Marine Geophysical Studies of the Conjugate Regions of the Bay of Bengal and Enderby Basin-Breakup and Evolution of Structure on Eastern Continental Margin of India

Thesis

submitted to

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Doctor of Philosophy

in

Marine Sciences

by

Laju Michael

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National Institute of Oceanography (CSIR)
Dona Paula, Goa-403004, India

to my parents

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CHAPTER 2

Statement

As required under the University ordinance 0.19.8.(vi), I state that the present thesis entitled "**Marine Geophysical Studies of the Conjugate Regions of the Bay of Bengal and Enderby Basin - Breakup and Evolution of Structure on Eastern Continental Margin of India**" is my original research work carried out at the National Institute of Oceanography, Goa, and it has not been submitted for any other degree or diploma in any university or institution. The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

Laju Michael

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Certificate

This is to certify that the thesis entitled **"Marine Geophysical Studies of the Conjugate Regions of the Bay of Bengal and Enderby Basin - Breakup and Evolution of Structure on Eastern Continental Margin of India"** submitted by Laju Michael for the award of the degree of Doctor of Philosophy in the Department of Marine Sciences, Goa University is based on her original studies carried out under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any university or institution.

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Certified that Ms. Laju Michael has attended to the corrections suggested by the referees and they were incorporated in the thesis.

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Preface

The Indian Ocean is youngest in age among the major oceans of the world, yet its evolution is very complex and includes almost all varieties of geological processes. The Indian Ocean had witnessed several tectonic events since its commencement, such as continental breakups at different geological ages, plate reorganizations, continental collision, intraplate deformation, fracture zones propagation, plume-lithosphere interactions, etc. The breakup of the eastern Gondwanaland during the early Cretaceous, particularly between the Eastern Continental Margin of India (ECMI) and East Antarctica, and subsequent processes of ridge jumps, plate reorganization and Himalayan Orogeny led to formation of the Bay of Bengal including major tectonic features like Ninetyeast Ridge, 85°E Ridge, oceanic fracture zones, unconformities, etc. Several marine geophysical investigations carried out earlier in the northeastern Indian Ocean, have brought out some broad understanding of the evolution of the Bay of Bengal lithosphere and sedimentation process. But the scientific questions like precise timings for the rift initiation and evolution between the Indian continental mass and East Antarctica, evolution of the oceanic lithosphere in conjugate regions of the Bay of Bengal and the Enderby Basin and origin of the aseismic ridges remain poorly understood. The 85°E Ridge in the Bay of Bengal is an enigmatic volcanic feature as the feature is associated with a prominent signature of negative gravity anomaly and complex magnetic anomaly signatures. Therefore, there is a necessity to investigate the origin and evolution of the 85°E Ridge in order to explain the continuity of the ridge track and geological processes that contributed to the formation of the ridge and associated anomalies.

In the present research work ship-borne geophysical data: bathymetry, seismic, magnetic and gravity, of the Bay of Bengal and Enderby Basin available at National Institute of Oceanography (NIO) database and at National Geophysical Data Centre (NGDC) database are utilized for the investigations. In addition, geoid, residual geoid and different wavelength components of the gravity data of both the regions are studied in detail to identify the structural features such as fracture zones, fossil ridge segments, etc. for the purpose of finding new constraints on breakup and early evolution of the oceanic lithosphere between India and Antarctica. The magnetic responses of the 85°E Ridge are also studied and carried out two-dimensional magnetic forward modeling to understand the origin of the ridge and geological processes involved in development of the ridge.

The thesis is divided into the eight chapters. A brief discussion of each chapter is given below.

CHAPTER 1 describes the evolution of the Indian Ocean lithosphere since its inception and the structural features present in the Indian Ocean. A general introduction on major aseismic ridges of the Indian Ocean and on conjugate margins of the Eastern Continental Margin of India (ECMI) and Enderby Land part of the East Antarctica is also presented.

CHAPTER 2 presents a type of geophysical data utilized and methodologies followed for the preparation of databases in the present research work. It further describes the theoretical aspects followed for obtaining the geoid, residual geoid and satellite gravity data. Details of ship-borne geophysical datasets used in the present study are also included in this chapter.

CHAPTER 3 deals with the qualitative analysis of the satellite and ship-borne gravity data of the conjugate regions - Bay of Bengal and Enderby Basin to identify the geophysical anomalies and associated structural features. It includes a description on classical geoid data of the Bay of Bengal and Enderby Basin, which generally provide the details on long-wavelength structural features lie at depth of approximately 100 km deep and occasionally reveal the information of shallow structures that have excessive mass density contrasts. 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 prominent geiodal lows have large influence on overall geoid data 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). The residual geoidal data of the Bay of Bengal and Enderby Basin, which generally provides the information of geological structures lying within the crust and undulations at crust-mantle boundary, are also described. Residual geoidal data of the Bay of Bengal shows geoidal lows over the 85°E Ridge (buried part) and over some isolated features in the Western Basin, while residual geoidal highs are noticed across the southern part (over intermittently exposed structure) of the 85°E 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. The satellite derived free-air gravity anomaly and ship-borne derived free-air gravity anomaly data in the Bay of Bengal shows prominent gravity signatures associated with 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. It also revealed 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. Satellite gravity anomaly data of western Enderby Basin revealed the presence of five fracture zones which trend in N4°E. The results of this chapter have been published in "Journal of Geophysical Research" (Krishna et al., 2009, Journal of Geophysical Research, 114, B03102, doi:10.1029/2008JB005808).

CHAPTER 4 deals with the qualitative analysis of the magnetic data of the conjugate regions - Bay of Bengal and Enderby Basin to demarcate the tectonic fabric of the ocean floor. The magnetic anomaly data of the Bay of Bengal and distal Bengal Fan region are studied in detail and the results obtained are explained in this chapter. The magnetic anomalies in the equatorial region are well developed with east-west oriented lineations, 30 through 34, whereas in the Bay of Bengal region, particularly close to ECMI no coherent magnetic anomalies generated by the Earth's magnetic reversals are observed. Suites of high amplitude positive and negative magnetic anomaly signatures are observed along the 85°E Ridge and significant negative magnetic anomalies are observed along the isolated features. The magnetic profiles in the equatorial region are stacked together and are analyzed to identify the magnetic lineations and fossil ridge segment of the region. The magnetic lineations are found dislocated in different lateral sense and the 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. The north-south trending magnetic profiles from the central, western and eastern Enderby Basin are stacked together and analyzed for identification of magnetic lineations and fossil ridge segment of the region. The present study reveals the presence of conjugate Mesozoic anomaly sequence (from M9N to M2) in the Enderby Basin and also discloses that seafloor spreading activity in the entire Enderby Basin has become extinct between anomalies M2o and M0 and took a northward ridge jump towards Indian continental margin due to the Kerguelen plume activity. The results of this chapter have been published in "Journal of Geophysical Research" (Krishna et al., 2009, Journal of Geophysical Research, 114, B03102, doi:10.1029/2008JB005808.

CHAPTER 5 deals with the comparison of interpreted gravity, magnetic and seismic reflection results of conjugate regions - Bay of Bengal and Enderby Basin. For the first time, five oceanic fracture zones trending in N36°W are identified confidently in the Bay of Bengal, which meet the 86°E FZ at an azimuth of ~39°. In the western Enderby Basin the geophysical data reveal the presence of five oceanic fracture zones trending in N4°E and they converge the Kerguelen FZ at an angle of ~37°. The fracture zones identified in both Bay of Bengal and western Enderby Basin regions, are found to be converged on 86°E FZ and Kerguelen FZ, respectively with a common azimuth of 37°–39°. These fracture zones have become important constraints on break-up of India from Antarctica and early evolutionary history between the continental blocks. Two geophysical profiles including gravity, magnetic and seismic data from the conjugate regions are presented and discussed in order to understand detailed evolution of the oceanic lithosphere between the conjugate margins. The geophysical results obtained from the present research work are coupled with published geophysical results, which led to reveal that the break-up started at age corresponding to magnetic anomaly M9y and continued upto anomaly M2o. Then a ridge jump towards north ECMI had detached the Elan Bank. Thus, the oceanic lithosphere evolved in the Cretaceous Magnetic Quiet Period is found in the Bay of Bengal and both sets of M-series anomalies and extinct ridge are found in the Enderby Basin region, south of the Elan Bank. Two-dimensional gravity forward model results explain the negative gravity anomaly of the 85°E Ridge with the presence of metasediments, denser than the volcanic rocks and the flexure of the lithosphere. The new constraints obtained in this study on break-up and early spreading history between India and Antarctica are explained in detail. The results of this chapter have been published in "Journal of Geophysical Research" (Krishna et al., 2009, Journal of Geophysical Research, 114 B03102, doi:10.1029/2008JB005808).

CHAPTER 6 deals with the classification of the continental margin segments on eastern continental margin of India. Bathymetry, gravity and magnetic profile data from both north and south segments of the ECMI are stacked for the analysis. A significant gravity anomaly of short-wavelength and high-amplitude is observed on the eastern margin of Sri-Lanka and south ECMI, while along the north ECMI, a contrasting character of gravity anomaly with reduced amplitude and extended wavelength is observed. On the south ECMI, the COB lies relatively closer (50–100 km) to the present-day coastline, whereas on the north ECMI, the boundary lies at a farther distance, approximately 100–200 km away from the coastline. Two seismic reflection profiles each from north and south segments of the ECMI are analyzed for identification of structural features associated with the continental break-up processes. On south ECMI the faulted 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 other geophysical features such as normal faults with major slips, narrow stretch of deformed crust, marginal-high and rifted basin describe the transform margin character for the south segment of the ECMI. The present study coupled with other geophysical studies suggests that a swap in tectonics from shearing to rifting on the south ECMI had allowed the margin to have mixed rift transform character. The results of this chapter have been published in "Journal of Geophysical Research" (Krishna et al., 2009, Journal of Geophysical Research, 114 B03102, doi:10.1029/2008JB005808.

CHAPTER 7 deals with three important geophysical aspects of the 85°E Ridge i) to determine the magnetic responses of the ridge all along the profiles (ii) to test the concept that the 85°E Ridge has been evolved during the period of post magnetic anomaly 34 and emplaced on oceanic crust created during the Cretaceous Magnetic Quiet Period, and (iii) to ascribe approximate ages to the 85°E Ridge track. To understand the geophysical response of the 85°E Ridge, all the available gravity and magnetic profiles running across the ridge are analyzed and discussed in detail. Four multichannel seismic reflection profiles run along the latitudes 13°N (MAN-03), 14°N (SK107-7), 14.64°N (MAN-01) and 15.5°N (SK 107-6) and extend from the ECMI to the vicinity of the Ninetyeast Ridge are presented in the form of line drawing sections and gravity and magnetic anomaly signatures are also stacked for interpretations and discussions. Eight seismic sequences are identified and described their formation in terms of various sediment depositional conditions. From the analysis of marine magnetic data of the 85°E Ridge, for the first time, it has been clearly demonstrated that the ridge is associated with alternate positive and negative magnetic anomaly signatures distributed for asymmetrical extents. Two-dimensional forward magnetic modeling along two profiles each with positive and negative magnetic anomalies associated with the 85°E Ridge, is carried out in order to obtain critical constraints on ridge origin. The results suggest that positive and negative magnetic anomaly belts associated with the 85°E Ridge for asymmetrical extents are generated by the ridge topography and magnetic polarity contrast, respectively. Thus the derived tectonic model for the 85°E Ridge is consistent with the hypothesis of hot spot volcanism on approximately 35 m.y. aged oceanic crust. The identified magnetic stripes of the ridge are correlated with the geomagnetic polarity timescale of Cande and Kent (1995) to assign approximate ages for the emplacement of the 85°E Ridge track. The present results and other geophysical results together suggest that the 85°E Ridge was originated by a short-lived hot spot from 80 to 55 Ma on already evolved oceanic crust of approximately 35 m.y. age. The results of this chapter have been published in "Current Science" (Laju Michael and K.S. Krishna, 2011, Current Science, Vol. 100, No. 9, pp 1314-1322).

CHAPTER 8 summarizes the results and major conclusions obtained from the present research work. This chapter also discusses the limitations on present work and further suggests the scope for future study in the region.

CHAPTER 1

Structure and Tectonics of the Indian Ocean

STRUCTURE AND TECTONICS OF THE INDIAN OCEAN

The study of the oceans is important to the mankind because nearly two thirds of the Earth's surface lies beneath the water body. Before the 19^{th} century itself it was realized that the oceans are home for variety of living and non-living resources. Though oceans are distinctly categorized as different entities, but their water body is connected to one another around the globe. There are five recognized oceans: the Pacific, Atlantic, Indian, Antarctic and Arctic Oceans on the Earth (Figure 1.1). Until the beginning of 20^{th} century, oceans were generally believed to be sunken continents, differing only in their elevation. In 1912 German meteorologist, Alfred Lothar Wegener put forth the ground breaking theory in earth science called continental drift. Since 1950's ocean explorations worldwide have greatly enhanced for various purposes and the seafloor data gathered in the expeditions led to the discovery of great mountain ranges that lay on the ocean floor, and this virtually encircles the world oceans called the global mid-ocean ridge (Figure 1.1). This immense submarine mountain chain, more than 60,000 km long and in places more than 800 km across zig-zags between the continents, winding its way around the Earth like the seam on a baseball. Though hidden beneath the ocean surface, the global mid-ocean ridge system is the most prominent topographic feature on surface of Earth planet.

Among the major global oceans the Indian Ocean is relatively younger, yet its evolution is very complex and experienced almost all range of geological processes. The Indian Ocean, since its inception witnessed tectonic events of breakup of continental fragments at different phases, major plate reorganizations, continental collision, intraplate deformation, fracture zone propagations, ridge migrations, hot spot drifts, etc. The Indian Ocean, the third largest of the world oceans with a total area of 74.11×10^6 sq. km, lies in the southern part of Asia bordered by Antarctica in the south, Africa and Madagascar in the west, Java-Sumatra in the east and Arabia and India in the north. Also the Indian Ocean has a special feature of complete encompass in its north by continental land mass, contrasting from other major oceans. The closure towards the northward of the ocean has great influence in ocean circulation and

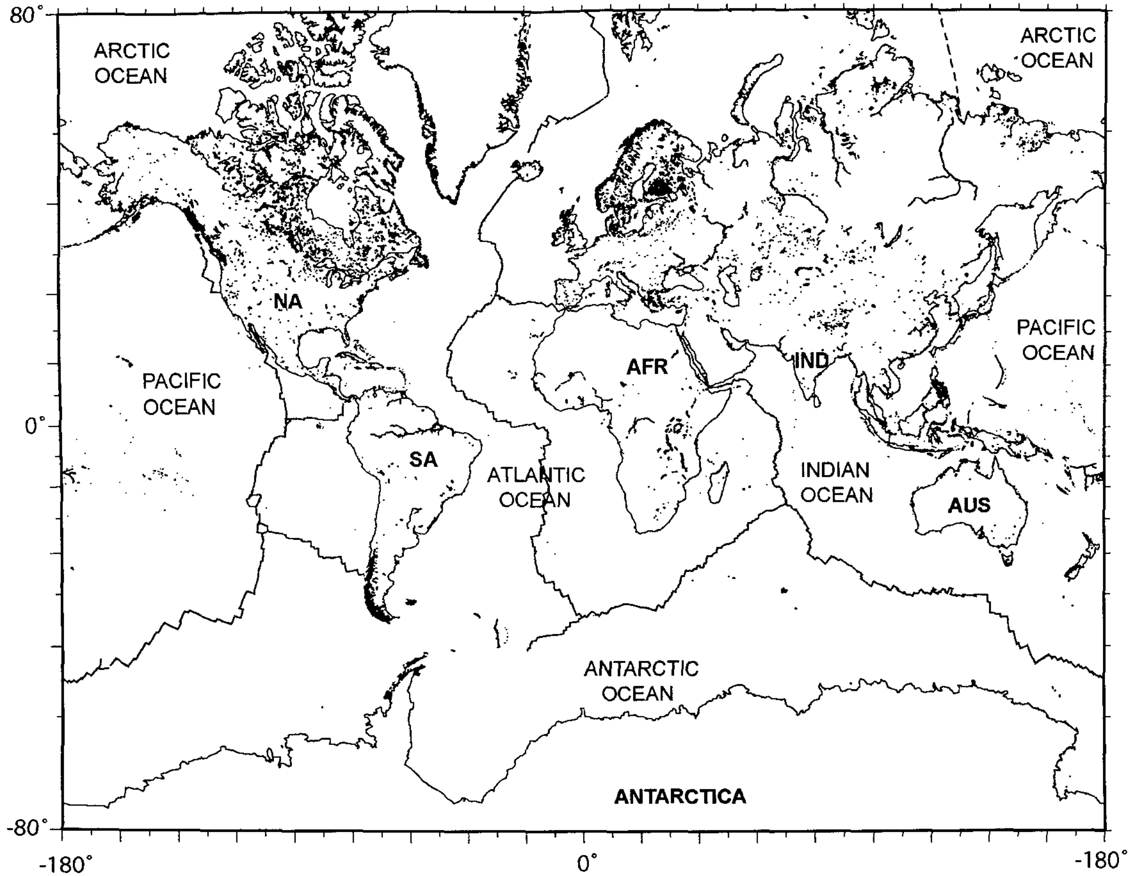


Figure 1.1: The map showing the five major oceans and global mid-oceanic ridge system of the Earth. The five oceans are Pacific, Atlantic, Indian, Antarctic and Arctic Oceans. AUS, IND, AFR, SA and NA represent Australia, India, Africa, South America and North America, respectively. The zigzag black line indicates the presence of mid-oceanic ridge system in world oceans.

environment in Asian region. The ocean consists of three major plate boundaries bordering the Indo-Australian, Antarctic and African plates with edge of seafloor spreading ridges, transform faults and subduction zones.

1.1 Evolution of the Indian Ocean

The Gondwana super-continent, consisting of mainly South America, Africa, Greater India, Madagascar, Australia and Antarctica, had broken into two major parts, the western and eastern Gondwanaland during the late Jurassic (~182 Ma). The western Gondwanaland comprised of South America and Africa, whereas eastern Gondwanaland comprised of mainly Greater India, Madagascar, Australia and Antarctica. Further breakup of eastern Gondwanaland into two continental masses, Australia-Antarctic and Greater India in the late Jurassic-early Cretaceous paved the way for commencement of the Indian Ocean (Figure 1.2) (Curray and Moore, 1971; Moore et al., 1974; Norton and Sclater, 1979; Curray et al., 1982; Royer and Coffin, 1992; Gopala Rao et al., 1997).

The seafloor of the Indian Ocean is characterized morphologically by mid-ocean ridges, trenches, continental shelves, oceanic plateaus, aseismic ridges, etc. The spreading activity of the Indian Ocean has witnessed several events of the major plate reorganizations, ridge jumps, migration of triple junction, interactions of hot spots with spreading centers, intraplate deformation, collision of India with Eurasia, Himalayan Orogeny, etc. Greater India and Madagascar as one entity was separated in northwesterly direction from Antarctica-Australia during the early Cretaceous, resulting in the formation of oceanic crust in the Mesozoic Basins off the western Australian margin, off the east African margin and as well adjacent to the eastern margin of India (McKenzie and Sclater, 1971; Curray et al., 1982; Veevers et al., 1975; Ramana et al., 1994; Gopala Rao et al., 1997; Krishna et al., 2009; Veevers, 2009). The breakup of Australia from Antarctica initiated during the mid-Cretaceous with the formation of the Australia-Antarctica Ridge (Figure 1.2), which is the southeastern part of present day Southeast Indian Ridge (Cande and Mutter, 1982; Veevers, 1986; Royer and Coffin, 1992).

Around the same period Madagascar and India got separated by the India-Madagascar spreading ridge (Norton and Sclater, 1979). Presently part of this ridge is existing in the form of abandoned spreading centre (ASC) on the east of Madagascar.

Northward movement of Indian plate from Antarctica (McKenzie and Sclater, 1971; Molnar and Tapponier, 1975; Johnson et al., 1976; Peirce, 1978; Liu et al., 1983; Negi et al., 1986; Klootwijk et al., 1992) took place during the mid-Cretaceous to middle Eocene during the formation of seafloor spreading anomalies 34 through 22 and this movement slowed down due to the initial collision of Greater India with the southern Asian plate (Curray et al., 1982; Patriat and Segoufin, 1988; Klootwijk et al., 1992; Krishna et al., 1995). Seychelles rifted from the Indian continent and gave birth to the Carlsberg Ridge around the time of spreading anomaly 28 (~68 Ma) (McKenzie and Sclater, 1971). Around this period the Rodriguez Triple Junction came into existence by connecting three major Indian Ocean ridge systems, whereas in the northern side the Reunion hot spot had created the Deccan flood basalts on western Indian Shield. The collision between India and Asia took place about 53 Ma, which set the initial stage for the formation of the mighty Himalayas. Soon after formation of spreading anomaly 19 the Wharton Spreading Ridge became totally inactive and jumped towards south (Liu et al., 1983; Royer and Sandwell, 1989; Royer and Coffin, 1992; Krishna et al., 1995, 1999, 2011a). Subsequently India-Antarctica and the Australia-Antarctica ridges have merged together to form a single continuous spreading ridge system called the Southeast Indian Ridge (Figure 1.2). This event led to the occurrence of second major plate reorganization during the middle Eocene period. Consequently the Indian plate and the Australian plate merged together to form a single Indo-Australian plate (Liu et al., 1983; Krishna et al., 1995, 2011a). Since then the central part of the Southeast Indian Ridge separated the Broken Ridge and Kerguelen-Gaussberg ridges (Mutter and Cande, 1983). On the western side around 30 Ma the northern part of the Central Indian Ridge separated the Chagos and Nazareth banks, created by the Reunion hot spot.

The younger events that occurred in the Indian Ocean were the opening of the Gulf of Aden around anomaly 5 (~10 Ma) by the Sheba Ridge (Laughton et al., 1970; Stein and Cochran, 1985). During the Miocene age high-magnitude earthquakes and large-scale lithospheric deformation occurred in the Central Indian Ocean, which eventually split

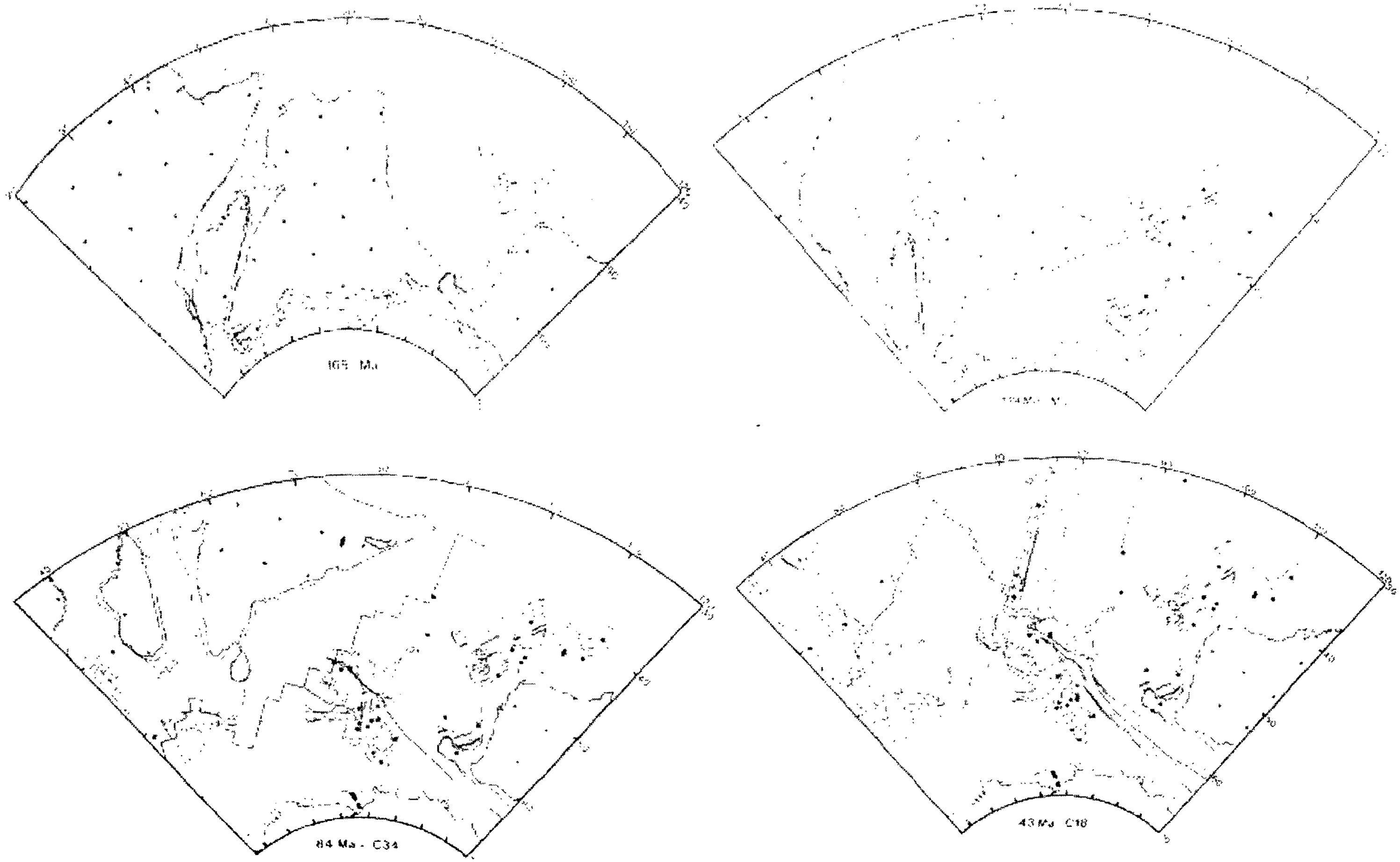


Figure 1.2: Plate reconstruction of Gondwanaland super-continent fragments from 165 Ma to 43 Ma (after Royer and Coffin, 1992)

the Indo-Australian plate into three component sub-plates (India, Capricorn and Australia) and multiple diffuse plate boundaries (Royer and Gordon, 1997; Gordon et al., 1998; Demets et al., 2005; Krishna et al., 1998, 2001a, 2009; Bull et al., 2010) and led to the separation of Arabia from Somalia and the inactivity of motion on the Owen Fracture Zone (Weins et al., 1985). Besides these tectonic processes, the hot spots in the Indian Ocean have also largely contributed towards shaping the Indian Ocean floor. The continental flood basalts (Deccan traps on western India, Rajmahal traps on northeastern India, Bunbary basalts in southwestern Australia, Karoo basalts on southeastern Africa, Ethopian basalts on northeastern Africa, and Aden and Yemen traps on southern Arabia) and linear ridges (Ninetyeast Ridge, Chagos-Laccadive Ridge, 85°E Ridge and Madagascar Ridge) were also emplaced during the development of the Indian Ocean.

1.1.1 Mid-Oceanic Ridges

The Indian Ocean floor is dominated by three major spreading ridges: the Central Indian Ridge (CIR), the Southwest Indian Ridge and the Southeast Indian Ridge (Figure 1.3). The major ridges converge at a point (25°S latitude, 70°E longitude) called Rodriguez Triple Junction, in the form ridge-ridge-ridge junction. The meeting point and arms of these three ridges resemble an inverted "Y" shape. The Central Indian Ridge extends towards north and turns in a northwesterly direction as a Carlsberg Ridge and finally joins the Sheba Ridge in the Gulf of Aden, Arabian Sea. The Southeast Indian Ridge runs from the Rodriguez Triple Junction to the Macquarie Ridge Complex separating the Indo-Australian plate from Antarctic plate while the Southwest Indian Ridge branches out from the Rodriguez Triple Junction to join the Bouvet Triple Junction in the South Atlantic Ocean separating the African and Antarctic plates.

1.1.1.1 The Central Indian Ridge

The Central Indian Ridge (CIR) is a near north-south oriented mid-oceanic ridge system in the Indian Ocean, which extends from the equator to the Rodriguez Triple Junction (Figure 1.3).

The ridge segments are dislocated by number of NE-SW trending transform faults and displace the NW-SE trending ridge axis in an en echelon fashion. At places the ridge segments are associated with major fracture zones, for example around 10°S latitude Vema FZ displaces the ridge axis by about 200 km (Von Herzen and Vacquier, 1966) and at another location around 18°S latitude the ridge axis is offset by about 220 km distance and is associated with Marie Celeste FZ (Fisher et al., 1971). The axis of the Central Indian Ridge is characterized by a significant rift-valley and associated with earthquake epicenters (Fisher et al., 1971). The half spreading rate of the Central Indian Ridge calculated from the magnetic anomalies varies from north to south between 1.8 cm/yr and 2.4 cm/yr. The Chagos-Laccadive Ridge (Ch-L R) and the Mascarene plateau are symmetrically displaced on either side of the Central Indian Ridge, which suggests that they were emplaced at the same time during the spreading episode (Fisher et al., 1971).

1.1.1.2 The Southeast Indian Ridge

The Southeast Indian Ridge (SEIR) is a NW-SE trending mid-oceanic ridge in the Indian Ocean, which extends in south eastward direction from the Rodriguez Triple Junction through the Amsterdam-St. Paul Islands to the Pacific-Antarctic Ridge at the Macquarie Ridge complex south of Australia (Figure 1.3). The SEIR separates the Crozet Basin to the south from the central Indian Basin in the north and farther to the east it separates the Australian-Antarctic Basin from the South Australian Basin.

The magnetic anomaly studies across the ridge reveal the presence of several transform faults and their inactive extensions on the ridge flanks and beyond in ocean basins as fracture zones in NE-SW direction. Major transform faults with large offsets are located near the Amsterdam-St. Paul islands and the half spreading rate is estimated around 3.4 cm/yr at 40°S. The changes in the spreading rates accompanied by changes in the spreading directions south of the ridge were observed by Schlich and Patriat (1971) based on the magnetic studies of the northern Crozet Basin. Magnetic anomalies 17 and 18 are identified on the east and west of the Kerguelen-Heard plateau. Two distinct spreading rates are identified in the last 40 Ma period with a half spreading rate of 3.4 cm/yr for anomalies 1 and 5 (10 Ma) and 2.5 cm/yr for anomalies 5 and 17 (40 Ma) (Le Pichon and Heirtzler, 1968; Schlich and Patriat, 1971; Schlich, 1975). In the

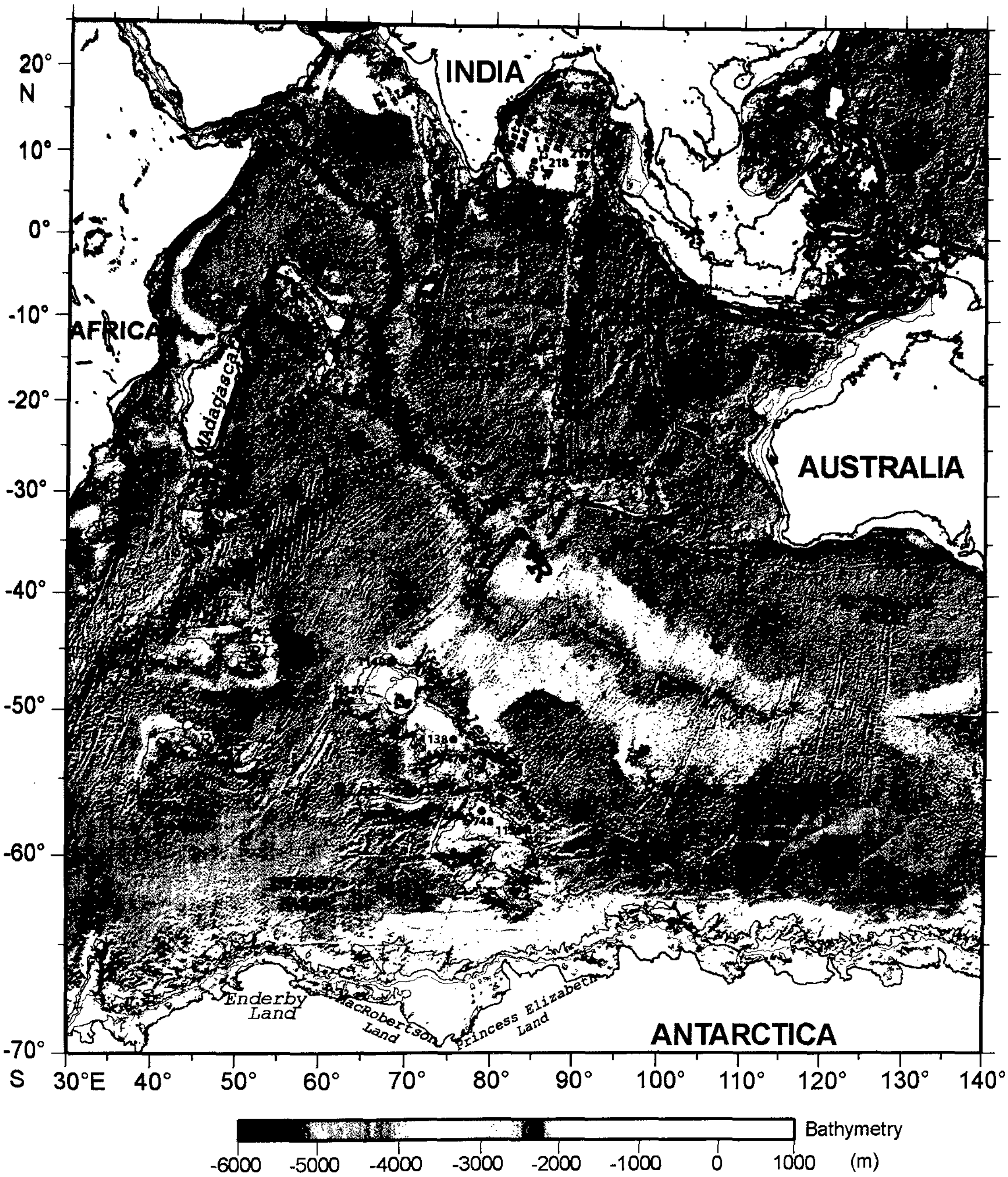


Figure 1.3: Generalized ocean floor map of the Indian Ocean showing the mid-oceanic ridge system and aseismic ridges - Ninetyeast Ridge, Chagos Laccadive Ridge and 85°E Ridge. DSDP and ODP sites are shown with solid triangles and circles, respectively. SWIR- Southwest Indian Ridge, CIR-Central Indian Ridge, SEIR-Southeast Indian Ridge, RTJ-Rodriguez Triple Junction, Ch-LR-Chagos Laccadive Ridge, CLR-Carlsberg Ridge, SB-Sheba Ridge, GA-Gulf of Aden, LR-Laxmi Ridge, LB-Laxmi Basin, OS-Osborne Knoll, ANS-Afanasy Nikitin seamount.

vicinity of the Kerguelen plateau no magnetic correlations are observed as the magnetic pattern is obliterated by large volcanic emplacements.

1.1.1.3 The Southwest Indian Ridge

The Southwest Indian Ridge (SWIR) is a NE-SW trending mid-oceanic ridge feature in the Indian Ocean, which extends from the Rodriguez Triple Junction, to the Bouvet Triple Junction (55°S latitude, 1°W longitude), in the south Atlantic Ocean (Figure 1.3). The Bouvet Triple Junction is another important meeting point for three major mid-ocean ridge systems: Southwest Indian Ridge, Mid-Atlantic Ridge and America-Antarctica Ridge.

The SWIR is characterized by rugged topography with relief in excess of 4000 m. The seafloor topography trends in NE-SW direction and is cut by several near N-S oriented fracture zones (Heezen and Tharp, 1965). The ridge has ultra slow spreading rates of the order of 0.8 to 1.3 cm/yr (Vine, 1966; LePichon and Heirtzler, 1968; Ewing et al., 1969). Detailed geophysical studies over the SWIR revealed that the ridge is dominated by a series of major fracture zones, which can be traced up to a distance of 2000 km from their active transform sections. The trend of these fracture zones changes progressively from NE-SW direction in the vicinity of Bouvet Triple Junction to N-S direction west of the Rodriquez Triple Junction.

1.1.2 Aseismic Ridges

Besides mid-oceanic ridge features, the Indian Ocean includes other major seafloor topographic features such as inactive ridges, plateaus, seamount chains, basins, etc., that are generally referred as aseismic ridges. Aseismic ridges seem to be originated either by breakup of continental fragments or by volcanism in the vicinity of lithospheric plate boundaries or in interior of the plates. These aseismic ridges, most striking features of the Indian Ocean, were evolved in very different tectonic frameworks and show great variability in their morphology. The Chagos-Laccadive and Ninetyeast ridges are the most prominent and longest aseismic ridges in the Indian Ocean. They are more or less continuous linear features traversing in the deep ocean floor and rises to more than 3000 m above from the surrounding ocean floor. The 85°E

Ridge is another, but less prominent aseismic ridge in the Indian Ocean. These features are studied in detail with the help of geophysical investigations and results of Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) (Figure 1.3).

1.1.2.1 The Ninetyeast Ridge

The Ninetyeast Ridge lying in the eastern Indian Ocean is one of the largest linear aseismic ridges of the world oceans. It is a long continuous volcanic ridge and trends approximately in N-S direction along the 90°E meridian (Figure 1.3). The ridge extends more than 5000 km long from 34°S latitude in the south to 17°N in the north into the Bay of Bengal with an average width of 200 km and height of more than 2 km (Sclater and Fisher, 1974; Udinstev, 1975; Schlich, 1982; Fisher et al., 1982). At 10°N latitude the ridge is covered by thin sediments and further north upto 17°N latitude the ridge is buried beneath thick sediments of the Bengal Fan (Curray et al., 1982; Gopala Rao et al., 1994, 1997). The ridge in the Bay of Bengal region separates the eastern Nicobar Fan from the main Bengal Fan. The morphology of the Ninetyeast Ridge is variable along its stretch with linear and flat topped features (Sager et al., 2007, 2010). At around 15°S latitude, a broad circular bathymetric high called Osborne Knoll is situated on immediate west of the ridge. Between the latitudes 7°S and 10°N the ridge segment consists of a complex of en echelon blocks of individual topographic highs, each with northeast-southwest elongation. The northern most part of the ridge is buried beneath the thick sediments of the Bengal Fan and in the southern end the ridge is abutted by E-W trending Broken Ridge (Sclater and Fisher, 1974; Curray and Moore, 1974). At several of the locations the flanks of the ridge on both sides have variable topographic gradients, and specifically the depth to the seafloor between 11° and 21°S is relatively deeper on the eastern flank than the western flank (Udinstev, 1975; Fisher et al., 1982; Krishna et al., 2001b). South of the Osborne Knoll, the ridge is wide and more massive than it is towards the north of the Osborne Knoll (Sclater and Fisher, 1974; Krishna et al., 1995).

Several theories have been proposed for the accretion of the Ninetyeast Ridge on the oceanic crust. They are horst type feature due to an upliftment of the oceanic crust (Francis and Raitt, 1967, Laughton et al., 1970), upthrusting caused by the convergence of the two fragments of the Indian plate (LePichon and Heirtzler, 1968), relict spreading ridge (McKenzie and Sclater, 1971), hot spot origin (Morgan, 1972), emplaced locally by gabbro (Bowin, 1973) and volcanism along a leaky transform fault due to relative motion of Indian and Australian plates (Sclater and Fisher, 1974). With the availability of DSDP and ODP drill-well information, it is widely believed that the Ninetyeast Ridge was formed as a result of hot spot volcanism near the spreading ridge that once separated the Indian plate from the Antarctic plate, leaving a trail of volcanism on the Indian plate as it drifted northward during the late Cretaceous and early Cenozoic period (Royer et al., 1991; Krishna et al., 1995, 1999, 2011a). This interpretation was supported mainly by geochronology data, which was obtained from DSDP and ODP core samples. The age data shows that the southern most part of the Ninetyeast Ridge at ODP Site 756 is ~45 Ma in age while along the northern most part of the ridge at ODP Site 758 it is found to be ~78 Ma in age, which suggest that the ridge was emplaced by the Kerguelen hot spot when the Indian plate moved northward over it (Weis and Frey, 1991; Klootwijk et al., 1992; Duncan, 1991; Duncan and Storey, 1992; Krishna et al., 2011a).

Major part of the Ninetyeast Ridge falls in a complex zone of deformation within the Indo-Australian plate. Some part of the ridge has experienced intense seismic activity in the past (Petroy and Wiens, 1989). The seismicity is more concentrated in the northern segment of the ridge (upto 10°S), where it undergoes NW-SE compression and vertical as well as strike slip motions occur. The seismicity is less along the southern segment of the ridge. The transition is evident from the morphology of the ridge where irregular en enchelon blocks in the north are separated from smooth flat topped highs in the south. It is also suggested that a diffuse triple junction is located in the middle of the Ninetyeast Ridge due to the deformation between Indian, Australia and Capricorn sub-plates. From bathymetry, gravity and seismic data it has been concluded that northern most part of the Ninetyeast Ridge is at the final stages of indention near the Andaman forearc and at the same time slipping northward (Subrahmanyam et al., 2008a).

1.1.2.2 The Chagos-Laccadive Ridge

The Chagos-Laccadive Ridge (Ch-LR), another major elongated aseismic feature, extends in near N-S direction for about 3000 km, approximately along 73°E meridian between 14°N and 10°S latitudes. The ridge is slightly arcuate with its concave side to the west. E-W trending deep channels separate the ridge structure into several irregular blocks with a width reaching up to 200 km. The ridge feature marks the western limit of the central Indian Basin and separates the basin from the Arabian Sea (Figure 1.3). In the Arabian Sea sector the ridge lies parallel to the western Indian margin. The surface topography of the ridge consists of shoals, coral reefs, banks and atolls, sloping downwards to depths of about 3000-4000 m from the sea surface. The ridge summit rises above the sea level at three locations and is named as the Chagos, Maldive and Laccadive coral islands. The height of the ridge relative to the adjacent deep basins is up to 2 km near the Maldive Islands and its width in the upper part is 75-150 km. The ridge is bounded by highly accumulated plains of sedimentary supply from the coral shallows and ridge slopes. In the south the ridge has an asymmetrical structure with its eastern slope steeper up to 10° when compared to the western slope 0.5° (Verzhbitsky, 2003). In the Chagos archipelago area, towards the eastern ridge foot lies the Chagos trench. Seismic refraction studies over the ridge confirmed that the ridge structure is a continuous volcanic feature with a thick crust having Moho discontinuity at a depth of 16-20 km under the Chagos Islands (Francis and Shor, 1966). The ridge flanks are bounded by fault scraps, which separate the ridge from the shelf margin and then Arabian Basin (Avraham and Bunce, 1977; Chaubey et al., 2002).

Several theories have been proposed for the formation of the Chagos-Laccadive Ridge. The ridge was considered as a transition zone between the oceanic crust in the west and the continental crust in the east (Narain et al., 1968); believed to be formed over an old transform faulting during the Cretaceous-Eocene period when Indian plate moved northward (Fisher et al., 1971; McKenzie and Sclater, 1971) and a hot spot trace (Dietz and Holden, 1970; Morgan, 1972; Whitmarsh, 1974; Duncan, 1981). Another view suggested that the ridge is composed of several segments of different origin, where the Laccadive and Chagos Islands consist of volcanic features formed from leaky transform faults, while the Maldive Island segment may be a micro-continent that has been rifted from India probably before the Paleocene (Avraham and Bunce, 1977). The ridge was initially emplaced at sub-areal depths, which was later subsided to about 2075 m water depth at a rate following the subsidence of normal oceanic crust (Detrick et al., 1977). The generally accepted hypothesis for the origin of the ridge is by the passage of the Indian plate over the Reunion hot spot. The convincing results come from the drilling of the ODP Leg 115 sites, which supported the earlier view that the ridge is inactive and was formed by volcanic outpouring during the northward motion of the Indian plate over the Reunion hot spot (Richards et al., 1989; Duncan, 1990).

1.1.2.3 The 85°E Ridge

The 85°E Ridge in the northeastern Indian Ocean has become an enigmatic aseismic ridge as the ridge feature is associated with complex geophysical signatures. The ridge extends from the Mahanadi Basin in the north Bay of Bengal takes an arcuate shape off Sri Lanka and finally joins the Afanasy Nikitin seamount (ANS) in the central Indian Basin (Figure 1.3). It is elongated for more than 2500 km between 5°S and 19°N as a combination of buried, partly buried and emergent hills (ANS) protruding through the distal end of the Bengal Fan (Curray and Munasinghe, 1991; Krishna, 2003; Krishna et al., 2011b). The shape and width of the ridge also varies from place to place. It appears as a double humped feature at around 13°N (Gopala Rao et al., 1994), as intrusive peak structure at around 10°N (Curray et al., 1982) and as broad basement swell (Gopala Rao et al., 1997) at 14.64°N. The northern part of the ridge is buried under the thick Bengal Fan sediments, whereas south of 7.5°N it partly rises above the seafloor and finally culminates with the ANS at 5°S (Krishna, 2003). In the north the ridge structure is buried under the Bengal Fan sediments and associated with a negative gravity anomaly, whereas in the south the structures are partly exposed and are associated with positive gravity anomaly signatures (Subrahmanyam et al., 1999; Krishna, 2003).

Different theories have been proposed for the development of negative gravity field and the origin of the 85°E Ridge. Plate reconstruction studies of Curray and Munasinghe (1991) suggested that the Rajmahal Traps, 85°E Ridge and ANS were a trace of the Crozet hot spot. Subsequently Müller et al. (1993) suggested that the 85°E Ridge segment between 10°N and ANS might have been formed by a hot spot now located underneath the eastern Conrad rise on the Antarctic plate. There were many more explanations documented in literature for origin of the ridge that include abandoned spreading centre (Mishra, 1991), volcanism through a weak zone within a short span of time (Chaubey et al., 1991), northward continuation of the 86° Fracture Zone (FZ) (Kent et al., 1992), shearing and sagging of the crust due to the compressional forces at the time of major plate reorganizations (Ramana et al., 1997, Anand et al., 2009). Liu et al. (1982) modeled the flexural and gravitational response of the ridge and concluded that the ridge was formed on a weak lithosphere, which subsequently gained strength along with the sedimentation. 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). Subsequently Krishna (2003) and Sreejith et al. (2011) have concluded that the presence of metasediments and flexure of the lithosphere beneath the ridge would explain the negative gravity anomaly of the ridge. Keeping this in view they have suggested that the ridge was formed in intraplate position when the underneath lithosphere was ~35 Myr old.

1.1.3 Abandoned Spreading Centers (ASC)

Plate reorganizations, ridge migrations and ridge jumps are the tectonic processes that have contributed extensively to the complexity of the evolution of oceanic lithosphere. During the evolution of ocean floor a few segments of the spreading ridge system cease its activity and start elsewhere by connecting other ridge segments with transform faults. The ceased segments with no spreading activity are known as abandoned spreading centers (ASC) or extinct spreading centers. They are generally developed during the plate reorganizations and major or minor ridge jumps. These ceased ridges or ridge segments subsequently become part of the ocean floor and experience the same movements as the lithospheric plates are undergoing.

The abandoned spreading centers identified in the Indian Ocean are the result of two major plate reorganizations that the ocean has witnessed and several major and minor ridge jumps. The magnetic anomaly patterns on either side of the ASC's exhibit mirror images of magnetic lineations. Abandoned spreading centers have been mapped in several locations of the Indian Ocean, for example spreading centers in northwest of Australia ceased soon after the formation of anomaly M4 (Fullerton et al., 1989), in northwest of Madagascar after anomaly M0, in east of Madagascar after anomaly 29, in the Wharton Basin after anomaly 19 (Liu et al., 1983; Krishna et al., 2011a), on west of the Ninetyeast Ridge with ceasing age of anomalies 30, 26 and 19 (Royer et al., 1991; Krishna et al., 1995, 2011a). The ASC's ceased on the northwest of Madagascar contributed to the first plate reorganization and in the Wharton Basin contributed to the second major plate reorganization. A chain of abandoned spreading centers (ASC's) of

~42 Ma age occur between 96°E FZ and 86°E FZ and are interpreted as the Wharton Ridge. These abandoned spreading centers have unified the Indian and Australian plates into single Indo-Australian plate during the middle Eocene.

1.1.4 Magnetic Lineations and Fracture Zones

The magnetic lineations and fracture zones are considered as important geophysical constraints for better understanding the tectonic fabric of the ocean floor. The ocean floor is characterized by long magnetic stripes that run roughly parallel to the ridge crests. These stripes are termed as magnetic lineations or chrons. They are symmetrical about the ridge axis and offset along the transform faults and fracture zones. The magnetic lineation patterns and their offsets are used for outlining the presence of transform faults, fracture zones, abandoned spreading centers and ridge jumps. The magnetic anomalies are indicated with numbers starting from the ridge axis to the older crust. The magnetic lineation pattern from present to the Jurassic period reveals two long single magnetic field periods: the Cretaceous Magnetic Quiet Period (118-84 Ma) and the early Jurassic Magnetic Quiet Period (prior to 169 Ma).

The pattern of magnetic lineations in the Indian Ocean is shown in Figure 1.4. The magnetic lineations of the Indian Ocean created from early Cretaceous to present are, in general, trending in three different directions and provide evidences of seafloor spreading in three phases. The first phase of spreading in early Cretaceous took place in NW-SE direction between India and East Antarctica and this was observed in the Bay of Bengal region (Gopala Rao et al., 1997; Veevers, 2009). The lineations from A34 to A19 created during the second phase of spreading trend in E-W direction (Kamesh Raju et al., 1993; Krishna et al., 1995; Krishna and Gopala Rao, 2000; Krishna et al., 2011a) and the third phase of lineations from A18 to A1 trend NE-SW direction (Royer et al., 1989; Müller et al., 1997). The magnetic lineations on west of the 86°E FZ are dislocated right laterally in the central Indian Basin, while in the Wharton Basin east of the 90°E FZ, they are dislocated left laterally. The magnetic anomalies on the oceanic crust between the 86°E FZ and the 90°E FZ follow neither of the patterns of magnetic anomalies with right or left lateral offsets (Krishna et al., 1995, 1999). Using magnetic anomaly offsets several fracture zones have been identified in the Indian Ocean. They are 73°E FZ, 79°E FZ (Indrani), 80°E FZ, 83°E FZ (Indira), 84°E FZ, 84.5°E FZ, 85°E

FZ, 86°E FZ. Fracture zones identified on east of the Ninetyeast Ridge are 89°E FZ, 90°E FZ, 92°E FZ, 94°E FZ and 96°E FZ and Investigator FZ.

The earliest spreading between Africa and Antarctica and to the west of the Gunnerus Ridge has been dated as the early Cretaceous age with well defined anomaly sequence from M24 (~153 Ma) onwards (Roeser et al., 1996; Jokat et al., 2003). Towards west and north of the Conrad Rise, magnetic anomalies from chron 34 to 28 (~83.5 to ~64 Ma) have been identified (Goslin and Schlich, 1976; Royer and Coffin, 1992). The spreading activity related to the early rifting of Australia-Antarctic is observed on east of the Bruce Rise and Vincennes FZ with identifications of late Cretaceous magnetic chrons between 34 and 31 (~83.5 Ma to ~71 Ma) (Tikku and Cande, 1999). In the Enderby Basin to the west of the Kerguelen plateau and to the south of the Elan Bank (central Enderby Basin) a symmetrical magnetic sequence M9Ny to M2o (~130.2 ma to ~124.1 Ma) has been observed on either side of the central axis (Gaina et al., 2003, 2007).

1.1.5 Oceanic Plateaus and Micro-Continents

Oceanic plateaus are relatively less understood magmatic provinces on the Earth. They cover for vast areas ranging to as much as 2×106 km^2 of elevated topography and generally 2-3 km above the abyssal ocean floor. The plateaus are the voluminous crustal emplacement of predominantly mafic rocks, which have primarily originated by a process different from normal seafloor spreading (Coffin and Eldholm, 1994). Accretions of plateaus are commonly attributed to plumes or hot spots that have originated from the Earth's deep mantle. The most prominent plateaus in the Indian Ocean are the Agulhas plateau, lies south of South Africa in the southwestern Indian Ocean, the Kerguelen plateau, lies southwest of Australia, the Mascarene plateau, lies north and east of Madagascar and the Naturaliste plateau, extends from the western Australia into the Indian Ocean (Figure 1.3).

Micro-continents are the small sliver fragments of the continental mass that have been broken off from the main continent and they drift away several hundreds of kilometers from their place of origin, and eventually the continental fragments are surrounded by newly accreted oceanic crust. It is still not clear the reasons for such detachments.

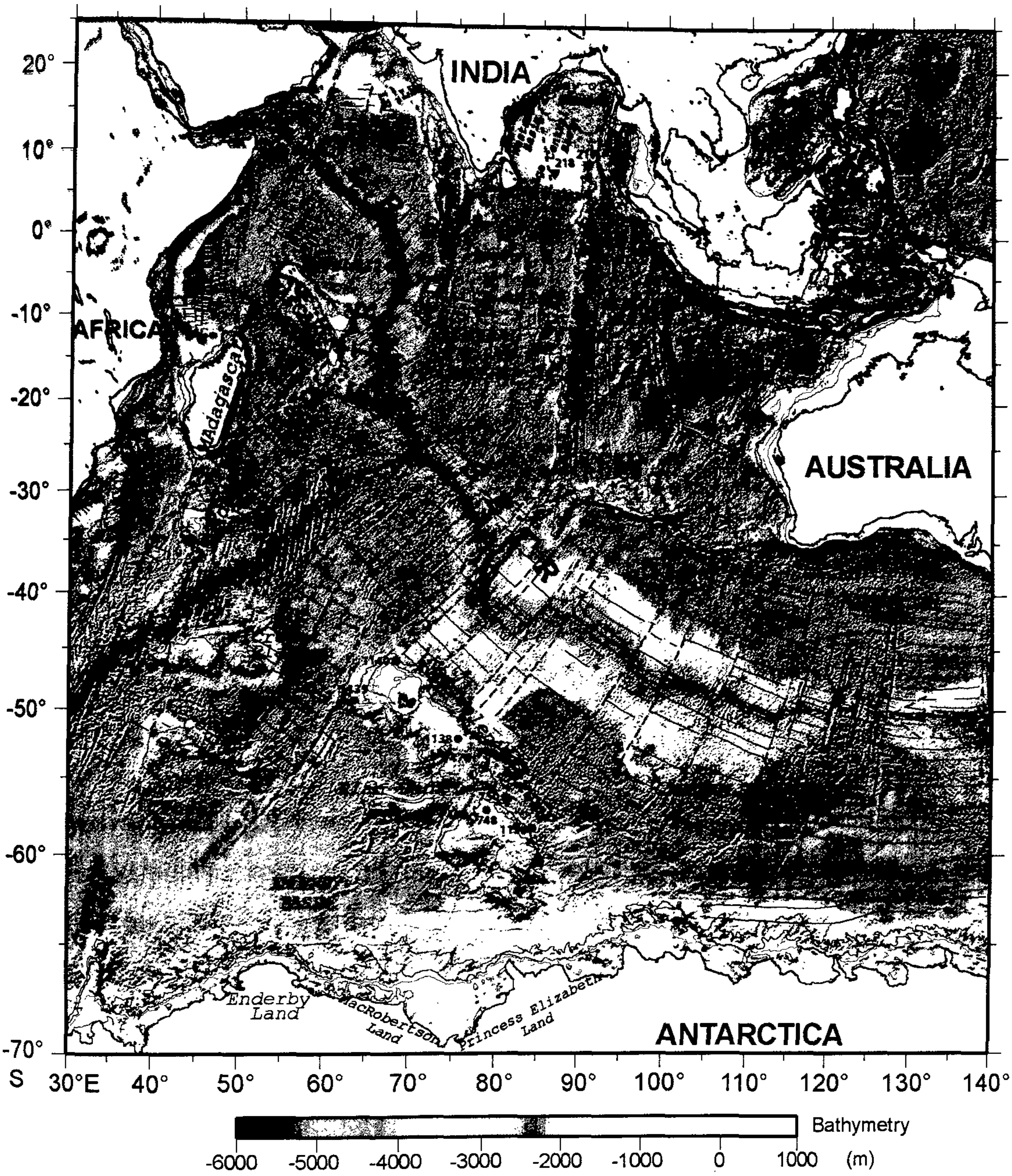


Figure 1.4: Generalised bathymetry map of the Indian Ocean showing the magnetic lineations (red lines) and fracture zones (black dashed lines) (after Royer et al., 1989; Müller et al., 1997). DSDP and ODP sites are shown with solid triangles and circles, respectively. SWIR- Southwest Indian Ridge, CIR-Central Indian Ridge, SEIR-Southeast Indian Ridge, RTJ-Rodriguez Triple Junction, Ch-LR-Chagos Laccadive Ridge, CLR-Carlsberg Ridge, SB-Sheba Ridge, GA-Gulf of Aden, LR-Laxmi Ridge, LB-Laxmi Basin, OS-Osborne Knoll, ANS-Afanasy Nikitin seamount.

It has been observed that these micro-continents are left behind when the main continental mass passes over a deep vigorous mantle plume. Micro-continents are generally found in major ocean basins, and these are expected to provide histories of continental fragmentation and help in unraveling the continental margin geology. The most prominent micro-continents in the Indian Ocean are the Seychelles and the Elan Bank, which lie near the Mascarene plateau and west of the Kerguelen plateau, respectively (Figure 1.3).

1.1.5.1 Kerguelen Plateau

The Kerguelen plateau is a large broad topographic high situated in the southern Indian Ocean adjacent to the Antarctica continent and is approximately equidistant from Australia and Africa (Figure 1.5). It is the second largest oceanic plateau in the world and stretches for about 2300 km in NNW-SSE direction between 46°S and 64°S latitudes. The plateau is bordered by deep ocean basins, Australian-Antarctic Basin in the northeast, Crozet Basin in the northwest, Africa-Antarctica Basin in the southwest, and to the south by 3500 m deep Princess Elizabeth Trough (Schlich et al., 1988). The plateau rises for about 3700 m above the adjacent ocean basins. The Kerguelen plateau is broadly divided into 3 major morphological sectors, the northern, central and southern (Schlich, 1975; Houtz et al., 1977; Coffin et al., 1986, 2002). The northern Kerguelen plateau between 45°S and 55°S lies at water depth of about 1000 m below sea level and emerges as subaerial manifestations of the Kerguelen Archipelago, Heard and McDonald Islands. The southern Kerguelen plateau between 58°S and 64°S is deeper lying in water depth of about 1500 m with subdued topography, but tectonically more complex. It is characterized by several large basement uplifts, normal faulting, graben formation and strike-slip faulting (Coffin et al., 1986; Fritsch et al., 1992; Rotstein et al., 1992; Royer and Coffin, 1992; Angoulvant-Coulon and Schlich, 1994; Konnecke and Coffin, 1994; Gladczenko et al., 1997). The northern and southern part of the Kerguelen plateau between 54°S and 58°S are separated by a transition zone of complex bathymetry with a large east trending Elan Bank, which extends westward from the main plateau over a distance of 600 km long.

There were several hypotheses proposed regarding the origin of the Kerguelen plateau: fragment of continental piece of Gondwanaland, failed spreading ridge, product of magmatic activity related to a fault, composed of thick oceanic crust uplifted either by isostatic forces or because of thermal expansion or the result of intraplate volcanic activity related to the plume that produced the Ninetyeast Ridge, etc. Coffin et al. (2002) opines that the Kerguelen plateau except the Elan Bank and Skiff Bank was formed by the Kerguelen hot spot in two distinct phases. In the first phase the southern and the central parts of the Kerguelen plateau were formed during 120-100 Ma, while the northern part is being formed since 40 Ma. The rugged northern part is dominated by NW-SE trending normal faults and are associated with sediment filled troughs, which are believed to be young relative to the rest of the plateau. Multichannel seismic reflection data show numerous intra-basement reflections from the uppermost igneous crust of the Kerguelen plateau, which are interpreted as sub-aerial flood basalts (Coffin et al., 1990; Schaming et al., 1990).

1.1.5.2 Elan Bank

The Elan Bank, a micro-continent located in the central part of the Enderby Basin, extends westward of the Kerguelen plateau from the boundary between the central and the southern Kerguelen plateau (Figure 1.5). It stretches in E-W direction for about 900 km and encompasses about ~140,000 km^2 of seafloor in water depths range from 1000 to 3500 m. The bank is asymmetric in shape with its steep slope facing south and its fairly gentle slope facing north. Recent geological and geochemical results from the ODP Leg 183 have revealed the Elan Bank as a micro-continent in the Southern Indian Ocean (Coffin et al., 2000; Frey et al., 2000; Nicolaysen et al, 2001; Weis et al., 2001). Wide-angle seismic reflection studies show that the crust of the Elan Bank is at least 14 km thick (Konnecke et al., 1997; Borrisova et al., 2003).

It is widely accepted that the East Antarctica margin was in conjugate with the Eastern Continental Margin of India (ECMI). The east coast of India along with fragments of the Kerguelen plateau and Elan Bank were conjugate to the East Antarctica margin (Stagg et al., 2004). The studies on discovery of the Elan Bank being of continental origin, led several workers to link the Elan Bank with the Indian continent particularly on its northeastern side (Frey et al., 2000; Nicolaysen et al, 2001; Weis et al., 2001; Coffin et al., 2002; Ingle et al., 2002; Kent et al., 2002; Borrisova et al., 2003). During the early phase of spreading, there was a ridge jump towards east of India, which seems

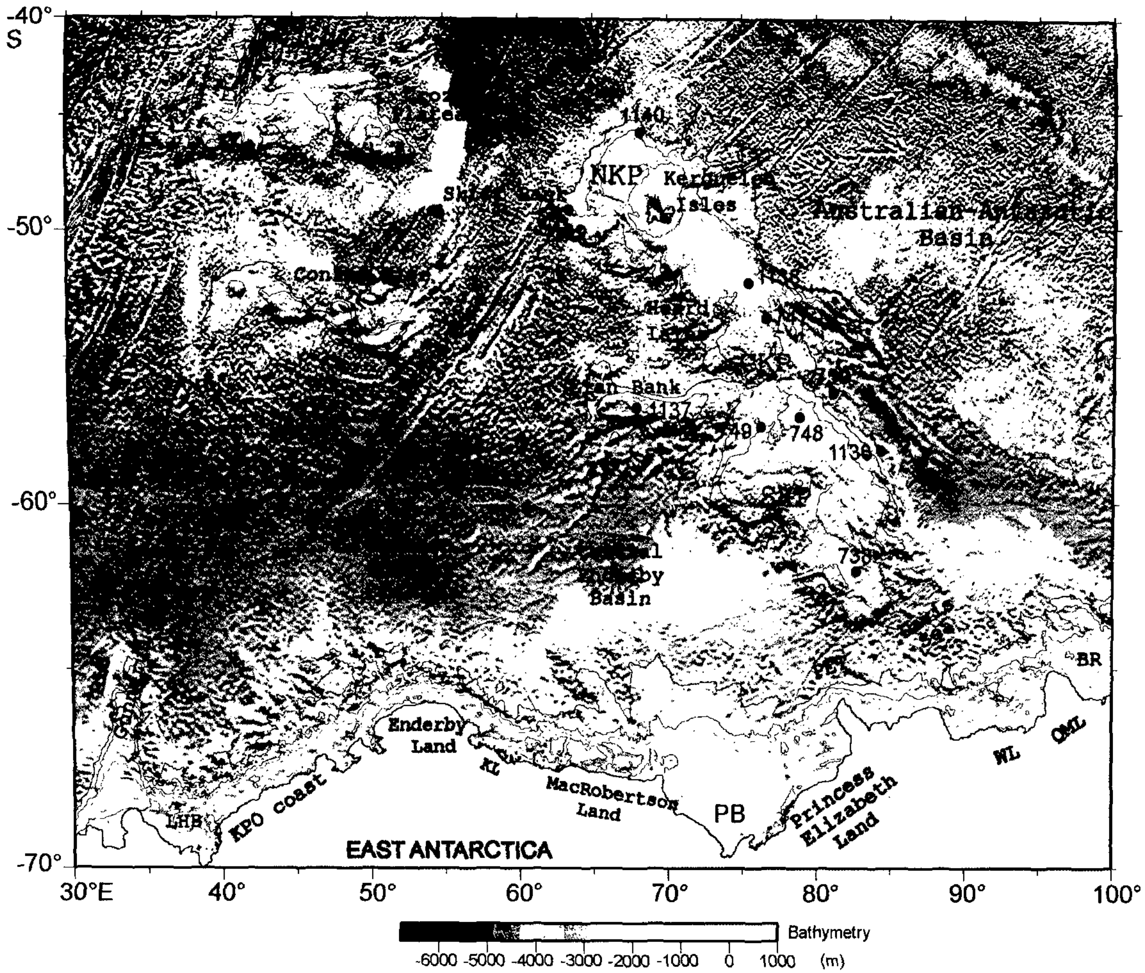


Figure 1.5: Generalised bathymetry map of the East Antarctic margin showing the Kerguelen plateau. CKP-central Kerguelen plateau, SKP-southern Kerguelen plateau, NKP-northern Kerguelen plateau, RLS-Riiser-Larsen Land, LHB-Lutzow-Holm Bay, KL- Kemp Land, KPO Coast-Kron Prinz Olav Kyst, PB-Prydz Bay, PET-Princess Elizabeth Trough, WL-Willem II Land, QML-Queen Mary Land, BR-Bruce Rise.

to have transferred the Elan Bank from India to Antarctic plate (Frey et al., 2000). Ingle et al. (2002) opined that the Elan Bank was connected to the eastern margin of India during early phases of rifting and proposed that the interaction of the Kerguelen hot spot with the ECMI and western Australia has resulted in the fragmentation of the Elan Bank and other micro-continents of the Southern Indian Ocean. The upper igneous crust of the Elan Bank consists of 2-3 km thick layer of accumulated lava flows originated from the Kerguelen hot spot (Borrisova et al., 2003).

1.1.6 Ocean Basins and Continental Margins

Ocean basins are in general created as a result of seafloor spreading between the continental blocks. Subsequently the basins may subside due to thermal cooling and sediment load. Some of the oceanic basins may further be divided into sub-basins with the formation of linear geological features or aseismic ridges. Ocean basins in the Indian Ocean are very low relief zones characterized by relatively thin homogenous sedimentary deposits. The Indian Ocean consists of several basins. The present study area includes the basins from Bay of Bengal, central Indian Basin, Wharton Basin and Enderby Basin (Figure 1.3).

Continental margins are the places of transition zone that separate the oceanic region from the continental realms and include the continental shelf, slope and rise and also include the landward extension of the geological provinces. The nature of coupling between the continental and oceanic crusts determines the physical properties of the continental margins (Todd and Keen, 1989; Lorenzo and Weissel, 1997). The morphology is determined by its formation mechanism and the processes that have been acted upon. The present study area includes the ECMI and Enderby Land margin off East Antarctica.

1.1.7 Conjugate Continental Margins-ECMI and Enderby Land, East Antarctica

The term conjugate continental margins means both the continental margins were together during the past geologic time. The rifting of the continents and the birth of a new oceanic spreading centre are the parts of plate tectonic process. The breakup of the conjugate continental margins, east coast of India and East Antarctica during the early

Cretaceous led to the development of the ECMI (Curray et al., 1982; Powell et al., 1988; Lawyer et al., 1991; Gopala et al., 1997). The ECMI is characterized by major river basins like Ganges, Brahmaputra, Mahanadi, Krishna-Godavari and Cauvery, which extend from inland to offshore regions to merge with the deep sea Bengal Fan (Biswas, 1996; Curray, 1991). The thickness of sediments within the basins varies from 3 to 5 km in onshore depressions to more than 10 km thick in offshore basins (Sastri et al., 1973). The northern part of ECMI is marked by the Eastern Ghats Mobile Belt (EGMB) of Proterozoic age, which extends for over 1000 km along the east coast. The southern part is marked by the southern granulite terrain (SGT) of Precambrian age. The continental shelf along the ECMI is relatively narrow, particularly in the south with a shelf width of about 50 km and is still narrow along the Sri Lanka margin.

The East Antarctic margin is comprised of relatively less thickness of sediments when compared to that of the ECMI. The continental shelf around Antarctica is often characterized by a trough up to 1 km deep near the coast and an unusual deep close towards the outer shelf region (400-700 m deep at the shelf edge). In some places like the Prydz Bay the water depth decreases from coastal trough, while at other places the seafloor is nearly flat.

Earlier studies clearly suggest the conjugate nature of the ECMI with East Antarctica (Sheraton, 1983, Cooper et al., 1991, Subrahmanyam et al., 1999, Federov et al., 1982, Yoshida et al., 1992, Chetty, 1995; Anand et al., 2002). From the reconstructions of the eastern Gondwanaland it is indicated that the present day East Antarctic margin agrees well with the ECMI along 2000 m bathymetry contour line. The disposition of 2000 m isobath helped in demarcating the Continent-Ocean Boundary (COB) for the conjugate margins of India-Sri Lanka and East Antarctica. This inference suggests that ECMI is a contiguous part to the East Antarctic margin.

1.1.7.1 Eastern Continental Margin of India and Adjoining Ocean Floor

The Eastern Continental Margin of India (ECMI), a matured passive margin, has been evolved as a result of its breakup from East Antarctica in early Cretaceous. The margin has variable continental shelf width that decreases gradually from north to south, while depth to the base of the slope deepens from north to south. The major river basins like

Cauvery, Krishna-Godavari, Mahanadi, Brahmaputra and Ganges mark the delta fronts along the margins, which extend from inland to offshore region. Several canyons flanked by steep faults on the continental slopes, have been mapped in Mahanadi, Krishna-Godavari and Cauvery Basins. The Ganges delta extends beyond the inner shelf.

Geophysical investigations along the ECMI speculated that the southern segment of the ECMI is a sheared margin, while the northern segment appears to be rifted in nature (Gopala Rao et al., 1997; Subrahmanyam et al., 1999; Chand et al., 2001). Adjoining the ECMI the Bengal Fan lies and forms the major part of the northeastern Indian Ocean. The Bengal Fan is the largest fan in the world, which is formed as a result of intense continent-continent collision of Indian and Asian plates with a consequent uplift and erosion of the Himalayas. It has a smooth southward slope, where the water depth varies from 200 m to 3500 m from the northern part of the fan towards the south near the Ten Degree Channel at 10°N latitude (Curray and Moore, 1971). A super thick sedimentary strata of about 22 km overlies the basement towards the northeast of the fan close to the Ganges cone (Curray, 1991). In the deep-sea the Bengal Fan is traversed by two hot spot traces: the 85°E Ridge, which runs through the central part of the fan and the Ninetyeast Ridge farther east close to the Andaman subduction zone (Gopala Rao et al., 1994, 1997; Subrahmanyam et al., 1999). The N-S trending 85°E Ridge extends from the Mahanadi Basin (18°N), takes an arcuate shape off Sri Lanka and joins to the Afanasy Nikitin seamount in the south at 5°S. Some studies reveal that the entire eastern region of India and the Bengal Basins represent a large volcanic province called as Eastern Volcanic Province (Subrahmanyam and Chand, 2006). The 85°E and Ninetyeast ridges divide the sedimentary fan into two basins: the Western Basin and Central Basin (Figure 1.3).

1.1.7.2 Enderby Basin

The Enderby Basin is a wide area located between the Kerguelen plateau and the Antarctic margin. It is bounded by the Gunnerus Ridge to the southwest, by the Kerguelen plateau and Elan Bank to the northeast and north, by the Kerguelen Fracture zone (FZ) and Conrad Rise to the northwest, and by the Princes Elizabeth Trough to the southeast (Figure 1.5). It includes the area conjugate to the ECMI and extends across

Enderby Land, Kemp Land, MacRobertson Land and Princess Elizabeth Land. 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 58°E longitude represents the western Enderby Basin.

The paucity of marine geophysical data in the Enderby Basin southwest of the Kerguelen plateau led to the suggestion that in the northwest Australia, rifting process started during the late Jurassic and propagated southward, which eventually caused for separation of India from Australia initially and subsequently from East Antarctica at about 120 Ma (Royer and Coffin, 1992; Müller et al., 2000). In the Enderby Basin, Mesozoic magnetic anomaly sequence from M9Ny to M2o has been observed on either side of the central axis (Gaina et al., 2003, 2007). From these studies it is assumed that during the onset of seafloor spreading about anomaly M9Ny (130 Ma) to M4o the spreading rate was 4 cm/yr and then decreased to 1.6 cm/yr until the spreading ceased at about 124 Ma. The magnetic anomaly signatures along the profiles suggest the existence of an ENE trending palaeo-spreading axis (Gaina et al., 2007). The rifting and seafloor spreading in the Enderby Basin occurred together with the opening of the Perth Abyssal Plain southwest of Australia starting at about 130 Ma. From the interpretation of the magnetic anomaly it is concluded that the seafloor spreading ceased in the Enderby Basin about 124 Ma after formation of magnetic anomaly M2o (Gaina et al., 2007). Then a ridge jump toward the eastern margin of India separated the Elan Bank leaving the M-sequence anomalies in the Enderby Basin.

1.2 Main Objectives of the Research Work

The present research work is carried out utilizing the ship-borne geophysical data and satellite gravity data in order to decipher the evolution of the conjugate regions- Bay of Bengal and Enderby Basin, East Antarctica. The present studies are focused over a part of the Bay of Bengal between longitudes 75°E and 96°E and latitudes 5°S and 25°N and Enderby Basin between longitudes 30°E and 90°E and latitudes 70°S and 45°S. The ship-borne geophysical data in the Bay of Bengal used for the present study were acquired on various Indian research vessels and a few were extracted from the NGDC database. The satellite geoid, residual geoid and free-air gravity anomaly database were generated using high resolution Seasat, Geosat, Gm, ERS-1 and Topex /Poseidon altimeters over the area of Bay of Bengal and Enderby Basin. The specific objectives of the present work are as follows:

1) Compilation and analyses of geoid, residual geoid, satellite free-air gravity and ship-borne gravity and magnetic data of the Bay of Bengal and Enderby Basin, East Antarctic margin.
2) Delineation of plate tectonic related structural features such as fracture zones, fossil ridge segments, etc. for the purpose of providing critical constraints on breakup and early evolution of the lithosphere between India and Antarctica.
3) Classification of continental margin segments on the eastern continental margin of India.
4) Determination of magnetic response of the 85°E Ridge in the Bay of Bengal keeping in view of its gravity and seismic results.
5) Magnetic model studies of the 85°E Ridge for determination of possible sources for negative and positive magnetic signatures of the ridge.
6) Correlation of the magnetic signatures to the Geomagnetic Polarity Timescale for assigning probable ages to the 85°E Ridge.

CHAPTER 2

Satellite and Ship-borne Geophysical Data and Methodology

SATELLITE AND SHIP-BORNE GEOPHYSICAL DATA AND METHODOLOGY

2.1 Introduction

Satellite altimetry is an emergent tool in geophysical studies for determining the gravity field of the Earth from space-borne observations. The term satellite normally refers to an artificial satellite that has been placed into the orbit to move around the Earth (or another body) by human endeavor. The satellite derived gravity databases are used for quick assessment of regional geological structures such as offshore sedimentary basins, linear ridges, seamount chains, structural and tectonic patterns of continental margins and deep-sea regions. With the launching of several altimetric missions with increasing accuracies and varying orbital configurations, it has now become possible to generate large-scale altimetry-derived geoid, residual geoid and gravity anomaly maps of the oceans.

Satellite altimetry was first developed in 1960s soon after the flight of artificial satellites became a reality. From a particular point in space, a radar altimeter is able to measure the shape of the sea surface globally and repeatedly in a short-span of period. Such measurements have a wide range of applications to sub-disciplines of Earth Science, viz. Oceanography, Geodesy, Geophysics, etc. In case of ship-borne measurements, it takes enormous time to make observations around the ocean, while the ocean is experiencing short-term changes in circulation, temperature and salinity. Therefore, it is not truly feasible to make synoptic observation of global oceans using in-situ instrumentation. With the advent of satellite radar altimetry, measurement of sea surface topographic corrections should be made with extreme precision. The measurement of sea surface height using radar altimeter, which leads to the generation of marine gravity, has been considered as a significant development over the last 20 yrs. The measurement precision over the time has improved from 300 cm to 2 cm (Wakker et al., 1988; Benada, 1993). It is now possible to map the marine geoid from altimeter derived sea surface heights, and its conversion into marine gravity data has helped to understand the wide ranging geodynamic processes undergoing beneath the ocean floor. Gravity data acquired by ship-borne gravimetric methods are mainly useful to map the short-wavelength features of the gravity field, whereas the satellite altimeter-derived marine geoid and gravity data provide global coverage and almost uniform characteristics, and this is a best approach for determining the subtle variations in the marine gravity field.

This chapter deals with the data sources and the general methodology followed for retrieval of marine geoid from the Sea Surface Height (SSH), generation of classical geoid and eventually conversion of geoid data into free-air gravity data. In addition ship-borne gravity, magnetic and bathymetry data are also used as basic data sources in this research work.

2.2 Data Sources

In the present research work following listed geophysical data sets has been used for the investigations:

I. Satellite derived geoid/ gravity data as obtained from satellite altimeter.
II. Ship-borne gravity, magnetic and bathymetry data acquired on Indian research vessels and a few profiles of data extracted from NGDC.
III. Satellite bathymetry data from General Bathymetric Chart of the Oceans (GEBCO).
IV. Seismic reflection data including new and previously published profiles by NIO and ONGC.

2.2.1 Satellite Derived Geoid/ Gravity Data

A very high-resolution satellite geoid and gravity data have been generated from different databases obtained from Seasat, Geosat (Exact Repeat Mission and Geodetic Mission), ERS-1 (1.5 year mean of 35 day, and GM), TOPEX/ POSEIDON (T/ P) (5.6 year mean) and ERS-2 (2 years mean) altimeter missions. Each of them varies from others in several ways, particularly type, mission period, orbit height, orbital inclination, frequency, measurement precision, mean track separator at the equator, etc. Table 2.1 lists the altimeter data used in computing the high-resolution database. The compilation and assimilation of data have been carried out by Hwang et al. (2002). The data are more accurate and the combined high-resolution geoid/ gravity data base is having a grid size of about 3.5 km.

Table 2.1: Details of different satellite altimeter data (Wakker et al., 1988; Majumdar et al., 1994; Hwang et al., 2002).

	Seasat	Geosat/GM		ERS-1		TOPEX/ POSEIDON	ERS-2
		ERM	GM	35 day	GM		
Launch	June 1978	March 1985 - December 1989		July 1991 – May 1996		October 1992 - Present	April 1995 - Present
Orbit Height (km)	780	788		781		1336	785
Orbital Inclination (^{o})	108	108	108	98.5	98.5	66	98.5
Repeat Cycle (day)	-	17	-	35	-	10	35
Frequency (GHz)	13.5		13.5		13.8	5.3/13.5	13.8
Measurement Precision (cm)	7		5		3	2/4	3
Mean track separator at the equator (km)	165	165	4	80	8	280	80

2.2.1.1 Methodology

The satellite altimeter basically makes the measurements of instantaneous Sea Surface Height (SSH) deviating from the mean sea level. The satellite carrying the radar altimeter transmits short duration microwave pulse of around 13.5 GHz in Ku-band with known power in a pencil beam towards the sea surface. The pulse interacts with the rough sea surface and a part of the incident pulse is reflected back as shown in Figure 2.1. The time taken for the pulse to reach the sea surface and get reflected back is recorded as two-way travel time. The SSH can be computed from the two-way travel time of the pulse after applying the corrections for atmospheric refraction with the velocity of light followed by oceanographic and other corrections in the measured range of the satellite.

The altimeter measurements show that the sea surface is not a flat surface all over the globe. Undulations to a few centimeters to several hundred meters have been measured. These sea surface undulations have time dependent components because of influence of winds, currents and tides and time independent components created due to density variations on and below seafloor and its beneath. These time independent undulations are used in the prediction of satellite gravity to map the density contrasts inside the Earth. The altimeter can measure the sea surface height over the entire world's ocean repeatedly at fairly short interval of time and provides a unique dataset (Wakker et al., 1988). The basic concept of satellite altimetry is shown in Figure 2.1. The distance of the sea surface above the reference ellipsoid refers to the Orbital Height (H). The altimeter measurement is referred as altimeter range (h) and is the distance from the center of gravity of the satellite to the surface of the earth. The dynamic sea surface height (h_d) is the oceanic condition at a particular time comprising ocean dynamics e.g., tide, ocean currents (CERSAT, 1996). Finally, the geoid height (h_g) is the mean sea surface height after removal of ocean dynamics.

The major corrections to be incorporated in the altimetric measurements include,
a) corrections due to atmospheric refractions generated by dry gases, water vapor, ionospheric electrons,

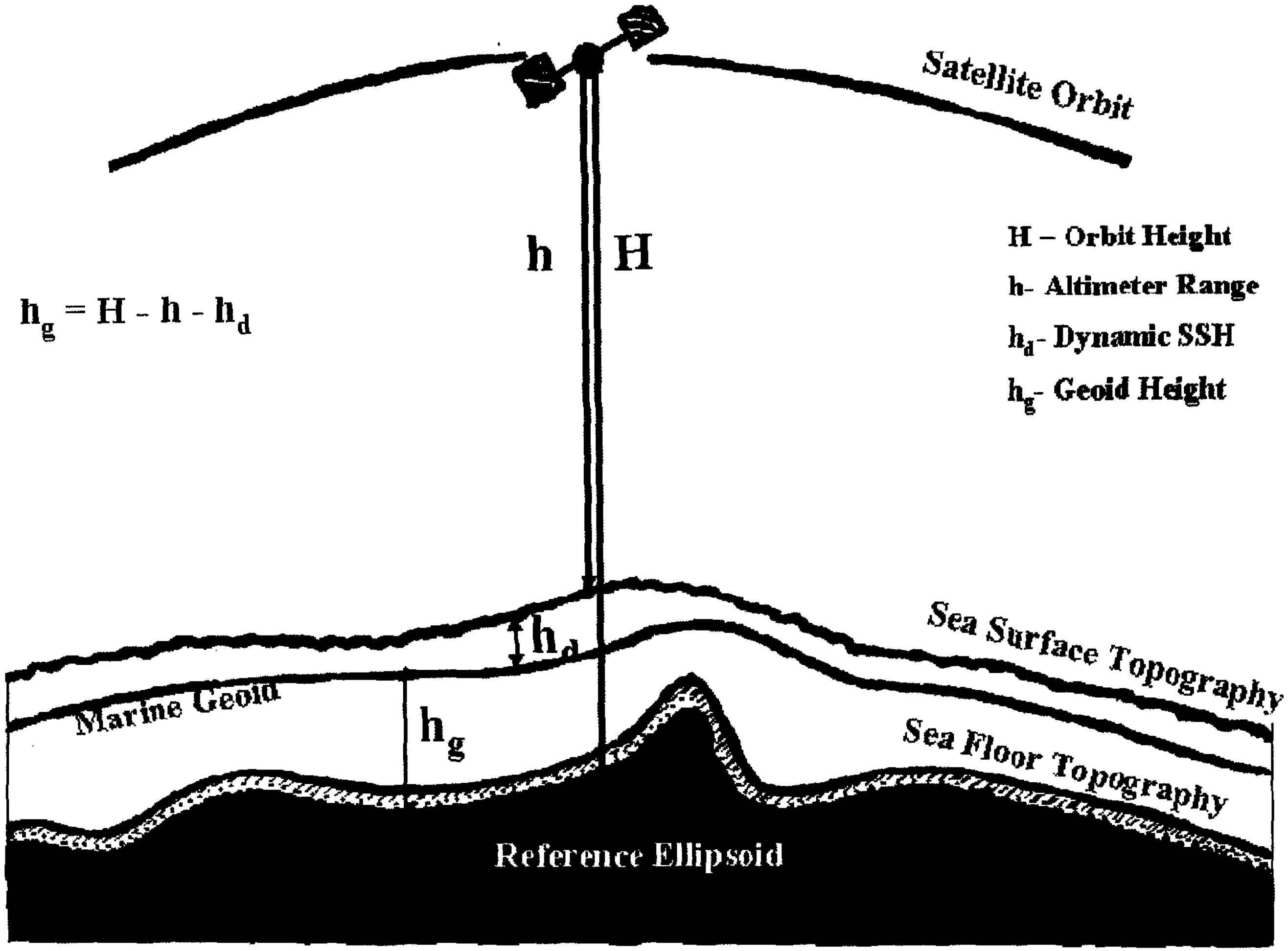


Figure 2.1: Basic concept of satellite altimetry (after Fu et al., 1988).

b) corrections due to air-sea interfaces, EM bias, skewness bias, etc.,

c) instrument corrections due to tracker bias, antenna gain pattern, AGC (Automatic Gain Control) pattern, antenna mispointing etc., and

d) external geophysical corrections mainly due to inverse barometer effect, tides, geoid height, orbit height etc. (Fu et al., 1988; Stewart, 1985; Robinson, 1985).

2.2.1.2 Corrections for Atmospheric and Oceanographic Effects

The one-way travel time of the returned altimeter pulse is used to compute the height of the altimeter (h) above the instantaneous sealevel (Allan, 1983; Cheney et al., 1987). The height of the satellite above the reference ellipsoid (H) is calculated from precise orbit modelling. The altimeter height is computed using the travel time of the returned pulse and speed of the pulse in vacuum and subsequently this has been corrected for the propagation delays in the ionosphere and the troposphere. The former is associated with dry gases, while the later is due to water vapor content in the atmosphere. The SSH observed by the altimeter is only an instantaneous sea surface, which includes various dynamic variabilities e.g. ocean tide, solid tide, electromagnetic bias, inverse barometric pressure effect, etc. These atmospheric and oceanographic parameters contribute a lot to the SSH and hence the ocean geoid, indicated in the Geophysical Data Record of ERS-1, has been used for correction of ERS altimeter data (CERSAT, 1996). Correction of SSH for dynamic variabilities yields Mean Sea Surface Height (MSH). The dynamic sea surface topography included in the MSH, is minimized by taking average of repeat observations over a period of time.

Atmospheric corrections such as refraction corrections and atmospheric range corrections are also applied to the SSH. Atmospheric range corrections take care of corrections from dry troposphere, wet troposphere, dry ionosphere and wet ionosphere. Also oceanographic corrections such as sea-state effects, dynamic sea-surface height correction, atmospheric pressure loading and tidal corrections are applied to the SSH. In tidal corrections the elastic ocean tide and solid tide corrections are applied.

2.2.1.3 Data Processing Steps for the Retrieval of Marine Geoid and Gravity

In the initial stage of processing raw data is converted in physical quantities after locating the tracks, corrected for the instrumental effects and storing them in an Off-line Intermediate Product (OIP). At this stage, the main parameter of interest is the altitude of the satellite above the sea surface. In later stages satellite along-track adjustments are applied to improve the signal to noise ratio. The effects of deeper Earth have been removed through spherical harmonic analysis and ultimately the residual geoid is converted into marine gravity after the waveform amplification. The block diagram of the generalized processing steps for various satellites is shown in Figure 2.2.

The third step describes the repeativity of data collection at a particular point or it's nearby with crossover correction, stacking and averaging of data, which are then converted into gridded data. The final sea surface grid almost free from sea surface dynamics, is the mean sea surface termed as Classical Geoid. The deeper earth effects are removed using Rapp's 50 x 50 geoid form determination of residual geoid data. The residual geoid data could be converted to free-air gravity data or in other case by removing bathymetric effects the data reveal a prospecting geoid, which is generally used for hydrocarbon prospectivity.

2.2.2 The Geoid

The geoid can be defined as the equipotential surface of the Earth's gravity field, which best fits in a least squares sense with the global mean sea level. The altitude can be measured by considering the mean sea level as a reference frame or datum. The geoid approximates well to the MSH (Li and Gőtze, 2001). The SSH observed by the altimeter is only an instantaneous sea surface and deviations of SSH from the geoid are due to ocean dynamic variability. Correction of SSH for dynamic variabilities due to electromagnetic bias yields MSH. The difference of MSH from the classical geoid is the dynamic sea surface topography (SST) which is due to currents, eddies etc. The dynamic sea surface topography part in the MSH is minimized by taking average of repeat observations over a period of time.

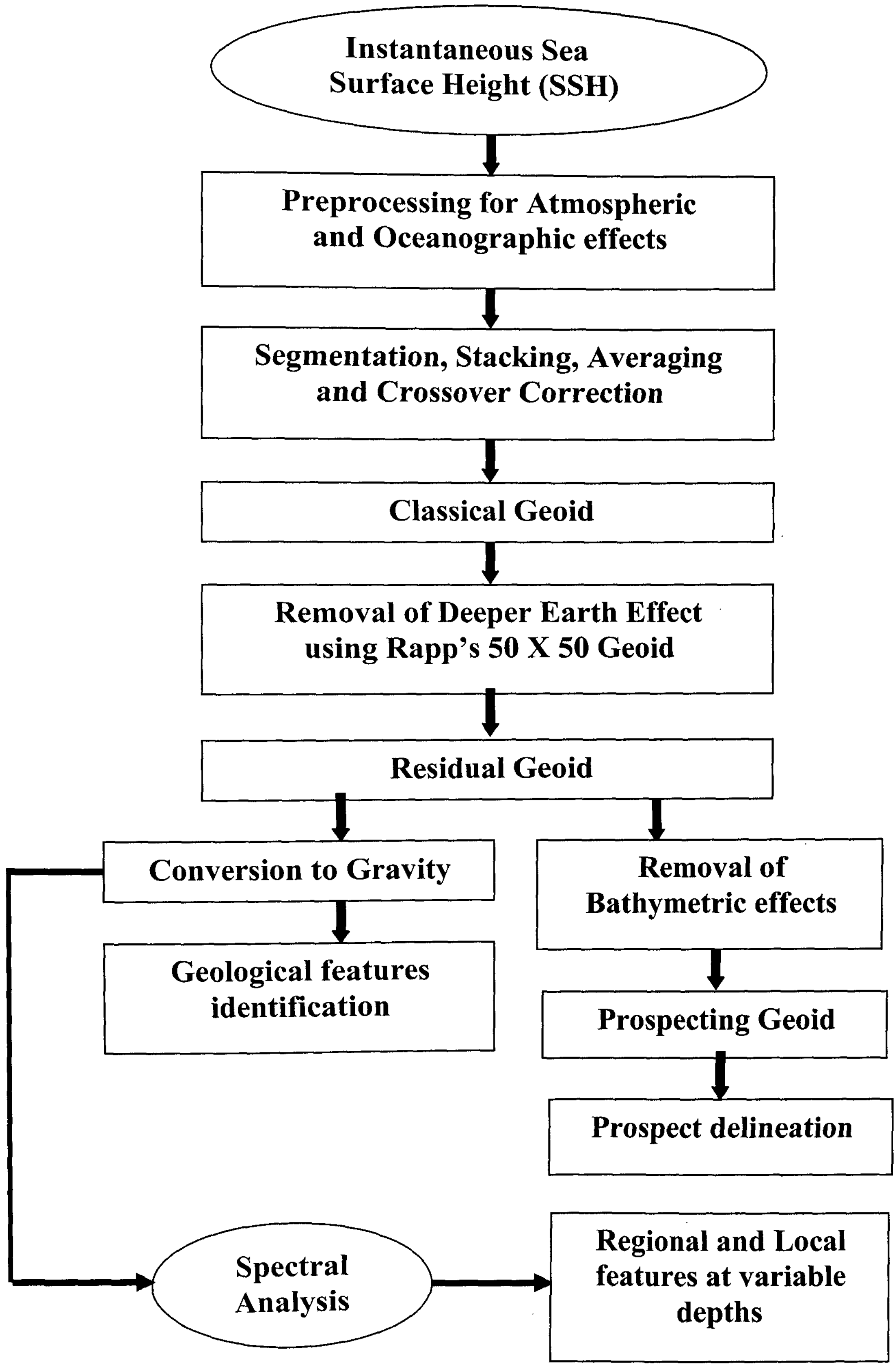


Figure 2.2: Generalised data processing steps for deriving marine geoid/ gravity.

2.2.3 Generation of High Resolution Geoid and Gravity Database of the Conjugate Regions-Bay of Bengal and Enderby Basin

Global mean sea surface heights (SSHs) and gravity anomalies for $2' \times 2'$ grid were determined from Seasat, Geosat (Exact Repeat Mission and Geodetic Mission), ERS-1 (1.5-year mean of 35-day, and GM), TOPEX/ POSEIDON (T/ P) (5.6-year mean) and ERS-2 (2-year mean) altimeter data for the Bay of Bengal region bounded by 75°E - 96°E longitudes and 5°S - 25°N latitudes and Enderby Basin region bounded by 30°E - 90°E longitudes and 70°S - 45°S latitudes (Figure 2.3).

To reduce ocean variabilities and data noises, SSHs from non repeat missions were filtered by Gaussian filters of various wavelengths. A Levitus oceanic dynamic topography was subtracted from the altimeter- derived SSHs, and the resulting heights were used to compute along track deflection of the vertical (DOV). Geoidal heights and gravity anomalies were then computed from DOV using the deflection-geoid and inverse Vening Meinesz formulae. The Levitus oceanic dynamic topography was added back to the geoidal heights to obtain a preliminary sea surface grid. The difference between the T/P mean sea surface and the preliminary sea surface was computed on a grid by a minimum curvature method and then was added to the preliminary grid. Details of the methodology for obtaining very high-resolution geoid and gravity from altimeter-derived sea surface height have been discussed by Hwang et al. (2002). They have used the deflection geoid and inverse Vening Meinesz formulae as the basic tools for computing MSH and gravity anomaly.

2.2.4 The Residual Geoid

The residual geoidal height data are important for interpretation of geological structures lying within the crust and undulations of crust-mantle boundary. The data eliminate the deeper Earth effect using spherical harmonic modelling of the geopotential field. The data thus obtained after removal of effects of long-wavelength geoid features, are predominantly associated with deep Earth mass distributions. Residual geoid is obtained after removing the deeper Earth effects from classical geoid, thus the data contain the information from the bathymetry as well as from the lithospheric inhomogenities.

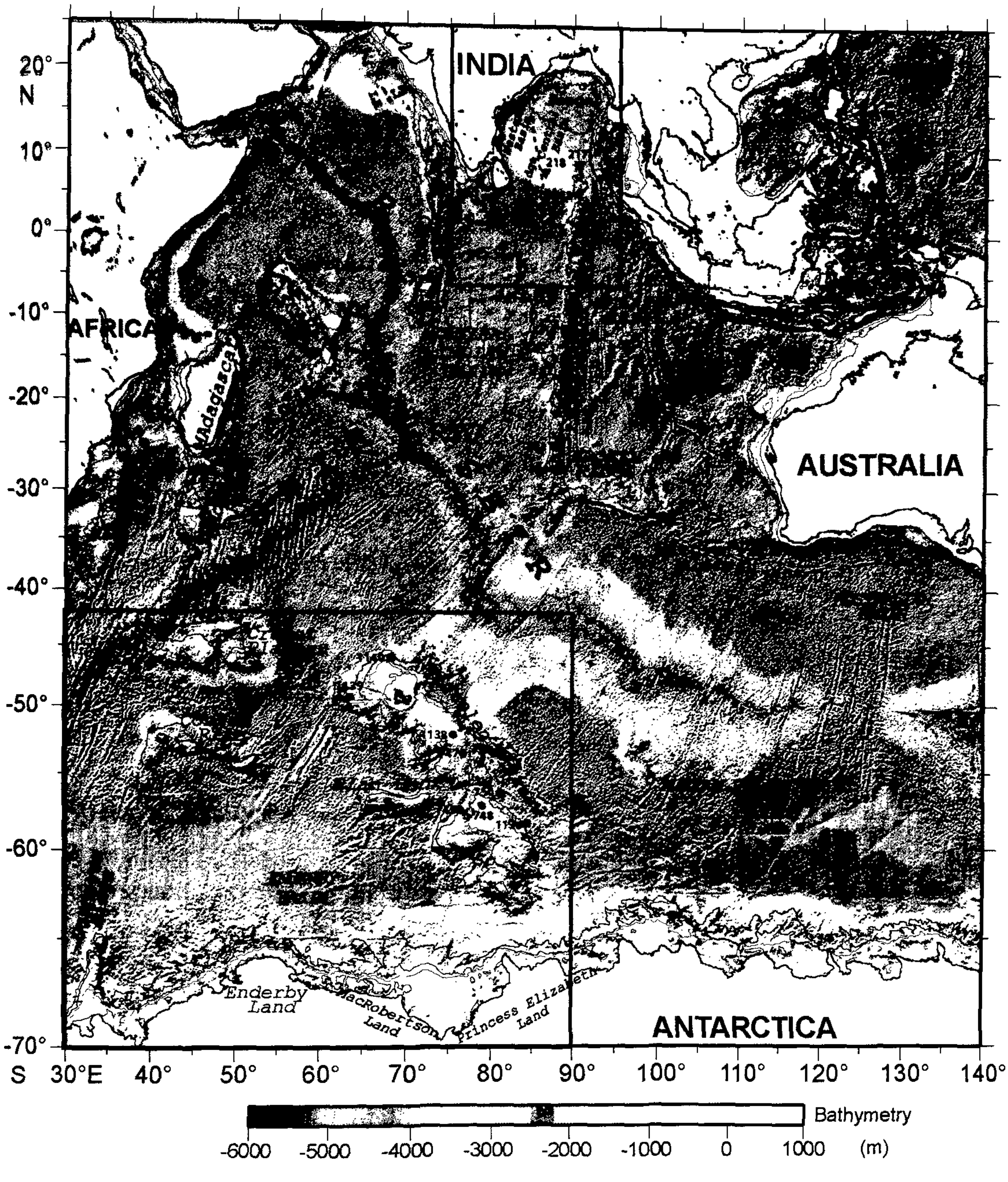


Figure 2.3: Generalised bathymetry map of the Indian Ocean showing the mid-oceanic ridge system and aseismic ridges - Ninetyeast Ridge, Chagos Laccadive Ridge and 85°E Ridge. DSDP and ODP sites are shown with solid triangles and circles, respectively. SWIR- Southwest Indian Ridge, CIR-Central Indian Ridge, SEIR-Southeast Indian Ridge, RTJ-Rodriguez Triple Junction, Ch-LR-Chagos Laccadive Ridge, CLR-Carlsberg Ridge, SB-Sheba Ridge, GA-Gulf of Aden, LR-Laxmi Ridge, LB-Laxmi Basin, OS-Osborne Knoll, ANS-Afanasy Nikitin seamount. The conjugate regions – Bay of Bengal and Enderby Basin considered for the present study have been marked by rectangular boxes.

2.2.5 Comparison of Ship-borne and Satellite Gravity Profile Data

The satellite derived free-air gravity data and the ship-borne gravity data (profile MAN-01) along the latitude 14.64°N in the Bay of Bengal were compared for the purpose of observing the consistencies and deviations between them (Figure 2.4). This profile has been chosen because of the availability of seismic reflection data along the profile.

Comparison of both data reveals that satellite and ship-borne anomalies are fairly in good agreement with some deviations of about 5 mGal, which is within the accuracy limits of the satellite free-air gravity data. Further, two major linear gravity features (Ninetyeast and 85°E ridges) are depicted significantly in both the datasets. Therefore, the satellite free-air gravity anomalies can reasonably be considered for mapping the major structural features of the regions – Bay of Bengal and Enderby Basin. Thereby the results can be used to study the tectonics and related oceanic processes of both conjugate regions.

2.2.6 Spectral Analyses

Different spectral components of geoid and free-air gravity anomaly are useful for delineation of varied geological features of different size lying at different depths within the crust and upper mantle. The residual geoid and the gravity anomaly data are segmented into short, medium and long-wavelength spectral components following the method of Davis (1973). The components are also interpreted to outline the real picture of the subsurface (Lundgren and Nordin, 1988; Majumdar et al., 1994).

a) ***Long-wavelength components (100-400 km)*** - it reflects the crustal events of regional proportions.
b) ***Intermediate-wavelength components (50-100 km)*** - it represents the shallower occurrences. These undulations can give information regarding development of regional depressions and tectonic trend.
c) ***Short-wavelength components (15-50 km)*** - these undulations are more closely related to basement topography and overlying sedimentary cover.

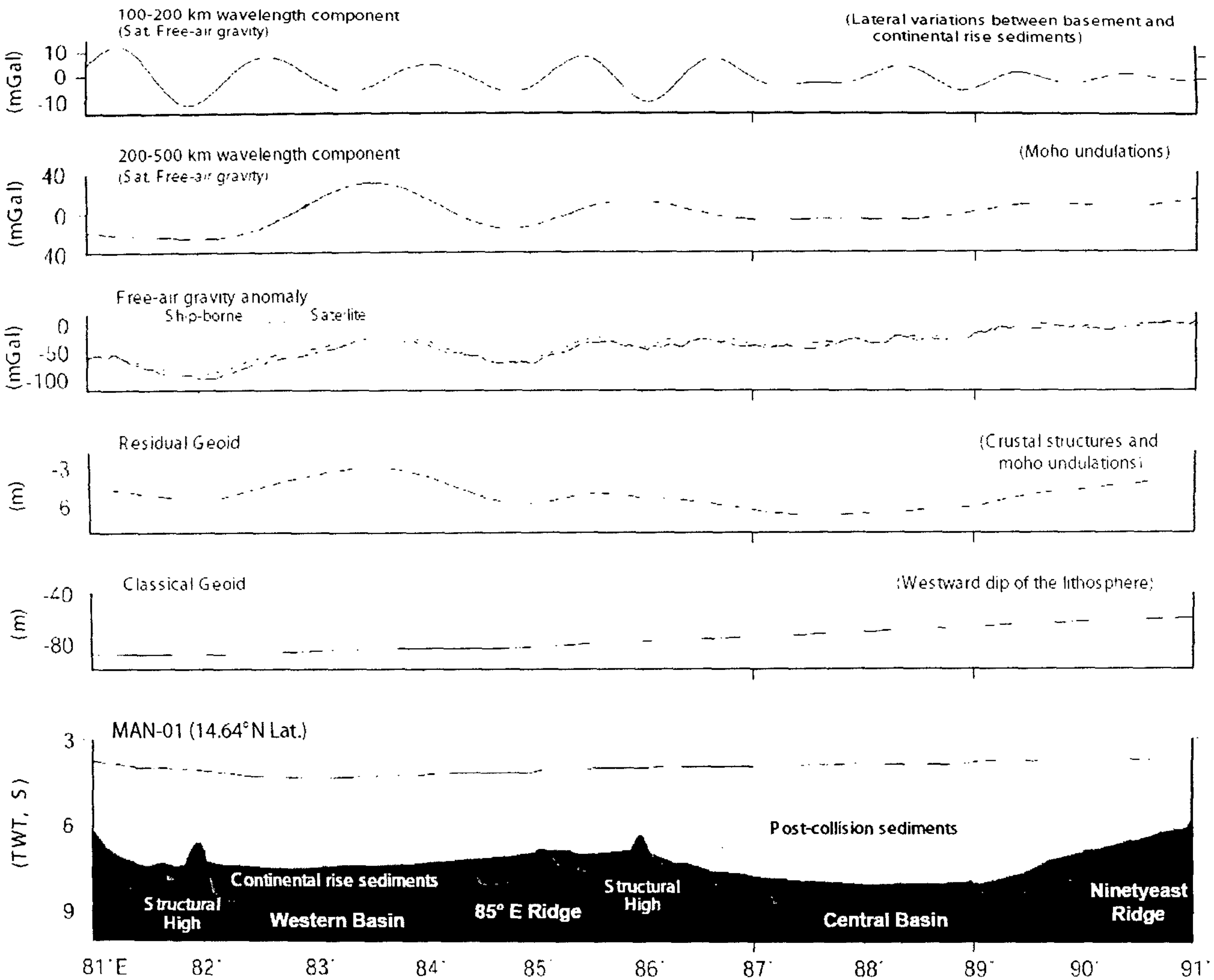


Figure 2.4: Geoid, residual geoid and free-air gravity anomaly data along 14.64°N latitude has been compared with the seismic reflection results (profile MAN-01). Basement topography and two sediment units separated by Eocene unconformity are considered from Gopala Rao et al. (1997). Satellite derived free-air gravity anomaly is compared with ship-borne gravity data for consistencies and deviations.

The coefficients of different harmonics were computed from geoid and gravity data and then the coefficients corresponding to different wavelengths 15-50, 50-100 and 100-400 km, were combined and inverse Fourier transformed to calculate short, medium, and long-wavelength components. The information obtained from the spectral analysis is of great interest for outlining the tectonic trends and for understanding the isostatic compensation of several geological structures at different depths. The results are described in Chapter-3.

2.2.7 Marine Geophysical Data

2.2.7.1 Reduction of Gravity Data

The measured gravity differences between an arbitrary reference point (base station) and a series of measured stations are subject to extraneous effects which are unrelated to the subsurface geology. For instance, the effects due to the oblateness of the Earth, and to changes in elevation and topography must be carefully removed from observed data before any geophysical interpretation can be attempted. This process of correction, or so called reduction of gravity data, is a well established routine work in any gravity survey works. The necessary corrections are latitude correction and eötvös correction.

2.2.7.1.1 Latitude Correction

Latitude correction corresponds to the variation of the Earth's gravity due to the Earth's elliptical shape and rotation. This correction is made to remove the effect of the increase of gravity from equator to poles due to a decrease in Earth's radius and centrifugal force. The basis of the correction is the internationally accepted Geodetic Reference System (GRS- 1967) formula for computing the normal sea level gravity at a latitude ϕ. The formula is,

$$g_\phi = 9.780318(1 + 0.0053204 \sin^2\phi - 0.0000059 \sin^2 2\phi)\ ms^{-}$$

In small-scale surveys, the data are corrected for latitude variations by using the following correction factor.

$$C_\Phi = (1/R_E)(dg/d\Phi) = 8 \cdot 12 \sin 2\Phi g \cdot u / km \text{ (north-south)}$$

where R_E is the Earth's mean radius (6371 km) and ϕ is the latitude of the arbitrary base station.

As the gravity increases towards the poles, the correction for stations closer to the pole than the base station must be subtracted from the measured gravity.

2.2.7.1.2 Eötvös Correction

The Eötvös correction (C_{EC}) is applied to gravity measurements taken on a moving vehicle such as a ship or an aircraft. Gravitational force changes are caused by the change in centrifugal acceleration resulting from eastbound or westbound velocity. When moving eastbound, the object's angular velocity is increased (in addition to the Earth's rotation), and thus the centrifugal force also increases, causing a perceived reduction in gravitational force. Movement of the observation platform causes the gravimeter to experience a centripetal acceleration that reduces the gravity reading if motion is to the east and increases it when movement is westwards.

This effect should be taken into consideration in airborne and ship-borne gravity surveys.

The correction required is

$$C_{CE} = 7.503\, V \sin\alpha \cos\varphi + 0.004154\, V^2\, mGal$$

where 'V' is the platform speed in knots, 'H' is the heading and 'ø' is the latitude.

In mid latitudes the Eötvös correction is about +75 g.u. for each knot of E to W motion so that speed and heading must be accurately known.

2.2.7.2 Free-Air Gravity Anomaly

Gravity anomaly is the difference between the observed value of g at some point and a theoretical value predicted by the GRS- 1967 formula for the same point. The observed value is determined by relative gravity measurements with reference to certain primary base stations, where absolute measurements have been made previously. The free-air anomaly is defined by applying only the free-air correction (Δg_{FA}) and the latitude correction (Δg_L) to the measured gravity. The free-air anomaly, g_{fa} is defined as,

$$g_{fa} = g_{obs} + (\Delta g_L + \Delta g_{FA}) - g_t$$

where g_{fa} is the free-air anomaly, g_{obs} is the observed gravity, g_t is the theoretical value, Δg_L is the latitude correction and Δg_{FA} is the free-air correction.

2.2.7.3 Gravity Data Interpretation

The gravity anomalies thus obtained after processing and corrections can be interpreted qualitatively and quantitatively in order to derive the information from geological sources. The qualitative interpretation provides approximate information about the shape and trend of the body. The quantitative approach yields dimension, depth and density of the anomalous body. In quantitative interpretations of gravity anomalies, both direct (inverse modeling) and indirect (forward modeling) methods are generally used.

a) Forward Modeling or Indirect Methods

Gravity anomalies are calculated over assumed models of mass distribution, which are then varied until an acceptable close match is obtained between computed and observed fields. Satisfactory fits are often based on residuals (observed-computed anomaly values) falling within specific limits. Most models are rather complex, so computer-based numerical integration is employed to calculate the gravity field. The interpreted structure is generally considered either in two-dimensional form, where the anomaly extent is at least four or five times its width, or three-dimensional form, if the anomaly does not exhibit a preferred orientation. Results derived from forward modeling are inherently non-unique. Whenever possible, borehole and other additional data are introduced to constrain derived models.

b) Inverse Modeling or Direct Methods

The inverse modeling involves solving of integral equations satisfying the observed anomaly for which no unique solution exists. Either the density contrast is assumed and the equations are solved for the shape of the body or the shape of the body is assumed and the density distribution is determined. As with forward modeling, independently determined model parameters, such as density or bounding depths, are used to restrict the range of density distributions.

Before applying these techniques it may be desirable to filter the gravity field in order to isolate those components due to either deep or shallow sources. Upward continuation is commonly employed to remove short-wavelength components so as to emphasize gravity contributions from deeper mass distributions.

2.2.7.4 Computations of Gravity Modeling over 2-D Bodies

Many of the oceanic features such as the sedimentary troughs and oceanic fracture zones are two-dimensional, with the length of strike at least ten times larger than other dimensions. The attraction of two-dimensional bodies of arbitrary shape is easily calculated using a line integral which is written in a form for computer-based numerical integration. The basics of the widely used method for finding the gravitational attraction of a two dimensional mass of constant density is described by Talwani et al. (1959), as shown in Figure 2.5. The mass is a polygon lying in the x-z plane and extending to infinity in the y-direction. The vertical component of gravitational attraction, Δg, at the origin P(0,0) is,

$$\Delta g = 2G\rho \oint z d\theta$$

Where $\oint z d\theta$ is a line integral given by (Hubbert, 1948)

$$\oint z d\theta = \int_A^B z d\theta + \int_B^C z d\theta + \int_C^D z d\theta + \dots\dots\dots \int_F^A z d\theta$$

For a point Q on the side BC

PS= a_i and $z=(x- a_i) \tan\gamma_i$

Thus

$$z = \frac{a_i \tan\gamma_i \tan\theta}{\tan\gamma_i - \tan\theta}$$

and

$$\int_{BC} z d\theta = \text{ai} \sin\gamma i \cos\gamma i \left\{ (\theta i - \theta + 1) + \tan\gamma i In \left[\frac{\cos\theta i (\tan\theta i - \tan\gamma i)}{\cos\theta i + 1 (\tan\theta i + 1 - \tan\gamma i)} \right] \right\}$$

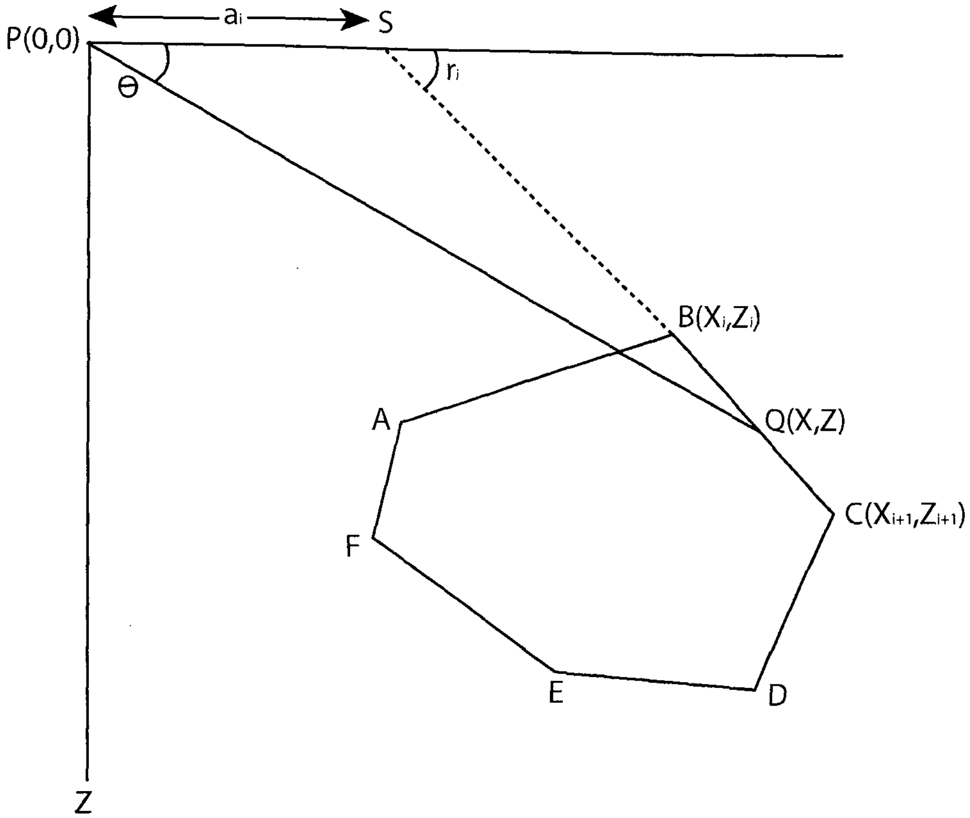


Figure 2.5: Geometry of a two-dimensional polygon, ABCDEF (after Jones, 1999).

The gravitational attraction around the whole polygon is therefore

where

$$\Delta g = 2G\rho\sum_{i=1}^{6}\left\{\frac{x_i z_{i+1} - z_i x_{i+1}}{(x_{i+1}-x_i)^2+(z_{i+1}-z_i)^2}\right\}\left\{(x_{i+1}-x_i)(\theta_i-\theta_{i+1})+(z_{i+1}-z_i)\ln\left(\frac{r_{i+1}}{r_i}\right)\right\}$$

$$r_i = (x_i^2 + z_i^2)1/2$$

The methods used to calculate the gravity response are based on the methods of Talwani et al. (1959) and make use of the algorithms described in Won and Bevis (1987). GM-SYS software is 2-D modeling software developed by the USGS, which uses an implementation of that algorithm for gravity studies. For the present studies 2-D gravity modeling has been extensively carried out along selective profiles, which are described elaboratively in Chapter-5.

2.2.7.5 Marine Magnetic Methods

Measurement of the Earth's past magnetic field is one of the most widely used marine geophysical techniques for various scientific purposes. Marine magnetic data are used as a tool to differentiate the areas underlain by continental and oceanic crusts and to address the questions pertaining to geodynamics.

The controlling physical property that is used in magnetic method is the magnetic susceptibility (k) and direction of magnetisation. This method is based on the fact that magnetic bodies present in the subsurface of the Earth contribute to the magnetic field of the Earth. The contribution of a magnetic body is directly proportional to the magnetic moment (m) of the body and inversely proportional to some power of the depth (r) of its occurrence.

This can be represented as,

$$F = \mu_0 m_1 m_2 / 4\pi \mu_R r^2$$

where F is the force between two magnetic poles and μ is the magnetic permeability.

2.2.7.5.1 Magnetic Data Acquisition and Processing

The total magnetic field measurements are made along the profiles designed perpendicular to the strike of the expected geological target. The magnetic field is sum of the magnetic fields of internal origin, external origin and of anomalous origin. But, the anomalous field only is of interest in the crustal studies, hence the components of internal and external magnetic fields have to be removed to obtain the magnetic anomalies caused by the crustal inhomogenities. In coastal area studies, effect of external magnetic field is reduced by applying the proper diurnal correction, which is employed by using the magnetic field variations recorded in the nearest magnetic observatory. The magnetic field effect of the internal origin is reduced using the International Geomagnetic Reference Field (IGRF), which is described in terms of spherical harmonic expansion containing main field and secular variation coefficients. It is possible to obtain a theoretical value for field strength of the Earth's internal magnetic field, and to correct the observed magnetic field data at any location on the Earth. The complexity of the IGRF requires the calculation of corrections by computer.

2.2.7.5.2 Magnetic Data Interpretation

The magnetic anomalies thus obtained after processing and corrections can be interpreted qualitatively and quantitatively. The qualitative interpretation provides approximate information about the shape and trend of the body and interfaces of magnetic reversals. The quantitative approach yields the dimension, depth and the direction of magnetization of the anomalous body. In carrying out quantitative interpretation of magnetic anomalies, both direct (inverse modeling) and indirect (forward modeling) methods may be employed.

a) Forward Modeling

In forward modeling method, the synthetic magnetic anomalies are calculated over assumed initial model bodies and are matched with the observed magnetic anomalies. Based on trial and error method, the parameters of the initial body are changed until a reasonable fit with the observed magnetic anomalies is obtained. Once the anomalies are matched, the theoretical model is adopted as one of the plausible interpretation of the causative magnetic body, which caused the observed magnetic anomaly. The results from forward modeling are inherently non-unique, therefore whenever possible, additional information (ex. from seismic/bore hole data) are introduced to constrain models. The most common method of computing the field over a two dimensional body of arbitrary shape is the algorithms developed by Talwani and Heirtzler (1964).

b) Inverse Modeling

The problem of finding the geometry and magnetization of submarine features can be approached by solving integral equations that satisfy the observed magnetic field. If the shape of the body and the direction of magnetization are specified then the determination of the magnetization distribution involves solving an integral equation, which is linear, since the magnetic anomaly and magnetization are linearly related. If the magnetization and the shape of part of the body are given then a non-linear integral equation must be solved to find the undefined surface.

2.2.7.5.3 Computation of Magnetic Anomalies over 2-D Bodies

As explained, the most common method of computing the magnetic field over two-dimensional bodies is by using the algorithm developed by Talwani and Heirtzler (1964). In this method, as a first step, the magnetic potential at a point caused by a volume element $\Delta x \Delta y \Delta z$ of an infinitely long magnetized rod (Figure 2.6a) is computed.

$$U_m = \left[\frac{M_x.x - M_y.y - M_z.z}{(x^2 - y^2 - z^2)3/2}\right] \Delta X \Delta Y \Delta Z$$

This magnetic potential, which is a function of the components of magnetization resolved in the x, y and z directions, is then integrated with respect to y to compute the magnetic potential of the rod extending to infinity in the Y-direction (Figure 2.6b).

The vertical field strength and the horizontal field strength can be computed by differentiating the above magnetic potential in Z-direction and X-direction respectively.

$$\Delta Z = 2\Delta z \frac{M_x z - M_z.x}{x^2 + z^2}$$

$$\Delta X = 2\Delta z \frac{M_x x + M_z.z}{x^2 + z^2}$$

To derive the field due to the prism KLMN (Figure 2.6b), the above horizontal and vertical magnetic strengths are integrated with respect to z along KN between the depth limits Z_1 and Z_2.

$$\Delta Z = 2 \int_{z_1}^{z_2} \frac{M_x z - M_x.x}{x^2 + z^2} .dx$$

To obtain the field over the bounded polygonal section KNPQR (Figure 2.6c), the anomalies due to prisms such as KLMN that extend to infinity in the +X direction are calculated. Systematic addition of field values on moving around the polygon will give the total anomaly at the field point of co-ordinates (0,0).The total field anomaly may thus be calculated over a body of an assumed shape and magnetization and then compare with the observed anomalies.

$$\Delta F = \Delta Z \sin I - \Delta X \cos I \cos(C - D)$$

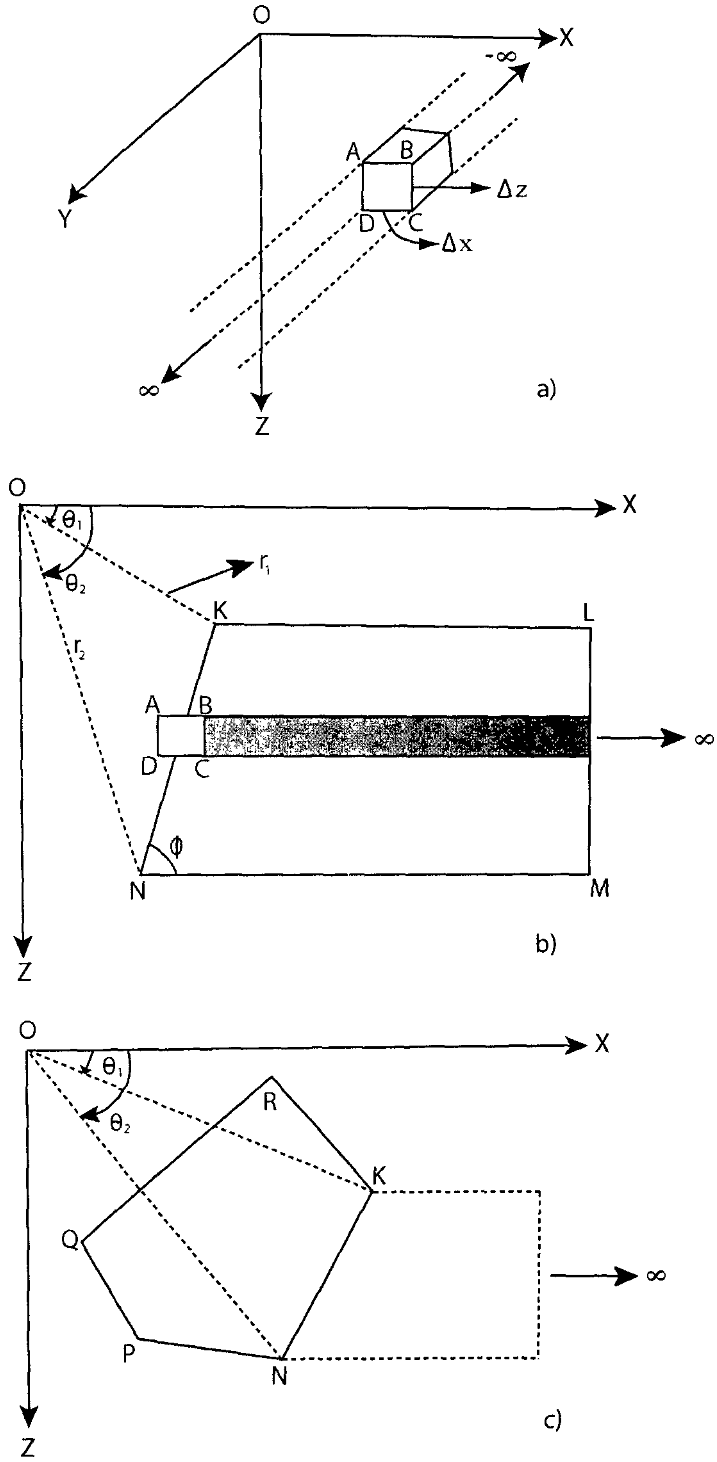


Figure 2.6: Computation of the total field magnetic anomaly over a two-dimensional polygon of infinite extent. (a) geometry of infinite rod, (b) lamina and (c) geometry of the polygon discussed in the text (after Talwani and Heitzler, 1964).

2.2.8 Ship-borne Geophysical Data of the Northeastern Indian Ocean

Ship-borne geophysical data of the northeastern Indian Ocean bounded by longitudes 75°E to 96°E and latitudes 25°N to 5°S are utilized in the present research work. Gravity, magnetic and seismic reflection data utilized in this work were collected on various research vessels such as ORV Sagar Kanya (profiles SK 72- 01, 03, 05, 07, 09, 11, 13; SK 82- 01, 03, 05, 07, 09, 11, 13, 14; SK 100- 01a, 01b, 01c, 10, 11, 13, 15, 17, 19, 20, 25, 27; SK 107- 1, 2, 3, 4, 6, 7; SK 31-01; SK 101-03, 05; SK 124-05, 06, 07, 08, 09, 10, 11 12, 12a), RV Gaveshani (GV-1, 2, 3, 4, 5); AA Sidorenko (AS 10-01, 02, 03, 05, 07), DSV Nand Rachit (NR-1, 5, 7, 9, 11, 13) and RV Sagar Sandhani (MAN-01, 03; Prof-10, 14, 25, 34) under Indian Research Programmes. Few data sets were extracted from the National Geophysical Data Centre (NGDC) such as Lamont LDEO-Robert Conrad (C1215; C1216, a, b, c, d; C1402a, b, c, d, e, f; C1708, a, b, c, d; C1709, a), Lamont LDEO-Vema (V1909, a, b; V2902; V3305; V3308; V3405; V3503; V3616, a), Woods Hole Oceanography Institute-Chain (CH100L06), Scripps Institute of Oceanography-Argo (CIRC05AR), Scripps Institute of Oceanography-Melville (ANTP11MV, INMD06MV, INMD07MV), Scripps Institute of Oceanography-Glomar Challeng (DSDP22GC), Texas A&M University-Joides Resolution (ODP116JR), Russia-Dmitry Mendelee (DME07a, b, c, 29040006,), France-Jean Charcot (84001211, a), Institute of Polar Research-Shirase (JARE27L4), NOAA-Pioneer (03010016) (Figure 2.7).

Ship-borne geophysical data collected in the Enderby Basin region bounded by longitudes 30°E to 90°E and latitudes 70°S to 45°S are utilized in the present study. The data were extracted from NGDC data base which were collected from various research institutes such as Japan Inst Pola-Shirase (JARE-27L2, 27L2a, 27L2b, 28L2, 28L3, 32L2, 32L6, 33L2), Lamont-Doherty-Eltanin (ELT-47, 54-1), Lamont Doherty-Robert Conrad (C0802-1, 2; C1704-1, 2, 3, 4, 5, 6; C1705-1, 2) and some profiles are taken from the published seismic information from Australian data sources which includes Japan National Oil Company (JNOC) (TH99 a and b) and Geoscience Australia surveys 228-01 and 06; 229-35, Agso 229 (1) and (2) (Figure 2.8).

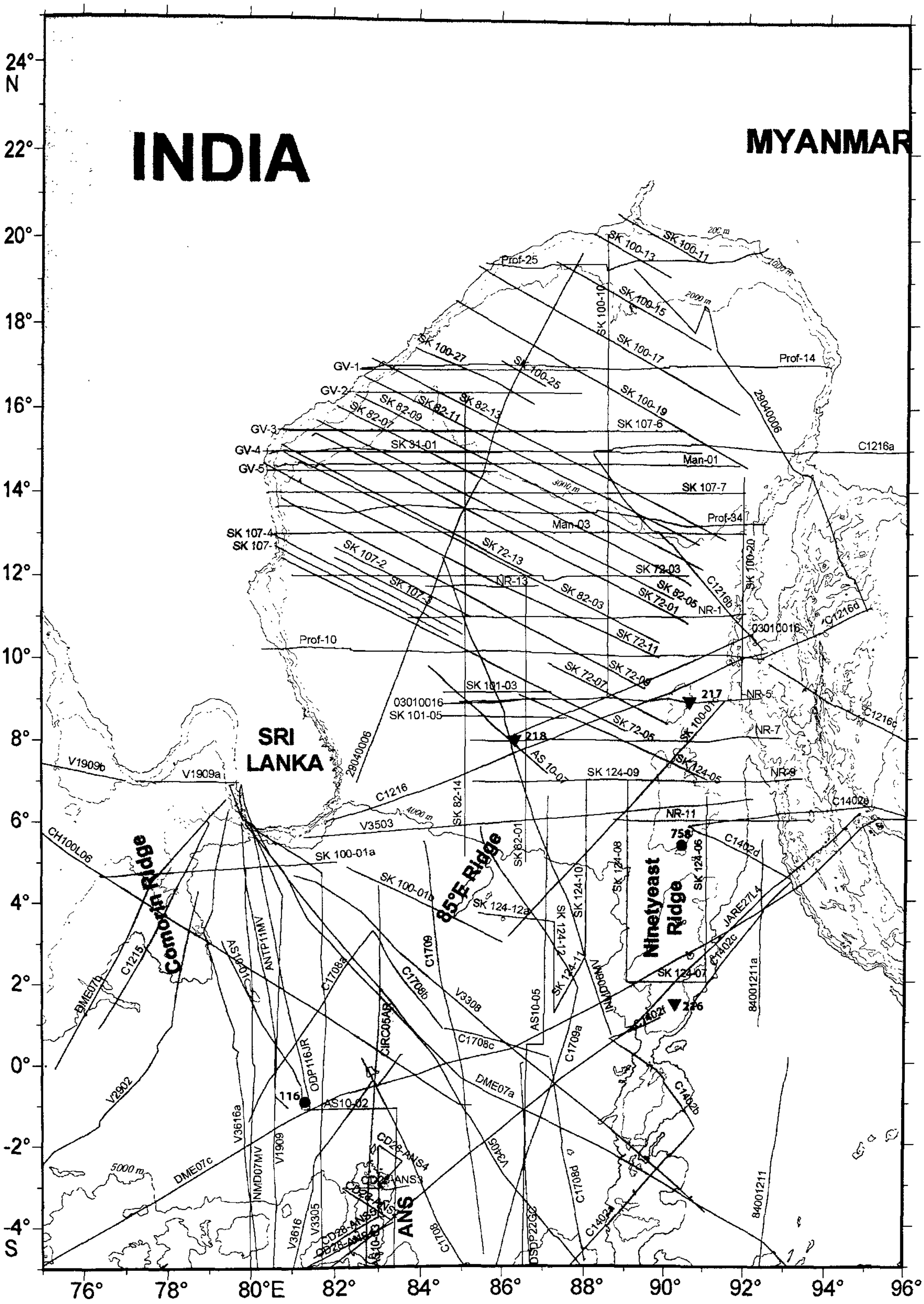


Figure 2.7: Track map showing the geophysical profiles of Bay of Bengal. The data were collected on board OVR Sagar Kanya, RV Gaveshani, AA Sidorenko, DSV Nand Rachit and M/V Sagar Sandhani under Indian Research Programs and few were extracted from NGDC cruise tracks.

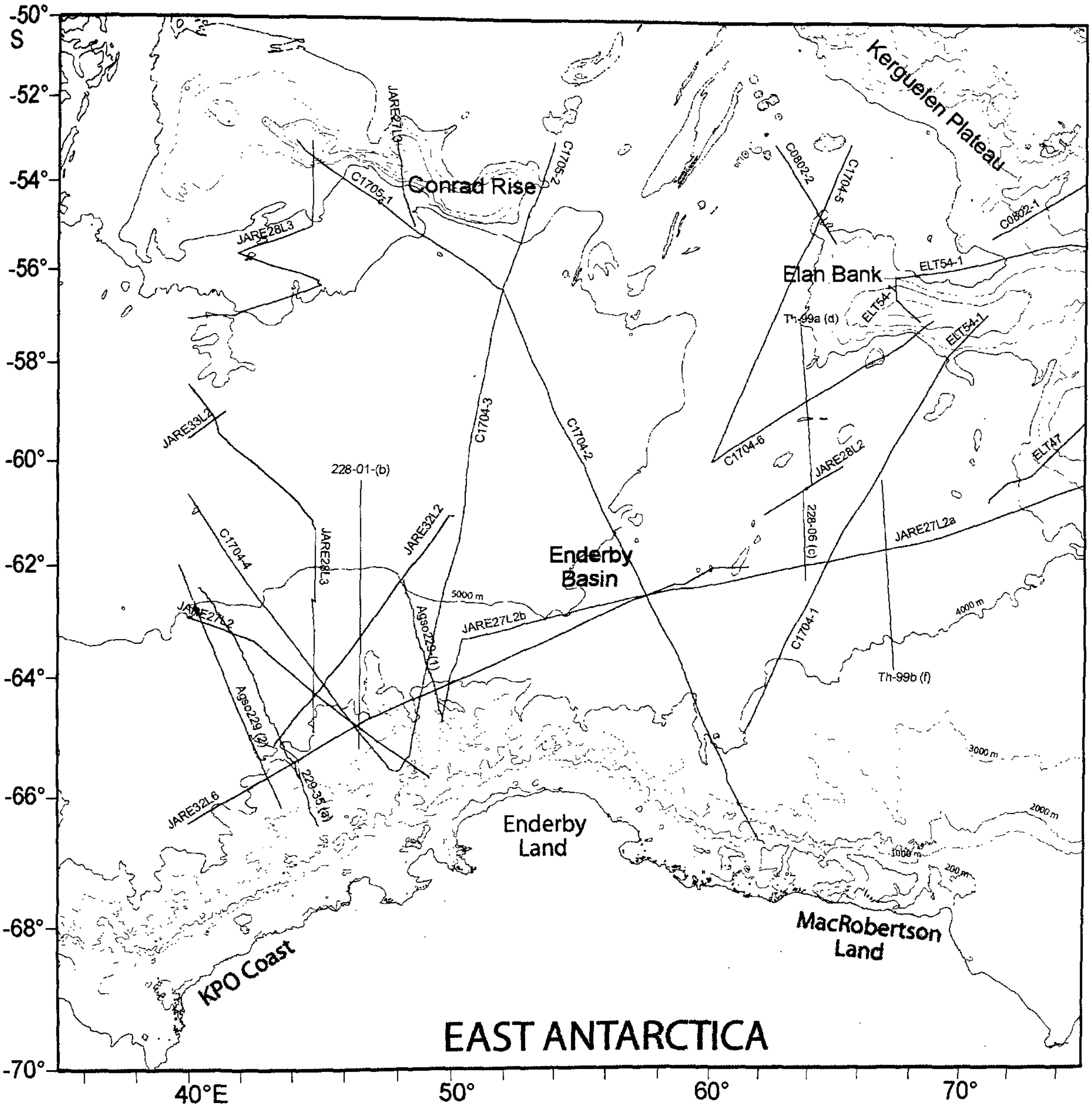


Figure 2.8: Track map showing the geophysical profiles of the Enderby Basin used in the present work. The data were extracted from NGDC cruise tracks and a few of the profiles have taken from published database (Gaina et al., 2007).

2.2.8.1 Data Collection and Corrections

2.3.2.8.1.1 Gravity Data

The gravity data in the Bay of Bengal collected onboard ORV Sagar Kanya and M/V Sagar Sandhani DSV Nand Rachit was obtained using the KSS-30 and 31 Bondenseewerk Sea Gravimeters with reference base system IGSN-71. By applying the Eotvos correction and normal gravity (with reference ellipsoid GRS 67) to the data, the free-air gravity anomalies have been determined.

2.2.8.1.2 Magnetic Data

The magnetic data collected in the Bay of Bengal onboard ORV Sagar Kanya, M/V Sagar Sandhani and DSV Nand Rachit was obtained using the Geometrics G 801 and G 886 proton precession magnetometers. The total magnetic field data were reduced to magnetic anomaly values by subtracting the International Geomagnetic Reference Field (IAGA Division V, 1992).

2.2.8.1.3 Bathymetry Data

The bathymetry data used for the present study in the Bay of Bengal were collected using the Honeywell Elac Narrowbeam Echosounder system. An integrated navigation system (INS), with satellite navigation system (Magnavox, 1107 RXT) and global positioning system (GPS) as primary sensors were used for the positions during the surveys.

2.2.8.1.4 Seismic Reflection Data

Multichannel seismic reflection data along profiles MAN-01, MAN-03, SK107-06 and SK107-07 collected onboard M/V Sagar Sandhani and ORV Sagar Kanya in the Bay of Bengal are used for the present work. The field parameters used for acquisition of seismic reflection data onboard M/V Sagar Sandhani and ORV Sagar Kanya were different. A 96-channel seismic streamer with 32 hydrophones per group spaced at 25 m and using two D-type array of nine air guns with a total capacity of 31.25 L at every 50 m shot firing were used onboard M/V Sagar Sandhani. The 24-fold coverage for a length of 10 s using 2-ms sampling interval was recorded and has been processed at Interra Exploration Company (India) to obtain the stacked sections along profiles MAN-01 and MAN-03. A 24-channel seismic streamer with 32 hydrophones per group spaced at 25 m, and a D-type array of seven air guns with a total capacity of 7.98 L and every 50 m shot firing were used onboard ORV Sagar Kanya. The 6-fold coverage for a length of 12 s using 4-ms sampling interval was recorded and has been processed using the standard GECO package to obtains the stacked sections along profiles SK107-06 and SK107-07.

2.2.8.2 Generation of Database and Presentation of Data

The processed bathymetry, gravity and magnetic data along all the profiles in the Bay of Bengal and Enderby Basin for the present studies are plotted along the ship-tracks and discussed in detail in Chapters-3, 4, 5, 6, and 7.

Generic Mapping Tools (GMT) software of Wessel and Smith (1998) has been extensively used for the data corrections and plotting of the data in required manner. Satellite gravity data of Sandwell and Smith (2009) over the regions of Bay of Bengal and Enderby Basin have been downloaded and image maps have been generated. The bathymetry data also has been downloaded from GEBCO database and presented for the present work.

CHAPTER 3

Analysis of Satellite and Ship-Borne Gravity Data of Conjugate Regions-Bay of Bengal and Enderby Basin

ANALYSIS OF SATELLITE AND SHIP-BORNE GRAVITY DATA OF CONJUGATE REGIONS- BAY OF BENGAL AND ENDERBY BASIN

Satellite altimeter data of the oceans are important for mapping the tectonic features/ elements, seafloor undulations and internal structure of the crust and upper mantle. The data are further used for proposing and/ or refining the existing plate tectonic models, for example how and when the spreading activity has changed within and between the tectonic plates. The altimetry-derived geoid data have been widely used to model the thermal and mechanical structure of the oceanic lithosphere and paleo-plate motions. It helps in studying the interaction of converging upper mantle with the lithosphere, spreading ridges, hot spots, while in some off-ridge regions the data are extensively helpful to understand the plate kinematics and to reconstruct the past motions of tectonic plates.

3.1 Classical Geoid Data of the Bay of Bengal

Classical geoid data obtained after removal of atmospheric and oceanographic effects from the sea surface height data generally provide the information on long-wavelength structural features that lies at depths greater than 100 km and occasionally bring out the information on some of the shallow structures that have excessive mass density contrasts.

The classical geoid data of the Bay of Bengal relative to the reference ellipsoid vary from about -104 m in south of Sri Lanka to -40 m in the southeast of Andaman Nicobar Islands (Figure 3.1). Earlier Rajesh and Majumdar (2004) have observed higher values of classical geoid in the deltaic front of the Ganges and the Brahmaputra and also near the Andaman Islands. The variation in the data corresponds to the general geoidal gradient with decrease towards the south of Sri Lanka at a rate of approximately 39 mm/km. On close scrutiny it is observed that steep geoid gradients rapidly decrease in E-W direction in a region between 85°E and 90°E meridians. While towards the east in the vicinity of Andaman- Nicobar Islands and towards the west close to the Eastern Continental Margin of India (ECMI) and Sri Lanka, the data vary relatively with lesser

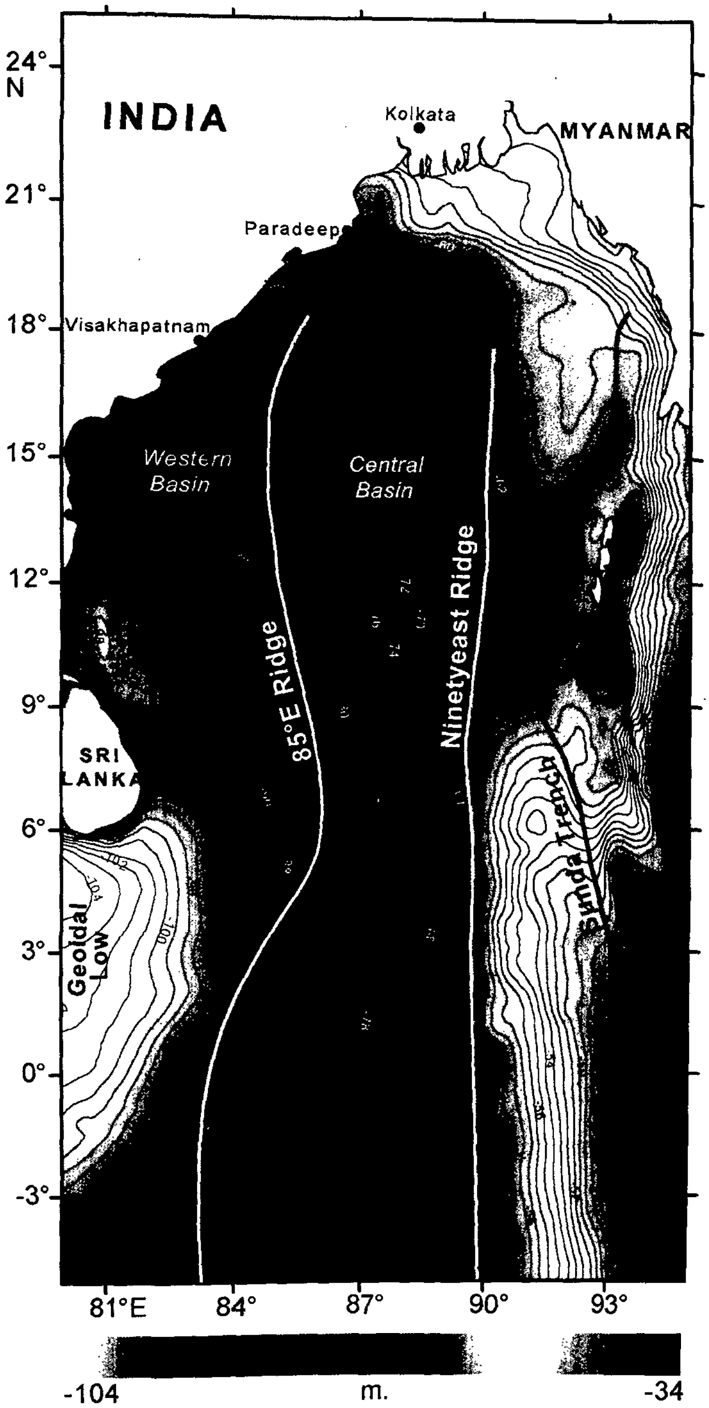


Figure 3.1: The Classical geoid data of the northeastern Indian Ocean. Geoidal lows, located in south of Sri Lanka and NNE of Sri Lanka, have influenced the signatures of most part of the Bay of Bengal region. Two major aseismic ridges (Ninetyeast and 85°E ridges) marked with white solid lines do not posses any geoidal pattern. Black solid line indicates the Sunda Trench, where Indian plate is subducting under the Burmese microplate.

gradients and trend in NW and SW directions due to the influence of the regional features such as Ninetyeast Ridge and Sunda Trench, and morphology of the continental margin, respectively. Towards the west of the Andaman Nicobar Islands a slight notch (local minima) is observed in the geoid contour data (Figure 3.1), which indicates the signature of the Sunda subduction zone, a convergent boundary between the Indian and the Burmese lithospheric plates. Near the continental margins two geoidal lows are observed upto 104 m and -98 m with variable wavelengths. The geoidal low observed south of Sri Lanka is dominated by long wavelength gravity anomaly centred on south of Sri Lanka (Negi et al., 1987). Earlier the major geoidal-low south of Sri Lanka was explained with the presence of depression lying presumably at the core-mantle boundary (Negi et al., 1987). Both the 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 toward the lows. The two major aseismic ridges Ninetyeast and 85°E ridges run longitudinally in the Bay of Bengal do not show any signatures in the geoidal data as they are relatively shallow features and lie within the crust and the uppermost part of the mantle.

3.2 Residual Geoid Data of the Bay of Bengal

The residual geoid data after removal of seafloor topography and deeper earth contributions generally provide information of geological structures that lie within the crust and crust-mantle boundary undulations. The deeper earth effects are removed using the spherical harmonic modeling of the geo-potential field (Rapp, 1983). The information thus obtained contains the contributions mainly from the bathymetric undulations and lithospheric heterogeneities.

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 the western margin of the Ninetyeast Ridge (Figure 3.2). Relative residual geoidal lows are clearly noticed up to 1 m associated with the Sunda Trench, 85°E Ridge (buried part, north of 5°N latitude) and over some isolated features in the western basin. In contrast, residual geoidal highs are noticed along the southern part of the 85°E Ridge and Ninetyeast Ridge. Thus the 85°E Ridge possesses 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

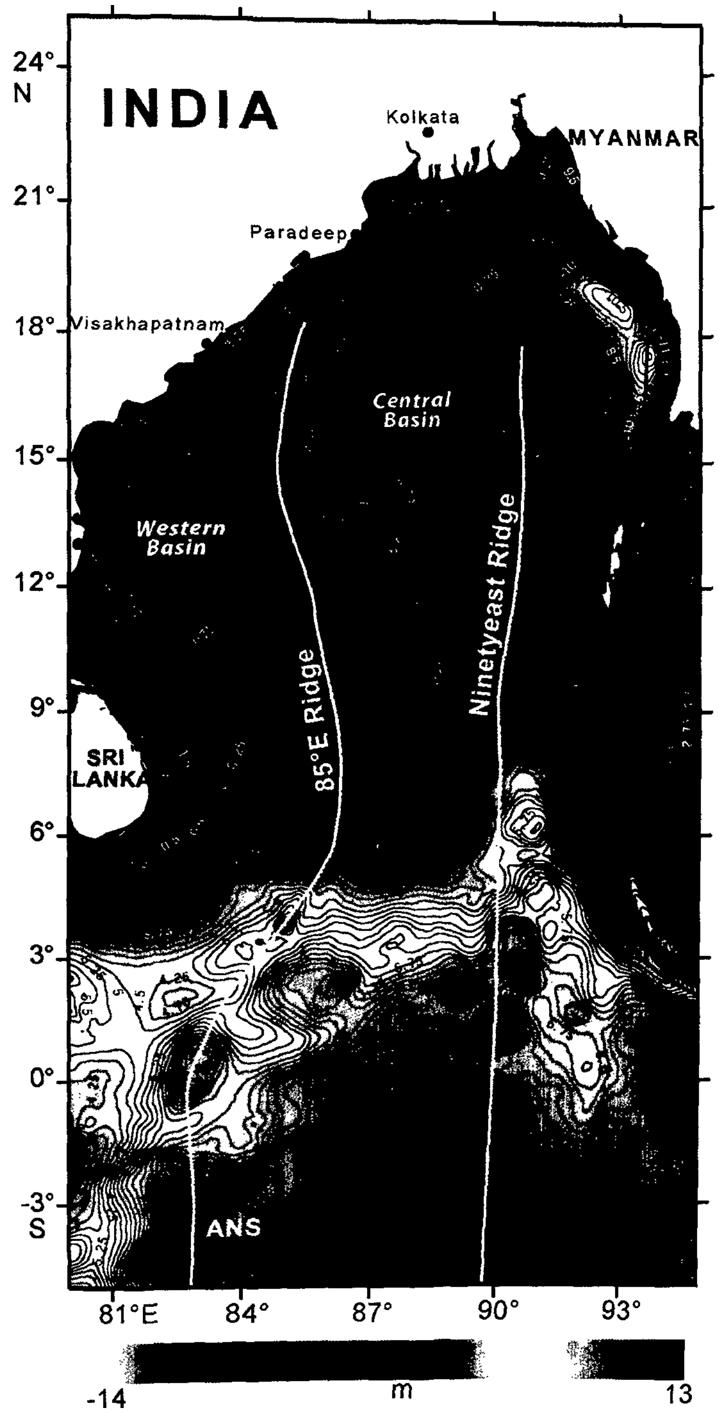


Figure 3.2: The Residual geoid data of the northeastern Indian Ocean. The Ninetyeast Ridge is associated with positive geoid anomaly, where as the 85°E Ridge is associated with negative anomaly in the north (north of 5°N) and positive anomaly in the south. E-W trending geoid anomalies on both sides of 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.

of the ridge toward south. This is in agreement with the results published earlier by 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 (ANS).

A small scale low residual geoid anomalies are observed at five places between the 85°E Ridge and south ECMI and they approximately trend in NE-SW direction. The anomaly features are reported for the first time and believe that they may provide some new insights in understanding the early evolution of the lithosphere between ECMI and East Antarctica. 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 3.2), suggesting that the oceanic basement deepens toward north due to excess thickness of pre-collision and post-collision sedimentary strata. The pattern was also noticed earlier by Rajesh and Majumdar (2004) in ERS-1 altimeter data and inferred that a general downward trend of the basement exists between latitudes 10°N to 14°N. Further they concluded that the basement trends downward and thickness of Bengal Fan sediments increases as well, as one proceeds towards north. Towards north of 13°N latitude surprisingly the anomaly gradients have considerably reduced, as basement may not be reflecting in the residual geoid data because of unusual deeper depths to the basement. Another notable point of interest in the data is the absence of long-wavelength geoidal feature generated by regional tilt of the oceanic crust in the Bay of Bengal.

3.3 Satellite and Ship-borne Free-Air Gravity Anomaly of the Bay of Bengal

The free-air gravity anomaly data of the northeastern Indian Ocean acquired onboard different research vessels are plotted at right angles to the ship-tracks (Figure 3.3). The data reveal prominent gravity signatures associated with the structural features of the Bay of Bengal and distal Bengal Fan region. In addition satellite derived free-air gravity anomaly data are also presented in Figure 3.4 for the discussion of signatures of regional features of the study region.

3.3.1 Eastern Continental Margin of India

Continental margin is a transition zone of the ocean floor that separates thin oceanic crust from thick continental crust. The ECMI together with adjacent coastal territory is covered by the Eastern Ghats Mobile Belt in the northern part, which extends for over 1000 km along the east coast, while the Southern Granulite terrain of Precambrium age occupies the southern part. It is generally believed that the ECMI, a matured passive continental margin, was evolved when the Indian continent drifted away from the East Antarctica during the early Cretaceous. The margin is characterized by rifted basins filled with thick sediments more than 5 km, while some of the basins prograde into deltas. The breakup of ECMI from East Antarctica seems to have been initiated along the Proterozoic Eastern Ghats Mobile Belt.

The satellite derived free-air gravity anomaly map of the Bay of Bengal shows two different anomaly signatures on north and south segments of the ECMI. The decrease in gravity anomaly value towards the margin agrees well with the earlier observations and interpretations (Gopala Rao et al., 1997; Krishna et al., 1998; Krishna, 2003) that the trend seems to be associated with the deepening of the basement towards the margin. On north of ECMI the gravity anomalies are broadened reflecting the wide shelf edge caused by the delta formations, whereas on southern margin the anomalies are short-wavelength showing the narrow shelf and steep slope. Along the southern part of the ECMI and the eastern margin of Sri Lanka the gravity data show low-anomaly signature with high amplitude and short-wavelength along the profiles. While towards the northern part of the ECMI, it shows gravity low with reduced amplitude and extended wavelength along the profiles. The gravity anomaly patterns are considered as useful constraints for the classification of margin segments and demarcation of the continent ocean boundary (COB) on ECMI and Sri Lanka. The location where a quick change in the low gravity anomaly from relatively short-wavelength to broader less significant anomaly is observed marks the location of the continent ocean boundary (COB) on ECMI and Sri Lanka.

3.3.2 The 85°E Ridge

The 85°E Ridge is an enigmatic near N-S trending aseismic ridge in the northeastern Indian Ocean. The ridge extends from the Mahanadi Basin in the north of Bay of Bengal to the ANS in the Central Indian Basin. But in the middle, the ridge track takes an arcuate shape off Sri Lanka region and is discussed in detail in Chapter-1.

The satellite and ship-borne derived free-air gravity anomaly maps of the Bay of Bengal show prominent gravity anomaly signatures associated with the 85°E Ridge. North part of the ridge in the Bay of Bengal (up to 5°N latitude) is associated with negative gravity anomaly, while the south part in the distal Bengal Fan coincides with positive gravity anomaly. The magnitude of low-gravity anomaly of the 85°E Ridge varies along its strike from north to south as shown in Figure 3.3. Ship-borne free-air gravity anomaly data as shown in Figure 3.4 display prominent negative gravity anomaly associated with the ridge between 5°N and 15°N latitudes. 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). The negative gravity anomaly signature is wider in the north and matches well with the gravity anomaly signatures observed in the ship-borne map. At around 5°N latitude the gravity signature takes a curvilinear trend and as we move towards south the negative gravity anomaly switches to positive anomaly. The low-gravity anomalies of the 85°E Ridge switch over to gravity high towards the south of 5°N latitude; 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 also explained with the presence of 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).

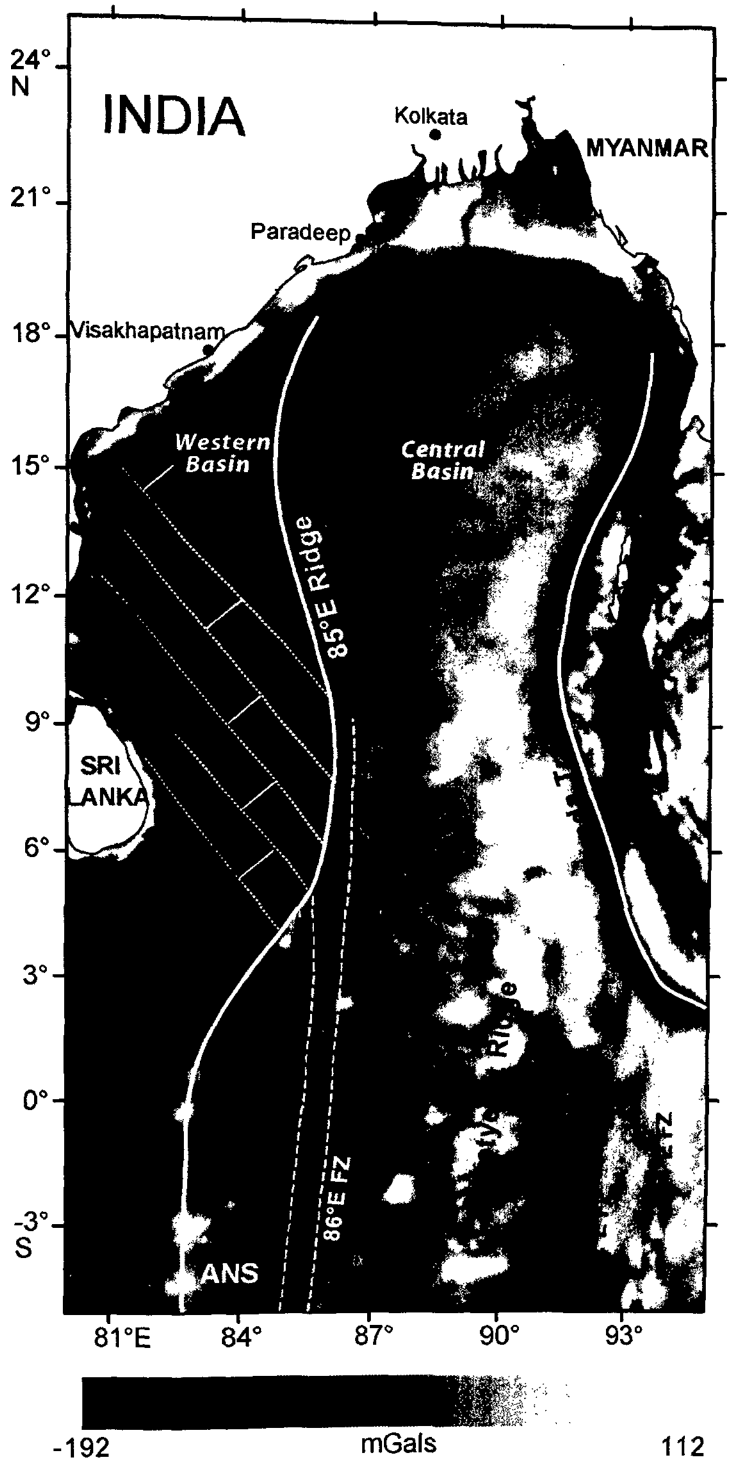


Figure 3.3: The satellite free-air gravity anomaly of the northeastern Indian Ocean. The gravity field in the western basin reveals five NW-SE oriented fracture zones and stripes of NE-SW trending low-gravity anomalies between the 85°E Ridge/ 86°E FZ and south ECMI. White dashed lines indicate the locations of fracture zones. White solid lines between the FZs show locations of gravity lows associated with structural highs.

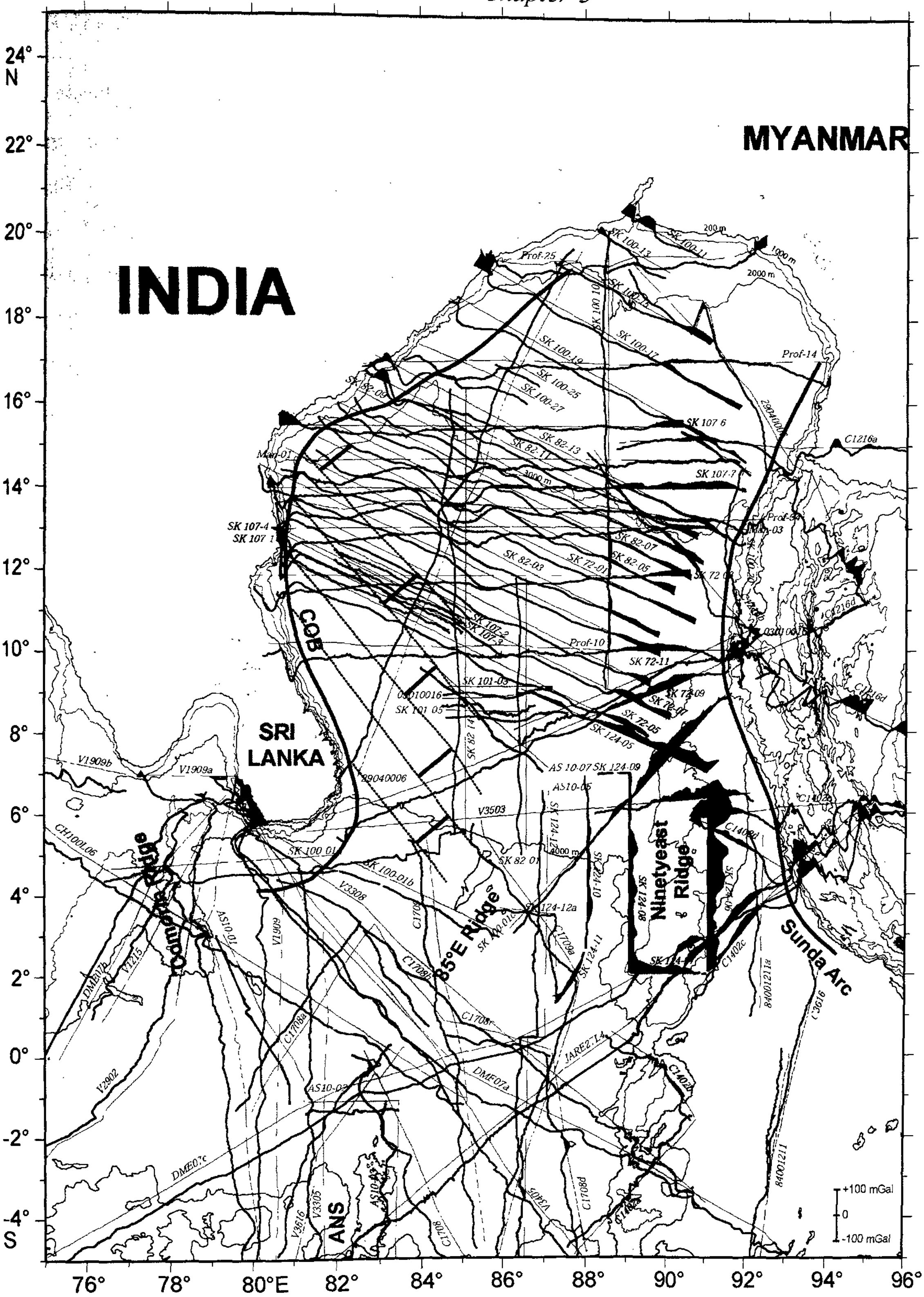


Figure 3.4: Free-air gravity anomaly data of the northeastern Indian Ocean plotted at right angle to the ship tracks. Variable bathymetric contours (200, 1000, 2000, 3000, and 4000 m) are shown to indicate the physiography of the region. Dark shaded regions show the locations of Ninetyeast, 85°E and Comorin ridges. Fracture zones and structural highs identified in satellite gravity data are superimposed. At two locations, structural highs are associated with low-gravity anomalies.

3.3.3 The Ninetyeast Ridge

The Ninetyeast Ridge in the eastern Indian Ocean extends from 34°S to 17°N latitudes along the 90°E meridian, is one of the longest linear feature in the world oceans. The feature trends in N-S direction and separates the Central Indian Basin from Wharton Basin. The ridge is straight and flat topped in the southern part, but towards the north of 10°S latitude it is composed of a complex series of en echelon blocks. In the northern part, the ridge is covered beneath the sediments of the Bengal Fan. At about 10°N latitude the sediment cover is thin but the thickness increases towards north. While in the south it abuts the east-west trending Broken Ridge.

The satellite derived and ship-borne free-air gravity anomaly data of the Bay of Bengal, in general, show low-amplitude gravity anomaly signatures associated with the Ninetyeast Ridge (Figures 3.3 and 3.4). Compensated positive anomaly signatures are seen associated with buried part of the Ninetyeast Ridge in the Bay of Bengal region extending up to 18°N latitude. At places the ridge is buried under about 3 km thick Bengal Fan sediments (Gopala Rao et al., 1997). The en enchelon block structures of the ridge are clearly reflected in satellite gravity data map (Figure 3.3). The overall structural trend of the Ninetyeast Ridge as observed in the satellite gravity map has a N-S strike, while the individual blocks of the ridge seem to be oriented in NE-SW direction in bathymetry as reported by Petroy and Wiens (1989), Sager et al. (2007, 2010). At 8°N latitude the ridge shows a gravity trend with distinct offset by about 100 km, where the ridge gravity high seems to merge with the Sunda Trench low gravity anomaly (Subrahmanyam et al., 2008a). Towards the south the ridge is associated with positive gravity anomaly and is displayed as N-S linear feature.

3.3.4 The Sunda Trench

The Sunda Arc extends from the eastern Himalayan syntaxes to southward through Burma, Andaman Sea and Andaman-Nicobar Ridge, Sumatra Islands and eastward through Java and continues into the Banda Arc of eastern Indonesia. It is a classic convergent plate boundary or subduction margin, with the Indo-Australian plate or Indian and Australian sub-plates under-thrusting the Eurasian or Southeast Asian plate or plates towards the north and northeast. The nature of convergence varies from continental type in the Burmese Arc to oceanic type in the Andaman Arc. The Sumatra subduction zone is approximately oriented NW-SE, while further north, the Andaman subduction zone is oriented N-S, at a highly oblique angle with the Ninetyeast Ridge oriented in a NNE-SSW direction and also the direction of paleo spreading in the central Indian Basin and the Wharton Basin.

The satellite and ship-borne derived free-air gravity anomaly data of the Bay of Bengal show distinct gravity low along the Sunda Trench. Towards the east of the Ninetyeast Ridge a sharp gravity low marks the trend of the Sunda subduction zone. The gravity signature of the trench appears as a defined feature on the satellite gravity map unlike the bathymetry map (Subrahmanyam et al., 2008a). The locations where the trench seems to have been filled with Bengal Fan sediments the gravity signatures are evident, which indicates that the younger and more recent sedimentation processes have not yet significantly altered the trench axis and the associated gravity anomaly. The most prominent gravity anomaly over the entire region is the gravity low that drops below -200 mGal, associated with the forearc basin. The gravity low associated with the Sunda Trench is shown as curvilinear belt of negative gravity contours running close to and just behind it.

3.3.5 Fracture Zones

The fracture zone features are the most important geophysical constraints for better understanding the tectonic fabric of the ocean floor and paleo spreading history and plate motions. Morphologically the fracture zones are the most dominant features in ocean basins, but occasionally they can be found as subsurface features beneath the sediments. As the lithospheric plates grow, transform faults show their continuity as traces or fracture zones in the oceanic basins or mid-plate regions. The fracture zones, as extension part of the transform faults, display evidence of past transform fault activity. Such traces are essential tectonic constraints in reconstruction of ancient plate motions and assemble of dispersed continental fragmentation. The fracture zones lie within a single oceanic plate with no lateral motion across it and seismicity.

The satellite derived and ship-borne free-air gravity anomaly data of the Bay of Bengal on detailed analysis show the presence of NW-SE trending narrow gravity features between the 85°E Ridge and south ECMI. In order to better track the signatures of narrow gravity features within this region, gravity data are generated along profiles running across the narrow gravity features of the Bay of Bengal as shown in Figure 3.5. From the profile data, it can be observed that the five fractures zones display changes in gravity anomaly gradients. These narrow gravity anomaly features are interpreted as signatures of fracture zones, which are related to the early rift of ECMI from East Antarctica. Between the fracture zone features the gravity closures are observed trending nearly perpendicular to the NW-SE oriented fracture zones. For the first time fracture zones close to the ECMI have been identified with confidence in the Bay of Bengal using the satellite free-air gravity data. Towards the immediate southeast of the 85°E Ridge the satellite derived free-air gravity anomaly map show two prominent nearly N-S trending FZs (85°E FZ and 86°E FZ), which are seen extending into the Bay of Bengal up to 6°N and 9°N, respectively. Towards the east of Ninetyeast Ridge three prominent N-S trending FZ's (90°E FZ, 92°E FZ, 94°E FZ) are also observed in the satellite derived free-air gravity anomaly map (Figure 3.3).

3.3.6 Fossil Spreading Ridge Segments

Fossil spreading ridge segments are the tectonic features that have once contributed extensively to the spreading phases of the seafloor and subsequently ceased due to change in spreading ridge configuration. Certain segments of the spreading ridge system cease their activity and start the activity at a new place by connecting the existing segments with transform faults. The segments that remain without spreading activity are known as fossil spreading segments or extinct spreading centers. They are generally created during the plate reorganizations or are associated with major or minor ridge jumps. The fossiled ridge segments become part of the ocean floor and experience the same movements that the ocean floor has been undergoing.

The satellite derived and ship-borne free-air gravity anomaly data of the Bay of Bengal show the presence of approximately NE-SW trending low-gravity anomaly closures between the 85°E Ridge and south ECMI. The gravity profile data generated perpendicular to the low-gravity closures of the Bay of Bengal (Figure 3.5) also reveal

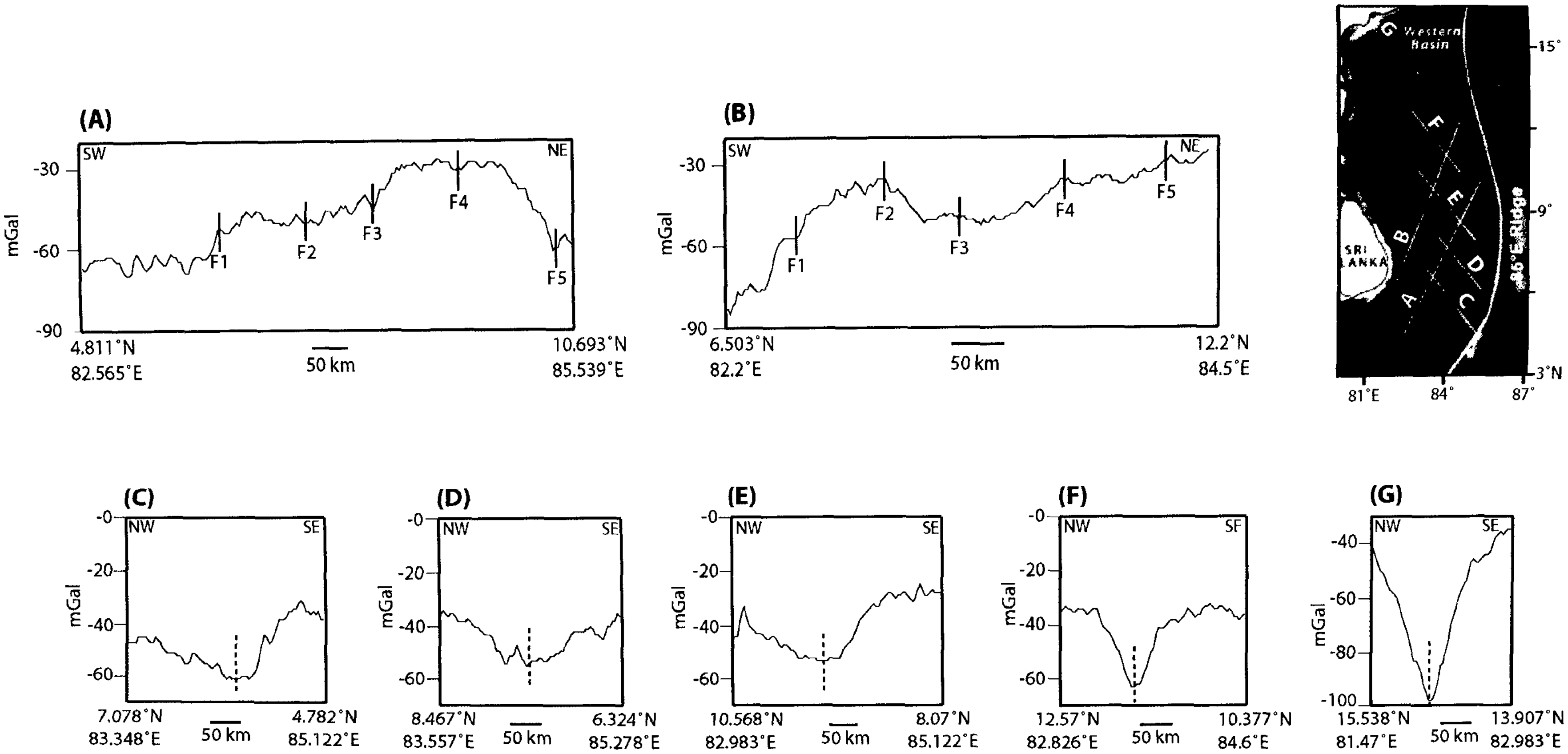


Figure 3.5: Gravity data along synthetic profiles (A and B) across the fracture zone pattern and (C, D, E, F and G) across the gravity lows between the fracture zones. Solid vertical lines with label 'F' show the locations of fracture zones. Dashed lines show the locations of gravity lows associated with suspected fossil ridge segments. Locations of profiles are shown in satellite gravity image map.

low gravity anomaly signatures. These low narrow gravity anomaly closures (structural rises) between the FZs of the Bay of Bengal are believed to indicate either fossil ridge segments, which possibly had been extinct during the early evolution of the Bay of Bengal lithosphere or may have formed by the volcanic activity when the hot spot was accreting the 85°E Ridge.

3.4 Classical Geoid Data of the Enderby Basin

The classical geoid data of the Enderby Basin, East Antarctica relative to the reference ellipsoid vary 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 3.6). From the geoidal signatures it is found that the data are in general controlled by the major seafloor features, whose relief and depressions are very high and change rapidly with large gradients. The Crozet plateau and the Conrad Rise are the prime features that control the overall geoid data of the East Antarctica region.

High geoidal data are observed along the other seafloor features such as the northern Kerguelen plateau, part of the central Kerguelen plateau and Elan Bank. In the Enderby Basin distinct geoid patterns are noticed following the trends of the Princess Elizabeth Trough, Kerguelen FZ and some linear structural rises within the Labuan Basin on east of the Kerguelen plateau. On detailed analysis it was found that the geoid data of the Enderby Basin have three distinct geoid patterns following the geographical extent of the sub basins (western and central) of the Enderby Basin.

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, some notches are found 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 3.6).

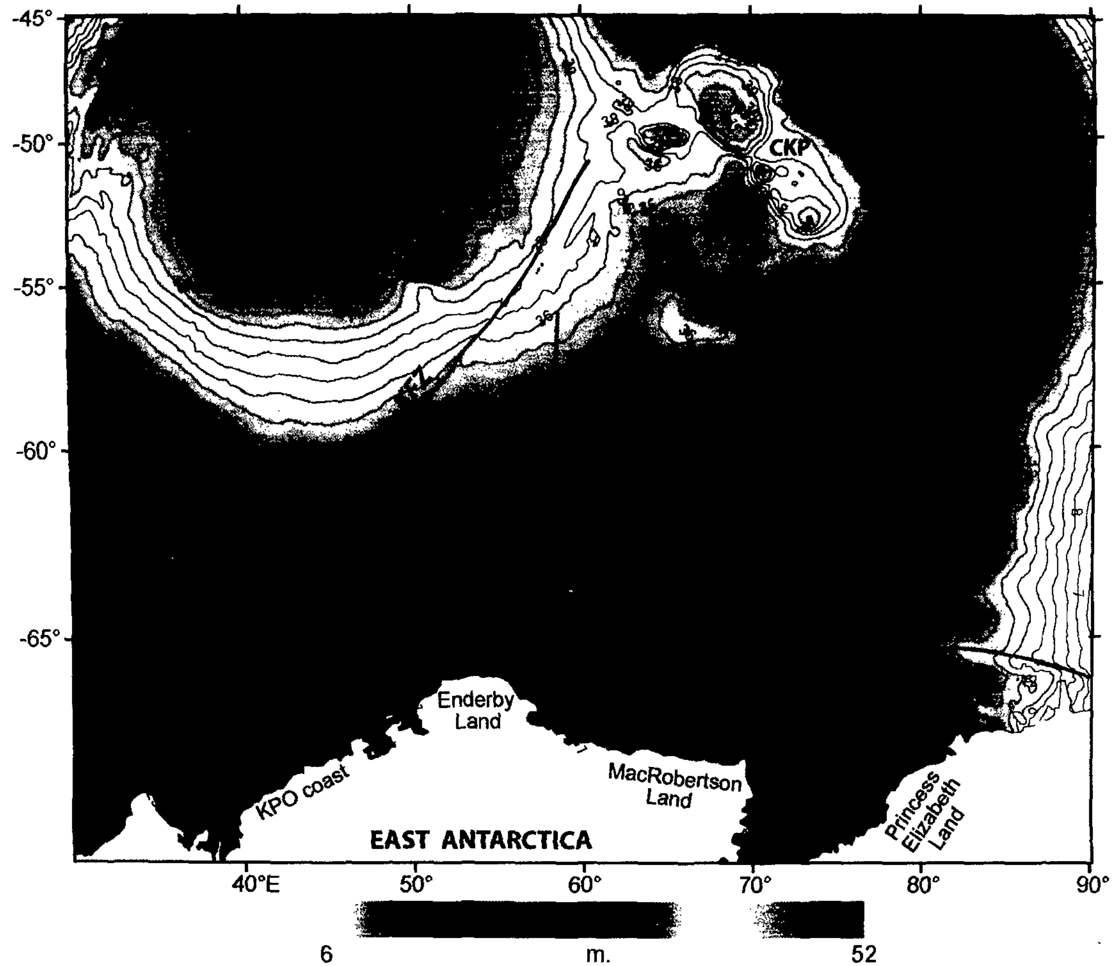


Figure 3.6: The Classical geoid data of the Enderby Basin and adjacent regions. Enderby Basin possesses three geoidal patterns. Solid lines along 58°E and 47°E separate the patterns. The Kerguelen FZ (KFZ) and Princess Elizabeth Trough (PET) show the low-geoid lineations. EB-Elan Bank, NKP-northern Kerguelen plateau, CKP-central Kerguelen plateau, GR-Gunnerus Ridge, CP-Crozet plateau, CR-Conrad Rise, PB-Pyrdz Bay.

3.5 Residual Geoid Data of the Enderby Basin

The residual geoid data of the Enderby Basin vary from 13 m in east of Crozet plateau to -2.5 m towards the west of Crozet plateau and also in the Australian-Antarctic Basin (Figure 3.7). Residual geoid highs are prominently seen over the seafloor features such as Crozet plateau, Conrad Rise, northern Kerguelen plateau, part of the central Kerguelen plateau and the Elan Bank. Distinct residual geoidal patterns are observed following the trend along the Kerguelen FZ. Relative residual geoidal lows upto 0.25 m is observed in the central and western Enderby Basins. Distinct residual geoidal patterns are observed between the Conrad Rise and Gunnerus Ridge trending in NNE-SSW direction, whereas between the Kerguelen FZ and Enderby Land the geoidal pattern trend in N-S direction and between the Elan Bank and Prydz Bay it trends in NW-SE direction.

3.6 Satellite Free-air Gravity Anomaly of the Enderby Basin

Satellite derived free-air gravity anomaly shows prominent gravity signatures along all the structural features of the Enderby Basin (Figure 3.8). The ship-borne free-air gravity anomaly data acquired onboard various research vessels are plotted at right angles to the ship tracks (Figure 3.9). The profile data do not reveal the trends in the gravity signatures associated with the structural features of the Enderby Basin due to the non-availability of closely spaced data in the region. So satellite derived free-air gravity anomaly data are presented in Figure 3.8 and analysed for discussing the signatures and trends of the regional features present in the Enderby Basin region.

3.6.1 Sub-Basins of the Enderby Basin

The Antarctica margin extends over a large part of the Enderby Basin, the Princess Elizabeth Trough and the Davis Sea Basin. The margin adjoins the major oceanic basins such as Crozet Basin, Enderby Basin, Labuan Basin, Davis Sea Basin and Australia-Antarctica Basin (Figure 1.5). The Enderby Basin is a wide area located between the Kerguelen plateau and the Antarctic margin. Following the geophysical signatures the Enderby Basin is further divided into sub-basins: the central Enderby Basin between MacRobertson Land and Elan Bank, the western Enderby Basin that lies south of the Kerguelen FZ and west of 58°E longitude.

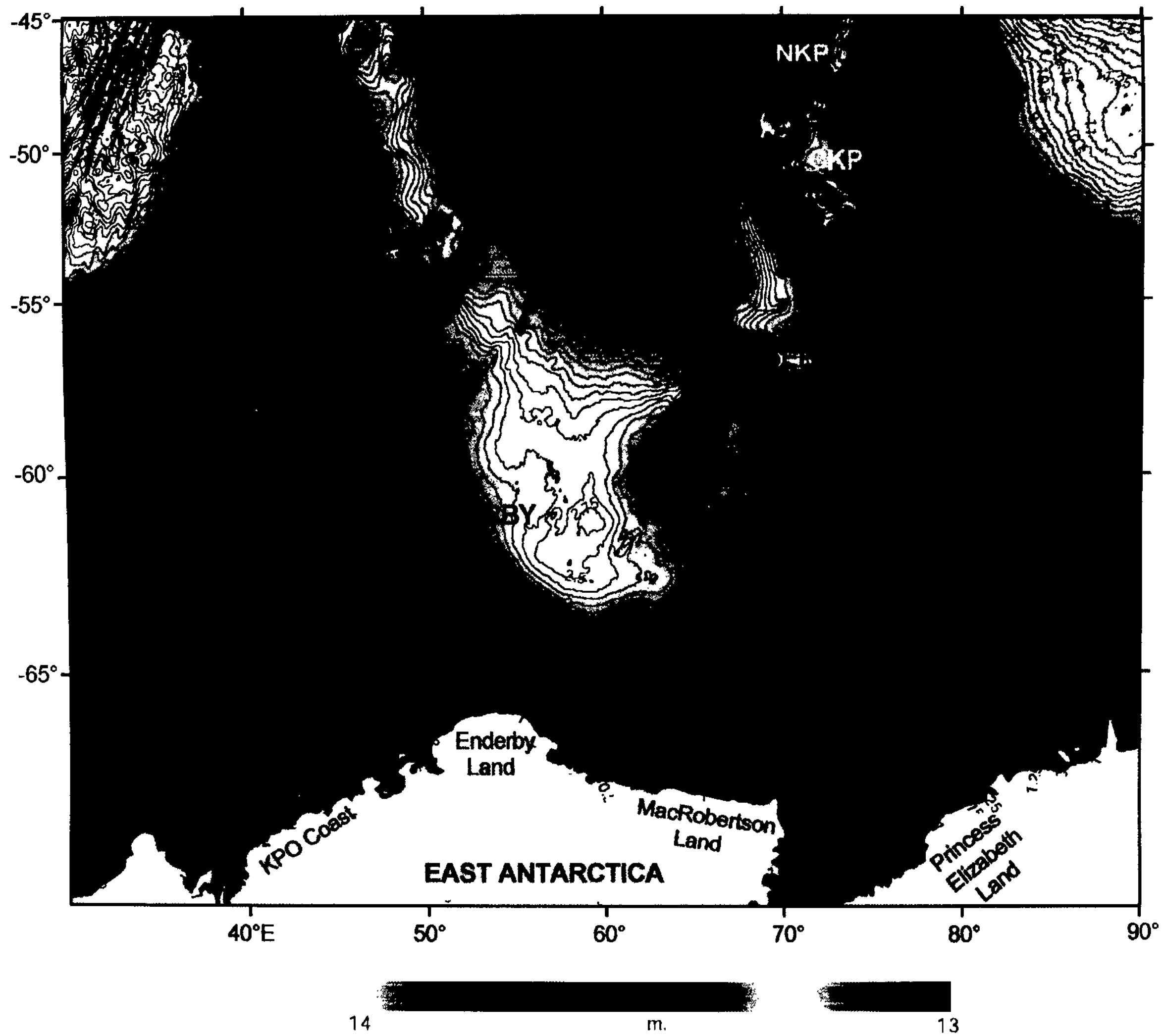


Figure 3.7: The Residual geoid data of the Enderby Basin and adjacent regions. EB-Elan Bank, NKP-northern Kerguelen plateau, CKP-central Kerguelen plateau, GR-Gunnerus Ridge, CP-Crozet plateau, CR-Conrad Rise, PB-Pyrdz Bay, PET-Princess Elizabeth Trough.

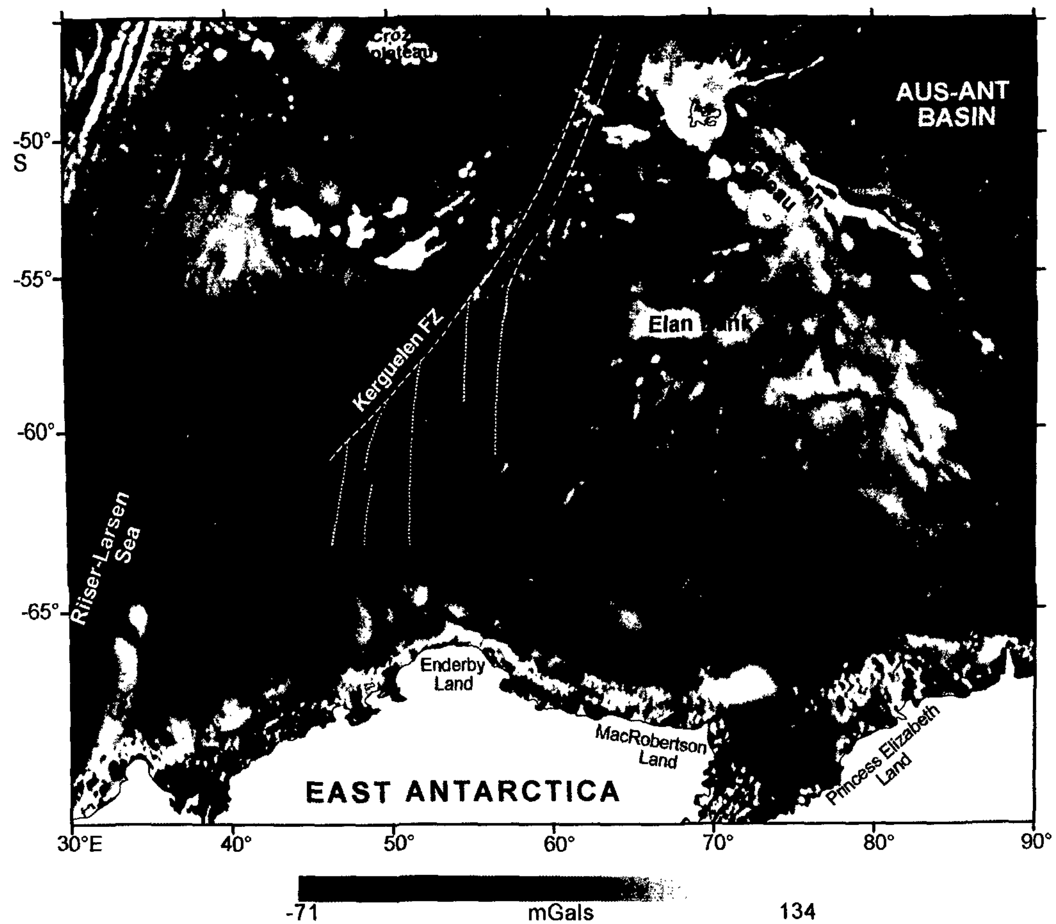


Figure 3.8: The satellite free-air gravity anomaly of the Enderby Basin and adjacent regions. The gravity field in the western Enderby Basin between 47°E and 58°E longitudes reveal five fracture zones trend nearly in N-S direction and meet the Kerguelen FZ with at angle of ~37°. White dashed lines indicate the locations of fracture zones.

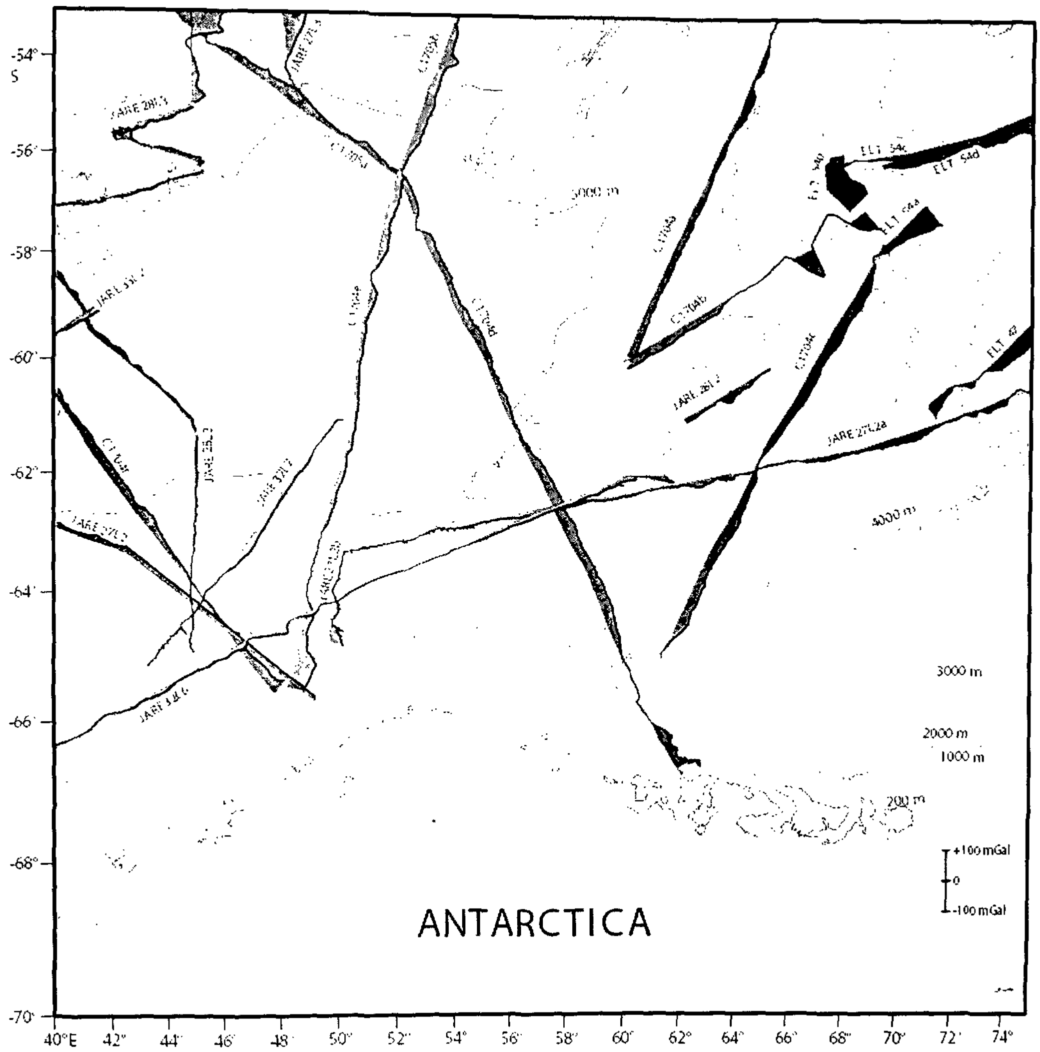


Figure 3.9: Free-air gravity anomaly data of the Enderby Basin plotted at right angle to the ship tracks. Variable bathymetric contours (200, 1000, 2000, 3000, 4000 and 5000 m) are shown to indicate the physiography of the region.

Satellite derived free-air gravity anomaly data of the East Antarctic margin and adjoining Enderby Basin generally present fairly long-wavelength free-air gravity anomalies as the overlying sediments and/ or thick ice may have altered the short-wavelength anomalies (McAdoo and Laxon, 1997; Rotstein et al., 2001). The sediment thickness is up to 2 km in abyssal parts of the Enderby Basin and towards the continental margin it increases up to 8 km (Mizukoshi et al., 1986; Murakami et al., 2000; Stagg et al., 2004). The gravity map show the presence of prominent gravity lineations revealing the pattern of oceanic fracture zones in the sub-basins viz., central and western Enderby Basins and Australian-Antarctica Basin.

3.6.2 The Kerguelen FZ

The Kerguelen Fracture Zone is a major tectonic feature in the Enderby Basin. It lies on the west of Kerguelen plateau and trends in a NNE-SSW direction. The satellite altimetry studies of Royer and Sandwell (1989) found set of fracture zones in the Crozet Basin and most prominent Kerguelen FZ in the Enderby Basin. These features are useful for constraining the direction of motions between India and Antarctica during late Cretaceous (anomaly 34) and middle Eocene (anomaly 20) time.

On detailed analysis satellite gravity data of the Enderby Basin show the presence of narrow gravity features trending in NNE-SSW direction, which is identified as Kerguelen FZ (Figure 3.8). The FZ feature starts its continuity from -46°S latitude between the Conrad Rise and the Kerguelen plateau and extends into the western Enderby Basin upto -62°S latitude.

3.6.3 The Elan Bank and the Kerguelen Plateau

The Elan Bank, a micro-continent, is located approximately in the central part of the Enderby Basin (Figures 1.5 and 3.8). It is situated on west of the Kerguelen plateau and from the boundary point between the central and the southern parts of the Kerguelen plateau. It extends in an E-W direction for about 900 km and encompasses about ~140,000 km^2 of seafloor between 1000 and 3500 m water depths. The Kerguelen plateau in the southern Indian Ocean having 2300 km long and 200 to 600 km wide, lies between 46°S and 64°S latitudes and trend in a NNW-SSE direction. The plateau is surrounded by deep ocean basins - to the northeast by the Australian-Antarctic Basin, to the south by the 3500 m deep Princess Elizabeth Trough, to the southwest by the Enderby Basin, and to the northwest by the Crozet Basin (Schlich et al., 1988). The Kerguelen plateau consists of 3 major morphological sectors- the northern, central and southern Kerguelen plateau (Schlich, 1975; Houtz et al., 1977; Coffin et al., 1986; Coffin et al., 2002). From the studies of Houtz et al. (1977) three structural trends have been identified on the Kerguelen plateau: NW-SE horsts and graben between the Kerguelen and Heard Islands, N-S trending grabens between northern and southern Kerguelen plateau and NW-SE horsts and grabens on the southern and eastern part of the Kerguelen plateau.

From the gravity map of the Enderby Basin (Figure 3.8), it can be observed that E-W trending Elan Bank and the northern Kerguelen plateau are associated with subdued gravity high anomalies. On western side of the plateau close to the central Enderby Basin the ocean floor is irregular with series of volcanic buildups. A linear boundary trending in NNW direction and separates the southern Kerguelen plateau from the Labuan Basin, is also observed from the satellite gravity data. The studies of Rotstein et al. (1992) have revealed that the boundary separating the southern Kerguelen plateau from the Labuan Basins are mostly fault controlled and in some place the morphology is induced with faults and is partially masked by the tectonic processes.

3.6.4 Fracture Zone Trends in Sub-Basins of the Enderby Basin

Satellite derived free-air gravity anomaly data of the Enderby Basin shows the presence of relatively short NNE trending fracture zones towards the east of the Crozet plateau, which run almost parallel to the trend of the Kerguelen FZ. These fracture zones express the northward motion of the Indian plate from late Cretaceous to early Tertiary period and they are also identified as conjugate features of 85°E FZ, 82°E FZ, 80°E FZ and 79°E FZ of the central Indian Basin. Two distinct sets of fracture zones are identified in the western Enderby Basin with one set trending in NNE-SSW direction north of Gunnerus Ridge extending into the Riiser-Larsen Sea which are more likely to belong to the Africa-Antarctica spreading system (Nogi et al., 1996; Jokat et al., 2003); and the other set consisting of five fracture zones trend in ~N4°E direction between the Enderby Land and the Kerguelen FZ (marked as white dashed lines in Figure 3.8). The fracture zones located north of Gunnerus Ridge are cut off by the NNW fracture zones which includes the Cretaceous Normal Superchron (CNS) crust which lies south of C34 isochron (Gaina et al., 2007). The fracture zones in the central Enderby Basin are found to be discretely converging to the Kerguelen FZ at an angle of about 37°.

CHAPTER 4

Analysis of Magnetic Anomaly Data of Conjugate Regions-Bay of Bengal and Enderby Basin

ANALYSIS OF MAGNETIC ANOMALY DATA OF CONJUGATE REGIONS-BAY OF BENGAL AND ENDERBY BASIN

Plate reconstruction studies carried out by several researchers (Lawyer et al., 1987; Scotese et al., 1988; Powell et al., 1988 and Yoshida et al., 1992) using tectonic constraints derived from sparsely distributed magnetic anomaly data, brought out plausible tectonic models for the breakup between the Eastern Continental Margin of India (ECMI) and East Antarctica. The reconstruction models proposed by Norton and Sclater (1979) indicate that the western margin of Australia was considered as conjugate margin to the northeast of Greater India (present-day Indian sub-continent and its northward extension believed to have consumed underneath the Asian plate) during the late Jurassic epoch. The Enderby Basin, Princess Elizabeth Trough and Davis Sea Basin on East Antarctica continental margin and its adjacent oceanic regions (Figure 1.5) may constitute key provinces for delineating the important tectonic constraints related to timing of rift initiation and orientation of breakup and early seafloor spreading between Antarctica and India. Unfortunately the regions were poorly explored, as of now only scanty geophysical data are available due to its inaccessibility and adverse weather conditions for field observations. The tectonic history related to breakup of Indian landmass from eastern Gondwanaland has still remained as a major riddle due to lack of adequate geological and geophysical data (Powell et al., 1988; Coffin, 1992; Grunow, 1999).

Various tectonic models were proposed for the timing of breakup of the Greater India from the eastern Gondwanaland and for the evolution of earliest oceanic lithosphere in the Bay of Bengal as well as in the Enderby Basin as magnetic and gravity signatures of both the regions do not provide unambiguous information. For example, in the Bay of Bengal, Ramana et al. (1994) and Gopala Rao et al. (1997) identified magnetic lineations as old as M11 and M0, respectively, whereas in the conjugate Enderby Basin region, Ramana et al. (2001) and Gaina et al. (2003, 2007) identified anomalies as old as M11 and pairs of anomalies M9Ny-M2o along with fossil ridge segment, respectively. In the present research work keeping these inconsistent interpretations in view, marine magnetic anomaly data together with gravity and seismic reflection data of both Bay of Bengal and Enderby Basin regions have been investigated in detail in order to identify the location of major seafloor spreading anomaly C34, segment of the oceanic crust formed during the Cretaceous Magnetic Quiet Period (120-83 Ma) and M-sequence anomalies closer to ECMI, if at all exists. The structural information such as Ninetyeast Ridge, 85°E Ridge, Comorin Ridge, fracture zones and isolated structures derived from satellite and ship-borne gravity data has been added to the Figure 4.1 to segregate the anomalies of the ocean floor contributed by the Earth's past magnetic reversals.

4.1 Magnetic Anomalies in the Distal Bengal Fan Region and the Bay of Bengal

The magnetic anomaly profiles of the Bay of Bengal and adjoining distal Bengal Fan region are analysed in detail to identify the seafloor spreading type anomalies, thereby to assign age constraints to the ocean floor. The magnetic anomaly data are plotted at right angles to the ship tracks and shown in Figure 4.1. The magnetic data of both distal Bengal Fan and Bay of Bengal regions are having typically high to moderate anomaly amplitudes ranging from 100 to 400 nT. From the magnetic anomaly map (Figure 4.1), it is observed that the anomalies in the equatorial region are well developed and seem to have good similarities in anomaly character, particularly in shape, amplitude and wavelength, on comparison from profile to profile.

The character of magnetic anomalies in the Bay of Bengal, particularly north of 6°N latitude is contrastingly differing from that of the anomalies observed in the equatorial region (Figure 4.1). Nearly N-NNW trending magnetic anomaly pattern consisting of significant positive and negative magnetic signatures is identified over the buried structural feature called the 85°E Ridge. Likewise short-segmented NE-SW trending significant magnetic low anomalies are observed over the features that lie between the oceanic fracture zones (exist at around 11° and 15°N latitudes in Figure 4.1). Apart from these, no significant coherent magnetic anomalies correlatable from profile to profile are observed in the Bay of Bengal region. There is a general view that thick-pile of pre-collision and post-collision sediments derived from east coast major rivers,

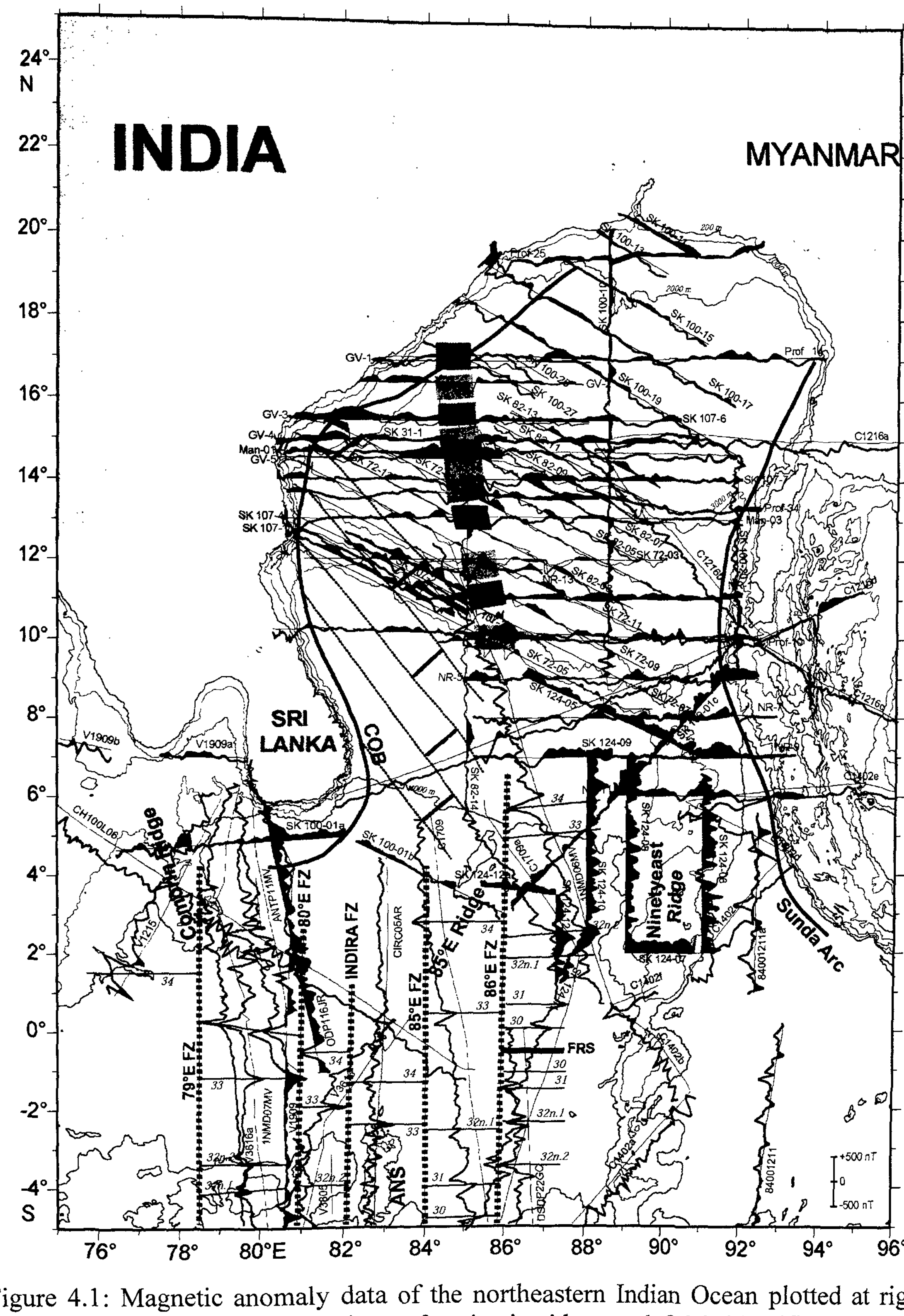


Figure 4.1: Magnetic anomaly data of the northeastern Indian Ocean plotted at right angles to the ship tracks. Locations of aseismic ridges and COB identified from the gravity data are shown. Spreading type lineations 30-34 are identified in distal Bengal Fan region. Fracture zones and structural highs identified in satellite gravity data are superimposed. At two locations (in the vicinity of 11° and 15°N latitudes), structural highs are associated with low magnetic anomalies.

Cauvery, Krishna, Godavari, Mahanadi, etc. and Ganges and Brahmaputra rivers from north have probably contributed to reduce the amplitudes of the magnetic anomalies.

4.1.1 Magnetic Lineations and Fossil Ridge Segment in the Distal Bengal Fan

Magnetic lineations are, in general, identified following the correlation of similar magnetic anomaly characters across the profiles and their dislocations are used for demarcation of oceanic fracture zones. Thus, the identification of magnetic lineations and fracture zones in oceanic regions is an important exercise for mapping the tectonic fabric of the ocean floor, thereby to proceed for reconstructing the lithospheric plates. Pairs of magnetic lineations on either side of central magnetic anomaly are commonly considered for interpretation of presence of fossil ridge segments, location for initiation of ridge axis jump, etc.

The magnetic anomaly profile data of the distal Bengal Fan are stacked and compared with the synthetic magnetic model profile with a purpose of identification of seafloor spreading type anomalies and fracture zones (Figure 4.2), thereby assigning age to the ocean floor of the distal Bengal Fan region. Earlier studies of (Cochran and Stow et al., 1989; Royer et al., 1991; Gopala Rao et al., 1997; Sarma et al., 1998) have suggested that the oceanic crust was formed due to northward motion of the Indian plate during the mid-Cretaceous to Paleocene period. The magnetic anomaly identifications of Krishna and Gopala Rao (2000) were taken into consideration to determine the half spreading rates and the magnetic polarities in order to calculate the synthetic magnetic model profile. Considering the magnetic reversals of this period and geomagnetic polarity time scale (Cande and Kent, 1995), a synthetic magnetic anomaly model profile was generated with half spreading rates of 4.1 to 7.5 cm/yr. The synthetic magnetic model has been generated using MATLAB based MODMAG algorithm (Mendel et al., 2005). It is user friendly based interface allows performing forward modeling of marine magnetic anomalies, which are resultant of several successive spreading periods with different spreading rates. The synthetic magnetic anomaly profile is generated and correlated to the magnetic anomaly profiles for the identification of seafloor spreading magnetic anomalies, thereby to assign a particular age to the oceanic crust. For the preparation of synthetic magnetic anomaly profile, the seafloor is divided into 500 m thick normal (solid) and reverse (open) polarity blocks with a magnetization of 0.01 A/m. The profile is generated normal to the ridge striking east–west and with a paleo-latitude of 40°S.

The magnetic anomaly sequence in model profile, particularly anomalies 30 through 32n.2, has characteristic shapes (see Figures 4.1 and 4.2) generated by an unique arrangement of short-period reversed geomagnetic polarities. These distinctive anomaly shapes and patterns are considered as reference picks for the correlation of observed anomalies to model profile. With this approach, most of the anomaly correlations have gained reasonably high confidence. A comparison of the magnetic profiles (V1215, V3616-a, INMD07MV, ANTP11M, V1909, ODP116JR, V3616-b, V3305, CIRC05AR, V1709, DSDP22GC, V1709-a, and INMD06MV) with synthetic model profile allows the identification of seafloor spreading type anomalies 30 through 34 (Figure 4.2), and lack of correlatable anomalies north of magnetic anomaly 34 indicates the presence of part of the oceanic crust evolved during the Cretaceous Magnetic Quiet Period (CMQP). The anomalies 30 to 34 are correlated from profile to profile to delineate magnetic lineations. The lineations are found dislocated in different lateral senses, outlining the existence of five N-S trending fracture zones of three right-lateral offset and two left-lateral (Figure 4.1). They are 79°E FZ, 80°E FZ, Indira FZ, 85°E FZ, and 86°E FZ with offsets of about 160, 90, 100, 480 and 220 km, respectively. The 85°E FZ acts as a boundary separating the oceanic crust with different magnetic isochron patterns.

The profiles north of magnetic lineation 34 are, in general, devoid of significant and correlatable anomalies, indicating that this oceanic crust was formed during the Cretaceous Long Normal Polarity Chron, prior to 83 Ma (Figure 4.1). The profile, CIRC 05AR running along the Afanasy Nikitin seamount (ANS) shows low-amplitude, short-wavelength anomalies that are superimposed on the spreading type anomalies 33 and 34 (Figure 4.1). Perhaps the superimposed anomalies have developed due to the volcanic activity associated with the evolution of the ANS. Careful examination of magnetic profiles that run between the 86°E FZ and the Ninetyeast Ridge revealed pairs of anomalies 30, 31, 32n.1, and 32n.2 and fossil ridge segment (Figures 4.1 and 4.2). The interpreted fossil ridge segment runs parallel to ~0.5°S latitude. Therefore it is

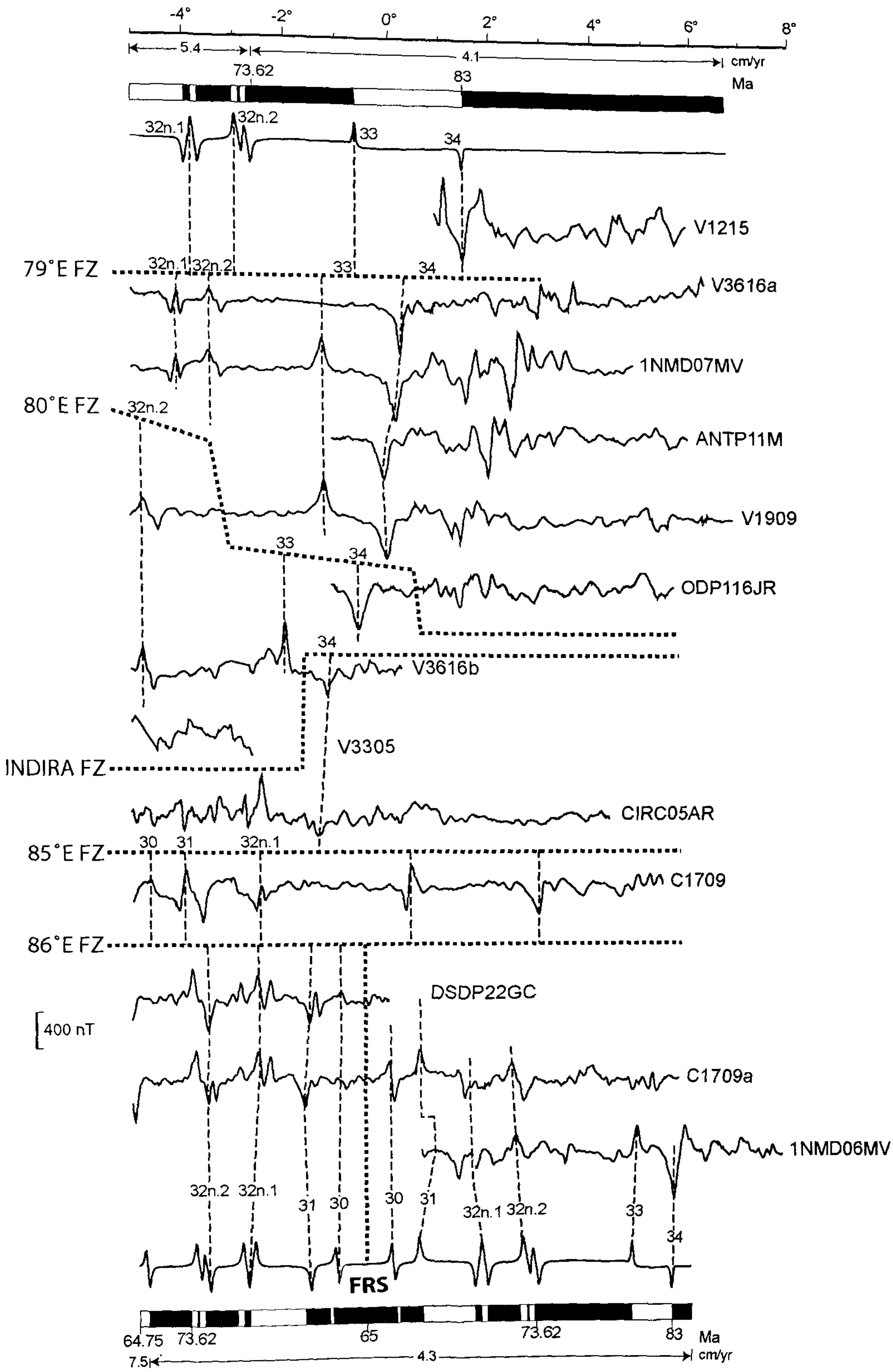


Figure 4.2: The magnetic anomalies of the northeastern Indian Ocean are plotted and correlated with the synthetic magnetic profiles. Cretaceous Magnetic Quiet Period and magnetic lineations 30-34 are marked. The geomagnetic polarity time scale of Cande and Kent (1995) was used for assigning the age of magnetic anomalies. Half spreading rates varying from 4.1 to 7.5 cm/yr, in north-south direction, are used in the calculations.

interpreted that during the evolution of the lithosphere in the central Indian Basin, the spreading center east of the 86°E FZ ceased its activity after formation of anomaly 30 and jumped southward between anomalies 32n.2 and 33. The seismic reflection data along the profile AS10-05 published by Krishna and Gopala Rao (2000) clearly demonstrate the structure of the fossil ridge segment as an undulating basement topographic rise (Figure 4.3). The profile location is shown in Figure 3.4 in Chapter-3. It clearly shows that the ridge segment is presently buried under approximately 2 km thick Bay of Bengal sediments.

4.1.2 Magnetic Signatures of the 85°E Ridge

The 85°E Ridge an enigmatic structural feature in the northeastern Indian Ocean, extends in near N-S direction from the Mahanadi Basin in the north, takes an arcuate shape off southeast Sri Lanka and finally joins the ANS in the south. Absence of age details from the 85°E Ridge either by deep-sea drilling or by geophysical studies led several researchers to postulate quite a few theories for the origin of the ridge. Earlier works carried out by researchers on this ridge have been discussed in detail in Chapter-1. Among the hypotheses listed for the evolution of the ridge, hot spot hypothesis is the one provides better convincing explanations for all anomalous geophysical characters and this will be discussed in detail in Chapter-7.

The E-W magnetic profiles that run across the 85°E Ridge are selected to investigate the magnetic response of the ridge (Figure 4.4). In addition the magnetic data over the 85°E Ridge are also contoured with an interval of 50 nT (Figure 4.5). Keeping the 85°E Ridge track observed from gravity and seismic data as a reference, magnetic profile data (Figure 4.4) and magnetic anomaly contour data (Figure 4.5) have been examined in order to identify the ridge's magnetic signatures. It is found that the ridge is associated with alternate stripes of strong positive and negative magnetic signatures, whose amplitudes range from -400 to 350 nT. For the first time suites of five each high amplitude positive and negative magnetic anomalies covering asymmetrical extents are observed along the 85°E Ridge track (Figures 4.4 and 4.5).

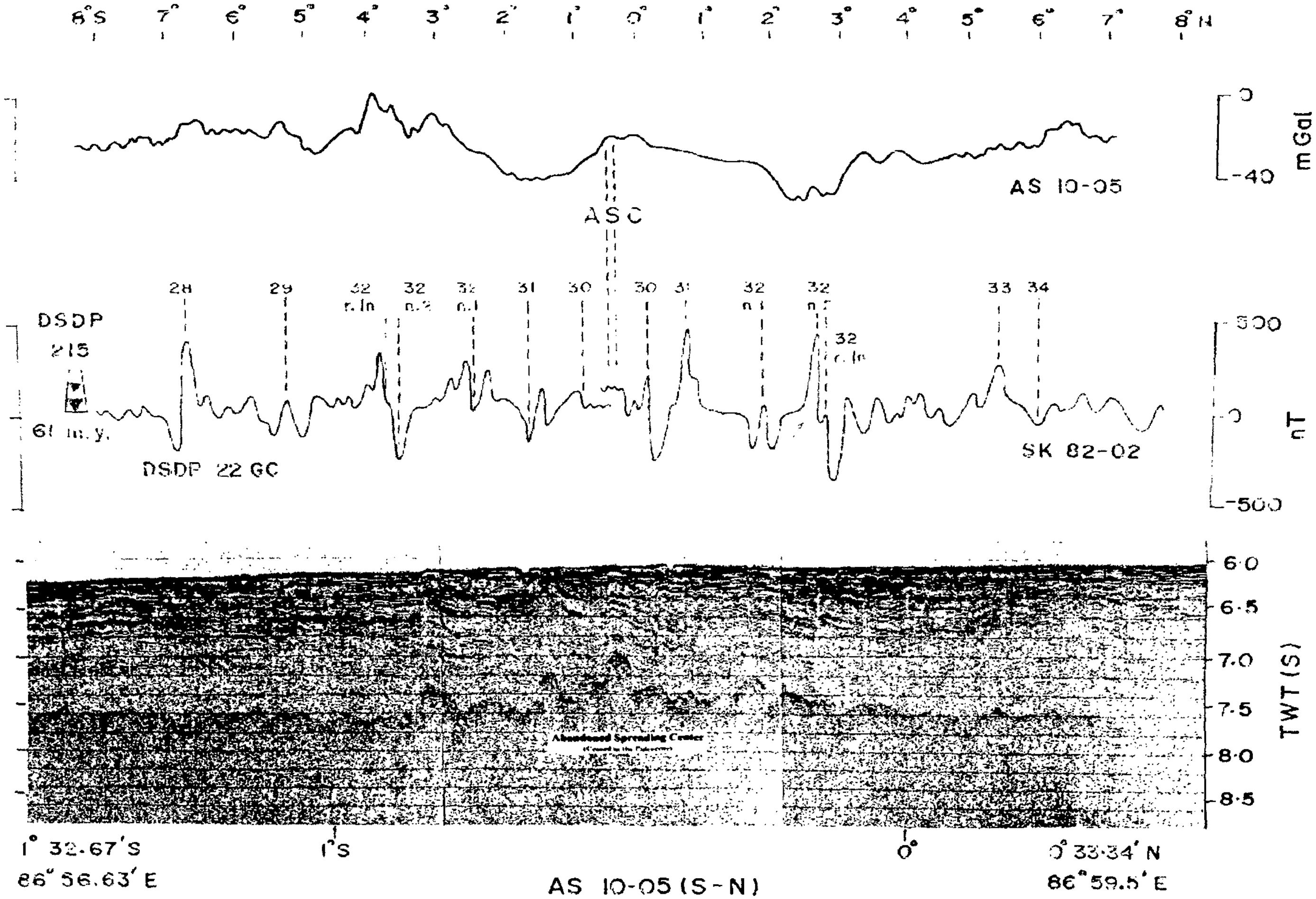


Figure 4.3: Seismic reflection section of the fossil ridge segment with identified magnetic anomalies and gravity data (after Krishna and Gopala Rao, 2000).

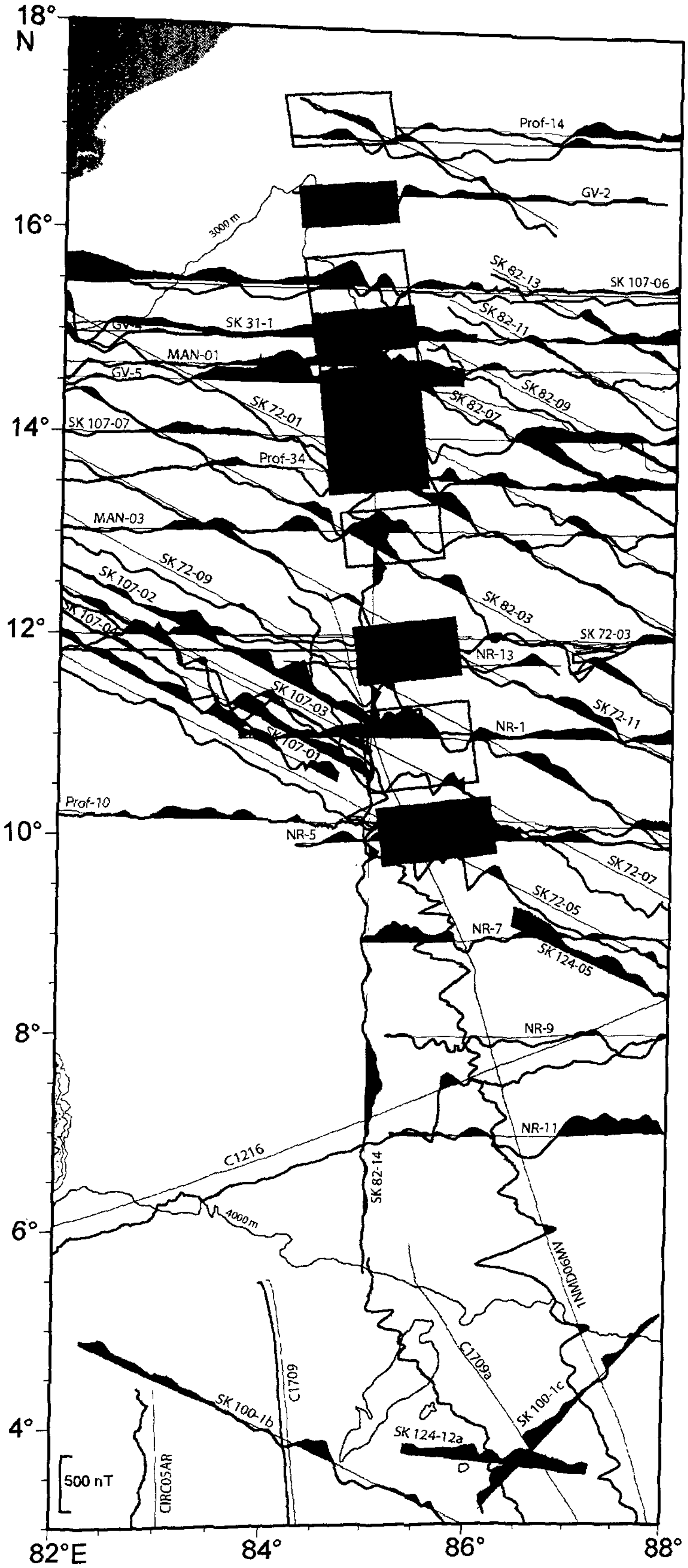


Figure 4.4: The 85°E Ridge in the Bay of Bengal region is associated with suits of high-amplitude positive and negative magnetic anomalies. The boxes with yellow colour indicate the ridge's positive magnetic signature, whereas those with green colour indicate the ridge's negative magnetic signature.

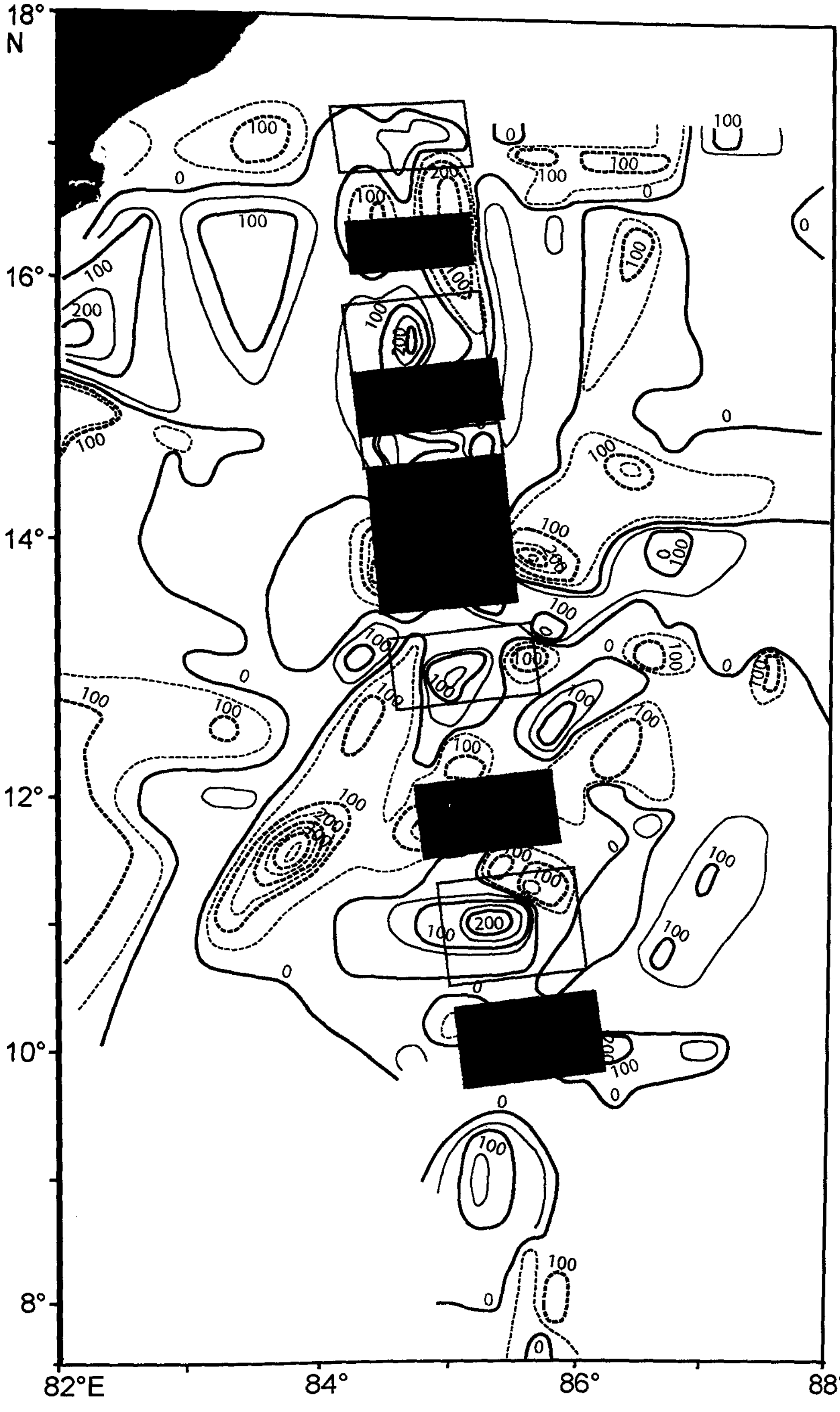


Figure 4.5: The magnetic anomaly contour data of the 85°E Ridge in the Bay of Bengal. Contour interval is 50 nT. Bands of high-amplitude positive and negative anomalies are marked by yellow and green coloured boxes, respectively. Light-gray coloured broad-path marks the location of the 85°E Ridge structure derived from gravity and seismic results.

4.1.3 Other Significant Magnetic Anomalies in the Bay of Bengal

In addition to the identification of magnetic lineations (C34 through C30) in the distal Bengal Fan region and suites of significant positive and negative magnetic anomalies associated with the 85°E Ridge, a small extent NE-SW trending significant negative magnetic anomalies are observed between the oceanic fracture zones (exist at around 11° and 15°N latitudes in Figure 4.1). These negative magnetic anomalies are well coinciding with the isolated features or fossil ridge segments interpreted from the free-air gravity data. Besides, no other recognizable and correlatable magnetic anomalies from profile to profile are apparently observed in the Bay of Bengal region. Some researchers have the opinion that the thick pile of sediments increasing up to 22 km towards Ganges mouth may probably have altered the original character of the magnetic anomalies.

4.2 Magnetic Anomalies of the Enderby Basin

The magnetic anomaly profile data of the Enderby Basin on East Antarctica continental margin are also analysed as this region is generally believed to be conjugate part of the oceanic crust lying adjacent to the ECMI. Identification of magnetic anomalies and fracture zones in both conjugate regions, based on their similarities and variations, may bring out the tectonics associated with the rifting of the eastern Gondwanaland fragments and early spreading history including multiple split of continental fragments and ridge jumps, etc.

The magnetic anomaly profiles extracted from NGDC and from published domain (Gaina et al., 2007), are studied in the present work. The data are plotted at right angles to the ship tracks and shown in Figure 4.6. The magnetic data of the Enderby Basin are, in general, having significant high-amplitude anomalies ranging from -1000 to 600 nT. It is further observed that the anomalies in the western Enderby Basin have relatively low-amplitude anomalies and generally agree with the interpretation of Gaina et al. (2007). While the central Enderby Basin consists of high-amplitude magnetic anomalies, perhaps the region may have influenced by the volcanic activity of the Kerguelen hot spot during its initial stages. Close to the margin, off Enderby Land prominent high-amplitude magnetic anomaly followed by a negative magnetic anomaly to the south is observed on profiles C1704 (1), Th-99a (d) and Th-99b (f) (Figure 4.6). Earlier Gaina et al. (2003) have termed this anomaly as MacRobertson Coast Anomaly (MCA) and indicated as a signature associated with the continent-ocean boundary. The most notable observation from magnetic studies of both Bay of Bengal and Enderby Basin regions is that no resemblance seems to be appearing in anomaly signatures, particularly in shapes, amplitudes and correlations from profile to profile.

4.2.1 Magnetic Lineations and Fossil Ridge Segments

Similar to the exercise of analysis of magnetic anomaly data carried out in the Bay of Bengal and distal Bengal Fan regions, magnetic anomaly profile data of the entire Enderby Basin are also analysed with a purpose of identification of seafloor spreading type anomalies and fracture zones (Figures 4.7 and 4.8), thereby assigning age to the ocean floor of the Enderby Basin region. Earlier studies (Müller et al., 2000; Royer and Coffin, 1992) have indicated that lack of adequate marine geophysical data in the Enderby Basin had led to the suggestion that the rifting process started in northwest Australia in the late Jurassic, which subsequently propagated southward and separated India from Australia - Antarctica landmass at about 120 Ma. Thus the Enderby Basin has been considered as a late early Cretaceous oceanic basin, underlained by oceanic crust formed during the Cretaceous Magnetic Quiet Period (120 – 83 Ma). Subsequent geophysical studies of the Enderby Basin (Ramana et al., 2001; Nògi et al., 2004; Gaina et al., 2007; Jokat et al., 2010) suggested that the oceanic crust in the basin was evolved prior to the Cretaceous Magnetic Quiet Period. In view of these interpretations a synthetic magnetic anomaly profiles were generated with half spreading rates varying from 0.8 to 3.9 cm/yr and using geomagnetic polarity time scale of Gradstein et al. (1994). It is assumed that the oceanic crust was magnetised with a paleo-latitude of 55°S.

The magnetic anomaly sequence in model profile, particularly anomalies closer to M9Ny, shows significant characteristic shapes (see Figures 4.7 and 4.8), which are generated by an unique arrangement of short period reversed geomagnetic polarities. These distinctive anomaly shapes and patterns are considered as reference picks for the correlation of observed anomalies to model profile. With this approach most of the

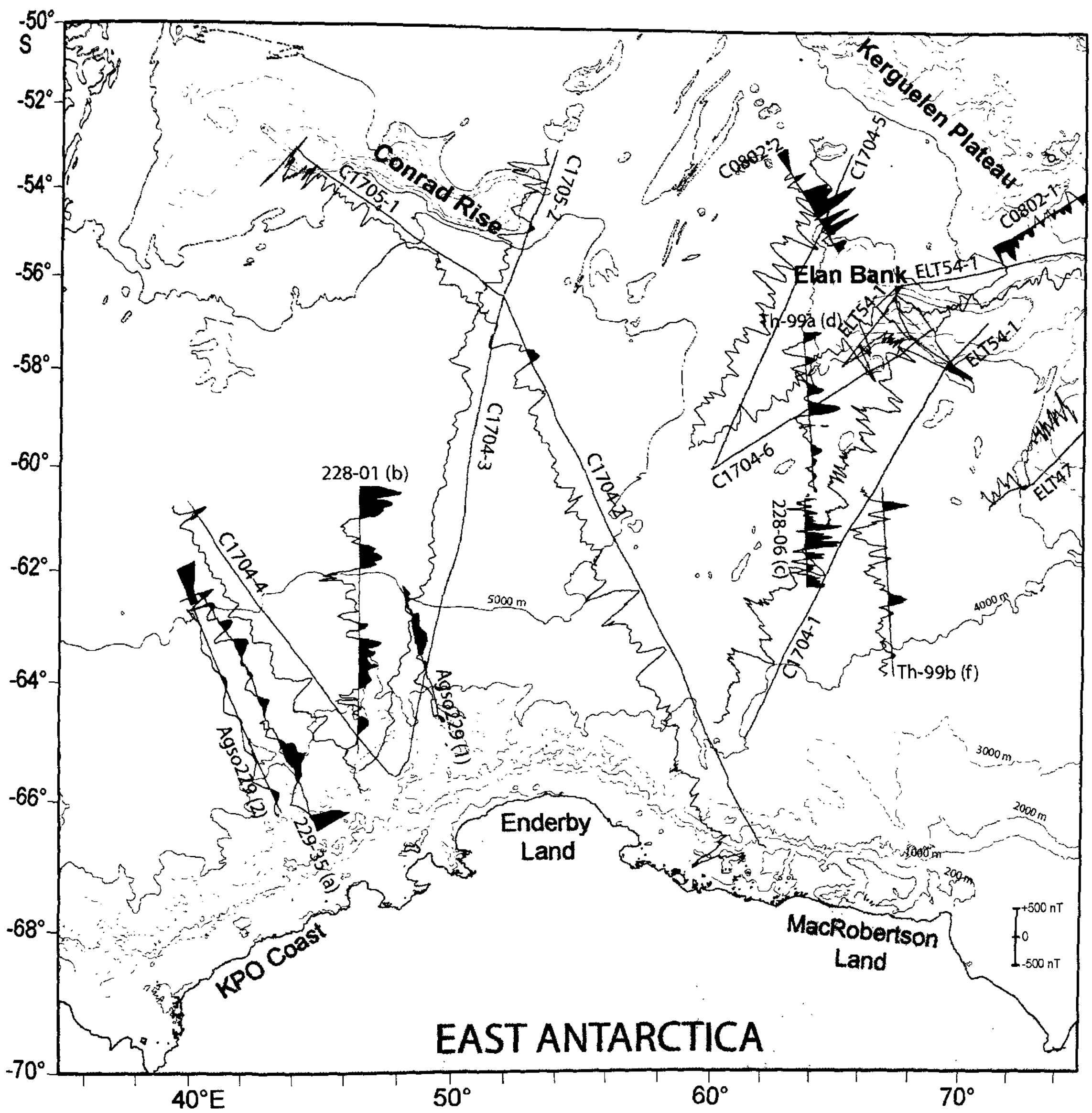


Figure 4.6: Magnetic anomaly data of the Enderby Basin plotted at right angles to the ship tracks. Variable bathymetric contours (200, 1000, 2000, 3000, 4000 and 5000 m) are shown to indicate the physiography of the region.

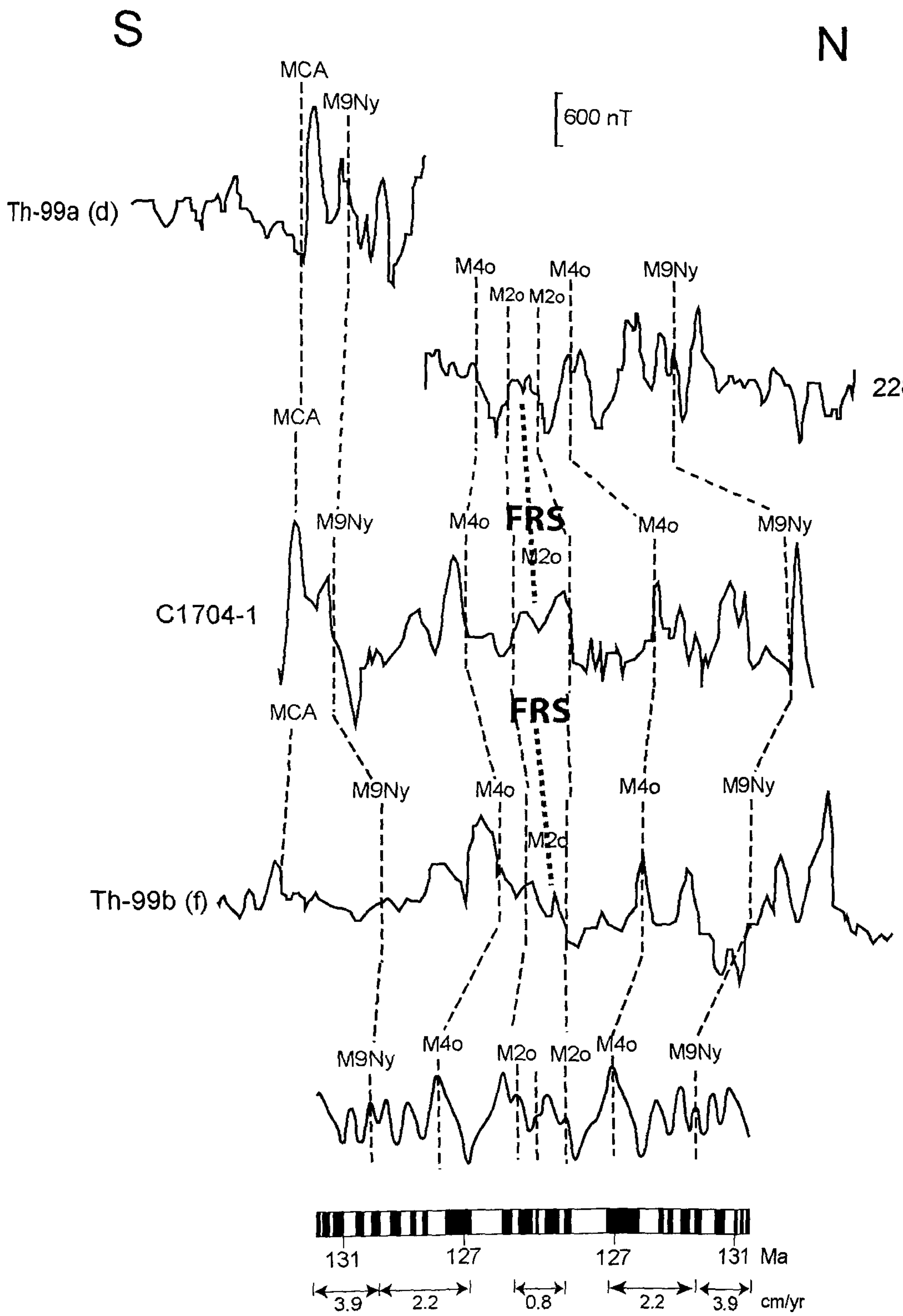
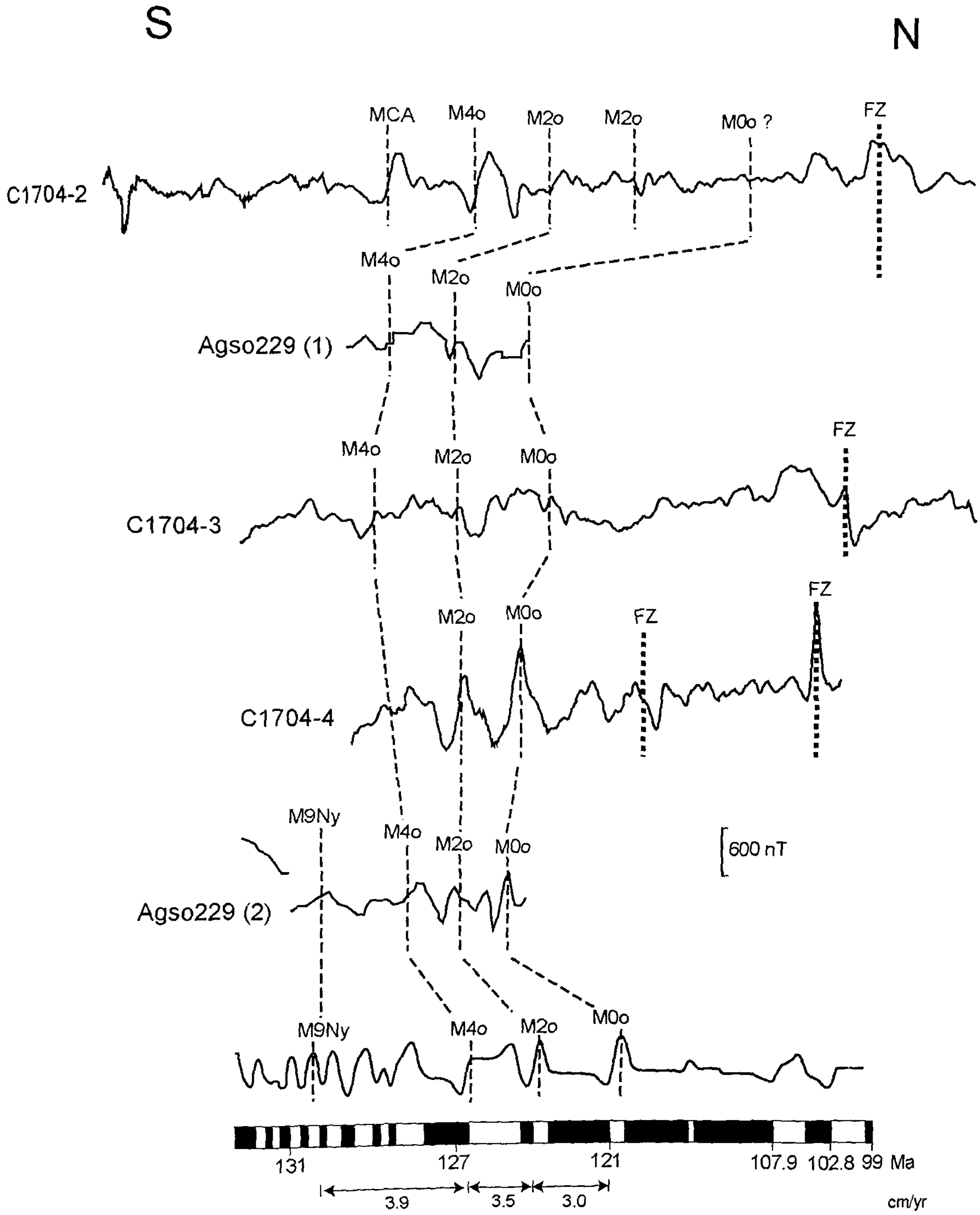


Figure 4.7: The magnetic anomaly profiles of the East Antarctic margin between the MacRobertson Land and Elan Bank are correlated with the synthetic model profile computed following the geomagnetic timescale of Gradstein et al. (1994). MCA indicates MacRobertson Land Coast Anomaly. Locations of the profiles are shown in Figure 4.6.



Figures 4.8: The magnetic anomaly profiles from the western Enderby Basin region are correlated with the synthetic model profile computed following the geomagnetic timescale of Gradstein et al. (1994). Locations of the profiles are shown in Figure 4.6.

correlations have gained reasonably high confidence. A comparison of the magnetic anomaly profiles of the central Enderby Basin (Th-99a (d), 228-06 (c), C1704-1 and Th-99b (f)) with the generated synthetic model profile helps in identification of M-sequence seafloor spreading type anomalies M2o through M9Ny (Figure 4.7).

In the region between the MacRobertson Land and Elan Bank the youngest magnetic anomaly is identified as M2o and this is characterized by low-amplitude magnetic anomaly signature. The anomaly peaks are separated by a trough, which is seen on most of the profiles. The oldest magnetic anomaly identified as M9Ny, is characterized by high-amplitude, narrow magnetic anomaly peak, which lies northward of the MacRobertson Land Coast Anomaly (MCA) as seen on profiles Th-99a (d), C1704-1 and Th-99b (f) along the southern flank. Towards the northern part along the profiles C1704-1 and 228-06 (c) the identification of the magnetic anomaly M9Ny is difficult.

The reason for the absence of magnetic anomaly M9Ny in the northern region may be because of the proximity of the Kerguelen plateau and the influence of the volcanic intrusions. The anomalies M2o through M9Ny are correlated from profile to profile to delineate magnetic lineations. On close scrutiny of the profiles, 228-06 (c), C1704-1 and Th-99b (f) (Figure 4.7) show pairs of magnetic anomalies M4o through M9Ny on each side of the fossil ridge segment, which has been interpreted as anomaly M2o or probably younger anomaly to M2o. This clearly suggests that the seafloor spreading activity in the central Enderby Basin has become extinct sometime between M2o and M0 due to the northward ridge jump as a result of the Kerguelen plume activity. The interpretations are well coinciding with the results of Gaina et al. (2007).

A comparison of magnetic anomaly profiles of the western Enderby Basin (C1704-2, Agso229 (1), C1704-3, C1704-4 and Agso229 (2)) with the generated synthetic model profile helps in identification of seafloor spreading type anomalies M0 through M9Ny, (Figure 4.8). The magnetic anomaly M0 through M4o is correlated in most of the profiles, while along few profiles M0 through M9Ny are identified. Along the profiles Agso229 (1), Agso229 (2) and C1704-3 prominent anomalies having high-amplitudes are identified as M0 and M2o, while the moderately developed anomaly is identified as M4o (Figure 4.8). The profiles C1703-3 and C1703-4 show chaotic and more subdued magnetic anomalies north of magnetic anomaly M0 (younger to the age of anomaly M0). The subdued anomalies may possibly have generated from the oceanic crust evolved during the Cretaceous Normal Superchron (CNS) and this region is identified as CNS.

In earlier studies Gaina et al. (2007) have concluded that the magnetic anomalies in the western Enderby Basin have generally lower amplitude, hence they could not correlate the seafloor spreading history with that of central and eastern Enderby Basin regions. Therefore it can be interpreted that northward ridge jump may have occurred only in the central and eastern Enderby Basin regions due to the proximity of the Kerguelen hot spot, whereas seafloor spreading continued in the western Enderby Basin even after 124 Ma.

CHAPTER 5

Study of Geophysical Data of Conjugate Regions-Bay of Bengal and Enderby Basin

5.1 Mapping of Fracture Zones in the Bay of Bengal

5.2 Mapping of Fracture Zones in the Enderby Basin

5.3 Comparison of Gravity and Magnetic Signatures of Conjugate Regions

5.4 Two-Dimensional Modeling of Gravity Profiles in the Bay of Bengal and the Enderby Basin

5.5 Correlations of Fracture Zones off South ECMI and Enderby Land Margin

5.6 New Constraints on Breakup and Early Spreading History between India and Antarctica

5.7 Breakup of India from Antarctica

STUDY OF GEOPHYSICAL DATA OF CONJUGATE REGIONS - BAY OF BENGAL AND ENDERBY BASIN

Sparsely available geophysical data and lack of reliable identification of tectonic elements in both Bay of Bengal and Enderby Basin regions led to equivocal interpretations on rift initiation of Greater India from contiguous Antarctica - Australia landmass. Therefore understanding of rifting process and early evolution of oceanic lithosphere from both conjugate regions has remained inconclusive. Even fairly detailed geophysical studies carried out by Ramana et al. (1994) and Gopala Rao et al. (1997) in the Bay of Bengal and by Ramana et al. (2001) and Gaina et al. (2003, 2007) in the Enderby Basin as well could not provide unique tectonic models for the rift-drift processes and for evolution of early spreading activity. As discussed in the earlier chapter, two Mesozoic anomalies M11 and M0 are suggested as oldest noticeable spreading type magnetic chrons in the Bay of Bengal, whereas in the Enderby Basin, particularly in the central region M11 to M0 and pairs of anomalies from M2o to M9Ny are reported.

Keeping in view of inconsistent magnetic interpretations of both conjugate regions, the present research work is focused on investigation of geoid, free-air gravity anomaly and seismic data and re-examination of complied magnetic anomaly data in order to obtain useful plate tectonic constraints such as magnetic chrons, oceanic fracture zones, fault patterns in the vicinity of margins, continent-ocean boundary, etc. In the present study, oceanic fracture zones have been delineated in both Bay of Bengal and its conjugate region Enderby Basin for the first time with great confidence, and they are expected to provide new insights for the improvement of lithospheric plate reconstructions and for assembling of the Eastern Continental Margin of India (ECMI) with the East Antarctic continental margin. Also two representative geophysical profiles each from the central Enderby Basin and from the Bay of Bengal are presented (Figures 5.1 and 5.2) for comparing the seismic structure and geophysical signatures and for discussions.

5.1 Mapping of Fracture Zones in the Bay of Bengal

The gravitational attraction caused by the morphological and tectonic features, in general, distorts the normal gravity field of the region. Therefore the gravity tool, particularly satellite derived gravity data, can effectively be used for mapping the oceanic fracture zones, fossil ridge segments, etc. Analysis of high-resolution satellite derived free-air gravity anomaly data of the Bay of Bengal (discussed in Chapter-3) has revealed the signatures contributed by the ocean floor topography and subsurface features lying within the crust and mantle, in greater detail than it was revealed previously.

Satellite derived free-air gravity image map of Bay of Bengal (Figure 3.3) reveal the presence of five NW-SE trending narrow gravity features between the south ECMI and the 85°E Ridge. The features trend in ~N36°W direction, are interpreted as earliest oceanic fracture zones formed soon after the completion of rifting process (for more details see Chapter-3). Towards the immediate southeast of the 85°E Ridge the gravity anomaly image shows two prominent nearly N-S trending fracture zones, 85°E FZ and 86°E FZ and their northward continuity is seen in the Bay of Bengal up to 6°N and 9°N latitudes, respectively (Figure 3.3). From the alignment of fracture zones derived from the satellite gravity anomaly map, it has been observed that the fracture zones of the western Basin (west of the 85°E Ridge) meet the N-S oriented 86°E FZ with an angle of ~39°. In addition a significant negative residual geoid, gravity and magnetic signatures are found oriented in NE-SW direction between the fracture zones identified in the western Basin. These features are interpreted as structural highs lying orthogonal to the fracture zones and may either represent fossil ridge segments which possibly have become extinct during the early evolution of the Bay of Bengal lithosphere or may have formed later by the volcanic activity which accreted the 85°E Ridge. It is further envisaged 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. Therefore, NE-SW trending structural highs are considered as fossil ridge segments ceased during the Cretaceous Magnetic Quiet Epoch. The postulation, however, needs to be validated with additional geophysical observations. There is an important point to notice that no fracture zones traces are obviously noticed on north ECMI region, because the region was evolved in different tectonic settings and/ or the convergence of continental margin with the 85°E Ridge structure may have obliterated the fracture zones signatures.

5.2 Mapping of Fracture Zones in the Enderby Basin

The geoid data of the Enderby Basin revealed three distinct patterns separated by N-S oriented narrow structural boundary features, their northward continuity is seen merging with NE-SW trending Kerguelen Fracture Zone (FZ) (Figure 3.8). The geoid patterns in western and central Enderby Basins trend in NE-SW, N-S and NW-SE directions and indicate the pathways of rifting and drifting from segment to segment between Greater India and East Antarctica landmasses. Free-air gravity image of the Enderby Basin region further brought out details of the presence of different oriented fracture zone sets as signatures of narrow gravity features (Figure 3.8). On east of the Crozet plateau and north of the Conrad Rise, four NE-SW trending relatively short fracture zones have been mapped, which run almost parallel to the trend of the Kerguelen FZ. These fracture zones reveal the direction of past Indian plate motions held from late Cretaceous to early Tertiary period, and the features are also interpreted as conjugate features of 85°E FZ, 82°E FZ, 80°E FZ and 79°E FZ of the central Indian Basin. Close to the margin, particularly off Gunnerus Ridge and Enderby Land two distinct sets of fracture zones have been mapped with one set trending in NNE-SSW direction north of Gunnerus Ridge extending into the Riiser-Larsen Sea, which are more likely to belong to the Africa-Antarctica spreading system (Nogi et al., 1996; Jokat et al., 2003); and the other set consisting of five fracture zones trend in ~N4°E direction found to lie between the Enderby Land and the Kerguelen FZ (Figure 3.8). From the geometry of fracture zone sets, it has been observed that the fracture zones off Enderby Land are discretely converging to the Kerguelen FZ at an angle of ~37°.

5.3 Comparison of Gravity and Magnetic Signatures of Conjugate Regions

The magnetic anomalies in the distal Bengal Fan region are well developed with E-W correlations from profile to profile, 30 through 34, while in the Bay of Bengal, particularly close to the ECMI no coherent magnetic anomalies that were caused by the Earth's magnetic reversals are observed. This suggests that magnetic lineations related to the M-sequence anomalies are also not obviously seen in the Bay of Bengal.

Therefore from this study, it can be robustly believed that most part of the oceanic crust in the Bay of Bengal was created during the Cretaceous Long Normal Polarity period. In order to validate this inference, a detailed study of geophysical signatures recorded in both Bay of Bengal and Enderby Basin regions was carried out. As an example two best profiles each from Enderby Basin and Bay of Bengal, consisting of magnetic, gravity and seismic results are shown for the discussions of evolution of earliest oceanic lithosphere.

For the Enderby Basin region the geophysical data acquired along the profiles 228-06 (c), Th99a (d) and line 179-05 have been joined together (Figure 5.1). The basement structure and sediment thickness data are extracted from the published results of Borissova et al. (2003) and Stagg et al. (2004), magnetic anomaly results are obtained from Gaina et al. (2007) and gravity data are derived from the satellite gravity database of Sandwell and Smith (1997). Whereas for the Bay of Bengal region seismic, gravity and magnetic data acquired along the profile SK 107-06 (run along 15.5°N latitude) are used for the analysis. Detailed seismic results along this profile are presented in Chapter-7 as part of discussion of 85°E Ridge structure. Integrated geophysical data along the two profiles of both the regions are shown in Figure 5.2.

As observed by Gaina et al. (2003, 2007), pairs of magnetic lineations, M9o (~130.2 Ma) through M2o (~124.1 Ma) on either side of magnetic anomaly are identified in the central Enderby Basin between MacRobertson Land and Elan Bank. The central magnetic anomaly is interpreted as fossil ridge segment and suggested that spreading activity has ceased after formation of anomaly M2o or possibly closer to M0 time (~120 Ma). The interpreted M-sequence anomalies and fossil ridge segment are shown in Figure 5.2 (left part). While in the Bay of Bengal region along the profile (SK 107-06), no magnetic anomaly signatures related to the past Earth's magnetic reversals or equivalent to the central Enderby Basin anomalies are observed (Figure 5.2).

A prominent structural high called Elan Bank exists on north of the spreading anomaly sequence M2o through M9o in the central Enderby Basin and on west of the Kerguelen plateau (Figure 5.1), has been investigated with seismic data and deep-sea drilling results. The stratigraphic results of the Elan Bank obtained from the ODP Leg 183 drill

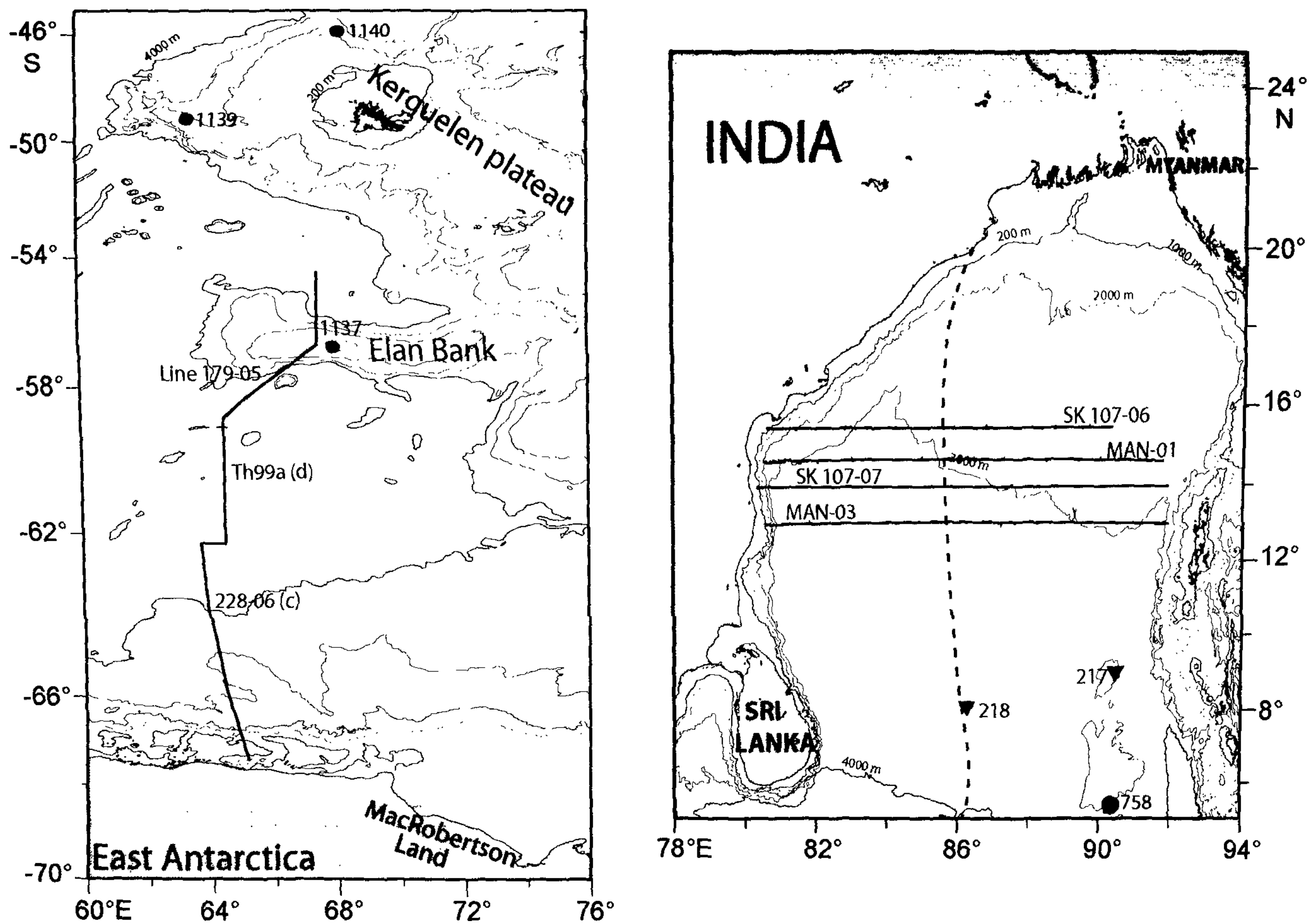


Figure 5.1: Track map of the profiles 228-06 (c), Th99a (d) and line 179-05 extending from MacRobertson Land to Elan Bank in the Enderby Basin and profiles SK 107-06, MAN-01, SK 107-07 and MAN-03 in the Bay Bengal used for crustal model studies.

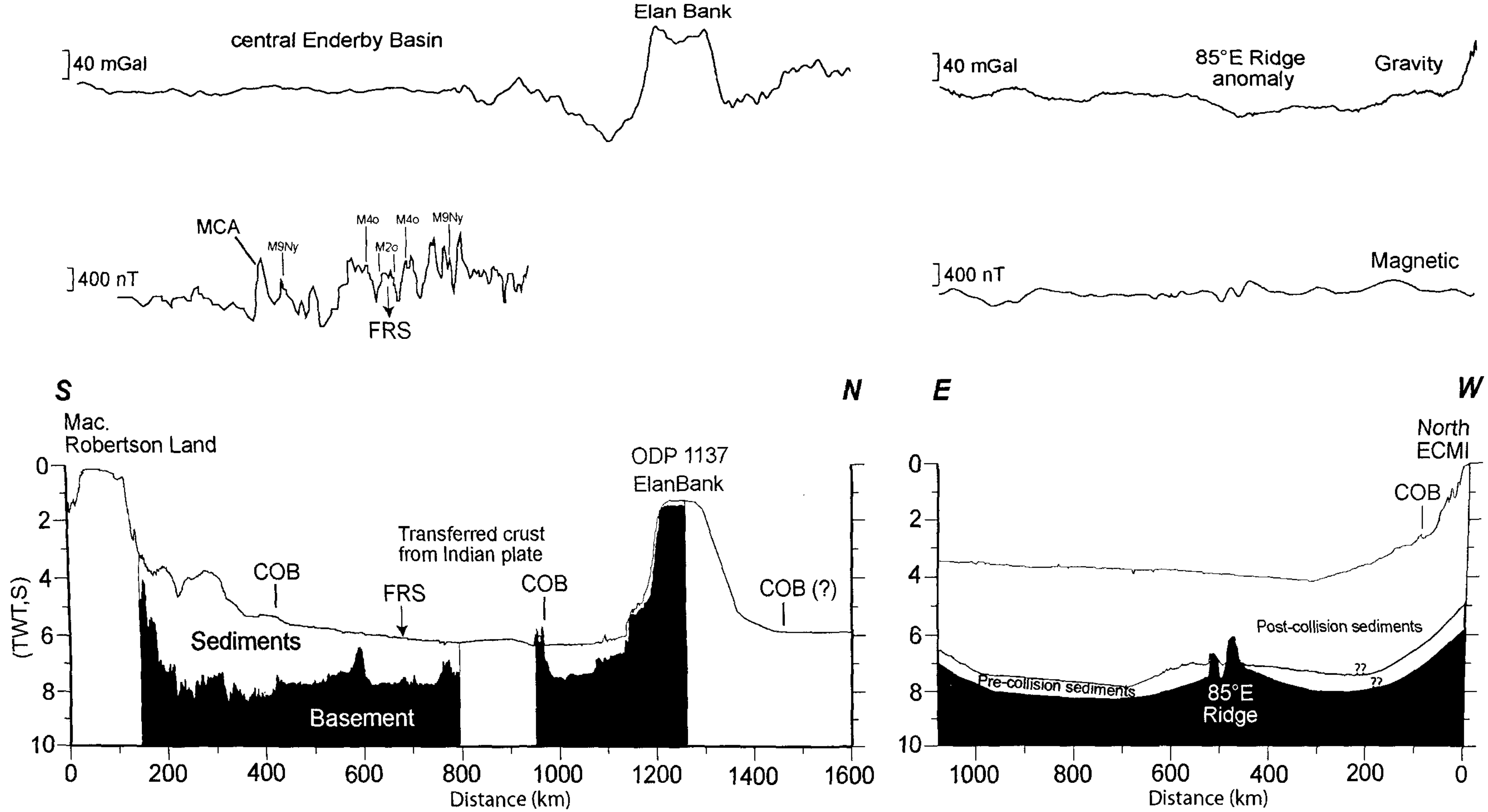


Figure 5.2: Gravity and magnetic data; basement structure and sediment thickness information from MacRobertson Land to Elan Bank and from Ninetyeast Ridge to ECMI are shown together to present early spreading history between east Antarctica, Elan Bank and India. MCA and FRS indicate MacRobertson Coast Anomaly and fossil ridge segment in central Enderby Basin. Locations of profiles are shown in Figure 5.1.

well (Site 1137) suggest that about 152 m thick basement rock samples were recovered in 10 basement units (Coffin et al., 2000) (Figure 5.3). Among the basement units the rock samples at unit 6 consist of clasts of garnet-biotite gneiss in a fluvial conglomerate intercalated with basaltic flows. The clasts within the conglomerate of unit 6 varies from pebble to cobble sized (with an average of pebble size range of 1.5 cm x 2 cm x 3 cm x 5 cm) (Figure 5.4) and has variable lithology including alkali basalt, rhyolite, granitoid and garnet bearing gneiss. Following the stratigraphic results of the ODP Site 1137 on the Elan Bank Nicolaysen et al. (2001), Weis et al. (2001) and Ingle et al. (2002) have suggested the continental origin to the bank.

From seismic profile (Line 179-06) data on correlation to drill results of ODP Site 1137 on the Elan Bank, Borrisova et al. (2003) have interpreted that the igneous basement consists of brecciated and massive basalts and they were dated as 107.7 Ma (Duncan, 2002). The basement is overlain by Campanio glauconitic sandy packstone and nannofossil pelagic oozes having ages from late Eocene to Pleistocene (Figure 5.5). In another study Nicolaysen et al. (2001) have reported that the volcaniclastic conglomerate, which has been recovered within the upper part of the basement complex (shown the horizon with blue colour in Figure 5.5) contains clasts of garnet-biotite gneiss. Coffin et al. (2000) and Frey et al. (2000) have opined that the conglomerate was formed due to a local source and had been deposited in a braided river environment, which also clearly suggests the rocks are of continental origin.

The crustal velocity model based on the travel times of seismic arrivals long the five OBS record stations along Line 179-06 (Borrisova et al., 2003) is considered to understand the crustal thickness and velocities of the layers. The sedimentary layer with a velocity of 2.10 km/s has been calculated by Borrisova et al, (2003) (as shown in Figure 5.6). The next phase is refracted in the upper igneous crust where velocities vary from 4.4 - 4.9 km/s at the top to 5.2 - 5.9 km/s at the base. The wide-angle seismic studies across the Elan Bank and its adjacent Enderby Basin region reveal the presence of 3 km thick upper igneous crust with seismic velocities ranging from 4.4 - 5.9 km/s. This layer on correlation to ODP Site 1137 results, confirms the presence of sub-aerial basaltic lave flows (Coffin et al., 2000; Frey et al., 2000). The next phase is refracted from the lower crust where seismic velocities range from 6.0 km/s at the top to 6.7 km/s at the base of the layer, whereas the seismic velocities reach upto 6.9 km/s beneath stations OBS 2 (Figure 5.6). From the velocity model it is found that the lower crust of Elan Bank is of 14 km thick and has velocities as low as 6.6 km/s at a depth of 18 km. This low velocity is generally not found in oceanic plateaus, where the lower crust always exhibits high velocity material (Coffin and Eldholm, 1994). Charvis et al. (1995) have reported that the lower crust of the northern Kerguelen plateau has velocities reaching up to 7.2 - 7.4 km/s. Operto and Charvis (1995, 1996) have inferred that the low velocity of 6.7 km/s in the lower crust of Raggatt Basin in the southern Kerguelen plateau has been interpreted as thinned continental crust. Based on these seismic velocity results it can be proposed that the low velocity lower crust in the Elan Bank clearly supports the continental origin of the crust (Borrisova et al., 2003). In the velocity model, two reflections R3 and R4 are at depths of 12.5 km and 18 km with a constant velocity of 6.65 km/s in the lowermost crust, where the reflector R4 is identified as the Moho.

Based on seismic and drilling results discussed above an inference has been drawn that gneiss clasts of the Elan Bank shows an affinity to crustal rocks from Indian continent, particularly those of the Eastern Ghats Belt. 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 5.2). The ridge jump placed the Kerguelen hot spot in Antarctica plate for emplacement of the Kerguelen plateau.

Keeping these geological sequences in view, it can be robustly believed 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 5.2) and beneath the central and northern Kerguelen plateau.

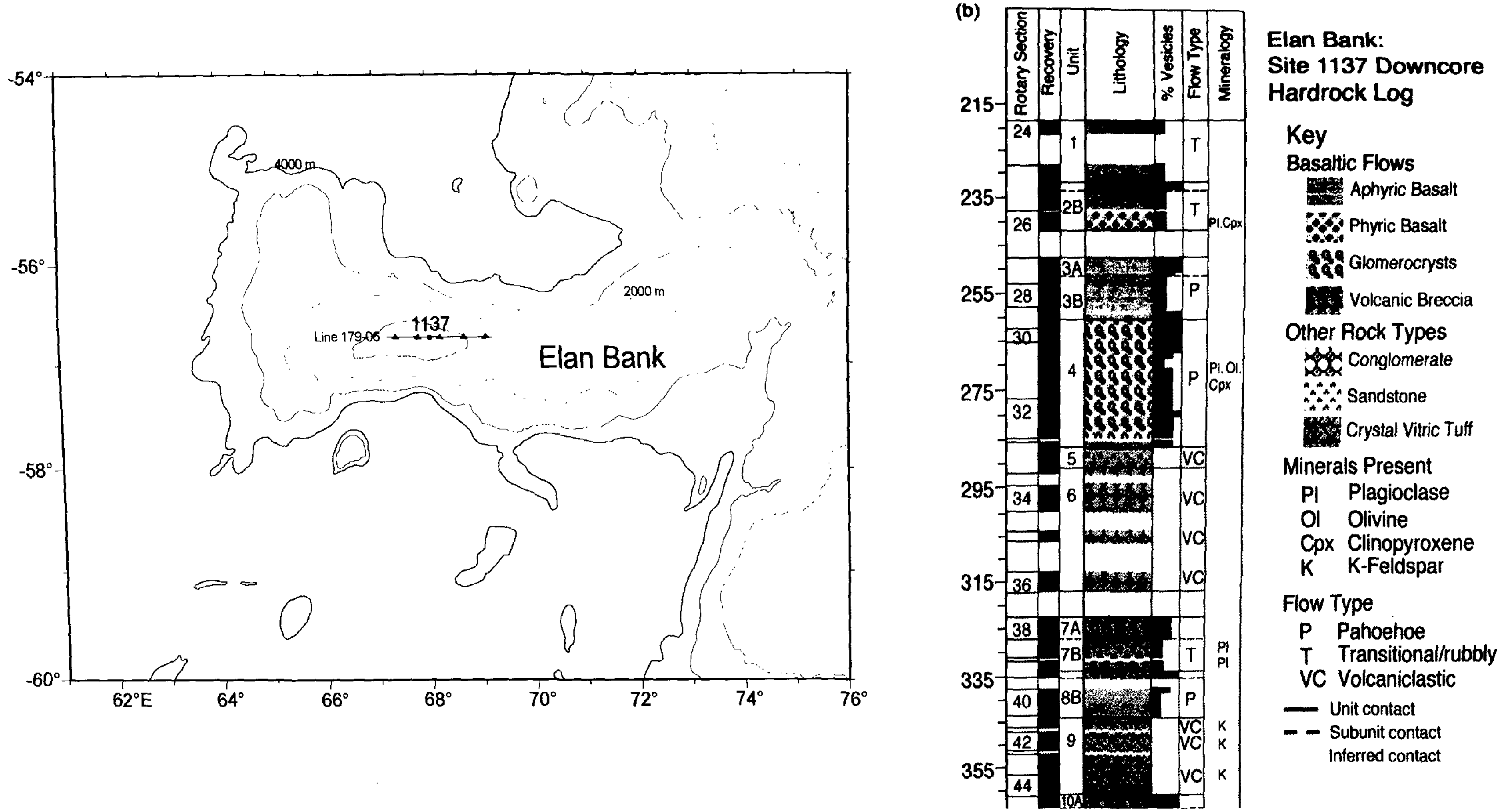


Figure 5.3: Litho-stratigraphic log of the basement samples recovered from the Elan Bank. ODP (Ocean Drilling Program) Site 1137 has drilled the core samples from the Elan Bank. Sample numbers show locations of units recovered from the core log, unit 5 and unit 6 indicate sandstone and conglomerate, respectively (after Ingle et al., 2002). Left diagram shows the track map for the seismic reflection line 179-06, ODP Site 1137 and OBS stations.

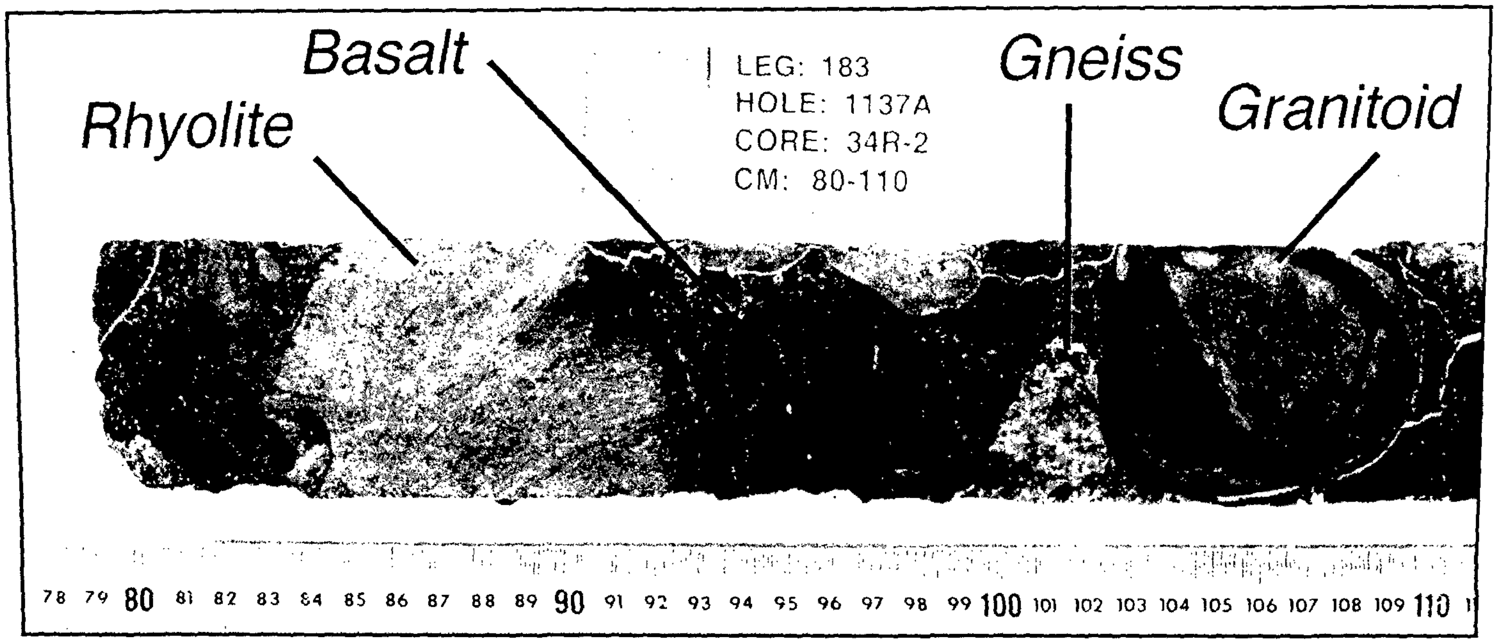


Figure 5.4: Photograph of a recovered core section within the Unit 6 conglomerate at ODP Site 1137 on Elan Bank. It depicts few of the types of clasts recovered and the typical clast size within the unit. The scale is in centimeters (after Ingle et al., 2002).

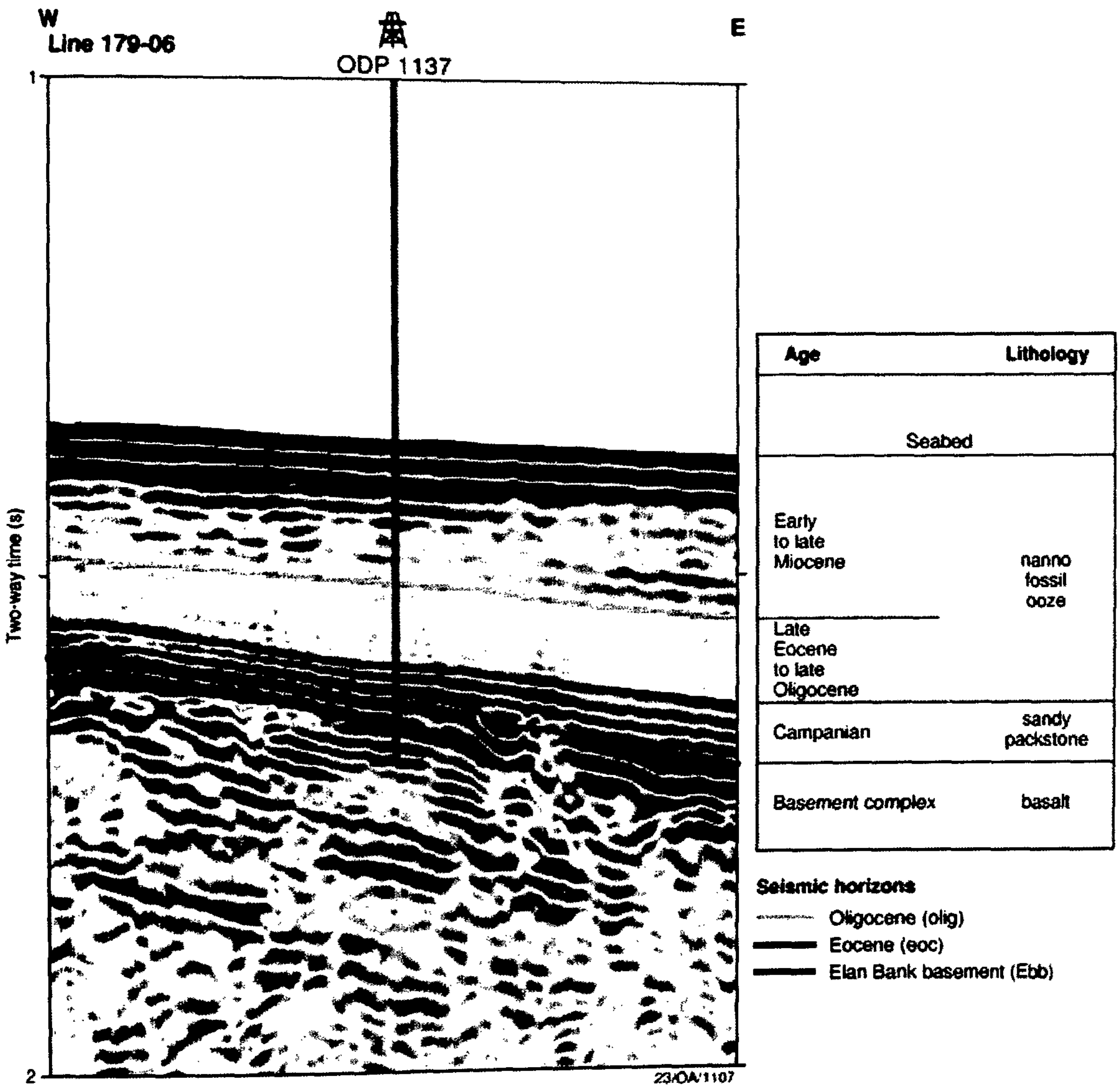


Figure 5.5: Seismic reflection section of the Elan Bank in the vicinity of ODP Site 1137. The drill well has penetrated through the nanno fossil ooze and sandy packstone sediments and basement complex (after Borrisova et al., 2003).

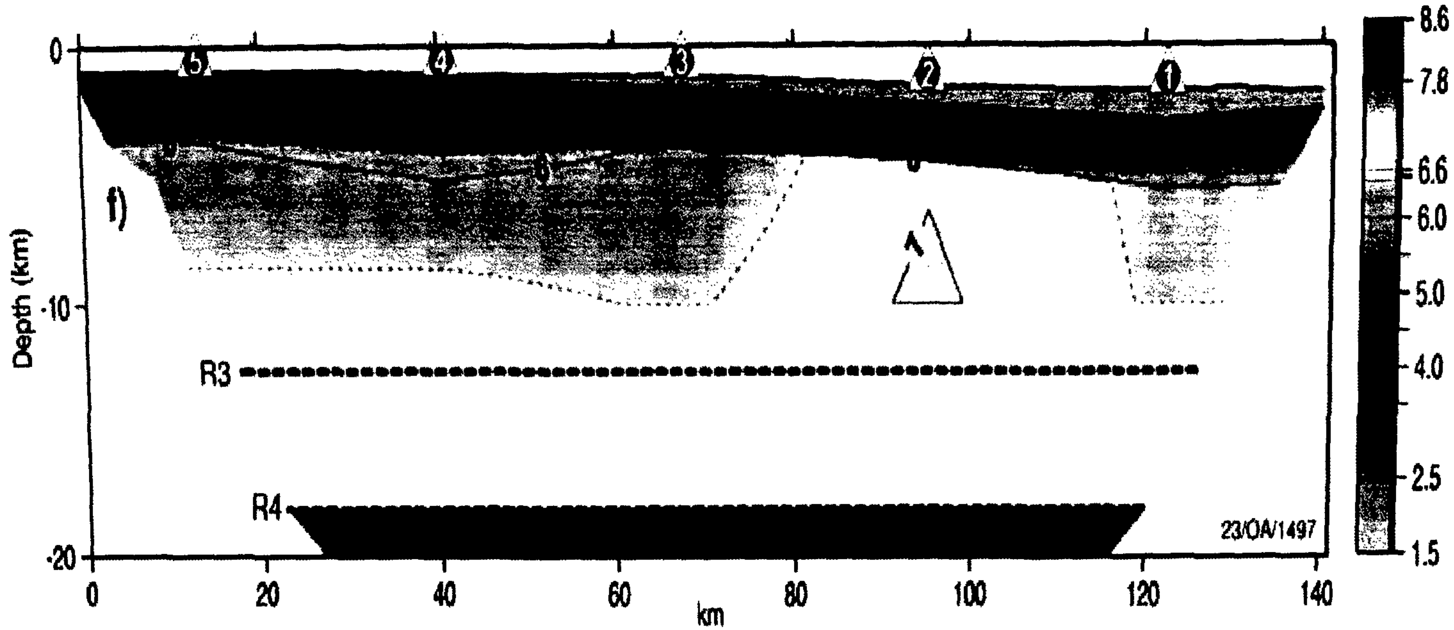


Figure 5.6: Derived velocity model along Line 179-06 beneath the Elan Bank. Velocities are color-coded and the velocity contour interval is 0.5 km/s. R3 indicates an horizon separates upper crust from the lower crust and R4 indicates the Moho boundary (after Borrisova et al., 2003)

5.4 Two-Dimensional Modeling of Gravity Profiles in the Bay of Bengal and the Enderby Basin

2-dimensional gravity model studies have been carried out along selected profiles in Bay of Bengal and Enderby Basin regions, where seismic results are available for constraining the basement topography, sediment thickness, etc. Initial crustal models are approximated for each profile based on the constraints available from seismic reflection and refraction results and drilling information. Also available P-wave velocities are used for determination of densities for various geological strata. Gravity response is calculated for each assumed geophysical model with specific densities and thickness of various layers and undulations along the interfaces. In 2-D modeling technique gravity anomalies are computed from a chosen crustal model and compared directly with the observed anomalies. The modeling has been performed using GM-SYS software, which allows intuitive, interactive computation of the geophysical model and real time calculation of gravity response. Gravity response is computed basically following the method of Talwani et al. (1965) and is described in Chapter-2.

Forward gravity modeling has been carried out along four profiles crossing the Bay of Bengal from east to west and one profile running from MacRobertson Land to Elan Bank in N-S direction (Figure 5.1). From the Bay of Bengal region four E-W profiles SK 107-06, MAN-01, SK 107-07 and MAN-03 along the latitudes 15.5°N, 14.64°N, 14°N and 13°N, respectively running from the ECMI to the Ninetyeast Ridge area have been considered for the modeling. The details of two sedimentary layers (pre-collision continental rise sediments and post-collision fan sediments), volcanic rocks and basement topography have been considered from the seismic stratigraphic results published by Curray et al. (1982) and Gopala Rao et al. (1997) and the seismic results shown in the present work (Figure 6.5). Relatively high density values are used for the pre-collision sediments as the sediments were interpreted as high-velocity and high-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 highs and the 85°E Ridge, and allow the structures to project into the post-collision fan sediments up to the Oligocene age. The densities of 2.95 gm/cc and 3.4 gm/cc are considered for oceanic crust and mantle, respectively for the model computations. Modelling was performed by applying small adjustments to the geometries of the crustal layers and densities till it satisfies an acceptable fit between observed and calculated gravity anomalies.

The derived crustal model for the profile SK 107-06 running along latitude 15.5°N is shown in Figure 5.7-a. Geometry of various geological strata and corresponding densities used for the computations are also shown in the Figure 5.7-a. The model results reveal that the crust beneath the 85°E Ridge is about 10 km thick including the volcanic material, while the overall crustal thickness range from 4 to 7 km along the profile. Relatively thick oceanic crusts are observed close to the margin region and in the vicinity of continent-ocean boundary and at other end below the Ninetyeast Ridge. The Moho boundary lies at a depth of 16-19 km thick from the sea surface with an average depth of 17 km along the profile.

The crustal model derived for the profile MAN-01 running along latitude 14.64°N is shown in Figure 5.7-b. It is found that numerous volcanic features and their loads have undulated the basement and Moho boundary to a large extent. The structural high close to the margin and the 85°E Ridge have undergone flexural compensation mechanisms, whereas beneath the Ninetyeast Ridge the crust thickness has increased and inclined towards the Andaman subduction zone as it was influenced by the subduction process of the Indian plate underneath the Burmese micro-plate. The model reveals that the crustal thickness is ranging from 6 to 8 km along the profile. The Moho boundary lies at a depth of 19 km from the sea surface below the 85°E Ridge and the structural high, which is relatively deeper than the average depths to the Moho boundary. This implies that the structural high and the ridge have emplaced the load of its volcanic material on the oceanic crust. Hence the down flexing of the Moho boundary has been observed beneath both the locations.

The best fit crustal model for the profile SK 107-07 running along latitude 14°N is shown in Figure 5.7-c. Except beneath the 85°E Ridge and Ninetyeast Ridges the crust thickness is almost close to 6 km. Beneath the ridge structures the thickness of crust has increased to more than 10 km due to the overburden of volcanic loads. The Moho boundary lies at a depth of 22 km below the 85°E and Ninetyeast ridges from the sea

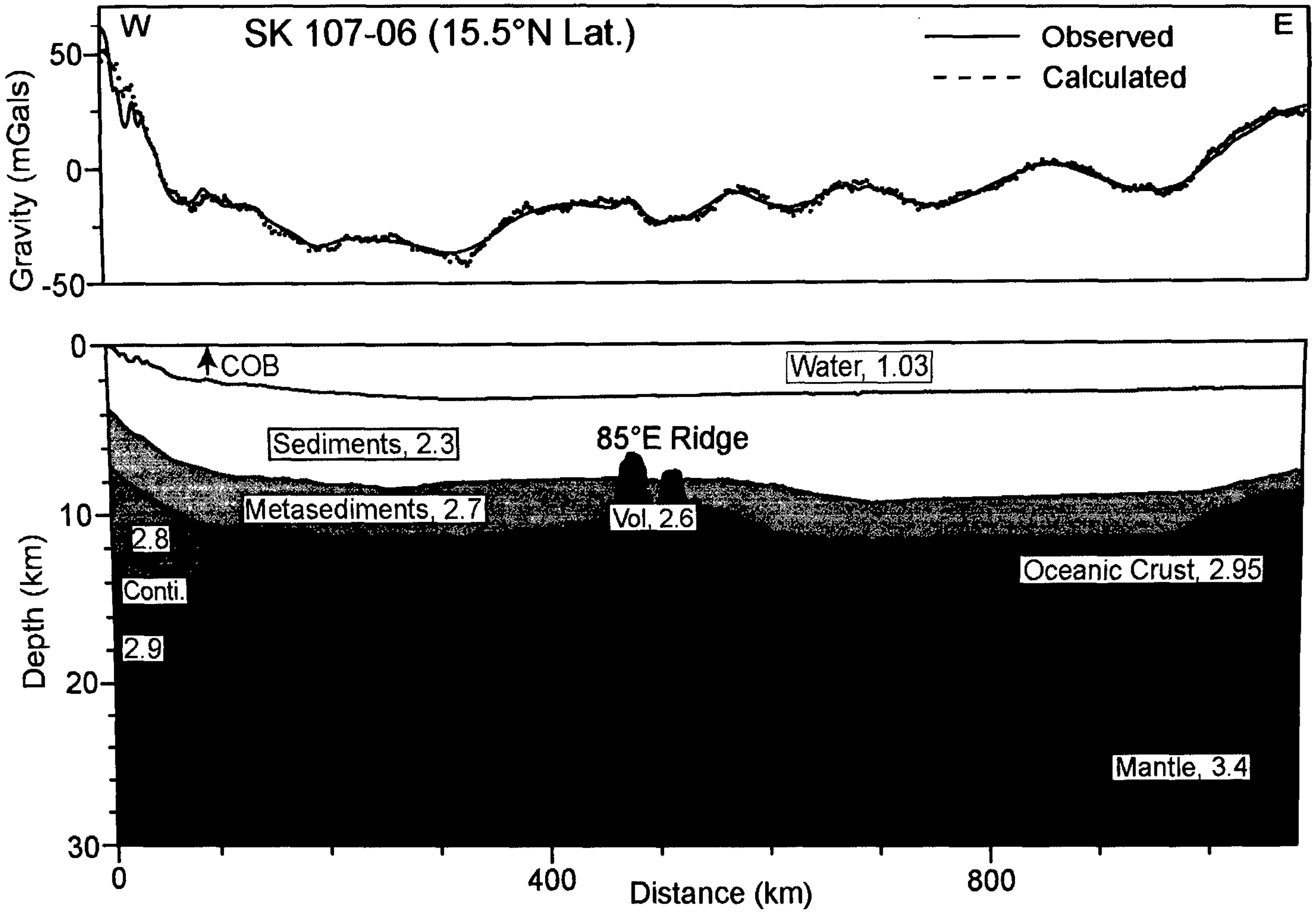


Figure 5.7-a: Two-dimensional gravity model with interpreted crustal structure along profile SK 107-06 in the Bay of Bengal. Numerical values within boxes indicate the densities (gm/cc) of different strata. Profile location shown in Figure 5.1.

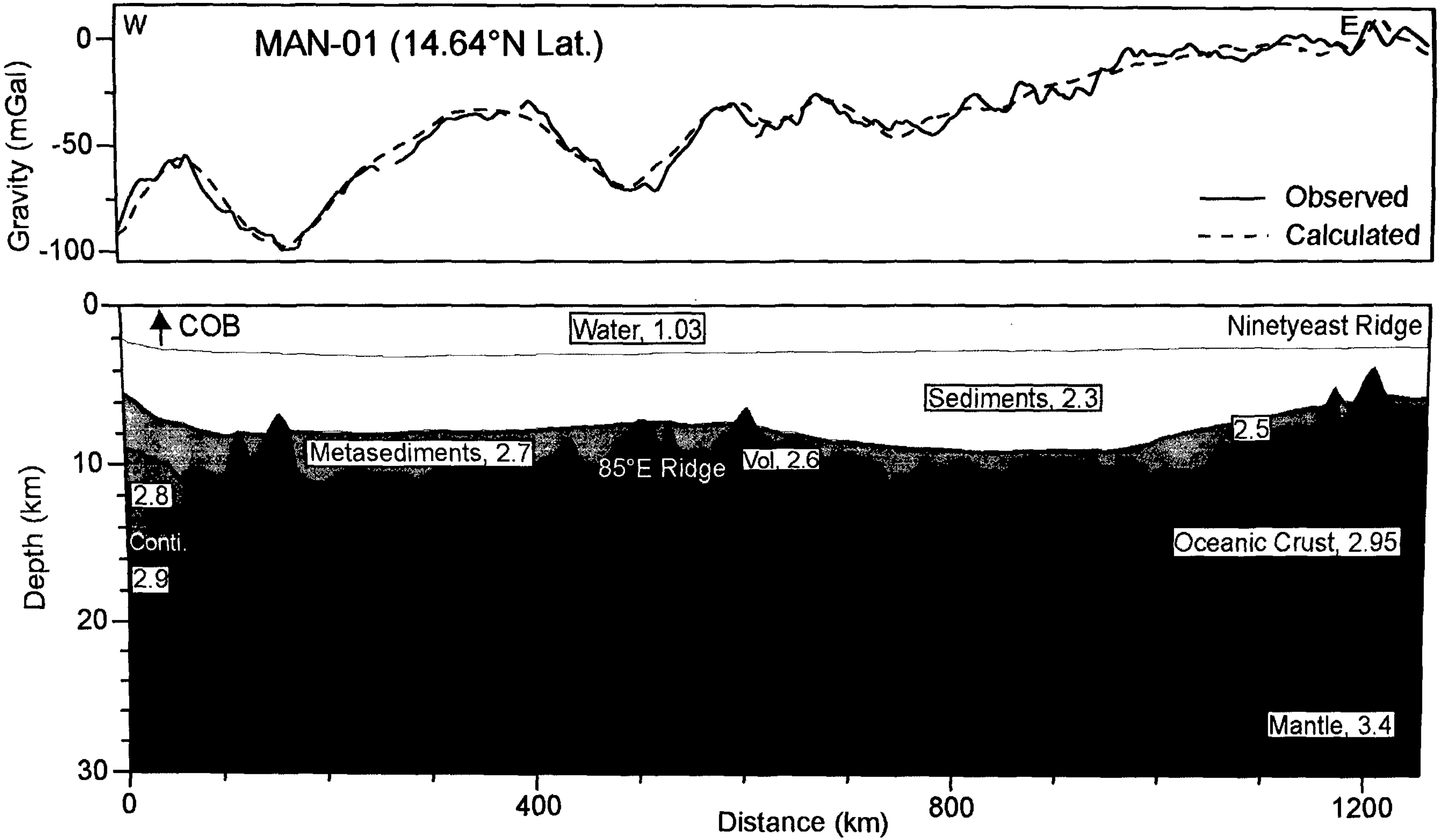


Figure 5.7-b: Two-dimensional gravity model with interpreted crustal structure along profile MAN-01 in the Bay of Bengal. Numerical values within boxes indicate the densities (gm/cc) of different strata. Profile location shown in Figure 5.1.

surface, while beneath the basins the Moho boundary is lying at a depth of about 18 km from the sea surface (Figure 5.7-c).

Approximately similar crustal model results are obtained for the profile MAN-03 running along latitude 13°N (Figure 5.7-d). The model results reveal that the crustal thickness is reaching more than 9 km beneath the 85°E and Ninetyeast ridges, while along the rest of the profile the crust thickness is ranging from 6 to 8 km. As described for other crustal models, the Moho boundary is deeper lying at a depth of about 20 km below the sea surface, while along the rest of the profile the Moho boundary lies at depth of about 18 km from the sea surface without many perturbations. The transition between the oceanic and continental crusts is relatively small and clearly expressed in gravity anomaly data changing from high-amplitude and short-wavelength anomaly to broadened regional anomaly (Figures 5.7-c and -d). The gravity model studies carried out along four profiles of the Bay of Bengal confirm the over thickening of the crust with variable dimensions beneath both the 85°E Ridge and Ninetyeast Ridge.

For gravity modeling of the Enderby Basin region including Antarctic margin and Elan Bank, the profiles 228-06 (c), Th-99a (d)) and 179-05 (Figure 5.1 left part) are combined from the published results of Borissova et al. (2003), Stagg et al. (2004) and Gaina et al. (2007). The combined profile approximately runs in N-S direction from Antarctic margin, particularly across the MacRobertson Land – Mesozoic age oceanic crust – continental nature Elan Bank – oceanic crust younger than the Enderby Basin region (Figure 5.1 left part). As no ship-borne gravity data are available along the profiles, satellite derived gravity data are extracted along the profiles and used for model studies. Details of sediment thickness, basement undulations and Moho boundaries are constrained by the seismic reflection and refraction results published by Borissova et al. (2003) and Stagg et al. (2004). The sediment thicknesses are in general greater reaching up to 4 km in the vicinity of MacRobertson Land, while over the Elan Bank the sediments are thin reaching as low as 0.5 km. In the basin region and on north of the Elan Bank, the sediments are of intermediate thick of about 2 km. About 16 km thick continental crusts are interpreted beneath the MacRobertson Land and Elan Bank; contrasting to this about 8 km thick oceanic crust (both layers 2 and 3 together) is interpreted between the continental structures (Figure 5.7-e). From the crustal model it

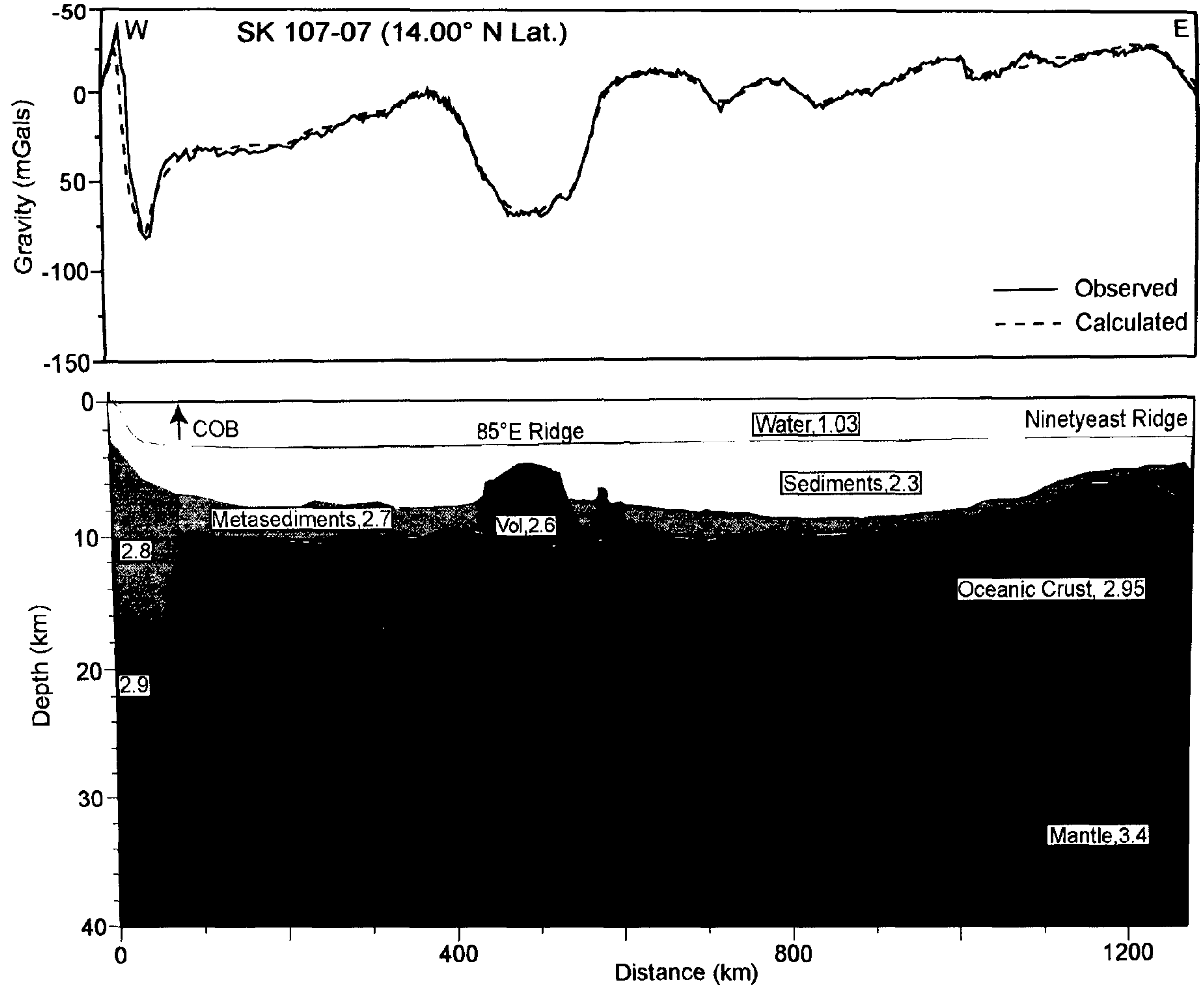


Figure 5.7-c: Two-dimensional gravity model with interpreted crustal structure along profile SK 107-07 in the Bay of Bengal. Numerical values within boxes indicate the densities (gm/cc) of different strata. Profile location shown in Figure 5.1.

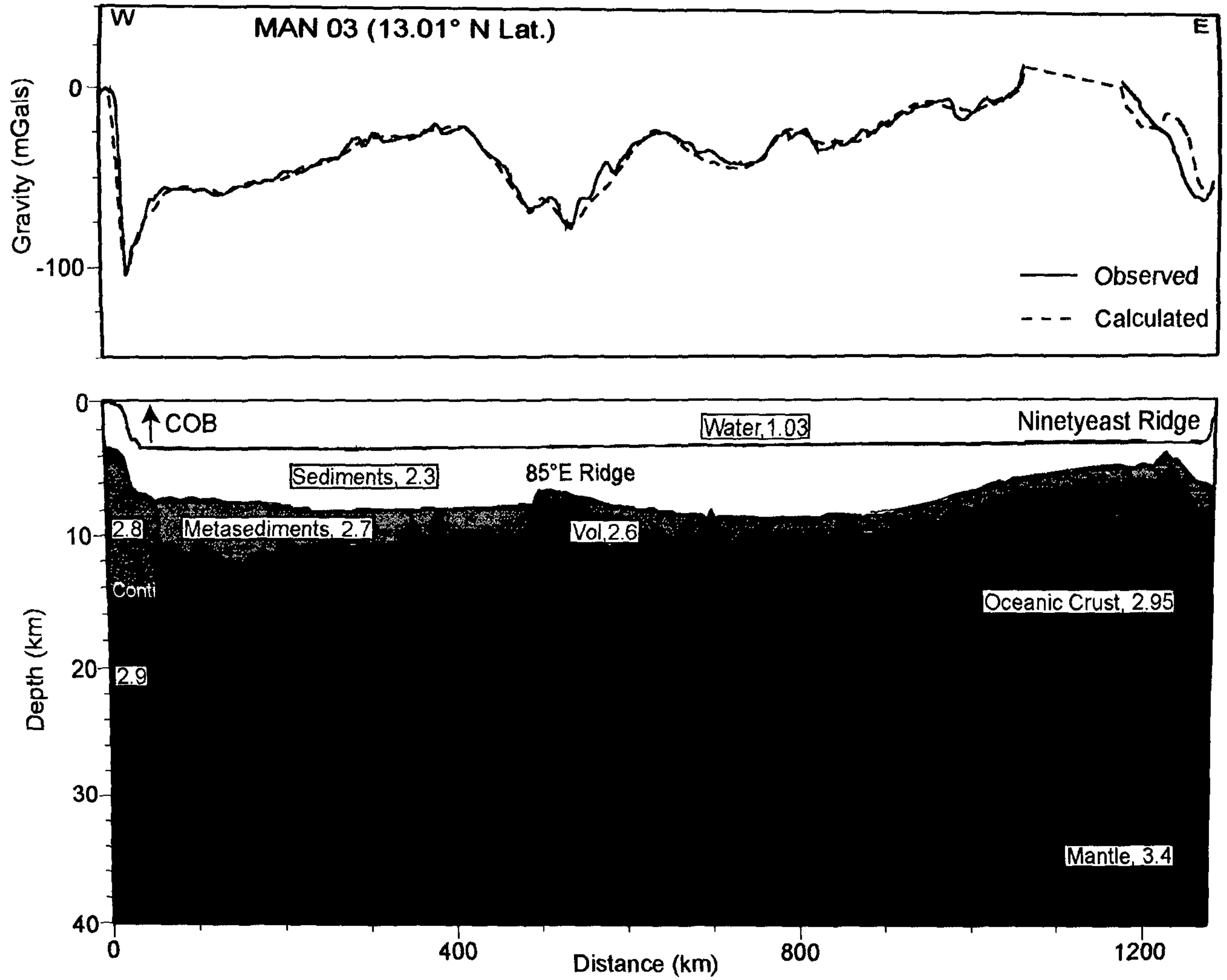


Figure 5.7-d: Two-dimensional gravity model with interpreted crustal structure along profile MAN-03 in the Bay of Bengal. Numerical values within boxes indicate the densities (gm/cc) of different strata. Profile location shown in Figure 5.1.

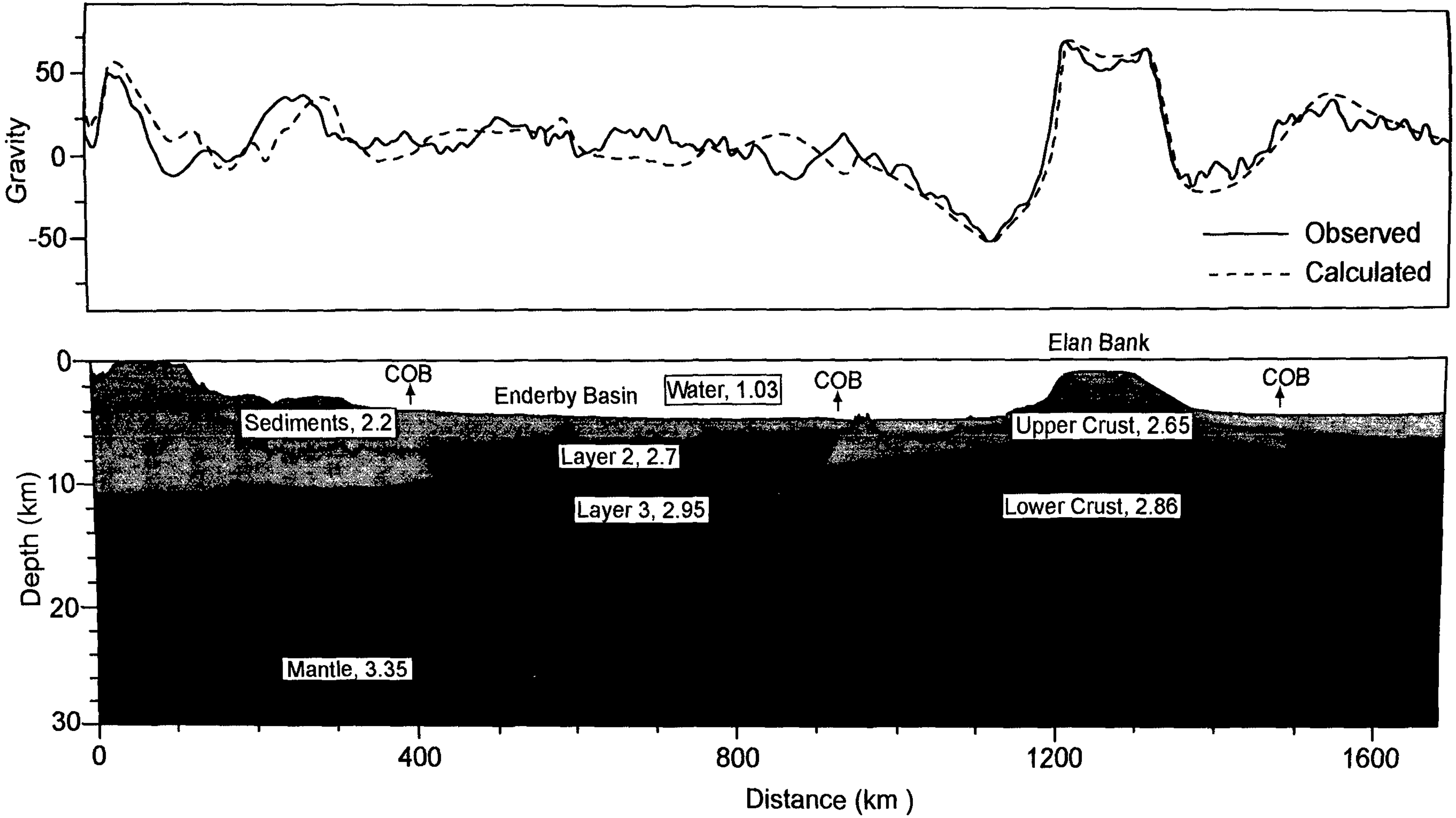


Figure 5.7-e: Two-dimensional gravity model with interpreted crustal structure along (profiles 228-06 (c) and Th 99a (d)) and Elan Bank (line 179-05 sectors (Borissova et al., 2003; Stagg et al., 2004; Gaina et al., 2007). Numerical values within boxes indicate the densities (gm/cc) of different strata. The profiles location is shown in Figure 5.1.

is observed that the Moho boundary is at a depth of 18 km beneath the Elan Bank and this Moho depth agrees well with the velocity model of Borissova et al. (2003). Also the derived crustal model allows demarcating the locations of continent-ocean boundaries on both sides of the Elan Bank and on Antarctic margin side (Figure 5.7-e).

5.5 Correlations of Fracture Zones off South ECMI and Enderby Land Margin

Fracture zones are long, linear scars in oceanic lithosphere that are the traces of previously active transform faults. Fracture zones separate oceanic lithosphere of different ages, with the age separation dependent on the transform length and the spreading rate at the time of crustal formation. Delineation of fracture zones in the Bay of Bengal and their conjugate features in the Enderby Basin from the satellite derived free-air gravity anomaly map provides new constraints for lithospheric plate reconstructions and for assembling the ECMI with the East Antarctic continental margin.

In the present study five ~N36°W trending fracture zones have been delineated between the south ECMI and the 85°E Ridge and also delineated five ~N4°E trending fracture zones which are found to lie in the western Enderby Basin between the Enderby Land and the Kerguelen FZ. In the Bay of Bengal it is observed that the fracture zones meet the N-S oriented 86°E FZ at an angle of ~39°. It is also observed that the fracture zones in the western Enderby Basin are discretely converging to the Kerguelen FZ at an angle of ~37°. For the present studies the assemble of the early Cretaceous fractures zones which are found off south ECMI in the Bay of Bengal and Enderby Basin is done (as shown in Figure 5.8) by taking in view that the major change in spreading direction was during 96-99 Ma. During that time there was a change in the spreading direction from 37° to 39°. The Kerguelen FZ and 86° FZs had started their evolution soon after the change in plate motion direction at 96-99 Ma. The Continent Ocean Boundary (COB) on East Antarctica margin was identified by Stagg et al., 2004. From the present study, it has been interpreted that the fractures zones delineated in Bay of Bengal and western Enderby Basin are conjugate FZ and were evolved when the south ECMI was rifted away from the Enderby Land during the early Cretaceous period (Figure 5.8). The delineation of new fracture zones pattern off the conjugate margins of south ECMI and Enderby Land will help us in better understanding the early opening of the Indian Ocean.

5.6 New Constraints on Breakup and Early Spreading History between India and Antarctica

From the interpretation of geophysical data of conjugate margins - Enderby Basin and Bay of Bengal - it is concluded 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 and beneath the central and northern Kerguelen plateau. On the other hand the oceanic crusts - off south ECMI - east Sri Lanka and off Enderby Land (from 47°E to 58°E longitudes) - were evolved simultaneously as conjugate parts in a specific tectonic setting, differing from the crustal evolution of the central Enderby Basin and off north ECMI. The crustal boundary delineated from the geoid data of the present study and other geophysical results (Stagg et al., 2004) along 58°E longitude distinguishes the evolution of both geological provinces.

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°. Earlier magnetic studies of the Enderby Basin (Gaina et al., 2003, 2007) and northeastern Indian Ocean (Schlich, 1982; Patriat, 1987; Royer and Sandwell, 1989; Krishna et al., 1995, 1999; Krishna and Gopala Rao, 2000) have concluded that the 86°E FZ and the Kerguelen FZ were conjugate FZs evolved by the India-Antarctica Ridge during the late Cretaceous-early Cenozoic period. Considering the tectonic constraints, particularly the azimuths between the fracture zones of two phases, it is interpreted 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, it can be opined 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).

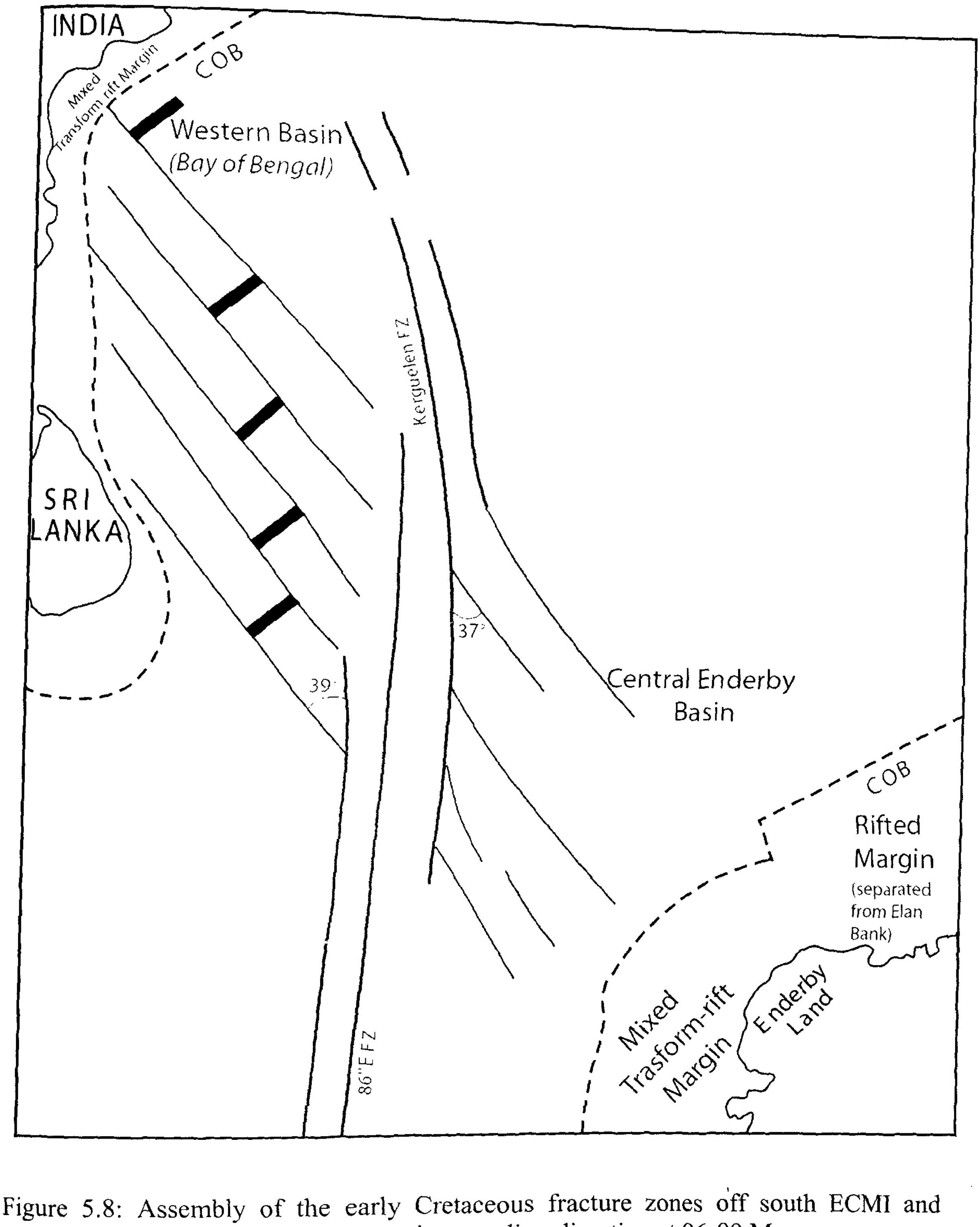


Figure 5.8: Assembly of the early Cretaceous fracture zones off south ECMI and Enderby Land prior to major changes in spreading direction at 96-99 Ma.

5.7 Breakup of India from Antarctica

As discussed earlier the studies of conjugate regions - Bay of Bengal and Enderby Basin – have brought out new tectonic constraints such as M-sequence spreading anomalies M2o through M9Ny, oceanic fracture zones, fossil ridge segments, crustal boundaries, etc. have shed light that the present day ECMI evolved in two rifting phases: initially at 130 Ma age drifted from East Antarctica and later at 120 Ma age a piece of continent, called Elan Bank and a kin to Eastern Ghats detached from the present-day margin and located close to the Antarctica margin. During the phase of drifting of ECMI from the Enderby Land and Elan Bank, 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 parallel FZs) and in Enderby Basin (Kerguelen FZ and parallel FZs). It is an interesting observation 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 3.6), 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 seismic character of oceanic crust, depth to the basement, crustal thickness 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) 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 fracture zones details obtained from the Bay of Bengal and western Enderby Basin, it can be opined that the oceanic crust (between 47°E and 58°E) off Enderby Land margin and off south ECMI - east Sri Lanka may have been evolved in a specific tectonic setting (Figure 5.1) and differs from the evolution of other continental margin segments.

Following the negative gravity and magnetic anomaly signatures of the small segmented features between the fracture zones of the Bay of Bengal and model results it is clearly understood the presence of NE-SW trending structural highs lying orthogonal to the fractures zones. Following the plate reconstruction studies of India, Australia and Antarctica carried out by Royer and Coffin (1992) and Kent et al. (2002), it can be envisaged 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. Therefore, it can be considered NE-SW structural fabric/ highs as fossil ridge segments ceased during the Cretaceous Magnetic Quiet Epoch. This postulation needs to be validated with additional geophysical observations as it will become a critical constraint for improving the plate reconstructions closer to the breakup phases. 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. 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-sequence 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, to hot spot 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 re-oriented during the mid-Cretaceous period without involving rotations and major ridge jumps. The re-oriented 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.

CHAPTER 6

Classification of Continental Margin Segments on Eastern Continental Margin of India (ECMI)

CLASSIFICATION OF CONTINENTAL MARGIN SEGMENTS ON EASTERN CONTINENTAL MARGIN OF INDIA (ECMI)

6.1 Introduction

Passive continental margins, in general, mark the transition between thin, dense oceanic crust and thicker, lighter continental or transitional crust. The isostatic balance between two types of crusts may undergo modification by subsequent sedimentation or erosion; subsequently the boundary may create a major step in the seafloor, termed as continental slope (Laughton and Roberts, 1978). The margins are evolved by the rifting process of super-continents or larger continental masses and drift apart by formation of a new oceanic lithosphere adjacent to the teared continents. The shape of the continental margins are controlled, in general, by style of continental breakup, rifting, shearing, stretching and following subsidence, occasionally the margins undergo modifications by sediments drained from the continent and by magmatic activity. The marine sediments deposited along the margins are enormous and their volumes seem to be more than half the total sediment volume of the oceans (Heezen and Tharp, 1965). The tectonic activity associated with the rifting and drifting of continental fragments is, in general, documented within the sediments and crustal rocks in the vicinity of continental margins, which enables to interpret the tectonics associated with the earlier phases of the continental breakup history.

Passive margins are generally the major sites of contact between the old Precambrian land masses and young ocean basins. These margins mark the breakup of continents and also are the result of the tectonic, magmatic and subsidence processes that have affected the margins. The tectonic and magmatic processes to which the passive margins have been subjected can therefore be classified as rifted or sheared, volcanic or non-volcanic margins, sediment rich or sediment starved, wide or narrow, active or passive modes of rifting, and so on (Davison, 1997; Ruppel, 1995; White, 1992; White et al., 2003). To understand the evolution of passive continental margins in terms of rifting, shearing or mixed, transform-rift process is an essential facet apart from knowing the history of early spreading processes. In order to obtain the useful information on classification of margin segments and to reconstruct the lithospheric plate models, the margins along the East Antarctica, Elan Bank and ECMI have been thoroughly investigated in the present work.

6.2 Geophysical Signatures of the Continental Margins of India

Passive margins of India have been evolved as a result of breakup between Madagascar and west coast of India and between the east coast of India and East Antarctica, which led to the development of both western and eastern Continental Margins of India and subsequently the margins have undergone subsidence and deposition of sediments in the marginal basins (Sastri et al., 1981; Curray et al., 1982; Mukhopadhyay and Krishna, 1991). Several investigations were carried out on east coast of India to understand the evolution of the Eastern Continental Margin of India (ECMI), as to whether the margin is a total pull-apart margin or as a segment which could have been evolved as a sheared or transform margin.

Bathymetry, gravity and magnetic data acquired along five profiles (SK 100-17, SK 100-19, Prof-14, SK 82-11 and SK 107-06) across the northern part of the ECMI and six profiles (MAN-01, SK 107-07, Prof-34, MAN-03 and Prof-10) across the southern part of the ECMI were investigated (Figure 6.1) for identification of main geological features, thereby the features are used to classify the margin segments. Stacked plots of bathymetry, free-air gravity anomaly and magnetic anomaly profiles along the north segment of ECMI (SK 100-17, SK 100-19, Prof-14, SK 82-11 and SK 107-06) and along the south segment of ECMI (MAN-01, SK 107-07, Prof-34, MAN-03 and Prof-10) are presented for depicting the seafloor morphology and geophysical signatures associated with simple and complex continental margin segments. Seafloor topography and geophysical signatures of the northern segment of the ECMI are different from that of southern segment of the ECMI. Gravity anomaly patterns are also considered as useful constraints for classification of continental margin segments.

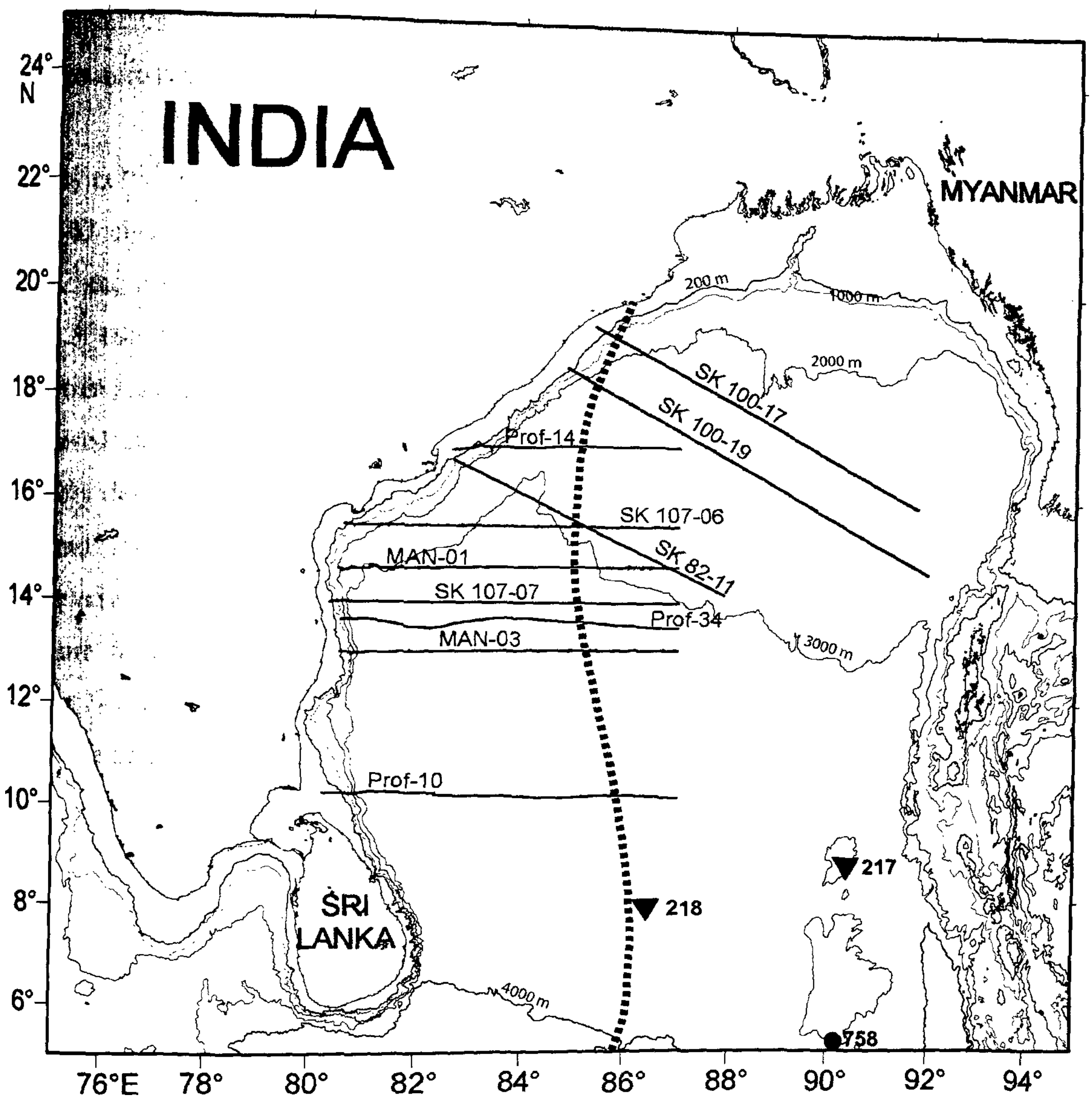


Figure 6.1: Track map of the profiles used for the classification of continental margin segments of ECMI. Thick dashed line represents the location of the 85°E Ridge. Solid triangles and circle indicate the positions of DSDP and ODP sites, respectively.

6.2.1 South Segment of ECMI

For the present analysis six profiles (MAN-01, SK 107-07, Prof-34, MAN-03 and Prof-10) are selected from the southern part of the ECMI (Figure 6.2). They run nearly perpendicular to the margin and extend from the continental margin to ultra-deep waters across the 85°E Ridge (Figure 6.1).

Bathymetry and free-air gravity anomaly data along profiles Prof-10, MAN-03 and SK 107-07 clearly show the shelf break, continental slope and foot of the slope, while along the profiles Prof-34 and MAN-01 the data show only the continental slope and foot of the slope. In close vicinity of the margin the gravity anomaly trend just follows the trend of the seafloor topography as it maintains significant density contrast as opposed to the water body. The free-air gravity anomaly along the profile Prof-10 rapidly decreases in the vicinity of the shelf edge by about 150 mGal for a distance of around 20 km towards slope region and then increases by about 90 mGal with relatively moderate gradient over a distance of around 40 km towards deep-waters (Figure 6.2). Along the profile MAN-03 the gravity anomaly rapidly decreases by about 140 mGal following the shelf edge morphology for a distance of about 10 km, then the anomaly increases by about 80 mGal with a moderate gradient over a distance of around 20 km. Similar gravity anomaly trends are observed on profiles, Prof-34 and SK 107-07. Along Prof-34 and SK 107-07 the gravity anomaly data decreases by 100 mGal and 90 mGal, respectively in the vicinity of shelf edge, then raise with moderate gradients by 50 mGal and 30 mGal, respectively for a seaward distance of 10 km and 20 km, respectively (Figure 6.2). Whereas along the profile, MAN-01 the free-air gravity anomaly trend differs significantly and increases from -90 to -40 mGal in the vicinity of foot of the slope and its seaward region.

On all the profiles the gravity anomaly is observed to be minima associated with the foot of the continental slope (Figure 6.2). The steep-low short-wavelength gravity anomaly, which is a typical signature associated with the foot of the continental slope swiftly returns back and merges with regional trend of the gravity anomaly. This characteristic gravity signature showing high-amplitude and short-wavelength is observed on the eastern margin of Sri Lanka and south ECMI extending up to 15°N latitude.

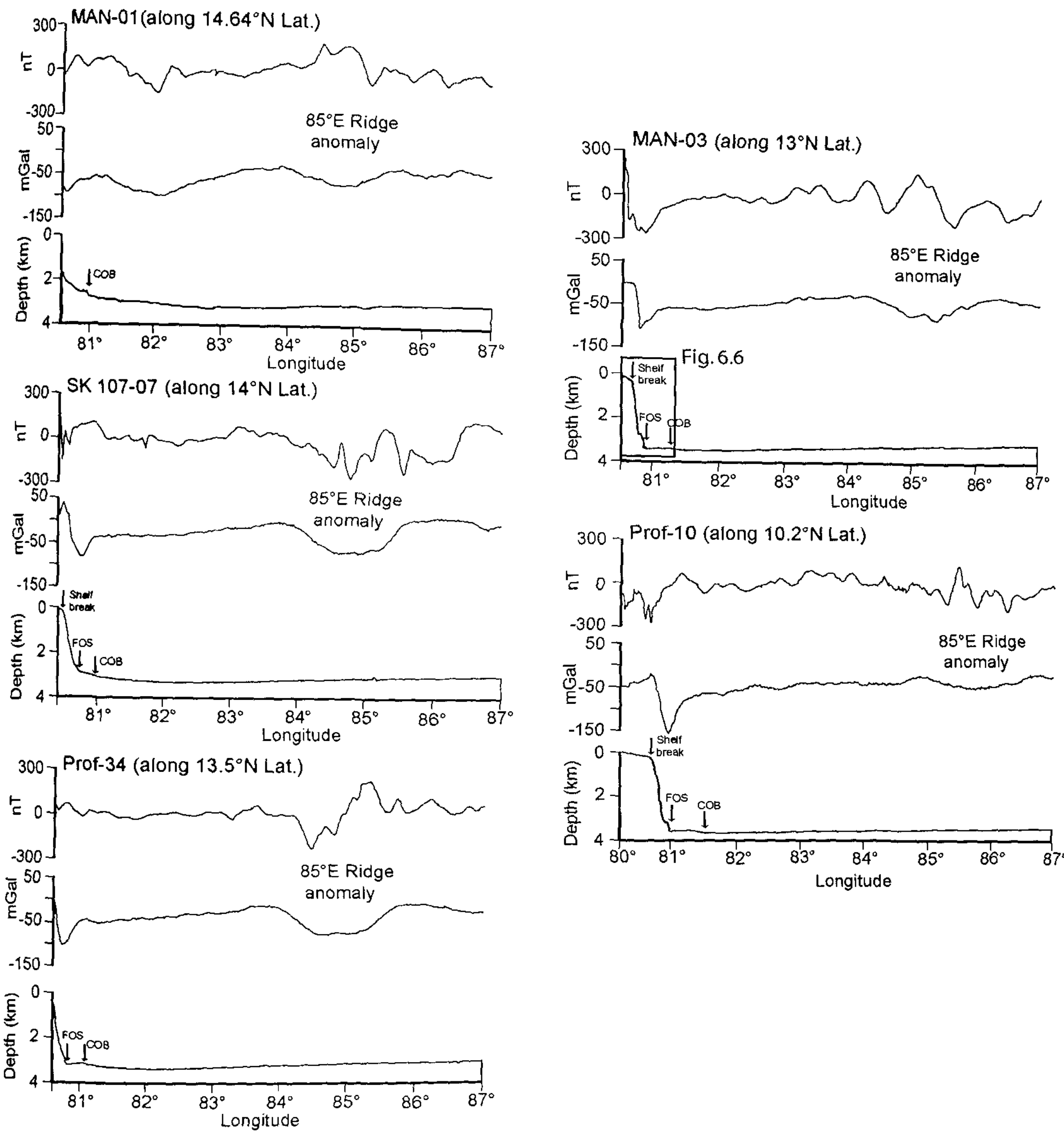


Figure 6.2: Stacked profiles of bathymetry, gravity and magnetic data from south segment of Eastern Continental Margin of India are shown to describe the seafloor morphology, anomaly character and location of COB. The box labelled with Fig. 6.6 on profile MAN-03 is shown in Figure 6.6.

On seaward side it can be observed that the 85°E Ridge, a subsurface structure in the Bay of Bengal, is associated with prominent negative gravity anomaly. The magnetic data along some of the profiles shows negative anomaly signatures in the vicinity of foot of the continental slope and alternate positive and negative anomaly signatures are seen associated with the 85°E Ridge along the profiles (Figure 6.2).

6.2.2 North Segment of ECMI

Another set of five profiles (SK 100-17, SK 100-19, Prof-14, SK 82-11 and SK 107-06) have been chosen from the northern segment of the ECMI (Figure 6.3) for the analysis of geophysical signatures associated with this margin. The profiles run nearly perpendicular to the north segment of the ECMI and extend from the continental margin to ultra-deep waters (Figure 6.1).

Bathymetry and free-air gravity anomaly data along profiles SK 107-06, SK 82-11, Prof-14, SK 100-19 and SK 100-17 clearly show the location of the shelf break, whereas continental slope and foot of the slope are not well-developed on all the profiles. The gravity anomaly trend generally follows the trend of the seafloor topography in the vicinity of the margin. The free-air gravity anomaly data on profiles SK 107-06, SK 82-11, Prof-14, SK 100-19 and SK 100-17, in general, decreases by 60 to 100 mGal from shelf edge to foot of the slope for an horizontal distance up to 90 km. Along all the profiles it can be observed that there is a sudden shift in gravity high along the shelf break and the gravity anomaly gently decreases towards the ocean basins.

The gravity anomaly minimum is observed coinciding with the foot of the continental slope (Figure 6.3). The gravity minima returns back to normal over a large distance up to 160 km, then merges with the regional gravity anomaly of the Bay of Bengal. This characteristic gravity signature showing reduced amplitude and extended wavelength is observed along the north ECMI from 15°N to nearly 19°N latitude. Towards deep-waters in the Bay of Bengal along profiles SK 107-06, SK 82-11 and Prof-14, negative gravity signatures are observed over the 85°E Ridge subsurface structure and this negative gravity anomalies were discussed in detail in Chapter-5.

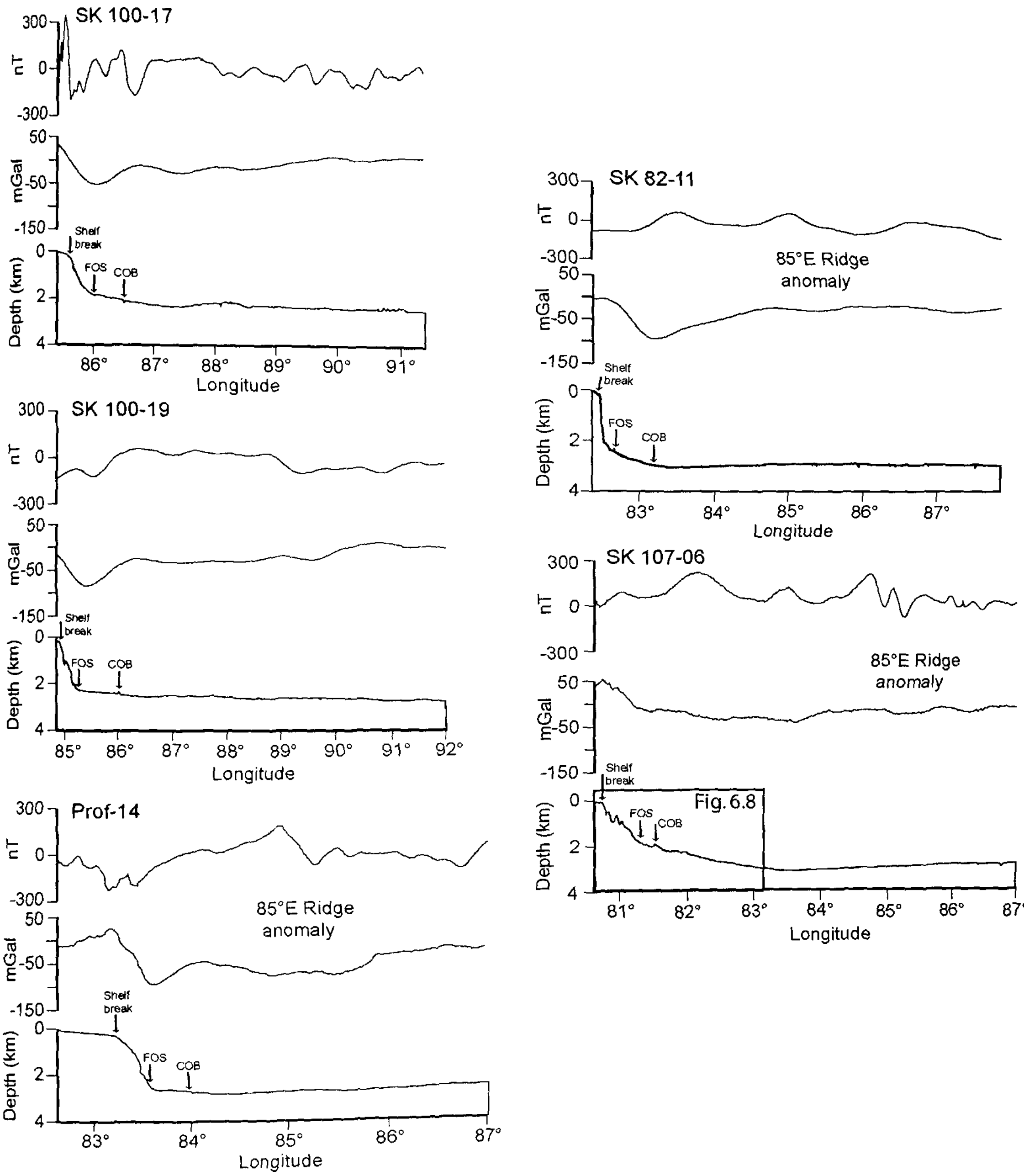


Figure 6.3: Stacked profiles of bathymetry, gravity and magnetic data from north segment of Eastern Continental Margin of India are shown to describe the seafloor morphology, both magnetic and gravity anomaly characters and location of COB. The box labelled with Fig. 6.8 on profile SK107-06 is shown in Figure 6.8.

The magnetic data along some of the profiles shows general negative anomaly signatures in the vicinity of foot of the continental slope while alternate mixed anomaly signatures are seen associated with the 85°E Ridge along the profiles (Figure 6.3).

6.3 Seismic Reflection Data and Interpretation

The breakup of eastern Gondwanaland and subsequent accretion of oceanic crust during the early Cretaceous paved the way for the formation of major geological/ tectonic features along the ECMI and its adjoining coastal region. The major river based sedimentary basins (Cauvery, Palar Pennar, Krishna-Godavari, Mahanadi and Bengal) along the ECMI were formed as a result of rifting and subsequent tectonic processes. The basins are parallel to the coastline and are oblique to the intra-continental late Triassic-early Cretaceous Gondwana basins of the adjoining area.

In earlier geophysical studies it was speculated that the breakup of ECMI from the East Antarctica has occurred in two stages along two different segments on north and south Krishna-Godavari Basin (Subrahmanyam et al., 1999; Ramana et al., 2003). During the initial breakup the Indian subcontinent had undergone an eastward tilt, hence most of the rivers originated on western part of Indian continent have an eastward flow into the Bay of Bengal (Murthy et al., 2010).

It is observed that during the Cretaceous period the sedimentary basins on the margin have undergone tectonic subsidence to a lesser extent due to low sedimentation caused by slow denudation along the rift flanks. The uplift of the rift flanks during the formation of the margin is conjectured due to the mantle plume activity and its interaction with the rifting process. The rifted basins along the ECMI have experienced high sedimentation as well as high subsidence at later phase during the Paleocene to Eocene period.

In order to map the seismic structure across the Bay of Bengal from ECMI to Andaman Islands, seismic stratigraphy analysis was carried out along two new profiles (SK 107-06 and SK 107-07) and two previously published profiles (MAN-01 and MAN-03), which run in E-W direction from the ECMI to margin of Andaman Islands (Figure 6.4).

Interpreted seismic reflection, gravity and magnetic data along the four profiles SK 107-06, MAN-01, SK 107-07 and MAN-03 are stacked together to have an integrated view of the geophysical response to the geological features along the continental margins and toward the deep ocean regions (Figure 6.5).

Following the earlier stratigraphic work (Gopala Rao et al., 1997), eight seismic sequences H1 to H8 within the sediment column with a total thickness of about 5s TWT (two-way travel time) are recognized in all four seismic profiles running from ECMI to Andaman Islands (Figure 6.4). The lower Eocene sedimentary horizon lying immediately above the basement topography divides the entire sediment column into two sediment packages. These packages are assumed to be deposited during pre-continental and post-continental collision between India and Asia. Earlier Curray et al. (1982) and Gopala Rao et al. (1997) have interpreted that the lower sedimentary package was deposited mainly from the rivers of east coast of India, whereas the upper package was deposited from the Ganges and Brahmaputra rivers after establishing the contact of the Indian subcontinent with the Asian continent.

In all four seismic interpreted line-diagrams (Figure 6.5), it is observed that the basement topography is broadly identical with the manifestation of two aseismic ridges, the 85°E and Ninetyeast ridges. The Ninetyeast and 85°E ridges divide the sedimentary fan in the Bay of Bengal into two basins, the Western and the Eastern basins. The Western Basin lies between the eastern margin of India and the 85°E Ridge and the Central Basin lies between both the aseismic ridges (Curray et al., 1982; Rao and Bhaskara Rao, 1986).

Besides the two aseismic ridges, the Ninetyeast and 85°E ridge, the basaltic basement underneath both Western and Central basins consists of isolated morphological features. Pair of structural rises separated by a tiny depression in between is observed on the profile MAN-01 in the vicinity of the margin region. Also along the profiles MAN-01 and MAN-03 small-relief isolated basement rises and troughs have been observed on flanks of the ridges (Figure 6.5). A regional basement tilt is also observed toward west from Ninetyeast Ridge to the margin. This tilt may indicate that towards the eastern margin of India, the age of the oceanic lithosphere increases, the lithosphere

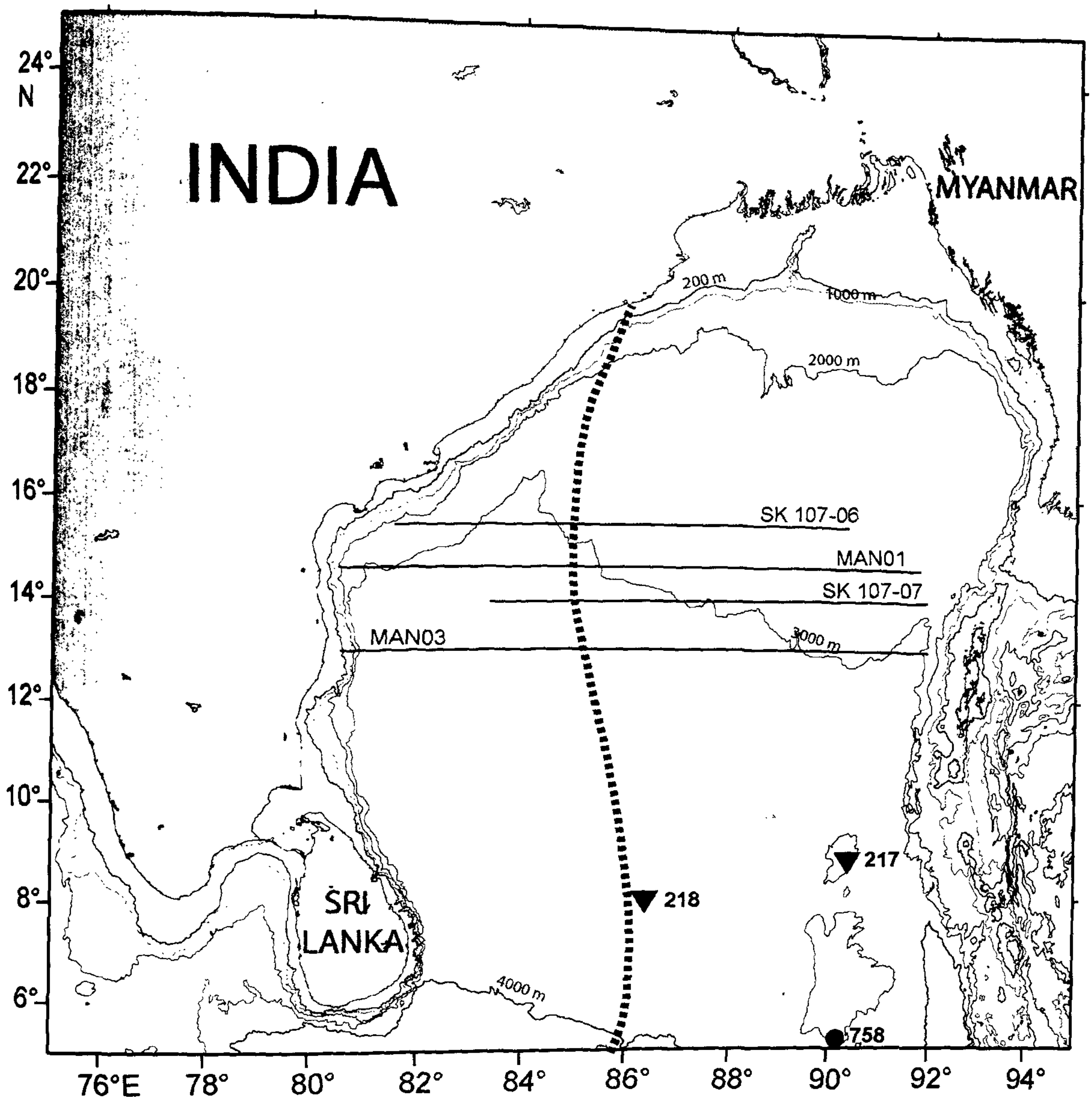


Figure 6.4: Track map of the seismic reflection profiles used for the interpretation of sedimentary layers and basement topography in the Bay of Bengal region. Thick solid line shows the location of the 85°E Ridge in the Bay of Bengal. Solid inverted triangles and solid circle indicate the locations of DSDP and ODP sites, respectively. Interpreted seismic data are shown together with free-air gravity and magnetic anomaly data in Figure 6.5.

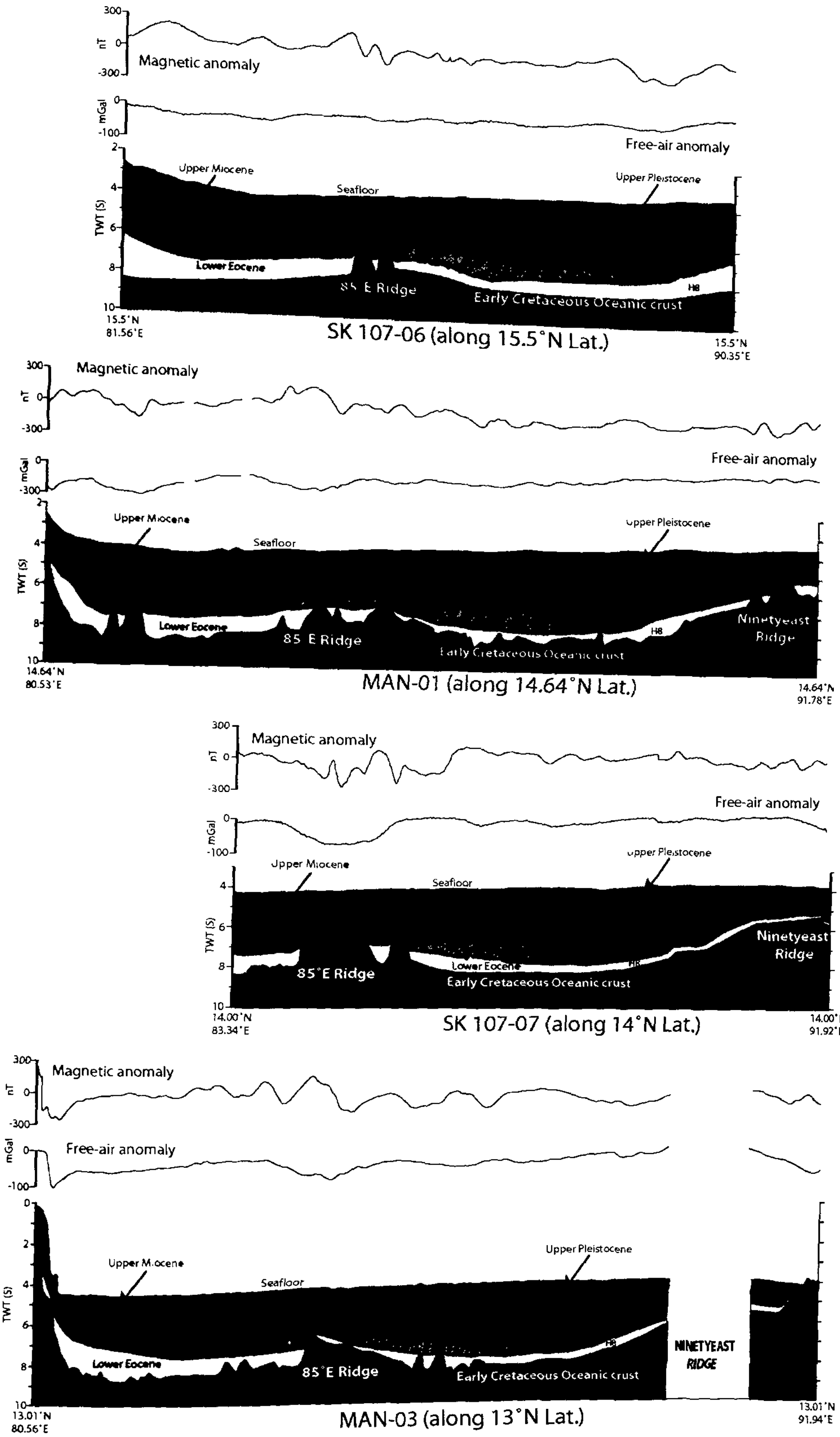


Figure 6.5: Line drawings of interpreted seismic reflection data together with free-air gravity and magnetic anomaly data along four regional profiles (SK 107-06, MAN-01, SK 107-07 and MAN-03) running from Eastern Margin of India to Andaman Islands. Profiles locations are shown in Figure 6.4.

cools and subsides to depths in a near linear-dipping pattern. Earlier, Gopala Rao et al. (1997) have also observed this regional tilt and explained that it was due to the subsidence of the oceanic lithosphere with crustal age.

Further the seismic stratigraphic results suggest that no evidence is found for the presence of seaward dipping reflectors and underplated material within the continental crust, hence the continental crust closer to the shelf-slope regions includes unaltered rift related deformed crust, which was emplaced during the continental breakup phases along the north and south segments of the ECMI. In order to obtain additional constraints on the character of ECMI segments, two seismic reflection sections one profile (SK 107-06) from northern segment of ECMI and another profile (MAN-03) from the southern segment of ECMI are further analysed. Also these seismic results are compared with well established Ghana transform continental margin, northern Gulf of Guinea.

6.3.1 South Segment of ECMI

The seismic reflection section (profile MAN-03 along latitude 13°N) of the southern segment of ECMI and its interpreted line-diagram are shown in Figure 6.6. Eight seismic sequences H1 to H8 within the sediment column are identified following the previous stratigraphic interpretations of Gopala Rao et al. (1997). On shelf-slope region the seismic data reveal the presence of relatively low-angle normal faults with major throws as high as 3.0 sec TWT. A major normal fault close to the shelf edge coinciding with the continental slope is observed which makes the slope an extremely high gradient steep surface. The fault surfaces are devoid of sediments or covered with thin-vein of sediments. A narrow stretch of deformed crust/ abrupt transition from continental to oceanic crust is observed in the data and shown in interpreted section (Figure 6.6).

The geophysical features such as marginal high, pull-apart rifted basin and normal faults with major throws and devoid of sediments, narrow stretch of deformed crust/ abrupt transition from continental to oceanic crust are observed as prominent structural features in slope region of south segment of ECMI. Basement reflections with the character of hyperbolic nature reflections are noticed terminating against the

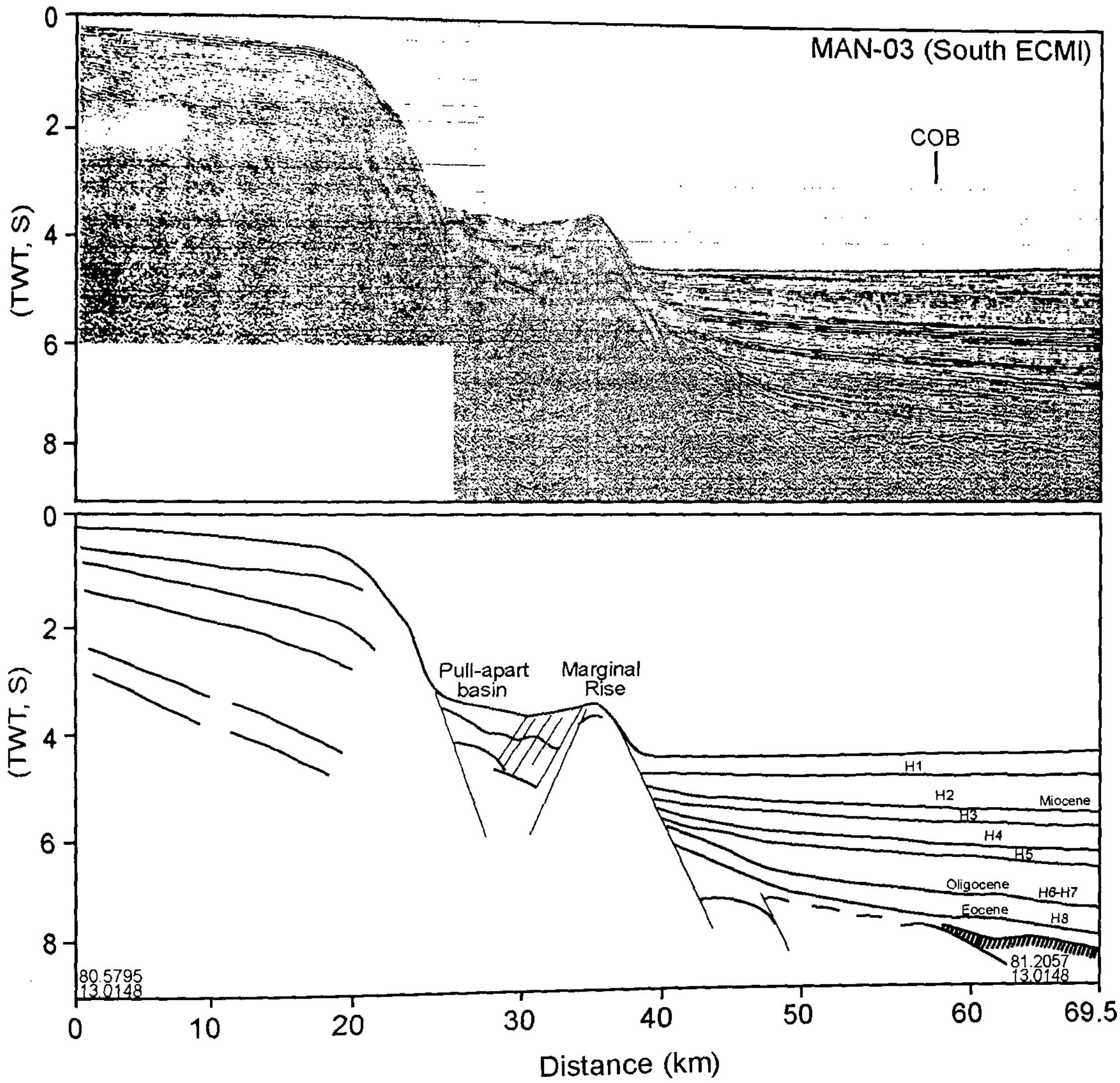


Figure 6.6: Seismic sections and interpreted results of profile MAN-03 from south segment of Eastern Continental Margin of India are presented to show the internal structure.

sedimentary layers and continental rocks in the vicinity of seaward of foot of the slope region (Figure 6.6), suggesting the location of continent-ocean boundary.

Similar type of marginal features has been identified elsewhere along the continental margin of Newfoundland (Todd et al., 1988) and Ivory Coast, which is conjugate to the Guiana margin (Basile et al., 1992, 1998). The seismic results of the offshore Ivory Coast region (Figure 6.7) including the marginal ridge and fault controlled basin are well comparable to the results of the south ECMI seismic results. Using these specific seismic characters, Mascle and Blarez (1987) and Edwards et al. (1997) have interpreted the Ghana margin as transform continental margin. As the crustal configuration of the south ECMI is similar to that of Ivory Coast results, it can be believed that south segment of the ECMI may have undergone a transform motion initially at least for a short period. The Enderby Land margin, East Antarctica, considered as conjugate region of south ECMI, has also experienced the transform motion initially followed by normal rift process, hence this margin is identified as mixed transform-rift margin (Stagg et al., 2004).

6.3.2 North Segment of ECMI

The seismic reflection section (profile SK 107-06 along latitude 15.5°N) of the northern segment of ECMI and its interpreted line-diagram are shown in Figure 6.8. Seven seismic sequences H1 to H7 in the sediment column are identified following the previous stratigraphic interpretations of Gopala Rao et al. (1997). Basement reflector could not be identified in this section as probably the basement reflections are masked by the multiple of dominant seafloor reflector. Hence only 7 reflectors in the sediments were identified.

The seismic section further reveals the presence of less significant normal faults extending for a distance of about 100 km from the shelf-edge. The seismic section clearly shows the continuity of the faults deep into the sediments.

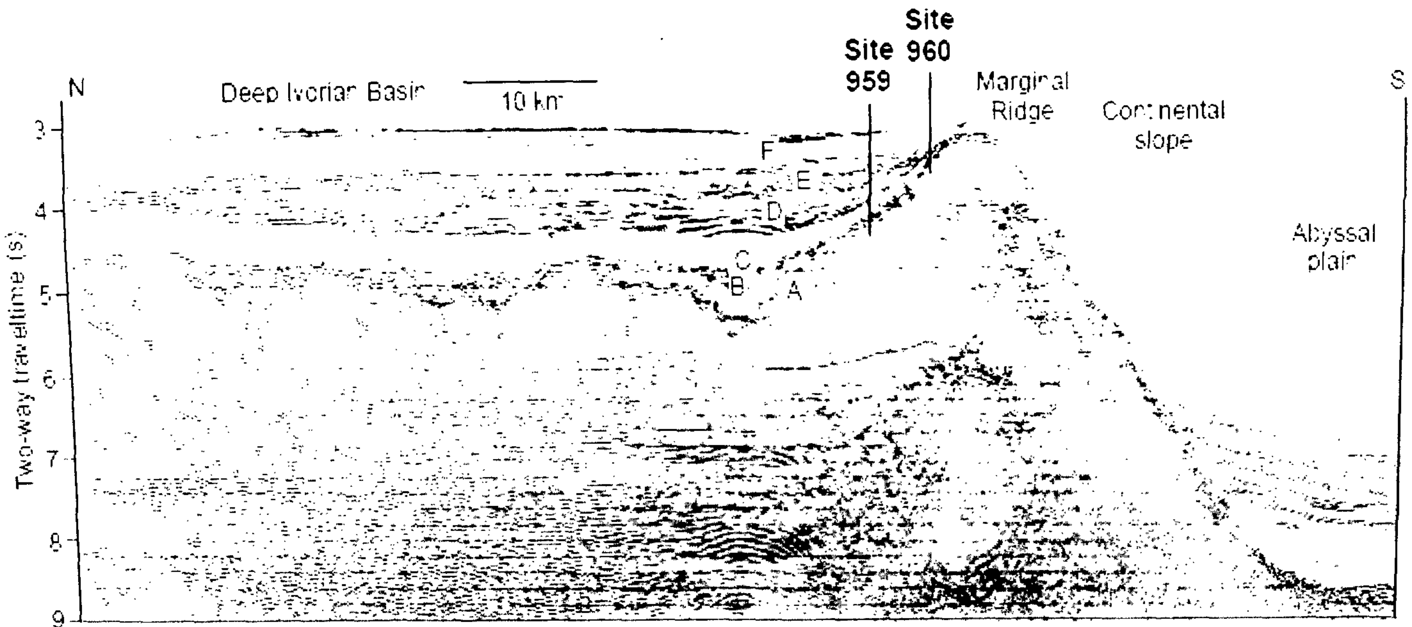


Figure 6.7: Multi-Channel Seismic section showing the marginal ridges from the conjugate margins of the Equatorial Atlantic from offshore Ivory Coast (Basile et al., 1998)

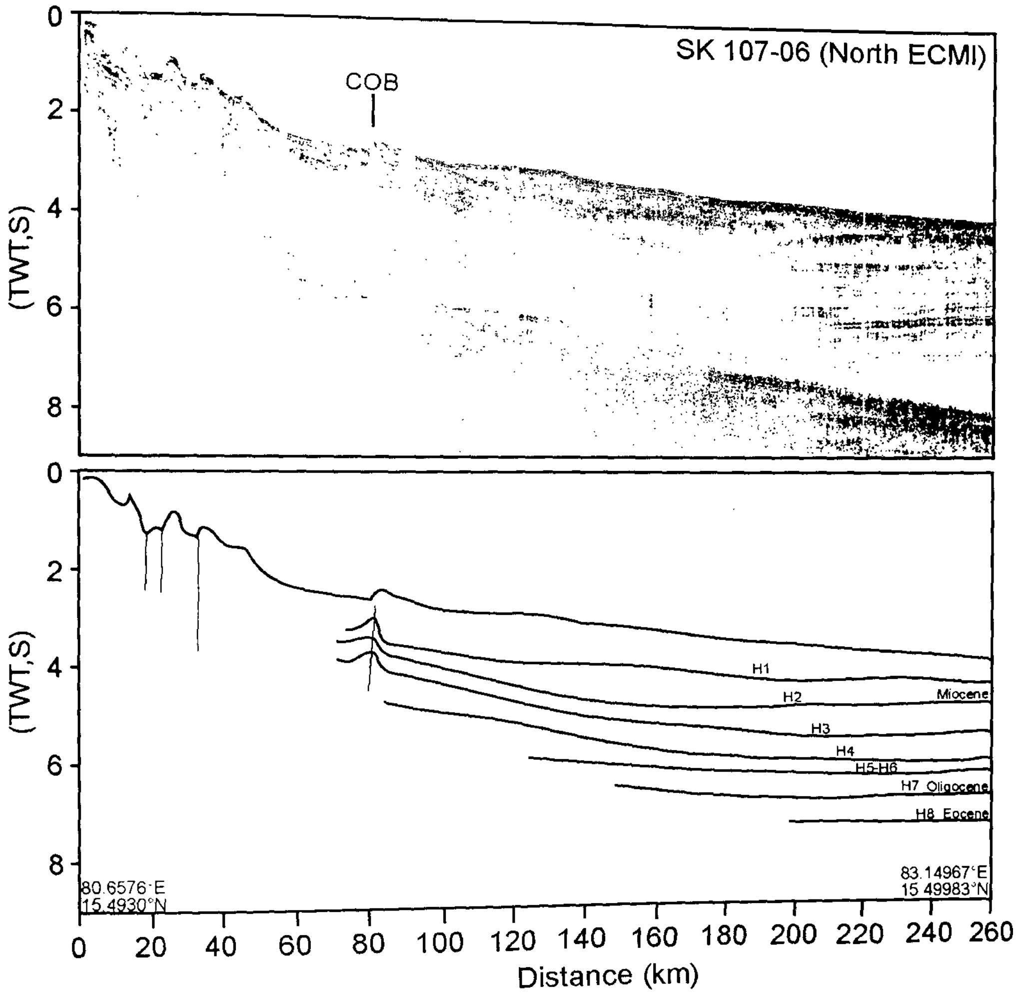


Figure 6.8: Seismic sections and interpreted results of profile SK 107-06 from north segment of Eastern Continental Margin of India are presented to show the internal structure.

6.4 Other Geophysical Characters Associated with South and North Segments of ECMI

From the present work it is observed that normal faulting is less significant on north segment of ECMI, while in the south segment of ECMI, prominent low-angle normal faulting with major slips are observed. From the residual geoid data of the Bay of Bengal (Figure 3.2 in Chapter-3) low-gradient residual geoid data associated with the north margin segment confirms the presence of broad stretch of deformed continental crust (about 2.5 m residual geoid high falls in a distance of about 100 km), while in the south ECMI a narrow stretch of deformed continental crust (1.5 m residual geoid high falls in a distance of about 50 km) is observed. The residual geoidal data gradients also support the interpretations that rifting had taken place on north ECMI and shearing on south ECMI before the continental breakup.

There are several evidences that suggest transform margin character for the margin on south ECMI. Earlier geophysical studies (Chand et al., 2001) have shown that the elastic plate thickness (Te) along the north ECMI is around 10-15 km thickness, while in the South ECMI the Te value is less than 5 km. Based on variable Te values they have inferred that the margin on south ECMI had developed as a consequence of shearing rather than rifting in the early stages of continental separation. In previous seismic studies Sastri et al. (1973) have observed that the trends of the ridge and graben structures on the north margin are parallel to the coastline, while in the south ECMI the structures are oblique trend to the coastline and supports the interpretation of transform margin character for the south ECMI. The studies of Chari et al. (1995) have also confirmed that the lithosphere of the Cauvery Basin has experienced limited extension and provides further evidence for the south ECMI to consider it as transform nature of the margin. For easy understanding of the margin characters and geophysical signatures associated with the south and north segments of ECMI are listed in Table 6.1.

The spreading history of conjugate oceanic regions, south of Sri Lanka and NE of Gunnerus Ridge, western Enderby Basin is not unambiguously known as no correlatable anomalies has become rather difficult and of less confidence. Following the structural fabric of the western Enderby Basin, Nogi et al. (2004) have interpreted the extinct magnetic anomalies are found in both regions. The magnetic anomalies in

Table-6.1-Variable geophysical characters associated with the south and north segments of Eastern Continental Margin of India

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 (Te)	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)

the western Enderby Basin are generally having lower amplitudes, hence identification of spreading centre (M0 anomaly age) and conjugate older oceanic crust at least up to 127 Ma on either side of it. In subsequent studies Gaina et al. (2007) found the difficulty in correlating the spreading history of western Enderby Basin with that of the central and eastern Enderby basins. In other conjugate region, south of Sri Lanka it is found that not more than 500 km oceanic stretch is available between the magnetic lineation 34 and continent-ocean boundary, to confirm that the crust was formed during the Cretaceous Magnetic Quiet Epoch (120-83 Ma) and the period older to it. In recent studies Sreejith et al. (2008) and Jokat et al. (2010) have confirmed that no M-sequence anomalies could be found in offshore region of south of Sri Lanka.

Keeping in view of present observations and discussions on south and north segments of ECMI, it can be believed that transform motion existed between the south ECMI and Enderby Land for a short period before the breakup. This shearing process followed by stretching along the south ECMI might have initiated the rifting process between combined north ECMI-Elan Bank and MacRobertson Land; and between southwest Sri Lanka and Gunnerus Ridge region of East Antarctica. From the studies of Gaina et al. (2003) it has been interpreted that the breakup between unified India-Elan Bank and Antarctica occurred during the chron M9Ny (~130 Ma). Coffin et al. (2002) and Duncan et al. (2002) have interpreted that the high volcanism associated with the Kerguelen hot spot has commenced on the southern Kerguelen plateau at around 119 Ma. A major ridge jump triggered by the massive volcanism of the Kerguelen hot spot positioned between the Elan Bank and north ECMI had detached the bank and transferred along with earliest oceanic lithosphere of the Indian plate to the Antarctic plate at around 110 Ma. ODP Leg 183 drill well (Site 1137) on the Elan Bank has recovered clasts of garnet-biotite gneiss in a fluvial conglomerate intercalated with basaltic flows, which suggest continental origin rocks (Nicolaysen et al., 2001; Weis et al., 2001; Ingle et al., 2002). The deposition of the garnet gneiss clasts within the Elan Bank confirms the proximity of the bank close to the Indian subcontinent (Figure 6.9) and suggests that Elan Bank was connected to the eastern margin of India (around 110 Ma) and the eastward flowing river on the margin of the Indian subcontinent has deposited conglomerate (Nicolaysen et al., 2001).

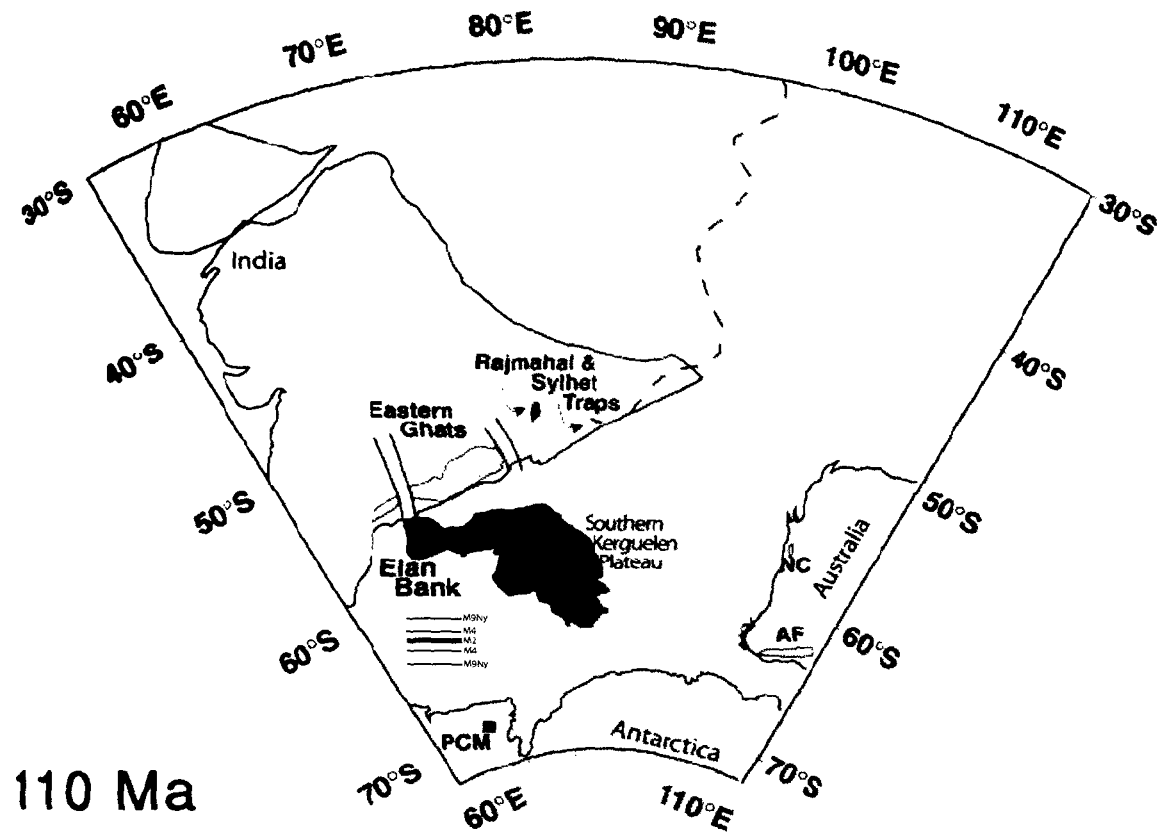


Figure 6.9: Plate tectonic reconstruction of India, Antarctica and Australia together with ocean features Elan Bank and part of Kerguelen plateau ca. 110 Ma (Nicolaysen et al., 2001). Dark gray areas indicate the position of Elan Bank and southern Kerguelen Plateau adjacent to Eastern Continental Margin of India during the early Cretaceous period. Light gray area shows the location of Eastern Ghats approximately between the Krishna-Godavari Basin and Mahanadi Basin, from where the Elan Bank is believed to be splitted and moved to Antarctica plate. Identified pairs of M-sequence magnetic anomalies from M2o to M9Ny and fossil spreading segment are shown in central Enderby basin.

This northward ridge jump between north ECMI and Elan Bank has re-organised the rifting process along the entire eastern margins of India and Sri Lanka during the periods between the anomalies M1 and M0. 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 it can be speculated that the rifting process along the entire ECMI and east of Sri Lanka was re-organized after the ridge jump occurred soon after the formation of anomaly M2o.

A swap in tectonics from shearing to rifting on south ECMI had allowed the margin to have mixed rift transform character. On the other hand, Stagg et al. (2004) have found from their studies that the margin, off Enderby Land (conjugate to south ECMI) was strongly influenced by the mixed rift-transform setting.

6.5 Continent-Ocean Boundary on ECMI

Continent-Ocean Boundary (COB) or Continent-Ocean Transition (COT) marks a location, where granite rocks terminate against the basaltic rocks formed by the mid-oceanic ridge. The feature is exclusively demarcated on passive/ rifted continental margins, whereas this is replaced by the lithospheric plate boundaries on active continental margins. Demarcation of COB along the continental margins provides useful geological information for understanding the evolution of the basins lying in the vicinity of the margins or oceanward. Several geophysical characters such as lateral shift in regional gravity field, changes in magnetic pattern, seaward dipping reflectors, velocity structure, crustal thickness, etc. are in general used as indicators for demarcation of the COB on rifted continental margins.

The bathymetric data along the profiles on north ECMI and south ECMI clearly show the locations of shelf break, slope and foot of the slope. Continental rise is observed with reasonable confidence along the profiles in the north ECMI, while on the south ECMI the rise seems to be non-existence. Shelf break, continental slope and its foot are clearly expressed in free-air gravity anomaly data, the anomaly trend in the vicinity of the margin just follows the trend of the seafloor topography as that was maintaining significant density contrast as opposed to water body along the profiles in the north ECMI and south ECMI. The location where a quick change from relatively short-wavelength low gravity anomaly to broader less significant anomaly is observed is demarcated as the COB along all the profiles in the north ECMI and south ECMI. The location, where gravity character changes significantly indicates the boundary separating lighter material (granite rocks) from denser material (basaltic rocks) on seaward side. Seismic reflections from the basement on south ECMI also support the demarcation of COB on south ECMI. COB lies relatively closer about 50-100 km to the present coastline on south ECMI, whereas along the north ECMI the COB lies more distinct approximately 100-200 km away from the coastline.

CHAPTER 7

Dating of the 85°E Ridge using Marine Magnetic Anomalies

DATING OF THE 85°E RIDGE USING MARINE MAGNETIC ANOMALIES

7.1 Introduction

The 85°E Ridge, one of the prominent aseismic ridges of the northeastern Indian Ocean, extends from the Mahanadi Basin in the north to the Afanasy Nikitin seamount (ANS) in the south (Figure 7.1). The northern part of the ridge (north of 5°N latitude) is buried under thick (up to 4 km) Bengal Fan sediments, whereas in the southern side the ridge structure intermittently rises above the seafloor with structural continuity at subsurface level (Curray et al., 1982; Liu et al., 1982; Curray and Munasinghe, 1991; Gopala Rao et al., 1997; Subrahmanyam et al., 1999; Krishna, 2003; Sreejith et al., 2011; Krishna et al., 2011b). Towards the southeast of Sri Lanka at around 5°N latitude, a westward shift of about 250 km is observed (Figure 7.1). This peculiarity in the ridge track exists only in this case among the hot spot tracks of the Indian Ocean. Such deviations are obviously not observed along other major hot spot related tracks such as the Ninetyeast and Chagos-Laccadive ridges in the Indian Ocean.

The 85°E Ridge has become an unexplainable geological feature in the Indian Ocean largely due to its uncharacteristic negative gravity anomaly and complex magnetic signatures. Therefore the said unusual geophysical characters led researchers to propose numerous postulations for the origin of the 85°E Ridge, each postulation has some strength in the absence of age details of the 85°E Ridge either by deep-sea drilling or by integrated geophysical studies. Earlier works on this aseismic ridge carried out by researchers have been described in detail in Chapter-1. In recent geophysical studies Krishna et al. (2011b) opined that short-lived volcanic activity had initiated the 85°E Ridge in Mahanadi Basin during the late Cretaceous and eventually terminated in the vicinity of already existing main plateau of the ANS in late Palaeocene. In other studies, Bastia et al. (2010a) and Radhakrishna et al. (2010) have also favoured the hot spot activity for the emplacement of the ridge, but the source of the volcanism remains speculative. Following the analogy of negative gravity signature of the Laxmi Ridge in the Arabian Sea and its continental silver interpretation (Naini and Talwani, 1983; Talwani and Reif, 1998; Krishna et al., 2006), it is also possible to view in similar direction of continental origin for the 85°E Ridge. Keeping the continental origin of the 85°E Ridge in view, in recent past petroleum industry has enhanced their geophysical exploration activities in search of hydrocarbons.

Among the theories proposed for the evolution of the 85°E Ridge, the hot spot hypothesis provides most convincing explanations for all anomalous geophysical characters. One important aspect which can resolve the issues related to the evolution and origin of the ridge is determining the age of the ridge by drilling. But the ridge-top is not easily accessible by drilling because of its deep burial under the fan sediments. Keeping these complexities in view, an attempt has been made in the present study to assign ages to the 85°E Ridge using the marine magnetic anomalies. Also seismic reflection and gravity data have been used in order to obtain important inputs related to ridge structure required for magnetic model studies. The major facets dealt are (i) determining the magnetic response of the ridge all along, thereafter to demarcate the spatial extent of positive and negative magnetic signatures, (ii) testing the concept that the 85°E Ridge has been evolved during the period of post-magnetic anomaly 34 and emplaced on oceanic crust created during the Cretaceous Magnetic Quiet Period, and (iii) to ascribe approximate ages to the 85°E Ridge track following the correlation of ridge magnetization pattern to the geomagnetic polarity timescale (Cande and Kent, 1995). Thereupon, the geological processes involved in development of the ridge are discussed in detail in this chapter.

7.2 Tectonic Setting

It is widely accepted that the conjugate ocean regions, Bay of Bengal and Enderby Basin, off East Antarctica have been simultaneously created during the early phase of drifting of Greater India from Australia-Antarctica contiguous landmass. Integrated geophysical studies of both Bay of Bengal and Enderby Basin regions described in detail in Chapter-6 have clearly established that the present day Eastern Continental Margin of India (ECMI) had experienced multiple rifting processes/ breakups. The first break-up of eastern Gondwanaland occurred with the separation of Greater India from Australia and East Antarctica at around 130 Ma. During this separation normal rifting existed between the unified north ECMI-Elan Bank and MacRobertson Land and between southwest Sri Lanka and Gunnerus Ridge region of East Antarctica, while transform motion existed along the other conjugate margin segments, south ECMI and Enderby Land. This transform motion has possibly facilitated the normal rifting in the north and as well in the south until 120 Ma. Approximately during this period the Elan Bank, a small continental piece, detached from the north ECMI and led to reorganization of the entire rifting process along the ECMI. Therefore this tectonic process suggests that most part of the ocean floor lying beneath the Bay of Bengal evolved during the Cretaceous Magnetic Quiet Epoch (120-83 Ma). Subsequently, within the Cretaceous Magnetic Quiet Epoch or probably later both aseismic ridges: 85°E and Ninetyeast ridges have initiated their volcanic emplacement in the Bay of Bengal. This implies that the 85°E Ridge is placed on an oceanic crust formed during the Cretaceous super-long normal polarity phase.

7.3 Geophysical Data

Gravity and magnetic anomaly data are extracted from the several research programmes of the Bay of Bengal and few are extracted from National Geophysical Data Centre (NGDC) database. New multichannel seismic reflection data collected onboard ORV Sagar Kanya along profiles, SK 107-06 and SK 107-07 and previously published profiles (MAN-01 and MAN-03) collected onboard MV Sagar Sandhani are used in the present chapter for model studies. The published seismic reflection profiles across the 85°E Ridge (Krishna, 2003; Bastia et al., 2010b) are also used for describing the continuity of the ridge track.

7.4 The 85°E Ridge - Seismic Structure and Gravity and Magnetic Responses

The 85°E Ridge continuity can easily be traced in satellite derived free-air gravity anomaly map (Figure 7.1) and in ship-borne gravity profile data (Figure 7.2) as prominent negative and positive gravity signatures running from Mahanadi Basin in north to ANS in equatorial region. In gravity profile data (Figure 7.2), the presence of well-developed negative anomaly in succession from profile to profile between 17°N and 7°N has been observed. The amplitudes of the anomalies range from -90 to -40 mGal with a lowest anomaly located at 14°10'N latitude. Earlier Subrahmanyam et al. (1999) and Krishna (2003) have noted the continuity of the negative gravity anomaly towards south up to 5°N, thereupon the anomaly switches to positive.

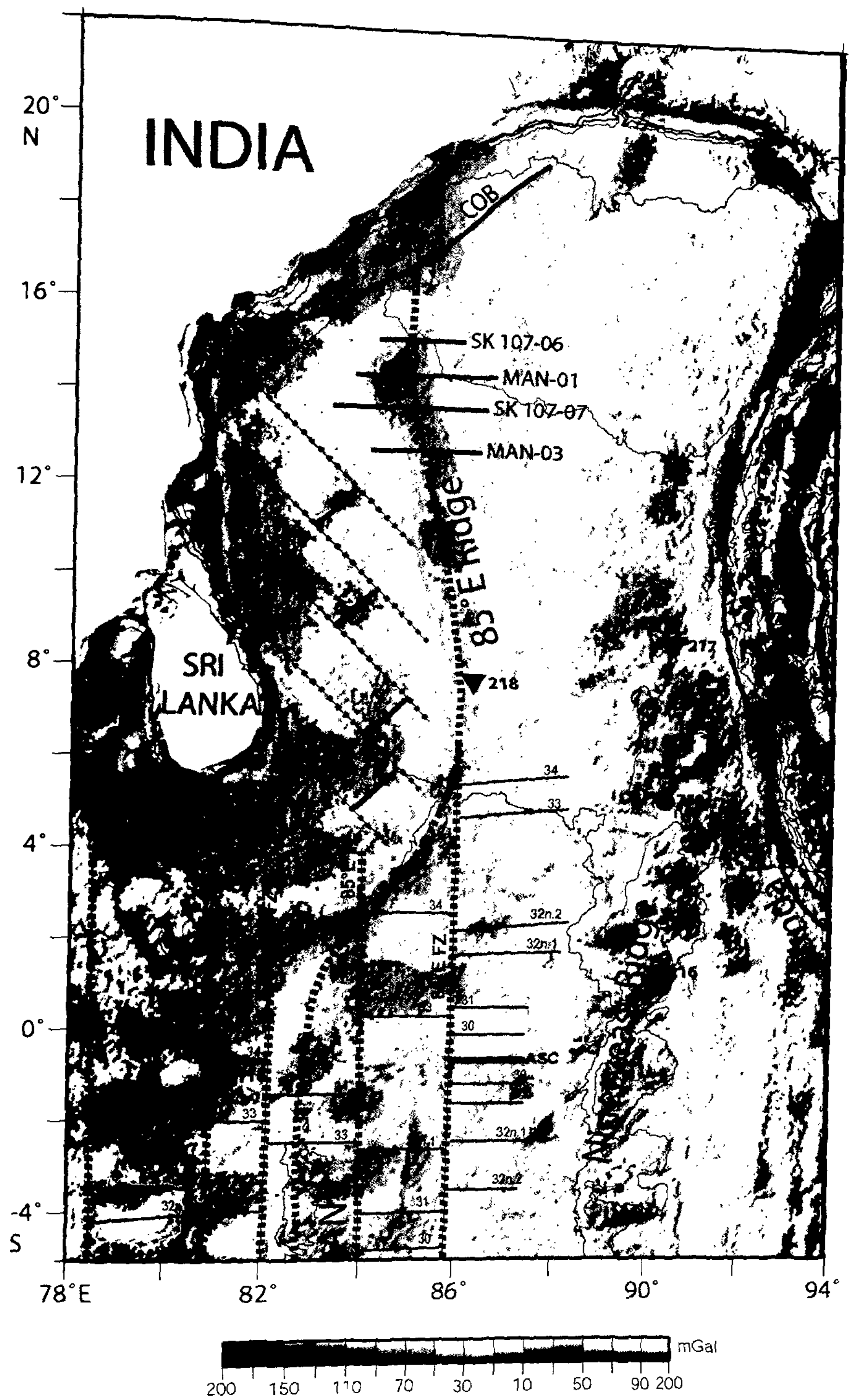


Figure 7.1: Satellite-derived free-air gravity anomaly map of the northeastern Indian Ocean (Sandwell and Smith, 1997). Different tectonic features are posted on the gravity data. Curved strip line indicates the continuity of the 85°E Ridge from Mahanadi Basin to ANS. Few bathymetry contours derived from ETOPO5 data are shown in the map. N-S oriented fracture zones, magnetic lineations from C30 to C34 and fossil ridge segment (FRS) shown in the distal Bengal Fan are adopted from Krishna and Gopala Rao (2000). In the Bay of Bengal region NW-SE trending oceanic fracture zones and COB along the ECMI and Sri Lanka coast are implemented from the present studies. Solid black triangles and circles indicate the DSDP and ODP drill sites, respectively.

Industry quality seismic reflection data and magnetic data in the vicinity of Mahanadi Basin helped Bastia et al. (2010b) and Subrahmanyam et al. (2008b) to trace the northward continuity of the 85°E Ridge in the offshore Mahanadi Basin and further towards the Chilka Lake. Further based on sediment structure Bastia et al. (2010b) reported that the major sediment source during the pre-collision time was from the Mahanadi and Godavari rivers and the 85°E Ridge was the major tectonic feature that controlled the sediment distribution in the Bay of Bengal (Figure 7.3a). The pre-collision sediments consists of pelagic and terrigeneous sediments, whereas the post-collision part mainly consists of Bengal Fan sediments (Curray et al., 1982). And also has reported that prior to soft collision (>59 My), the depositional system has not been active in the north, while the major sediment supply was from the west from the Mahanadi and Godavari rivers. From the published seismic results it can be observed that the ridge continues northward towards the Mahanadi continental slope and shelf of the ECMI.

In distal Bengal Fan region Krishna (2003) has demonstrated the southward continuity of the 85°E Ridge through isolated buried hills and intervening subsurface features towards the ANS (Figure 7.3b). The morphology of the ridge is varying in each seismic section. Keeping seismic and sediment isopach results in view, Krishna (2003) has prepared a sketch map for the basement topography and overlying sediment section along the ridge- apex, buried hills and ANS (Figure 7.3c). The map is compared with interpreted section of the Central Basin along 88°E longitude (Curray, 1991, 1994) to understand the gravity responses associated with the peaks of the ridge structure and the contribution of pre-collision (Eocene) continental sediments. It is observed that along the 85°E Ridge, the basement topography is highly undulating, which clearly indicates uneven eruptions of hot spot. On a general view the ridge basement structure presents two regional trends with a change at 8°N latitude. The ridge is associated with two contrasting signatures, along the north of 9°N latitude the ridge basement peaks are associated with negative gravity signatures, while in the south along the buried hills and along the ANS, positive gravity signatures are noticed. Along the ridge the pre-collision sediments terminate at ~10°N latitude, while the post-collision sediments continue towards south. The change in gravity signature along the 85°E Ridge in the north and south coincides approximately with the termination of pre-collision sediments.

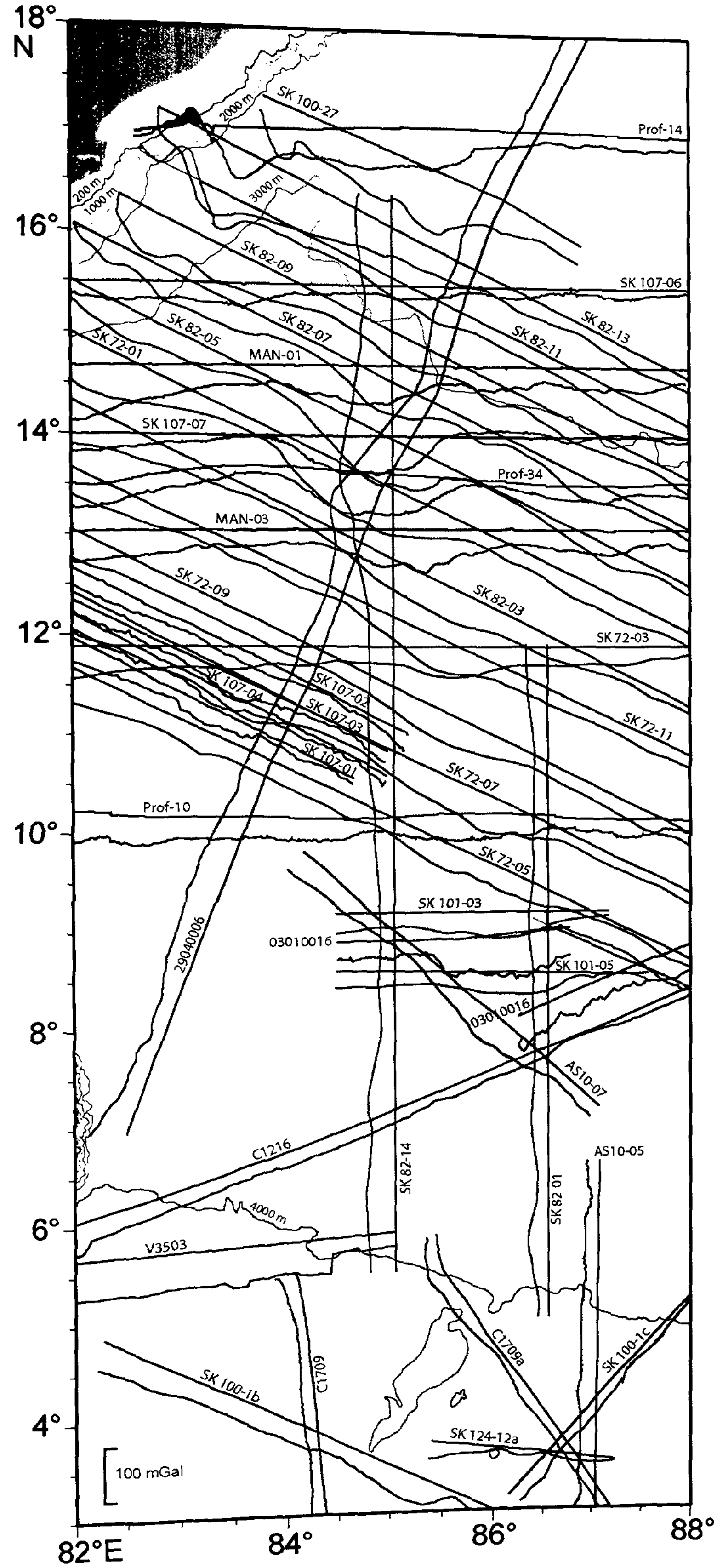


Figure 7.2: Ship-borne free-air gravity anomaly data plotted at right angles to the ship tracks in the vicinity of the 85°E Ridge. Gray shaded portion between the latitudes 84° and 86°E indicates the ridge continuity derived from satellite gravity data.

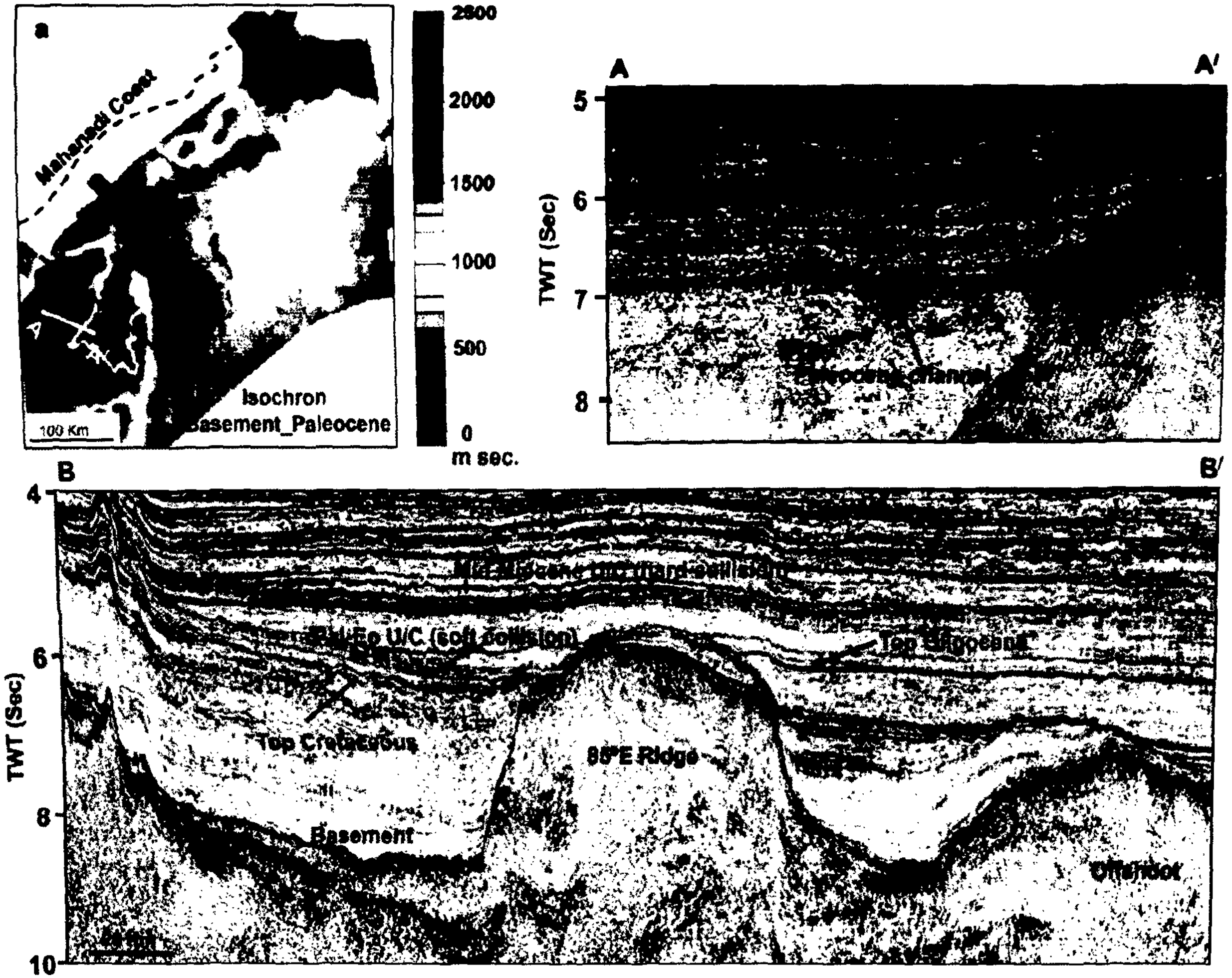


Figure 7.3a: The profile A-A' shows western flank of the 85°E Ridge and sediment character of pre- and post-collisional sediments. Paleocene channel is noticed on top of the Eocene sedimentary horizon. Another profile B-B' shows the ridge morphology and adjacent offshoot structure and intervening mini basin (after Bastia et al., 2010b).

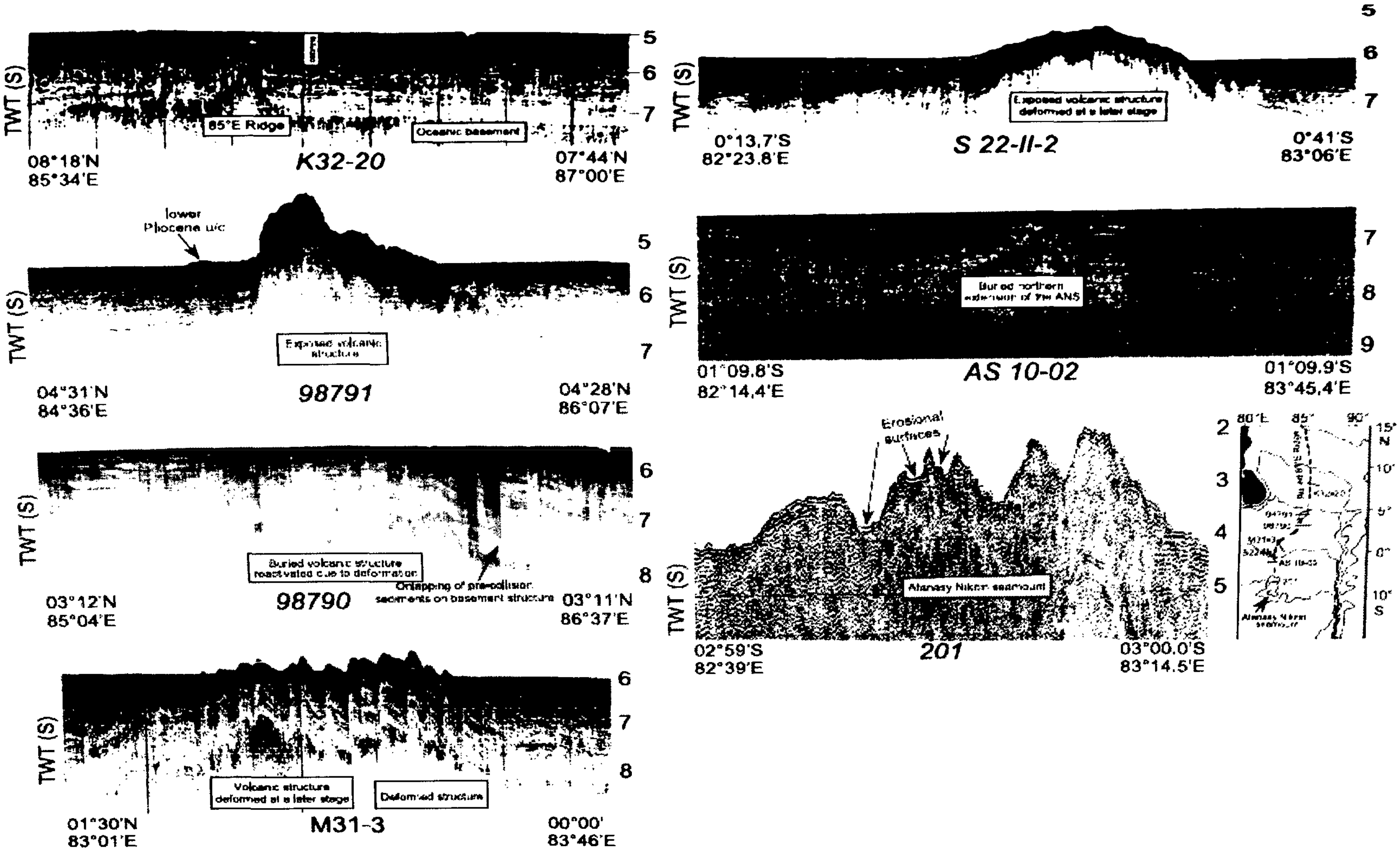


Figure 7.3b: Seismic reflection sections showing the structural continuity of the 85°E Ridge from 8°N latitude to the Afanasy Nikitin seamount (ANS) (after Krishna, 2003).

Four seismic reflection records crossing the 85°E Ridge at various latitudes (15.5°, 14.64°, 14° and 13°N) have been stacked with gravity and magnetic anomaly data (Figure 7.4) for identifying the ridge structure and its contribution in gravity and magnetic data. Also the seismic sections provide information on ridge morphology and sedimentation on top and on either side. From the profiles it can be clearly seen that the ridge is completely buried under the thick Bengal Fan sediments, but the ridge structure and size vary from profile to profile (Figure 7.4). Along the latitudes 15.5°N, 14.64°N and 13°N, it can be seen that the ridge is carpeted by fan sediments having 2.4, 2.8 and 1.7 s two-way travel time (TWT), respectively. While along the latitude 14°N, the ridge reaches to shallower depths and is covered by relatively less thick (about 0.8 s TWT) sediment strata. It is surprising to notice that the ridge structure along latitude 15.5°N is very small with a dimension of about 75 km wide and almost no response is observed in gravity anomaly data (Figure 7.4). Further it is observed that in all four profiles negative gravity anomaly is seen associated with the 85°E Ridge, whereas variable magnetic anomaly signatures are observed along all the profiles. Along 14°N latitude the profile SK 107-07 shows that the ridge is associated with a negative magnetic anomaly, whereas along 13°N latitude on profile MAN-03 the ridge shows positive magnetic anomaly (Figures 7.4 and 7.5a).

Seismic reflection and gravity data across the 85°E Ridge (Figure 7.4) show that prominent negative gravity anomaly is associated with the ridge structure, therefore this specific anomaly character has been used as a criterion for demarcation of the ridge crest and its spatial continuity in the Bay of Bengal. The ridge structure in the north Bay of Bengal region is seen continuing into the Mahanadi Basin (Bastia et al., 2010a), but in the central Bay of Bengal the ridge is completely buried under variable thick Bengal Fan sediments (Curray et al., 1982; Liu et al., 1982; Gopala Rao et al., 1997). For example along 14°N latitude, the ridge is carpeted by about 0.8 s TWT fan sediments, whereas along 13°N about 1.7 s TWT thick sediments overlie the ridge crest (Figure 7.4).

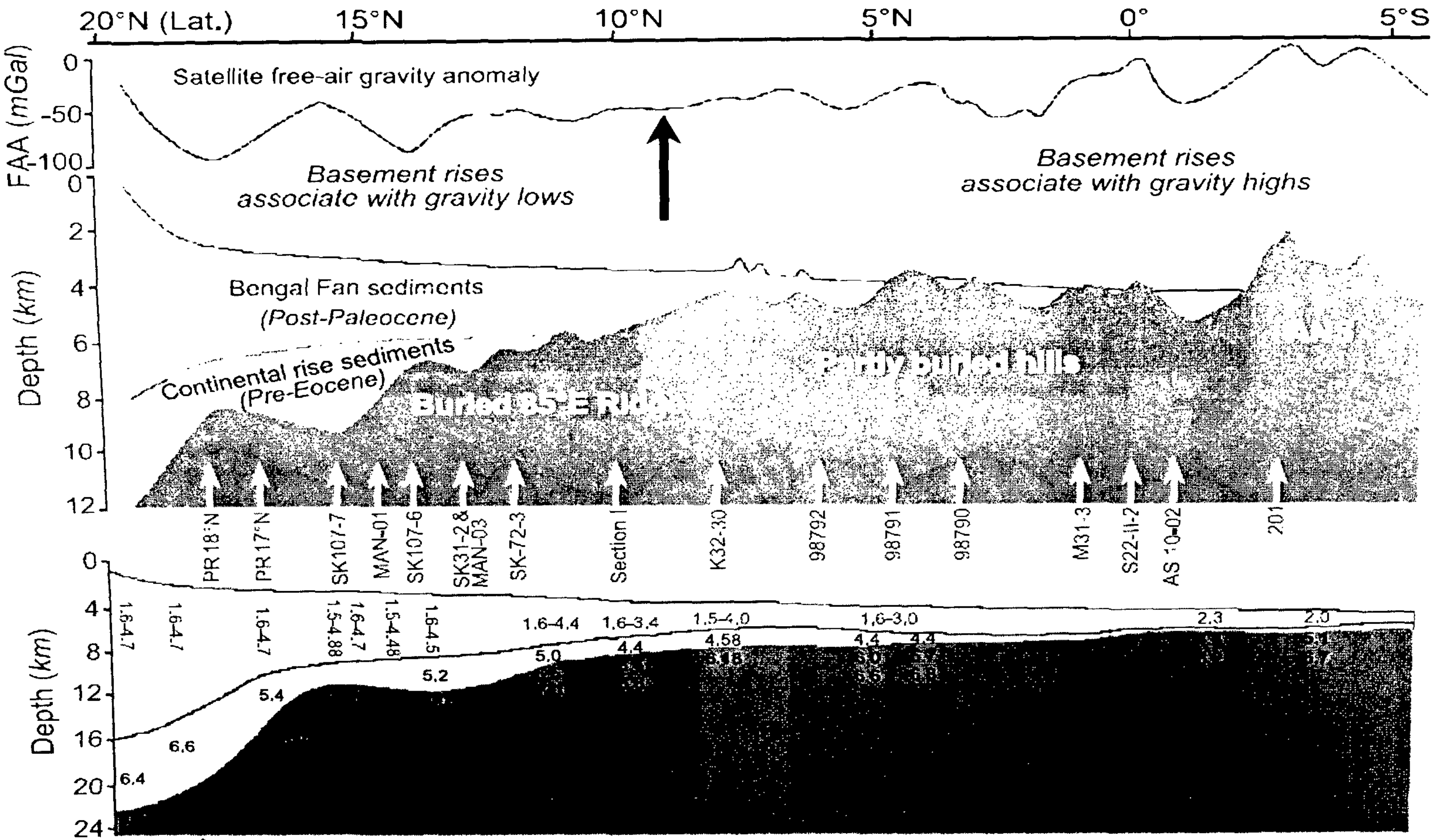


Figure 7.3c: Simplified (sketch) sediment section and basement topography along the 85°E Ridge, buried hills, and ANS constructed from published seismic results and isopachs of pre- and post-collision sediments (after Krishna, 2003). On top of this free-air gravity anomaly is shown for correlations. The bottom section shows the configuration of sediments and basement of Central Basin running along the 88°E longitude.

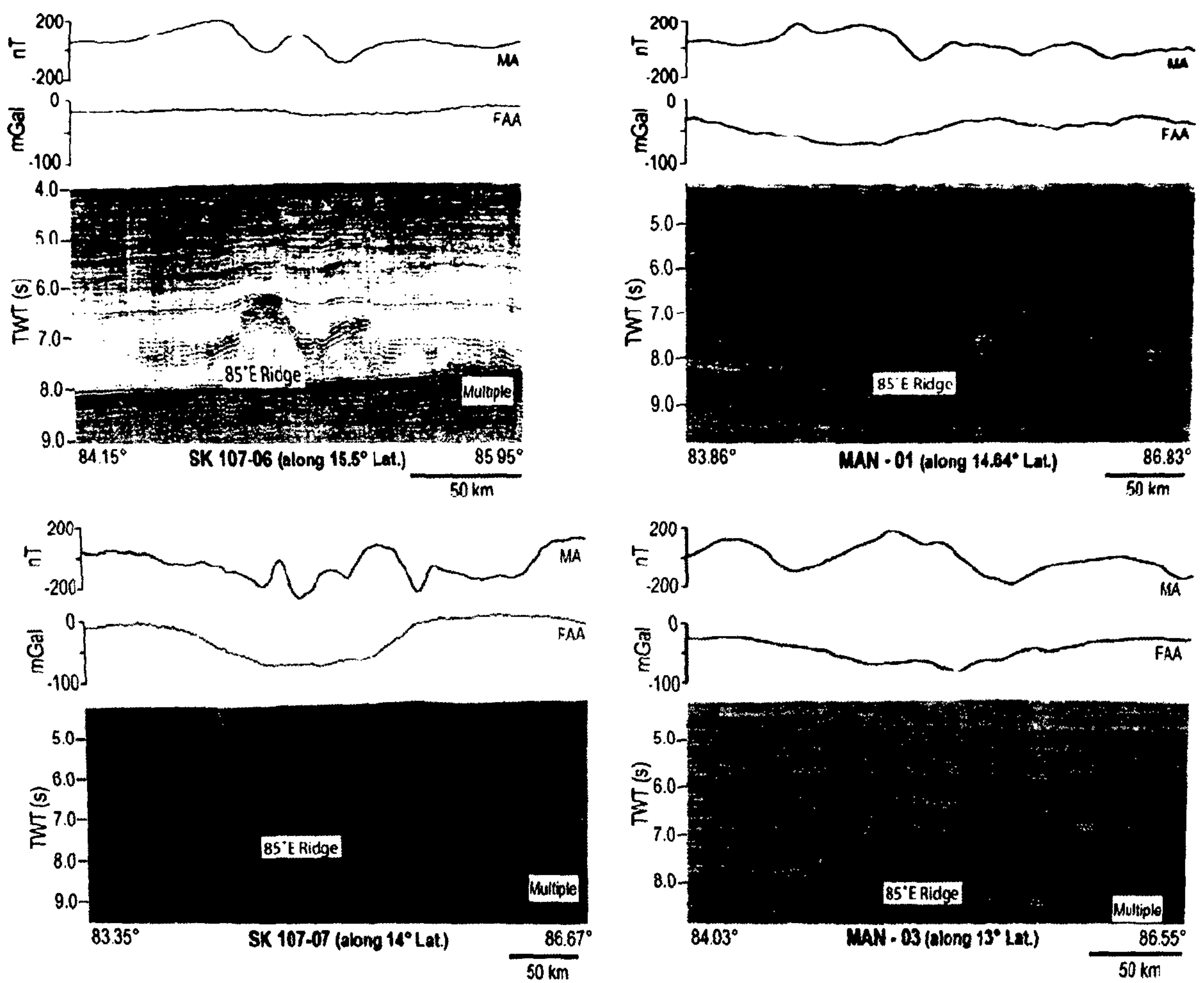


Figure 7.4: Seismic images and gravity and magnetic signatures of the 85°E Ridge along latitudes: 15.5°, 14.64°, 14° and 13°. Seismic data show variable ridge morphology and its depth of burial. The gravity anomaly of the ridge is consistently negative, but its magnetic signatures show variable anomalies. Profiles locations are shown in Figure 7.1

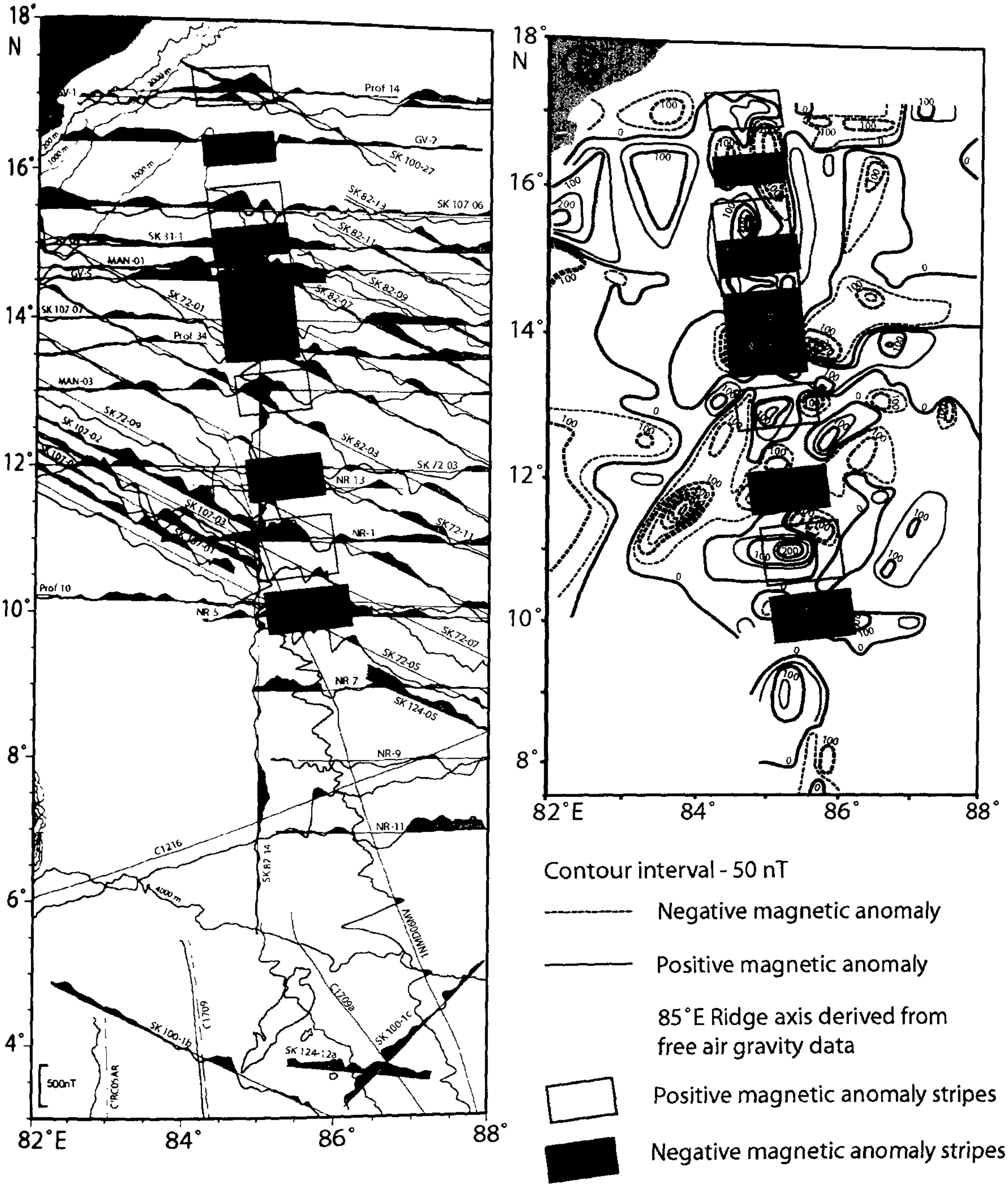


Figure 7.5: Ship-borne magnetic anomaly data of the 85°E Ridge shown in panel A and ship-borne magnetic anomaly contour data with 50 nT interval of the 85°E Ridge is shown in panel B. Gray shaded portion between the latitudes 84° and 86°E indicates the location of the ridge. Yellow and green color blocks shown indicate the locations of positive and negative magnetizations, respectively.

The seismic results together with other published geophysical results (Curray et al., 1982; Gopala Rao et al., 1997; Krishna, 2003; Bastia et al., 2010a) reveal that the ridge morphology including its depth of occurrence is greatly varying along the ridge track. Further, it is found that the ridge in the Bay of Bengal is in general buried under sediments deposited approximately since the Oligocene. The magnetic signatures of the 85°E Ridge track are indeed very complex as described in Chapter-4. Keeping the ridge track recognized from gravity and seismic data as a reference, the magnetic profile data have been examined in order to identify the ridge's magnetic responses (Figures 7.4 and 7.5a). It is found that the ridge is associated with alternate stripes of strong positive and negative magnetic signatures, whose amplitudes range from -400 to 350 nT. In order to have a better view of the alternate stripes of positive and negative magnetic signatures associated with the ridge, the magnetic anomaly data have been contoured at an interval of magnetic intensity 50 nT (Figure 7.5b). For the first time in this present work, suites of five each high amplitude positive and negative magnetic anomalies covering asymmetrical extents have been observed along the strike of the 85°E Ridge feature (Figures 7.5a and b). As an example the negative and positive magnetic anomalies associated with the ridge along 14°N and 13°N latitudes, respectively have been described earlier (Figure 7.4). Apart from these the magnetic anomalies of the Bay of Bengal are in general subdued and no correlations seem to be apparent between the profiles, suggesting that most part of the oceanic crust in the Bay of Bengal was created during the Cretaceous Long Normal Polarity period (120-83 Ma) as discussed in detail in Chapter-4.

7.5 Magnetic Modeling - A Test for the Hot spot Hypothesis

From the present magnetic studies, suites of alternate positive and negative magnetic signatures are observed all along the strike of the 85°E Ridge. In order to delineate the sources for generation of positive and negative magnetic anomalies over the ridge, 2-dimensional forward magnetic modeling has been carried out using the GM-SYS software. Prior to the magnetic modeling work, gravity anomalies along the profiles were modeled (discussed in Chapter-5) and the results were considered for the approximation of initial magnetic models. The magnetic model computation is performed following the method of Talwani and Heirtzler (1964) and is described in detail in Chapter-2. Forward modeling initially involves a creation of a hypothetical geophysical model and calculating its magnetic response. The magnetic anomaly data of two profiles MAN-03 and SK 107-07 running perpendicular to the ridge crest have been considered for modeling studies. The initial model is constrained from the available bathymetry, basement and isopach data from published seismic reflection data (Figure 7.4) and gravity model results discussed in Chapter-5.

Hypothetical magnetic models are considered in this work are shown in Figure 7.6 for explaining how negative and positive magnetic signatures are generated from the ridge's remanent magnetic field. The models show two distinct magnetic signatures along the profiles MAN-03 and SK 107-07 (Figure 7.6) and they consist of three layers water, sediments, ridge material and oceanic crust. The models follow a broad concept that the positive anomaly along the profile MAN-03 is generated solely by the ridge topography and its relief, while the negative anomaly along the profile SK 107-07 is generated due to the magnetic polarity contrast between the ridge rocks and the oceanic crust that are created due to the changes in Earth's magnetization fields.

For model computations, a magnetic layer of approximately 1 km thick oceanic crust with normal magnetic field and ridge structure with reverse magnetic field for negative magnetic anomaly and with normal field for positive anomaly have been considered (Figures 7.7a and b). It is assumed that the ridge magma is extruded through the existing oceanic crust, therefore the mixed oceanic crust and ridge material attain a new Earth's magnetic field prevailed at the time of ridge formation.

For the present model the magnetic basement is assumed below the sediment layer and above the upper part of the crustal layer with a magnetization of 0.008-0.014 emu/cc and susceptibility of 0.003-0.004 cgs units. The intensity of total magnetic field was considered as 42000 gammas. The induced inclination and declination were considered as 12.5° and -2.5°, respectively. The remanent inclinations for oceanic crust 67° and for the ridge material 62° were used in computations by taking into consideration of paleo-latitude of 50°S for the oceanic crust and 43°S for the 85°E Ridge volcanism, respectively (O'Neill et al., 2003), in view of that the 85°E Ridge was emplaced approximately 35 m.y. after the formation of underlying oceanic crust (Krishna, 2003;

Sreejith et al., 2011), while the remanent declination was considered as 40°. With the variation of different parameters within the limits several attempts were made to achieve reasonably best fit models between the observed and calculated anomalies and final models along the pre-collision and post-collision sediments are shown in Figures 7.7a and b.

Computed magnetic model for the profile SK 107-07 is shown in Figure 7.7a, where the oceanic crust was considered its formation in normal magnetic field and 85°E Ridge was in reverse magnetic field. The derived model also suggests that calculated magnetic anomaly best fits with the observed anomaly and corroborates that the 85°E Ridge was formed in the Earth's reverse magnetic field, whereas the oceanic crust was formed earlier during the Cretaceous long normal magnetic field (120-83 Ma). The polarity contrast existing between the ridge rocks and the adjacent oceanic crust is generally producing the negative magnetic anomaly from the ridge feature. Whereas in second magnetic model studies along the profile MAN-03 (Figure 7.7b), for both oceanic crust and 85°E Ridge normal magnetic field were considered.

Model results suggest that the calculated anomaly best fits with the observed anomaly, further validate the formation of both ridge material and the oceanic crust during the normal magnetic field, but in different ages. In this case the positive magnetic anomaly is created solely by the ridge topography and its relief, not by the magnetic polarity contrasts. Following the present results, it can be confirmed that the positive and negative magnetic anomaly belts associated with the 85°E Ridge for asymmetrical extents are generated by the ridge topography and polarity contrast, respectively. Therefore it can be interpreted that the ridge was emplaced over a period, wherein the Earth's magnetic field has changed from normal to reverse and vice-versa, and underlying oceanic crust was formed in a lone normal magnetic field of the Cretaceous Quiet Period. Thus the derived geological model for the 85°E Ridge is consistent with the hypothesis of hot spot volcanism on approximately 35 m.y. aged oceanic crust.

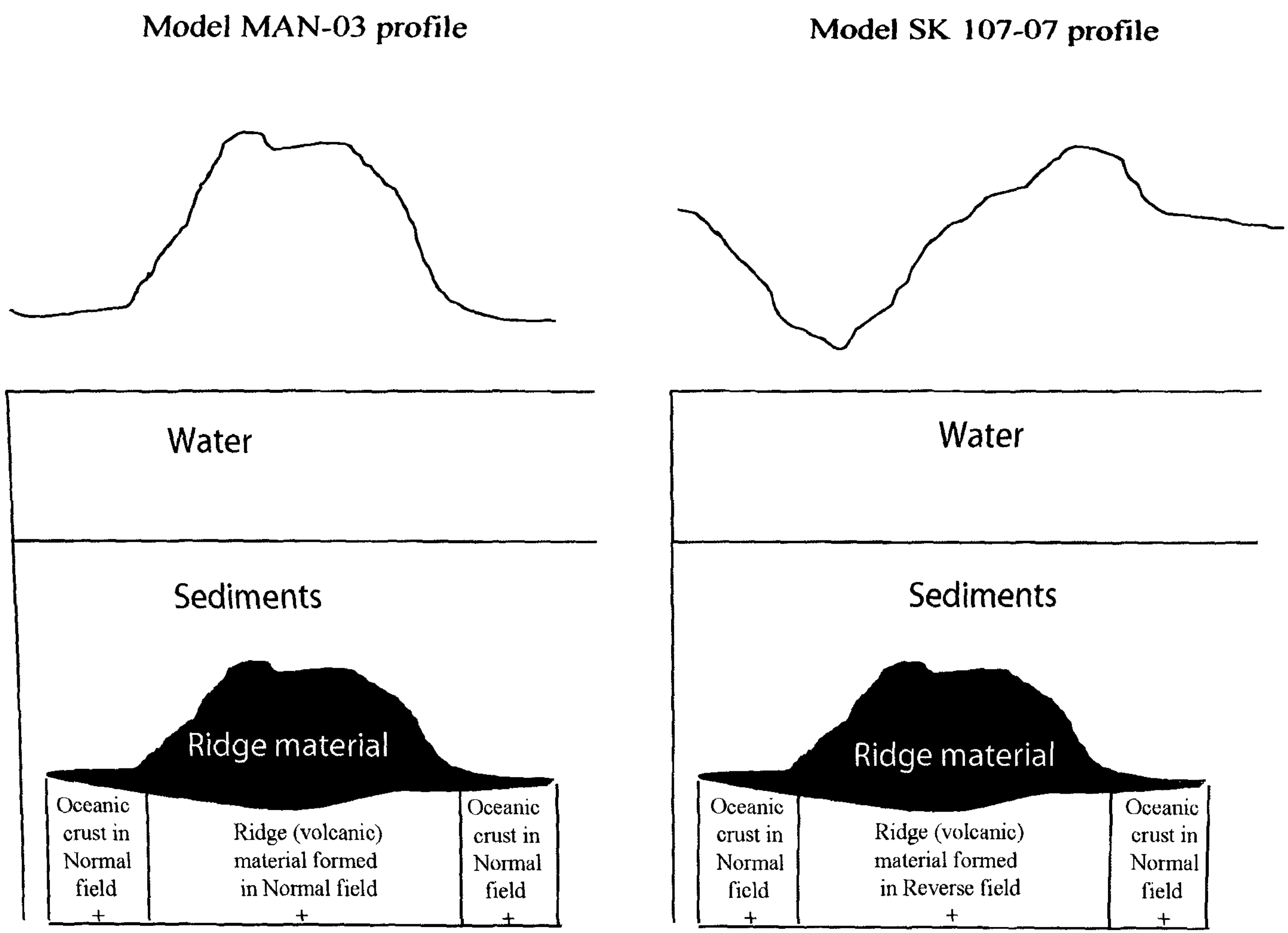


Figure 7.6: Hypothetical magnetic models showing a broad concept that the ridge generates a positive magnetic anomaly solely by ridge topography and its relief (left part), whereas the negative anomaly is created on the whole due to the changes in Earth's magnetization fields (right part).

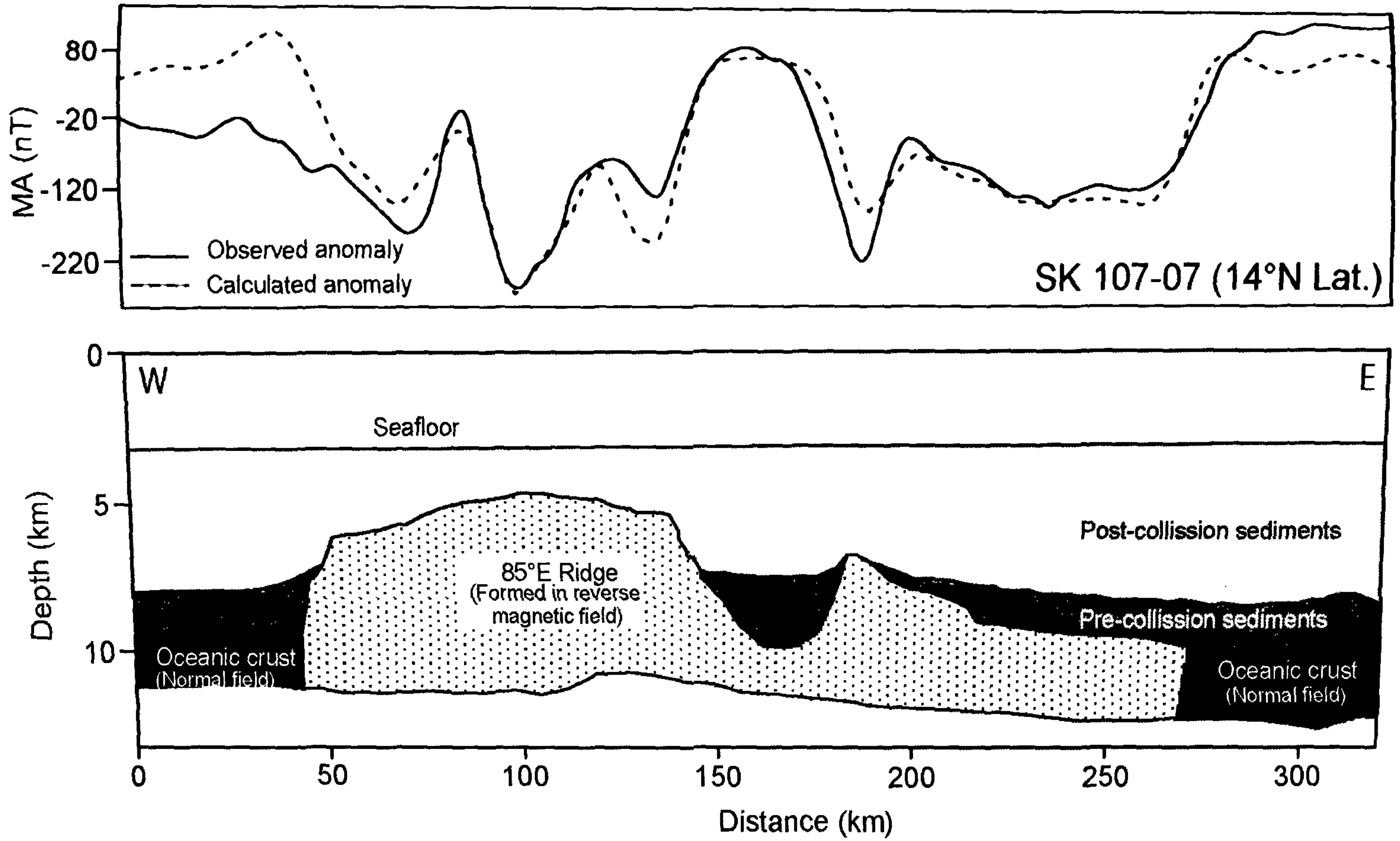


Figure 7.7a: Two-dimensional magnetic model for the profiles SK 107-07 is shown along with pre- and post-collision sedimentary layers. Parameters used in anomaly computations are total magnetic field 42000 nT, remanent magnetization 0.008-0.014 emu/cc, magnetic susceptibility 0.003-0.004 cgs units, inclination for oceanic crust 67° and for the ridge material 62°. Profile location is shown in Figure 7.1

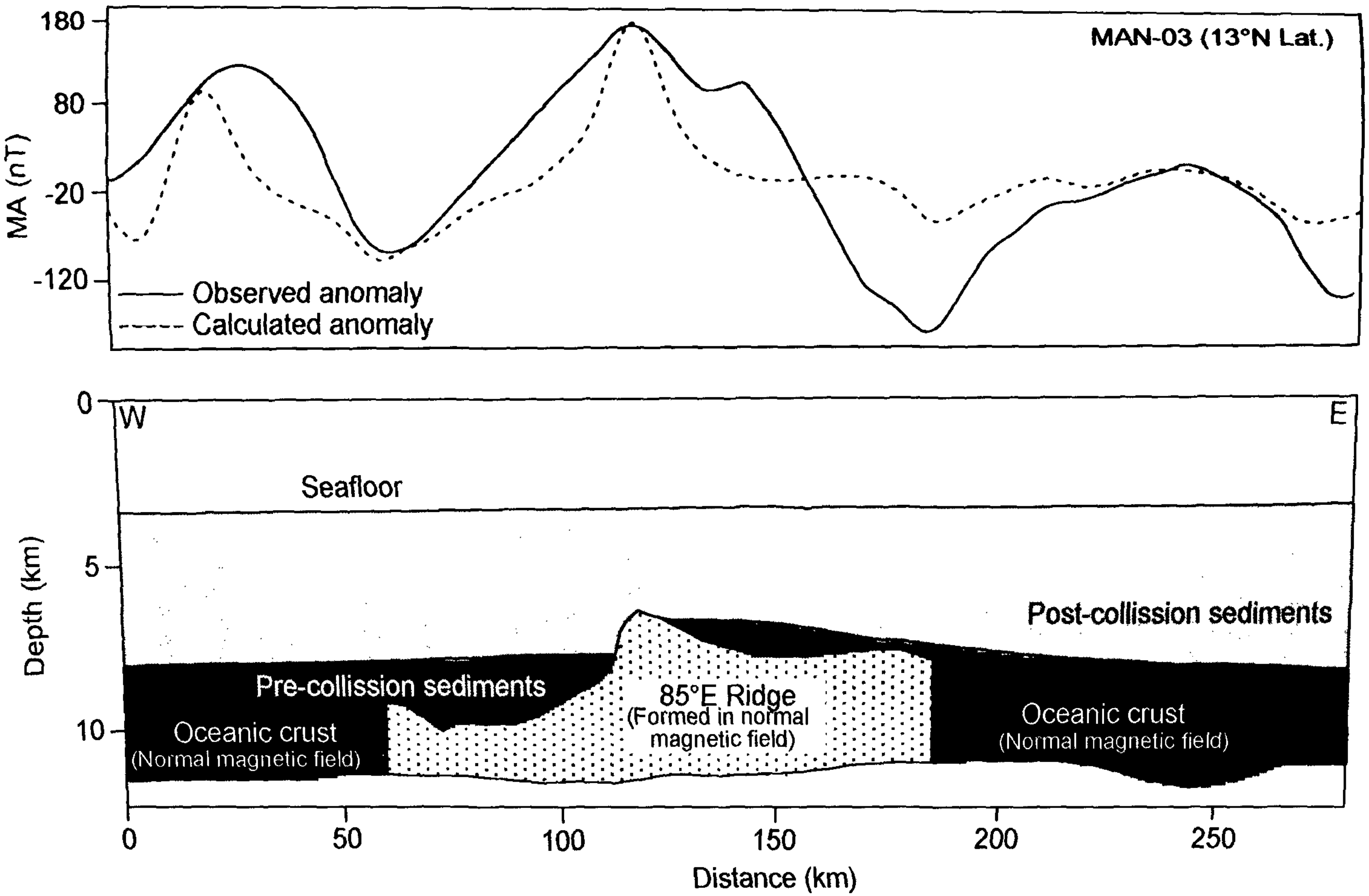


Figure 7.7b: Two-dimensional magnetic model for the profile MAN-03 is shown along with pre-and post-collision sedimentary layers. Parameters used in anomaly computations are total magnetic field 42000 nT, remanent magnetization 0.008-0.014 emu/cc, magnetic susceptibility 0.003-0.004 cgs units, inclination for oceanic crust 67° and for the ridge material 62°. Profile location is shown in Figure 7.1

7.6 Magnetic Pattern of the 85°E Ridge - Correlation with the Geomagnetic Polarity Timescale

In ocean regions marine magnetic anomalies are considered in general as a useful tool to date the oceanic crust, where the crust is unaltered during the period of subsequent geological processes. In some cases in oceanic regions, when the volcanic edifies are formed on already existing ocean crust, it becomes difficult to identify the magnetic signature of the crust as it records the composite magnetic signatures due to mixed sources. For example Ninetyeast Ridge was emplaced by the Kerguelen hot spot during the northward movement of the Indian plate in a N-S direction during the period late Cretaceous to early Cenozoic. So the ridge and the oceanic crust exhibit composite magnetic signature, as a result no systematic magnetic pattern can be identified over the Ninetyeast Ridge track (Krishna et al., 1995; 2011a). In contrast, the 85°E Ridge has formed on approximately 35 m.y. old oceanic crust created during the Cretaceous Magnetic Quiet Period (120-83 Ma). Therefore the ridge magnetic signatures are expected to be remained as strong as the observed one (Figures 7.4, 7.5a and 7.5b). From the magnetic data, five each alternate positive and negative magnetic anomaly stripes over the 85°E Ridge covering for asymmetrical extents have been identified from the present studies. And from the model studies, it has been interpreted that the positive and negative magnetic anomalies were generated by the ridge material which was formed during the normal and reversed magnetic fields, respectively.

In order to assign approximate ages to the 85°E Ridge, the identified magnetic stripes of the ridge are compared to the Geomagnetic Polarity Timescale of Cande and Kent (1995). The half-spreading rates ranging from 2.1 to 2.7 cm/yr have been considered and the geomagnetic polarity timescale (Cande and Kent, 1995) from the period 33r to 28r has been used to create the synthetic magnetic anomaly profile. MATLAB based MODMAG algorithm was used for generation of synthetic magnetic anomaly profile (Mendel et al., 2005) and the profile has been compared with the magnetic anomaly profile along the ridge for correlations. The magnetic anomaly profile data along the ridge from north to south has been extracted from the magnetic anomaly contour data (Figure 7.5b). This helps in identification of approximate spreading type magnetic anomaly numbers, thereby assigning age to the ridge. The reversed magnetic block for the chron 33r is correlatable to the negative magnetic signature of the ridge identified in the Mahanadi Basin (Subrahmanyam et al., 2008b). Rest of the polarity blocks correlated to the chrons 33n to 28r come from the present study. The solid and the open blocks show the normal and reversed magnetic polarities (Figure 7.8). The dotted blocks represent the locations where the magnetic data are absent for the identification of magnetizations. On careful examination, it has been found that the distribution of observed normal and reversed magnetization patterns seems to be consistent with the intervals of Earth's geomagnetic polarities corresponding to the magnetic chrons 33r through 28r (Figure 7.8). Also it can be observed that the identified negative magnetic anomalies are in good correlation between the synthetic and observed anomaly profiles and are shown with shaded box in Figure 7.8.

From the correlations (Figure 7.8) it can fairly be suggested that the 85°E Ridge was initiated in the Mahanadi Basin during the magnetic chron 33r time (~80 Ma) and the ridge volcanism continued towards south through 9°N latitude at magnetic chron 28r (~64 Ma). Earlier Maia et al. (2005) have used similar methodology to date the volcanic edifices of the Foundation seamount chain, close to Pacific-Antarctica Ridge. In this work they have determined the age constraints using the magnetic anomalies and found that the ages, thus deduced are in good agreement with the radiometric dating. Therefore it can be believed that the ages deduced from the magnetic pattern of the 85°E Ridge in the present work are reasonably fair and may possibly be considered as key tectonic constraints for better understanding the evolution of the 85°E Ridge and northeastern Indian Ocean.

A sketch diagram is shown for illustrating the models discussed for ages 83-73 Ma and 55 Ma (Figure 7.9). The ANS plateau and Marion Dufresene seamount were emplaced nearly at the same time by a short-lived hot spot close to the ridge crest of the India-Antarctica Ridge at around 80 Ma (Krishna et al., 2011b). Concurrently another short-lived hot spot had started its activity in the northern Bay of Bengal and that led to the construction of the 85°E Ridge on already evolved and relatively older (35 m.y.) oceanic lithosphere (Figure 7.9). As the spreading process was in progress, the hot spot lying close to the India-Antarctica Ridge, had moved to the Antarctica plate.

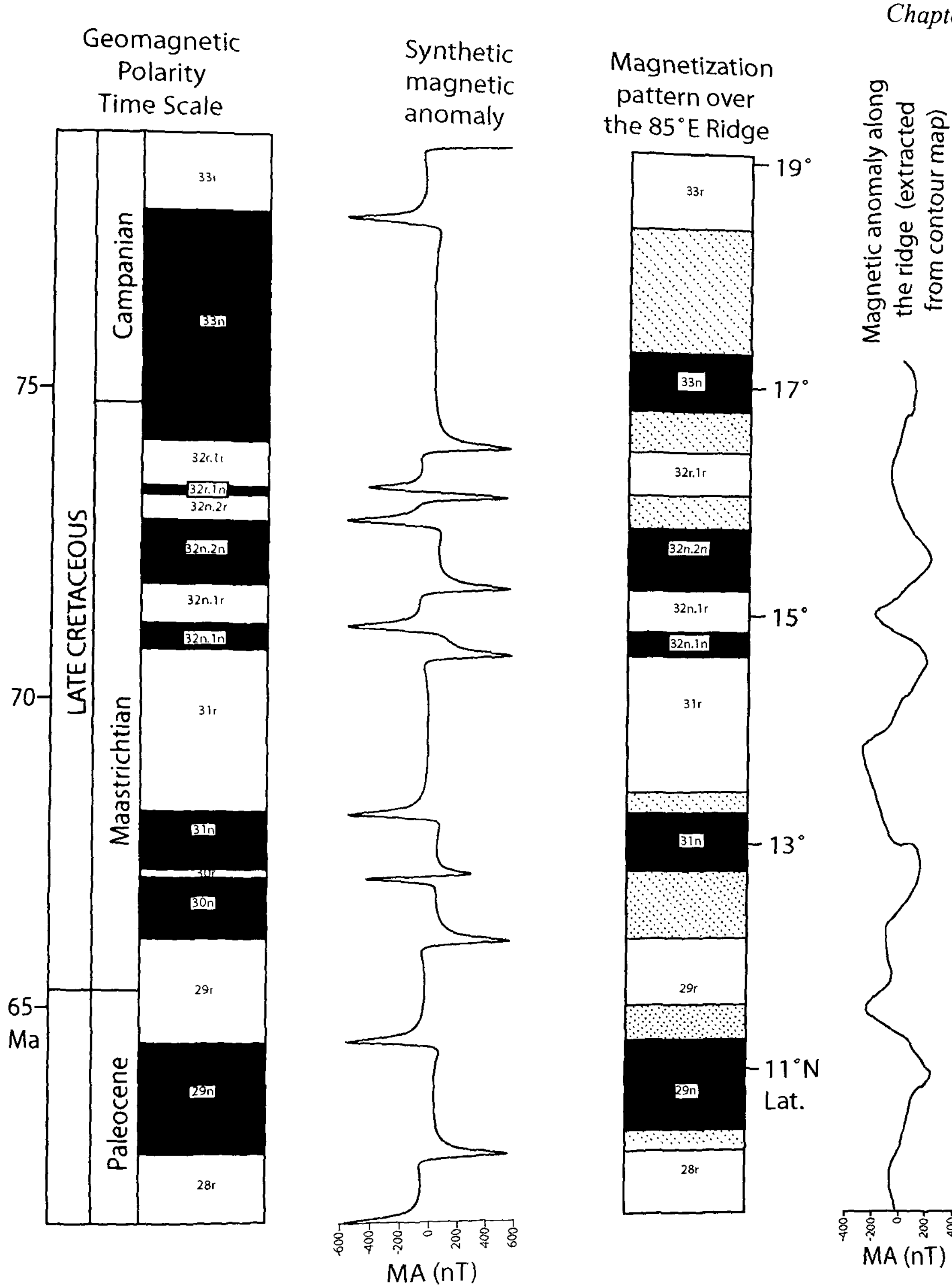


Figure 7.8: Magnetization pattern of the 85°E Ridge correlated to the Geomagnetic Polarity Timescale of Cande and Kent (1995). Solid and open blocks show the normal and reversed magnetic polarities. Dotted blocks show the locations, where magnetic data are absent for identification of magnetizations. Synthetic magnetic anomaly profile prepared for magnetic chrons 33r-28r is shown to the right side of the polarity timescale. Profile data extracted from the observed magnetic anomaly contour data is shown to the right side of the observed magnetic anomaly stripes. Shaded boxes indicate the correlation of identified negative magnetic anomalies between the synthetic and observed anomaly profiles.

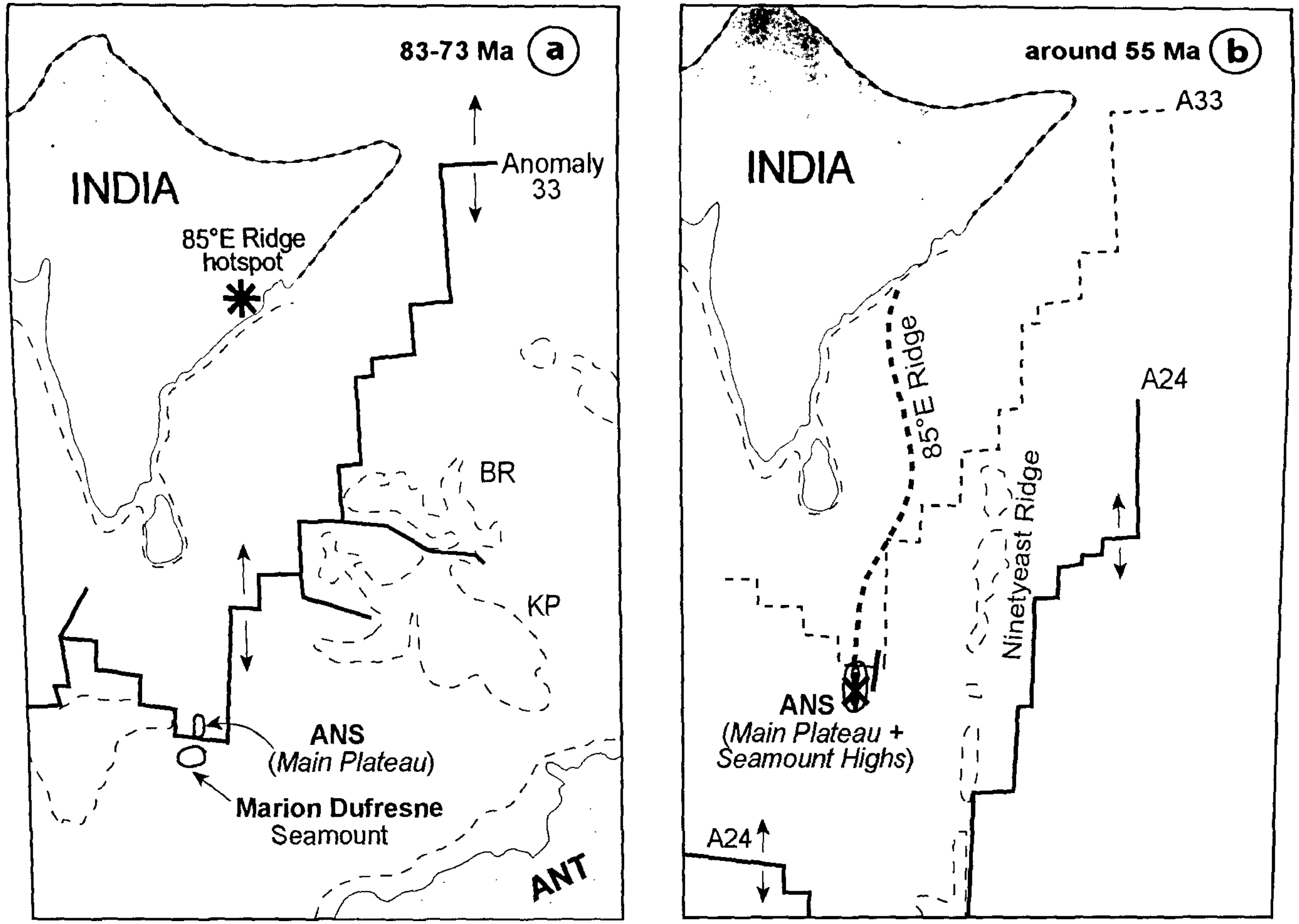


Figure 7.9: Sketch diagram of the formation of the 85°E Ridge through time. a, Initial emplacement of the 85°E Ridge in the vicinity of Mahanadi Basin and emplacement of the main plateau of the ANS and Marion Dufresne seamount near the India- Antarctica Ridge between 83 and 73 Ma. b, Interaction of the 85°E Ridge hot spot with the already existing main plateau at about 55 Ma. BR, Broken Ridge; KP, Kerguelen plateau

Another hot spot that started its activity close to the Mahanadi Basin interacted with the already existing seamount plateau (ANS) in Paleocene age (Figure 7.9) and brought it to the shallow water environment. Thus the hot spot activity has modified the ANS plateau with inclusion of seamount highs (Krishna et al., 2011b). It can also be noted that there is no southward continuity of the structure (85°E Ridge-buried hills-ANS) in the central Indian Basin.

7.7 Summary and Conclusions

Analysis of the marine magnetic data of the 85°E Ridge has clearly demonstrated that the ridge is associated with alternate positive and negative magnetic signatures distributed for asymmetrical extents. For the first time the distribution of normal and reversed magnetization pattern has been identified under the firm control of gravity and seismic results. Recent understanding on evolution of the conjugate oceanic regions of Bay of Bengal and Enderby Basin (Gaina et al., 2007) and results from previous chapters show that the most part of the oceanic crust in the Bay of Bengal was accreted during the Cretaceous super long normal polarity phase. Also the studies of Sreejith et al. (2011) have reported the intermediate elastic plate thickness (10-15 km) which strongly supports the emplacement of the ridge on an oceanic crust of about 35 m.y old.

Magnetic modeling of the ridge reveals that positive and negative magnetization suites are generated, in general, by the ridge topography and polarity contrast, respectively. Considering the magnetization pattern of the 85°E Ridge and age of the underlying oceanic crust, it can be interpreted that the ridge was emplaced over a period, wherein Earth's magnetic field has changed from normal to reverse and vice-versa, and underlying oceanic crust was formed in a lone normal magnetic field of Cretaceous Quiet Period. Thus the derived geological model for the 85°E Ridge is consistent with the hypothesis of hot spot volcanism on approximately 35 m.y. old oceanic crust. Correlation of the ridge magnetic stripes to the Geomagnetic Polarity Timescale of Cande and Kent (1995) suggested that the distributed normal and reversed magnetization pattern resembles with the intervals of Earth's geomagnetic polarities related to the magnetic chrons from 33r to 28r. Therefore the present study supports the origin of the 85°E Ridge by a hot spot volcanism on already evolved oceanic crust of approximately 35 m.y. old.

The results obtained in this work are integrated with the earlier geophysical results of the 85°E Ridge (Krishna, 2003; Krishna et al., 2011b) and Conrad Rise (Diament and Goslin, 1986), and with the geochronology of the rocks recovered from the ANS (Sborshchikov et al., 1995) in order to understand the evolution of the ridge and ANS in a broader perspective. The 85°E Ridge volcanism started approximately 80 Ma ago in Mahanadi Basin by a short-lived hot spot. Around this period the Conrad Rise hot spot had emplaced the main plateau of the ANS and Marion Dufresene seamount together close to the India-Antarctica Ridge, thereafter the hot spot moved to the Antarctica plate leaving the plateau of the ANS as an isolated feature on the Indian plate. At other end in the Bay of Bengal the hot spot continued the process towards south and finally ended at ~55 Ma in the vicinity of the ANS. Thus the ANS was built by two short-lived hot spots in two phases, largely in late Cretaceous and a minor component in the Paleocene as an end product of the 85°E Ridge.

CHAPTER 8

Summary and conclusions

SUMMARY AND CONCLUSIONS

8.1 Introduction

The present research work was carried out with a broad objective of studying conjugate margins and adjoining oceanic basins - the Bay of Bengal and Enderby Basin – for understanding the rift initiation within the eastern Gondwanaland and early spreading activity adjoining the Eastern Continental Margin of India (ECMI) and East Antarctica, thereby classifying the continental margin segments on both ECMI and East Antarctica. Detailed analyses of bathymetry, magnetic, satellite and ship-borne gravity and seismic reflection data of the conjugate regions - Bay of Bengal and Enderby Basin - have been carried out and modeled important geophysical anomalies for determination of causative sources and for delineation of tectonic elements helpful for reconstruction of the oceanic basins and continental margins. Also the work has vividly shown the importance of the satellite altimeter data such as classical geoid, residual geoid and gravity anomaly data in deriving the hitherto unknown tectonic constraints related to the continental rifting and evolution of the oceanic regions. Otherwise ship-borne geophysical datasets alone, particularly free-air gravity data would not have been revealed the presence of early Cretaceous oceanic fracture zones and stretches of continental deformation on both ECMI and East Antarctica margin segments. Further the gravity data were segmented into different wavelength components with a view to qualitatively visualize the causative sources contributing to the anomalies and modeled for determining the crustal structure across the Bay of Bengal from ECMI to Andaman Islands and across the Enderby Basin from MacRobertson Land to northward of the Elan Bank. A special focus was paid over the 85°E Ridge structure in Bay of Bengal in order to understand the anomalous geophysical characters and origin of the ridge, thereby assign possible ages using marine magnetic anomalies. The summary of the work presented in this thesis and important conclusions obtained are discussed below.

8.2 Discussions and Conclusions of the Present Research Work

The classical and residual geoid data of the Bay of Bengal and Enderby Basin regions were analysed with a view to map and understand the geophysical signatures associated with geological/ tectonic features lying at different depths inside the Earth. The classical geoid data of 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 with a gradual decrease of approximately 39 mm/km towards the south of Sri Lanka. In the vicinity of continental margin close to south ECMI and Sri Lanka two geoidal lows up to -98 m and -104 m with variable wavelengths are observed. Both lows are extremely dominant in the Bay of Bengal and have influenced the geoid data for most part of the region trending toward the lows.

The residual geoid data, in general, are sensible to the geological structures lying within the crust and to the topography of crust-mantle interface. Residual geoidal lows up to 1 m are observed over the buried 85°E Ridge (north of 5°N latitude) in the Bay of Bengal. In contrast, residual geoidal highs are noticed over the southern part of the 85°E Ridge. Thus the 85°E Ridge possesses two residual geoid signatures with negative anomaly associated with buried part of the ridge in the Bay of Bengal and positive anomaly associated with intermittently exposed structures of the ridge toward south. Intriguingly the signatures are in agreement with free-air gravity results of Subrahmanyam et al. (1999) and Krishna (2003), wherein they have reported change in gravity field from negative, associated with the buried 85°E Ridge, to positive, associated with partly buried structures and the Afanasy Nikitin seamount. Deepening of oceanic basement toward north due to excess thickness of pre-collision and post-collision sedimentary rocks is also observed in residual geoid data between the Ninetyeast and 85°E ridges which changes from 12.5 m at 4°S latitude to -6.5 m at 13°N latitude. Further low residual geoid anomalies are identified at five places between the 85°E Ridge and south ECMI trending approximately in NE-SW direction.

The geoid height data of the Enderby Basin, East Antarctica revealed that the basin has three 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. Further the sub-basins are bordered by lineated geoidal highs along 47°E and 58°E longitudes. The geoid data patterns indicate the direction of the flow lines of early Cretaceous plate motions and direction of seafloor spreading that prevailed during the early drift stage of India from East Antarctica.

Satellite derived free-air gravity anomaly data and ship-borne gravity profile data of the Bay of Bengal show prominent gravity signatures associated with the major geological/ tectonic features. Prominent feature among them is the 85°E Ridge, running from the Mahanadi Basin to the Afanasy Nikitin seamount. The gravity data, in general, decrease toward the continental margin, as reported earlier suggests that the trend seems to associate with the deepening of the seafloor as well oceanic basement. The magnitude of the gravity low associated with the 85°E Ridge is varying along the strike of the ridge from north to south. The low-gravity anomalies of the 85°E Ridge switch over to gravity highs toward south of 5°N latitude; the change was attributed to coincide with termination/ thinning of pre-collision continental sediments in the Bay of Bengal (Krishna, 2003). In the 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, display two distinct (low and high) gravity signatures. Besides these regional structures, steep gradient gravity anomalies are also observed along the continental slope of eastern margin of India and Sri Lanka. The presence of NW-SE trending narrow gravity features and approximately NE-SW trending low-gravity anomaly closures are found between the 85°E Ridge and south ECMI. This is the first time close to ECMI oceanic fracture zones related to early rift of ECMI from East Antarctica have been identified with confidence. Toward the immediate southeast of the 85°E Ridge two prominent nearly N-S trending FZs (85°E FZ and 86°E FZ) are seen extending into the Bay of Bengal up to 6°N and 9°N, respectively.

Along the East Antarctica margin region the satellite derived free-air gravity anomaly data shows prominent gravity lineations corresponding to spreading related fracture zones in the Enderby Basin, in southeast of the Crozet plateau and in the Australian-Antarctic Basin. The most prominent one is the Kerguelen FZ runs in NE-SW direction between the Conrad Rise and the Kerguelen plateau. Towards the east of Crozet plateau, the satellite map showed the presence of three fracture zones, which run parallel to the trend of the Kerguelen FZ. The fracture zones express the northward motion of the Indian plate from the late Cretaceous to early Tertiary period and are also interpreted as the conjugate features of 85°E FZ, 82°E FZ, 80°E FZ and 79°E FZ in the Central Indian Basin. Further two sets of fracture zones were observed in the western Enderby Basin, with one set trending in NNE-SSW direction close to Gunnerus Ridge and the other set consisting of five fracture zones that trend in ~N4°E direction between the Enderby Land and the Kerguelen FZ.

The satellite gravity map of the Bay of Bengal reveals the presence of 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. It is found that the five FZs meet the 86°E FZ at an angle of ~39°. The NE-SW trending gravity and geoid anomaly closures are oriented orthogonal to the FZs pattern. While in the western Enderby Basin it is found that N4°E trending five fracture zones meet the Kerguelen FZ at an angle of ~37°. From the configuration of fractures zones mapped in the Bay of Bengal and Enderby Basin, it is found that the earliest oceanic FZs are converged on 86°E FZ and Kerguelen FZ at a common azimuth of 37°-39°. Therefore it is interpreted that the fractures zones identified in both the regions - Bay of Bengal and Enderby Basin - are conjugate and were evolved after rifting of the south ECMI from the Enderby Land during the early Cretaceous period. The structural rises which are found between the FZs of the Bay of Bengal may represent fossil ridge segments, which possibly have become extinct during the early evolution of the Bay of Bengal lithosphere or may have formed due to a volcanic activity during the accretion of the 85°E Ridge by a hot spot.

In order to emphasize the similarities and deviations exist in geophysical signatures of two conjugate rifted continental margins – north ECMI and off MacRobertson Land - two representative geophysical profiles consist of gravity, magnetic and seismic results from both the margins are compared. The magnetic signatures observed in both regions are entirely dissimilar, suggesting that the crust was evolved in different geological ages. Pairs of M-sequence anomalies M2o through M9Ny and a fossil ridge segment are identified in the central Enderby Basin, while no significant magnetic anomalies corresponding to the Earth's magnetic reversals are observed on profile from the Bay of Bengal. The M-sequence 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 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 and transferred along with earliest oceanic lithosphere of the Indian plate to the Antarctic plate. The ridge jump placed the Kerguelen hot spot in Antarctic plate for emplacement of the Kerguelen plateau. Keeping these geological sequences in view, it can be believed that 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 and beneath the central and northern Kerguelen plateau.

The magnetic anomaly profiles of the Bay of Bengal and distal Bengal Fan, on correlation to the synthetic model profile, show the presence of seafloor spreading type anomalies 30 through 34 in equatorial region. While on profiles north of magnetic anomaly 34, no correlatable magnetic anomalies are observed, which suggested that this part of the oceanic crust was formed during the Cretaceous Long Normal Polarity Chron (prior to 83 Ma). 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 and fossil ridge segment (FRS). In the Bay of Bengal, particularly close to the Eastern Continental Margin of India no coherent magnetic anomalies from profile to profile are obviously observed. But, along the 85°E Ridge suites of high amplitude positive and negative magnetic anomalies are observed.

Gravity forward modeling has been carried out along selected profiles from Bay of Bengal and Enderby Basin, where seismic reflection data are available. The derived crustal models across the Bay of Bengal indicate the presence of excess thickening of the crust beneath the 85°E Ridge, Ninetyeast Ridge and isolated features between the FZs of the Western Basin. Whereas the gravity model across central Enderby Basin and Elan Bank clearly demarcates the locations of the Continent- Ocean Boundary (COB) on both sides of the Elan Bank and on East Antarctica margin. Further the model confirms the continental nature of the crust beneath the Elan Bank with a crustal thickness of about 16 km.

The segments of Eastern Continental Margin of India (ECMI) have been investigated based on the information derived from bathymetry, gravity and seismic reflection data. Stacked geophysical data revealed that on south ECMI up to 15°N latitude, the gravity anomaly is associated with a specific character with short-wavelength and high-amplitude, while on 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 place, where gravity anomaly changes from short-wavelength significant negative anomaly to broader less-significant anomaly, suggested the location of Continent-Ocean Boundary (COB) on ECMI 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.

Seismic sections on south and north ECMI segments show the presence of relatively low angle normal faults with different crustal configurations. On south ECMI the fault surfaces are found almost devoid of sediments, whereas on north ECMI the faults lie at 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 strongly support 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), that support the interpretation of transform margin character for the south ECMI. From the above geophysical results, it can be concluded that transform motion 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.

The 85°E Ride, a linear feature in the northeastern Indian Ocean, is an enigmatic structure due to it's two different gravity and complex magnetic anomaly signatures. The seismic reflection sections across the ridge reveal that the ridge structure in the

Bay of Bengal is completely buried below the Bengal Fan sediments, but its size and relief vary from profile to profile. Keeping the 85°E Ridge apex derived from gravity and seismic results in view, it is found that the ridge is associated with positive and negative magnetic anomalies distributed for asymmetrical extents. For the first time in this present work, it has been identified that the ridge is associated with alternate positive and negative magnetic signatures. Since the oceanic crust in the Bay of Bengal was evolved during the Cretaceous Quiet Period, the magnetic pattern of the 85°E Ridge has become fairly useful for assigning the ages to the ridge.

Magnetic modeling of positive and negative magnetization of the 85°E Ridge has been carried out to delineate the magnetic sources within the ridge and their emplacement with respect to earth's magnetic field. The model studies revealed that the ridge's positive and negative magnetization belts are generated, in general, by the ridge topography and polarity contrast, respectively. Considering the magnetization pattern of the 85°E Ridge and age of the underlying oceanic crust, it is interpreted that the ridge was emplaced over a period, wherein the Earth's magnetic field has changed from normal to reverse and vice-versa, and the underlying oceanic crust was formed in a lone normal magnetic field of the Cretaceous Quiet Period. Thus derived geological model for the 85°E Ridge is consistent with the hypothesis of hot spot volcanism on approximately 35 m.y. old oceanic crust.

For assigning an approximate age to the 85°E Ridge track, the interpreted suite of alternate positive and negative magnetic anomalies are correlated to the Geomagnetic Polarity Timescale of Cande and Kent (1995). This correlation suggests that the distributed normal and reversed magnetization pattern resembles with the intervals of Earth's geomagnetic polarities related to the magnetic chron from 33r to 28r. Therefore the present study strongly supports the origin of the 85°E Ridge by a hot spot volcanism on already evolved oceanic crust of approximately 35 m.y. old. The 85°E Ridge volcanism started approximately 80 Ma ago in Mahanadi Basin by a short-lived hot spot. Around this period the Conrad Rise hot spot has emplaced the main plateau of the ANS and Marion Dufresene seamount together close to the India-Antarctica Ridge, thereafter the hot spot has moved to the Antarctica plate leaving the plateau of the ANS as an isolated feature on the Indian plate. At other end in the Bay of Bengal the hot spot has continued the process towards south and finally ended at ~55 Ma in the vicinity of the ANS. Thus the ANS has been built by two short-lived hot spots in two phases, largely in late Cretaceous and a minor component in the Paleocene as an end product of the 85°E Ridge.

8.3 Suggestions for Further Research

During the course of present research work it is found that there are some interesting research aspects related to the age of the ocean floor in the Bay of Bengal and origin of the 85°E Ridge. These aspects may further be investigated in detail for better understanding of the evolution of the regions.

Age of the Ocean Floor in the Bay of Bengal

The timing for the break-up of Greater India from Antarctica and the evolution of the ocean floor in the Bay of Bengal still remain as ambiguous issues because of lack of integrated geophysical approach and lack of identification of acceptable tectonic elements in both the regions, Bay of Bengal and Enderby Basin. Also the ECMI has experienced breakups in two phases and during the Cretaceous Magnetic Quiet Epoch, therefore it is felt that seafloor spreading records of Bay of Bengal have become less useful in deriving the details of age constraints to the earliest oceanic crust existing adjacent to the ECMI.

There is a general belief that the continental breakup related signatures are documented within sediments of the rifted basins of the passive continental margins. Therefore, it is more likely that industry quality seismic reflection data across the major east coast basins of India may provide valuable information on rift-fabric and tectonics of the eastern continental margin in terms of time and space domains. Rift related structural features such as faulted blocks, unconformities related to breakups, etc. need to be mapped from seismic reflection records for understanding the evolution of the margin stage by stage and the lithosphere of the Bay of Bengal. Important stratigraphic horizons/ boundaries need to be correlated to drill-well sites in order to assign the age to post-rift or breakup unconformity. The findings are necessary to be synthesized to arrive at a meaningful identification of tectonic scheme that has controlled the present-day margin configuration.

Origin of the 85°E Ridge

The present study reasonably well explains the magnetic responses of the 85°E Ridge and its formation through geological period from ~80 Ma to 55 Ma. The model results and anomaly correlations with the geomagnetic polarity timescale confirm the hot spot origin of the 85°E Ridge in an intraplate setting. However, several issues related to the ridge evolution are yet to be understood very clearly such as, which hot spot was responsible for the emplacement of the 85°E Ridge? What is the exact timing of the emplacement? Why the clock-wise turn exists in the ridge track? etc. Some of the researchers believe that the ridge was emplaced by the Crozet hot spot (Curray and Munasinghe, 1991), while others opine that it is a product of the Kerguelen hot spot (Bastia et al., 2010a). In the latter case, the extension of the ridge towards Rajmahal Traps needs to be established by geophysical and geochemical studies. Also, a plate reconstruction model, which allows emplacement of both the 85°E Ridge and the Ninetyeast Ridge, needs to be developed and tested. Therefore integrated geophysical and geochemical studies are essential to be carried out to unravel the complexities associated with the origin of the 85°E Ridge.

In the recent past petroleum industry has intensified geophysical exploration works over the 85°E Ridge, as it was viewed that the ridge structure is potential for hydrocarbon prospectivity. The negative gravity anomaly signature associated with the Laxmi Basin in the Arabian Sea was convincingly explained in terms of continental nature. Following the analogy, petroleum industry feels that it may also be possible to think in the direction of assigning continental origin to the 85°E Ridge. Deep seismic refraction studies and drilling may possibly resolve this ambiguous issue and lead to better understanding of the nature of the ridge.

8.4 Limitations of this work

During the investigations of present work it has been observed that there are some limitations for understanding the evolution of the ocean floor of the Bay of Bengal and the 85°E Ridge feature.

Thick file of pre- and post- collision sediments in the Bay of Bengal have reduced the amplitude of the magnetic anomalies and changed the magnetic character. Therefore it indeed becomes difficult to use the magnetic anomalies of the Bay of Bengal for interpretation of M-series spreading type anomalies. Further it is not clear how close to the ECMI the oceanic crust generated during the Cretaceous Magnetic Quiet Period extends.

Probably integration of potential field data with industry-quality multi-channel seismic reflection data along the east coast of India could provide better information on the tectonics of the region. Also the correlation of the seismic horizons with the drill well data in the region gives us better information on the stratigraphy of the region to better explain the geodynamics of the region.

In the present studies it has been concluded that the origin of the 85°E Ridge was due to a short lived mantle source (hot spot). But the study could not explain the hot spot type, which was responsible for the emplacement of the ridge. So the geochemical and geophysical data along the ridge is essential for the hot spot emplacement. Also the dating of the Afanasy Nikitin seamount rocks may throw some new insights on continuity of the 85°E Ridge track and its origin. The nature of the ridge can also be explained with the help of deep seismic refraction studies and drill well data, which can provide good information on the crustal structure of the ridge.

8.5 Major Conclusions

Primary and most important results of this research work are briefed below:

1. Geoid data of Bay of Bengal show two prominent lows on south ECMI (up to-98 m) and on south of Sri Lanka (up to -104 m).
2. The 85°E Ridge possesses two residual geoid signatures with negative anomaly up to 1 m associated with buried part of the ridge in the Bay of Bengal and positive anomaly associated with intermittently exposed structures of the ridge toward south.
3. Gravity anomaly data of the Bay of Bengal, particularly between the 85°E Ridge and south ECMI reveal five notable N36°W oriented oceanic fracture zones and

NE-SW trending short features between the fracture zones. The fracture zones meet the N-S trending 86°E FZ at an angle of ~39°.

4. Gravity anomaly data of the western Enderby Basin reveal five N4°E oriented fracture zones and meet the Kerguelen FZ at an angle of ~37°.
5. The fracture zones in Bay of Bengal and western Enderby Basin are found to be conjugate and were evolved during the early Cretaceous period after rifting of the south ECMI from the Enderby Land.
6. No coherent magnetic anomalies that lead to the identification of M-series anomalies are observed in Bay of Bengal region. Where as in Enderby Basin, between Elan Bank and MacRobertson Land, pairs of anomalies, M9Ny-M2o (129.5 - 124.7 Ma) and fossil ridge segments are observed.
7. The south segment of ECMI shows the gravity anomaly with short-wavelength and high-amplitude, while along the north segment of ECMI it shows gravity anomaly with reduced amplitude and extended wavelength. On south segment the COB lies closer to the coast (50-100 km), whereas in the north segment COB lies away from the coast (100-200 km).
8. Seismic data on south ECMI show low angle normal faults, which are almost devoid of sediments. While the data on north ECMI show low angle normal faults extending to a distance of about 100 km from the shelf edge. Thus it can be concluded that the margins in the north and south segments of ECMI have different rifting characters.
9. The 85°E Ridge structure possesses alternate stripes of positive and negative magnetic anomalies distributed for asymmetrical extents. It is interpreted that the ridge's positive and negative magnetizations are generated, in general, by the ridge topography and polarity contrast, respectively.
10. Correlation of the ridge magnetic stripes to the Geomagnetic Polarity Timescale reveals that the normal and reverse magnetization pattern resembles to the magnetic chrons from 33r to 28r.
11. Considering the Paleocene age constrain of the peaks of the Afanasy Nikitin seamount, it can be inferred that the 85°E Ridge was placed by intraplate setting by a short lived hot spot between 80 and 55 Ma.

8.6 Tectonic Scheme Proposed for - Breakup and Spreading History between India and Antarctica

The rifting process that occurred between India and Antarctica is not a simple process as previously thought. A complexity exists on breakup of individual margin segments of India and Antarctica. Keeping the interpreted results and derived models in view, the following tectonic scheme is suggested.

Age 130 – 120 Ma

Initially, at around 130 Ma rift commenced between north ECMI-Elan Bank and MacRobertson Land segments. Nearly at same age rift started between SW Sri Lanka and Gunnerus Ridge region of Antarctica. Transform motion had existed between south ECMI and Enderby Land margin and facilitated the spreading between other margin segments.

Age 120 - 95 Ma

Ridge jump towards India allowed detachment of the Elan Bank micro-continent from north ECMI and reorganized the rift process along the entire ECMI and Sri Lanka.

Age 95 Ma and younger

A major change in spreading direction occurred and led to the northward movement of the Indian plate.

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List of Publications

- **Laju Michael** and K.S. Krishna (2011). Dating of the 85°E Ridge (northeastern Indian Ocean) using marine magnetic anomalies. Current Science, Vol 100, No. 9, pp 1314-1322.

- K.S. Krishna, **Laju Michael**, R. Bhattacharyya and T. Majumdar (2009). Geoid and gravity anomaly data of conjugate regions of Bay of Bengal and Enderby Basin: New constraints on breakup and early spreading history between India and Antarctica. Journal of Geophysical research, Vol. 114, B03102, doi: 10.1029/2008JB005808.

- S. Chatterjee, R. Bhattacharyya, **Laju Michael**, K.S. Krishna and T.J. Majumdar (2007). Validation of ERS-1 and high resolution satellite gravity with in-situ ship-borne gravity over the Indian offshore regions–accuracies and implication to subsurface modeling. Marine Geodesy, Vol 30, No. 3, pp 197-216.

- T.J. Majumdar, K.S. Krishna, S. Chatterjee, R. Bhattacharyya and **Laju Michael** (2006). Study of high-resolution satellite geoid and gravity anomaly data over the Bay of Bengal. Current Science, Vol 90, No. 2, pp 211-219.

Dating of the 85°E Ridge (northeastern Indian Ocean) using marine magnetic anomalies

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The 85°E Ridge is a typical aseismic ridge in the northeastern Indian Ocean in view of the fact that it associates with exceptional gravity and magnetic signatures. The ridge possesses two different gravity anomalies: the north part (up to 5°N latitude) is associated with negative gravity anomaly, whereas the south part coincides with positive gravity anomaly. In contrast to this, the ridge consists of alternate streaks of positive and negative magnetic signatures distributed for asymmetrical extents. With the consideration of ridge seismic structure and geomagnetic polarity reversals, we modelled both positive and negative magnetic anomalies of the ridge. This shows that the 85°E Ridge was formed during the period of rapid changes in the Earth's magnetic field, earlier to that, the underlying oceanic crust was created in the Cretaceous super-long normal polarity phase. The results further reveal that the positive and negative magnetic signatures of the ridge have been created, in general, by a relief of the ridge and polarity contrast between the ridge material and adjacent oceanic crust, respectively. On correlation of the ridge's magnetization pattern to the geomagnetic polarity timescale, we believe that the 85°E Ridge volcanism started at anomaly 33r time (~80 Ma) in the Mahanadi Basin by a short-lived hotspot, thereafter the process continued towards south and finally ended at ~55 Ma in the vicinity of the Afanasy Nikitin Seamount.

Keywords: Afanasy Nikitin Seamount, magnetic polarities, northeastern Indian Ocean, 85°E Ridge, short-lived hotspot volcanism.

IT is widely accepted that the ocean floor below the Bay of Bengal and Enderby Basin, off East Antarctica has been simultaneously created during the early phase of drifting of Greater India from Australia–Antarctica. Integrated geophysical studies of the Bay of Bengal and Enderby Basin carried out by Krishna *et al.*[1] have clearly established that the present day Eastern Continental Margin of India (ECMI) had experienced multiple rifting processes/break-ups. During the early break-up of eastern Gondwanaland at around 130 Ma, normal rifting prevailed between combined north ECMI–Elan Bank and MacRobertson Land and between southwest Sri Lanka and Gunnerus Ridge region of East Antarctica. Whereas between other conjugate margin segments, south ECMI and Enderby Land, transform motion was existed, this possibly had facilitated the normal rifting in the north as well as in the south until 120 Ma. Approximately during this period the Elan Bank, a small continental piece, detached from the north ECMI and led to reorganization of the entire rifting process along the ECMI. This model suggests that most part of the ocean floor in the Bay of Bengal evolved during the Cretaceous Magnetic Quiet Period (120–83 Ma). Subsequently within the Cretaceous Magnetic Quiet Period or probably later both aseismic ridges: 85°E and Ninetyeast ridges have initiated their volcanic emplacement in the Bay of Bengal. This implies that the 85°E Ridge is placed on an oceanic crust formed during the Cretaceous super-long normal polarity phase.

The 85°E Ridge is an enigmatic structural feature in the northeastern Indian Ocean (Figure 1) as it associates with complex gravity and magnetic signatures. The northern part of the ridge (north of 5°N) is completely buried under thick Bengal Fan sediments and show distinct negative gravity anomaly (Figures 2 and 3), whereas in the south the ridge structure occasionally rises above the seafloor and associates with positive gravity anomaly[2–5]. But the magnetic signatures of the ridge are indeed very complex[1]. In addition, a peculiarity exists in the ridge track off southeast of Sri Lanka, shifting westward by about 250 km (Figure 1). Thus the 85°E Ridge has become a mysterious geological feature in the Indian Ocean. Among the several hypotheses proposed for the evolution of the ridge, the hotspot hypothesis provides better convincing explanations for all anomalous geophysical characters.

Absence of reliable age details of the 85°E Ridge either by deep-sea drilling or by geophysical studies led several researchers to postulate quite a few theories for the origin of the ridge. Using plate reconstruction studies, Curray and Munasinghe[2] postulated that the Rajmahal Traps, 85°E Ridge and Afanasy Nikitin Seamount (ANS) forms the trace of Crozet hotspot from 117 to 70 Ma, but the geochemistry results of lava samples collected from the ANS do not support the Crozet hotspot volcanism[6]. Later Müller *et al.*[7] have suggested that the 85°E Ridge segment between 10°N and ANS may have been formed by another hotspot now located underneath the eastern Conrad Rise on the Antarctic plate. Subsequent geophysical

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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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[1] 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 shipborne 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.

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1. Introduction

[2] 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 [*Curray et al.*, 1982; *Powell et al.*, 1988; *Lawver et al.*, 1991; *Gopala Rao et al.*, 1997; *Gaina et al.*, 2003, 2007]. Elan Bank, a microcontinent 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, second drifted in N-S direction until early Tertiary and finally continuing in NE-SW

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Validation of ERS-1 and High-Resolution Satellite Gravity with *in-situ* Shipborne Gravity over the Indian Offshore Regions: Accuracies and Implications to Subsurface Modeling

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Geoid and gravity anomalies derived from satellite altimetry are gradually gaining importance in marine geoscientific investigations. Keeping this in mind, we have validated ERS-1 (168 day repeat) altimeter data and very high-resolution free-air gravity data sets generated from Seasat, Geosat GM, ERS-1 and TOPEX/POSEIDON altimeters data with in-situ shipborne gravity data of both the Bay of Bengal and the Arabian Sea regions for the purpose of determining the consistencies and deviations. The RMS errors between high resolution satellite and ship gravity data vary from 2.7 to 6.0 mGal, while with ERS-1 data base the errors are as high as 16.5 mGal. We also have generated high resolution satellite gravity maps of different regions over the Indian offshore, which eventually have become much more accurate in extracting finer geological structures like 85° E Ridge, Swatch of no ground, Bombay High in comparison with ERS-1 satellite-derived gravity maps. Results from the signal processing related studies over two specific profiles in the eastern and western offshore also clearly show the advantage of high resolution satellite gravity compared to the ERS-1 derived gravity with reference to ship gravity data.

Keywords Satellite gravity, Indian offshore, validation, power spectral density, coherences, subsurface modeling

Introduction

In recent years, satellite altimetry has emerged as a powerful reconnaissance tool for exploration of sedimentary basins on both the Indian continental margins and in deep-water regions (Biswas 1982; Majumdar et al. 1998). With the advent of more and more altimetric missions with increasing accuracies and varying orbital configurations, it has been possible

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is kept as vertical. The process is repeated when the antenna is covered with radomes along with ground plane. Radiation patterns are plotted using pattern recorder on the same chart for comparison. The whole process is carried out for both L_1 and L_2 antennas and for both polarizations.

Two circularly polarized circular patch antennas are designed and fabricated at L_1 and L_2 frequencies using RT-5880 substrate ($\varepsilon_r = 2.2$, $h = 1.6$ mm) by adopting photolithographic process. Vertical ground planes are designed taking beamwidth of the antennas and cut-off angles for multipath rejection into consideration. GFRP radomes are designed to cover the antennas. The vertical ground planes are embedded into radomes to give more mechanical strength and firm fixing into the antenna. The mounting configuration of the antenna with radomes and vertical ground plane is shown in Figure 4. Return loss measurements of the antennas are carried out using network analyser and are found to be less than 20 dB at resonance frequencies of the two antennas. Radiation pattern measurements were carried out in an RF anechoic chamber for the two antennas (Figures 3 and 4). Initially, the radiation pattern of the antenna is plotted without the presence of the vertical ground planes and radomes. Later the ground planes and radomes are integrated with the antenna and the measurements were repeated. The patterns are superimposed on the same chart for easy comparison of the performance of the antenna with and without the presence of ground plane and radome. The typical radiation patterns of L_1 and L_2 antennas with and without the presence of ground planes and radomes are given in Figure 5. From the radiation pattern plots it is found that the transmission loss of the radome is 1 dB (90% transmission) for both the antennas. The half power beamwidth of the antenna in the presence of radome and ground plane increased by 10% (80 to 88° and 75 to 83° for L_1 and L_2 respectively). Variation in gain in the operating band is only 0.5 dB. Beam sharpening by 3 and 4 dB at the lower elevation angles for L_1 and L_2 respectively is achieved.

Various multipath rejection techniques are discussed and compared. A technique based on vertical ground plane is developed to reject multipath signals entering the GPS receiving antenna through low elevation angles above and below the horizon. The technique is validated with design and development of two circular patch antennas with vertical ground planes. Experimentation is carried out on these two circular polarized patch antennas at L_1 and L_2 frequencies with vertical ground planes and radomes. At low elevation angles (±5°), beam sharpening takes place, which will help in rejecting multipath signals. Beamwidth of the antennas is improved significantly by 10%.

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Study of high-resolution satellite geoid and gravity anomaly data over the Bay of Bengal

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Geoid and gravity anomalies derived from satellite altimetry are gradually gaining importance in marine geo-scientific investigations. Very high-resolution gravity database generated from Seasat, Geosat GM, ERS-1 and TOPEX/POSEIDON altimeters data of the northern Indian Ocean, has been used in the preparation of geoid and free-air gravity maps. In the present work, we have investigated various products of satellite data of the Bay of Bengal, thereby correlated to known plate tectonic feature (Sunda subduction zone), volcanic traces (Ninetyeast and 85°E ridges) and continental margin features. Besides, Swatch of No Ground and modified continental slope due to sediment discharge from East Coast rivers are some of the finer structures observed in free-air gravity anomaly data. Furthermore, the data are compared with ship-track gravity anomalies along 14.64°N lat. for their consistencies and interpreted under the constraints of seismic results for understanding the evolution of structural features of the region. Two different wavelength (100–200 and 200–500 km) components derived from satellite gravity anomaly data have been studied to explain the geophysi-

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