8200 km acquired in 1992 in the BOB, Early Cretaceous magnetic anomalies M11 to M0 were identified (Ramana et al., 1994). These anomalies were reinterpreted (Fig. 2a) (Ramana et al., 2001) and a similar set of magnetic anomalies was identified in the EB (Fig. 2b). Similar magnetic anomalies were proposed in the region south of Sri Lanka (Fig. 2a) with unequal extent of mid-Cretaceous crust (Ramana et al., 1997; Desa et al., 2006). The above studies postulating a single breakup episode between India and Antarctica were preliminary, and plagued with numerous problems including the emplacement timing and dispersal of the Kerguelen plume products.

Detailed investigations in the KP began with wide-angle seismic data suggesting that southern KP is a volcanic passive margin fragment (Operto and Charvis, 1995). Drilling results also suggested its continental nature (Frey et al., 2000; 2002; Kent et al., 2002). The discovery of gneiss clasts in a polymict conglomerate at site 1137 on Elan Bank, west of KP (Weis et al., 2001; Ingle et al., 2002; Borissova et al., 2003) with similarities to the Eastern Ghats along the Indian east coast, suggested that Elan Bank is a continental sliver which was attached to the Indian plate. These continental fragments may have been transferred from India to Antarctica due to a northward spreading ridge

jump (Frey et al., 2000). These results laid the foundation for the two-phase breakup model between India and Antarctica.

In order to explain the above drilling results with a geodynamic model, Gaina et al. (2003) compiled the existing magnetic data and identified conjugate Mesozoic magnetic anomaly sequence (M9 to M2) about an extinct spreading ridge (ESR) in the eastern EB (Fig. 2b). The ESR with double limbed magnetic anomalies was extended in the western EB (Stagg et al., 2004). In contrast, Gaina et al. (2007) suspected that the northward ridge jump may be restricted to the eastern EB. Further, they identified magnetic anomalies M9 to M0 south of Sri Lanka and in western EB (Fig. 2).

In contrast to the above results, new aeromagnetic data collected east of Gunnerus Ridge (GR) suggested that the western EB crust was formed during the Cretaceous Normal Superchron (CNS) (Jokat et al., 2010). The age of oldest oceanic crust in the western basin of the BOB, south of Sri Lanka, and their conjugates was estimated at 127 Ma (Gibbons et al., 2013) with NW-SE spreading till 108 Ma (Fig. 2). Further, they reduced the age (115 Ma) of the northward ridge jump that transferred the microcontinents and oceanic crust from the Indian to Antarctica plate, and proposed that the spreading direction changed to N-S by 100 Ma. The Continent Ocean Boundary (COB) inferred off East Antarctica roughly matched that by Stagg et al. (2004) and Gaina et al. (2007).

Based on multichannel seismic data in BOB, Desa et al. (2013) proposed that the northern portion of the 85ER overlies a pseudofault along which a northward ridge jump occurred transferring the microcontinents from the Indian to Antarctica plate. Further, they proposed that these microcontinents were located northeast of Mahanadi offshore, and their transfer to Antarctica was followed by the formation of the relatively shallow basement east of 85ER. In a follow up study, existing magnetic datasets were reinterpreted and Mesozoic magnetic anomalies M12n to M0 were identified in the western basin of the BOB and entire EB (Fig. 2) (Talwani et al., 2016). Further, the presence of an ESR was asserted south of Elan Bank using geophysical signatures such as a prominent gravity low and symmetric magnetic anomalies. It was postulated that only the eastern segment of the spreading ridge between India and Antarctica jumped to the Kerguelen plume along a pseudofault (Talwani et al., 2016). A new line of opening was thus formed along the R-S traps, joining the western spreading segment via the pseudofault.

Spreading was now initiated in the eastern basin of the BOB (Desa and Ramana, 2016) and its direction gradually changed from NW-SE to N-S (Fig. 2a) by the Late Cretaceous (Royer and Sandwell, 1989) with major transform activity along the 86°E Fracture Zone (FZ)/Kerguelen FZ (86E/KFZ). Analysis of magnetic data west of NER suggested the occurrence of small northward

ridge jumps in the Late Cretaceous (Desa et al., 2009) due to Kerguelen plume-spreading ridge interaction (Fig. 2a). New magnetic datasets in the western basin of BOB confirmed the presence of magnetic anomalies M12n to M0 (Desa et al., 2018).

Using FZ trends and magnetic isochrons, Eagles and Konig (2008) proposed crustal ages of M10n to A34 for the region east of GR. Gravity trends and vector magnetic data were used (Nogi et al., 2004) to infer an initial breakup time of 127 Ma for the region east of GR. Leitchenkov et al. (2014) suggested that spreading in the EB began around 134 Ma and proceeded with half-spreading rates (HSR) of 2-6 cm/yr till 120 Ma. Two northward ridge jumps were proposed at 128 and 120 Ma, east of 60°E (Fig. 2b). Crustal structure of the EB was defined using gravity signature (Davis et al., 2019) and the COB was inferred south of that inferred by Gibbons et al. (2013). Moreover, they proposed that the Mac Robertson Coast Anomaly is coincident with a basement rise separating pure oceanic crust from the proto-oceanic crust as inferred by Gaina et al. (2007).

The above studies mainly based on the interpretation of magnetic, seismic reflection and gravity data, recommend that the BOB and EB formed due to seafloor spreading in two episodes: the first occurred passively in the NW-SE direction and formed the oceanic crust in the western basin of BOB, south of Sri Lanka, and western EB. The second occurred due to Kerguelen plume-spreading ridge interaction causing a northward ridge jump and transfer of microcontinents from India to Antarctica.

Recent contradictions to the above results include those by Sibuet et al. (2016), Jokat et al. (2021) and Altenbernd-Lang et al. (2022a & b). Based on observed low seismic velocities, Sibuet et al. (2016) proposed that the crust in the northern BOB (north of 19°N) is thinned continental crust with minor underplating, and intruded by volcanism. This was refuted by Talwani et al. (2017) saying that these low velocities are typical of volcanic passive margins (Eldholm and Grue, 1994), and the northern BOB is indeed a volcanic passive margin.

Deep wide-angle seismic and magnetic experiments were carried out in the eastern EB and south of Sri Lanka (Jokat et al., 2021). Variable HSR of 2 to 10.5 cm/yr for chrons M1r to M9n were inferred along the profiles in eastern EB with no signature of an ESR (Jokat et al., 2021). Further, their velocity-depth model indicated that the region south of Sri Lanka is oceanic; and dense ship-borne magnetic data aided to propose Q1 and Q2 isochrons of mid-Cretaceous age (HSR: ~3 cm/yr). Thus they concluded that the separation of India-Sri Lanka from Antarctica occurred in a single phase without any major ridge jumps, but by action of three spreading ridges with different timings and velocities, including significant intracontinental deformation. Their proposition was questioned by

Krishna and Ismaiel (2023) as it could not justify the presence of old continental material beneath Elan Bank and southern KP (Weis et al., 2001; Ingle et al., 2002; Borissova et al., 2003), as well as similar ages of R-S traps and southern KP basalts (Mahoney et al., 1983; Baksi, 1995; Coffin et al., 2002; Frey et al., 2002).

Altenbernd-Lang et al. (2022a) used seismic refraction and gravity data along a profile south of Sri Lanka to infer the COB beyond stretched continental crust, and unusually high velocities in the upper mantle of the oceanic crust. Based on seismic reflection and refraction data off Prydz Bay, Altenbernd-Lang et al. (2022b) suggested that oceanic crust begins 160 km further south than previously proposed (Fig. 2b) and the Mac Robertson Coast Anomaly is not a COB but chron M4.

### 2.1 Mid-Cretaceous reorganisation

The mid-Cretaceous (120 to 83 Ma) is characterised by a global major plate reorganisation (Veevers, 2000; Matthews et al., 2012). It also corresponds to the CNS wherein no reversals in the Earth's magnetic field are reported. Hence it is difficult to directly date the events taking place during this period. In contrast to the belief that this period is characterised by normal polarity, Tarduno (1990) reported a short reversal at ~115 Ma. Granot et al. (2012) reported two major fluctuations in the dipolar geomagnetic field intensity globally in the CNS and termed them as Q1 (92 Ma) and Q2 (108 Ma).

In the Indian Ocean, the mid-Cretaceous major plate reorganisation is associated with 50° bend of the FZs in Wharton Basin, spreading ridge extinction, ridge jumping, etc (Müller et al., 2000). Extinctions were identified in the Perth and Wallaby Basins off Western Australia wherein large amount of oceanic crust was transferred from the Indian to the Australian plate (Gibbons et al., 2012). Williams et al. (2013) reported that Gulden Draak and Batavia Knolls in the Perth Basin are continental fragments separated from India due to north-westward ridge jumps after spreading ceased at ~102 Ma. Further, the Dirck Hartog Ridge formed as an ESR under the influence of the Kerguelen plume (Watson et al., 2016).

The conjugate FZ bends in the EB and BOB (Rotstein et al., 2001) also belong to the mid-Cretaceous plate reorganisation. These bends represent a clockwise change in spreading direction between India and Antarctica around 98 Ma (Matthews et al., 2012; Gibbons et al., 2013). Further, the appearance of a FZ-perpendicular ridge-like pattern in the vertical gravity gradient map truncating the NNE-SSW trending FZs in the western EB represents ridge jumping (Rotstein et al., 2001). Nogi et al. (2004) postulated a northward ridge jump between western EB and Conrad Rise during this period.

The Kerguelen plume activity which began beneath eastern India by 120 Ma (Kent, 1991) may have triggered the major plate reorganisation in the Indian Ocean.

## 2.2 The Ninetyeast Ridge

The Ninetyeast Ridge (NER) is ~4500 km long topographic feature extending between 35°S and 10°N (Fig. 1). The ridge has an average width of 200 km and an elevation of more than 2 km along most of its length. It is buried under thick Bengal sediments north of 10°N (Curry et al., 1982). However, Maurin and Rangin (2009) imaged the ridge using seismic data up to 20°N with Miocene and older sediments draping on it.

Though numerous hypotheses have been proposed for the formation of NER and Broken Ridge (eg. Bowin, 1973; Sclater and Fisher, 1974), the hotspot hypothesis is widely accepted (Peirce, 1978; Royer et al., 1991; Klootwijk et al., 1992). The NER formed as the Indian plate moved over the nearly stationary Kerguelen hotspot. The hotspot volcanism underplated the pre-existing crust causing its anomalous thickness of up to 24 km (Grevemeyer et al., 2001). Drilling data on the NER suggests that the ridge ages towards north (43 Ma at site 254 near Broken Ridge to >80 Ma for deepest drilled sediments at site 217 at 9°N) (Pringle et al., 2008). Further, the ridge basalts have erupted at ~49°S (Klootwijk et al., 1992).

The ridge was attached to the Indian plate, and both have moved rapidly northward since Late Cretaceous (Sclater and Fisher, 1974; Pierce, 1978). The oceanic crust west of NER depicts increasing age northwards similar to that of the ridge, while east of NER, the crustal ages increase southwards (Sclater and Fisher, 1974).

## 3 Data and Methodology

A dense network of ship-borne magnetic data acquired in the BOB by CSIR-NIO for the last five decades has been used in the present study. This dataset combined with the publicly available magnetic data (NCEI, NOAA) amounted to 77,400 km (Fig. 3a). The magnetic anomalies are plotted along their tracks (Fig. 3b) to make the chron identifications which form the base to generate the reconstructions as well as the updated crustal age map of BOB. Further, we have used the global grids EMAG2 (Maus et al., 2009) and recent satellite gravity (Sandwell et al., 2014) to complement our datasets.

We begin our analysis cognizant of the two-phase breakup scenario and then we discuss why we favour this scenario over the single phase. The profiles in the western and eastern basins of the BOB are handled separately as these basins are known to belong to different time periods (Talwani et al., 2016; Desa and Ramana, 2016). The synthetic seafloor spreading models are generated with

parameters provided in table 1. The Early Cretaceous identifications in the western basin are done using the Gee and Kent (2007) geomagnetic polarity time scale (Fig. 4a). The magnetic anomalies in the eastern basin have been studied in terms of the two geomagnetic field incursions (Q1 and Q2, Granot et al. (2012)) as done by Desa and Ramana (2016) (Fig. 4b). All the profiles are compared with the models despite their varying azimuths, and identifications are made with utmost care considering various spreading parameters and FZ locations. These anomaly identifications are extended throughout the study area and posted onto the magnetic anomaly map (Fig. 5a). The modulus of the analytic signal has been computed from the magnetic anomalies (Supplementary Information; Fig. S1). The refined crustal age map is also prepared based on our identifications (Fig. 5b). Spreading velocities are calculated in both the single and two-phase breakup scenarios (Supplementary Information; Tables S1 & S2).

Further, the prominent gravity lineation (Fig. 3a), major magnetic anomaly trends and increasing distance between Q1 and Q2 identifications (Fig. 5a) in the eastern basin prompted us to perform additional geophysical analysis. Gravity and magnetic signatures were studied to identify the presence of any ambiguous structures (Fig. 6a and b) such as ESR, additional crust, etc.

### 3.1 Gravity grid reconstructions

Gravity grid reconstruction models have been generated for A34 (83 Ma), Q1 (92 Ma) and Q2 (108 Ma) (Fig. 7) in order to investigate how the conjugate plate boundaries have changed during the mid-Cretaceous (Table 2). The A34 Late Cretaceous model is well defined and accepted for the entire Indian Ocean (Norton and Sclater, 1979; Powell et al., 1988; Royer and Sandwell, 1989; Williams et al., 2013) (Fig. 7c). This reconstruction has been considered as the base and we have moved backwards from the known to unknown domain of the mid-Cretaceous period. The overall complex scenario seen in the A34 grid reconstruction also prompted us to look closely for signatures manifesting any plate boundary reorganisation. The constraints include the magnetic picks, locations of the magnetic edges and FZs on both the conjugate plates. Here we mention that the constraints in the EB are limited and obtained only from published literature/global grids. Spreading corridors separated by major FZs are delineated, and the velocities during different time periods are estimated (Table S1). Further, the pros and cons of both single and two-phase models are discussed in terms of crustal asymmetry, spreading velocities and directions in a regional framework.

## 4 Results

The magnetic anomalies in the BOB are subdued probably due to thick sediment load (Curry et al., 1982) and are rather difficult to recognize (Fig. 3b). Nonetheless the Early to mid-Cretaceous



magnetic anomalies could be identified confidently in the BOB (Figs. 4 and 5). The synthetic seafloor spreading model (Fig. 4a) proposes the identification of Early Cretaceous magnetic anomalies M12n to M0 and mid-Cretaceous incursion Q2 in the western basin. HSR are moderate ranging between 2.8 and 4.4 cm/yr. The disposition of these anomalies suggests that spreading occurred in the NW-SE direction during the Early Cretaceous (Fig. 5a). The anomalies show minor offset which is left lateral towards south. Further, towards north, these anomalies appear truncated along the N-S trending northern portion of the 85ER (Fig. 5a).

The synthetic seafloor spreading model (Fig. 4b) suggests the presence of mid-Cretaceous incursions Q2 (108 Ma) and Q1 (92 Ma), and Late Cretaceous anomaly A34 (83 Ma) in the eastern basin. HSR are steady at ~4.0 cm/yr. Their disposition indicates that Q2 trends NE-SW with left lateral offsets in the north, east of 85ER. These Q2 picks join those in the south, west of 85ER (Fig. 5a). The Q1 and A34 isochrons trend E-W with left lateral offsets east of 85ER. Based on the offsets in the magnetic anomalies, a few FZs can be inferred which bend from NW-SE in the north to N-S towards south. The distance between Q2 and Q1 is seen increasing towards east. Further, diverging trends are seen in the easternmost corridor.

The prominent NE-SW trending lineation seen on the satellite gravity data in the eastern basin (Figs. 3a & 6a) is a strong gravity low. Analysis of the magnetic data on its either side reveals that this lineation is flanked by symmetric magnetic anomalies (Fig. 6b). This scenario prompted us to infer the presence of an ESR along the gravity lineation (Jonas et al., 1991). Further, a wedge-shaped additional crust, lying between 89 and 92.5°E and 14.5 to 18°N, is inferred (Fig. 6a). It tapers towards west (120 km) from an extent of 300 km in the east.

The crustal age map (Fig. 5b) depicts ages from 133 Ma to 92 Ma in the western basin of BOB. Towards east, crustal ages younger to 120 Ma with trends changing from NE-SW to E-W are inferred. The crustal ages are offset along FZs with the largest offset along the 86EFZ. The additional crust depicts ages between 98 and 105 Ma indicating that the ridge jump occurred at ~98 Ma and captured crust of age up to 105 Ma.

#### 4.1 Gravity grid kinematics

The gravity grid reconstructions trace the temporal evolution of the oceanic crust in the conjugate BOB and EB (Fig. 7). Five (A to E) spreading corridors between India and East Antarctica are inferred. One can clearly see that unequal extent of the crust is generated at different times in these corridors (Table S1). The conjugate FZs are well aligned till Q2 time (Fig. 7a), and the conjugate of the pseudofault (northern portion of the 85ER) has moved away by about 550 km. Circular trend of

the FZs is observed in corridor D between the isochrons Q2 and Q1 (Fig. 7b). The 86E/KFZ is seen as a double limbed FZ having a large (900 km) offset within which the Q1 and A34 isochrons can be identified (Fig. 7c). The corridors A and B truncate at this FZ while the corridor C thins/wedges into it. Further, the models depict 40° clockwise rotation of the spreading center to align E-W by Q1 time (Fig. 7). The complex tectonics seen in the above reconstructions has been interpreted in terms of crustal accretion asymmetry and changes in plate motion in the conjugate basins.

#### 4.1.1 Asymmetry in corridors

Corridor A between Sri Lanka and western EB depicts slightly deficient crust older to Q1 on the Indian plate (Table S1, Fig. 7). Between Q1 and A34, significant amount of excess crust is seen on Antarctica plate. This excess crust depicts prominent cross trends along with positive gravity signature. In Corridor B, excess crust was generated prior to Q2 on Antarctica plate (Table S1, Fig. 7). But between chronos Q2 and Q1, slightly excess crust is produced on Indian plate. No crust younger to Q1 is seen in this corridor. Excess crust is seen of age between M0 and Q2 as well as of age between Q2 and Q1 on the Antarctica plate (Table S1), in corridor C.

Corridor D is associated with the truncation of Early Cretaceous crust along a pseudofault, the northern extent of the 85ER (Fig. 7a). Thereafter, asymmetric crust is seen forming with excess crust generated on the Antarctica plate until Q2 time. Between Q2 and Q1, excess crust is seen increasing towards east on Indian plate as fan-shaped spreading. The corridor E also depicts excess crust on the Antarctica plate until Q2 time (Fig. 7, Table S1). Between Q2 and Q1, highly excess crust is seen as continuation of fan-shaped spreading on the Indian plate. The prominent gravity lineation marks the location on an ESR with the wedge-shaped additional crust to its south (Fig. 6). Between isochrons Q1 and A34, one can see symmetric crust generated in corridors D and E (Fig. 7c).

## 5 Discussion

Both the single and two-phase breakup models predict that seafloor spreading occurred in the NW-SE direction between India and Antarctica during the Early Cretaceous (Powell et al., 1988; Lawver et al., 1998; Gaina et al., 2007; Gibbons et al., 2013; Talwani et al., 2016; Jokat et al., 2021). Thereafter, the spreading became N-S by the Late Cretaceous (Royer and Sandwell, 1989; Royer and Coffin, 1992). Our magnetic anomaly reinterpretation and the gravity grid reconstructions are in agreement with this spreading pattern (Figs. 5 & 7). Further, the presence of an ESR and wedge-shaped additional crust has been inferred based on their characteristic gravity and magnetic signatures in corridor E (Fig. 6). Ship-borne gravity contour map of BOB clearly depicts trends

changing from NE-SW in the north to E-W towards south in this region (Subrahmanyam et al., 2001).

Gibbons et al. (2013) proposed a pseudofault in the western basin of BOB which isolated Early Cretaceous isochrons M0 to M4 from the younger crust towards east (Fig. 2a). Similar pseudofault was marked in the EB separating the double limbed Mesozoic crust inferred south of Elan Bank from the younger crust towards west (Fig. 2b). These pseudofaults were based on a faint lineation visible in marine gravity grid. Our gravity as well as magnetic analysis did not find any evidence of this pseudofault in the western basin of BOB (Fig. 3). Rather, the abrupt termination of the Early Cretaceous magnetic anomalies M12n to M2 at the northern portion of the 85ER (Fig. 5) points to a pseudofault along the ridge as inferred by Desa et al. (2013). Indeed, the northern portion of the 85ER and its conjugate, are considered pseudofaults along which the northward ridge jump took place after M2 time (Talwani et al., 2016).

Further, synthetic isochrons at 108 Ma and 100 Ma (Fig. 2) were marked in the conjugate basins by Gibbons et al. (2013). The present study depicts that our 108 Ma is nearly similar to the 108 Ma synthetic isochron of Gibbons et al. (2013) (Fig. 7a). But our 92 Ma is nearly same as their 100 Ma isochron (Fig. 7b). Their 90 Ma reconstruction depicts that the 86E/KFZ was formed by this time, while our reconstructions suggest that the 86E/KFZ formed by 92 Ma (Fig. 7).

### 5.1 Changes in plate motion

Changes in trends in magnetic anomalies and FZs across world oceans have been attributed to major changes in relative motion between two plates (Menard and Atwater, 1968). In the present study, and in agreement to both the models, the change in the magnetic isochron trend from NE-SW to E-W from the Early to Late Cretaceous implies a change in plate motion between India and Antarctica during that period (Fig. 5). This change in plate motion occurred in the mid-Cretaceous and can be associated with the global major plate reorganization (Matthews et al., 2012). Moreover, a rapid change in spreading direction with high degree of obliquity is proposed in the eastern basin of BOB (Seton et al., 2020).

The changes in spreading direction may occur by smooth and continuous rotations of individual spreading ridge segments (Menard and Atwater, 1968). Alternately, ridge reorientation may occur by rift propagation of a new ridge with a different trend, gradually replacing the old ridge (Hey, 1977). The rift propagation hypothesis suggests that these changes occur at abrupt discontinuities such as failed rifts or pseudofaults (Hey et al., 1988). The crust is progressively transferred from one plate to another between the propagating and failed rifts, and FZs form only after propagation ends.

Further, reorientation of rift segments occurs rather rapidly in response to changes in plate motion and ridge jumps could actually be fast propagation episodes (Caress et al., 1988).

In the present study, the change in the magnetic isochron trends depicts  $\sim 40^\circ$  clockwise rotation of the spreading center from Early to Late Cretaceous. This change may have been accomplished by either mode of ridge reorientation. Reorientation of the spreading center (Fig. 7) may have occurred as continuous rotation with fan-shaped spreading as displayed by the circular trend of the FZs in corridor D (Menard and Atwater, 1968). This fan-shaped spreading is absent on the Antarctica plate, hence it may have occurred in off-axis setting. Further, the southward ridge jump facilitated the clockwise rotation of the spreading center in corridor E. In the absence of any FZs in this corridor we propose that this is a case of rift propagation as suggested by Hey (1977).

## 5.2 Crustal accretion asymmetry

Asymmetric crustal accretion is reported in the Indian Ocean (Müller et al., 2008) and is attributed to small ridge jumps sustained by asthenospheric flow. Such ridge jumps occur due to plume-ridge interaction keeping the ridge in the proximity of the plume (Small, 1995). As the Indian plate moved north with respect to the nearly stationary Kerguelen plume, small southward ridge jumps of the spreading center west of the NER kept the spreading center in the vicinity of the plume (Desa et al., 2009; Krishna et al., 2012) transferring up to  $11^\circ$  of oceanic crust from the Antarctica to Indian plate (Sclater and Fisher, 1974). Indeed, excess crustal accretion of  $>60\%$  is proposed in eastern BOB (Seton et al., 2020).

In the single breakup scenario, excess crustal accretion can be inferred on Antarctica plate due to HSR (2 - 3.1 cm/yr) in comparison to that on Indian plate (1.8 - 2.1 cm/yr) (Table S2). According to the two-phase breakup model, asymmetric crustal accretion between the two plates first began around 120 Ma, when a northward ridge jump to the R-S line occurred due to Kerguelen plume-ridge interaction (Talwani et al., 2016). Here, oceanic crust and microcontinents were transferred from India to Antarctica with the 85ER as a pseudofault for its western boundary (Fig. 7). The excess crust generated on the Antarctica plate between 120 and 108 Ma, (Fig. 7a, Table S1) may be due to plume-ridge interaction (Gibbons et al., 2013). Another possibility is that the northward ridge jump around 120 Ma is itself a rift propagation (Hey, 1977) with 85ER as a major outer pseudofault resulting in excess crust (fossil transforms and ridge segments) on one plate, Antarctica plate in this case.

Between 108 and 92 Ma, (Fig. 7b), the relatively excess crust seen on Indian plate in corridor D, can be attributed to the fan-shaped spreading causing rotation of the spreading center (Table S1). This

asymmetric crustal accretion may comprise minor southward ridge jumps which are not discernible with our datasets. Crustal asymmetry seen on the Indian plate in corridor E is (Fig. 6) due to a southward ridge jump of the spreading center at around 98 Ma capturing wedge-shaped crust of up to 300 km extent and age up to 105 Ma. The fluctuations in crustal accretion between plates in corridors B and C may be related to the initiation of the new transform fault (86E/KFZ) cutting through old seafloor leaving fossil ridge segments on either plate (Caress et al., 1988). Fossil ridge segments have indeed been inferred in western basin of BOB based on gravity signature (Krishna et al., 2009).

### 5.3 Spreading Corridor 'A' tectonics

Corridor A has been generally considered as the full-fit location of Sri Lanka prior to breakup between India and Antarctica (eg. Powell et al., 1988; Lawver et al., 1998). Early Cretaceous crust was inferred in this corridor on the Indian plate (Desa et al., 2006; Gaina et al., 2007), and on Antarctica plate (Nogi et al., 2004; Eagles and Konig, 2008). Further, oceanic crust of age 127 to 100 Ma, with spreading direction change around 108 Ma was inferred on both plates by Gibbons et al. (2013). Additionally, plate and grid reconstructions asserted the continuity of Early Cretaceous crust from western basin of the BOB to south of Sri Lanka (Talwani et al., 2016). In contrast to these results, Jokat et al. (2010) inferred that this corridor on Antarctica plate is of mid-Cretaceous age. More recently, the age of the oldest crust south of Sri Lanka was estimated at 112 Ma (Jokat et al., 2021).

West of corridor A, Mesozoic crust has formed since 152 Ma between Africa and Antarctica (Marks and Tikku, 2001; Leitchenkov et al., 2014). East of this corridor, the breakup time ranging between 132 and 127 Ma has been reported (Gaina et al., 2007; Gibbons et al., 2013; Talwani et al., 2016). Based on existing geophysical data, Gibbons et al. (2013) proposed that ~200 km extension between Sri Lanka and India before M0 time followed by compression/subduction would be needed, if mid-Cretaceous age is assigned for the crust east of GR. Further, if we consider the mid-Cretaceous age of Jokat et al. (2021) for this corridor, high HSR (4.8 and 3.2 cm/yr on Antarctica and Indian plates respectively; Table S2) are inferred, in comparison to those in adjoining corridors. Moreover, we opine that the misalignment between the magnetic tracks (Jokat et al., 2010; 2021) and FZ trends east of GR as well as south of Sri Lanka could be the reason for their incorrect age assignment.

Our reconstructions point towards an Early Cretaceous age for the start of seafloor spreading in this corridor (Fig. 7a). The relatively excess crust seen on Antarctica plate between 108 and 92 Ma, (north of GR) (Fig. 7b; Table S1) can be attributed to a northward ridge jump as postulated by Nogi et al. (2004). Between 92 and 83 Ma, the highly asymmetric crustal extent indicates another episode

of northward ridge jumping transferring large amount of Indian crust to Antarctica plate (Fig. 7c, Table S1). This ridge jump may have also been accompanied by volcanism, as seen by the prominent positive gravity signature and can be attributed to Marion plume activity (Storey et al., 1995; Torsvik et al., 2000) and/or triple junction dynamics (Desa et al., 2019).

#### 5.4 Formation of NER

The NER was attached to the Indian plate and depicts northward increasing ages (Peirce, 1978). Further several southward ridge jumps along the ridge have been proposed which resulted in significant lengthening of the ridge (Sclater and Fisher, 1974). Southward ridge jumps have been reported along the NER since 75.8 Ma (Desa et al., 2009) and during Tertiary (65 and 42 Ma) (Krishna et al., 2012). Such spreading ridge jumps towards the relatively stationary Kerguelen hotspot as the Indian plate moved northward are attributed to plume-ridge interaction (Small, 1995). Krishna et al. (2012) discussed various scenarios for plume-ridge interaction during the formation of NER. They proposed that before 74 Ma, the ridge formed in intraplate setting (off-axis volcanism) with the Kerguelen hotspot beneath Indian plate. Thus it was proposed that the NER formed due to off-axis volcanism north of 5°N in the BOB.

The southward ridge jump in the easternmost spreading corridor E inferred in the present study lies along the NER trace (Fig. 7). The additional crust transferred from the Antarctica plate coincides with the volcanic basement inferred by Maurin and Rangin (2009) suggesting that NER is present on the additional crust too (Fig. 6a). Thus volcanism may have occurred on both plates as on-axis volcanism during the mid-Cretaceous. This is in contrast to the inference made by Krishna et al. (2012) that the ridge has formed in intraplate settings north of 5°N. Further, based on our magnetic analysis (Fig. 6) we can assign a starting age of 100 Ma for the formation of the NER.

#### 5.5 Two-phase breakup tectonics

Detailed analysis of previous results together with those inferred in this study prompts us to favour the two-phase breakup model. The seed of a two-phase breakup scenario was planted by Powell et al. (1988) despite lack of strong evidence. Their 84 Ma model depicted a drastic realignment of the spreading ridge after 96 Ma wherein a sizeable extent of oceanic crust together with spreading ridge was transferred from India to Antarctica. A dilemma arose when global relative plate motions indicated that the Kerguelen plume lay beneath the Antarctica plate forming the KP between 118 and 95 Ma (Müller et al., 1993) and simultaneously forming the R-S Traps (Baksi, 1995; Mahoney et al., 1983), located >1000 km north. Drilling results on the KP went in favour of the two-phase breakup

scenario when the presence of continental fragments having Indian Eastern Ghats affinity was proposed (Frey et al., 2002; Borissova et al., 2003).

FZ trends both in the BOB and EB manifest change in spreading direction during the mid-Cretaceous (Wessel et al., 2015). Further, the 86E/KFZ is seen as a prominent FZ with older FZs terminating onto it suggesting drastic change in plate motion which cannot be explained by a single phase model (Rotstein et al., 2001). Multichannel seismic records in the northern BOB revealed shallow basement east of 85ER in comparison towards west (Desa et al., 2013). Further, similar records indicated thick oldest sediments west of 85ER, and their absence to its east (Desa et al., 2023). Above seismic results indicate younger ages to the oceanic crust east of 85ER favoring the two-phase breakup between India and Antarctica.

Ridge jumps and transfer of crust including microcontinents from Indian to Australian plate were reported in the mid-Cretaceous (Gibbons et al., 2012; Williams et al., 2013; Watson et al., 2016) due to Kerguelen plume-spreading ridge interaction. Likewise, the northward ridge jump (Talwani et al., 2016) transferred several microcontinents from Indian to Antarctica plate (Frey et al., 2002; Borissova et al., 2003) and initiated the formation of the mid-Cretaceous crust, east of the 85ER (Desa and Ramana, 2016).

Clockwise rotation of the spreading center east of 85ER began after 108 Ma as fan-shaped spreading in corridor D and southward ridge jumping in corridor E (Fig. 7). This ridge jump is probably the earliest southward ridge jump after the northward ridge jump to the R-S line. These tectonics belong to the major plate reorganisation that occurred in the mid-Cretaceous (Matthews et al., 2012), wherein the spreading direction became N-S by 92 Ma. FZ1 and FZ2 merged into the 86E/KFZ to act as a major transform fault along which symmetric spreading occurred in the eastern basin. As India was moving over the relatively stationary Kerguelen plume, the NER formed as on-axis volcanism since 100 Ma.

Low confidence is assigned to the crustal age grid of the conjugate basins BOB and EB (Seton et al., 2020) recommending reinterpretation of existing datasets or collection of additional data. Based on reinterpretation of existing datasets, we have drawn our major conclusions. New datasets in the form of high resolution deep seismics and magnetic data are needed to substantiate the presence of ESR, additional crust and the northern extension of the NER in the BOB.

## **6 Conclusions**

The present study favours the two-phase breakup scenario between India and Antarctica wherein the Kerguelen plume-spreading ridge interaction caused the NE-SW trending Early Cretaceous

spreading center in the BOB to align E-W by 92 Ma. This change was accomplished by a 40° clockwise rotation of the spreading center during the mid-Cretaceous coinciding with the global major plate reorganisation.

Marine magnetic data reveals Mesozoic magnetic anomalies M12n to M0 and mid-Cretaceous incursion Q2 (108 Ma) in the western basin of the BOB, while Q2 and Q1 (92 Ma), and Late Cretaceous isochron A34 are seen in its eastern basin. The BOB is divided into five spreading corridors by prominent FZs.

The 108 Ma model depicts continuation of NW-SE spreading east of 85ER in the north and west of 85ER in the south. Asymmetric crustal accretion is seen with excess crust on the Antarctica plate. The 92 Ma model depicts that the 86E/KFZ became active with the southern corridors terminating/wedging into it. The circular trend of the FZs in corridor D suggests that rotation of the spreading center occurred as fan-shaped spreading with excess accretion towards east on Indian plate.

In the easternmost spreading corridor E, a southward ridge jump transferred a wedge-shaped crustal block from the Antarctica to Indian plate. This jump probably occurred at 98 Ma and the crust captured is of age up to 105 Ma. This ridge jump facilitated the spreading ridge to remain in the vicinity of the plume and also aided in the clockwise rotation of the spreading center. The presence of volcanic basement in the transferred crust suggests that NER has formed as on-axis volcanism since 100 Ma.

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### **Data availability statement**

The magnetic data in the study includes 44,100 km acquired by CSIR-NIO and 33,300 km by NCEI, NOAA. Sharing of data acquired by CSIR-NIO within the EEZ of India is prohibited. Hence the data outside the EEZ will be shared from the CSIR-NIO repository <https://publication-data.nio.org/>.



## Figure Captions:

Figure 1: Bathymetry map of the Indian and Southern Oceans (Smith and Sandwell, 1997). The present day mid-oceanic ridge is marked in red. Large igneous provinces are outlined in pink (Eldholm and Coffin, 2000). Study area is marked in a box. CBR: Carlsberg Ridge; CIR: Central Indian Ridge; CKP: Central Kerguelen Plateau; CLR: Chagos-Laccadive Ridge; GR: Gunnerus Ridge; NER: Ninetyeast Ridge; NKP: Northern Kerguelen Plateau; SEIR: Southeast Indian Ridge; SKP: Southern Kerguelen Plateau; SWIR: Southwest Indian Ridge.

Figure 2: Previous magnetic interpretations (continuous line), FZs (thin dashed line) and pseudofaults (thick dashed line) are marked in different colours as per legend and superimposed on the crustal age map (Seton et al., 2020). (a) BOB: COB by Nemčok et al. (2012) is marked in white, gravity low of 85ER is marked in pink (b) EB: COB by Davis et al. (2019) is marked in cyan, by Gibbons et al. (2013) in red, and by Altenbernd-Lang et al. (2022b) in green.

Figure 3 (a): Magnetic tracks plotted on the satellite gravity map of the BOB (Sandwell et al., 2014). The tracks acquired by CSIR-NIO are in black, while the tracks from NOAA are in white. The gravity low of the 85ER is outlined in blue. A prominent gravity lineation towards east is marked as a blue dashed outline. The Sunda Trench is marked as black outline. (b): Magnetic anomalies are plotted along the tracks. The wiggles of the tracks acquired by CSIR-NIO are in red, while those from NOAA are in blue. The gravity low of the 85ER is outlined in green. The profiles along which seafloor spreading modelling is done are marked in yellow and labelled. The Sunda Trench is marked as black outline.

Figure 4: Synthetic seafloor spreading model (red) and magnetic anomalies (black) along profiles whose location is given in figure 3b. Synthetic model parameters are given in table 1. HSR are in cm/yr. (a) western BOB: Early Cretaceous magnetic anomalies M12n to M0, and magnetic incursion Q2 are prominently seen on most profiles. The extent of anomalies affected by the 85ER is shaded in pink. (b) eastern BOB: Magnetic incursions Q2 and Q1 and Late Cretaceous magnetic anomaly A34 are seen on most profiles.

Figure 5 (a): Magnetic data plotted in black along the tracks marked in blue in the BOB. Magnetic anomalies are identified by colored circles as per legend. FZs marked as red dashed outlines: the thinner ones are from this study, while the thicker ones are from Wessel et al. (2015). The gravity low of the 85ER is shaded pink. The diverging trends seen towards east are marked as green outlines. The Sunda Trench is marked as red outline. COB marked in dashed brown outline is by Nemčok et al. (2012). Black rectangle depicts the region described in figure 6. (b): Oceanic crustal age map of the BOB derived from this study. Older crust is seen towards west. Symmetric crust bearing age 105 to 98 Ma is seen towards east. 85ER is shaded pink. FZs are marked in red.

Figure 6: (a) Magnetic anomalies plotted along selected profiles superimposed on satellite gravity (Sandwell et al., 2014) in an area shown in figure 5a. Symmetric magnetic anomalies about a central anomaly (thick dashed line) associated with a gravity low indicates an ESR. The extent of additional crust is shaded gray. The limit of the 6.2 km depth of volcanic basement is outlined in black circles (Maurin and Rangin, 2009). Syn is a synthetic profile generated using EMAG2 (Maus et al., 2009) and satellite gravity. FZs are marked as dashed black outlines. Magnetic incursions Q1 and Q2 are marked. Red outline belongs to the Sunda Trench. (b) Stacked plot of magnetic anomalies (in black) and satellite/ship-borne gravity (in blue) along the profiles shown in figure 6a. Symmetric magnetic anomalies are seen about a central anomaly (dashed black line) associated with a typical gravity low. These signatures belong to an ESR with additional crust shaded gray.

Figure 7: Satellite gravity grid reconstruction models depicting the evolution of the BOB. Rotation parameters are given in table 2. India is kept in its present day position. The magnetic anomalies (M0, A34) and incursions (Q1, Q2) identified in the BOB are marked in different colors as per

legend. Dashed colored lines represent the isochrons extrapolated or from published literature. FZs are marked as thin black lines, and the prominent ones are named. Conjugate corridors are named A to E. The Kerguelen Plume location is shown as white star (Dobrovine et al., 2012). Pseudofault is marked as blue dashed line in both the conjugate basins. The ESR inferred in this study in BOB is marked as white dashed line, while ESR on Antarctica plate (Talwani et al., 2016) is marked as black dashed line. EB: Elan Bank; SKP: Southern Kerguelen Plateau. (a) Q2 (108 Ma); (b) Q1 (92 Ma); (c) chron A34 (83 Ma).

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## Tables

Table 1: Parameters used for generation of synthetic seafloor spreading model

Parameter	Figure 4a	Figure 4b
Paleolatitude	50°S	48°S
Magnetisation on-axis	10 A/m	10 A/m
Magnetisation off-axis	7 A/m	7 A/m
Spreading direction	320°	0°
Magnetised layer thickness	0.5 km	0.5 km
Susceptibility (cgs units)	0.02	0.015

Table 2: Finite rotation parameters used for generating grid reconstructions. Clockwise rotation is negative.

Age in Ma	Latitude in °N	Longitude in °E	Rotation angle
83	9.3	11.1	64.5
92	9.2	10.1	70.6
108	7.0	9.7	75.8

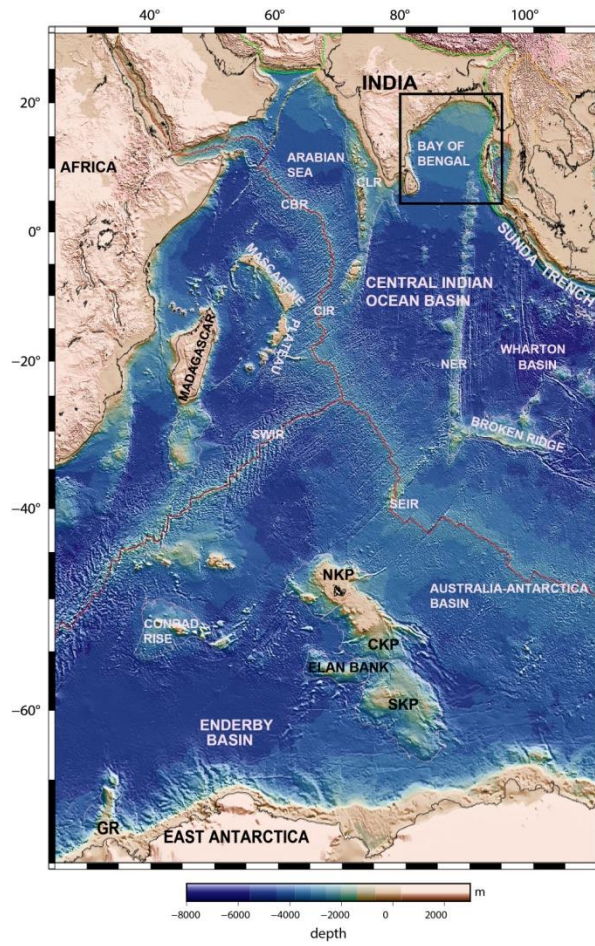


Fig. 1

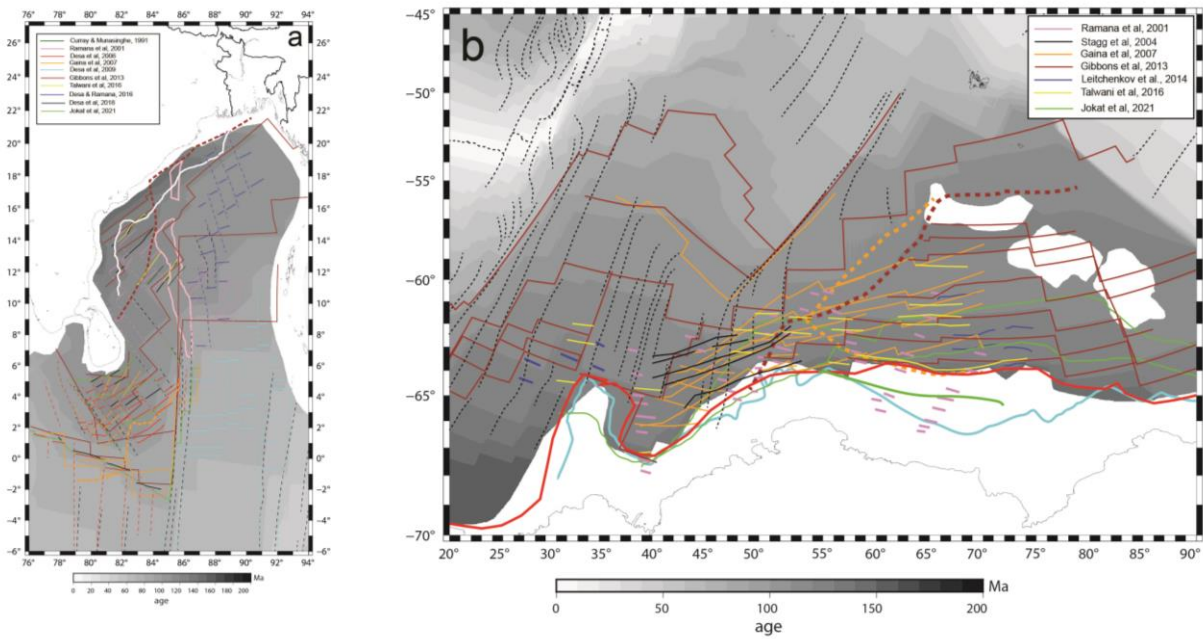


Fig. 2

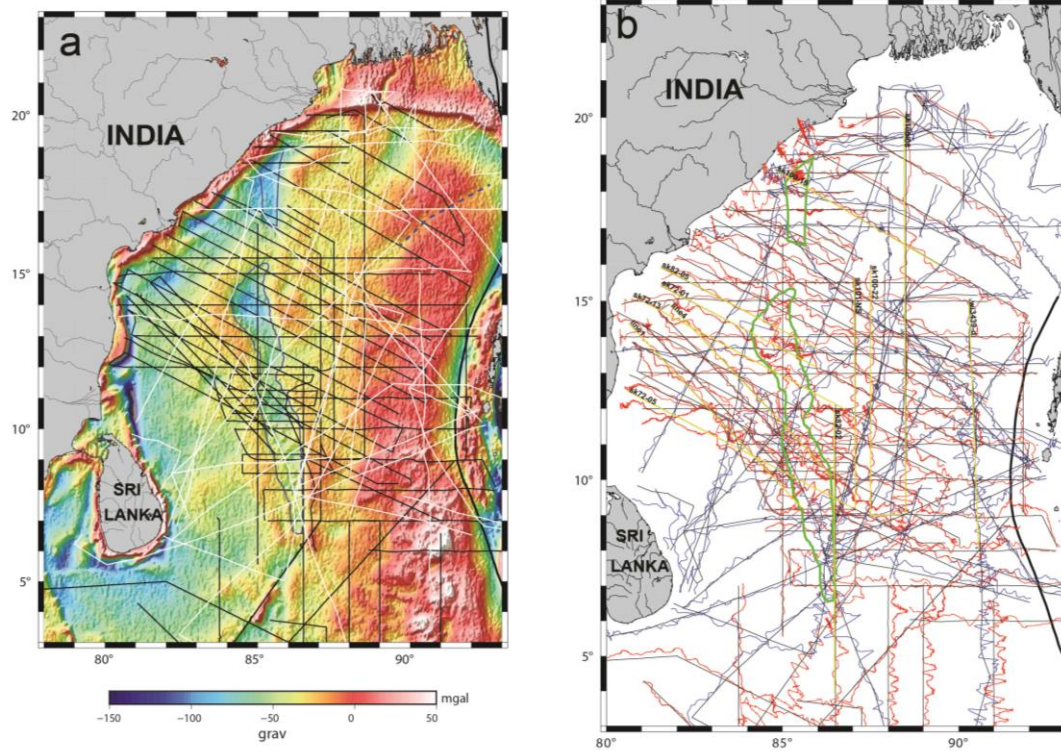


Fig. 3

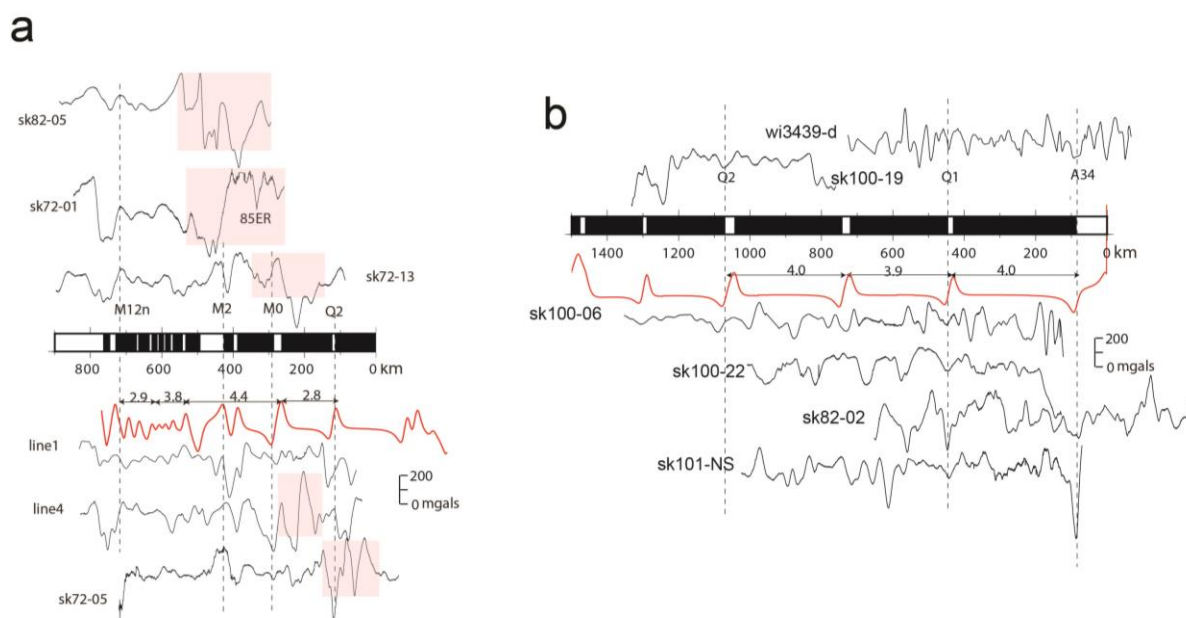


Fig. 4



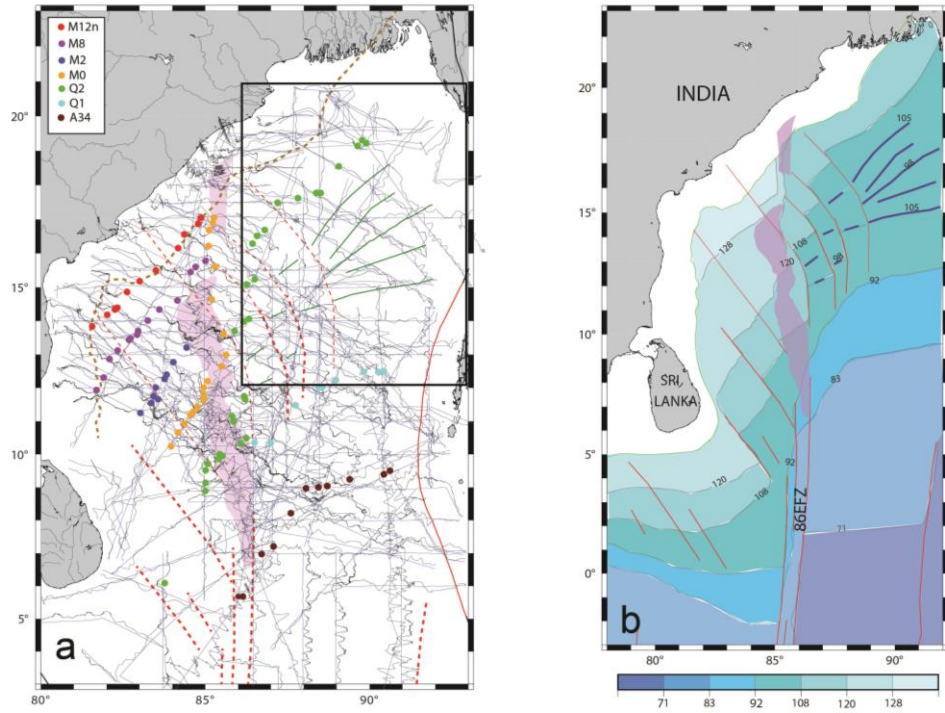


Fig. 5

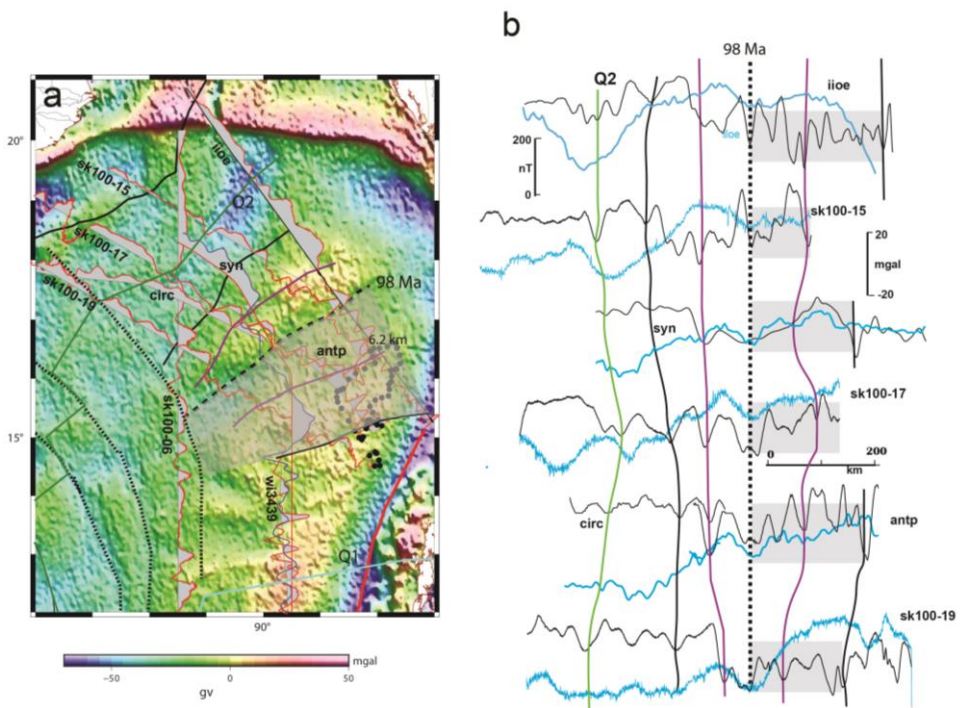


Fig. 6

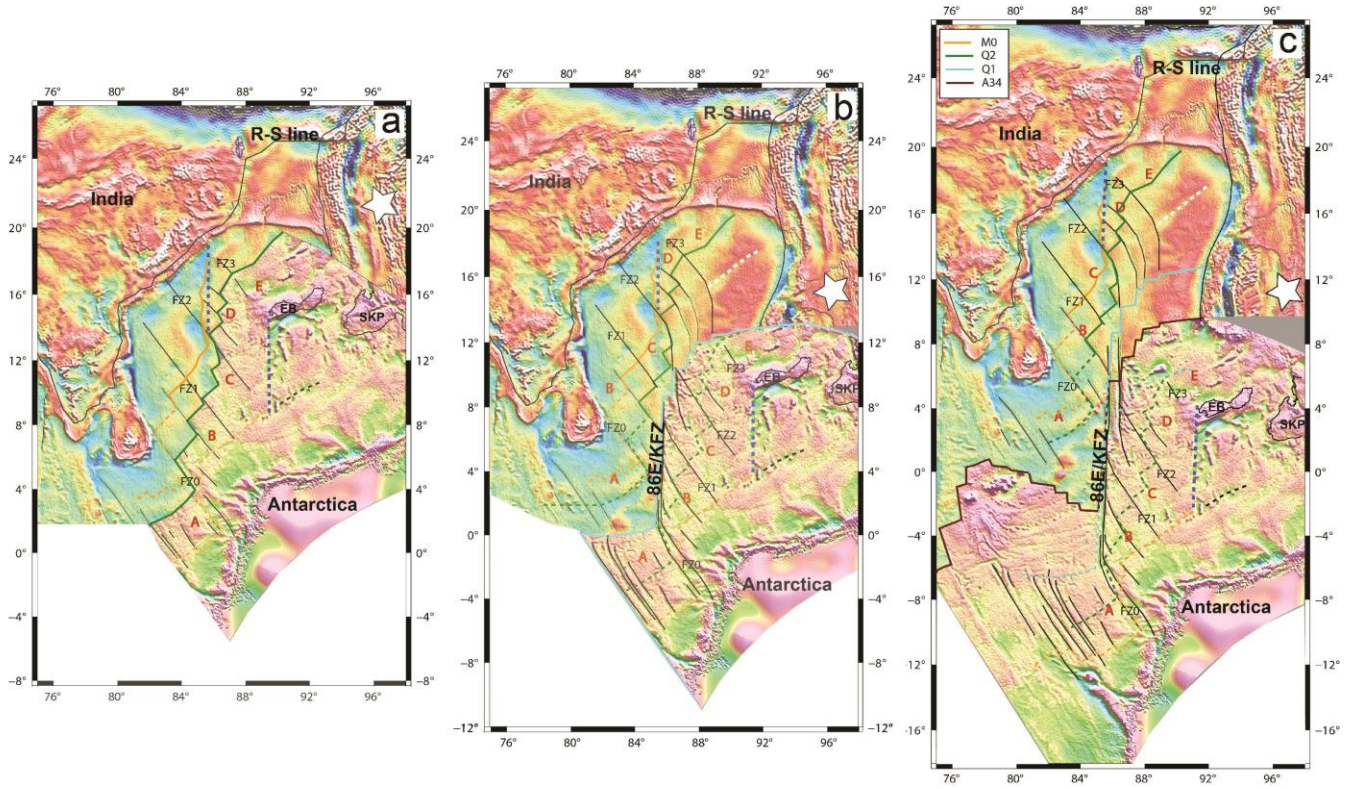


Fig. 7

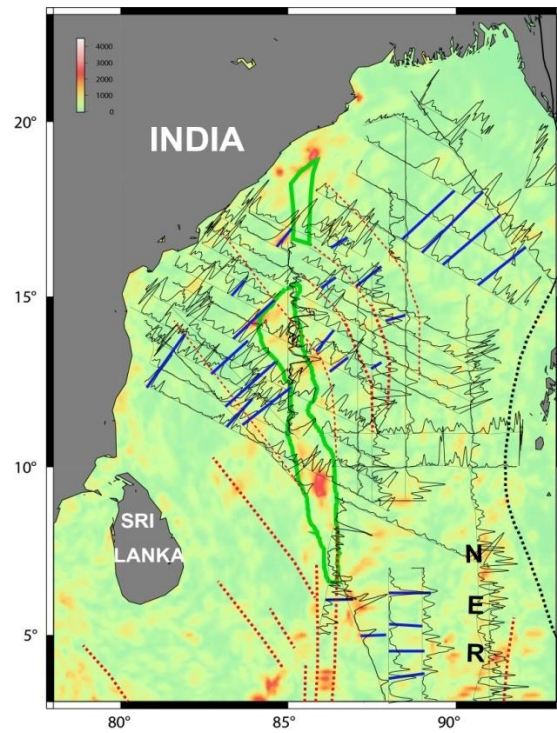


Fig. S1

Supplementary information

## **Reinterpretation of marine magnetic anomalies in the Bay of Bengal:**

### **Implications for plate tectonics during the mid-Cretaceous**

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#### **The analytic signal of the magnetic data**

Magnetic anomalies are not always observed atop the causative bodies. The remanent magnetization and present day magnetic field are not vertical vectors causing skewness of these anomalies (Schouten and McCamy, 1972). The modulus of the analytic signal computed from the magnetic anomalies reaches a maximum (bell shape) at the top of the magnetic contrasts and helps to precisely demarcate magnetic boundaries (Nabighian, 1972; 1974). The modulus of analytic signal of the magnetic data has been successfully used to infer ridge propagators, change in spreading direction, etc (Chaubey et al., 2002). The moduli of the analytic signal manifest as bell shapes of varying sizes. The large bell shapes represent zones with higher magnetic field contrasts including the polarity reversals.

In this study, we have used this technique and attempted to infer the major magnetic boundaries (Fig. S1). Overall, the bell shapes distribution map depicts NE-SW trend in the western basin of the Bay of Bengal (BOB). Further, frequent and large bell shapes are seen along the two ridges, the 85°E Ridge (85ER) and Ninetyeast Ridge. East of 85ER, the trend of the bell shape locations is E-W in the south, while the trends appear diverging in the north. We note here that the bell shapes do not clearly ascertain the magnetic edges probably due to the absence of frequent polarity reversals in the Cretaceous Normal Superchron period and/or huge sediment load of the Bengal Fan (Curry et al., 1982).

#### **Spreading velocities for the different models**

Two hypotheses are proposed to explain the evolutionary tectonics between India and Antarctica. One involves a single breakup followed by normal continuous spreading (Lawver et al., 1998; Ramana et al., 2001; Jokat et al., 2021), while the second invokes another breakup episode (Gaina et al., 2007; Gibbons et al., 2013; Talwani et al., 2016). Both the models predict that the seafloor spreading in the NW-SE direction between India and Antarctica during the Early Cretaceous period became N-S by the Late Cretaceous period (Royer and Sandwell, 1989; Royer and Coffin, 1992).

The spreading velocities within the five spreading corridors as half spreading rates (HSR) were inferred in both the scenarios (Tables S1 and S2).

In a two-phase scenario (in our study), higher velocities are seen in the Enderby Basin (EB) on the Antarctica plate from 120 to 108 Ma (Table S1). Between 108 and 92 Ma, higher velocities are seen in corridor A and C on Antarctica plate, while velocities are higher in corridors B, D and E in the BOB on Indian plate. Between 92 and 83 Ma, high velocities are seen on Antarctica plate in corridor A. Spreading velocities are calculated for the single phase scenario at different initial breakup timings (Gaina et al., 2007; Gibbons et al., 2013; Talwani et al., 2016; Jokat et al. 2021) and the end time for the calculation is 83/84Ma (A34) as per the geomagnetic polarity time scale. We find that the velocities are high on the Antarctica plate in general (Table S2). Velocities are higher if ages and Continent Ocean Boundary (COB) by Jokat et al. (2021) are considered.

Table S1: Extent of oceanic crust in km and velocities in cm/yr in the conjugate corridors at different time periods inferred in this study for a two-phase model

Corridor		120-108 Ma kms & HSR (min-max)		108-92 Ma kms & HSR (min-max)		92-83 Ma kms & HSR (min-max)	
A	BOB	148-190	1.2-1.6	132-267	0.8-1.7	<30-309	.3-3.4
A	EB	265-321	2.2-2.7	308-390	1.9-2.4	351-636	3.9-7.1
B	BOB	167-240	1.4-2.0	121-315	0.76-2.0	0	0
B	EB	210-310	1.75-2.6	<30-305	0.2-1.9	0	0
C	BOB	128-188	1.1-1.6	<20-149	0.13-0.9	320-323	3.6
C	EB	336-378	2.8-3.15	314-415	2.0-2.6	338-340	3.7
D	BOB	<30-264	<.25-2.2	391-495	2.4-3.1	340-342	3.8
D	EB	373-543	3.1-4.5	119-280	.74-1.75	339-345	3.8
E	BOB	121-235	1.1-2.0	448-651	2.8-4.1	343-351	3.8
E	EB	209-314	1.7-2.6	<20-163	0.13-1.0	338-350	3.8



Table S2: Extent of oceanic crust in km and velocities in cm/yr in the conjugate corridors in a single phase scenario using published ages

Corridor		Jokat et al., 2021 (Min. age=84Ma)			Gaina et al., 2007; Gibbons et al., 2013 and Talwani et al., 2016 (Min. age=83Ma)		
		extent kms	HSR	Max. age (Ma)	extent kms	HSR	Max. age (Ma)
A	BOB	888	3.2	112	888	1.9	130*
A	EB	1332	4.8	112	1332	2.8	130*
B	BOB	750	-	-	750	1.8	125
B	EB	780	-	-	780	1.9	125
C	BOB	950	-	-	950	2.0	130*
C	EB	1155	-	-	1155	2.5	130*
D	BOB	970	-	-	970	2.1	130*
D	EB	1535 <sup>#</sup>	3.1	133	1375	2.9	130*
E	BOB	1000	-	-	1000	2.1	130*
E	EB	1610 <sup>#</sup>	3.3	133	1450	3.1	130*

\*If maximum age is increased to 132 Ma, velocities reduce by 0.1 cm/yr

- means this corridor is not described

<sup>#</sup>160 km is added as per COB identification

Figure caption:

Figure S1: The bell shapes of the modulus of analytic signal of the magnetic anomalies along selected profiles are plotted at appropriate angles. The image of the modulus of the analytic signal of the EMAG2 data (Maus et al., 2009) is plotted in the background. Different trends are marked in blue based on the prominent bell shapes. Fracture zones are marked as dashed red lines. 85ER is marked as green outline. Sunda Trench is marked as dashed black outline. NER: Ninetyeast Ridge

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