

Geoid and gravity anomaly data of conjugate regions of Bay of Bengal and Enderby Basin – new constraints on breakup and early spreading history between India and Antarctica

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Abstract

Timing of breakup of the Indian continent from eastern Gondwanaland and evolution of the lithosphere in the Bay of Bengal still remain as ambiguous issues. Geoid and free-air gravity data of Bay of Bengal and Enderby Basin are integrated with ship-borne geophysical data to investigate the early evolution of the eastern Indian Ocean. Geoid and gravity data of the Bay of Bengal reveal five N36°W fracture zones (FZs) and five isolated NE-SW structural rises between the Eastern Continental Margin of India (ECMI) and the 85°E Ridge/ 86°E FZ. The FZs meet the 86°E FZ at an angle of ~39°. The rises are associated with low gravity and geoid anomalies and are oriented nearly orthogonal to the FZs trend. The geoid and gravity data of the western Enderby Basin reveal a major Kerguelen FZ and five N4°E FZs. The FZs discretely converge to the Kerguelen FZ at an angle of ~37°. We interpret the FZs identified in Bay of Bengal and western Enderby Basin as conjugate FZs that trace the early Cretaceous rifting of south ECMI from Enderby Land. Structural rises between the FZs of Bay of Bengal may either represent fossil ridge segments, possibly have extinct during the early evolution of the Bay of Bengal lithosphere or may have formed later by the volcanic activity accreted the 85°E Ridge. Two different gravity signatures: short-wavelength high-amplitude negative gravity anomaly and relatively broader low-amplitude negative gravity anomaly, are observed on south and north segments of the ECMI respectively. The location of Continent-Ocean Boundary (COB) is at relatively far distance (100-200 km) from the coastline on north ECMI than that (50-100 km) on the south segment. On the basis of geoid, gravity and seismic character and orientation of conjugate FZs in Bay of Bengal and western Enderby Basin we believe that transform motion occurred between south ECMI and Enderby Land at the time of breakup, which might have facilitated the rifting process in the north between combined north ECMI - Elan Bank and MacRobertson Land; and in the south between southwest Sri Lanka and Gunnerus Ridge region of East Antarctica. Approximately during the

period between the anomalies M1 and M0 and soon after detachment of the Elan Bank from north ECMI, the rifting process possibly had reorganized in order to establish the process along the entire eastern margins of India and Sri Lanka.

Key Words: Satellite altimetry, Geoid and gravity anomaly data, Bay of Bengal, Enderby Basin, Kerguelen and 86°E FZs, Ninetyeast and 85°E ridges, transform-rift continental margin

1. Introduction

The evolution of the eastern Indian Ocean began with the breakup of eastern Gondwanaland into two separate continental masses, Australia-Antarctica and Greater India, in the Early Cretaceous (Curry et al., 1982; Powell et al., 1988; Lawver et al., 1991; Gopala Rao et al., 1997; Gaina et al., 2003, 2007). Elan Bank, a micro-continent presently lies on the western margin of the Kerguelen Plateau in the southern Indian Ocean (Figure 1), detached from the present day Eastern Continental Margin of India (ECMI) at about 120 Ma (Ingle et al., 2002; Borissova et al., 2003; Gaina et al., 2003, 2007). Thus the ECMI witnessed two stages of continental breakup in early period of eastern Gondwana splitting. During the evolution of the eastern Indian Ocean the ocean floor experienced three major phases of seafloor spreading: initially moved in NW-SE direction until mid-Cretaceous, secondly drifted in N-S direction until early Tertiary and finally continuing in NE-SW direction. In the past, the lithospheric plates (Indian, Australian and Antarctica) of the Indian Ocean were reorganized in major sense at three geological ages. During the late-Cretaceous (83 Ma) Australia had separated from Antarctica (Mutter et al., 1985; Sayers et al., 2001). The second major plate reorganization occurred during the middle Eocene and resulted in merging of the Australian and Indian plates as single Indo-

Australian plate (Liu et al., 1983; Royer and Sandwell, 1989; Krishna et al., 1995). Subsequently at Miocene age high magnitude earthquakes and large-scale lithospheric deformation in the central Indian Ocean have contributed to the splitting of traditionally believed single Indo-Australian plate into three component plates (India, Capricorn and Australia) and multiple diffuse plate boundaries (Wiens et al., 1985; Gordon et al., 1990; Van Orman et al., 1995; Royer and Gordon, 1997; Gordon et al., 1998; Krishna et al., 2001a; DeMets et al., 2005; Krishna et al., 2008).

Ship-borne marine geophysical measurements of the Bay of Bengal and Enderby Basin, East Antarctica have provided valuable information on structural fabric and the nature of the crust and have contributed to the understanding of the evolution of conjugate regions. Two linear features (Ninetyeast and 85°E ridges) emplaced by the Kerguelen and Crozet hotspots respectively, sit longitudinally on the early Cretaceous oceanic crust of the Bay of Bengal (Figure 1). The ridges divide the Bengal Fan into two basins: Western Basin lies between the ECMI and the 85°E Ridge and Central Basin lies between the 85°E and Ninetyeast ridges (Figure 2a) (Rao and Bhaskara Rao, 1986). The Rajmahal traps erupted by the Kerguelen hotspot at ~118 Ma are found in the Bengal Basin, while the Sylhet traps formed at ~107 Ma are found in the Mahanadi Basin (Baksi et al., 1987). The Enderby Basin is bounded by the Gunnerus Ridge to the southwest, by the Kerguelen Plateau and Elan Bank to the northeast, by the Kerguelen FZ to the northwest, and by the Princes Elizabeth Trough to the southeast (Figure 1). The oceanic region between MacRobertson Land and Elan Bank is termed as central Enderby Basin; whereas the region south of the Kerguelen FZ and west of the 58°E longitude represents the western Enderby Basin (Figure 2b). The Kerguelen Plateau, except the Elan Bank, was formed by the Kerguelen

hotspot in two distinct phases (Coffin et al., 2002). In the first phase, during 119-100 Ma southern and central parts of the Kerguelen Plateau were formed, while the northern part of the plateau is being formed since 40 Ma. Southern and possibly central Kerguelen Plateaus are underlain by continental rocks. The Elan Bank, a micro-continent detached from the ECMI (Müller et al., 2001; Borissova et al., 2003; Gaina et al., 2003), is presently lying on west of the Kerguelen Plateau and become an integral part of the Kerguelen Plateau.

Although it is generally accepted that the crust in the Bay of Bengal and in the Enderby Basin is oceanic in nature, there are differing views concerning the ages for breakup and rifting events between India and Antarctica. On the basis of identification of M-series magnetic anomalies (M11-M0) in Bay of Bengal and in offshore region of Sri Lanka, Ramana et al. (1994) and Desa et al. (2006) have inferred the occurrence of rifting between India and Antarctica at about 132 Ma. In another investigation Gopala Rao et al. (1997) found that the seafloor spreading in the Bay of Bengal was initiated mostly around the start of Cretaceous magnetic quiet epoch (~120 Ma). Magnetic studies in the Enderby Basin using widely spaced profiles also led to identification of variable M-series magnetic anomalies. Following the structural pattern of the western Enderby Basin, Nogi et al. (2004) have interpreted the initiation of spreading in the western Enderby Basin before 127 Ma and introduced the extinct spreading center (M0 anomaly age) between the Gunnerus Ridge and Conrad Rise.

In the central Enderby Basin, several researchers (Ishihara et al., 2000; Brown et al., 2003; Gaina et al., 2003, 2007) have identified pairs of M-series magnetic anomalies (M9Ny-M2o) and a fossil ridge. At Elan Bank in the southeast Indian Ocean, Leg 183 of the Ocean Drilling Program (ODP) recovered clasts of garnet-biotite gneiss in a fluvial conglomerate intercalated

with basaltic flows (Nicolaysen et al., 2001). The gneiss clasts show an affinity to crustal rocks from India, particularly those of the Eastern Ghats Belt (Ingle et al., 2002). From these results it is discernible that the Elan Bank detached from the eastern margin of India after 120 Ma (Gaina et al., 2003, 2007). The magnetic anomaly interpretations of both regions could not provide unambiguous information related to timing of breakup of eastern margin of India from eastern Gondwanaland and age of the oceanic crust in the Bay of Bengal.

In this paper we investigate satellite geoid and free-air gravity data of conjugate regions, Bay of Bengal and Enderby Basin together with ship-borne gravity, magnetic and seismic data to identify structural features such as fracture zones, fossil ridge segments, etc. for the purpose of providing new constraints on breakup and early evolution of the lithosphere between India and Antarctica. The results are further discussed to classify the nature of the continental segments on the eastern continental margin of India (ECMI).

2. Satellite and ship-borne geophysical data

With the advent of more satellite altimetry missions it has become possible to generate large-scale altimeter-derived residual geoid and gravity anomaly maps over the oceans. In the present work, we have used high-resolution gravity database generated from Seasat, Geosat, GM, ERS-1 and TOPEX/ POSEIDON altimeters data of the Bay of Bengal and Enderby Basin (Hwang et al., 2002; Majumdar and Bhattacharyya, 2004; Rajesh and Majumdar, 2004; Majumdar et al., 2006). The data are more accurate and detailed (off-track resolution: about 3.33 km and grid size: about 3.5 km) compared to earlier satellite gravity data generated mainly from ERS-1 (168 day repeat) altimeter data (off-track resolution: about 16 km and grid size: about 20 km). The geoid, in general provides information on mass distribution inside the earth including

those due to large sharp changes in seafloor topography and plate tectonic boundaries. Residual geoidal height data - hypothetical surfaces related to mass distributions within the lithosphere (Lundgren and Nordin, 1988) - are calculated using spherical harmonic modeling of the geopotential field (Rapp, 1983). Following the relation between geoid undulation and gravity anomaly data (Chapman, 1979) we have computed the free-air gravity anomaly. The geoid, residual geoid and gravity anomaly databases are prepared for the regions of Bay of Bengal and Enderby Basin and shown in Figures 2a, 2b, 3, 4a and 4b. Further we have used the profile data extracted from satellite gravity anomaly data of the Bay of Bengal (Figure 4a) in order to support the interpretations of fracture zone pattern and fossil ridge segments (Figure 5).

Ship-borne geophysical data acquired on various Indian research vessels in the Bay of Bengal are also used in this study. The data include a few regional seismic reflection profiles running from ECMI to Andaman Islands, along latitudes 13°N (MAN-03), 14°N (SK107-7), 14.64°N (MAN-01) and 15.5°N (SK 107-6). In addition we have also extracted gravity and magnetic profiles of the Bay of Bengal from NGDC database and used for integrated investigations. Gravity and magnetic anomaly data of the Bay of Bengal are plotted at right angle to the profiles and shown in Figures 6 and 7, respectively. Gravity anomaly data along the profile MAN-01 (Bay of Bengal) are segmented into intermediate (100-200 km) and long-wavelength (200-500 km) spectral components with a view to examine the contributions of mass distributions lying at different depths. This profile was chosen as we have scope to compare the anomaly components with seismic reflection data. A long-wavelength gravity component mainly reflects the undulations at crust-mantle boundary, whereas intermediate-wavelength component reveals the details of lateral variations at basement level (Figure 8). Also satellite free-air gravity data are compared with the ship-borne gravity data for the purpose of observing the consistencies and

deviations between them (Figure 8). This reveals both satellite and ship-borne anomalies are fairly in good agreement with deviations of ~ 5 mGal, which is within the accuracy bounds of the satellite free-air gravity data. Further, two major linear gravity features (Ninetyeast and 85°E ridges) are imaged clearly in both ship-borne and satellite data sets. Therefore, the satellite free-air gravity anomalies of the Bay of Bengal can reasonably be considered to map the main structural features of the region.

3. Geoid and gravity signatures of geological features of Bay of Bengal and Enderby Basin

Geoid and gravity (satellite and ship-borne) data of the Bay of Bengal and the Enderby Basin are combined with magnetic and seismic reflection data of the Bay of Bengal for delineation of various structural features (Figures 2a, 2b, 3, 4a, 4b, 6, 7 and 8). The basement topography along profile 14.64°N latitude in the Bay of Bengal (Figure 8) generally shows two major structural rises (Ninetyeast and 85°E ridges) and troughs (Western and Central basins). The structures regionally extend near N-S direction (Krishna et al., 1995; Gopala Rao et al., 1997; Subrahmanyam et al., 1999; Krishna et al., 2001b; Krishna, 2003) and have broadly transformed the Bay of Bengal oceanic crust into alternative structural highs and depressions. Morphologically the depressions are much wider than the highs. Additionally a broad regional-tilt deepening towards eastern margin of India is also observed at basement level as well as at seafloor level. In addition two isolated structural highs (local features) are noticed near the continental margin and to the east of the 85°E Ridge (Figure 8). Sedimentary sections (shown as two different gray tones in Figure 8) formed during the pre- and post-collision tectonic settings are separated by the Eocene erosional unconformity (Curry et al., 1982; Gopala Rao et al., 1997). While the lower sedimentary section consists of pelagic sediment and terrigenous material derived from India before collision, the upper sedimentary section includes the Bengal

Fan sediments. The pre-collision (continental-rise) sediments are considerably thicker in the Western Basin than those in the Central Basin (Figure 8).

The geoid height data of the Bay of Bengal relative to the reference ellipsoid varies from -104 m in south of Sri Lanka to -40 m in the southeast of Andaman-Nicobar Islands (Figure 2a). The data gradually decrease towards the south of Sri Lanka at a rate of approximately 39 mm/km. On close examination it is observed that the geoid data rapidly decrease in E-W direction in an area between 90° and 85° E meridians. Towards the east in the vicinity of Andaman-Nicobar Islands and towards the west close to ECMI and Sri Lanka, the data vary relatively with lesser gradients and trend in NW and SW directions, respectively. On west of the Andaman-Nicobar Islands a slight notch (local minima) in geoid contour data indicates the signature of Sunda subduction zone, boundary between the Indian and the Burmese lithospheric plates (marked as solid-black line in Figure 2a). Near the continental margins two geoidal lows up to -104 m and -98 m with variable wavelengths are observed. Earlier the major geoidal low south of Sri Lanka was explained with the depression lying presumably at core-mantle boundary (Negi et al., 1987). Both geoidal lows are extremely dominant in the Bay of Bengal and have influenced the geoid data of the most part of the region to trend towards the lows (Figure 2a), thus the westward linear tilt is observed in geoid data along the seismic profile MAN-01 (Figure 8). Two major aseismic ridges (Ninetyeast and 85° E ridges) run longitudinally in the Bay of Bengal, do not have signatures in geoidal data (marked as white solid-lines in Figure 2a) as they are relatively shallow features lie within the crust and uppermost part of the mantle.

The geoid height data of the Enderby Basin, East Antarctica varies from 6 m in the Princess Elizabeth Trough region in the southeast to as high as 51 m in Conrad Rise - Crozet

Plateau region in the northwest (Figure 2b). It is observed that the geoid data are in general controlled by major seafloor features, whose relief and depressions are very high and change rapidly with extreme gradients. The Crozet Plateau and Conrad Rise are the prime features controlling the geoid data of the East Antarctica region, likewise other seafloor features such as the northern Kerguelen Plateau, part of the central Kerguelen Plateau and Elan Bank are also associated with high geoid data (Figure 2b). Further it is found that the Enderby Basin has three relatively distinct geoid patterns following the geographical extent of the sub-basins (western and central Enderby Basins). In the western basin between the Conrad Rise and Gunnerus Ridge the geoid data trend in NNE-SSW direction, while in the region between the Kerguelen FZ and Enderby Land the data trend in N-S direction, whereas in the central basin between the Elan Bank and Prydz Bay the data trend in NW-SE direction. In the western basin, particularly south of the Kerguelen FZ we found some notches in geoid pattern in the form of lineated geoidal highs along 47°E and 58°E longitudes (marked as N-S black solid- lines in Figure 2b).

The residual geoid data of the Bay of Bengal vary from -11.5 m in west of Myanmar to +12.5 m in south on west of the Ninetyeast Ridge (Figure 3). Relative residual geoidal lows up to 1 m are observed across the Sunda Trench and 85°E Ridge (buried part, north of 5°N latitude) and over some isolated features in the Western Basin (marked as black-solid lines in Figure 3). In contrast, the residual geoidal highs are noticed over the southern part of the 85°E Ridge and the Ninetyeast Ridge. Thus the 85°E Ridge possess two residual geoid signatures with negative anomalies associated with buried part of the ridge in the Bay of Bengal and positive anomalies associated with intermittently exposed structures of the ridge toward south. This is in agreement with the results of Subrahmanyam et al. (1999) and Krishna (2003), wherein they reported the change in free-air gravity field from negative, associated with the buried 85°E Ridge, to positive,

associated with partly buried structures and the Afanasy Nikitin seamount. The low residual geoid anomalies are identified at five places between the 85°E Ridge and south ECMI (marked as black solid-lines in Figure 3) and they approximately trend in NE-SW direction. Further, it is also observed that residual geoid anomalies between the Ninetyeast and 85°E ridges are broadly deepening from 12.5 m at 4°S latitude to -6.5 m at 13°N latitude (Figure 3), suggesting that the oceanic basement deepens towards north due to excess thickness of pre- and post-collision sedimentary rocks.

Satellite derived free-air gravity anomaly data (Figure 4a) and ship-borne gravity profile data (Figure 6) of the Bay of Bengal show prominent gravity signatures associated with the Sunda Trench (distinct gravity low), Ninetyeast Ridge (subdued gravity high), 85°E Ridge (distinct gravity low), continental shelf-slope of the eastern margin of India (gravity low with variable amplitude and wavelength) and some isolated structures (gravity lows marked with white solid-lines between the ECMI and the 85°E Ridge in Figure 4a). The gravity anomaly data, in general, decrease towards continental margin as have been reported earlier (Gopala Rao et al., 1997; Krishna et al., 1998; Krishna, 2003), suggesting that the trend seems to associate with the deepening of the seafloor as well as basement. The gravity low associated with the 85°E Ridge is varying along the strike of the ridge from north to south (Figures 4a and 6). At 14°10' N latitude the gravity low reaches up to -95 mGal (with a net anomaly of -70 mGal), while in the south along 7°N, the gravity low reaches to -40 mGal (with an anomaly of about -15 mGal). In central Bay of Bengal region both aseismic ridges (85°E and Ninetyeast ridges), in spite of their burial under more than 3 km thick Bengal Fan sediments (Gopala Rao et al., 1997), display two distinct (low and high) gravity signatures. The low gravity anomalies of the 85°E Ridge switch over to gravity highs toward south of 5°N; the change was interpreted (Krishna, 2003) to coincide with

termination/ thinning of pre-collision continental sediments in the Bay of Bengal. The enigmatic gravity low of the 85°E Ridge was explained by the underplating material and crustal root at the base of the crust (Subrahmanyam et al., 1999). In contrast, in another investigation the gravity low was explained with the presence of metasediments, more dense than volcanic rocks, on both sides of the ridge and flexure of the lithosphere beneath it (Krishna, 2003). Besides these regional structures, we have also noticed steep gradient gravity anomalies on continental slope of the eastern margins of India and Sri Lanka (Figures 4a and 6). Free-air gravity anomaly data along 14.64°N latitude are segmented into two components (Figure 8) varying with wavelengths of 200-500 and 100-200 km. While the major component generally provides information on Moho boundary, the secondary component possibly indicates the lateral density contrasts between basement rocks (structural high) and continental-rise sediments. On close investigation we found the presence of NW-SE trending narrow gravity features and approximately NE-SW trending low gravity anomaly closures between the 85°E Ridge and south ECMI (Figure 4a). The gravity anomaly profile data, generated perpendicular to the narrow gravity features and low gravity closures of the Bay of Bengal, display changes in gravity anomaly gradients and distinct low gravity anomalies (Figure 5). Narrow gravity anomaly features are interpreted as signatures of fracture zones related to early rift of ECMI from East Antarctica. The gravity closures are nearly perpendicular to the NW-SE oriented fracture zones (Figures 4a and 6). The low gravity anomaly closures are also found to be associated with distinct negative magnetic anomalies (marked as black solid NE-SW lines in Figure 7). This is the first time fracture zones close to the ECMI have been identified with confidence in the Bay of Bengal. On immediate southeast of the 85°E Ridge two prominent nearly N-S trending FZs (85°E FZ and 86°E FZ) are seen extending up to 6°N and 9°N, respectively (Figure 4a).

Satellite free-air gravity anomaly data of the offshore region of East Antarctica show prominent gravity lineations revealing the presence of fracture zones in the Enderby Basin, in southeast of the Crozet plateau and in the Australia-Antarctica Basin (Figure 4b). The most prominent one is the Kerguelen FZ runs in NE-SW direction between the Conrad Rise and the Kerguelen Plateau. In east of the Crozet Plateau three fracture zones are observed running almost parallel to the trend of the Kerguelen FZ. All those fracture zones express the northward motion of the Indian plate from late Cretaceous to early Tertiary period and also identified them as conjugate features of 85°E FZ, 82°E FZ, 80°E FZ and 79°E FZ of the Central Indian Basin (Figure 7). The FZ east of the Kerguelen FZ (Figure 4b) and 86°E FZ (Figure 4a) are the conjugate traces of the major transform fault that had connected the Indian-Antarctica and Wharton ridges (Schlich, 1982; Patriat, 1987; Royer and Sandwell, 1989; Krishna et al., 1995, 1999, 2000). We have further observed two sets of fracture zones in western Enderby Basin with one set trend in NNE-SSW direction close to Gunnerus Ridge and the other set consist of five fracture zones trend in ~N4°E direction between the Enderby Land and the Kerguelen FZ (marked as white dashed-lines in Figure 4b). The fracture zones in the central Enderby Basin are discretely converging to the Kerguelen FZ at an angle of about 37°.

4. Breakup of eastern Gondwanaland and evolution of fracture zones in Bay of Bengal and Enderby Basin

Timing for breakup of the Indian continent from eastern Gondwanaland and evolution of the lithosphere in the Bay of Bengal as well as in the Enderby Basin still remain as unresolved issues because magnetic and gravity data of both the regions do not provide unambiguous information. For instance, in the Bay of Bengal, Ramana et al. (1994) and Gopala Rao et al. (1997) identified magnetic anomalies as old as M11 and M0, respectively, whereas in the

conjugate Enderby Basin, Ramana et al. (2001) and Gaina et al. (2003, 2007) identified anomalies as old as M11 or conjugate pairs of anomalies M9o-M2o, respectively. In view of this we have re-examined an up-to-date compilation of marine magnetic anomalies of the Bay of Bengal (Figure 7) and compared the data with a profile data of the central Enderby Basin (Figure 10).

The magnetic anomalies in the equatorial region are well-developed with east-west oriented lineations, 30 through 34, whereas in the Bay of Bengal, particularly close to ECMI no coherent magnetic anomalies caused by the earth's magnetic reversals are observed (Figure 7). In the equatorial region the magnetic lineations are found dislocated in different lateral sense, outlining the presence of five N-S trending fracture zones. They are 79°E FZ, 80°E FZ, Indira FZ, 85°E FZ and 86°E FZ with the offsets of about 160, 90, 100, 480 and 220 km, respectively. Magnetic profiles that run on the oceanic crust between the 86°E FZ and the Ninetyeast Ridge show pairs of anomalies 30 through 32n.2, suggesting the existence of fossil ridge segment of the early Tertiary age. In Bay of Bengal region we found some correlatable magnetic anomalies from profile to profile, particularly associated with the 85°E Ridge and isolated features within the Western Basin (Figure 7). The 85°E Ridge possess a suite of high amplitude positive and negative magnetic anomalies, whereas the isolated features associate with significant negative magnetic anomalies. Except those there are no significant magnetic anomalies found attributable to magnetic reversals formed prior to the Cretaceous magnetic quiet epoch. There is a view that huge thickness of sediments in the Bay of Bengal may have reduced and/or altered the shape and amplitude of the anomalies. Contrary to this, the 85°E Ridge and isolated features in the Bay of Bengal show significant magnetic anomalies.

Delineation of fracture zones in the Bay of Bengal and their conjugate features in the Enderby Basin provides new constraints for lithospheric plate reconstructions and for assembling the ECMI with the East Antarctic continental margin. In the present study we mapped five \sim N36°W trending fracture zones between the south ECMI and the 85°E Ridge (Figure 4a) and their corresponding features are found to lie in the western Enderby Basin between the Enderby Land and the Kerguelen FZ in \sim N4°E direction (Figure 4b). In the Bay of Bengal the fracture zones meet the N-S oriented 86°E FZ at an angle of \sim 39° (Figures 4a and 9). Between the fracture zones isolated geoid, gravity and magnetic anomaly lows are found oriented in NE-SW direction and are orthogonal to the FZs pattern (Figures 3, 4a, 6 and 7). The fracture zones in the western Enderby Basin are discretely converging to the Kerguelen FZ at an angle of \sim 37° (Figures 4b and 9). We interpret that the fractures zones delineated in Bay of Bengal and western Enderby Basin are conjugate and were evolved when the south ECMI was rifted away from the Enderby Land during the early Cretaceous period (Figure 9). The new fracture zones pattern off the conjugate margins of south ECMI and Enderby Land will better constrain the modeling of early opening of the Indian Ocean. After the early breakup the Indian plate rotated counterclockwise relative to the Antarctica plate for the formation of second phase conjugate fracture zones in Bay of Bengal (86°E FZ) and in Enderby Basin (Kerguelen FZ). It is interesting to note that the region that includes fracture zones of the western Enderby Basin is bounded by lineated geoidal highs running along 47°E and 58°E longitudes (Figure 2b), suggesting that the crust in this sector was evolved in uniform tectonic setting and is distinguishable from the evolution of adjacent regions. Following the variations in character of oceanic crust, depth to the basement, thickness of crust and velocity structure, Stagg et al. (2004) have divided the East Antarctica continental margin into two distinct western and eastern sectors by a strong north-south crustal boundary along 58°E longitude. Further they revealed that the continental margins

on either side of this crustal boundary are underlain by variable width rift basins ranging from 100 km wide off Enderby Land to more than 300 km wide off MacRobertson Land. Along the western lineated geoidal high (at about 47°E in Figure 2b) no crustal boundary is delineated as the seismic profiles are very sparse in this region. Considering the geophysical results of Stagg et al. (2004) and details obtained from fracture zones of the Bay of Bengal and western Enderby Basin, we opine that the oceanic crust (between 47°E and 58°E) off Enderby Land margin and off south ECMI and east Sri Lanka may have evolved in a specific tectonic setting (Figure 9) and differing from the evolution of other continental margin segments.

Barring the magnetic anomalies associated with the 85°E Ridge and isolated features in the Western Basin, no magnetic lineations related to the M-series anomalies are obviously discernible in the Bay of Bengal (Figure 7), therefore we believe that most part of the oceanic crust in the Bay of Bengal was created during the Cretaceous Long Normal Polarity period. To validate this interpretation we have examined the published magnetic anomaly results of the conjugate region, Enderby Basin (Ramana et al., 2001; Nogi and Seama, 2002; Nogi et al., 2004; Gaina et al., 2003, 2007). In the central Enderby Basin between MacRobertson Land and Elan Bank conjugate pairs of magnetic lineations, M9o (~130.2 Ma) through M2o (~124.1 Ma) and fossil spreading center have been observed by Gaina et al. (2003, 2007) and suggested that spreading activity was ceased after anomaly M2, possibly around M0 time (~120 Ma) (also see in Figure 10 for anomalies and extinct ridge identifications). ODP Leg 183 drill well (Site 1137) on the Elan Bank recovered clasts of garnet-biotite gneiss in a fluvial conglomerate intercalated with basaltic flows (Nicolaysen et al., 2001; Weis et al., 2001; Ingle et al., 2002), suggesting a continental origin rocks. The gneiss clasts of the bank show an affinity to crustal rocks from Indian continent, particularly those of the Eastern Ghats Belt (Ingle et al., 2002). The magnetic

pattern in the central Enderby Basin and continental nature of the Elan Bank suggest that the bank was alongside the north ECMI until the spreading activity was ceased (at around 120 Ma) between the MacRobertson Land and Elan Bank. Then a northward ridge jump probably triggered by the Kerguelen plume, positioned between the Elan Bank and the north ECMI, had detached the bank (Müller et al., 2001; Gaina et al., 2003, 2007; Borissova et al., 2003) and transferred along with earliest oceanic lithosphere of the Indian plate to the Antarctica plate (Figure 10). The ridge jump placed the Kerguelen hotspot in Antarctica plate for emplacement of the Kerguelen Plateau. Keeping these geological sequences in view, we robustly believe that the oceanic crust presently lying adjacent to the north ECMI is not a conjugate part of the oceanic crust off MacRobertson Land, rather that was evolved concurrently with the crust presently situated north of the Elan Bank (Figure 10) and beneath the central and northern Kerguelen Plateau.

The oceanic crust off south ECMI - east Sri Lanka and off Enderby Land (from 47°E to 58°E) were evolved as conjugate parts in a specific tectonic setting, differing from the crustal evolution of the central Enderby Basin. The crustal boundary at 58°E longitude delineated from the geoid data (Figure 2a) and other geophysical results (Stagg et al., 2004) distinguishes the evolution of both geological regions. The fracture zones identified in the Bay of Bengal (between the south ECMI and the 85°E Ridge) and in the western Enderby Basin (between the Enderby Land and the Kerguelen FZ) are found to converge on 86°E FZ and Kerguelen FZ, respectively with a common azimuth of 37° - 39° (Figures 4a, 4b and 9). Earlier magnetic studies of the Enderby Basin and northeastern Indian Ocean (Schlich, 1982; Patriat, 1987; Royer and Sandwell, 1989; Krishna et al., 1995, 1999, 2000) have concluded that the 86°E FZ and the Kerguelen FZ were conjugate FZs during the late Cretaceous – early Tertiary period of the India-Antarctica

Ridge. Considering the constraints, particularly the azimuths between the fracture zones of two phases, we interpret that the fracture zones of Bay of Bengal and western Enderby Basin are conjugate features and were formed by a common spreading ridge system. As there were no magnetic lineations identified with certainty in both the regions, we opine that the oceanic crust may have evolved at a later time to the evolution of the central Enderby Basin crust, possibly during the Cretaceous magnetic quiet epoch (120-83 Ma).

As discussed earlier the Bay of Bengal region possesses distinct geoid, gravity and magnetic anomaly lows between fracture zones (Figures 3, 4a, 7 and 8). At one of the lows (northern most one located at around 15°N, Figures 4a and 6), Gopala Rao et al. (1997) using seismic reflection data, have shown association of negative gravity anomaly with the structural high. The negative anomaly is usually not expected for structural highs lying on the oceanic basement and buried under the sediments. Earlier Krishna (2003) has explained the mechanism that how the structural highs of the Bay of Bengal, particularly in the Western Basin, are associated with the negative gravity anomalies. Free-air gravity anomaly profile running along 14.64°N latitude (MAN-01) is modeled with a view to explain the development of negative gravity anomalies over the structural high and the 85°E Ridge (Figure 11). Seismic results of Curray et al. (1982) and Gopala Rao et al. (1997) are used to constrain two sedimentary layers (pre-collision continental rise sediments and post-collision fan sediments), volcanic rocks and basement topography. The pre-collision sediments are interpreted as high-velocity and -density metasedimentary rocks due to their excessive old age and depth of burial comparing to the volcanic rocks (Curray, 1991, 1994; Krishna, 2003). The metasedimentary rocks terminate on both sides of the structural high and the 85°E Ridge, and allow the structures to project into the post-collision fan sediments up to the Oligocene age (Figure 11). The derived crustal model explains the negative gravity anomalies

over the structural highs with the presence of metasediments, more dense than the volcanic rocks, and flexure of the lithosphere. Following the negative gravity and magnetic anomalies (Figures 3, 4a, 6 and 7) and model results (Figure 11) we suppose the presence of NE-SW trending structural highs between the fractures zones. From plate reconstruction studies of India, Australia and Antarctica (Royer and Coffin, 1992; Kent et al., 2002) we envisage that an early rift-evolution between south ECMI and Enderby Land may possibly have left the spreading fabric in NE-SW direction (present day) off south ECMI. We, therefore, considered a NE-SW structural fabric/highs as fossil spreading centers ceased during the Cretaceous magnetic quiet epoch. The postulation needs to be validated with additional geophysical observations.

The magnetic anomalies of the Bay of Bengal are in general subdued except over the 85°E Ridge and some isolated features in comparison to those of distal Bengal Fan region (Figure 7). It is believed that the subdued nature is due to presence of huge thick pre- and post-collision sedimentary rocks, therefore the lack of developed anomalies led to number of non-unique interpretations on the formation of the Bay of Bengal region. In one of the possibilities, we suppose that the breakup between the ECMI and East Antarctica margin might have occurred at magnetic anomaly M11 time by a simple normal rifting process and that continued until (90±5 Ma) first major plate reorganization of the Indian Ocean. In this tectonic model the magnetic anomalies M11 through M0 and variable stretch of crust formed during the Cretaceous Magnetic Quiet Epoch are expected to remain in both Bay of Bengal and Enderby Basin regions. The subdued nature of the anomalies in the Bay of Bengal neither supports nor disagrees with the existence of M-series anomalies. However, identification of conjugate pairs of anomalies M9o-M2o in central Enderby Basin (Gaina et al., 2007), continental nature of the Elan Bank with an affinity to the Eastern Ghat Belt rocks of the Indian subcontinent (Ingle et al., 2002) and shear-rift

margins on south ECMI (Chand et al., 2001) and on Enderby Land margin (Stagg et al., 2004) conflicts the presence of M-series anomalies in Bay of Bengal. Another possibility is to relate the formation of structural highs associated with negative gravity anomaly closures between the FZs of Bay of Bengal (Figure 4a), to hotspot volcanism. The structural highs probably co-evolved at the time (at about 80 Ma) of accretion of the 85°E Ridge or at the time (K-T boundary time) of the Rajahmundry traps in Krishna-Godavari Basin on south ECMI (Biswas, 1996). Since the supporting conjugate magnetic fabric is not available for the interpretation of fossil ridge segments in the Bay of Bengal, it can also be considered that the ridge system might have been reoriented during the mid-Cretaceous period without involving rotations and major ridge jumps. The reoriented ridge system, called India-Antarctica Ridge, had continued its activity from mid-Cretaceous to early Cenozoic period and formed the Central Indian and Crozet basins.

5. Classification of continental margin segments on ECMI

Understanding the evolution of passive continental margins in terms of rifting, shearing or mixed transform-rift process is an essential aspect apart from knowing the history of early seafloor spreading for precise assembly of the continental fragments. Therefore, there is a need to investigate East Antarctica, Elan Bank and ECMI margins to obtain useful information on margin character in order to reconstruct the lithospheric plate models. In general, two types of gravity signatures are observed along the ECMI and eastern margin of Sri Lanka. On southern part of the ECMI the gravity high associated with the shelf-edge rapidly decreases by about 140 mGal in a distance of around 20 km seawards, and then increases by about 80 mGal with relatively lower gradient over a distance of around 40 km (Figures 6 and 12). The gravity minima coincide with the foot of the continental slope (Figure 12). This characteristic gravity signature, high amplitude and short-wavelength, is recognizable on the eastern margin of Sri Lanka and south ECMI up to

15°N latitude. Contrastingly on north ECMI, gravity signatures show reduced amplitude (up to 100 mGal) and extended wavelength (up to 90 km) (Figures 6 and 12). Gravity anomaly patterns can be considered as useful constraints for classification of continental margins (Karner and Watts, 1982). The location, where a quick change from relatively short-wavelength low gravity anomaly to broader less-significant anomaly is observed, indicates the presence of the Continent-Ocean Boundary (COB) on eastern continental margins of India and Sri Lanka. On south ECMI the COB lies relatively closer (50-100 km) to the present coastline, whereas on the north ECMI the boundary lies more distant, approximately 100-200 km away from the coastline (Figures 6 and 12). Seismic reflection results of both segments of the ECMI show no evidence for the presence of underplated material and seaward dipping reflectors within the continental crust (Figure 13), hence the continental crust closer to the shelf-slope regions preserves the deformed crust that was emplaced during the phases of continental breakups. On south of Elan Bank, Borissova et al. (2003) found seaward dipping reflectors similar to the features generally observed on rifted volcanic passive margins. From these observations it implies that the margin on northern Elan Bank, conjugate to the north ECMI, might have evolved by normal rifting processes.

With a view to obtain additional constraints on character of ECMI segments, we have investigated two seismic reflection sections, one each from north and south ECMI and compared with the seismic results of well established Ghana transform continental margin, northern Gulf of Guinea (Masle and Blarez, 1987). Seismic section (MAN-03 along 13°N latitude) on south ECMI shows the presence of relatively low-angle normal faults with throws as much as 3 sec TWT (Figure 13). A major fault close to the shelf edge coincides with the continental slope, making the slope as an extremely high gradient steep surface. Also the fault surfaces are devoid

of sediments or covered with thin-vein of sediments. On the other hand seismic section (SK-107-06 along 15.5°N latitude) on north ECMI shows the presence of less significant normal faults for a distance of about 100 km from the shelf-edge. The rifting process that took place during the period from earliest rifting to final continental breakup, in general, deforms broad region of continental crust in the form of low-angle normal faults, whereas the shearing process along transform segments can deform only a limited stretch of continental crust. It is observed in residual geoid data of the Bay of Bengal that the data sharply fall by 1.5 m in a distance of about 50 km on south ECMI and by 2.5 m in a distance of about 100 km on north ECMI (Figure 3). The rate of fall in residual geoidal data on both north and south ECMI indicates the stretches of deformed crust primarily caused by the processes of rift on north ECMI and shear on south ECMI before the continental breakup. The geophysical features such as normal faults with major throws and devoid of sediments, narrow stretch of deformed crust/ abrupt transition from continental to oceanic crust, marginal high and pull-apart rifted basin are observed on south ECMI transform margin (Figure 13) and are comparable with well-accepted Ghana transform continental margin (Masclé and Blarez, 1987; Edwards et al., 1997). There are other evidences in support of transform margin character to the south ECMI. Using admittance analysis and various isostatic models, Chand et al. (2001) have determined low elastic plate thickness (T_e) of less than 5 km for the south ECMI and inferred that the margin had developed as a consequence of shearing rather than rifting in the early stages of continental separation. Seismic studies of Cauvery Basin on south ECMI reveal oblique trending (NE-SW direction to the coastline) horst and graben structures (Sastri et al., 1973), which support the interpretation of transform margin character for the south ECMI. From subsidence modeling results, Chari et al. (1995) have found that the Cauvery Basin had experienced limited lithospheric extension, which provides further evidence for the south ECMI to consider it as transform nature of the margin. For easy understanding of

the margin characters geophysical signatures associated with the south and north segments of ECMI are listed in Table 1.

The spreading history in conjugate oceanic regions, south of Sri Lanka and western Enderby Basin, NE of Gunnerus Ridge is still not very clear, as there were no correlations found between the anomalies. Since the magnetic anomalies in the western Enderby Basin have lower amplitude, Gaina et al. (2007) could not identify the anomalies with confidence and found difficulty to correlate the spreading history with that of the central and eastern Enderby Basins. Based on structural pattern of the western Enderby Basin, Nogi et al. (2004) have interpreted the extinct spreading center (M0 anomaly age) and conjugate older oceanic crust at least up to 127 Ma on either side of it. On the other side, south of Sri Lanka not more than 500 km oceanic stretch is available between the magnetic lineation 34 and continent-ocean boundary (Figure 7) for accounting the crust accreted during the Cretaceous magnetic quiet epoch (120-83 Ma) and the period older to it.

In summary, on the basis of our observations and discussions we believe that transform motion existed between south ECMI and Enderby Land for a short period before the breakup. The shearing process followed by stretching on south ECMI might have facilitated the rifting process between combined north ECMI - Elan Bank and MacRobertson Land; and between southwest Sri Lanka and Gunnerus Ridge region of East Antarctica. During the period between the anomalies M1 and M0, the rifting process might have reorganized due to the northward ridge jump between north ECMI and Elan Bank and established along the entire eastern margins of India and Sri Lanka. At present, there is no information available on how long continent-to-continent contact continued during the transform motion between south ECMI and Enderby Land.

In absence of this we tend to speculate that the rifting process along the entire ECMI and east of Sri Lanka was reorganized soon after the ridge jump occurred after anomaly M2. A swap in tectonics from shearing to rifting on south ECMI had allowed the margin to have mixed rift-transform character. Stagg et al. (2004) have found that the margin, off Enderby Land (conjugate to South ECMI) was strongly influenced by the mixed rift-transform setting.

6. Summary and conclusions

Study of high-resolution satellite geoid and free-air gravity anomaly, ship-borne magnetic and gravity and seismic reflection data of the Bay of Bengal and the Enderby Basin has provided new insights on breakup of the eastern Gondwanaland and early seafloor spreading between India and Antarctica. Important observations are as follows.

1. The geoid data of the Bay of Bengal reveal two prominent lows on south ECMI (up to -98 m) and on south of Sri Lanka (up to -104 m). Both lows have strong influence on the geoid data of most part of the Bay of Bengal. Contrastingly, in the Enderby Basin the geoid data pattern (trends of NNE-SSW, N-S and NW-SE), in general, follow the direction of flow lines (early Cretaceous plate motions). These patterns indicate the direction of seafloor spreading prevailed during the early opening between India and Antarctica. In the western Enderby Basin, particularly south of the Kerguelen FZ lineated geoidal highs are found along 47°E and 58°E longitudes, which possibly indicate that the lithosphere in this sector was created in a specific tectonic setting and is distinguishable from the evolution of adjacent regions. Residual geoidal height data of the Bay of Bengal show lows up to 1 m across the 85°E Ridge (buried part) and over some isolated features in the Western Basin. In contrast, the residual geoidal highs are noticed across the southern part (intermittently exposed) of the 85°E Ridge.

Thus, the 85°E Ridge possess two types of residual geoid signatures with negative associated with the buried part of the ridge and positive associated with the exposed structures of the ridge. The low residual geoid anomalies are identified at five places between the 85°E Ridge and south ECMI and each of them trends in NE-SW direction.

2. Satellite-derived and ship-borne free-air gravity anomaly data of the Bay of Bengal reveal five notable N36°W oriented fracture zones and NE-SW trending low gravity anomaly closures between the 85°E Ridge/ 86°E FZ and south ECMI. The low gravity closures are found to be associated with distinct negative magnetic anomalies. The FZs meet the 86°E FZ at an angle of ~39°. The rises, associated with low gravity and geoid anomalies are oriented orthogonal to the FZs pattern. Satellite gravity anomaly data of the western Enderby Basin reveal five fracture zones trend in N4°E and meet the Kerguelen FZ at an angle of ~37°. The fracture zones identified in both Bay of Bengal and western Enderby Basin are found to be converged on 86°E FZ and Kerguelen FZ respectively, at a common azimuth of 37° - 39°. We interpret that the fracture zones are conjugate and were evolved during the early Cretaceous period after rifting of the south ECMI from the Enderby Land. Structural rises between the FZs of the Bay of Bengal may either represent fossil ridge segments, which possibly had extinct during the early evolution of the Bay of Bengal lithosphere or may have formed by the volcanic activity when the hotspot was accreting the 85°E Ridge.
3. Magnetic lineations related to the M-series anomalies are obviously not discernible in the Bay of Bengal. This observation is well compatible with the identifications of pairs of M-series magnetic anomalies with extinct spreading center in the central Enderby Basin and continental nature of the Elan Bank. Therefore, we strongly believe that most part of the

oceanic crust in the Bay of Bengal was generated during the Cretaceous Long Normal Polarity period, i.e. after 120 Ma and is not a conjugate part of the oceanic crust off MacRobertson Land, rather that was evolved concurrently with the crust that presently lie north of the Elan Bank and beneath the central and northern Kerguelen plateau.

4. The gravity anomaly with a specific character of short-wavelength and high amplitude is observed on the eastern margin of Sri Lanka and south ECMI up to 15°N latitude. Contrastingly on the north ECMI, a different character of gravity anomaly with reduced amplitude (up to 100 mGal) and extended wavelength (up to 90 km) is observed. The location, where gravity anomaly changes from short-wavelength low anomaly to broader less-significant anomaly, suggests the presence of Continent-Ocean Boundary (COB) on eastern continental margins of India and Sri Lanka. On the south ECMI, the COB lies relatively closer (50-100 km) to the present coastline, whereas on the north ECMI, the boundary lies at a further distance, approximately 100-200 km away from the coastline.

5. Seismic sections on south and north ECMI show the presence of relatively low-angle normal faults with different configurations. On south ECMI the fault surfaces are found almost devoid of sediments, whereas on north ECMI the faults lie in a distance of about 100 km from the shelf-edge. The geophysical features such as normal faults with major slips, narrow stretch of deformed crust, marginal high and rifted basin ascribe the transform margin character to the south ECMI. There are several other evidences (low elastic plate thickness, horst and graben structures and limited lithospheric extension), which support the interpretation of transform margin character for the south ECMI. From the above geophysical results, we believe that transform motion was existed between the south ECMI and the

Enderby Land initially for a short period at the time of breakup, which might have facilitated the rifting process between combined north ECMI - Elan Bank and MacRobertson Land; and between southwest Sri Lanka and Gunnerus Ridge region of East Antarctica. Approximately during the period between the anomalies M1 and M0, the rifting process was reorganized due to the northward ridge jump between north ECMI and Elan Bank and established along the entire eastern margins of India and Sri Lanka. A switchover in tectonics from shearing to rifting on the south ECMI had allowed the margin to have mixed rift-transform character.

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Figure Captions

Figure 1: General tectonic map of the Indian Ocean showing mid-oceanic ridge system, aseismic ridges, plateaus, fracture zones and magnetic lineations (after Royer et al., 1989; Müller et al., 1997). Bathymetric contours 2000 and 4000 m (GEBCO data) are shown to outline important geological features. DSDP and ODP Sites, discussed in the present work are shown with solid circles. Boxes show the regions (evolved as conjugate oceanic parts) investigated in this work. SWIR, Southwest Indian ridge; SEIR, Southeast Indian Ridge; CIR, Central Indian Ridge; NER, Ninetyeast Ridge; EFER, 85°E Ridge; ANS, Afanasy Nikitin seamount; EB, Elan Bank; KP, Kerguelen Plateau; KFZ, Kerguelen Fracture Zone; CP, Crozet Plateau; CR, Conrad Rise; GR, Gunnerus Ridge; PET, Princes Elizabeth Trough; EL, Enderby Land; MRL, MacRobertson Land; PEL, Princes Elizabeth Land; BB, Bunbary Basalts; RT, Rajmahal Traps; DT, Deccan Traps.

Figure 2a: Classical geoid data of the northeastern Indian Ocean. Geoidal lows, located in south of Sri Lanka and NNE of Sri Lanka have influenced the signatures of most part of the Bay of Bengal region. Two major aseismic ridges (Ninetyeast and 85°E ridges) marked with white solid lines do not possess any geoidal pattern. Black solid line indicates the Sunda Trench, where Indian plate is subducting under the Burmese micro-plate.

Figure 2b: Classical geoid data of the Enderby Basin and adjacent regions. Enderby Basin possess three geoidal patterns. Solid lines along 58°E and 47°E separate the patterns. The Kerguelen FZ and Princes Elizabeth Trough (PET) show the low geoid lineations.

Figure 3: Residual geoid data of the northeastern Indian Ocean. The Ninetyeast Ridge is associated with positive geoid anomaly, where as the 85°E Ridge is associated with negative anomaly in the north (north of 5°N) and positive anomaly in the south. E-W trending geoid anomalies on both sides of the Afanasy Nikitin seamount (ANS) indicate the axis of the long-wavelength folds of the lithosphere. In the western Basin five NE-SW trending low geoid anomaly closures (marked as black solid-lines) are identified and they are dislocated by the fracture zones.

Figure 4a: The satellite free-air gravity anomaly of the northeastern Indian Ocean. The gravity field in the Western Basin reveal five NW-SE oriented fracture zones and stripes of NE-SW trending low gravity anomalies between the 85°E Ridge/ 86°E FZ and south ECMI. White dashed lines indicate the locations of fracture zones. White solid lines between the FZs show locations of gravity lows associated with structural highs.

Figure 4b: The satellite free-air gravity anomaly of the Enderby Basin and adjacent regions. The gravity field in the western Enderby Basin between 47°E and 58°E longitudes reveal five fracture zones trend nearly in N-S direction and meet the Kerguelen FZ with at angle of ~37°. White dashed lines indicate the locations of fracture zones.

Figure 5: Gravity data along synthetic profiles across the fracture zone pattern and across the gravity lows between the fracture zones. Solid vertical lines with label F show the locations of fracture zones. Dashed lines show the locations of gravity lows associated with suspected fossil ridge segments. Locations of profiles are shown in satellite gravity image map.

Figure 6: Free-air gravity anomaly data plotted at right angle to the ship tracks. The gravity data along the profile MAN-01 (14.62°N latitude) are used for crustal model studies. Variable bathymetric contours (200, 1000, 2000, 3000 and 4000 m) are shown to indicate the physiography of the region. Light shaded regions show the locations of Ninetyeast, 85°E and Comorin ridges. Fracture zones and structural highs identified in satellite gravity data are superimposed in this figure. At two locations structural highs are associated with low gravity anomalies.

Figure 7: Magnetic anomaly data plotted at right angles to the ship tracks. Locations of ridges and COB identified on the basis of gravity character are shown. Seafloor spreading lineations, 30-34 are identified in distal Bengal Fan region. Fracture zones and structural highs identified in satellite gravity data are superimposed. At two locations structural highs are associated with low magnetic anomalies. The 85°E Ridge in Bay of Bengal region is associated with belts of high amplitude positive and negative magnetic anomalies. At least in four locations shown with light gray, the ridge was emplaced during the normal magnetic field period, whereas at five locations shown with relatively dark gray, the ridge was emplaced during the reversed magnetic field period.

Figure 8: Geoid, residual geoid and free-air gravity anomaly data along 14.64°N latitude compared with seismic data (profile MAN-01). Basement topography and two sediment units separated by an Eocene unconformity are considered from Gopala Rao et al. (1997). Satellite derived free-air gravity anomaly compared with ship-borne gravity data for consistencies and deviations. Two different wavelength components (100-200 km and 200-500 km) are also shown for understanding the mass distributions at varied depth levels.

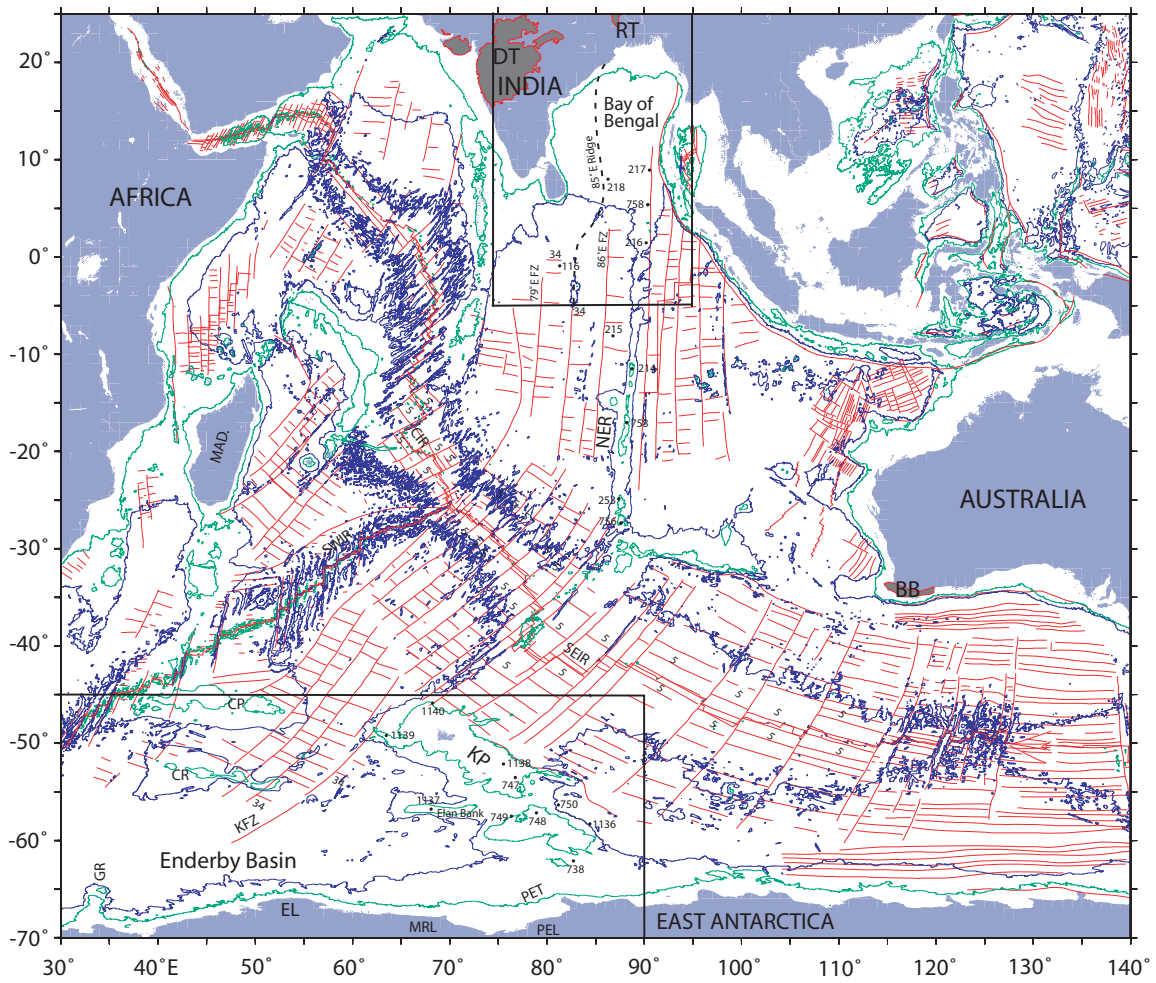
Figure 9: Assemble of the early Cretaceous fracture zones off south ECMI and Enderby Land prior to major change in spreading direction at 96-99 Ma. At this time there was a change in spreading direction (37°-39°). Kerguelen and 86°E FZs had started their evolution soon after change in plate motion direction at 96-99 Ma. COB on East Antarctica margin identified by Stagg et al. (2004) is shown.

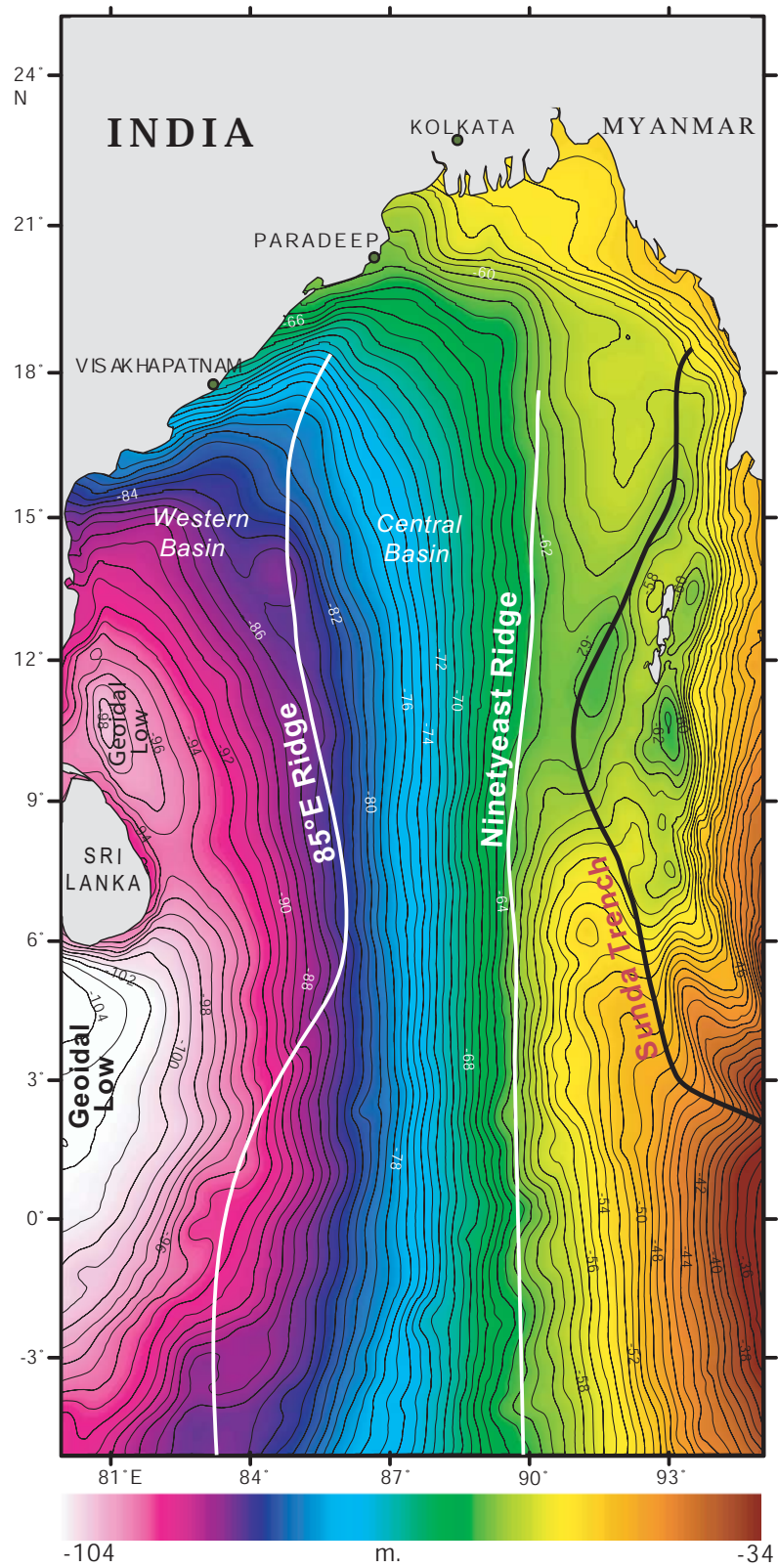
Figure 10: Gravity and magnetic data; basement structure and sediment thickness information from MacRobertson Land to Elan Bank and from Ninetyeast Ridge to ECMI are shown together to present early spreading history between east Antarctica, Elan Bank and India. The data from East Antarctica (profiles 228-06 (c) and Th 99a (d)) and Elan Bank (Line 179-05) sectors are compiled from the published results (Borissova et al., 2003; Stagg et al. 2004; Gaina et al., 2007), whereas in Bay of Bengal sector interpreted seismic results have presented from unpublished seismic profile (SK-107-06) running along 15.5°N latitude. MCA and XR indicate MacRobertson Coast Anomaly and extinct ridge in central Enderby Basin.

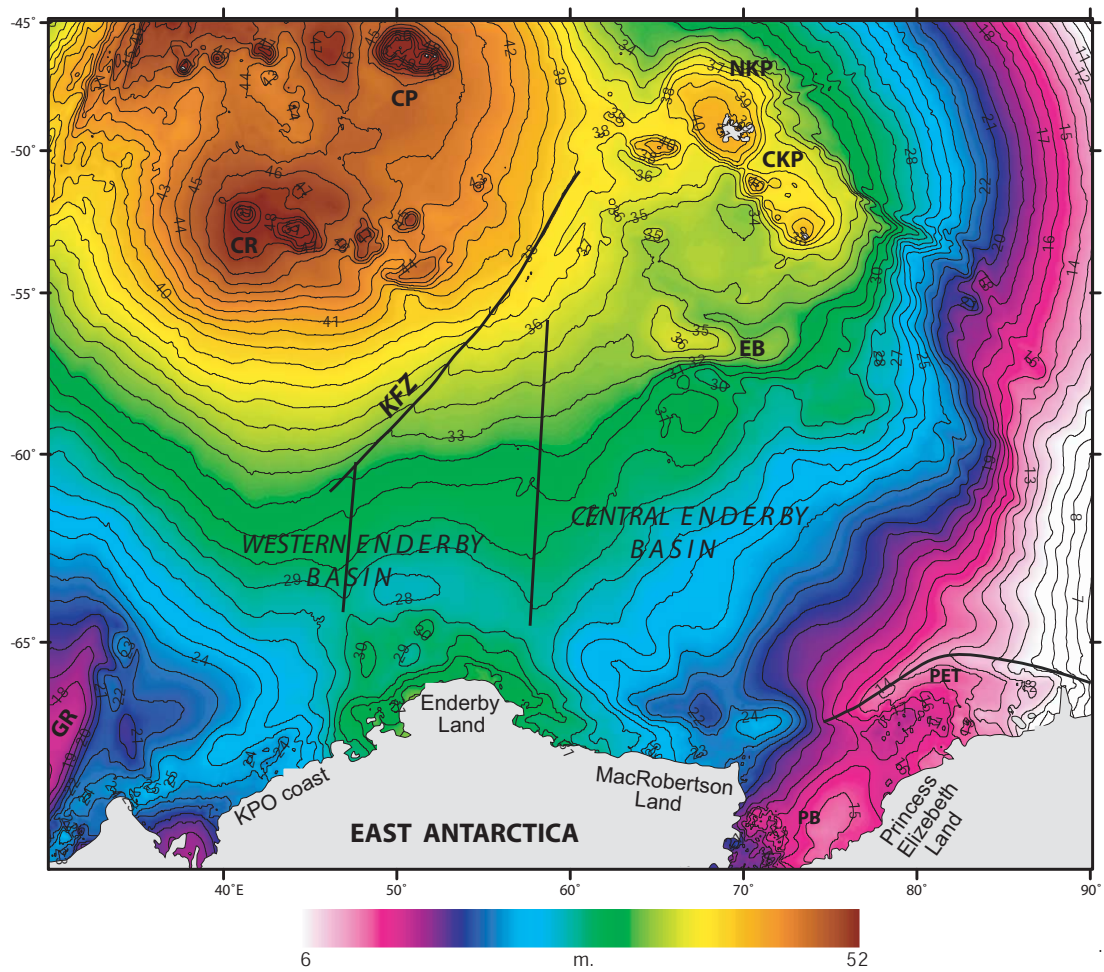
Figure 11: Two-dimensional gravity model with interpreted crustal structure along profile MAN-01. Location of the profile is shown as solid ship-track in Figure 6. Numerical values within brackets indicate the densities (gm/cc) of different strata.

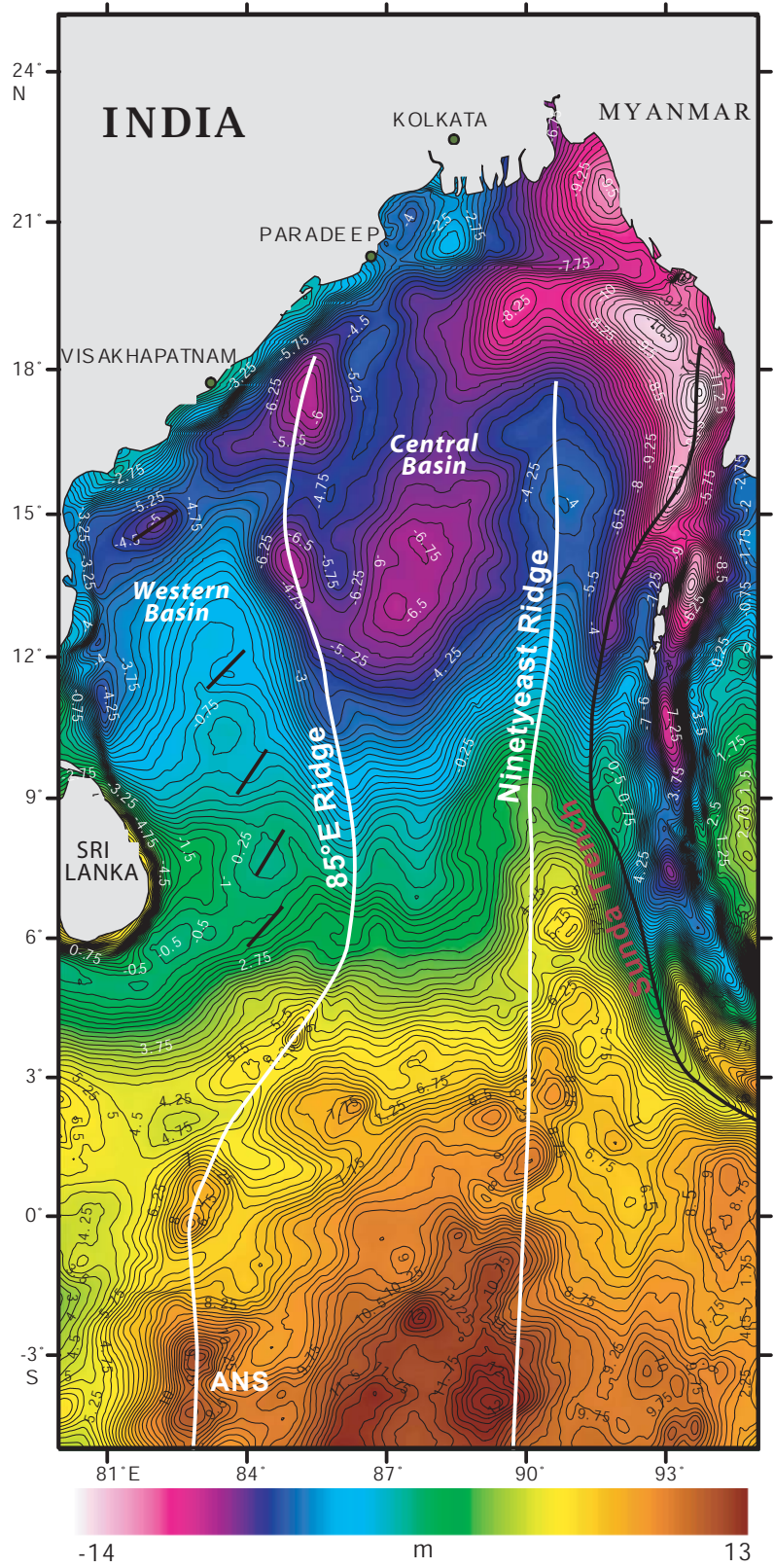
Figure 12: Representative profiles of bathymetry, gravity and magnetic data from both south and north segments of ECMI are shown to distinguish the seafloor morphology, anomaly character and location of COB.

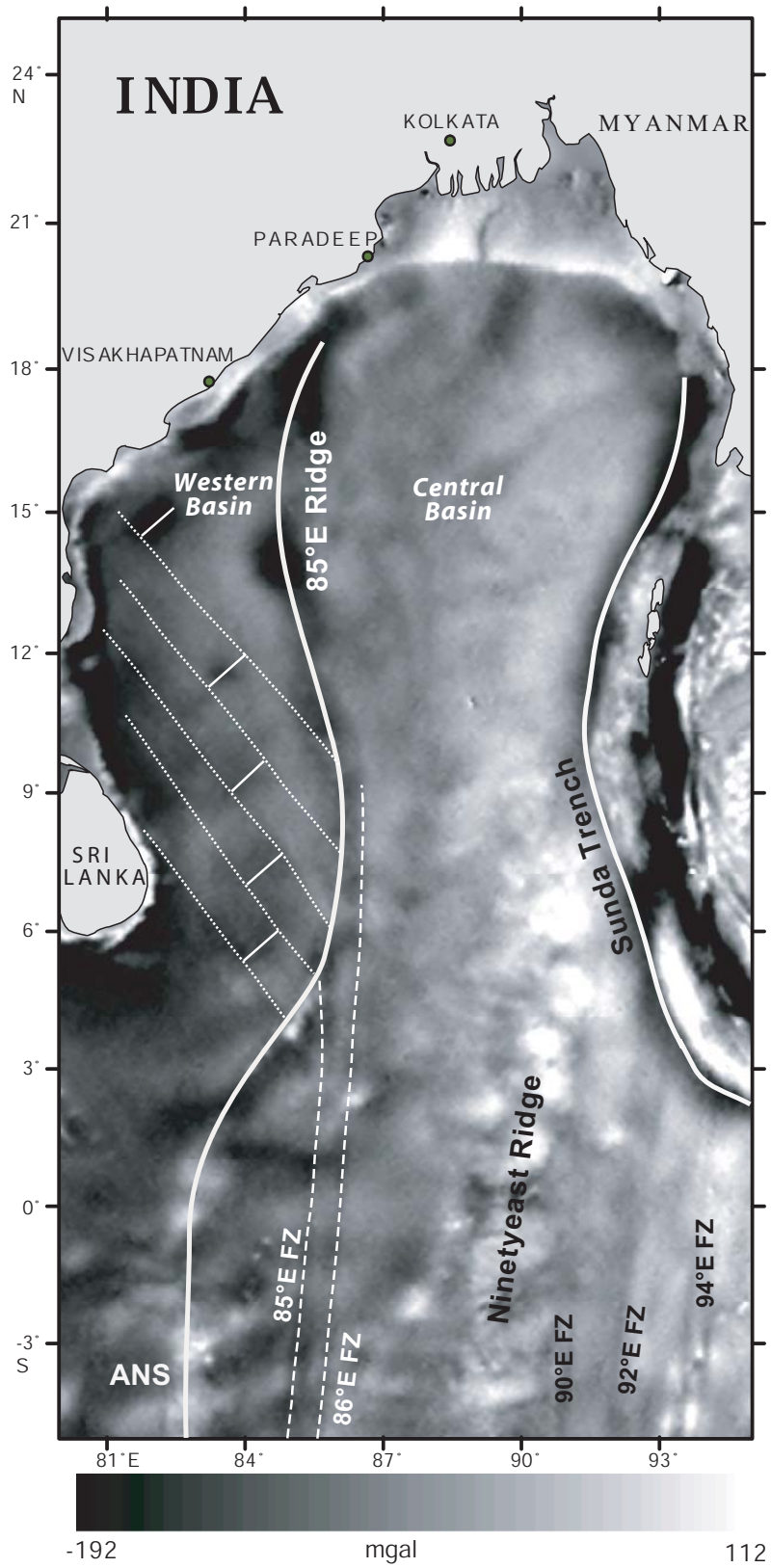
Figure 13: Seismic sections and interpreted results of representative profiles (MAN-03 from south ECMI, SK-107-06 from north ECMI) are presented to show internal structure of both segments of the ECMI.

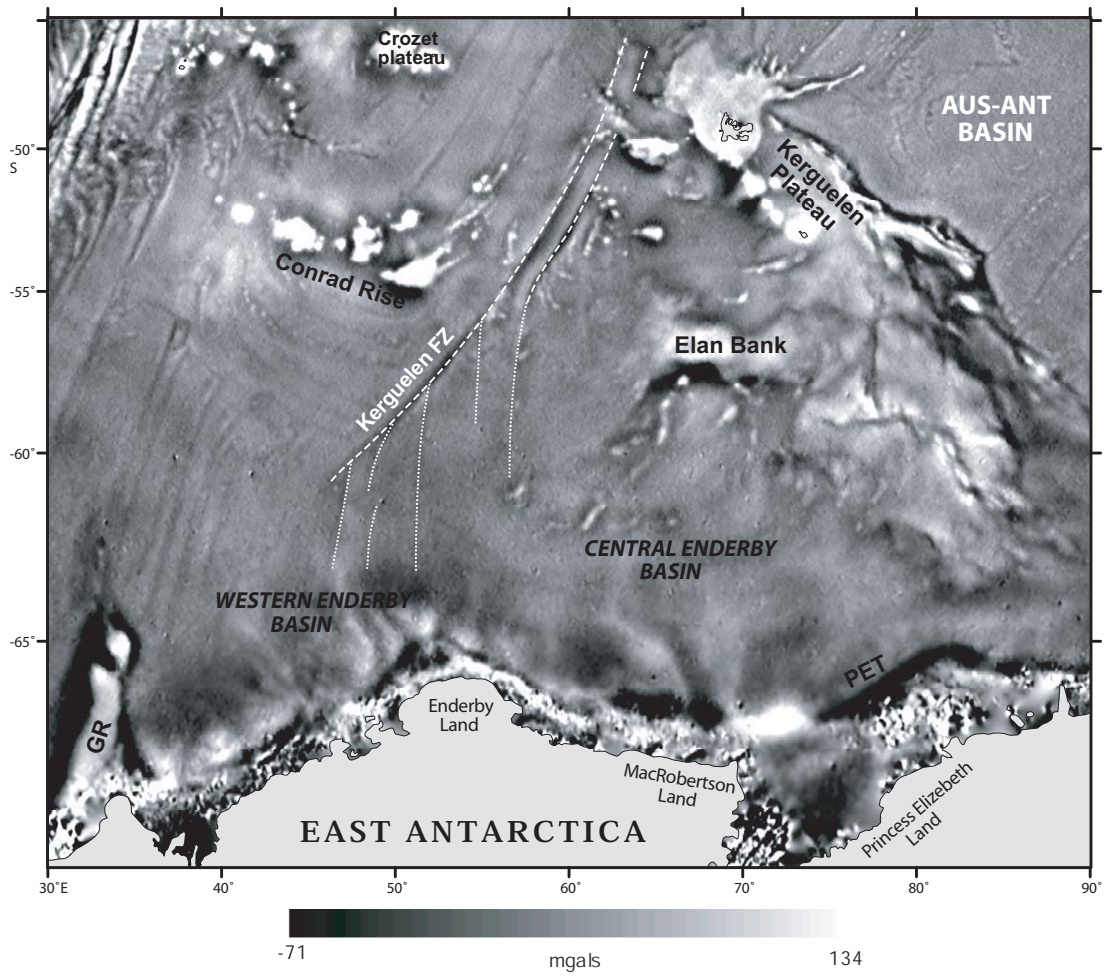


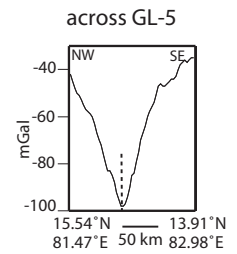
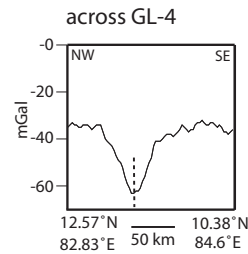
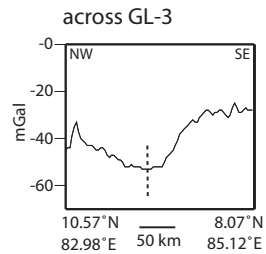
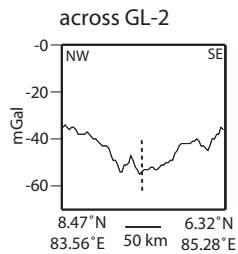
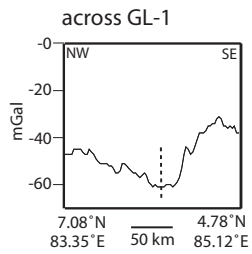
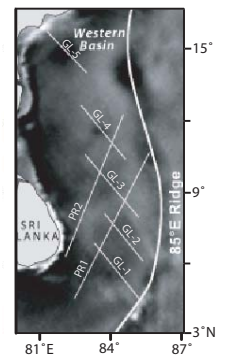
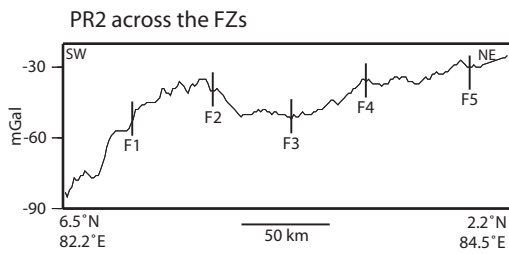
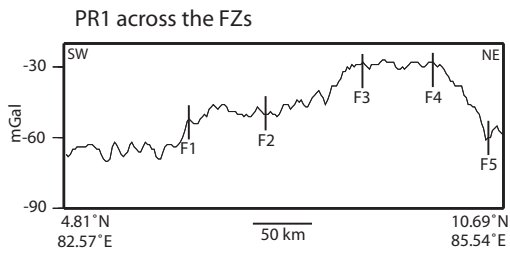


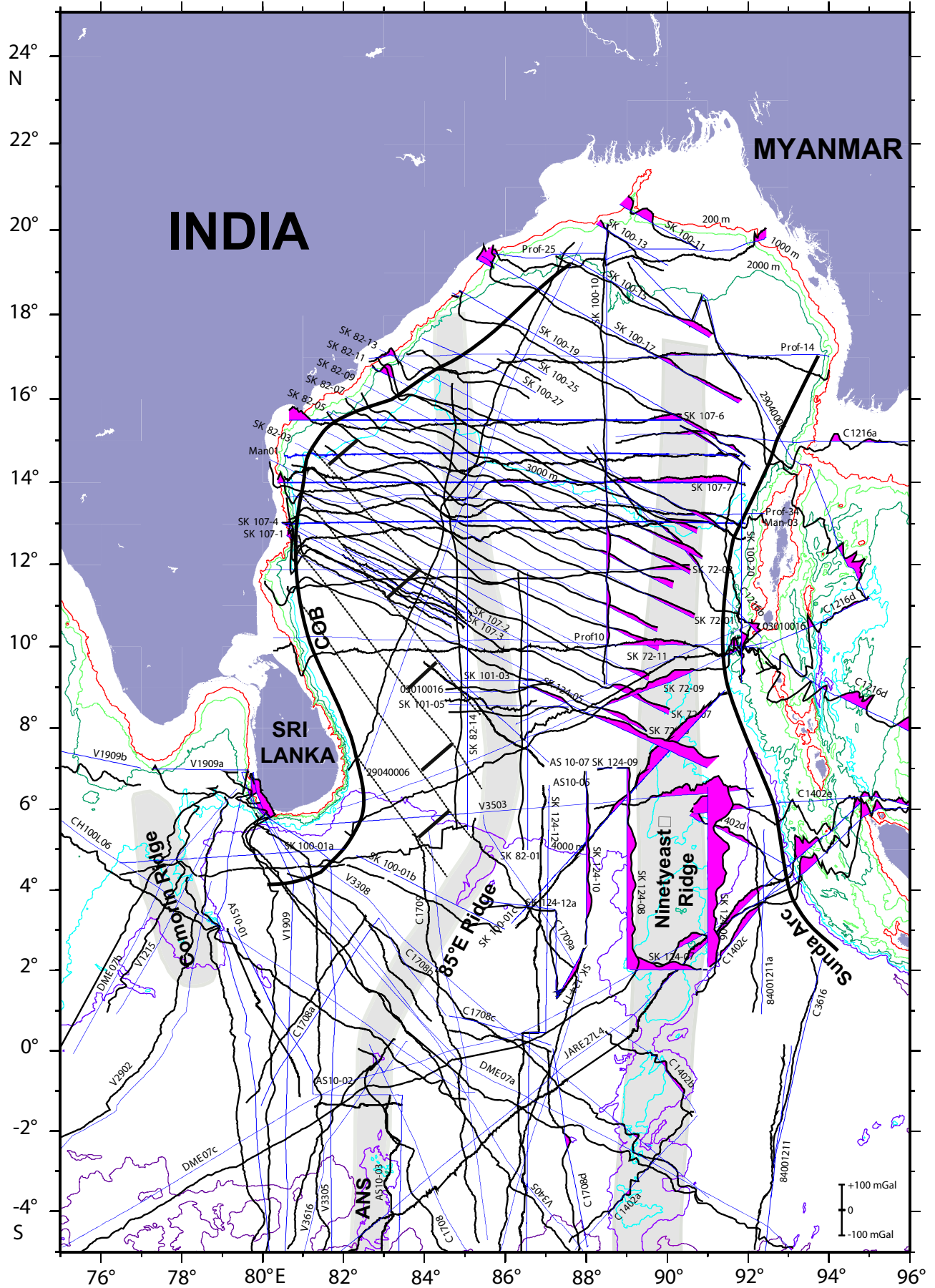


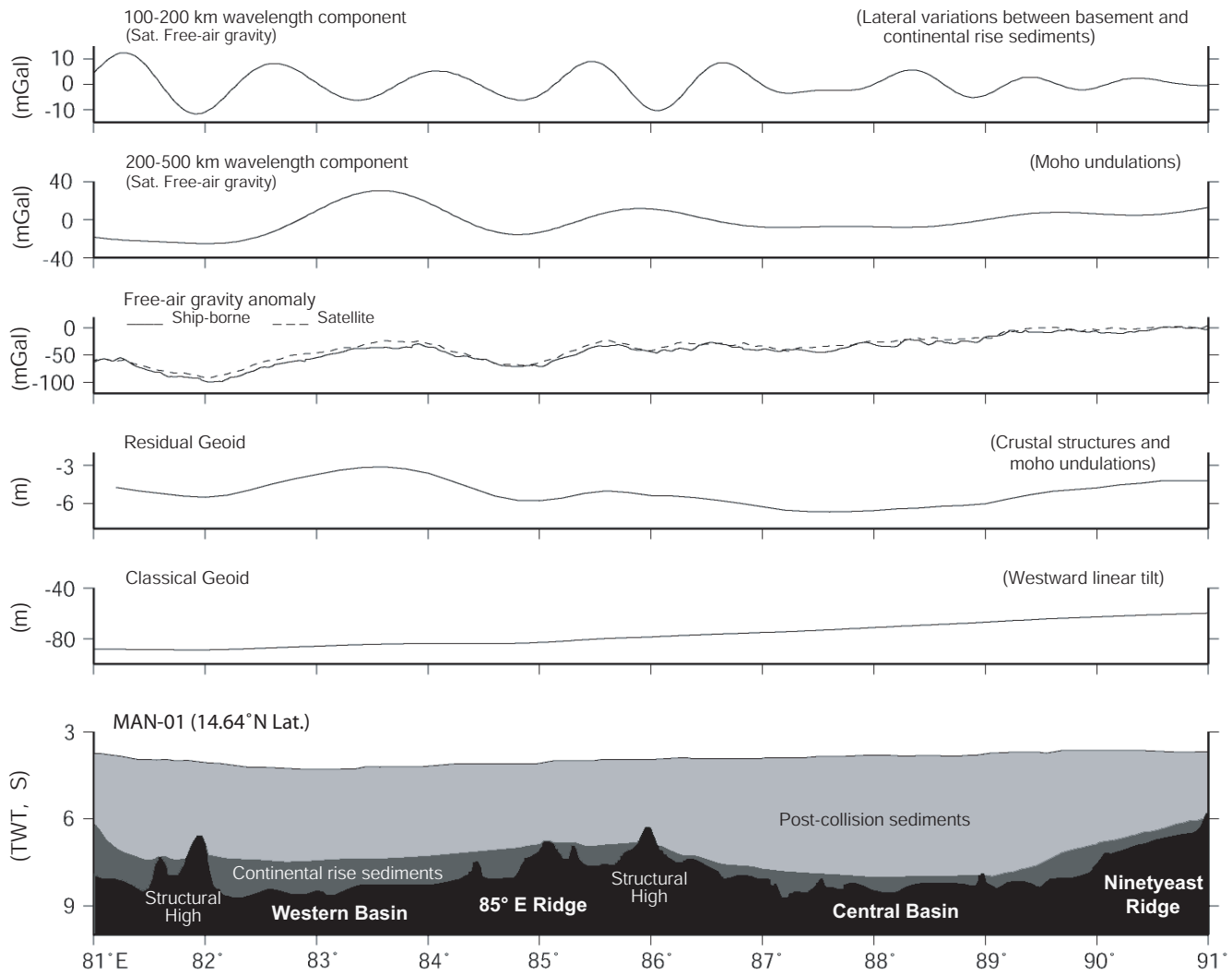


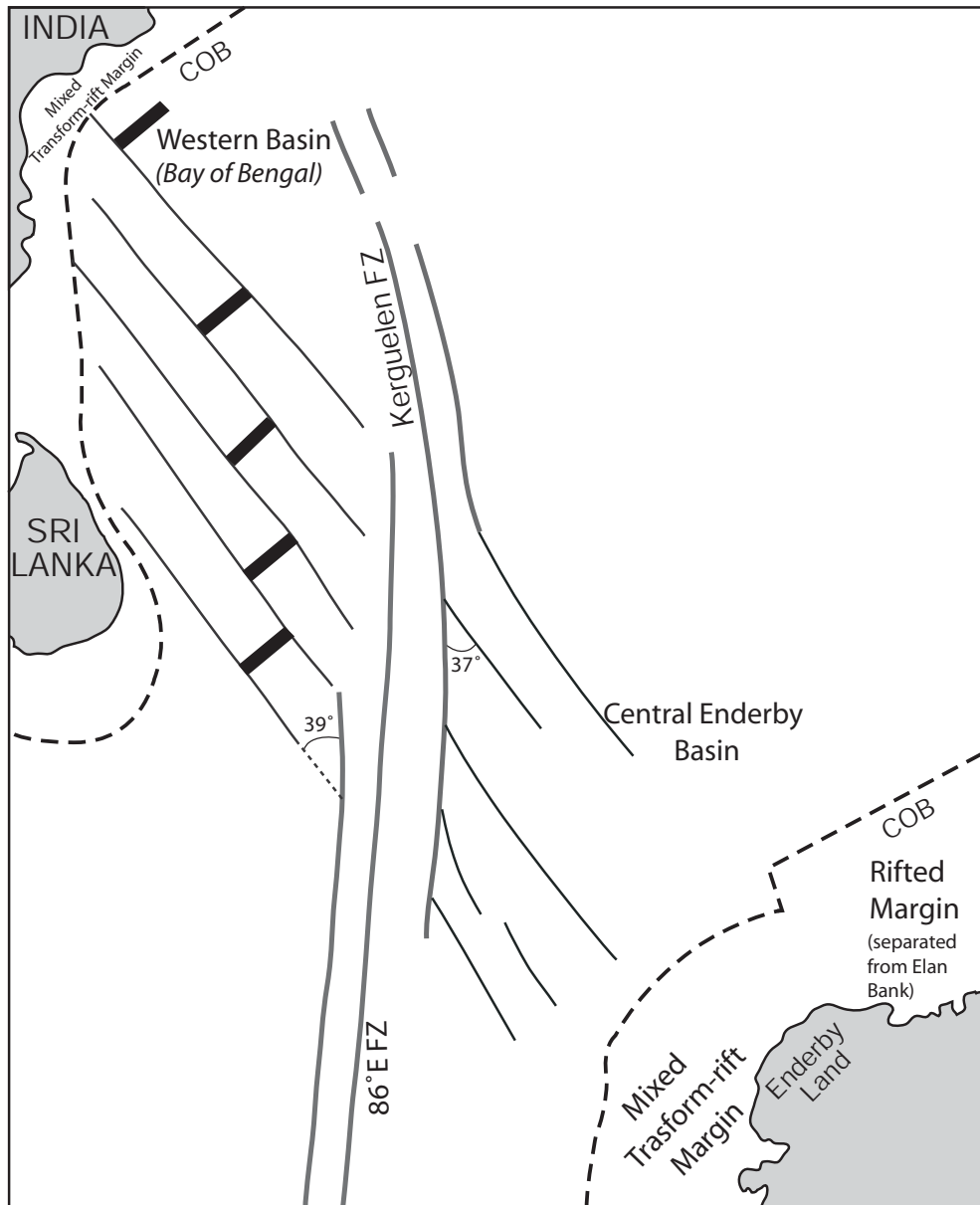


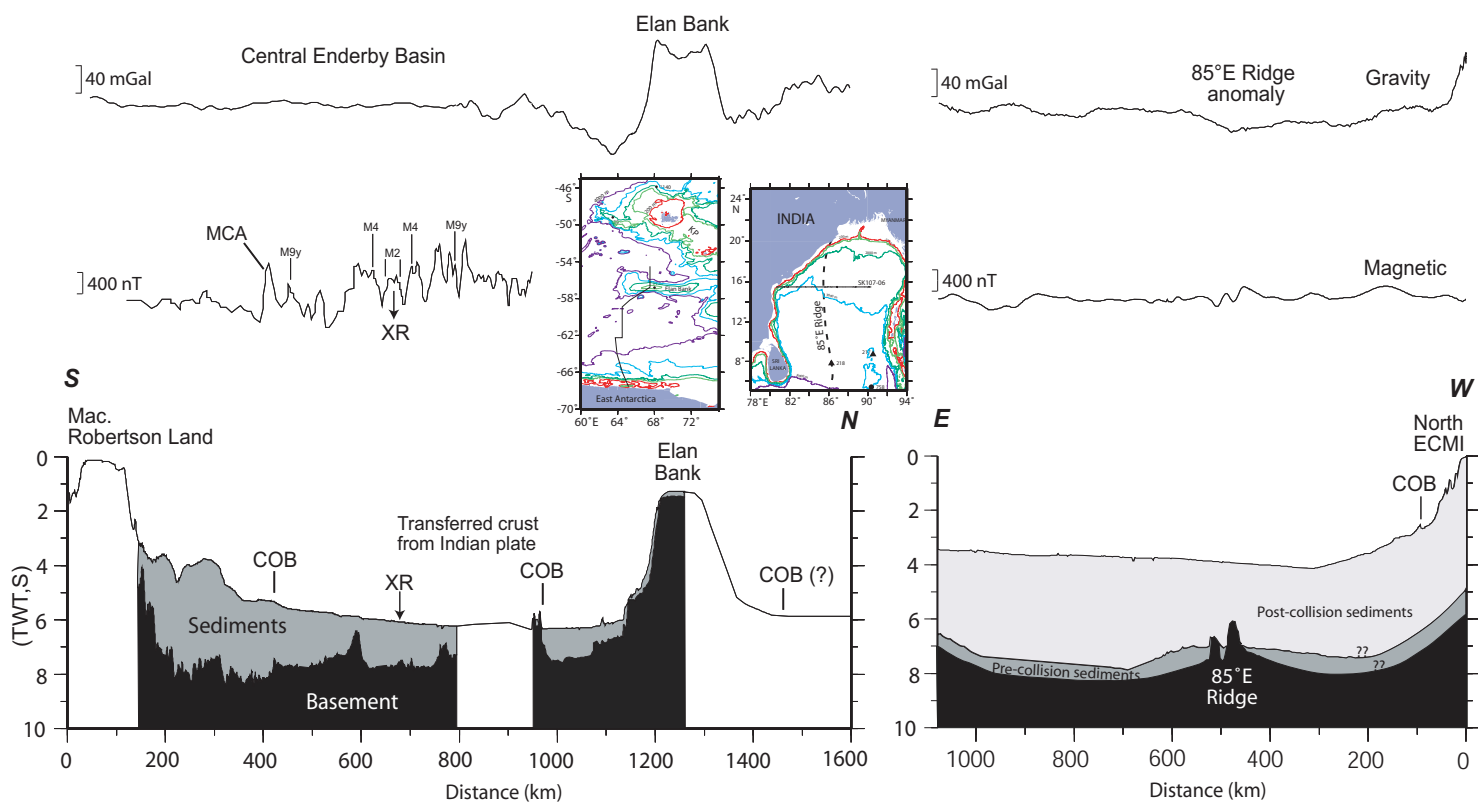


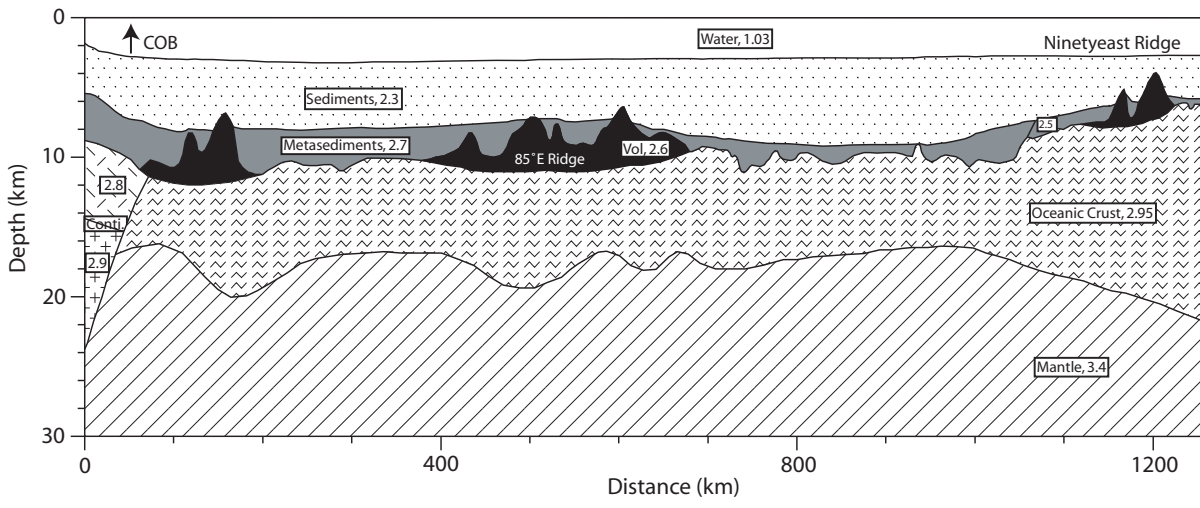
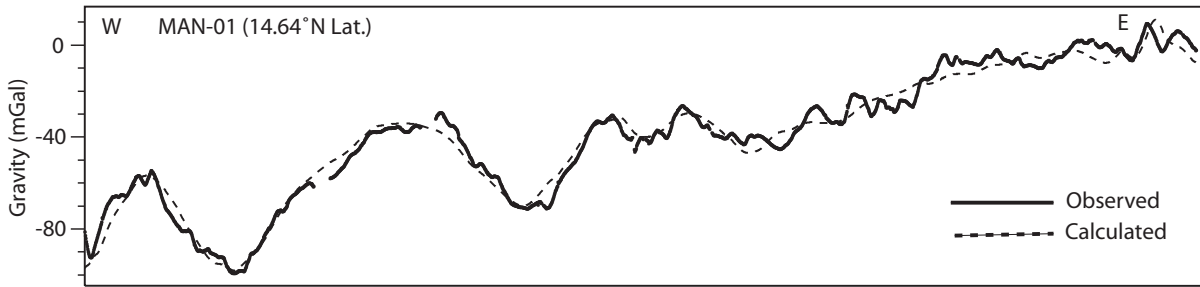












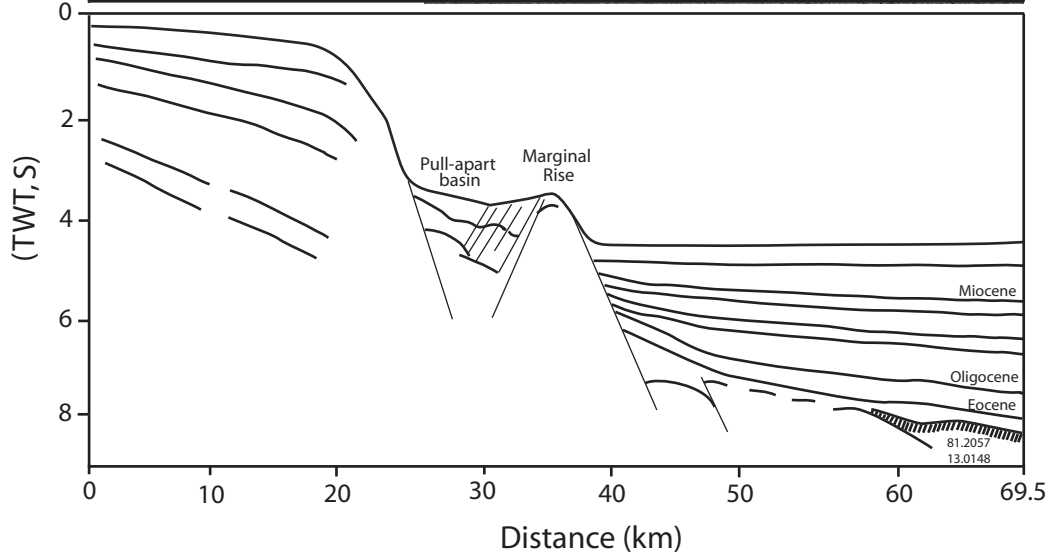
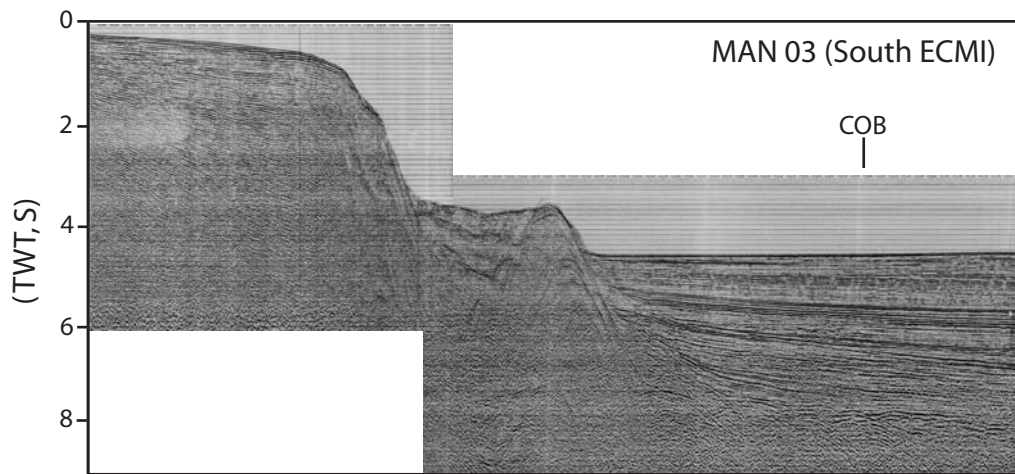
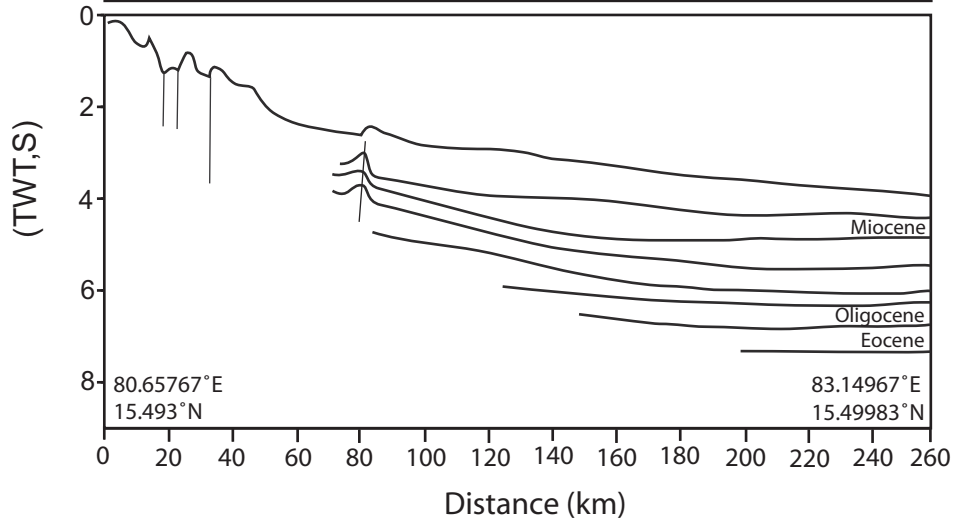
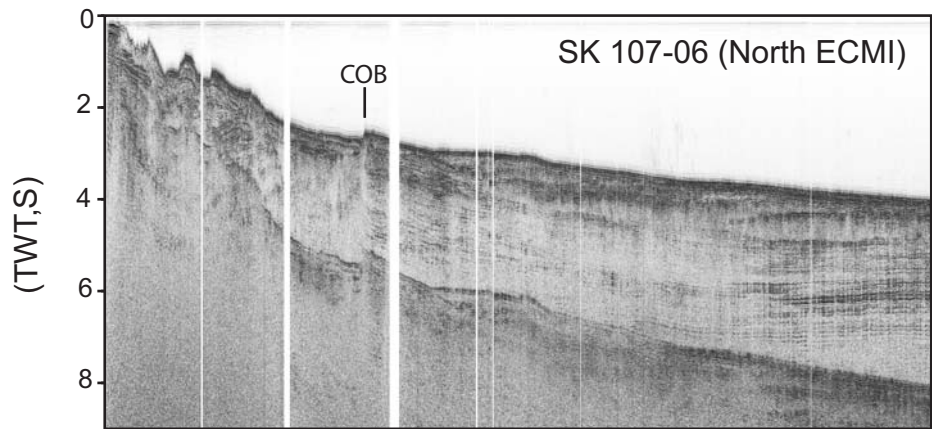


Table 1: Variable geophysical characters associated with the south and north segments of ECMI

| Geophysical results | Signature on north ECMI | Signature on south ECMI | Reference |
|---|---|---|----------------------|
| Fault pattern | Less significant normal faulting | Low-angle normal faulting with major slips | Present study |
| Sediment thickness | Faults are buried under the pre-collision continental rise sediments | Fault surfaces are almost devoid of sediments | Present study |
| Extent of deformation observed on residual geoid data | Broad stretch of continental crust deformed (2.5 m residual geoid high falls in a distance of about 100 km) | Narrow stretch of continental crust deformed (1.5 m residual geoid high falls in a distance of about 50 km) | Present study |
| Amplitude and wavelength of gravity anomalies | 100 mGal anomaly extends to a distance of about 90 km | 140 mGal anomaly falls in 20 km distance and rise by 80 mGal in 40 km distance | Present study |
| Location of Continent-Ocean Boundary | 100-200 km away from the coastline | 50-100 km away from the coastline | Present study |
| Elastic plate thickness (T_e) | 10-25 km thickness | Less than 5 km | Chand et al. (2001) |
| Trends of ridge and graben structures on the margin | Parallel to the coastline | Oblique to the coastline | Sastri et al. (1973) |
| Lithospheric deformation | ---- | Lithosphere of the Cauvery Basin experienced limited extension | Chari et al. (1995) |