# EARLY CRETACEOUS BREAKUP HISTORY OF INDIA FROM THE CONTIGUOUS ANTARCTICA-AUSTRALIA AS INFERRED FROM MARINE MAGNETIC DATA

THESIS SUBMITTED FOR THE DEGREE OF

**DOCTOR OF PHILOSOPHY**

IN

**MARINE SCIENCE**

TO THE

**GOA UNIVERSITY**



BY

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# DECLARATION

As required under the University Ordinance 0.19.8 (vi), I state that the present thesis entitled "**Early Cretaceous Breakup history of** India from the **contiguous Antarctica-Australia as inferred from marine magnetic data**" is an original research work carried out by me at the National Institute of Oceanography, Dona Paula, Goa, and that no part of the thesis has been submitted before in part or in full, for any other degree in any university or institute.

(Maria Ana Desa)
Candidate

# CERTIFICATE

This is to certify that the thesis entitled "**Early Cretaceous Breakup history of India from the contiguous Antarctica-Australia as inferred from marine magnetic data**", submitted for the award of the degree of Doctor of Philosophy in Marine Science at Goa University is the bonafide research work carried out by Ms. Maria Ana Desa, under my supervision. This work is original and has not been submitted earlier for any degree in any university or institute.

Place: Dona Paula

Date: 18.2.2011

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All the corrections suggested by the referees have been incorporated.

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# Contents

# PREFACE

The Indian Ocean has formed as a result of seafloor spreading between Africa, Madagascar, Greater India, Antarctica and Australia since Late Jurassic, and its present configuration was attained by the end of Miocene. Major plates reorganization during the Middle Cretaceous resulted in changes in spreading rates and directions, and plate configurations, particularly of India and the contiguous Australia-Antarctica. The separation of Madagascar from India and the breakup of Australia from Antarctica started during this period. Rapid northward motion of India from Antarctica took place from the Late Cretaceous to Middle Eocene time. This motion of the Indian plate ended due to its collision with the Eurasian plate triggering the second major plate reorganization. The India-Antarctica and Australia-Antarctica spreading ridges merged into the Southeast Indian Ridge (SEIR) and since Oligocene, seafloor spreading in the Indian Ocean is taking place along the present-day mid-oceanic ridge system. Most of the major ocean basins and aseismic ridges in the Indian Ocean have evolved during the Middle Cretaceous to Eocene period.

Though the evolutionary history of the Indian Ocean is well documented, several grey areas do exist where assumptions are made while generating plate reconstruction models. One such area is the India-Antarctica plate boundary during the Early Cretaceous, where seafloor spreading resulted in the formation of the northeastern Indian Ocean (Bay of Bengal) and Enderby Basin, East Antarctica.

Several models for the evolution of these two conjugate margins are proposed but they differ over the mode and timing of early separation between conjugate margins as M0, i.e. ~120 Ma, whereas others suggested based on the interpretation of magnetic data that the breakup took place prior/around the formation of magnetic anomaly M11, i.e. ~134 Ma. Therefore, an attempt has been made to resolve this ambiguity by undertaking detailed analyses of geophysical data in the Bay of Bengal and its conjugate, Enderby Basin.

The proposed research work comprises of compilation, interpretation and synthesis of existing and new geophysical (bathymetry, gravity, magnetic and multichannel seismic reflection) data sets in the Bay of Bengal and Enderby Basin to achieve the following objectives:

i. To study the detailed geomorphology of the two regions using bathymetry data.

ii. To identify the magnetic anomaly pattern using seafloor spreading model studies.

iii. To identify various tectonic elements such as fracture zones, extinct spreading centers, hotspot traces, ridges, etc.,

iv. To map the age provinces of the oceanic crust using magnetic anomaly distribution and fracture zones.

v. To delineate the plate boundaries and motions in the past.

vi. To discuss the role of various tectonic elements in the evolutionary history of these two conjugate basins

vii. To trace the early breakup history of the conjugate margins using plate reconstruction models.

The techniques used in this research work include generation of synthetic seafloor spreading model using geomagnetic polarity time scales, application of analytical signal processing and forward modeling. New parameters like magnetic anomaly isochrones and oceanic fracture zones and their orientation form additional constraints, which have been used to generate plate reconstruction models for different chrons. The results of the research work form the thesis and have been organized in 7 chapters. The chapter wise summary of the thesis is given below.

The **first chapter** outlines the general concept of plate tectonic theory and the mechanism of seafloor spreading and continental drift. This chapter also deals with the Indian Ocean, its evolution in time and space and major tectonic features have been described briefly. A review of earlier geophysical works, the objectives of the present study and the role of geophysical methods to achieve these objectives are discussed.

The **second chapter** deals in detail the two study areas i.e., the Bay of Bengal on the Indian plate, and the Enderby Basin on the Antarctica plate (conjugate margins). Results obtained from the previous geophysical studies, i.e. bathymetry, magnetics, gravity (shipborne and satellite derived free-air) and multichannel seismics in both the regions are summarized. The geomorphology, sediment thickness, drilling results and various tectonic elements such as the Ninetyeast Ridge, the 85°E Ridge and Afanasy Nikitin seamount chain in the Bay of Bengal are discussed in detail. Tectonic features such as the Kerguelen Plateau, Conrad Rise, and Gunnerus Ridge in the Enderby Basin are also discussed. The existing information on the structure and tectonics of these two study areas is included in this chapter to appreciate the overall geotectonic scenario of the Indian Ocean.

The **third chapter** deals with the bathymetry, magnetics, gravity and multichannel seismic reflection data used in the present study. A brief description of the various instruments used in data acquisition, methodology of data processing and presentation of geophysical results is provided. The synthetic seafloor spreading modeling technique and the identification of magnetic anomalies is discussed. Brief description about the generation of plate reconstruction models to trace the evolutionary history of the conjugate margins is included. Forward modeling technique to derive the crustal structure across the Bay of Bengal using potential field data has also been described.

The **fourth chapter** deals with the geomorphology of the two study areas with an emphasis on the aseismic ridges, basins and the continental margins. Multichannel seismic data along two profiles in the Bay of Bengal are studied in detail to infer the sediment overburden and basement characteristics. The sequence stratigraphy has been tentatively established by identification of unconformities based on reflection pattern and impedance contrast under the constraints of published reflection and refraction results. This sequence stratigraphy facilitated in understanding the nature of depositional environment in time and space. An attempt has also been made to understand the tectonics of the 85°E Ridge, which is well depicted as a basement high along the seismic section MN-01.

The **fifth chapter** deals with the identification and interpretation of the magnetic data in the two study areas. The occurrence of Mesozoic magnetic anomalies world over are briefly described along with the geomagnetic polarity time scales used in interpretation. Magnetic anomalies have been identified using the synthetic seafloor spreading model. Half-spreading rates are estimated and the spreading pattern of the oceanic crust is inferred. The results obtained from forward modeling under seismic constraints are also discussed.

The **sixth chapter** deals with the inferences drawn from the interpretation of the multichannel seismic data in the Bay of Bengal in terms of sedimentation, basement types, ridge emplacement, etc. Integrated analyses of magnetic and gravity data in both the conjugate margins show the presence of complete sequence of Mesozoic magnetic anomalies M11 through M0 (~134-120 Ma) thereby suggesting a continuous evolution of the Early Cretaceous crust in the Bay of Bengal and the Enderby Basin. Plate reconstruction models facilitated in defining the age provinces of the conjugate margins and delineating the plate boundaries and motions in the past. The early breakup history of the Indian plate from the contiguous Antarctica-Australia has been proposed.

The **seventh chapter** highlights the summary and conclusions of the entire research work in both the study areas. This chapter describes the major inferences such as geomorphology, crustal structure and tectonic framework derived from gravity and seismic reflection data. Interpretation of magnetic data facilitated in inferring seafloor spreading magnetic anomalies, oceanic fracture zones, and spreading rates and directions. These new constraints are used to generate plate reconstruction models. The limitations of this work and the future scope of work in this field based on the present interpretation have been suggested.

## ACKNOWLEDGEMENT

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I am extremely grateful to ***Dr. S. R. Shetye***, Director, NIO, Goa, for granting me permission to do my thesis and allowing me to avail the necessary facilities. I am grateful to my Co-Guide ***Prof. G. N. Nayak***, Department of Marine Sciences, Goa University, for his constant help and support right from my post-graduation days. I am very thankful to my Project Leader ***Sh. T. Ramprasad***, for allowing me to do research work and assisting me with data processing software and techniques whenever possible.

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Maria Ana Desa

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# Chapter 1

## *Introduction*

## 1.1 General Background

The oceans, which cover about 71% of the earth's surface, are considered as a future potential reserve for both living and non-living resources. The dwindling land resources, rapid urbanization and ever-increasing human population have prompted an urgent need for exploration and exploitation of the marine environment. With the advent of modern technology, most of the hurdles to study the oceans have been overcome. Marine geophysical techniques have been successively used as tools to study the geology, crustal structure and tectonic evolution of the ocean floor.

The disposition of the continents and oceans puzzled mankind for several centuries. Alfred Wegener, a German meteorologist put forward the concept of continental drift in 1912. Based on the close fit of the continents, occurrence of similar fossils, glacial deposits and rock types, it was suggested that all the continents were once united as a supercontinent 'Pangaea', which later fragmented into several smaller continents (Wegener, 1929). He further postulated the mechanism for the drifting of the lighter continents as their movement over the yielding ocean floor. After initial rejection and criticism, this theory was accepted when stronger evidences to support it were discovered. Du Toit (1937) ascertained that 'Pangaea' existed during the Paleozoic, which split into two subcontinents i.e., the northern Laurasia and southern Gondwanaland in the Mesozoic era. Gondwanaland further broke up into the Eastern and Western Gondwanaland, while

Laurasia split into several macro and micro continents, and drifted apart in time and space.

It was suggested that convection currents in the mantle are the primary driving force for the continental drift and opined that the earth's interior is characterized by large convection cells, which account for the transfer of heat from the interior to the earth's surface (Holmes, 1928). Further, he attributed the upwelling of heat along with mantle material at the mid-oceanic ridges and downwelling at the trenches to the convection belt mechanism, and suggested that the continents moved along with the adjacent ocean floor.

Dietz (1961) and Hess (1962) subsequently put forward the hypothesis of seafloor spreading wherein new crustal material is generated at the mid-oceanic ridges situated at the centers of the oceans and the older crust destroyed at the trenches. The high temperatures and energy within the mantle sustain this continuous process. Wilson (1965) synthesized the concepts of continental drift, seafloor spreading and convection currents into the theory of plate tectonics and revolutionized the evolutionary history of the lithosphere. According to plate tectonic theory, the earth's surface comprises of a number of macro and micro plates, which are in constant motion relative to each other. The plates have either constructive, destructive or translation boundaries. New crust is being generated at the constructive plate boundary i.e., the mid-oceanic ridges, while older crust is being destroyed at the destructive plate boundary or the subduction zones. At the transform faults, where either lateral or strike-slip motion between plates takes place, the crust is neither created nor destroyed. These plates grow or diminish in size depending on the distribution of the constructive and destructive boundaries. These plates may consist of either continental or oceanic crust, or a combination of both. They may undergo reorganizations, i.e. they either fragment or unify over geological time. Thus, the proposed plate tectonic theory explains the concepts of continental drift, seafloor spreading, orogeny, subduction, earthquake activity, evolution of tectonic features, etc. The present day tectonic configuration and distribution of the global plates is shown in figure 1-1.

A plate consisting of continental and/or oceanic crust evolves at the mid-oceanic ridges as new oceanic crust is added to it. The new crust spreads laterally and moves away on either side of the ridge axis till it reaches a subduction zone (Hess, 1962). The heavier oceanic crust on collision with the lighter continental crust sinks/subducts into the mantle and is subjected to heating and recycling. On the other hand, a continental block on collision with another continental block/plate results in mountain building activity. Classical examples of a subduction and mountain building are the Java-Sumatra trench in the Indian Ocean and uplift of Himalayas respectively. The thermal convection cells with upwelling limbs below the mid-oceanic ridges and downwelling limbs beneath the subduction zones are responsible for the plate motions. In addition, hot spots and/or mantle plumes also play a major role in the plate motion.

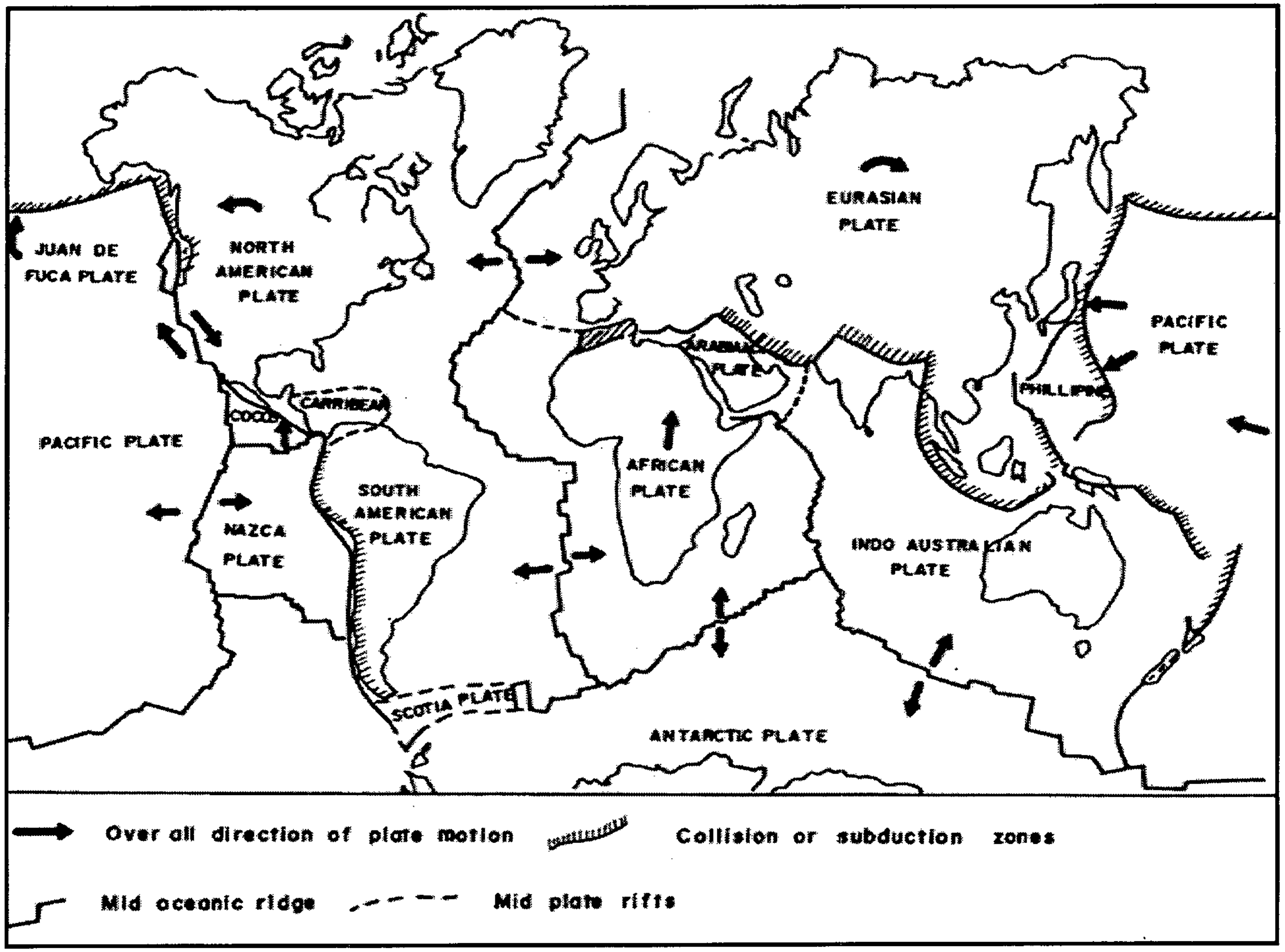


Figure 1-1 Map depicting the present day tectonic configuration and distribution of global plates

The hot magma which rises at the mid-oceanic ridges acquires remanent magnetization parallel to the direction of the Earth's magnetic field prevailing at the time of its cooling below the Curie temperature. As this part of the crust moves away from the ridge axis due to new upcoming magmatic /crustal material, it retains its magnetization. Since the earth's magnetic field reverses polarity periodically, crustal blocks of alternating normal and reversed polarity are generated. This type of crust generated on either side of a mid-oceanic ridge with a typical magnetic anomaly pattern is shown in figure 1-2. Vine and Mathews (1963) were the first to correlate the linear magnetic anomaly patterns across the mid-oceanic ridges with the reversals in the geomagnetic field. The timings of these reversals have been established and several geomagnetic polarity time scales for different geological periods have been proposed (Heirtzler et al., 1968; Kent and Gradstein, 1985; Cande and Kent, 1992; Gradstein et al., 1994; Berggren et al., 1995, etc.). These polarity time scales suggest that the geomagnetic field has reversed several times in the past and these reversals are not episodic. Further, these time scales indicate that the entire ocean floor is not more than 200 million years (m.y.) old. It is demonstrated world over that the age of the seafloor can be determined using the marine magnetic anomalies. Thus, marine magnetic anomalies provide the strongest evidence to the theories of plate tectonics and seafloor spreading.

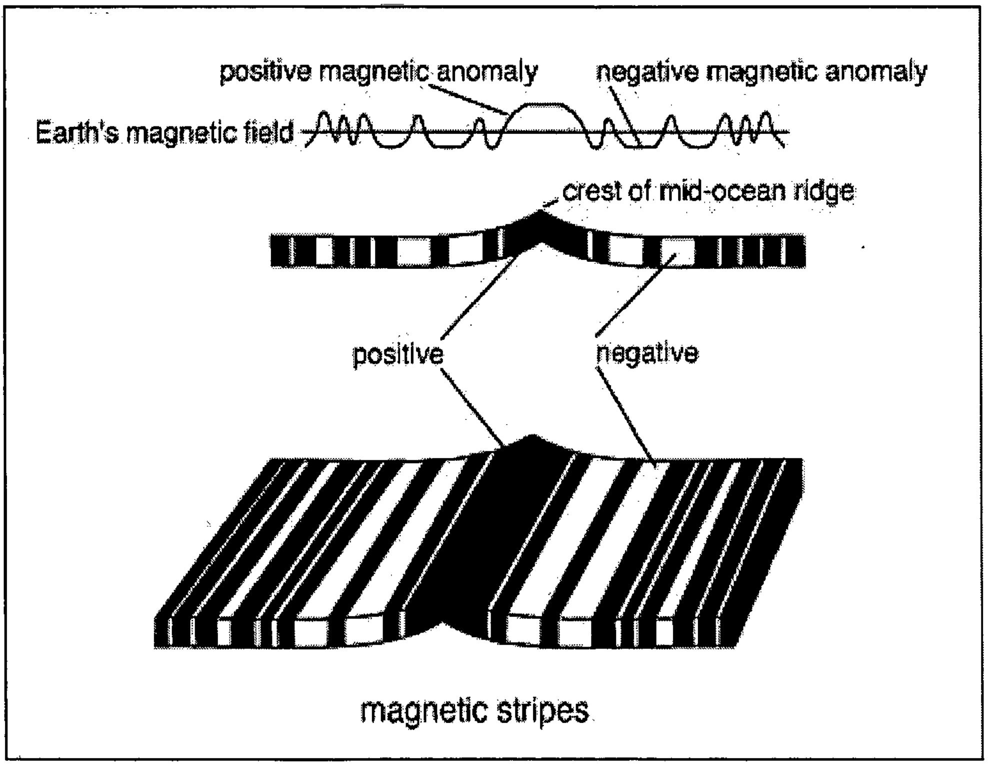


Figure 1-2 Schematic representation of oceanic crust across the mid-oceanic ridge depicting stripes of alternate polarity geomagnetic field along with the corresponding normal and reversed magnetic anomaly pattern

## 1.2 The Indian Ocean

The supercontinent 'Pangaea' split into Laurasia in the north and Gondwanaland in the south. Gondwanaland further split into the Eastern and Western Gondwanaland during the Mesozoic era. Western Gondwanaland comprised of Africa and South America, while the Eastern Gondwanaland comprised of Antarctica, Australia, Madagascar and Greater India (Du Toit, 1937). The closure of the 1000 fathom isobath and paleomagnetic results support the reconstructions of Du Toit (1937) and Smith and Hallam (1970). The breakup of Eastern Gondwanaland and the subsequent dispersal of the continents resulted in the birth and growth of the Indian Ocean in time and space since Early Cretaceous.

The Indian Ocean is the third largest ocean and has the most complex evolutionary history. Unlike the other oceans, the Indian Ocean is landlocked towards the north. It is bordered by the African continent on the west, Eurasian continent towards north, Australia in the east and Antarctica towards south. The Indian Ocean is connected to the Atlantic and Pacific Oceans in the southwest and southeast respectively. The physiography, morphology and complex structure of the Indian Ocean floor (Heezen and Tharp, 1964) are shown in figure 1-3. The major features of the Indian Ocean floor are the mid-oceanic ridge system, aseismic ridges, basins and plateaus, volcanic islands, back-arc basins, islands and trenches. The mid-oceanic ridge system begins with the Sheba Ridge in the northwestern Indian Ocean running E-W into the Gulf of Aden and then continues as the NW-SE trending Carlsberg Ridge between the Owen Fracture Zone and the equator. The ridge then continues southwards as the N-S trending Central Indian Ridge (CIR). The CIR bifurcates into the Southwest Indian Ridge (SWIR) and Southeast Indian Ridge (SEIR) at the Indian Ocean Triple Junction (Fisher et al., 1971). These active ridges form an inverted 'Y' shaped geomorphic feature and mark the boundaries between the Indian, African and Antarctica plates (Fig. 1-3). The SEIR extends upto 100°E longitude and seafloor spreading is active in the NE-SW direction since the last 45 m.y. The slow spreading SWIR trending NE-SW is characterized by extremely rugged topography and offset by several N-S trending fracture zones (Royer et al., 1989).

The Indian Ocean is characterized with several basins such as the Arabian Sea, Bay of Bengal, Somali, Mozambique, Central Indian, Crozet, Wharton and Enderby basins (Schlich, 1982). The Arabian Sea forms the major constituent of the northwestern Indian Ocean. It is bordered by the western continental margin of India, the Persian Gulf and the Carlsberg Ridge. The evolution and tectonics of the Arabian Sea have been studied by several workers (e.g. Naini, 1980; Naini and Talwani, 1982; Miles et al., 1988; Bhattacharya et al., 1994; Chaubey et al., 1993[1]; 1995; 1998; Subrahmanyam et al., 1995; Bhattacharya and Chaubey, 2001). The Bay of Bengal, a major constituent of the Northeastern Indian Ocean, is one of the largest and thickest ocean basins in the world, and is bordered by peninsular India,

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[1] *Chaubey, A.K., Bhattacharya, G.C., Murty, G.P.S. and Desa, M., 1993. Spreading history of the Arabian Sea: Some new constraints, Mar. Geol., 112, 343-352.*

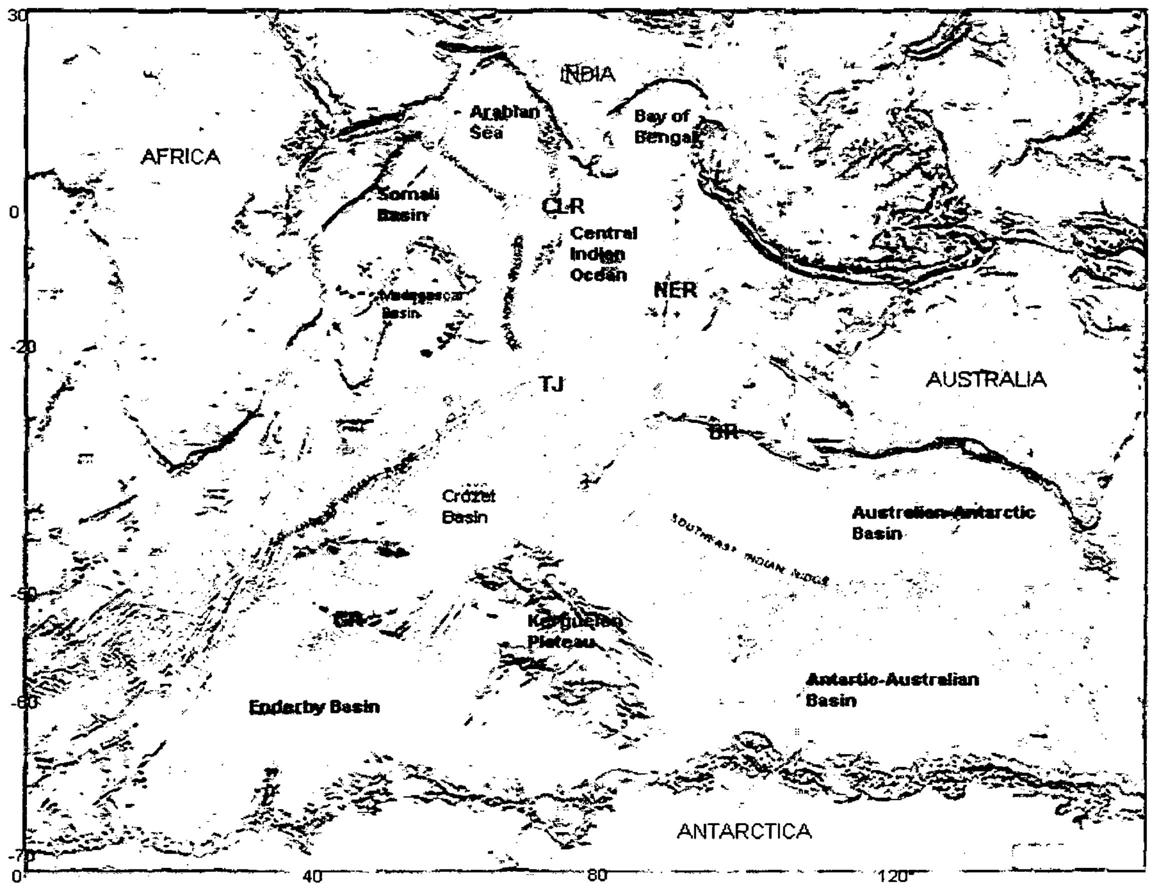


Figure 1-3 Physiographic map of the Indian Ocean floor (Heezen and Tharp, 1964). The inverted 'Y' shaped mid-oceanic ridge system is seen. The ocean floor is characterized by several plateaus, basins and linear ridges. CLR: Chagos-Laccadive Ridge; NER: Ninetyeast Ridge; BR: Broken Ridge; CR: Conrad Rise; ST: Sunda Trough; TJ: Triple Junction.

Sri Lanka, Bangladesh, Burma and the Andaman and Nicobar Islands. The Bay of Bengal receives tremendous amount of terrigenous sediments from the Ganges and Brahmaputra rivers that drain the Himalayas, and other major rivers such as Mahanadi, Krishna-Godavari and Cauvery. The evolution and tectonics of the Bay of Bengal has been documented by several researchers (Curray and Moore, 1971; 1974; Curray et al., 1982; Rao and Rao, 1985; 1986; Curray, 1991; 1994; Murthy et al., 1993; Ramana et al., 1994a, b[2]; 1997a[3], b[4]; 2001a[5], b[6]; Gopala Rao et al., 1994[7], 1997; Krishna et al., 1995; 2009; Krishna and Gopala Rao, 2000; Krishna, 2003; Desa et al., 2006[8]; 2009[9]).

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[7] *Gopala Rao, D., G.C. Bhattacharya, M.V. Ramana, V. Subrahmanyam, T. Ramprasad, K.S. Krishna, A.K. Chaubey, G.P.S. Murty, K. Srinivas, Maria Desa, S.I. Reddy, B. Ashalata, C. Subrahmanyam, G.S. Mittal, R.K. Drolia, S.N. Rai, S.K. Ghosh, R.N. Singh and R. Majumdar, Analysis of multichannel seismic reflection and magnetic data along 13°N latitude across the Bay of Bengal, Marine Geophys. Res., 16, 225-236, 1994.*

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The northern Indian Ocean comprises of several aseismic ridges such as the Chagos-Laccadive, Laxmi and Comorin ridges in the Arabian Sea and the Ninetyeast and 85°E Ridges in the Bay of Bengal. The Chagos-Laccadive Ridge, an approximate N-S trending linear feature that extends over 2500 km is a trace of the Reunion hotspot (Naini, 1980; Duncan, 1990). The NW-SE trending Laxmi Ridge is another important submarine feature in the Arabian Sea, which is flat-topped, largely buried and its origin still debatable (Talwani and Reif, 1998). The NNW-SSE trending Comorin Ridge, 100 km wide and ~ 450 km long, southwest of Sri Lanka is characterized by rugged topography. Kahle et al., (1981) suggested that it marks a significant structural crustal boundary. Some researchers are of the opinion that the Comorin Ridge extends as the NW-SE trending Pratap Ridge in the Kerala-Konkan basin. The Ninetyeast Ridge, a 5000 km long, 200 km wide linear topographic feature along the 90°E meridian is a trace of the Kerguelen hotspot (Sclater and Fisher, 1974; Duncan, 1991). The 85°E Ridge is another ~N-S trending buried feature extending over 2000 km along the 85°E meridian (Liu et al., 1982; Curray and Munasinghe, 1991; Kent et al., 1992; Muller et al., 1993; Ramana et al., 1997a).

The Central Indian Ocean Basin extends from the Central Indian Ridge to the Ninetyeast Ridge and is bounded in the south by the Indian Ocean Triple Junction and the Southeast Indian Ridge. Late Cretaceous to Middle Eocene magnetic

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[9] *Desa, M., Ramana, M. V. and Ramprasad, T., 2009. Evolution of the late Cretaceous crust in the equatorial region of the Northern Indian Ocean and its implication in understanding the plate kinematics, Geophys. J. Int., **177**:1265-1278.*

anomalies are reported in this basin (Sclater and Fisher, 1974; Schlich, 1982; Royer et al., 1989, Desa et al., 2009). Large-scale deformation is seen associated with the diffuse plate boundary separating the Indian Ocean lithosphere from the Australian and Capricorn plates (Bull and Scrutton, 1990; Krishna et al., 1998; 2001).

### 1.2.1 Evolution of the Indian Ocean

The evolution of the Indian Ocean since Late Jurassic has been reported from the interpretation of marine magnetic anomalies (Mckenzie and Sclater, 1971; Norton and Sclater, 1979; Patriat and Segoufin, 1988). The three phase evolution is surmised in the following section.

1. Late Jurassic to Middle Cretaceous

The initial breakup of Gondwanaland occurred around 152 Ma and resulted in the separation of Africa from Madagascar and Antarctica (Schlich, 1982). Subsequently, Greater India separated from the contiguous Antarctica-Australia in the Early Cretaceous and started moving in a NW-SE direction (Markl, 1974; Larson, 1977; Powell et al., 1988). This movement resulted in the evolution of the northeastern Indian Ocean (Liu et al., 1983), the northwestern regions off Australia (Larson, 1977; Johnson et al., 1980; Fullerton et al., 1989) and the Enderby Basin, East Antarctica (Ramana et al., 2001b) and continued till around 120 Ma. During the Middle Cretaceous (120-84 Ma), the first major plate reorganization took place and the direction of the Indian plate motion changed from NW-SE to N-S (Powell et al., 1988; Royer and Sandwell, 1989). Australia-Antarctica separation (Veevers, 1986) and the breakup of Madagascar from India (Norton and Sclater, 1979) began during this period.

2. Late Cretaceous to Middle Eocene

This period recorded a rapid northward drift of the Indian plate towards the Eurasian plate resulting in the formation of the major portion of the Indian Ocean floor (Mckenzie and Sclater, 1971; Johnson et al., 1976; Pierce, 1978; Schlich, 1982). The spreading ridge between Madagascar and India jumped north in the Early Paleocene and separated Seychelles from India. India started moving northward between the two great transform faults, i.e. the Ninetyeast Ridge in the east and the parallel, but shorter Chagos-Laccadive Ridge in the west (Sclater and Fisher, 1974). During this period, the major basins of the Indian Ocean such as the Mascarene, Madagascar, Central Indian, Crozet and Wharton Basins were evolved (Liu et al., 1983). This phase ended with the collision of India with Eurasia (Patriat and Segoufin, 1988; Klootwijk et al., 1991).

3. Late Eocene to Present

The collision of India with Eurasia initiated the second major plate reorganization and the spreading rates decreased drastically. The soft collision between continental India and an island arc seaward off Asia was followed by the hard collision consuming the backarc basin and resulting in the main uplift of the Himalayas (Molnar and Tapponnier, 1975). The Wharton Ridge became extinct, and the Indian and Australian plates fused into one plate (Liu et al., 1983). Spreading between Australia and Antarctica continued rapidly. The direction of motion of the Indo-Australian plate changed from N-S to NE-SW with a new mid-oceanic ridge system taking birth. This pattern of seafloor spreading continues till date (Royer et al., 1989).

## 1.3 Earlier geophysical works

The International Indian Ocean Expedition (IIOE) undertaken during 1959-'66 laid the foundation for oceanographic studies in the Indian Ocean. This exercise culminated into the establishing of the first oceanographic institute, the National Institute of Oceanography (NIO), Goa, along the Indian subcontinent in 1966 to carry out multidisciplinary oceanography studies of the continental margins of India and the surrounding ocean basins. The major geophysical results from the IIOE expedition include the physiographic map of Indian Ocean floor (Heezen and Tharp, 1964) and the Geological and Geophysical Atlas of the Indian Ocean (Udintsev, 1975). Subsequent geophysical contributions revealed the preliminary tectonics of the Indian Ocean (Le Pichon and Heirtzler, 1968; McKenzie and Sclater, 1971; Laughton et al., 1971; Naini and Leyden, 1973; Sastri et al., 1973; Sclater and Fisher, 1974; Norton and Sclater, 1979). Detailed studies in the 80's improved the understanding of the structure of the Indian Ocean (Naini, 1980; Sastri et al., 1981; Naini and Talwani, 1982; Schlich, 1982; Curray et al., 1982; Liu et al., 1983; Veevers, 1986; Patriat, 1987; Patriat and Segoufin, 1988; Royer et al., 1989; etc.). Several plate reconstruction models were generated to explain the evolutionary history of the Indian Ocean (Powell et al., 1988; Royer and Sandwell, 1989; Muller et al., 1993).

Geological and geophysical investigations were conducted by NIO using the research vessels RV Gaveshani and ORV Sagar Kanya in addition to several chartered and coastal vessels. The northern Indian Ocean including the Arabian Sea and Bay of Bengal was studied in great detail since the 1970s, using various geophysical techniques for research and resource purposes. NIO's major contributions in the Arabian Sea include the structural configuration of Bombay High, extension of onshore lineaments offshore, delineation of Narmada-Son lineament, delineation of mid-shelf basement high, boundaries and linear extent of Pratap Ridge, crustal structure of NW continental margin of India, Laxmi Ridge and the extinct spreading ridge in the Laxmi Basin (Gopala Rao, 1984; 1990; Ramana et al., 1993[10]; Bhattacharya et al., 1994; Chaubey et al., 1993; 1995; Subrahmanyam et al., 1995; etc).

Major works in the Bay of Bengal include delineation of basement structure in the form of horst and grabens, rift phase volcanic intrusives in the nearshore areas, major geological unconformities from Paleocene to Recent, presence of Mesozoic magnetic anomalies, depth to magnetic basement, deformation of lithosphere, new fracture zones, boundary and axis of the 85°E Ridge, etc. (Rao and Rao, 1985; 1986; Murthy et al., 1993; Ramana et al., 1994a; b; Gopala Rao et al., 1994; Krishna et al., 1995; Ramana et al., 1997a; b; Subrahmanyam et al., 1997; Krishna et al., 1998; Subrahmanyam et al., 1999; Sarma et al., 2000[11]; 2002[12]; Subrahmanyam et al., 2001[13]; 2008; Purnachandra Rao and Kessarkar, 2001). The Central Indian Basin was also explored during the 1980s and various geophysical investigations were conducted during the polymetallic nodules project (Kamesh Raju and Ramprasad, 1989; Kamesh Raju, 1990; 1993; Kamesh Raju et al., 1993; 1997 etc). In 1981, scientific studies of the Southern Indian Ocean were initiated

[10] *Ramana, M.V. Ramprasad, T. Kamesh Raju, K.A. and Desa, M., 1993. Geophysical studies over a segment of the Carlsberg Ridge, Indian Ocean. Mar. Geol., 115, 21-28.*

[11] *Sarma, K.V.L.N.S., Ramana, M.V., Subrahmanyam, V., Krishna, K.S., Ramprasad, T. and Desa, M., 2000. Morphological features in the Bay of Bengal, J. Indian Geophys. Union, **4**: 185-190.*

[12] *Sarma, K.V.L.N.S., Ramana, M.V., Ramprasad, T., Desa, M., Subrahmanyam, V., Krishna, K.S. and Rao, M.M.M., 2002. Magnetic basement in the central Bay of Bengal, Mar. Geophys. Res., **23**: 97-108.*

[13] *Subrahmanyam, V., Krishna, K.S., Murthy, I.V.R., Sarma, K.V.L.N.S., Desa, M., Ramana, M.V. and Kamesh Raju, K.A., 2001. Gravity anomalies and crustal structure of the Bay of Bengal, Earth Planet. Sci. Lett., **192**: 447-456.*

with India's first expedition to Antarctica (Gopala Rao et al., 1992a; b; Ramana et al., 2001a).

The Deep Sea Drilling Project (DSDP) was the first international scientific ocean-drilling program undertaken to obtain deep sedimentary cores of the ocean bottom. Analysis of these cores, which include both sediments and basement rocks helped to determine the age and evolution of the ocean basins. The D/V Glomar Challenger during its Legs 22 to 27 in 1972 drilled sites 211 to 263 at various locations in the Indian Ocean to study the characteristics of the sediments and rocks beneath the ocean floor (Davies et al., 1974; Von der Borch et al., 1974). Subsequently, the Ocean Drilling Program (ODP), the second international deep drilling program used the vessel JOIDES Resolution to further understand the evolutionary history of the world oceans. The scientific results of the Legs 115-123,183 and 188 have contributed to a better understanding of the crustal structure, nature and evolution of the Indian Ocean floor (Cochran et al., 1989; Pierce et al., 1989; Duncan, 1991; Royer and Coffin, 1992; Coffin et al., 2000; Cooper and O'Brien, 2004; etc).

## 1.4 Aims and objectives of the present study

The Bay of Bengal and the Enderby Basin (Fig. 1-4) have resulted due to the separation of India from the contiguous Antarctica-Australia in the Early Cretaceous. Two different opinions prevail over the timing of this breakup and subsequent

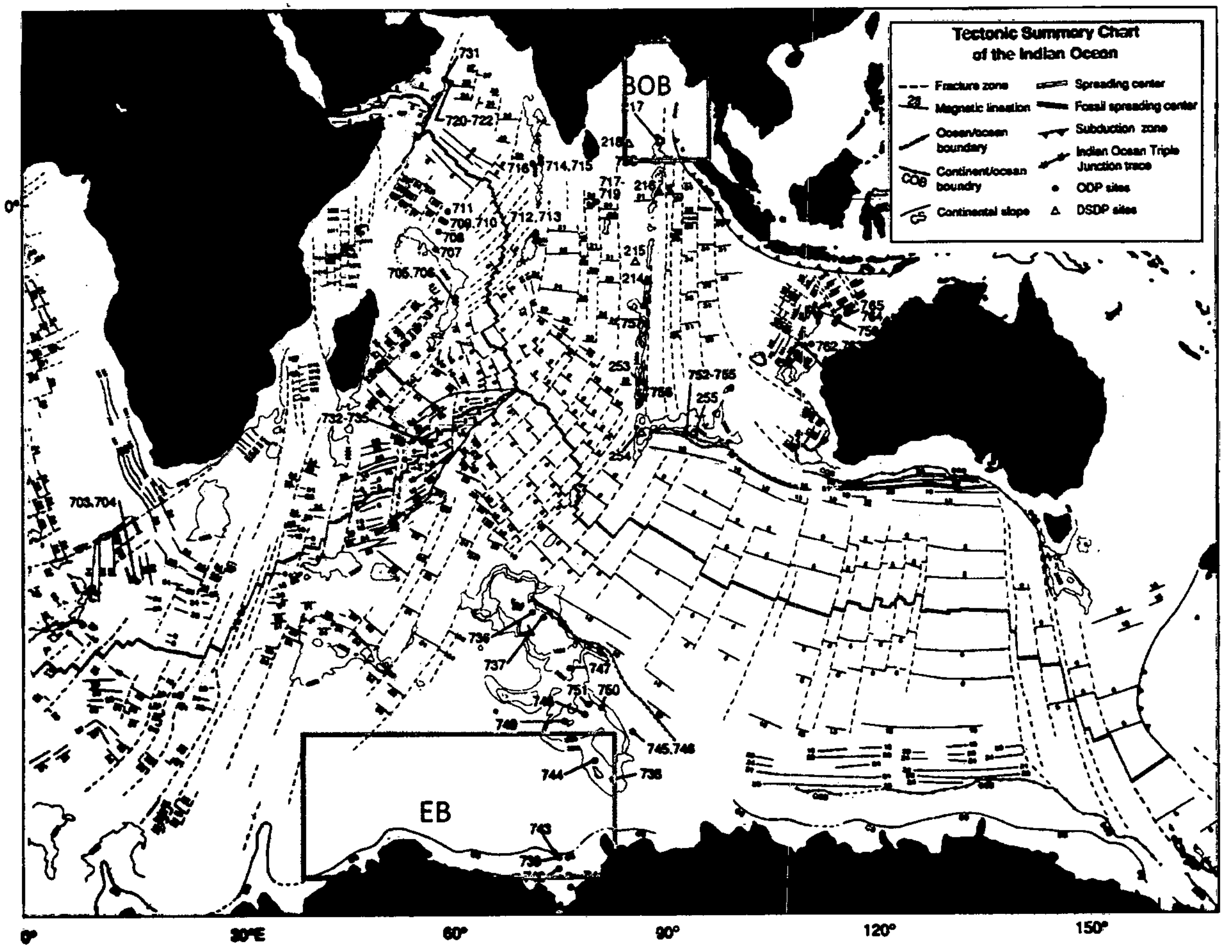


Figure 1-4 Tectonic summary chart of the Indian Ocean (Royer et al., 1989). The two study areas: Bay of Bengal (BOB) and Enderby Basin (EB) are shown as red blocks

evolution of these two conjugate basins. One school believes that the breakup occurred around chron M0 i.e., ~120 Ma (Norton and Sclater, 1979; Gopala Rao et al., 1997), while the other believes the breakup time is around chron M11 i.e., ~133 Ma (Powell et al., 1988; Scotese et al., 1988). Digital age grid of the ocean floor (Muller et al., 1997) indicated the presence of a large area of unknown age in these two regions, probably displaying uncertainty in the mode and timing of breakup between India and Antarctica. Ramana et al., (1994b; 2001a) based on the interpretation of systematically acquired magnetic data in the Central Bay of Bengal identified the presence of Mesozoic magnetic anomaly sequence M11 through M0 and proposed that the breakup occurred prior to the formation of magnetic anomaly M11.

The Bay of Bengal is well understood in terms of its geomorphological characteristics. However, a detail understanding of its structural evolution is severely constrained by lack of close grid geophysical and age information data in both the conjugate basins, i.e. the Bay of Bengal and the Enderby Basin. To resolve the ambiguity in timing of separation and to achieve better understanding of the evolution of these two conjugate margins, detailed geophysical investigations have been proposed and undertaken in this thesis work. The proposed thesis work comprises compilation and interpretation of the existing and new geophysical data (bathymetry, gravity, magnetic and multichannel seismic reflection) in both the conjugate margins, the Bay of Bengal and Enderby Basin to achieve the following objectives:

i. To study the detailed geomorphology of the two regions using bathymetry data.
ii. To identify the magnetic anomaly pattern using seafloor spreading model studies.
iii. To identify fracture zones, extinct spreading centers, hotspot traces, ridges, etc.,
iv. To map the age provinces of the oceanic crust using magnetic anomaly distribution and fracture zones.
v. To delineate the plate boundaries and motions in the past.
vi. To trace the early breakup history of the conjugate margins using plate reconstruction models.
vii. To discuss the role of various tectonic elements in the evolution of these two conjugate basins

## 1.5 Role of geophysical investigations

Geophysical data and in particular marine magnetic anomalies have been extensively used to delineate the structure, nature and evolutionary history of the ocean basins. Various geophysical datasets can be used to infer the regional geology and form a precursor to the more expensive geological methods such as drilling and coring. The geophysical data used in the present study include bathymetry, gravity – shipborne and satellite, magnetics and multichannel seismics.

Geophysical data acquired by the National Institute of Oceanography, Dona Paula, Goa, under the program "Crustal studies of the Bengal Fan" have been used in addition to the data extracted from the National Geophysical Data Center (NGDC), Colorado in the Bay of Bengal. In the Enderby Basin, not only the geophysical data extracted from NGDC, Colorado but also data from published maps, publications and personal communication have been used.

Bathymetry

A detailed knowledge of topography is a fundamental requirement towards understanding most of the Earth's processes. In the oceans, detailed bathymetry is essential for understanding the physical oceanography, biology and marine geology. Currents and tides are controlled by the overall shapes of the ocean basins, ridges and seamounts. Sea life is abundant where rapid changes in water depth deflect nutrient-rich water towards the surface. Because of minimum erosion and low sedimentation rates in deep oceans, detailed bathymetry sometimes reflects the imprints of the mantle convection patterns, cooling/subsidence of the oceanic lithosphere, and extent of plate boundaries, oceanic plateaus and off-ridge volcanoes. Acoustic methods form the principal means of mapping seabed topography. High-resolution mapping of the seabed morphology is essential for geophysical investigations, and can be achieved by single-beam and multibeam echosounding, and side scan sonar imaging. In regions inaccessible for shipborne investigations, satellite altimetry techniques are used to image the seabed.

Gravity

Gravity observations provide an important means of studying the changes in mass distribution due to various processes taking place within the earth. They reflect the lateral density variations, which can be used to delineate not only the crustal and mantle configuration, but also the sediment overburden thickness and sedimentary basin architecture. Marine gravity measurements are classified into shipborne and satellite derived based on their source technique.

Magnetics

Magnetic prospecting is one of the oldest geophysical exploration technique used in mapping the structural configuration and nature of the basement, locating faults and igneous bodies, inferring the evolution of the ocean floor, structurally controlled oil and gas fields, etc. Magnetic data processing and interpretation involves the application of mathematical filters to the observed data to enhance the amplitudes of anomalies of interest and gain some preliminary information on source location and magnetization. Marine magnetic anomalies can be used to infer the rate and direction of spreading, and nature and age of the seafloor.

## Seismics

Seismic methods utilize reflection or refraction techniques to investigate the interior of the Earth. Seismic reflection profiling can be used extensively to study the stratigraphy and structure of sediments around continental margins and in ocean basins. Basement configuration and type can be inferred fairly confidently. Refraction method facilitates in determining the velocity structure of the subsurface strata and to a larger extent the low velocity layers, discontinuities, etc. Seismic methods are commonly used by the oil industry to map the subsurface structure of rock formations, which may be structural traps for hydrocarbons and gas hydrates.

In the present thesis work, the results obtained from the magnetic and gravity investigations under seismic constraints have been used to derive the structural and tectonic framework, and propose the evolutionary history of the conjugate basins, the Bay of Bengal and Enderby Basin.

# Chapter 2

## *Study Areas*

The present research work includes the Bay of Bengal (Eastern Continental margin of India and Bengal Fan) and the Enderby Basin, East Antarctica due to their conjugate nature. The Indian Ocean can be divided into northern, central and southern Indian Ocean depending upon the area of interest. The Bay of Bengal is an integral part of the northern Indian Ocean, while the Enderby Basin is situated in the southern Indian Ocean. The Indian Ocean has formed as a result of seafloor spreading between Africa, Madagascar, Greater India, Antarctica and Australia since Late Jurassic (McKenzie and Sclater, 1971; Norton and Sclater, 1979). The separation of Africa from Antarctica in the Late Jurassic was followed by the Early Cretaceous breakup of Greater India from the contiguous Antarctica-Australia (Mckenzie and Sclater, 1971; Powell et al., 1988). Though the evolutionary history of the Indian Ocean is well documented, there exist several areas where assumptions are made while generating plate reconstruction models. One such poorly understood area is the India-Antarctica plate boundary during the Early Cretaceous, where seafloor spreading resulted in the formation of the northeastern Indian Ocean comprised of the Bay of Bengal and the Enderby Basin, East Antarctica. The mechanism and timing of the separation is under debate mainly due to lack of adequate geophysical, geological and ground truth data in these two conjugate margins. Differing plate reconstruction scenarios were suggested based on the results obtained from investigations in individual conjugate margins

(Mckenzie and Sclater, 1971; Norton and Sclater 1979; Powell et al., 1988; Royer and Sandwell, 1989; Muller et al., 1993; Ramana et al., 2001a[1]; Gaina et al., 2003).

The National Institute of Oceanography, Goa acquired huge volume of geophysical data in the Bay of Bengal under the program "Crustal studies of the Bengal Fan" during 1988-'97 along predetermined cruise tracks primarily to understand its structure and tectonic evolution in time and space. This information is also vital to understand the evolution of its conjugate margin i.e., the Enderby Basin. It was felt that detailed geophysical investigations both in the Bay of Bengal and Enderby Basin and a joint interpretation would resolve the evolutionary history of both the conjugate margins and provide a comprehensive understanding of the plate kinematics since the breakup of India from Antarctica-Australia.

## 2.1 Bay of Bengal

The Bay of Bengal extends from 22°N to 7°S latitudes and 80°E to 93°E longitudes in the Northeastern Indian Ocean, and is bordered by India, Sri Lanka, Bangladesh, Burma, Sumatra and the Andaman and Nicobar Islands (Fig 2-1). It comprises the Eastern Continental margin of India (ECMI) and the adjoining abyssal plains. The continental margin is characterized by a very narrow continental shelf followed by a steep continental slope and deep abyssal plains with smooth

[1] *Ramana, M. V., Ramprasad, T. and Desa, M., 2001a. Seafloor spreading magnetic anomalies in the Enderby basin, East Antarctica, Earth Planet. Sci. Lett.,* ***191****: 241-255.*

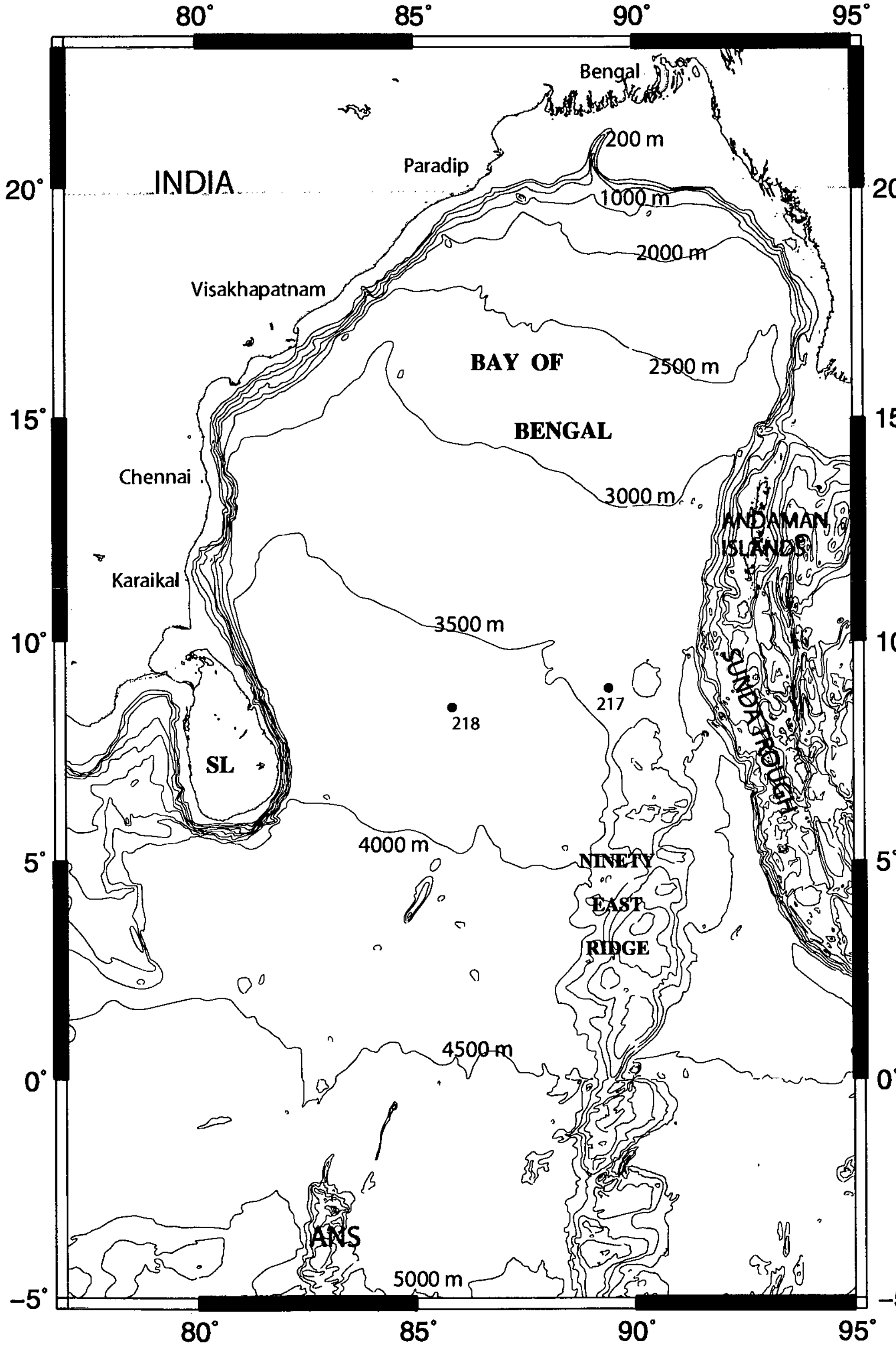


Figure 2-1 Generalised bathymetry map of the Bay of Bengal (GEBCO) with variable contour interval. SL: Sri Lanka, ANS: Afanasy Nikitin Seamount chain.

topography (Heezen and Tharp, 1964; Curray and Moore, 1971; Curray et al., 1982). The water depths increase from near zero at the Ganges mouth in the north to >4500 m around the equator.

Onshore geology

Peninsular India is characterized by (i) Precambrian cratons and mobile belts, (ii) Proterozoic sedimentary basins, (iii) Continental flood basalts, (iv) Himalayan orogen and (v) Indo-Gangetic plains (Wadia, 1966). The Precambrian cratons including the Dharwar Craton, Singhbhum Craton, Bundelkhand Craton, Aravalli Craton and Southern Granulite Terrain consists of Archean gneisses and schists (Radhakrishna and Naqvi, 1986). The Proterozoic sedimentary basins initiated around 1800 Ma include among others the Cuddapah, Vindhyan, etc., The Gondwana sedimentary basins dated between lower Permian (295 Ma) to Lower Jurassic (200 Ma) are deposited in the prominent rift valleys such as the Godavari, Mahanadi and Damodar. The mobile belts include the Pandian, Achankovil, Eastern Ghat, Satpura-Singhbhum, Aravalli-Delhi, etc., while the Deccan and Rajmahal Traps constitute the continental flood basalts. The Himalayas is a 2500 km long arc of mountain ranges rising 500 to 8000 m above sealevel formed since Early Paleozoic (Gansser, 1964; Valdiya, 1998) with its maximum uplift due to collision of the Indian plate with the Eurasian plate during the Tertiary period. The evolution of the Himalayas led to the formation of the Indo-Gangetic plains (Singh, 1996). The Eastern Ghat Mobile Belt between Ongole and Bhubaneshwar parallel to the east coast of India was an integral part of Eastern Gondwanaland (Yoshida et al., 1992). The geology and tectonics of peninsular India therefore appears to be complex and variable.

Crustal thickness contour map of peninsular India depicts that the Moho is within normal depths throughout India, but deeper in the central east coast region and doming up at the eastern flank of the Bengal Basin (Reddy et al., 1999). The ECMI has evolved as a consequence of rifting and subsequent drifting of India from the contiguous Antarctica-Australia in the Early Cretaceous (Powell et al., 1988; Ramana et al., 2001b[2]; Chand et al., 2001). The east coast basins, namely Bengal, Mahanadi, Krishna-Godavari, Pennar-Palar and Cauvery are pericratonic with horst graben type of architecture upto Late Jurassic. Numerous down-to-basin extensional faulting along with subsidence took place in these basins during the rifting stage. Syn-rift sediments are the fresh water/shallow marine deposits, while the post-rift sediments constitute the marine deposits. The geological uplift of eastern India during its breakup from Antarctica-Australia created a westward drainage pattern which persisted upto the Late Cretaceous (Kent, 1991). The Deccan Trap volcanism produced buoyant uplift in the northwest, which resulted in a reversed drainage pattern that continues till date. Rigorous monsoon activity subsequent to the Himalayan uplift after the hard collision of India with Eurasia caused rejuvenation of the major rivers along the east coast of India (Curray and

[2] *Ramana, M.V., Krishna, K.S., Ramprasad, T., Desa, M., Surbrahmanyam, V. and Sarma, K.V.L.N.S., 2001b. Structure and tectonic evolution of the Northeastern Indian Ocean, In: Sen Gupta, R. and Desa, E. (Eds.), The Indian Ocean: A perspective, Oxford & IBH, New Delhi (India),* **2***: 731-816.*

Moore, 1971; Curray et al., 1982). This led to the formation of sediment filled delta fronts in the onshore basins, which extend to deep offshore (Rao, 1993).

The NE-SW trending horst and graben structures parallel to the coast constitute the major structural trends in the northern Bengal, Mahanadi and Krishna-Godavari basins, while the southern Palar and Cauvery basins depict horst-graben features oblique to the coast. The Bengal basin displays a NE-SW trending flexure called Eocene hinge zone (Sengupta, 1966). There are evidences of volcanic activity in the Mahanadi and Bengal basins (Baksi et al., 1987; Mall et al., 1999; Nayak and Rama Rao, 2002; Behera et al., 2004). The NE-SW trending horsts and grabens in the Krishna-Godavari basin are filled with variable thickness of volcanic flows with intertrappen clays, limestone and sand beds of Upper Cretaceous to Recent age (Rao, 2001). The Cauvery and Palar basins are characterized by rhomb-shaped grabens, limited crustal attenuation, associated smaller tectonic subsidence and low heat flow. The syn-rift origin of these basins is envisaged as a pull-apart kinematic model associated with right lateral strike slip motion between India and Sri Lanka (Chand and Subrahmanyam, 2001).

Offshore tectonics

The Bay of Bengal encompasses the ECMI and is carpeted by the Bengal Fan sediments. The Bengal Fan is the largest and thickest sedimentary fans of the world and extends over a length of ~3000 km upto 10°S. The average width of the fan is about 1000 km. The Bengal Fan sediments are mostly derived from the rivers Ganges and Brahmaputra, which drain the southern and northern slopes of the Himalayas respectively. These rivers discharge about 1.7 x $10^9$ tons/year of continental sediments (Curray et al., 1982). The sediments enter through the submarine canyon "The Swatch of No Ground" and get distributed through a system of turbidity current channels or fan valleys that extend the entire length of the Bengal Fan (Curray and Moore, 1974). The Swatch of No ground does not head the shoreline during the present day, but during Pleistocene lowered sealevel, the sediment discharge brought in by the rivers was fed directly into the canyon. The canyon now heading on the shelf delivers the sediment load to the apex of the fan at the foot of the continental slope and in turn into an intricate network of turbidity channels or fan valleys (Fig. 2-2). The channels migrate over time, i.e. new ones form and the old ones are abandoned. The present day active channel extends upto the equator without any bifurcation.

The fan is divided into: i) upper fan, which includes the Ganges delta and Swatch of No Ground; ii) middle fan, and iii) lower fan (Fig. 2-2). The upper fan lies to the extreme north of the Bengal Fan in water depths of upto 2000 m. The middle fan extends between 2000 and 3000 m water depth and covers mostly the northern part of the Bay of Bengal. The outer or lower fan extends from ~3000 to >4500 m water depth (Emmel and Curray, 1984). Sediment thickness of the Bengal Fan decreases from north to south rather than parallel to the coast as might be expected of a normal continental margin suggesting that the fan buildup is taking place from

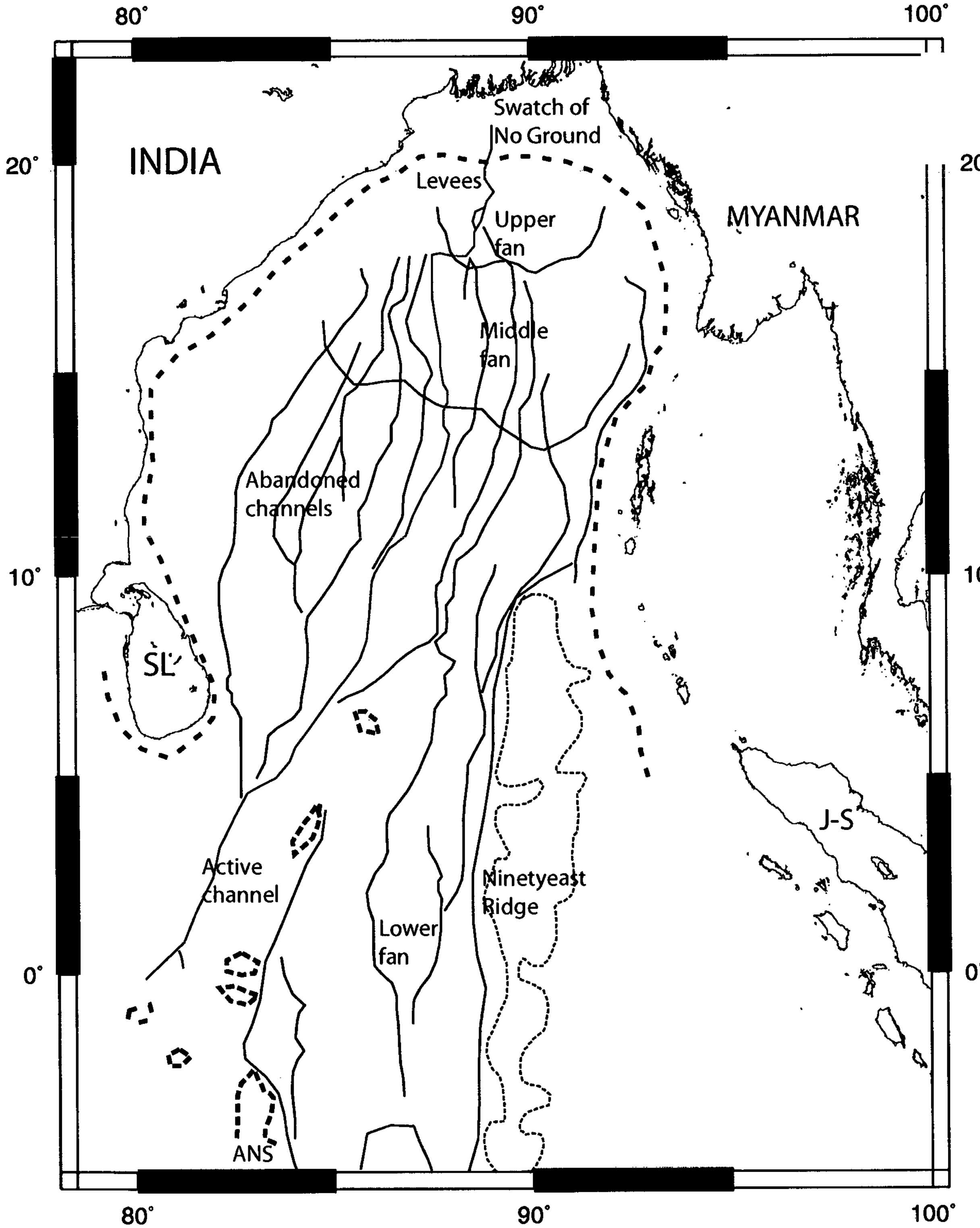


Figure 2-2 Morphometric map of the Bengal Fan (Emmel and Curray, 1984). Present-day active (pink) and abandoned (blue) channels are shown. Fan boundaries are marked. Red dashed line represents base of the slope. SL: Sri Lanka, ANS: Afanasy Nikitin Seamount chain. J-S: Java-Sumatra

north and the main source of sediment is from the rivers Ganges and Brahmaputra. Seismic reflection and refraction studies across the Bay of Bengal (Curray 1991; 1994) reveal the presence of 22 km thick sediments at the head of the Bay of Bengal. The sediment thickness decreases gradually to <2 km towards the southern end of the distal Bengal Fan (Fig. 2-3). Magnetic data interpretation in the Central Bay of Bengal depicts >8 km thick sediments resting over the Early Cretaceous basement (Ramana et al., 1994a; Sarma et al., 2002[3]). The major offshore basins, namely the Mahanadi, Krishna, Godavari and Cauvery mark the delta fronts on the inner shelf of the ECMI. These delta fronts are characterized by several V shaped canyons flanked by steep faults, which appear to continue on the continental slope of these basins (Rao et al., 1980).

### 2.1.1 Previous studies

Bathymetry

The ECMI has a narrow shelf, which varies between <17 km off Karaikal to >200 km off Bengal coast (Sastri et al., 1981; Ramana et al., 2001b). The shelf break occurs at a water depth of around 200 m. The continental slope is gentle north of 14°N (30 m/km), while it is as steep as ~90 m/km to its south. Water depth

[3] *Sarma, K.V.L.N.S., Ramana, M.V., Ramprasad, T., Desa, M., Subrahmanyam, V., Krishna, K.S. and Rao, M.M.M., 2002. Magnetic basement in the central Bay of Bengal, Mar. Geophys. Res.,* ***23****: 97-108.*

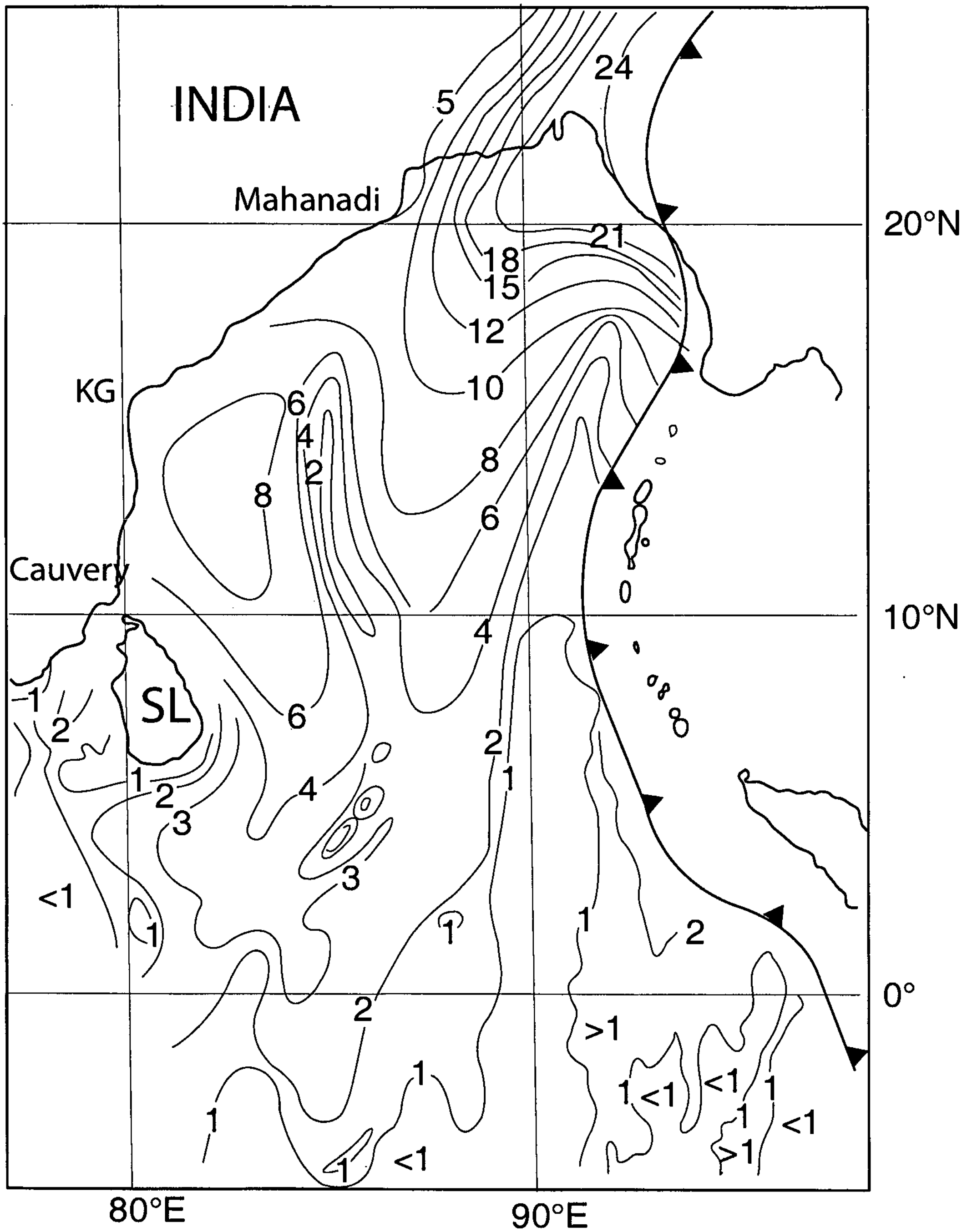


Figure 2-3 Total sediment thickness map of the Bay of Bengal inferred using seismic reflection and refraction data (Curray, 1994). Variable contour interval in km. KG: Krishna-Godavari; SL: Sri Lanka

then gradually increases from ~2500 m at the foot of the slope towards offshore. The depth to the seabed increases with a gentle gradient from the head of the bay in the north upto ~5000 m as far as 5°S (Fig. 2-1). Topography is smooth throughout the region except along the 90°E meridian due to the presence of an approximately N-S trending positive bathymetry of the Ninetyeast Ridge. A deep valley like feature corresponding to the Sunda Trough is noticed immediately east of the Ninetyeast Ridge. The seabed topography becomes shallower to <1200 m while approaching the Andaman group of Islands (Emmel and Curray, 1984). Some isolated seamounts are also seen towards the south of the Bay of Bengal. The seabed is also traversed by a number of turbidity channels with levee wedges.

Magnetics

The earliest magnetic studies in the Bay of Bengal are by Rao and Bhattacharya (1976). Based on aeromagnetic studies along four tracks running from the east coast of India to the Sunda Trough area, they estimated depths to the basement and inferred the presence of fracture zones, basins and valleys. Further studies by Rao and Rao (1985; 1986) suggested the presence of two major structural elements: i) a marginal high, and ii) a marginal basin in the Bay of Bengal. Rao et al., (1987) computed depth to the magnetic basement using analytical signal and Werner Deconvolution techniques and inferred the presence of grabens and basement highs based on five E-W trending magnetic profiles in the Bay of Bengal.

National Institute of Oceanography, Goa, acquired large amount of total intensity magnetic data all along the ECMI and its deep offshore using the research vessels RV Gaveshani, ORV Sagar Kanya, DSV Nand Rachit, etc. A magnetic anomaly contour map along the ECMI has been prepared using all the magnetic data acquired by the NIO (NIO, 1993). The map shows the presence of anomaly contours parallel to sub-parallel to the coast within the shelf region (Fig. 2-4). The region north of 17°N is characterized by dense high amplitude magnetic anomaly closures as compared to the south. This highly anomalous zone indicates the presence of shallow intrusive bodies (dykes) associated with rift phase volcanism during the breakup of eastern Gondwanaland. Murthy et al., (1993) inferred three major trends based on bathymetry and magnetic data in the Bay of Bengal. These are (i) The continent-ocean boundary (COB) located at the foot of the continental slope at ~3000 m water depths, (ii) the 85°E Ridge and its northern extension abutting the continental shelf off Chilka Lake, and (iii) folded nature of the continental basement between Visakhapatnam and Paradip.

It was opined that the huge sediment overburden (>18 km) in the Bay of Bengal might obscure the magnetic anomaly signatures (Brune and Singh, 1986; Powell et al., 1988; Curray, 1991). Curray and Munasinghe (1991) suspected the presence of Mesozoic magnetic anomalies M4 and M5 in the Bay of Bengal. Magnetic studies between 6 and 11°N latitudes in the Bay of Bengal suggested the presence of four magnetic anomaly provinces (i) the 85°E Ridge; (ii) NNE-SSW trending basement high/ridge system, (iii) the Ninetyeast Ridge, and (iv) Sunda

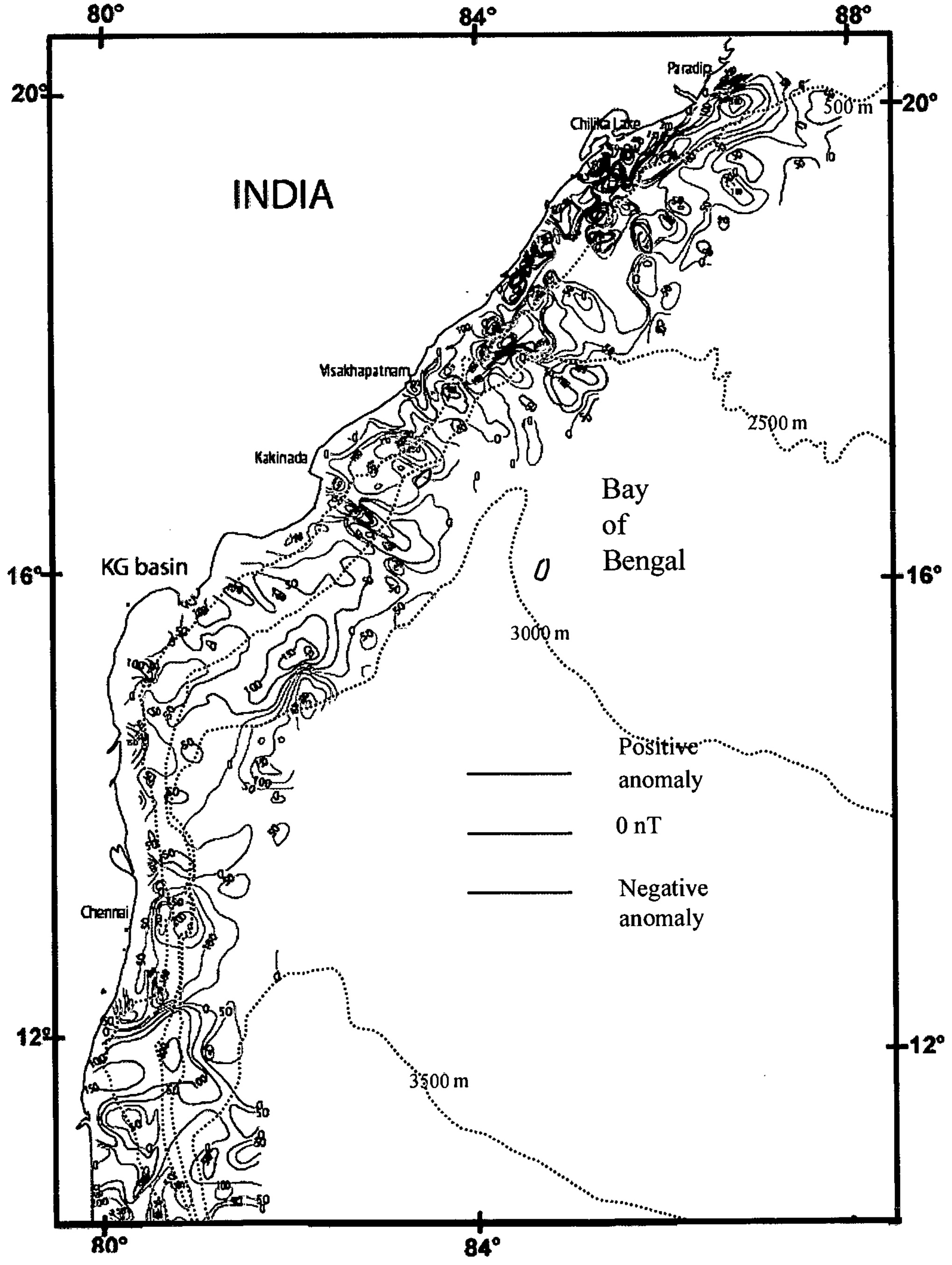


Figure 2-4 Magnetic anomaly contour map of the Eastern Continental margin of India (NIO, 1993). Thin dashed outlines are bathymetry contours

Trough system (Ramana et al., 1992). Ramana et al., (1994b[4]) reported low amplitude magnetic anomalies (100-200 nT) in the Central Bay of Bengal except on the 85°E Ridge, and seafloor spreading model studies indicated that these anomalies belong to the Mesozoic magnetic anomaly sequence M11 through M0 with half-spreading rates (HSRs) of ~3.5 cm/yr. Further, some NW-SE trending fracture zones were inferred based on the disposition of the successive magnetic anomaly isochrons (Fig. 2-5). Banerjee et al., (1995) proposed an alternate model for the Bay of Bengal in which they suggested that the Rajmahal hotspot powered the rifting of India from Antarctica around 117 Ma (Barremian), whereas Ramana et al., (1997b[5]) inferred the presence of a magnetic quiet zone in the southern Bay of Bengal. This magnetic quiet zone crust was formed during the first major plate reorganization in the Middle Cretaceous when the spreading direction of the Indian plate changed from NW-SE to N-S at a slow spreading rate of 1.2 cm/yr.

The subsurface 85°E Ridge is characterized by large-amplitude (100-400 nT) magnetic anomalies all along its length (Ramana et al., 1997a[6]), and magnetic model studies revealed that the rocks of the ridge are reversely magnetized.

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[4] *Ramana, M. V., Nair, R. R., Sarma, K. V. L. N. S., Ramprasad, T. Krishna, K. S., Subrahmanyam, V., D'Cruz, M., Subrahmanyam, C., Paul, J., Subrahmanyam, A. S. and Chandrasekhar, D. V., 1994b. Mesozoic anomalies in the Bay of Bengal, Earth Planet. Sci. Lett.* ***121:*** *469-475.*

[5] *Ramana, M. V., Subrahmanyam, V., Sarma, K.V.L.N.S, Desa, M., Malleswara Rao, M. M. and Subrahmanyam, C., 1997b. Record of the Cretaceous Magnetic Quiet Zone: A precursor to the understanding of the evolutionary history of the Bay of Bengal, Curr. Sci.* ***72:*** *669-673.*

[6] *Ramana, M. V., Subrahmanyam, V., Chaubey, A. K., Ramprasad, T., Sarma, K.V.L.N.S, Krishna, K. S., Desa, M. and Murty, G.P.S., 1997a. Structure and origin of the 85°E Ridge, J. Geophys. Res.,* ***102:*** *17995-18012.*

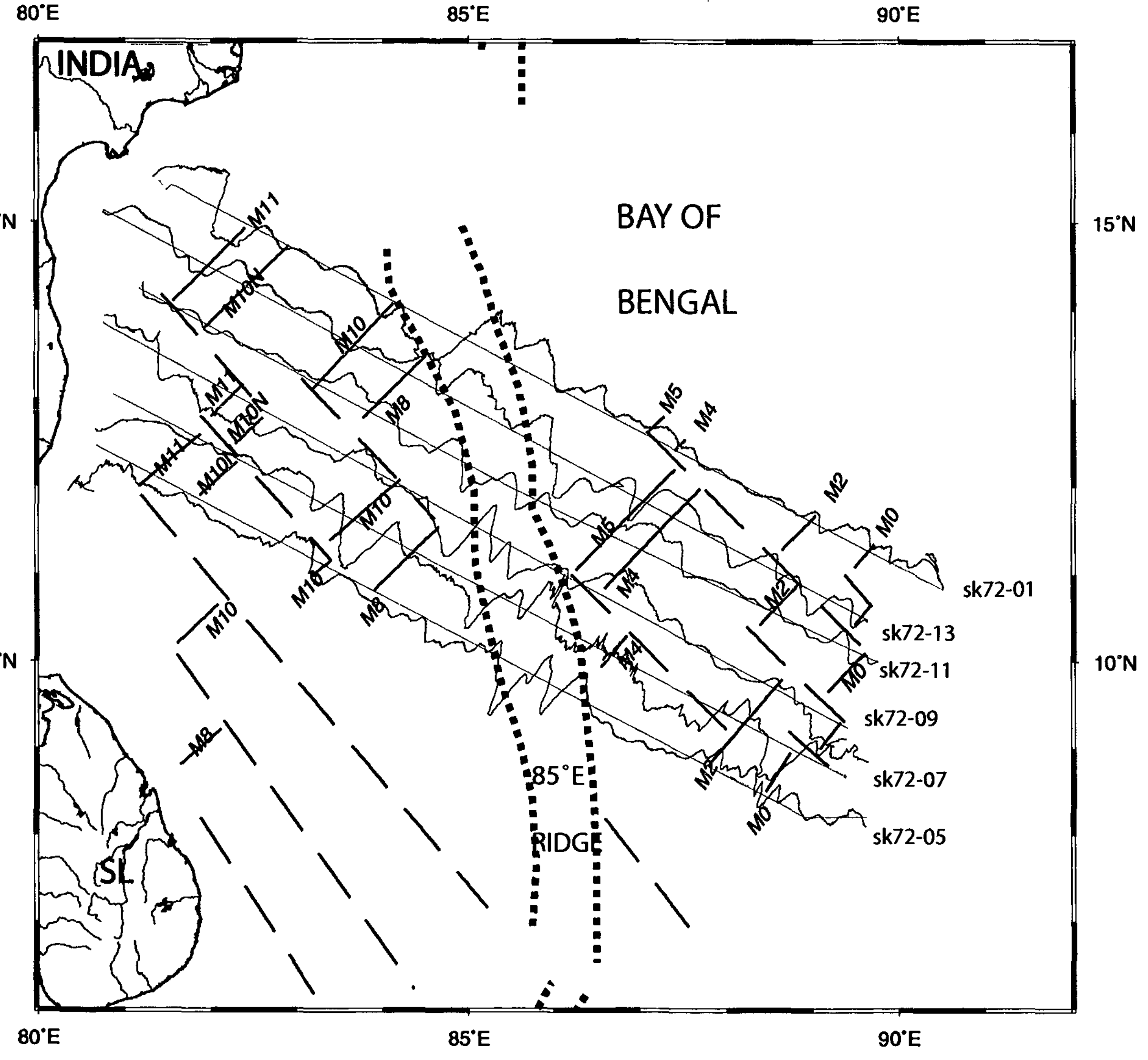


Figure 2-5 Magnetic anomalies stacked along the tracks in the Central Bay of Bengal (Ramana et al., 1994b; 2001a). Dashed lines indicate inferred fracture zones. Positive anomaly is shaded. Numbers prefixed with 'M' indicate the Mesozoic magnetic anomalies marked as red lines.

Analysis of magnetic data south off Sri Lanka suggested the presence of Mesozoic magnetic anomaly sequence M11 through M0 occurring in an arcuate shape offset by NW-SE to NNW-SSE trending fracture zones (Desa et al., 2006[7]). Late Cretaceous magnetic anomalies 34 to 31 have been identified in the equatorial region between the 86°E FZ and Ninetyeast Ridge (Desa et al., 2009[8]). These anomalies are offset left laterally and the crust is generated at higher spreading rates and characterized by the presence of extra crust. Magnetic anomalies on the Ninetyeast Ridge do not follow a well-defined pattern.

Gravity

The free-air gravity map of the Indian subcontinent (NGRI, 1978; Sreedhar Murthy, 1999) depicts the major structural and tectonic features associated with the Indian peninsula. Based on gravity and magnetic expressions, the onshore tectonic lineaments are found to extend into the deep offshore. The Eastern Ghats of India are characterized by NE-SW trending gravity 'lows' and 'highs', which are almost parallel to the coast. However, there are two centers of linear gravity 'lows' trending NW-SE perpendicular to the coast coinciding with the Godavari and Mahanadi basins. These two Gondwana basins developed when India was part of

[7] *Desa, M., Ramana, M. V. and Ramprasad, T., 2006. Seafloor spreading magnetic anomalies south off Sri Lanka, Mar. Geol.,* ***229****: 227-240.*

[8] *Desa, M., Ramana, M. V. and Ramprasad, T., 2009. Evolution of the late Cretaceous crust in the equatorial region of the Northern Indian Ocean and its implication in understanding the plate kinematics, Geophys. J. Int.,* ***177****:1265-1278.*

Gondwanaland and juxtaposed with Antarctica (Fedorov and Ravich, 1982), and are characterized by Permian-Triassic-Early Cretaceous sediments comprised of sandstones, limestones, shales, etc. (Raja Rao, 1982). Rao and Rao (1985) inferred a marginal high characterized with gravity high all along the east coast of India. Further offshore, the presence of a marginal basin was inferred in the southern Bay of Bengal.

Free-air gravity anomaly analysis in the Bay of Bengal reveals a depressed gravity field inspite of the huge sediment overburden (Mukhopadhyay and Krishna, 1991). Detailed free-air gravity anomaly map (Fig. 2-6) depicts negative gravity field of –20 to –30 mgal (Subrahmanyam et al., 2001[9]). The shelf edge of the Eastern Continental margin of India is seen associated with a prominent gravity low. This strong low is caused by the lateral variations in density between the oceanic (2.9 gm/cc) and continental (2.6 gm/cc) crusts. Another distinct gravity low trending approximately N-S along the 85°E longitude corresponds to the subsurface 85°E Ridge. The 85°E Ridge anomaly and other isolated gravity lows have been attributed to Moho undulations. A depression ~6 km deeper than the regional Moho boundary is envisaged beneath the 85°E Ridge (Subrahmanyam et al., 2001). The NE-SW trend of the gravity contours indicates the orientation of the subsurface crustal features. The distribution of the free-air gravity anomalies in the Bay of

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[9] *Subrahmanyam, V., Krishna, K.S., Murthy, I.V.R., Sarma, K.V.L.N.S., Desa, M., Ramana, M.V. and Kamesh Raju, K.A., 2001. Gravity anomalies and crustal structure of the Bay of Bengal, Earth Planet. Sci. Lett.,* ***192****: 447-456.*

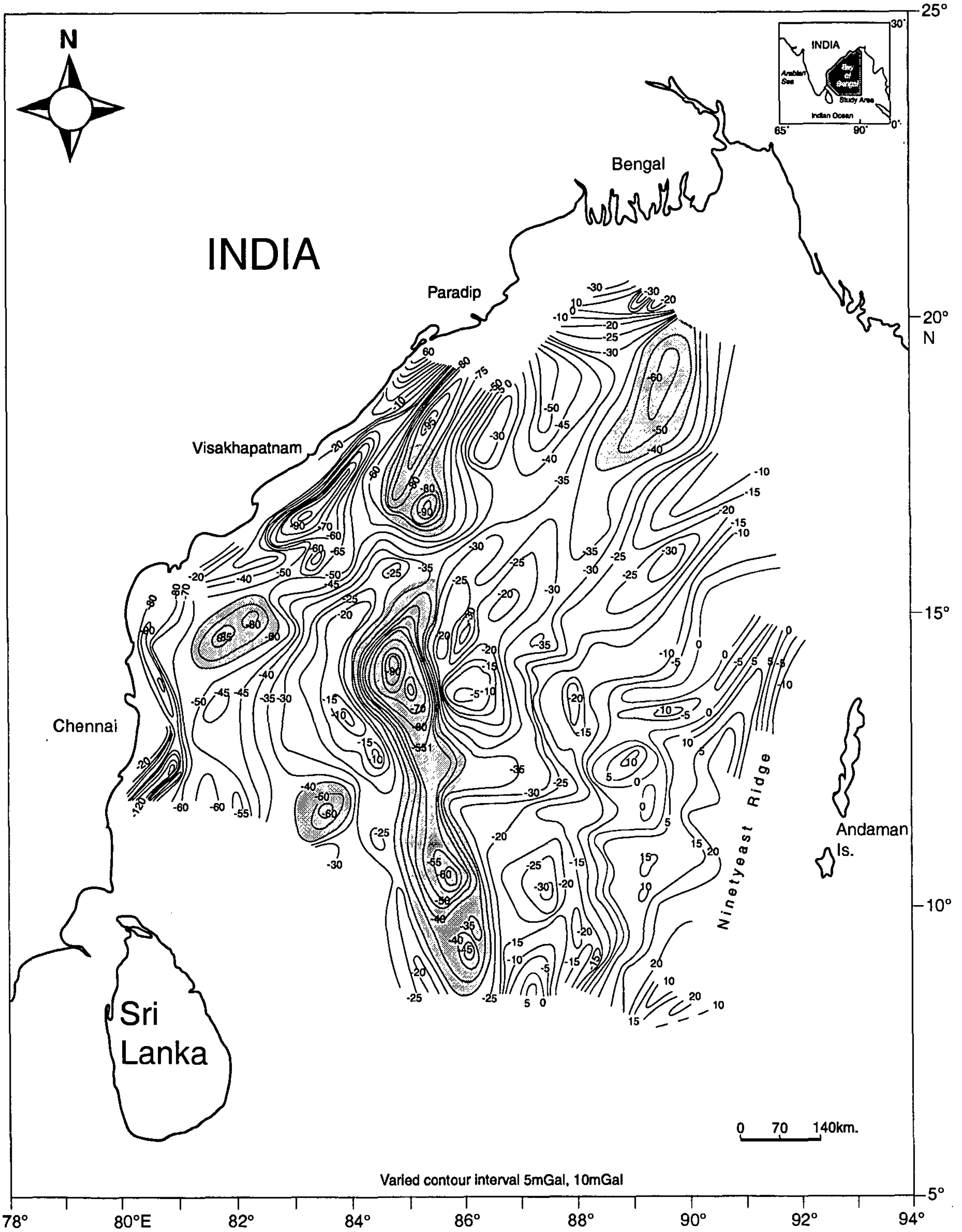


Figure 2-6 Shipborne free-air gravity anomaly map of the Bay of Bengal (Subrahmanyam et al., 2001). Elongated contours along 85°E meridian are due to the subsurface 85°E Ridge

Bengal suggests that the Eastern Continental Margin of India can be divided into the northern rifted and southern transform segments (Subrahmanyam et al., 1999).

The satellite derived free-air gravity mosaic of Sandwell and Smith, (1997) depicts a broad distribution of the gravity field in the Bay of Bengal (Fig. 2-7). The continental shelf is characterized with positive gravity. The steep negative gradient immediately seaward of it perhaps marks the continent-ocean boundary. Here too, the NE-SW trending fine grains in the mosaic are seen near the Eastern Continental margin of India and around Sri Lanka. NNW-SSE trending fracture zones can be inferred based on the offsets in the mosaic grains. The positive elongated gravity field in the vicinity of the 90°E meridian is due to the Ninetyeast Ridge. Towards the southeast, the north-south trending lineations are due to the oceanic fracture zones offsetting the Late Cretaceous crust (Liu et al., 1983). The gravity mosaic also depicts distinctly the imprints of the subsurface 85°E Ridge that takes an arcuate shape around Sri Lanka. Isolated positive signatures seen in the distal Bengal Fan are attributed to the presence of seamounts.

Seismics

Preliminary seismic investigations based on wide angle seismic reflection and refraction experiments show nine distinct sedimentary layers across the Bengal Fan with average P-wave velocities ranging between 2.05 and 6.22 km/s (Naini and Leyden, 1973). The total sediment thickness varies between 7 and 9 km, with the

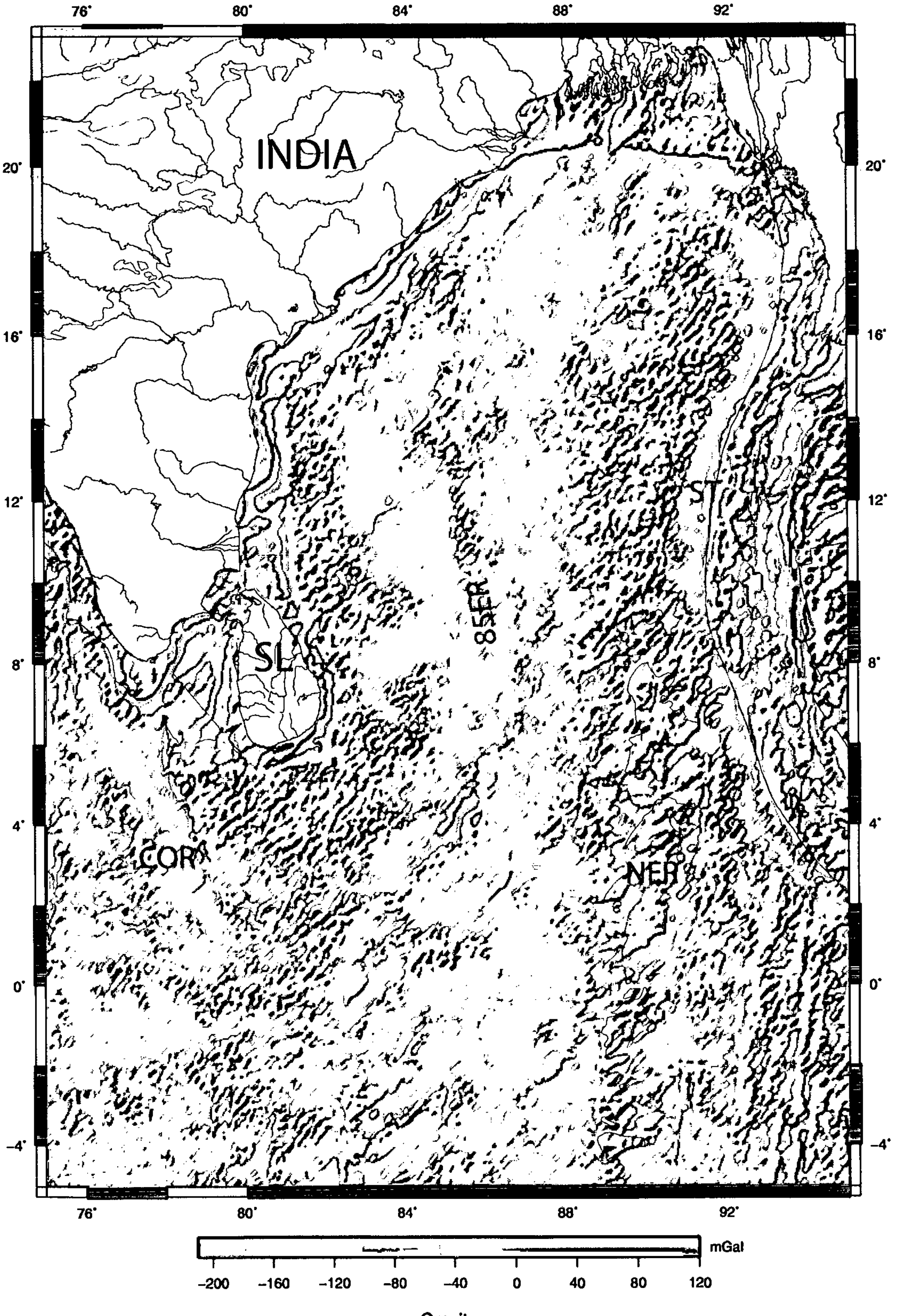


Figure 2-7 Satellite derived free-air gravity map of the Bay of Bengal (Sandwell and Smith, 1997). N-S oriented lineations in the south and east represent oceanic fracture zones. 85ER: 85°E Ridge; ST: Sunda Trough; NER: Ninetyeast Ridge; COR: Comorin Ridge; SL: Sri Lanka

layers from seafloor through layer 5 having a regional dip towards south. The lower layers (6 – 9) dip north indicating a marked increase in sediment thickness from south to north since Late Miocene.

Curray et al., (1982) compiled all the seismic data and inferred major unconformities, and the velocity structure of sediments and basement rocks in the Bay of Bengal. Study of a seismic profile along 10°N latitude reveals that the oldest marine rocks in the Cauvery basin are reef limestones, sandstone and shale possibly of Albian age, while the seismic profile along 13°N latitude indicates that the oldest marine sediments are probably of Early Cretaceous age, and include "splintery, gray and greenish shales containing dark gray gypseous clay and interbedded sandstone, ironstone and limestone". These overlie Permian Gondwana continental sediments and are interpreted to be of brackish or shallow marine origin. Seismic refraction results reveal that continental crust at the foot of the slope is characterized with a velocity of 6.4 km/s. Further east, the crustal or third layer velocities range from 7.5 to 6.8 km/s decreasing towards east, indicating the presence of very old oceanic crust beyond the foot of the slope and relatively younger crust towards east. A thick sedimentary section with velocity range of 4 - 4.5 km/s of Early Cretaceous to Paleocene age overlies this oceanic crust. Further, Curray et al., (1982) identified two major unconformities, i.e. the uppermost Miocene (M) and top of Paleocene (P).

The presence of the ~N-S trending 85°E Ridge has been inferred from the multichannel seismic reflection data (Curray and Moore, 1971). Further, Curray et al., (1982) suggested that the 85°E Ridge has been in existence since the P unconformity and the thinning of the Tertiary section above it appears to be due to differential compaction and local erosion, rather than by continued uplift of the ridge. Sediment thickness of more than 8 km and similar crustal structure on both sides of the 85°E Ridge was inferred. The pre-Eocene sediments are considered as the pre-fan, while the post-Paleocene sediments as the post-fan sediments.

Multichannel seismic reflection data acquired by the oil industry along two regional seismic lines across the Bay of Bengal (Man-01: Lat: 14°38'N; Long: 80° 16.5' to 92°11.5'E and Man-03: Lat 13°N; Long 80°31' to 92°14.8'E) depict the presence of four seismic sequences (Pateria et al., 1992). The top two sequences include Miocene-Recent and Eocene-Oligocene sediments. They tend to wedge out towards the rise and the internal configuration show parallel reflections suggesting low energy environment. The bottommost sequence thickens towards the continental rise and constitutes the Cretaceous deposits. The overlying sequence gradually thins towards the rise and its top corresponds to the Paleocene-Eocene unconformity assigned as reflector P by Curray et al., (1982). These two bottom sequences are sub-parallel with transparent zones and thin out over basement highs. The 85°E Ridge remained a positive feature during the deposition of these sequences. A marginal fault corresponding to the continental margin and/or rise having a wrench component has been reported.

Gopala Rao et al., (1994[10]) inferred eight sequences (Fig. 2-8) and three major unconformities (Eocene, upper Miocene and upper Pleistocene) along a regional seismic section within the sedimentary column overlying the Early Cretaceous basement. The inferences are based on the interpretation of Curray et al., (1982). The bottommost sequence H8 has been interpreted as the pre-collision clastics, while the sequence H7 as post-collision clastics and hemi-pelagics of Eocene-Oligocene age. Sequences H3 to H6 constitute mud turbidites and gray silt deposited during the events such as intraplate deformation, growth and denudation of the Himalayas, and sealevel regression of the Miocene. These deposits thicken towards offshore and north. The sequences H2 and H1 represent the Pliocene/Pleistocene to Recent deposits. Further, Gopala Rao et al., (1997) inferred pairs of basement rises separated by depressions trending oblique to the 85°E Ridge. These rises have a relief of about 0.8 to 1.2 s, and represent the oceanic fracture zones indicating the direction of the seafloor spreading. Kundu et al., (2008) reported the onlapping of thick Pleistocene and Pliocene, and thin Miocene sediments on the Paleocene deposits from the information of two well log data in the Krishna-Godavari offshore. The seismo-geological section on the continental slope indicates the presence of Cretaceous sediments below the Paleocene unconformity.

[10] *Gopala Rao, D., G.C. Bhattacharya, M.V. Ramana, V. Subrahmanyam, T. Ramprasad, K.S. Krishna, A.K. Chaubey, G.P.S. Murty, K. Srinivas, Maria Desa, S.I. Reddy, B. Ashalata, C. Subrahmanyam, G.S. Mittal, R.K. Drolia, S.N. Rai, S.K. Ghosh, R.N. Singh and R. Majumdar, Analysis of multichannel seismic reflection and magnetic data along 13°N latitude across the Bay of Bengal, Marine Geophys. Res., 16, 225-236, 1994.*

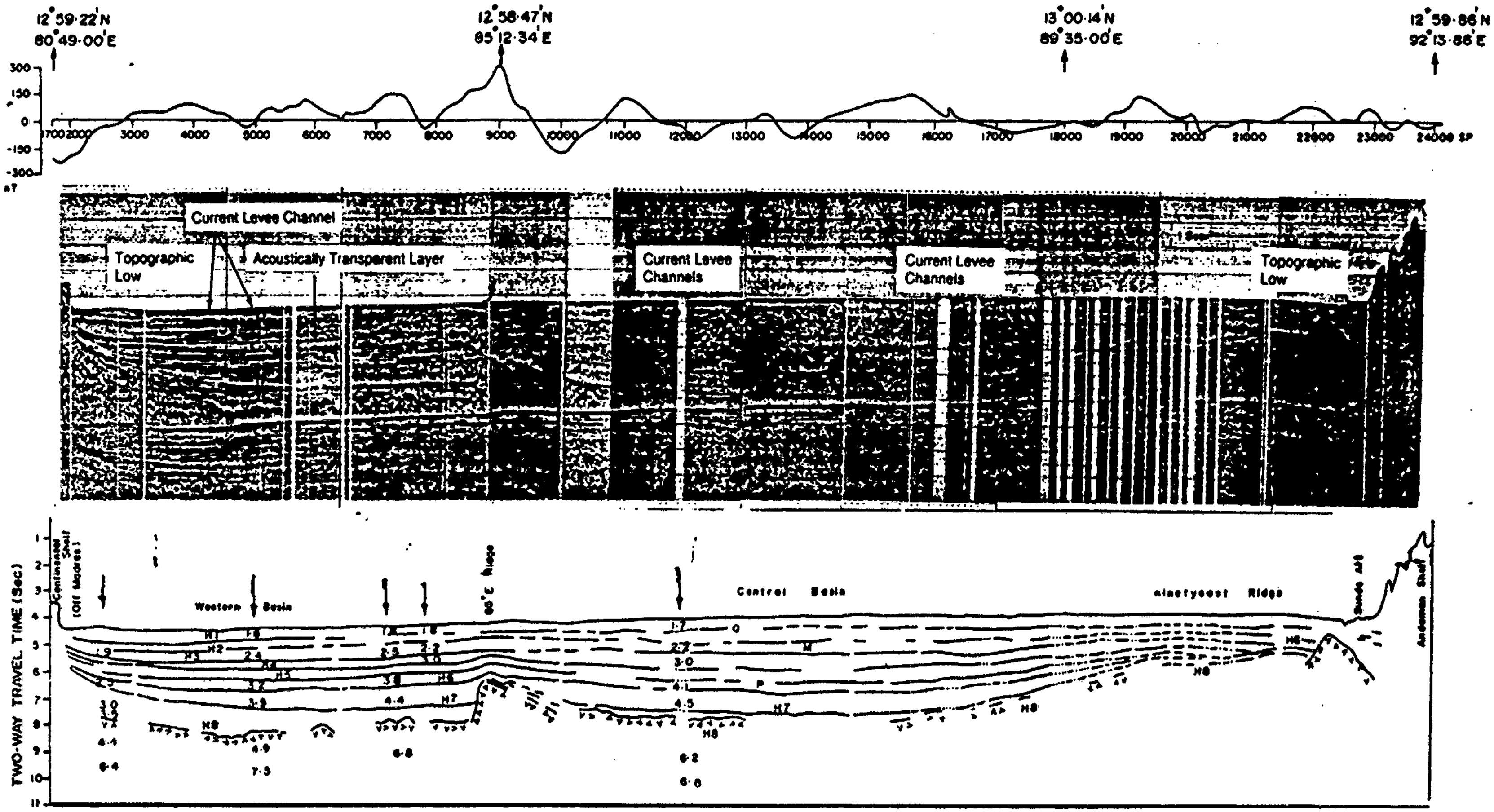

Figure 2-8 Multichannel seismic reflection record across the Bay of Bengal (13°N latitude) along with its interpretation. Magnetic profile is also superimposed (Gopala Rao et al., 1994). P, M, Q, etc. denote the major unconformities

Drilling results

The Deep Sea Drilling Project (DSDP) was initiated to acquire deep sedimentary cores to trace the depositional history of the ocean basins. During Leg 22 of Glomar Challenger, several locations were drilled in the Indian Ocean of which sites 217 (8.926°N, 90.539°E) and 218 (8.0°N, 86.283°E) located in the Bay of Bengal (Fig. 2-1) are used in the present study (Von der Borch et al., 1974). Detailed analyses of the site 218 drilled in water depths of 3749 m reveal that the upper 200 m of the core consists of Pleistocene-Recent sediments, while the sediments between 200 and 320 m are of Pliocene age (Fig. 2-1). The bottom 320-773 m comprises sediment upto Middle Miocene. Four major turbidite pulses have been interpreted within the core at 50 m, 300 m, 580 m and 700 m. Based on seismic velocities, three sediment units have been inferred having velocities 1.6 to 2.3 km/s of upto Upper Miocene, 2.4-3.3 km/s of Upper Miocene to Middle Eocene and 4-5 km/s of Pre-Upper Paleocene. When compared with seismic records, the bottommost sediment drilled at this site corresponds to 0.8 s TWT, while at 0.25 s TWT the horizon represents the Plio-Pleistocene boundary. A major unconformity at 0.45 s TWT represents the top of Miocene. The lithology revealed turbidite sedimentary sequence of silts, sandy silts, clayey silts and some nannofossil ooze layers of Quaternary to Middle Miocene age. The maximum depth drilled at this location was 773 m and the basement could not be reached.

DSDP site 217 was drilled on the Ninetyeast Ridge in water depths of 3010 m (Fig. 2-1). The uppermost unit consisting of clay rich carbonate sediments (0 to 145 m) are of Quaternary to Middle-Late Miocene age. It is underlain by a unit of nannofossil ooze chalk and chert upto 600 m thickness of Late Miocene to Campanian age. The final unit (600 to 664 m) consists of interbedded sequence of dolomite sandstone, chalk and chert of Late Campanian age. The biostratigraphy and lithology suggest gradual subsidence of the ridge from near sealevel and northward migration towards the source of terrigenous material (Von der Borch et al., 1974).

### 2.1.2 Tectonic elements

Regional geological and geophysical studies in the Bay of Bengal reveal the presence of several large scale structural features such as the Ninetyeast Ridge, the submerged 85°E Ridge, the submarine canyon, several channels, fracture zones and seamounts.

Ninetyeast Ridge

The Ninetyeast Ridge is an important physiographic feature of the Bay of Bengal, which divides the Bengal Deep Sea Fan into the western Bengal Fan and eastern Nicobar fan (Fig. 2-1). This ridge approximately 5000 km long, extending from south of 35°S to about 17°N trending N-S along the 90°E meridian (Heezen and Tharp, 1964) is one of the longest linear topographic feature in the world. Seismic reflection data indicates that along 10°N latitude, the ridge is carpeted by a thin veneer of sediment and for another 700 km, i.e. upto 17°N, it is buried under thick Quaternary-Eocene sediments of the Bengal Fan. The ridge is characterized by variable width, with an average of 200 km (Fisher et al., 1982; Curray et al., 1982; Gopala Rao et al., 1997). The ridge exhibits a relief of ~2500 m from the surrounding water depth and is associated with elongated highs and intermittent troughs. The shallowest of them lies at 1400 m water depth south of 15°S. The southern part of the ridge is linear and flat topped, whereas north of 7°S, the ridge comprises of a complex series of en echelon blocks. The eastern flank of the ridge is relatively steeper than the western flank (Pierce, 1978; Pierce et al., 1989). The seafloor to the east of the ridge displays a complex of narrow ridges and troughs approximately parallel to the ridge (Bowin, 1973; Krishna et al., 1995). This complex topography has been interpreted as a transform fault between the Indian and Australian plates. Around 15°S, the portion of the ridge protruding in a westerly direction with large areal extent and an oval shape is known as the Osborn Knoll. To the south, the ridge adjoins the Broken Ridge (Curray et al., 1982).

Several theories were put forward to explain the origin of the ridge prior to scientific drilling activity. Some such theories are: (i) a horst, (ii) localized emplacement of gabbros, (iii) result of overthrusting, (Le Pichon and Heirtzler, 1968), (iv) a volcanic pile generated at the intersection of a ridge crest and a transform fault (Sclater and Fisher, 1974), and (v) hotspot trace, (Morgan, 1972).

Seismic refraction studies on the ridge indicate the presence of thin (~2.8 km) crustal layer and low velocity mantle below the crust, thereby suggesting that the ridge may be a horst (Francis and Raitt, 1967). However, Bowin (1973) argued that if the ridge is a horst type structure, then the free-air gravity should be largely positive, but the amplitude of the gravity field is small, therefore it was inferred that the ridge evolved as a result of emplacement of gabbros and serpentinized peridotite beneath the normal oceanic crustal layers.

DSDP results (Leg 22: sites 214, 216 and 217; Leg 26: 253 and 254) indicate that the ridge is an extrusive volcanic basement that formed subaerially or in shallow environment and subsided with time (Davies et al., 1974; Von der Borch et al., 1974). Paleomagnetic studies confirm that the ridge was attached to the Indian plate and both have moved rapidly northward since Late Cretaceous. Ages of the basement increase northward along the ridge and are of the same order as the ages of the Indian plate to the west. The ridge appears to have subsided with time and follows the age-depth relation for the oceanic crust (Parsons and Sclater, 1977).

ODP Leg 121 sites 756, 757 and 758 further improved the understanding of the tectonic and evolutionary history of the ridge (Royer et al., 1991; Weissel et al., 1991). A general increase in age from 38 Ma at around 35°S to >90 Ma towards the northern end of the ridge (~10°N) is inferred. The paleolatitudes of the ridge also indicate that its volcanic source was around 50°S latitude, which is in the vicinity of the Kerguelen Island (Pierce, 1978). The recovered basaltic rocks are not primary magmas derived from the mantle but are moderately evolved tholeiites. Similarity in the basaltic composition between the Ninetyeast Ridge and the Kerguelen Heard Islands indicates a common magma source (Frey et al., 1977; Mahoney et al., 1983). From the ODP and DSDP results it was concluded that the ridge has originated due to mantle plume volcanism at or near a spreading center (Weis et al., 1991; Klootwijk et al., 1991; Duncan and Storey, 1992; Class et al., 1993).

The Ninetyeast Ridge is seismically active with its northern segment lying in the zone of deformation and undergoing NW-SE compression with both vertical and strike-slip motion. The southern portion of the ridge is far less active seismically as is evident from the ridge morphology (Stein and Okal, 1978). Crustal studies suggest that the ridge is isostatically compensated by over-thickening of the oceanic crust. This implies that the ridge was formed on hot, relatively weak lithosphere, at or near a spreading center (Mukhopadhyay and Krishna, 1991). Seismic velocities range from 6.8 to 7.0 km/s with crustal thickness of about 25 km (Grevemeyer et al., 1999).

Detailed studies indicate that the gravity field over the ridge is not uniform and there is a close correlation between the trend of the free-air gravity and topography. Presence of several isolated gravity highs suggest that the ridge consists of several blocks of anomalous masses, and denser rock masses underlie the ridge at depth. The northern part of the ridge is characterized by positive gravity with amplitude of upto 50 mgal and average wavelength of about 350 km (Mukhopadhyay and Krishna, 1995). South of equator, the gravity anomalies are relatively subdued when compared to the topographic relief (Bowin, 1973). The zero contours define the ridge boundary with respect to the adjacent ocean floor. Gravity falls sharply to a minimum of –60 mgal on the eastern side of the ridge across the postulated transform fault.

### 85°E Ridge

Another equally important feature in the Bay of Bengal is the submerged 85°E Ridge (Curray and Moore 1971; 1974; Curray et al., 1982; Liu et al., 1982). This ridge trends approximately N-S between 19° and 6°N latitudes and then takes an arcuate shape off the southeast coast of Sri Lanka and seems to culminate with the northern extension of the Afanasy Nikitin seamount chain situated around 2°S latitude. The width of the ridge is about 120-180 km and the relief is about 3-4 km.

The 85°E Ridge is characterized by positive (100-400 nT) magnetic (Ramana et al., 1997a) and negative (-60 mgal) free-air gravity (Liu et al., 1982) anomalies. The ridge divides the main Bengal Fan longitudinally into two basins having >8 km thick sediments. The two basins are the western basin lying between the east coast of India and the ridge, and the eastern basin between the 85°E and Ninetyeast Ridges (Gopala Rao et al., 1994). The ridge is buried under >3 km thick sediments in the north, i.e. 13°N latitude, and relatively thin (<2 km) sediments in the south, i.e. 10°N latitude (Pateria et al., 1992). The western flank of the ridge along 13°N latitude is steeper than the eastern flank (Gopala Rao et al., 1994). The ridge appears as a double-humped feature around 12 and 13°N latitudes and as an intrusive peak and broad basement rise around 10°N. The eastern hump of the ridge at 13°N latitude has been interpreted as carbonate buildup (Gopala Rao et al., 1997). Seismic sections indicate that the ridge has been in existence prior to the lower Eocene unconformity (Curray et al., 1982).

Several theories have been postulated to explain the origin of the ridge. The ridge may have been formed by emplacement of probable extrusive rocks when the underlying lithosphere was young (5-15 m.y. old) and low in flexural rigidity resulting in the steep negative free-air gravity anomaly due to lithospheric flexure (Liu et al., 1982). Mukhopadhyay and Krishna (1991) suggested that the ridge comprised of thick oceanic crustal material with its underlying root in the lithosphere. Theories such as abandoned spreading center (Mishra, 1991), volcanism through a weak zone within a short span of time (Chaubey et al., 1991) and northward continuation of the 86°E FZ (Kent et al., 1992) were also proposed. Curray and Munasinghe (1991) believed that the ridge is a trace of the Crozet hotspot, which also formed the Rajmahal Traps. Another opinion was that the ridge and Afanasy Nikitin seamount chain might have been formed by a hotspot now located underneath the eastern Conrad Rise on the Antarctica plate (Muller et al., 1993). However, a common view is that the ridge was evolved during the Cretaceous long normal polarity epoch (120-84 Ma).

Ramana et al., (1997a) argued based on the distinct gravity and magnetic anomaly signatures, and its buried nature under thick sediments as well as its deep occurrence that the ridge might have least affinity towards hotspot origin, and favors a volcanic emplacement during a short span of time when a major plate reorganization took place. Further two alternate processes have been postulated for the ridge emplacement (Ramana et al., 1997a). These processes include (a) shearing of the lithosphere caused by stretching and compressional forces associated at the time of major plate reorganization immediately after the evolution of the Early Cretaceous crust in the Bay of Bengal, more precisely at M0 polarity chron or during the Middle Albian (107-102 Ma) reversals within the K-T superchron coupled with the slow northward motion of the Indian plate, or (b) sagging of the lithosphere followed by deformation, caused by horizontal compressional forces on the passive continental margin.

Afanasy Nikitin Seamount chain

The Afanasy Nikitin Seamount chain (ANS) stretches along 83°E longitudes between 2° and 6°S latitudes (Schlich, 1982). It is ~450 km in the N-S direction and its width is ~150 km (Fig. 2-1). It is bounded on the west by the Indira FZ and on the east by the 84.5°E FZ. The subsurface 85°E Ridge buried under the Bengal

Fan sediments rises above the seafloor south of 7.5°N and appears to abut with the northern extension of the ANS. The basement platform rises to 3800 m water depth on which several elongated peaks exist. The shallowest summit of the seamount rises to 1600 m towards north (Krishna, 2003).

Curray and Munasinghe (1991) proposed that the Rajmahal Traps, the 85°E Ridge and the ANS were emplaced by the Crozet hotspot that now lies beneath the Crozet Islands. Magnetic studies suggest that the ANS is lying on 79-73.5 Ma aged oceanic crust and may be a palaeovolcanic structure formed near a spreading axis (Paul et al., 1990). The crust beneath the ANS is ~18 km thick and the seamount is compensated by flexure of layer 2 to the extent of ~1.5 km and by 8 km thick magmatic rocks in the lower crust (Krishna, 2003). The composition of the basaltic rocks dredged from the summit indicates that they are the product of intraplate volcanism that is similar to hotspot activity. During the volcanic activity, the summit of the seamount rose above the sealevel as an island. This was dissected by abrasion in Paleocene (?) and resulted in formation of conglomerate sequence on the upper parts of the slope. The presence of deepwater foraminifera indicates its subsequent subsidence (Banakar et al., 1997). Borisova et al., (2001) detected the involvement of lower continental crust in the petrogenesis of the olivine-phyric basaltic rock of the ANS. Interpretation of magnetic data covering the ANS region revealed the presence of a fossil spreading ridge (FSR) and 75 km extra crust on the ANS. This extra crust has been attributed to a southward ridge jump that occurred around 75.8 Ma (Desa et al., 2009).

## 2.2 Enderby Basin

The Enderby Basin is the conjugate of the Bay of Bengal and is therefore relevant to the present study. Published scientific results pertaining to this area provide immense support to the joint interpretation of geophysical data in the two study areas. Therefore these results have been compiled and incorporated here.

Onshore geology

The Antarctica continent is divided by the Transantarctic Mountains into East and West Antarctica. East Antarctica has a Precambrian shield that is stable, while the West Antarctica segment consists of several young tectonic units that are rather mobile on a geological time scale (Tingey, 1991). Antarctica is considered to play an important role in the tectonic history of Gondwanaland.

The region of East Antarctica between 30 and 60°E longitudes is called Enderby Land, while to its east is the Kemp and MacRobertson Lands (Fig. 2-9). Yoshida and Santosh, (1995) described extensively the geological framework of East Antarctica. The onshore geology is fairly well exposed along the coasts and adjacent hinterland of Enderby Land. Outcropping rocks from Enderby, Kemp and MacRobertson Lands, Antarctica have been divided into two main groups, an Archean age Napier Complex of granulite metamorphic grade, and a Late Proterozoic age Rayner Complex that was largely formed by remetamorphism of

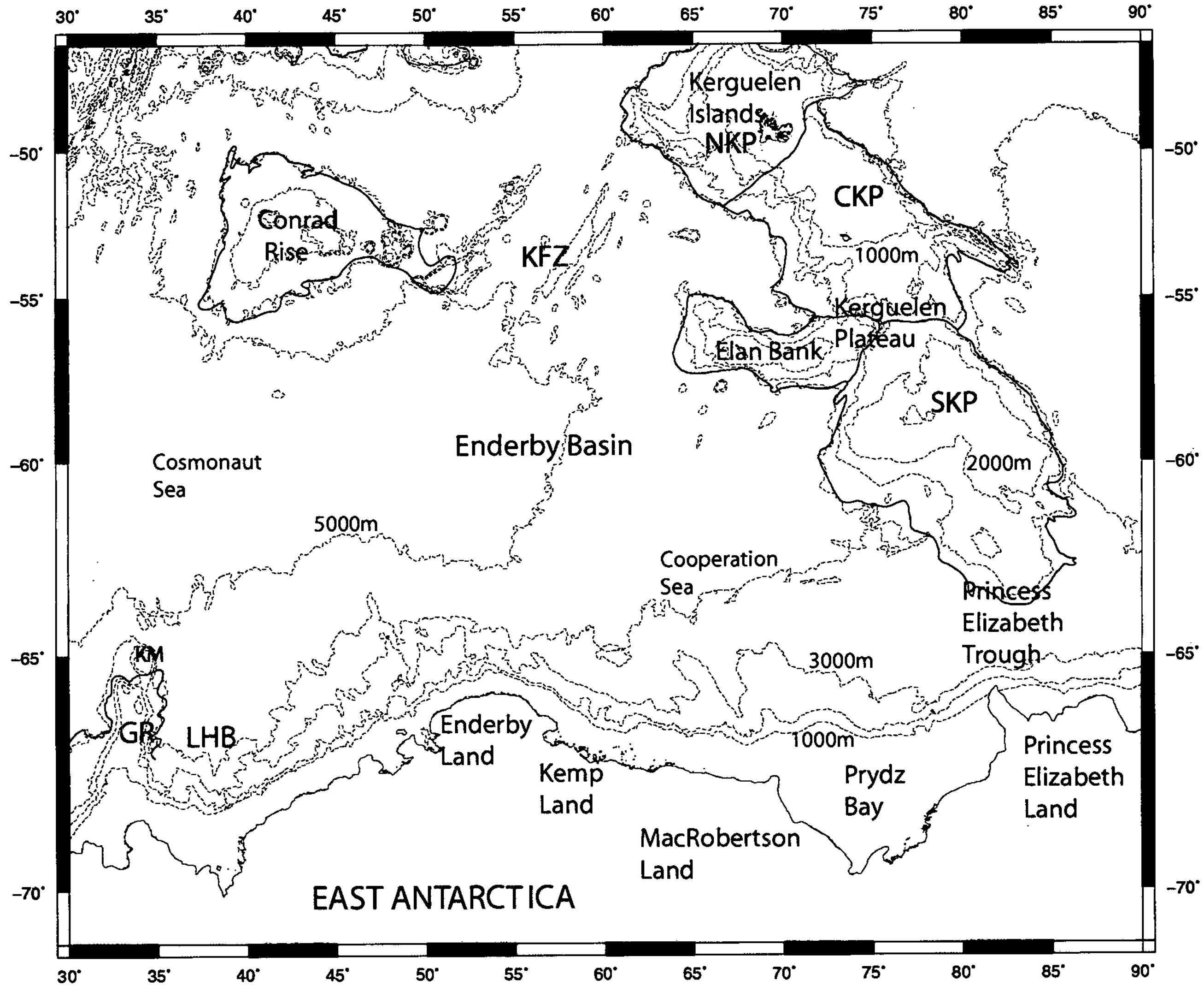


Figure 2-9 Generalized bathymetry map of the Enderby Basin (GEBCO). Contour interval is 1000 m. Large igneous provinces are shown in blue outline. NKP: Northern Kerguelen Plateau; SKP: Southern Kerguelen Plateau; CKP: Central Kerguelen Plateau; GR: Gunnerus Ridge; KM: Kainan Maru Seamount; KFZ: Kerguelen Fracture Zone

the older rocks to a slightly lower metamorphic grade (Black et al., 1983). In the absence of basement samples from offshore, it is assumed that basement rocks underlying the continental margin are also Archean to Proterozoic gneisses that have been intruded by granitoid plutons and mafic dykes. It is suggested that the Napier zone of the Enderby landmass and the Indian granulite charnockite belt might be an Archean mobile belt, and the peninsular gneiss of Dharwar and granite rocks of southern Prince Charles Mountains as Archean cratonic nuclei (Yoshida and Kizaki, 1983). Rock type boundaries are mapped between outcrops using magnetic anomalies and rock susceptibilities. The isostatic compensation of topography is both regional and deep, and the upper crustal rocks have a nearly constant density (Wellman, 1983).

Offshore tectonics

The Enderby Basin is bounded by the Princess Elizabeth Trough to the east, by the Kerguelen Plateau to the northeast and north, by the Kerguelen Fracture Zone and Conrad Rise to the northwest, and by the Gunnerus Ridge to the west (Stagg et al., 2004). The western Enderby Basin is termed the Cosmonaut Sea while the Eastern Enderby Basin is termed the Cooperation Sea (Fig. 2-9).

### 2.2.1 Previous studies

Bathymetry

The Enderby margin is characterized by a continental shelf of variable width, an average water depth of 500 m and rugged topography that deepens towards the continent (Johnson et al., 1982). The slope is dominated by spur and canyon topography towards west, while it is relatively smooth on the east (Fig. 2-9). This spur and canyon topography is the result of a complex interplay of depositional and erosional processes on account of glaciation for millions of years (Stagg et al., 2004). The Enderby Basin deepens towards the northwest with water depths reaching to >5000 m. Towards the northeast of the Enderby Basin, complex positive topography of the Kerguelen Plateau is observed. Here, the bathymetry shallows to <1000 m from the surrounding water depths of ~4000 m. The northwestern region of the Enderby Basin is dominated by the approximately WNW-ESE trending Ob, Lena and Marion Dufresne seamount chain belonging to the Conrad Rise. Another prominent bathymetric feature is the N-S trending Gunnerus Ridge and its northern extension, the Kainan Maru seamount off the western Enderby shelf, where the water depth rises to <1000 m from the surrounding depths of ~4500 m.

Gravity

Satellite derived free-air gravity mosaic (Fig. 2-10) depicts a high-amplitude anomaly consisting of positive gravity field immediately followed by a steep gravity low along the East Antarctica continental margin akin to the continent-ocean boundary (COB) (Sandwell and Smith, 1997). This anomaly has a strong linear northeast trend east of 40°E longitude. At 52°E longitude, the trend changes abruptly to east-southeast and the negative limb of the anomaly becomes more subdued. Between 62-69°E longitudes, the negative gravity is again prominent. Beyond 69°E longitude, off Prydz Bay, a prominent positive gravity closure is observed. Gravity anomalies on the upper continental slope strongly reflect the canyon and spur topography, suggesting that these sedimentary and erosional features are largely uncompensated. There is no obvious gravity expression of the underlying crustal structure.

Further offshore, gravity trends in the Enderby Basin are very subdued, except for the N5-10°E, NE-SW and N-S trending linear features probably representing fracture zones (Fig. 2-10). The NE trending Kerguelen Fracture zone (KFZ) is very prominently seen as a gravity low, which separates the Crozet Basin from the Enderby Basin. Some N-S gravity trends are seen from the KFZ into the Enderby Basin. In the Eastern Enderby Basin, there is little evidence of any fracture zones probably due to the thick sediment cover. A strong edge effect anomaly is seen on the southern margin of Elan Bank and may probably indicate a boundary

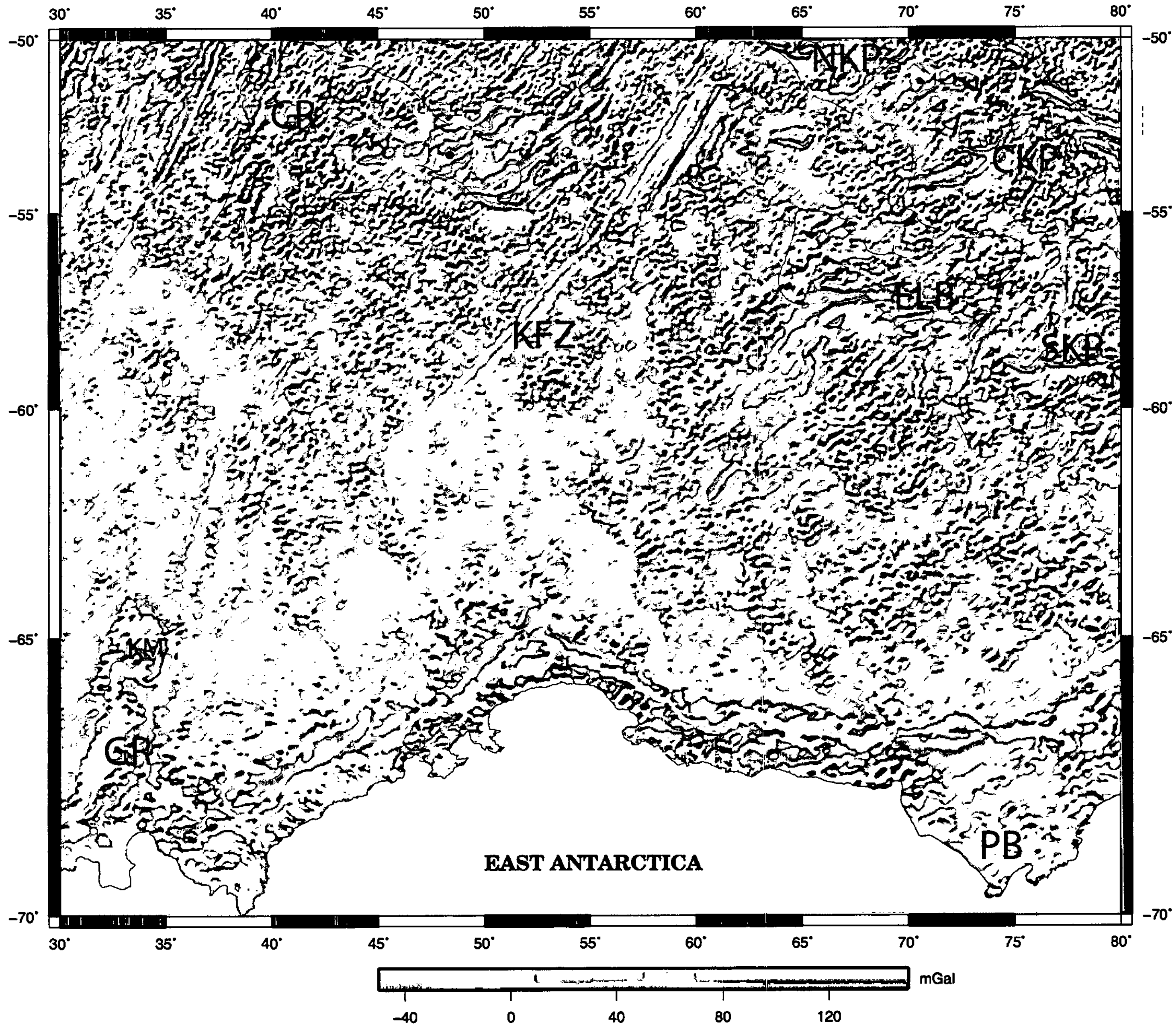


Figure 2-10 Satellite derived free-air gravity map of the Enderby Basin depicting major tectonic elements (Sandwell and Smith, 1997). ELB: Elan Bank; PB: Prydz Bay. Other notations as in figure 2-9

between the interpreted continental fragment of Elan Bank and the oceanic crust of the Enderby Basin (Stagg et al., 2004).

The Kerguelen Plateau is characterized by positive gravity signature. Several lineations on the plateau depict various structural trends such as grabens, ridges, etc. Similarly, the Ob, Lena, Marion Dufresne seamount chain of the Conrad Rise, northwest of the Enderby Basin is characterized with positive gravity field. Prominent gravity minima surround the Gunnerus Ridge and Kainan Maru seamount, while strong positive gravity maxima are seen on the top of the seamount and Ridge.

Seismics

Extensive multichannel seismic, sonobuoys and wide angle reflection studies have been carried out off East Antarctica during the last two decades. On the continental shelf, the top of the pre-rift continental crust cannot be well demarcated. Only the acoustic basement can be marked as a change in character from stratified to non-stratified section (Stagg et al., 2004). The shelf edge and upper slope are underlain by a major basin-bounding fault system beyond which the basement downfaults by at least 6 km. The area at the base of the continental slope and beneath the rise is interpreted as extended continental crust with Jurassic rift structures having local relief of 0.3-1.0 km. The shelf basement is overlain by 0.5-2.0 km of sediments in the western Enderby Basin (Gandyukhin et al., 2002).

Towards offshore, the sediments thin rapidly, pinching out against the oceanic crust. In the eastern Enderby Basin, the sediment thickness of 6-8 km just beyond the continental margin decreases to 1-2 km towards offshore masking the bathymetric and gravimetric expressions of fracture zones (Cooper and O'Brien, 2004).

The COB is a prominent and sharp boundary in the seismic reflection data and correlates with the marked change in the upper crustal velocities from 5.9-6.3 km/s (continental) to 5.2-5.5 km/s (oceanic) based on refraction results. A variable continental-ocean transition zone 100 km wide in the west and >300 km in the east followed by oceanic crust has been inferred (Stagg et al., 2004). The crust in this zone has been divided into two types ecot1 and ecot2 based on the degree of faulting (Stagg et al., 2005). The type ecot1 is highly faulted, while ecot2 is devoid of much faulting. In the eastern Enderby basin, the COB coincides with a 700-800 m step in basement and a high-amplitude magnetic anomaly (350-500 nT).

Based on the reflection characteristics and velocity profiles, the oceanic crust in the Enderby Basin has been classified into several distinct types - ebo1 to ebo10 (Stagg et al., 2004). Figure 2-11 depicts the different transition and oceanic crust types along two multichannel seismic profiles in the Enderby Basin. The continental margin and corresponding offshore regions of the Enderby Basin, East Antarctica has been divided into 3 zones based on seismic results and geophysical signatures. These zones lie (i) west of 52°E; (ii) 52-58°E, and (iii) 58-76°E longitudes.

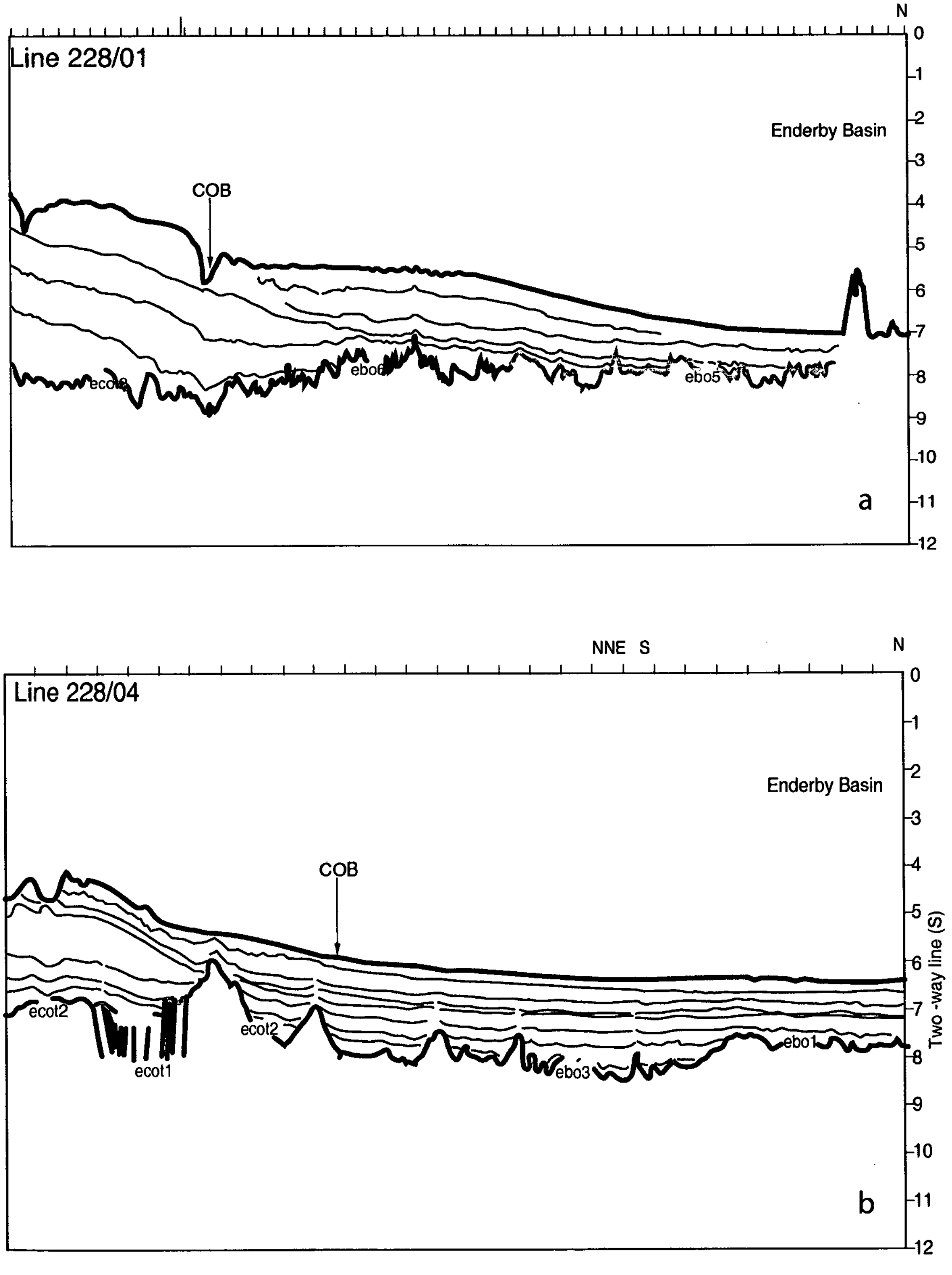


Figure 2-11 Interpreted line drawings of multichannel seismic reflection sections in the Enderby Basin depicting the different types of oceanic and transitional crust (Stagg et al., 2005). COB: Continent-Ocean Boundary; ecot1 & ecot2 are different transition crust types; ebo1, ebo3, ebo5 & ebo6 are different oceanic crust types

In the sector west of 52°E, the character of the oceanic crust is more varied due to its mixed rift/transform setting. The basement appears to vary from rough to extremely rugged with wavelength ranging from a few to 20 km. Also, the internal crustal character is generally reflection free with no distinct Moho reflection (Fig. 2-11a). The narrow sector between 52 and 58°E longitudes is characterized by ebo3 type oceanic crust. It is much deeper and may be a remnant of an older phase of seafloor spreading (Late Jurassic?). The rough to rugged basement surface is dominated by short, landward dipping volcanic flows with distinct scarps on their oceanward flanks (Fig. 2-11b).

The eastern sector between 58-76° longitudes contains the ebo2 type oceanic crust followed by the ebo1 type towards north. It is characterized by a smooth and strong basement reflector with a continuous Moho reflection. Towards north, the basement surface becomes rough to rugged and the Moho is weakened. The transition from ebo2 to ebo1 indicates changes in thickness and character of the crust. This implies that a significant change occurred in spreading rate as well as magma volume. A marked change in the character of oceanic crust around 58°E longitude prompted Stagg et al., (2005) to infer a crustal boundary at this location.

Multichannel seismic data in the Cooperation Sea and Prydz Bay area (Fig. 2-9) reveal six seismic sequences separated by prominent unconformities, which include glacial erosion, glacial onset, breakup and rifting episodes (Joshima et al., 2001). The upper three units comprise of horizontally, well stratified marine deposits, while the lower units consist of some older deposits and volcanic basement. The Moho reflection seen at ~10 s TWT north of 64°S disappears in the south. More than 7 km thick sediments are seen off Prydz Bay area.

Detailed seismic investigations in the Cosmonaut Sea off the western Enderby shelf (Fig. 2-9) reveal four major seismic sequences separated by prominent reflectors overlying the Early Cretaceous basement (Solli et al., 2008). The lowermost sedimentary unit thins towards offshore and constitutes continuous and parallel reflectors. A reflector probably corresponding to the Early Cretaceous post-breakup event separates this unit from the overlying sequence signaling stronger sediment supply from the continental margin. This sequence in turn is overlain by a wedge like sequence consisting of more continuous and smoother reflectors. This wedge may have evolved over a long period (Middle to Late Cretaceous to Oligocene). The uppermost sequence represents the post glaciation deposits upto Recent.

Magnetics

Late Cretaceous crust has been inferred north of the Enderby Basin with the identification of magnetic anomalies 34 and younger west of the Kerguelen Fracture Zone (Fig. 2-12; Royer et al., 1989). These anomalies are right-laterally offset by several N28°E trending fracture zones with age decreasing towards north (Schlich, 1975; 1982; Patriat, 1987). North of the Kerguelen Plateau, younger Tertiary

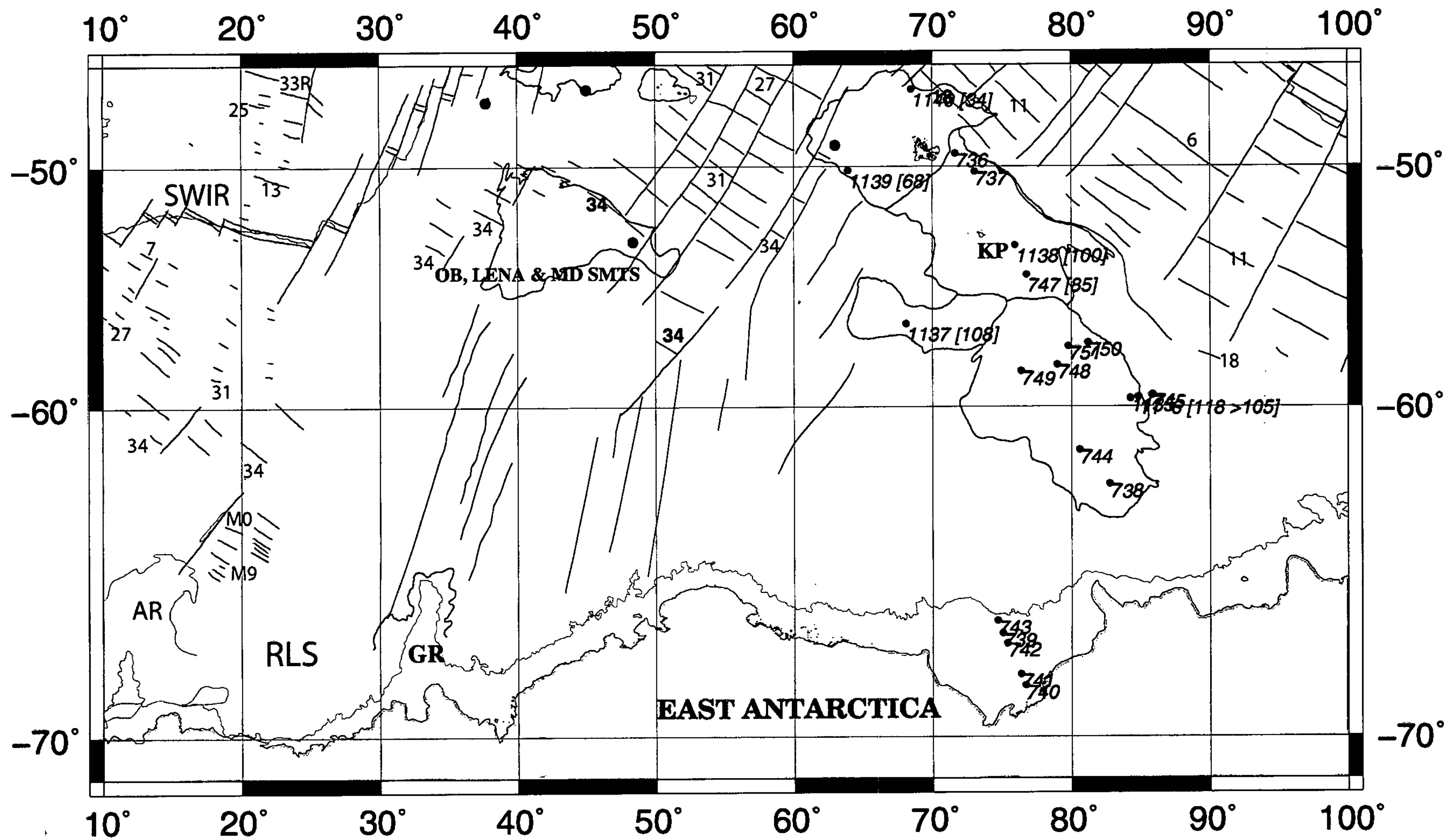


Figure 2-12 Tectonic map of the Enderby Basin (Royer et al., 1989). Fracture zones are indicated as black lines, magnetic anomalies are shown in red lines with some anomalies numbered. DSDP/ODP sites with its corresponding numbers and ages in brackets are indicated as dots. Large igneous provinces are shown in blue outline. SWIR: Southwest Indian Ridge, KP: Kerguelen Plateau; GR: Gunnerus Ridge; RLS : Riiser-Larsen Sea; AR: Astrid Ridge

anomalies (18 to recent) of the present day Southeast Indian Ridge occur. West of the Gunnerus Ridge in the Riiser-Larsen Sea, Mesozoic magnetic anomalies M16 through M0 offset by several NE-SW trending fracture zones have been inferred (Bergh, 1977; Jokat et al., 2003).

The continental shelf is characterized by a high amplitude magnetic anomaly. Near the base of the upper continental slope, the prominent magnetic trough approximately correlates with a trough in the gravity and bathymetric data and a basement depression in the seismic reflection data (Stagg et al., 2004). Low amplitude magnetic anomalies in the Enderby Basin due to sediment overburden of upto 5 km and large positive magnetic anomalies (upto 1000 nT) over the Kerguelen Plateau are inferred (Golynsky et al., 2002). A ~120 km wide curvilinear belt of positive magnetic anomalies (150-600 nT) running parallel to the East Antarctica coast has been mapped. This belt termed as ACMMA (Antarctic Continental Margin Magnetic Anomaly), may mark the continental crustal discontinuity formed during Gondwanaland breakup. It mostly overlies the continental slope and shelf areas, while at some places it overlies the onshore coastal areas and the continental crust of the Gunnerus Ridge.

In the eastern Enderby Basin, the magnetic anomalies exhibit strong parallel to sub-parallel lineations with an unequivocal ENE trend. An approximately E-W trending prominent, high-amplitude magnetic anomaly flanked to the south by a magnetic anomaly low was reported (Brown et al., 2003). This anomaly termed the

MacRobertson Coast Anomaly marks the southern limit of the identified seafloor spreading magnetic anomalies and also coincides with the oceanward step-up in basement observed in seismic records (Stagg et.al., 2004).

It was mentioned that no magnetic anomalies have been identified in the Enderby Basin between the Kerguelen Plateau and Antarctica (Royer and Coffin, 1992), though, Mizukoshi et al., (1986) hinted that magnetic anomalies of apparent seafloor spreading nature, possibly Mesozoic, exist in the Enderby Basin. Recently Russian, Japanese and Australian surveys have improved the magnetic data coverage in the southern Enderby Basin, but the coverage north of 61°S latitude is still sparse. Based on these magnetic surveys, different magnetic interpretations have been postulated. Ishihara et al., (2000) identified anomalies M10n, M4 and M2, while Gandyukhin et al., (2002) and Brown et al., (2003) have identified M11a through M8 and M10y through M2o respectively. Joshima et al., (2001) reported the presence of magnetic anomalies M10n through M2 in the eastern Enderby Basin (Fig. 2-13). Ramana et al., (2001a) interpreted the presence of Mesozoic magnetic anomaly sequence M11 through M0 in the Enderby Basin and estimated HSRs varying between 6.5 and 2.9 cm/yr. Rotstein et al., (2001) have reported the presence of magnetic anomalies M3 through M0 in the eastern Enderby Basin. Stagg et al., (2004) based on Brown et al., (2003)'s interpretation identified magnetic anomalies M9 through M2 symmetric about an extinct spreading center in the western Enderby Basin. Further, Gohl et al., (2008) suggested the presence of symmetric sets of magnetic anomaly sequence M10n through M6 in the Princess

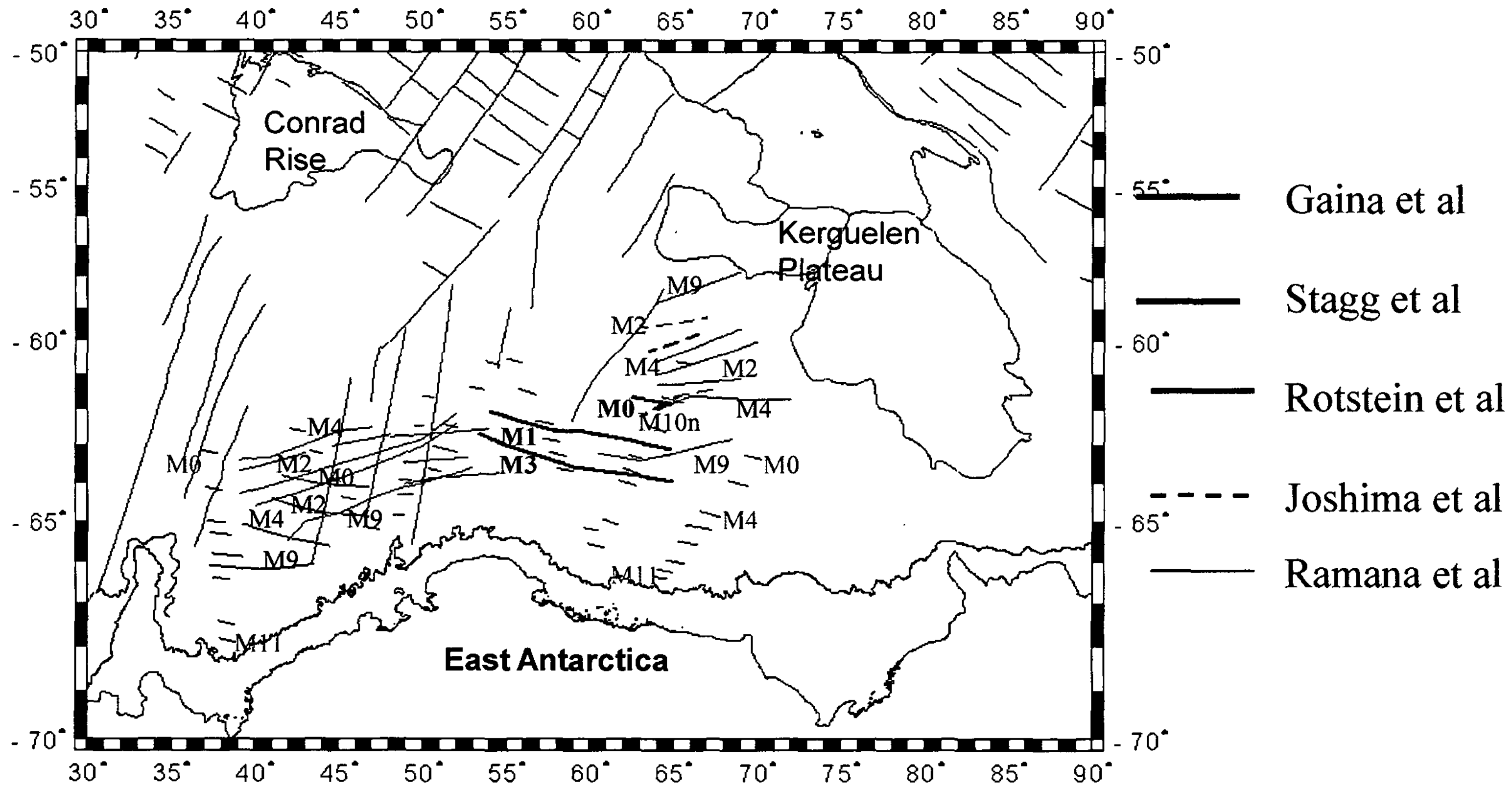


Figure 2-13 Magnetic anomalies identifications made by various researchers (as per legend) in the Enderby Basin. Large igneous provinces are shown in red outline. Blue outline denotes the 2000 m isobath surrounding East Antarctica. Black lines represent fracture zones, while blue lines are magnetic anomalies (Royer et al., 1989).

Elizabeth Trough. HSRs of 3.3 cm/yr in the north and 3.7 cm/yr in the south on either side of an extinct spreading ridge were calculated.

Gaina et al., (2003) suggested the occurrence of seafloor spreading with a NNW azimuth in the Enderby Basin and proposed the presence of magnetic anomalies M9 through M2 symmetric about an extinct spreading center south of Elan Bank (Fig. 2-13). Further, HSRs of 4.0 cm/yr from the onset of spreading at about 130 Ma to chron M4 (126.7 Ma), which decreased to about 1.6 cm/yr until spreading in the Enderby Basin ceased at about 124 Ma (chron M2) were estimated. At this time, a northward ridge jump was suggested to have occurred towards the Eastern Continental margin of India, which transferred the Elan Bank microcontinent to the Antarctica plate. It was further suggested that no magnetic anomalies older to M2 should occur in the Bay of Bengal. However, Gaina et al., (2007) refined this interpretation by suggesting that the ridge jump may have occurred only in the eastern Enderby Basin and not all the Mesozoic crust from the Bay of Bengal was transferred to the Antarctica plate.

### 2.2.2 Tectonic elements

Kerguelen Plateau

The Kerguelen Plateau (KP) has been identified as a large igneous province formed due to voluminous volcanism associated with the Kerguelen mantle plume activity on the young Indian Ocean lithosphere (Duncan and Storey, 1992). The major tectonic trends, structural elements and stratigraphy of the KP were described in detail (Houtz et al., 1977). The Kerguelen Plateau forms the northeastern part of the Enderby Basin and extends for ~2300 km between 46 and 64°S latitudes in a NW-SE direction towards the Antarctica continental shelf (Schlich, 1982). It is a broad (200-600 km wide) topographic high and can be divided into distinct domains: Southern Kerguelen Plateau (SKP), Central Kerguelen Plateau (CKP), Northern Kerguelen Plateau (NKP) and Elan Bank (Fig. 2-9). The KP is bounded to the south by the 3500 m deep Princess Elizabeth Trough, to the west by the Crozet Basin and to the east by the Australian-Antarctic Basin.

The SKP is entirely submarine and has subdued topography averaging 1500-2000 m below the sealevel. It comprises of about 22 km thick igneous crust (Operto and Charvis, 1995; 1996). It consists of a broad anticlinal arch, broken by several stages of N-S normal faulting and graben formation including the 77°E graben (Coffin et al., 1986; Duncan and Storey, 1992). The CKP has water depths of <1000-2000 m and about 19-21 km thick igneous crust. The CKP and Broken Ridge formed as a single entity, and at about 40 Ma the Broken Ridge began to separate from the CKP along the nascent Southeast Indian Ridge (Mutter and Cande, 1983). The NKP has water depths of <1 km, and includes the Kerguelen Archipelago of Kerguelen, Heard and McDonald islands. Wide angle studies across the archipelago reveal about 8-9.5 km thick upper igneous crust and 6-9.5 km thick lower crust (Recq et al., 1990). A sedimentary basin, termed Kerguelen-Heard basin having an overall NW-SE trend lies between these islands (Munschy and Schlich, 1987).

The Kerguelen Plateau has existed as a shallow oceanic structure since at least 100 Ma and was probably created between 130 and 100 Ma at or near an active spreading center in the gap between the Indian and Antarctica-Australia plate (Frey et al., 2000). Analysis of rock samples collected during ODP Legs 119, 120 and 183 on the KP provided its detailed evolutionary history. Leg 119 of the ODP drilled the northernmost (sites 736 and 737) and southernmost (sites 738, 744 to 746) regions of the Kerguelen Plateau, while the Leg 120 of the ODP drilled the central and southern plateau (sites 747-751) (Barron et al., 1991; Wise et al., 1992). The basement drilled at sites 747, 749 and 750 is composed of basaltic flows, which are silica-saturated transitional tholeiites. Tholeiitic basalt is the dominant lava type in the igneous crust of the KP derived from the long-lived Kerguelen plume. While much of the SKP and Elan Bank was formed at ~110 Ma, the CKP and BR have younger ages and the NKP is <35 Ma (Coffin et al., 2000) under subaerial or shallow marine conditions.

Elan Bank

The Elan Bank, aligned approximately in an east-west direction covers an area of about 140,000 sq. km. Its position between the older SKP and relatively younger CKP is critical in understanding the spatial and temporal evolution of the

KP (Fig. 2-9). The bank shallows from surrounding average water depth of 4000 to <1000 m. Satellite derived free-air gravity mosaic indicates positive gravity field on the bank, with a steep gradient towards south (Fig. 2-10).

Borissova et al., (2003) described the tectonic and structural development of Elan Bank and suggested that its shape has been controlled by ENE-WSW and NW-SE trending faults and volcanic flows. Further, the NW-SE trending faults probably acted as transform faults at the time of breakup. Seismic and wide angle studies (Operto and Charvis, 1996; Charvis and Operto, 1999) revealed that the upper igneous crust of ~3 km is similar to that inferred in KP, and is comprised of originally subaerial basaltic lava flows (Coffin et al., 2000, Frey et al., 2000). The 14 km thick lower crust with low velocity (~6.6 km/s) is not consistent with oceanic plateaus where lower crust is characterized by high velocity material (Coffin and Eldholm, 1994) but similar to thinned lower continental crust. Multichannel seismic data (Borissova et al., 2003) showed the presence of a sedimentary cover of <1 s TWT on the Elan Bank, followed by a strong erosional and angular unconformity between the sediment and the basaltic basement, whose age has been interpreted as Campanian (Coffin et al., 2000). The acoustic basement displays seaward dipping reflectors belonging to massive subaerial lava flows characteristic to volcanic passive margins. The absence of older Cretaceous sediment on shallow parts of Elan Bank suggests that it remained above sealevel at least until Maastrichtian time, when most of the SKP and CKP had subsided beneath sealevel. The persistent relatively high elevation of the bank could be due to buoyancy of its continental root. South of the Elan Bank, a possible continent-ocean transition zone is inferred based on seismics and gravity signature (Borissova et al., 2003).

ODP Leg 183 Site 1137 drilled on a basement high (water depth 1016 m) in the central part of the bank yielded an age of 108 Ma for its igneous basement (Duncan, 2002). Clasts of garnet-biotite gneiss in a fluvial conglomerate intercalated with basalt flows were also recovered (Nicolaysen et al., 2001). U-Pb and Pb-Pb dates of zircons and monazites in these clasts and an overlying sandstone range from 534 to 2547 Ma, which is much older than the surrounding Indian Ocean seafloor. These dates show that old continental crust resides in the shallow crust of the Elan Bank (Ingle et al., 2002). The discovery of Proterozoic continental crustal rocks within the uppermost basaltic basement similar to Northeast India, Western Australia and Eastern Antarctica at this site, shows that direct shallow-level contamination of basaltic magmas by isolated continental crust fragments may have produced anomalous isotopic ratios of some Indian Ocean basalts (Weis et al., 2001).

Prydz Bay

The Prydz Bay is a north-south trending deep graben located between MacRobertson Land in the west and Princess Elizabeth Land in the east (Fig. 2-9). It lies at the oceanward end of the Lambert Graben, which extends ~700 km landward in East Antarctica (Stagg, 1985). The graben is now occupied by the

Lambert Glacier and Amery Ice Shelf, the largest glacier system flowing from East Antarctic Ice sheet. The Prydz channel runs longitudinally into a large sedimentary fan on the continental slope (O'Brien, 1994). Seismic stratigraphy and ODP Leg 119 results revealed that >5 km sediments fill the Bay beneath the inner shelf (Stagg, 1985; Cooper et al., 1991). Stagg (1985) interpreted the Prydz Bay basin and the Lambert Graben as a failed rift arm of a triple junction in the initial breakup phase of Gondwanaland in the Early Cretaceous. Detailed magnetic analyses reveal the presence of highly magnetized rocks in the Bay, probably Mesozoic intrusive rocks related to the breakup of Gondwanaland (Ishihara et al., 1999). Further, gravity analysis revealed the presence of the COB around the shelf edge, ~8 km sediment thickness overlying a granitic layer and Moho at a depth of ~22 km.

Gunnerus Ridge

The Gunnerus Ridge has a nearly N-S trend and occupies an area of about 25,000 sq. km. It extends for almost 300 km north from the Riiser Larsen Peninsula to 65°45'S latitude (Fig. 2-9). It rises upto <1000 m from the surrounding ~4500 m water depth. The Kainan Maru seamount lying just 15 km north of the Gunnerus Ridge is clearly its extension (Kodagali et al., 1998). The seamount may have rifted and rotated clockwise away from the ridge during the breakup of Gondwanaland. Seismic studies on the Gunnerus Ridge point to the presence of a graben-like depression to the east, which seems to be connected with the fault system in Lutzow-Holm Bay (Moriwaki et al., 1987). Prominent gravity minima surround the seamount and a strong positive gravity maximum is seen on the top of the seamount and ridge (Fig. 2-10).

Conrad Rise

The Conrad Rise consists of a WNW-ESE trending chain of Ob, Lena and Marion Dufresne seamounts separating the Southern Crozet Basin from the Enderby Basin (Schlich, 1975; Udintsev, 1975). Identification of magnetic anomaly 34 just north and around the seamount chain (Schlich, 1982) implies that these seamounts are of 80 to 88 m.y. age (Fig. 2-12). The Marion Dufresne seamounts and the Afanasy Nikitin seamount chain in the Central Indian Basin have emplaced simultaneously in the vicinity of the spreading center (Mckenzie and Sclater, 1971; Goslin and Schlich, 1982). Further investigations indicate that the Marion Dufresne seamount chain has been emplaced by anomalous volcanism during a major reorganization of the plate boundaries in the Late Cretaceous (Diament and Goslin, 1986).

# Chapter 3

# *Data and Methodology*

Marine geophysical data (particularly gravity, magnetic and seismic reflection/refraction) are useful to decipher the structure of a continental margin and its adjoining deep offshore basins, and the presence of tectonic elements such as faults, ridges, fracture zones, etc. These techniques are relatively inexpensive and serve as a precursor to the more expensive drilling techniques. In the present study, geophysical data have been used to infer the structure and tectonics of the two study areas i.e., the Bay of Bengal including the Eastern Continental margin of India, and the Enderby Basin, including the continental margin of East Antarctica.

## 3.1 Source of data

Geophysical data has been obtained from different sources in the two study areas. In the Bay of Bengal, geophysical data acquired by the National Institute of Oceanography, Goa under the research program "Crustal studies of the Bengal Fan" are used. The datasets include gravity, magnetic and bathymetry acquired onboard research vessel ORV Sagar Kanya during the cruises SK72, SK82, SK100, SK101 and SK124 from 1988 to 1997. Additional geophysical data has been extracted from the National Geophysical Data Centre, Colorado (NGDC, 1998) to achieve better data coverage (Fig. 3-1), which aided in qualitative interpretation. In the Enderby Basin of East Antarctica, most of the geophysical data is obtained from NGDC, Colorado. In addition, published and personally communicated datasets have been used (Fig. 3-2). The quantum of data used in the Bay of Bengal and Enderby Basin is given in tables 1 and 2 respectively.

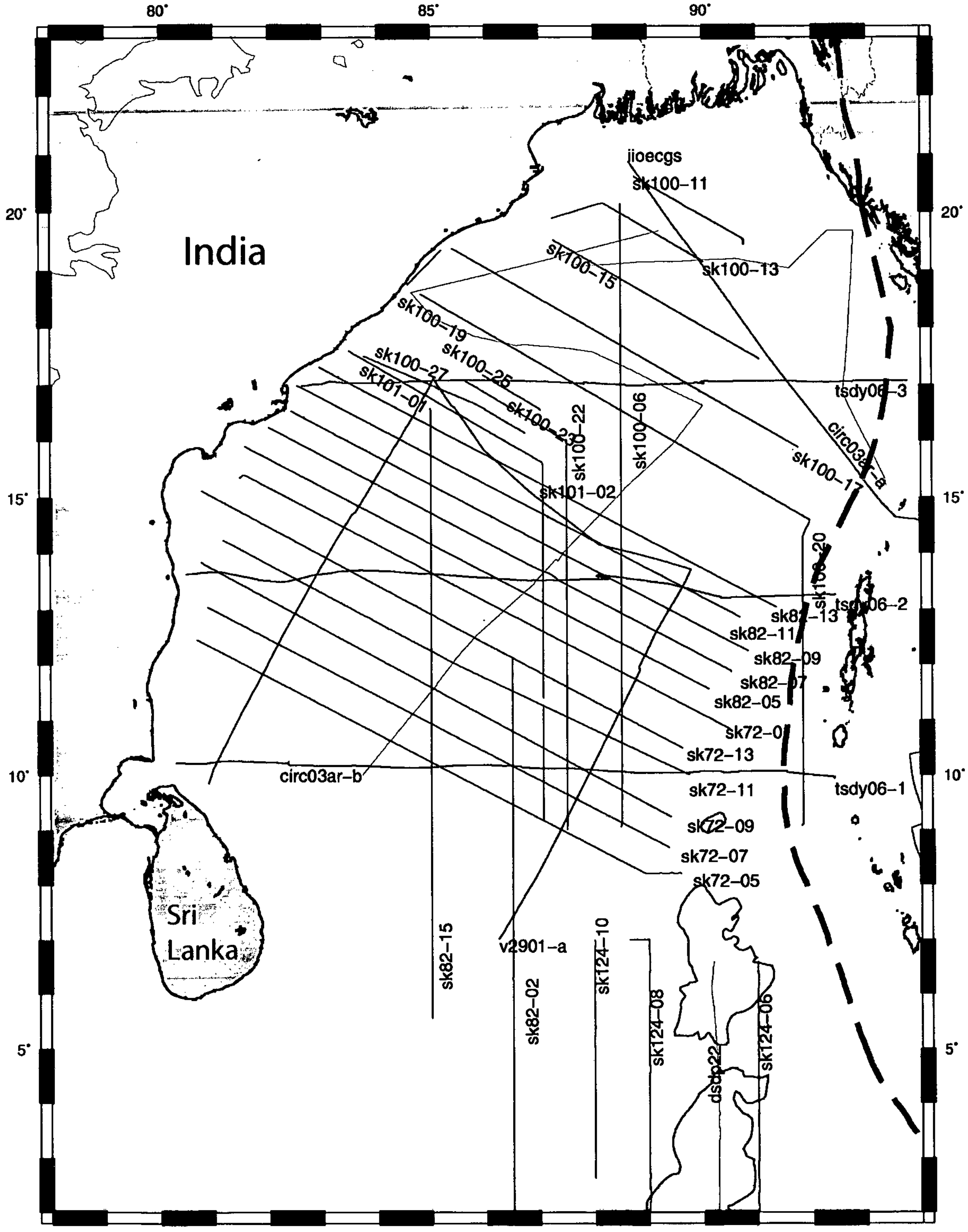


Figure 3-1 Track map of geophysical data in the Bay of Bengal used in the present study. Black lines are tracks along which data were acquired using ORV Sagar Kanya. Other colored lines are tracks along which data are downloaded from the NGDC, Colorado. Thick dashed line represents the Sunda Trough. Blue curves belong to the volcanic outcrops of the Ninetyeast Ridge.

Table 1: Quantum of data used in the Bay of Bengal

| Cruise No | Line Name | Line kms | Source |
|---|---|---|---|
| sk72 | sk72-01, sk72-05, sk72-07, sk72-09 sk72-11, sk72-13 | 6464 | NIO Database |
| sk82 | sk82-05, sk82-07, sk82-09, sk82-11 sk82-13, sk82-15, sk82-02 | 6572 | NIO Database |
| sk100 | sk100-19, sk100-17, sk100-15, sk100-13 sk100-27, sk100-25, sk100-23, sk100-06 sk100-20, sk100-22, sk100-11 | 6144 | NIO Database |
| sk101 | sk101-01, sk101-02, sk101-08 | 1416 | NIO Database |
| sk124 | sk124-06, sk124-08, sk124-10 | 1505 | NIO Database |
| NGDC | circ03ar-a, circ03ar-b, iioecgs, v2901-a, tsdy06-1, tsdy06-2, tsdy06-3, dsdp | 10990 | NGDC |
| | **Total** | **33,091** | |

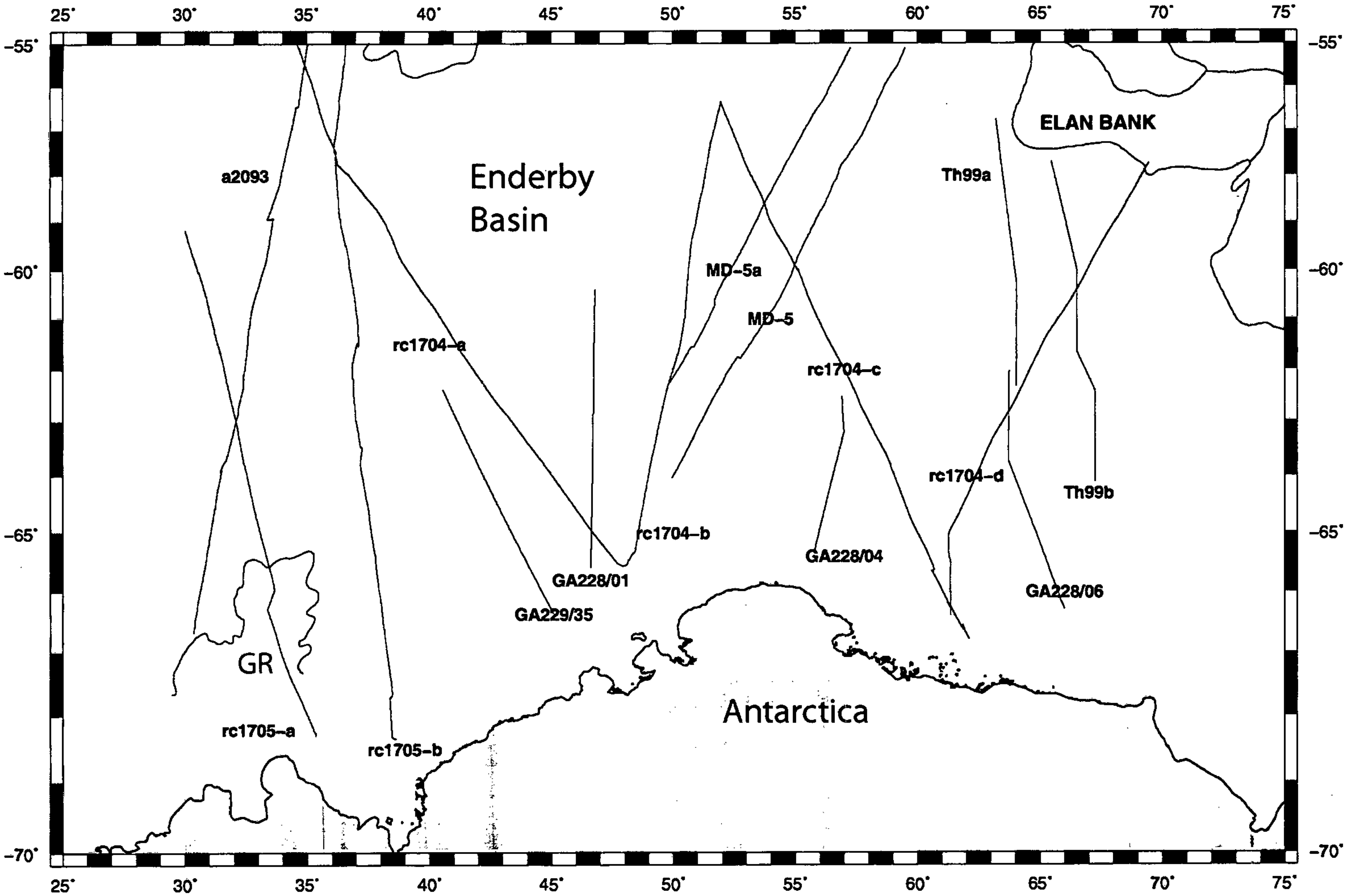


Figure 3-2 Track map of geophysical data used in the present study in the Enderby Basin. Tracks shown in black are downloaded from the NGDC, Colorado while tracks in red are from other sources. Large igneous provinces are shown in blue outline. GR: Gunnerus Ridge.

Table 2: Quantum of data used in the Enderby Basin

| Profile Names | Line kms | Source |
|---|---|---|
| a2093 | 1967 | NGDC |
| rc1704-a, rc1704-b, rc1704-c, rc1704-d | 4781 | NGDC |
| rc1705-a, rc1705-b | 2000 | NGDC |
| GA229/35 | 494 | Stagg et al., 2005 |
| GA228/01, GA228/04, GA228/06 | 1392 | Stagg et al., 2005 |
| Th99a, Th99b | 1354 | Joshima et al., 2001 |
| MD-5, MD-5a | 1548 | Ramana et al., 2001a[1] |
| **Total** | **14,266** | |

The satellite derived free-air gravity mosaics (Sandwell and Smith, 1997) have been used in both the conjugate areas to infer the major structural features such as fracture zones, COB, ridges, etc. and their trends (Figs. 2-7 & 2-10). Processed multichannel seismic reflection data along two profiles (KG-01 and MN-01 totaling 777 km) in the Bay of Bengal have also been used to infer the sediment thickness and nature of the underlying crust (Fig. 3-3). These multichannel seismic reflection records have been provided by the Directorate General of Hydrocarbons, Ministry of Petroleum and Natural Gas, Government of India for research purpose.

[1] *Ramana, M. V., Ramprasad, T. and Desa, M., 2001a. Seafloor spreading magnetic anomalies in the Enderby basin, East Antarctica, Earth Planet. Sci. Lett.,* ***191****: 241-255.*

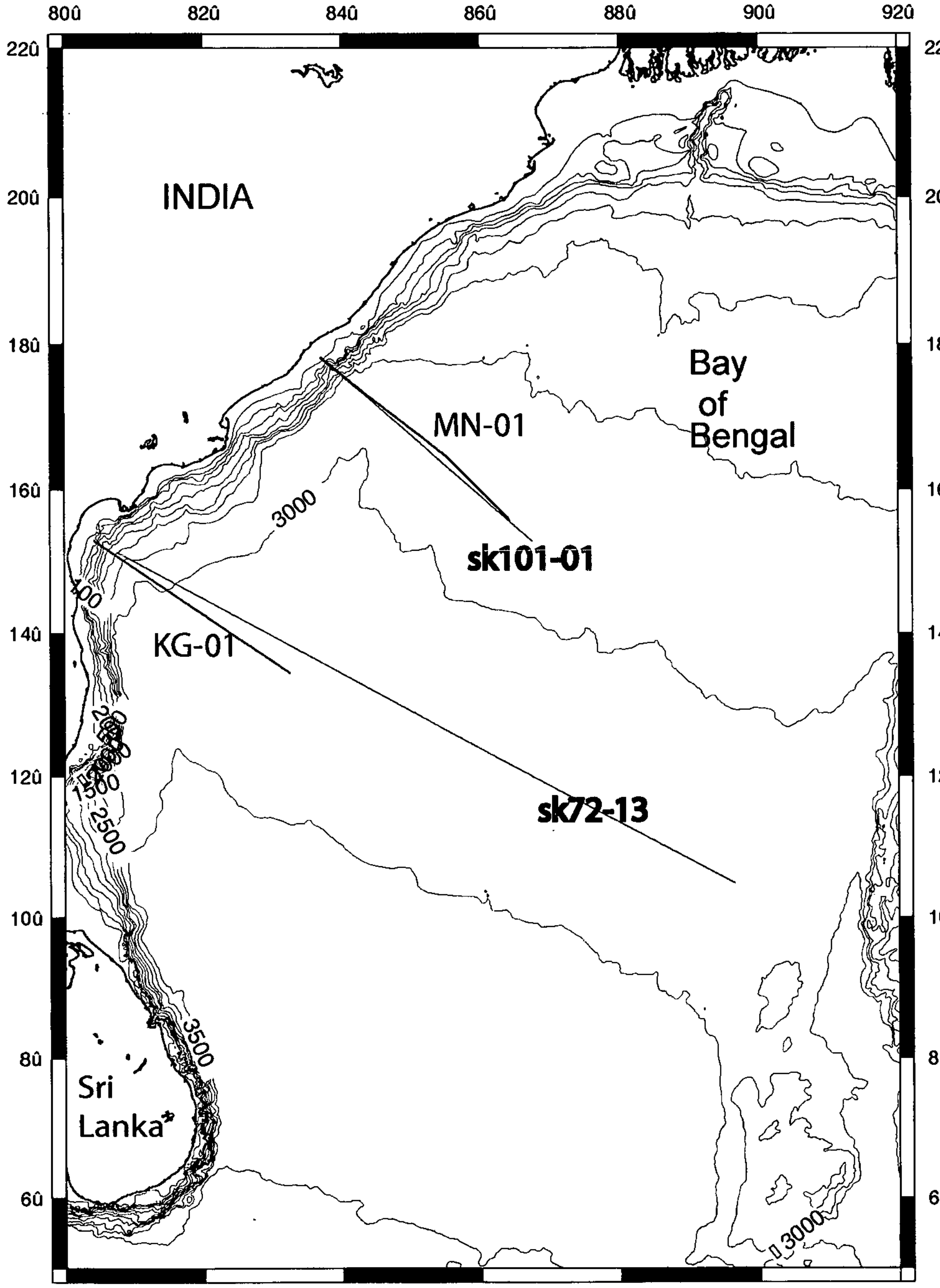


Figure 3-3 Location of the multichannel seismic reflection profiles KG-01 and MN-01 (black lines) in the Bay of Bengal used in the present study. Corresponding geophysical profiles sk72-13 and sk101-01 are shown as red lines. Thin lines represent bathymetry with variable contour interval

### 3.1.1 Instrumentation

The geophysical data comprising magnetic, gravity, and bathymetry data were acquired onboard the research vessel ORV Sagar Kanya (Fig. 3-4) during 1988-'97. The Magnavox Series Model 5000 Integrated Navigation System (INS) coupled with the Global Positioning System (GPS) was used to obtain the accurate position of the ship during the cruises. Navigational data along with the other geophysical datasets were logged on magnetic tapes and compact discs.

Bathymetry data has been recorded using a Honeywell-Elac Narrow Beam echosounder. This echosounder has been operated at frequencies of 12, 20 and 30 KHzs depending on the depth to the seafloor. Analog recording was also done with optional delay setting on the slave recorder for quality checking as well as good resolution. Marine magnetic data has been acquired using a Geometrics G801/3 of EG&G model proton precession magnetometer. The sensor was towed about 300 m aft the ship to avoid the ship's noise. Data was recorded onto magnetic tapes and chart paper at a sampling interval of 6 seconds. Gravity data has been acquired using the Bodenseewerk Gravimeter GSS30. Both analog and digital data were obtained with high accuracy. Multichannel seismic data has been acquired using M/V Geo Searcher. The acquisition parameters are given in table 3.

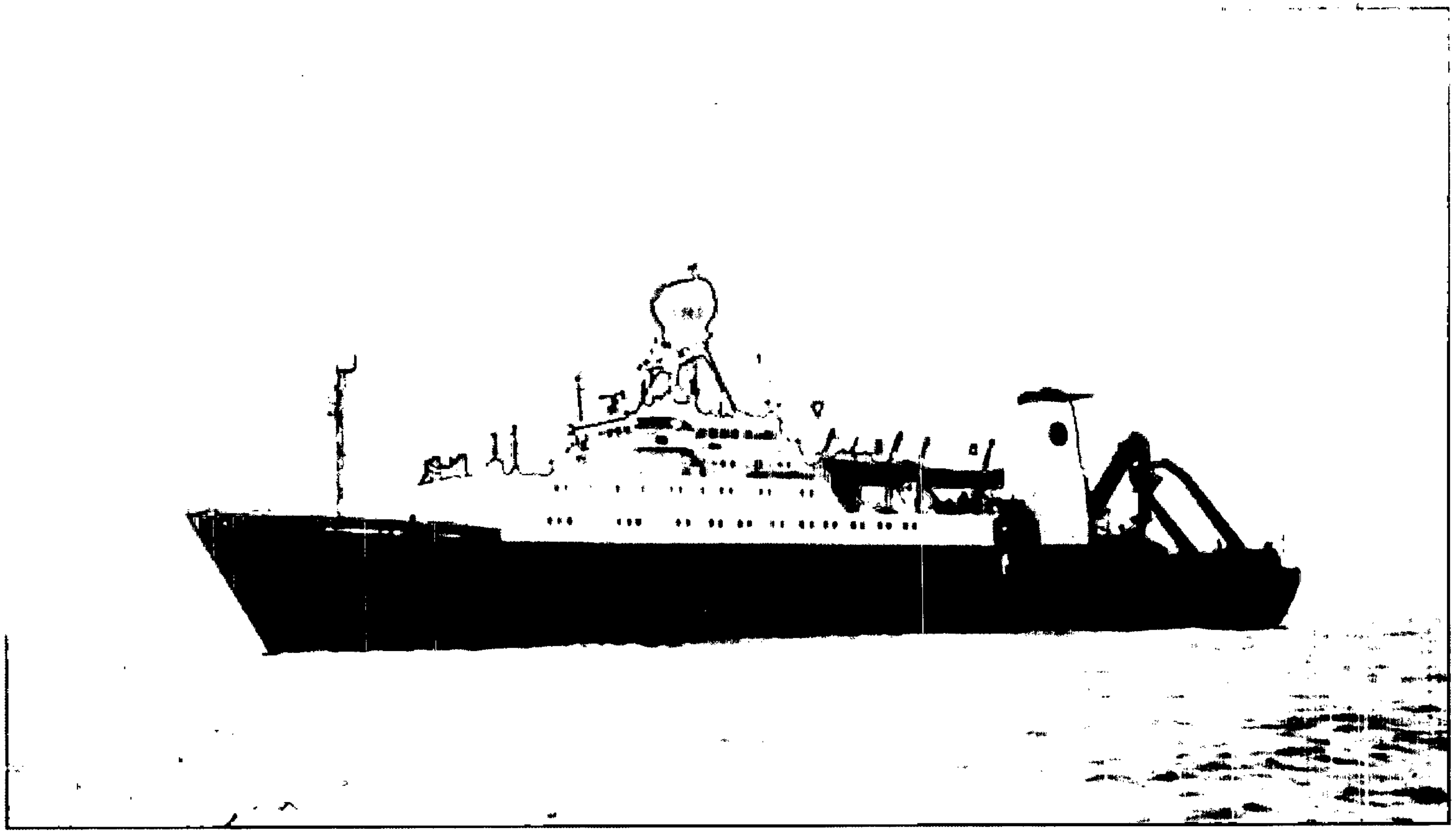

Figure 3-4 Research vessel ORV Sagar Kanya used for geophysical data acquisition in the Bay of Bengal

Table 3: Multichannel seismic data acquisition parameters

| Sr. No | Parameters | Specifications |
|---|---|---|
| i. | Air guns source volume | 7,510 cubic inches. |
| ii. | Shot point interval | 50 m |
| iii. | Type of air gun | Bolt gun |
| iv. | Location and depth of source | RGPS, acoustic, laser, 8.5m |
| v. | Streamer and its length | I/O MSX, 10 km |
| vi. | Group interval | 25 m |
| vii. | Number of channels | 400 |
| viii. | Hydrophones per group | 32 |
| ix. | Depth of the streamer | 9.5 m |
| x. | Recording instrument and length | MSX I/O – 24 bit, 18 seconds |
| xi. | Sampling rate | 2ms, 100 fold |

## 3.2 Processing of data

All the datasets have been examined for any spikes or spurious values to ensure the data quality. Bathymetry data has been corrected for variation in sound velocity using Carters tables (Carter, 1980). Digital contour data from the General Bathymetric Chart of the Oceans database (GEBCO, 1983) has also been used in addition to the shipborne bathymetry data to generate high quality bathymetry contour maps of the study areas.

The measured Earth's total intensity magnetic field varies from the equator to the poles. Hence the measured data needs to be corrected for this regional variation to obtain the magnetic anomaly. This is done by subtracting the theoretically computed International Geomagnetic Reference Field (IGRF) from the measured magnetic data (IAGA, 1986). The IGRF is a series of mathematical models of the main geomagnetic field and its secular variation. The International Association of Geomagnetism and Aeronomy (IAGA) define the IGRF for an epoch spanning 5 years. At the end of each epoch, the predicted IGRF is revised based on the available data and a Definitive IGRF (DGRF) is generated. The relevant DGRFs have been used to reduce the measured total intensity magnetic data and obtain the magnetic anomaly, which represents the characteristics of the underlying crust.

The shipborne gravity measurements are not absolute, hence at the beginning and end of the survey, the gravimeter is calibrated with respect to a base station, where the absolute gravity value is known. Thereafter, all the measurements are made with reference to this station. The measured data is then converted to absolute values by using the reference station value. Gravity measurement at a point is due to the Earth's rotation and lateral density variations. The gravity component due to Earth's rotation is called the Earth's normal gravity. It is a function of the latitude and is estimated by the International Gravity Formula 1967

$$g_n=978032.7(1+0.0053024\sin^2\partial-0.0000058\sin^2 2\partial)\text{mgal}$$

where $\partial$ is the latitude.

This correction is applied to remove the normal gravity component in the measured value. Further reduction is carried out for various acquisition parameters such as ship's heading and speed, station elevation, etc. Since the gravity measurements are made on a moving ship, the ship's heading and speed affect these measurements. A correction known as the Eotvos gravity correction is applied to remove the effect of the ship's heading relative to the Earth. The formula used for calculating Eotvos correction is

$$E_c= 7.503V\cos\partial\sin\Phi \ +0.004154V^2 \text{ mgal}$$

where V is the ship's speed, $\partial$ is the latitude and $\Phi$ is the heading from true North.

A correction for the elevation of a gravity measurement is required whenever measurements are made at different heights from the center of the Earth other than the datum, which is normally the sealevel. This correction is termed the free-air correction and is given by the formula

$$F_{ac}=0.3086 \text{ mgal/m}$$

The resultant gravity obtained after all these corrections is termed as the free-air gravity anomaly and represents the lateral density variations.

The free-air gravity data has been used in conjecture with magnetic and bathymetry data to derive the tectonic framework of the two study areas, i.e., the Bay of Bengal and the Enderby Basin. The misties at all cross points were minimized after systematic adjustment/leveling, and all the data were merged into one database. The geophysical data has been presented in the form of track maps, profile plots and contour maps generated using the GMT software of Wessel and Smith (1998).

## 3.3 Interpretation of data

The geophysical data thus processed has been interpreted using various techniques to understand the subsurface structure and underlying tectonics. Magnetic data were subjected to seafloor spreading modeling in order to infer its age and spreading parameters. Analytical signal technique was also performed on the magnetic data to locate magnetic boundaries within the basement. Potential field forward modeling was attempted along two geophysical profiles in the Bay of Bengal under seismic constraints. Plate reconstruction modeling has been carried out using the identified magnetic anomalies and inferred fracture zones. The results have been used to trace the complete evolutionary history of these conjugate basins.

### 3.3.1 Seafloor spreading modeling

Study of magnetic data across the mid-oceanic ridge system from various ocean basins depicts a distinct parallel and bilaterally symmetric pattern. This pattern of alternating stripes of normal and reversely magnetized blocks is linked to the reversals in the Earth's magnetic field (Vine and Mathews, 1963). In general, a geomagnetic polarity reversal time scale is used to assign the age to the oceanic crust, based on the characteristic pattern of the magnetic anomaly. Simulation of the observed sequence of alternating stripes of normal and reversely magnetized material constitutes the hallmark of the seafloor spreading modeling technique. The shape and amplitude of a magnetic anomaly depend on the spreading direction and rate, present and paleo-latitudes, depth and magnetization parameters of the crust, etc. Synthetic Mesozoic magnetic anomalies generated at various paleolatitudes are shown in figure 3-5a. The shape and amplitude of the synthetic magnetic anomaly change despite constant magnetization direction and observation point. Synthetic magnetic anomalies computed for same paleolatitude and observation point but different magnetization directions are shown in figure 3-5b. Prior

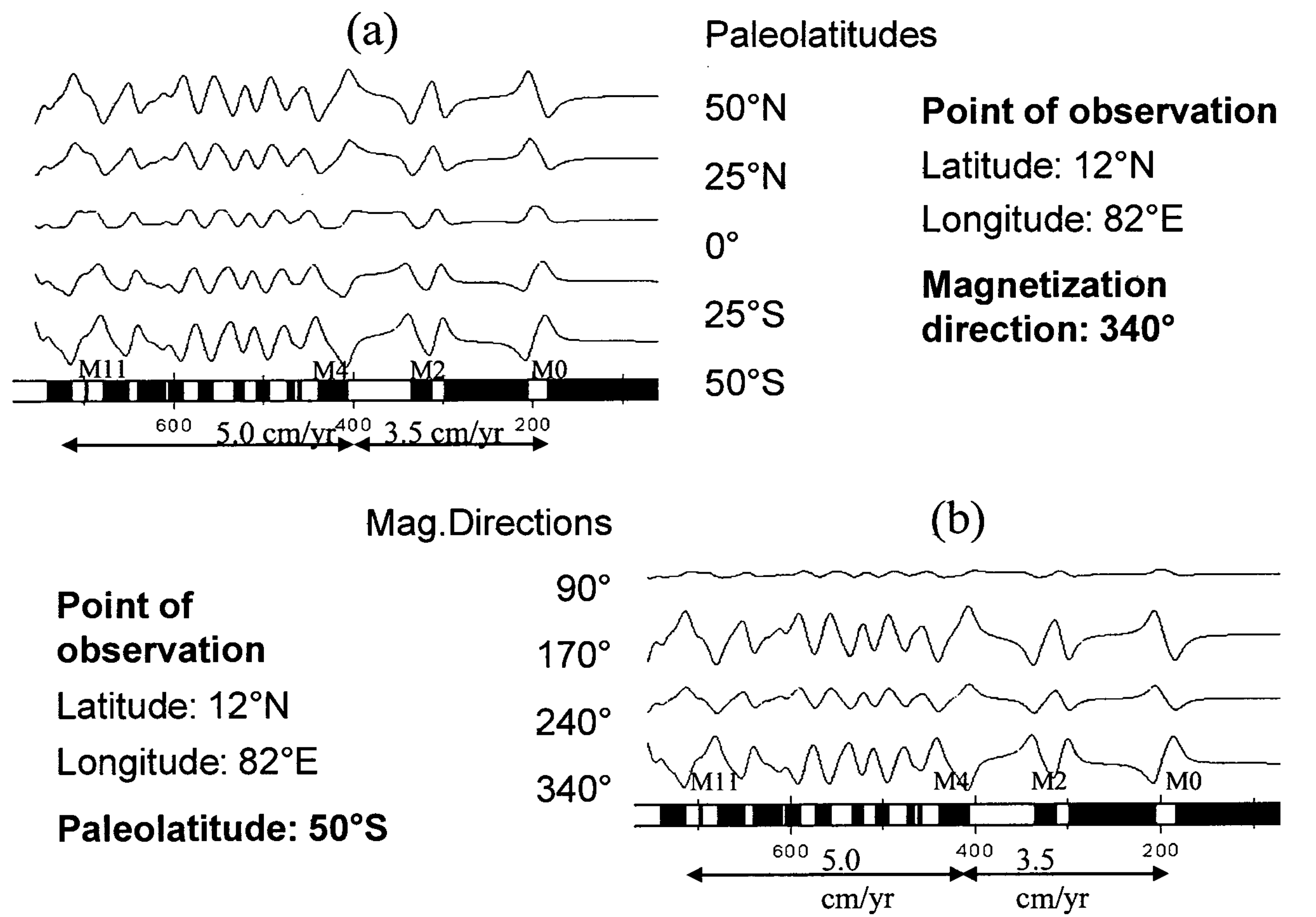


Figure 3-5 Synthetic models of the Mesozoic magnetic anomaly sequence M11 through M0 generated using the seafloor spreading modeling technique for various (a) paleolatitudes; (b) magnetization directions. HSRs are as indicated

knowledge of the direction and latitude of the formation of the crust, the present day latitude and strike direction, magnetic susceptibility, depth to the basement, etc. is essential to generate the synthetic model. Comparison of the observed magnetic anomalies with the synthetic seafloor spreading magnetic model generated using the relevant magnetic polarity time scale facilitates in identification of the magnetic anomalies. Based on the best fit synthetic model, spreading rates and directions are estimated.

### 3.3.2 Analytical signal technique

As mentioned earlier, the shape of the magnetic anomalies depends upon the magnetic latitude and the orientation of the source body. Nabighian (1972; 1974) introduced the concept of the analytical signal for locating the edges of a magnetic body. This technique includes the computation of the modulus of the analytical signal (MAS), a zero phase of the original signal using the Hilbert transform. The MAS corresponds to the envelope of all possible phase shifts of an observed anomaly. The envelope has a maximum that is located directly above the magnetization contrast, and its amplitude yields a bell-shaped function. The maximum of the bell-shaped curve is located exactly over a corner of the body, and the width of the curve at half its maximum amplitude equals twice the depth to the corner. The shape of the analytical signal is independent of the Earth's magnetic field and magnetization direction of the causative rock. For magnetic profile data, the horizontal and vertical derivatives fit naturally into the real and imaginary parts of the MAS (Roest et al., 1992). The locations of the maxima in the MAS indicate the vertices of the source bodies such as tectonic/volcanic features, secondary magnetization contrasts in addition to polarity boundaries of the seafloor spreading isochrons. The analytical signal technique therefore appears to be one of the powerful tools to demarcate boundaries of causative bodies.

The oceanic crust of the Bay of Bengal was formed at southern magnetic latitudes (~50°S) and has subsequently drifted northward. This movement resulted in skewness of the observed magnetic anomalies making its Interpretation cumbersome. Therefore, the observed anomalies need to be deskewed by applying a phase shift filter as designed by Schouten and McCamy, (1972). The required phase shift was calculated and applied to deskew the magnetic data. The analytical signal technique was applied to the magnetic data in the Bay of Bengal and Enderby Basin to locate the boundaries of magnetization of the basement. One such example is shown in figure 3-6.

### 3.3.3 Forward modeling technique

Modeling of potential field data yields the spatial distribution of gravity and magnetic sources. This modeling can be divided into two types, i.e. forward and inverse modeling. In the forward modeling, an initial model of the source body is constructed under geological and geophysical constraints. The synthetic anomaly is calculated and compared with the observed anomaly. By a number of

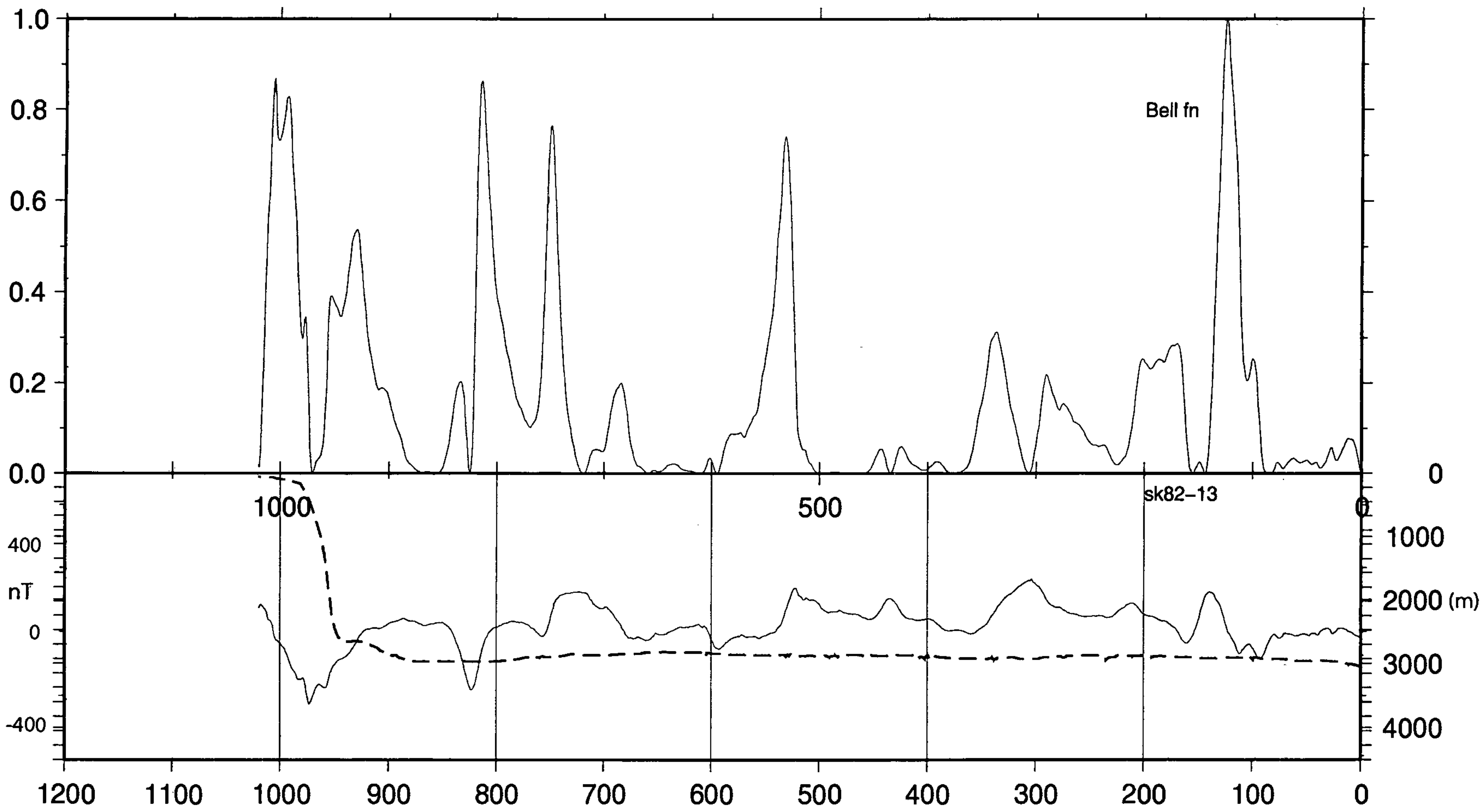


Figure 3-6 Computed analytical signal (bell-shaped functions) along the profile sk82-13. Bathymetry (dashed line) and magnetics (continuous line) are plotted below.

permutations and combinations, the model parameters are adjusted to obtain the best fit between the observed and calculated anomalies. In the inverse method, one or more body parameters are calculated directly from the observed anomaly and a geological model is created that fits the observed data. Ground truth information in the form of well log or seismics are useful to constrain the model.

In the present study, forward modeling has been attempted along two geophysical profiles in the Bay of Bengal. Multichannel seismic reflection data either along the profile or in its vicinity has been used to constrain the subsurface lithological and basement information (Fig. 3-3). The modeling studies have been undertaken to derive the structure of the sedimentary column and underlying crust. Forward modeling was done using the GM-SYS software designed for 2-dimensional forward/inverse modeling. The computation is based on the methods of Talwani et al., (1959) and Talwani and Heirtzler, (1964) and makes use of the algorithms described in Won and Bevis, (1987) and Blakely, (1996). The gravity response based on density variations within the sediments and underlying crust has been calculated and a best fit for the gravity data was obtained. For modeling the magnetic data, the three-layer model of Kent et al., (1993) was adopted to incorporate the seafloor spreading magnetic anomalies. A magnetic anomaly is considered to have an induced component due to the present day magnetic field and a component due to remanent magnetization. The remanent magnetization with inclination 67° and declination 310° (Ramana et al., 1997a[2]) was used since the oceanic crust of the Bay of Bengal was created at southern latitudes (~50°S). The magnetic response has been calculated and the model modified till a very got fit was obtained between the observed and calculated magnetic anomalies.

### 3.3.4 Plate reconstruction modeling

PLACA is a general-purpose computer program used to demonstrate the plate tectonic theory, from the representation of plate reconstructions to the determination of best-fit poles using magnetic anomalies, fracture zones or volcanic alignments (Matias et al., 2005). In the "forward" mode, PLACA has the features of most available demonstration software, in addition to the ability of simulating mid-oceanic ridges (MOR) as dynamic segments that move with a fraction of the relative motion between two plates. The movement can be illustrated by the generation of flow lines plate trajectories and/or pseudo-magnetic anomalies on the ocean floor. The evolution of simple triple junctions of the R–R–R type can also be studied. In the "modifying" mode, best-fit poles can be computed either visually or by a systematic search routine. Five methods are available to evaluate the residuals between predicted and observed reconstructed points. Once the best-fit pole is obtained, several statistical tests can be done to evaluate the confidence on the fit.

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[2] *Ramana, M. V., Subrahmanyam, V., Chaubey, A. K., Ramprasad, T., Sarma, K.V.L.N.S, Krishna, K. S., Desa, M. and Murty, G.P.S., 1997a. Structure and origin of the 85°E Ridge, J. Geophys. Res.,* ***102:*** *17995-18012.*

The PLACA software has been used to calculate finite rotation poles to reconstruct the palaeo positions of the Indian and Antarctica plates for different magnetic chrons. The input to this software includes magnetic anomaly and fracture zone locations. Both, visual fit controlled by the computer as well as automatic fit was used to determine the best pole parameters for various chrons. Once the pole parameters were calculated, the Indian plate was then rotated using in-house designed FORTRAN program keeping Antarctica in the present day position. The output values were then plotted using GMT software. Satellite derived free-air gravity grid reconstruction for chron 34 was also achieved using GMT software.

# Chapter 4

## *Physiography and subsurface configuration*

The two study areas, the Bay of Bengal and Enderby Basin encompass the continental margins and the corresponding deep offshore basins of India and Antarctica respectively. Understanding the physiography of a continental margin is vital since various structural features such as fracture zones, seamount chains, aseismic ridges, etc., which might have evolved along with the ocean floor, reveal the evolutionary history of the margin in time and space. Since the continental margins and adjoining deep offshores are generally covered by thick sediments, the physiography may not fully reveal the existence of buried structural features. Such buried/subsurface structural features can be inferred by the analysis of magnetic, gravity and seismic data. Similarly, the structures within the sedimentary column such as buried reefs, palaeochannels, faults, etc. and the lithostratigraphy can by inferred from analysis of multichannel seismic reflection data.

In the present study, bathymetry data obtained from single and multibeam echosounder has been used to infer the seabed topography and surface expressions of various structural features in the Bay of Bengal. Further, multichannel seismic reflection data along two profiles have been used to infer the subsurface features. GEBCO derived bathymetry and predicted topography has been used to study the surface expressions of various structural features of the Enderby Basin.

## 4.1 Bay of Bengal

The physiography of the Indian Ocean in general and the Bay of Bengal in particular has been described by Heezen and Tharp, (1964). Curray and Moore (1971) subsequently updated the bathymetry chart of the Bay of Bengal and showed the presence of surface channels formed by turbidity currents extending from the head of the Bay of Bengal to the south of Sri Lanka. Further, Udintsev, (1975) compiled all available geological, geophysical, physical, biological and other relevant data, and prepared an atlas of the Indian Ocean, which serves as a base to undertake advanced research in the Indian Ocean sector. Additional contribution towards the physiography of the Bay of Bengal is by Rao, (1968); Sastri et al., (1981); Rao and Rao, (1985; 1986) and Murthy et al., (1993). A detailed physiographic map of the Bay of Bengal is prepared by incorporating the bathymetry data from the General Bathymetric Charts of Oceans (GEBCO, 1983) and the bathymetric measurements made in the present study (Fig. 4-1).

### 4.1.1 Physiography

The east coast of India aligns in a NE-SW direction north of 15°N latitude and an approximate N-S direction towards south. This coastal configuration controls the bathymetry of the Bay of Bengal upto the continental slope region. The depth to the seabed in general increases gradually from the head of the bay to as far as 5°S in the Bay of Bengal. The huge sediment influx brought in by the rivers particularly

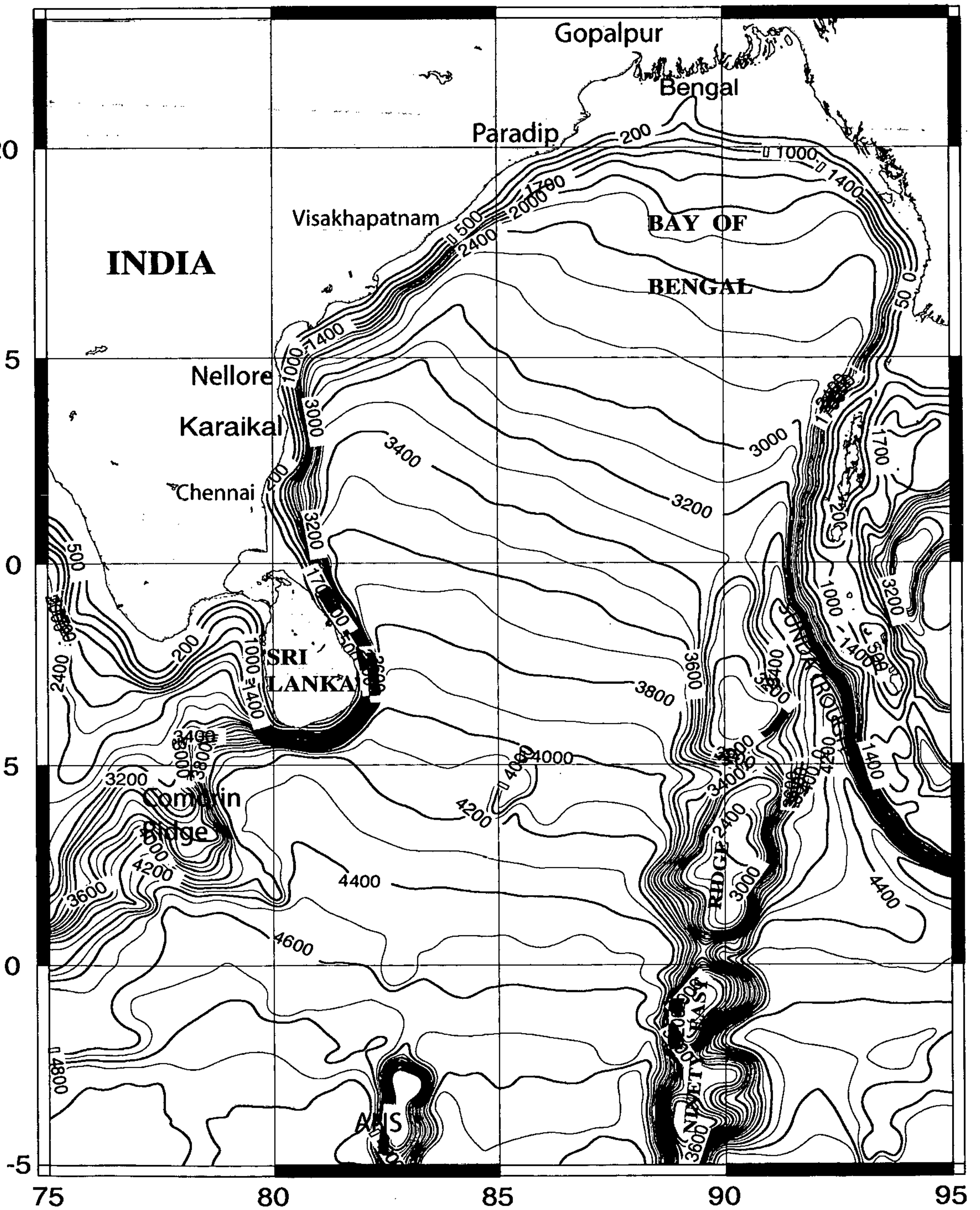



Figure 4-1 Detailed physiography of the Bay of Bengal using bathymetry data acquired by NIO and derived from GEBCO. Contour interval is variable upto 3000 m water depth and 100 m beyond. ANS: Afanasy Nikitin Seamount chain.

the Ganges and Brahmaputra determines the geomorphology. The seabed is traversed by a number of turbidity channels with levee wedges. No major bathymetric outcrops are seen north of 6°N, with the exception of the N-S complex topography along the 90°E meridian and a deep valley like feature corresponding to Sunda Trough immediately to its east. The seabed topography shallows to 1200 m while approaching the Andaman group of Islands.

The depth contours of the seabed along the Eastern Continental margin of India depict four distinct trends (Fig. 4-1) viz., i) NNW-SSE trend south of Chennai (13°N), ii) ~N-S trend between Chennai and Nellore (14°30'N), iii) NE-SW trend north of Nellore upto Paradip (20°15'N), and iv) E-W trend south off Bengal coast. This E-W trend continues south into the entire Bay of Bengal. The eastern continental shelf is relatively narrower than the western continental shelf of India. Further, the eastern continental shelf is narrow in the south and wider towards north. The minimum shelf width is about 16 km off Karaikal (south central east coast), while it is maximum (>200 km) off the Bengal coast. The shelf break occurs in water depths ranging between 70 m off Karaikal and 220 m off Gopalpur. Small scale undulations in topography are seen on the shelf. These are generally V-shaped channels and valleys flanked by steep faults associated with the delta fronts of offshore basins such as the Mahanadi and Krishna-Godavari.

The continental slope is steep with a gradient of ~90 m/km south of 14°N latitude as depicted by the bathymetry along the profile sk72-07 (Fig. 4-2). The

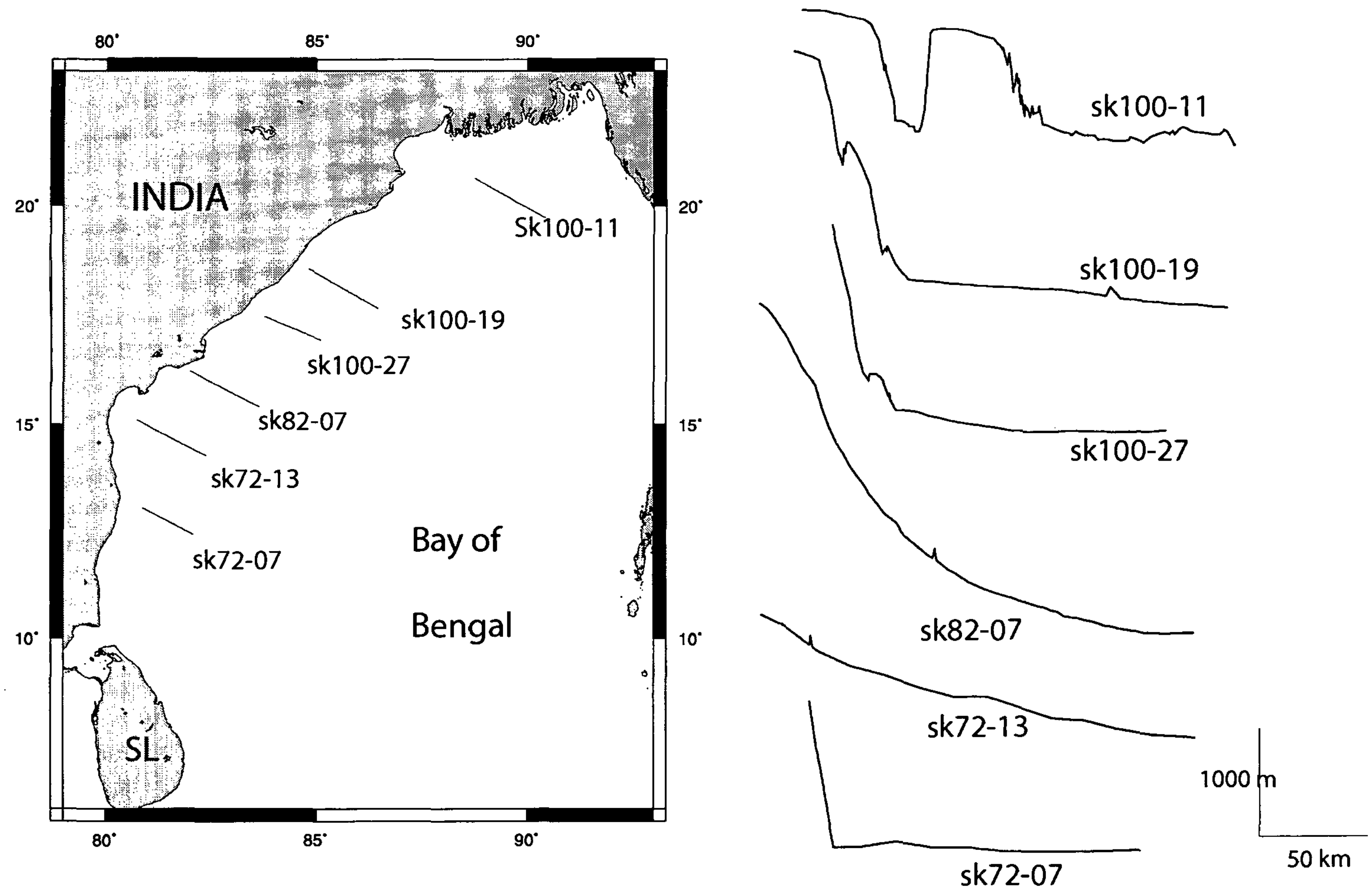
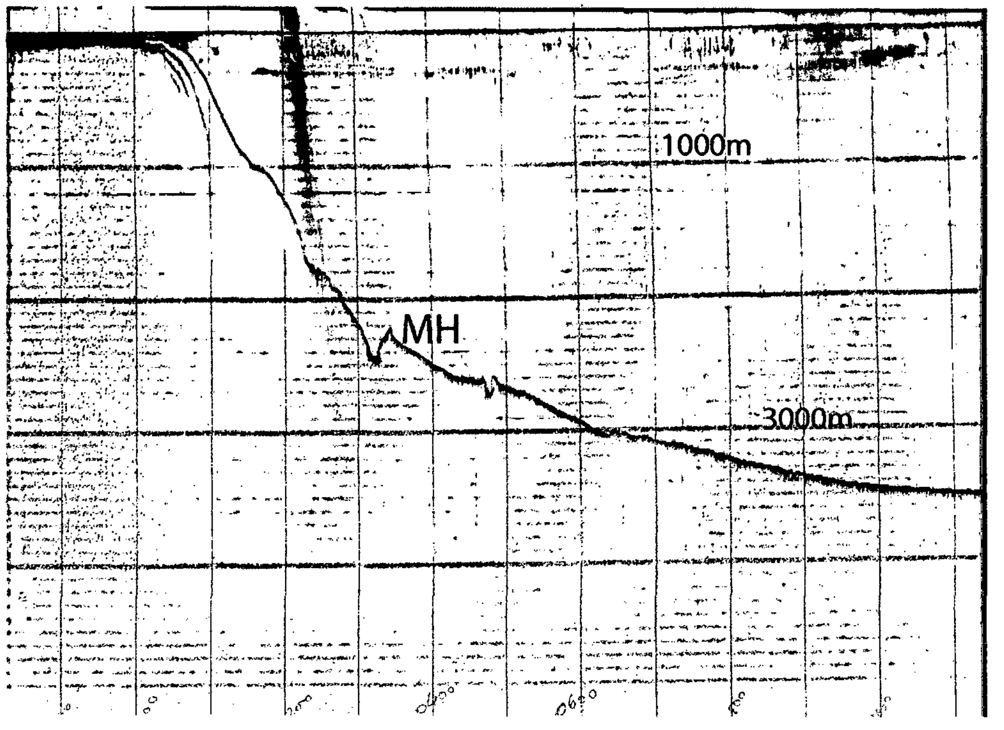



Figure 4-2 Bathymetry across the Eastern Continental Margin of India along selected tracks. Location of these tracks is shown in the adjacent position map.

slope is gentle (~30 m/km) north of 14°N while the topography may be uneven with several small-scale step like features. This uneven topography is attributed to periodic slumping of the rapidly accumulating sediments brought in by the rivers. In figure 4-2, the slope is fairly gentle along profiles sk72-13 and sk82-07, while profiles sk100-27 and sk100-19 display step like features. Along the oblique profile sk100-11, the submarine canyon 'Swatch of No Ground' is seen cutting the shelf, while the slope is characterized by sharp positive topography features. The foot of the continental slope occurs around 3000 m water depths in the south and <2000 m in the north.

The continental rise is relatively gentle and occurs within 2000 to 3000 m water depths. It is at times characterized by a prominent topographic high known as the 'marginal high' having relief of a few tens of meters to 300 m. This high is about 20 km wide in the south, while it is seen as a sharp peak in the north. The topographic variation from the shelf to the abyssal plains is shown in figure 4-3. The topography is steep and uneven along the slope, while the rise is fairly gentle and characterized by a marginal high (MH).

The Bay of Bengal is floored by a huge abyssal cone 'Bengal Fan' built by sediments discharged from the Indo-Gangetic plains and transported by the Ganges and Brahmaputra rivers (Curray and Moore, 1971). Presently, these sediments are deposited predominantly in the huge subaerial deltas of these rivers, but during the lowered sea levels of Pleistocene time they probably poured largely into a



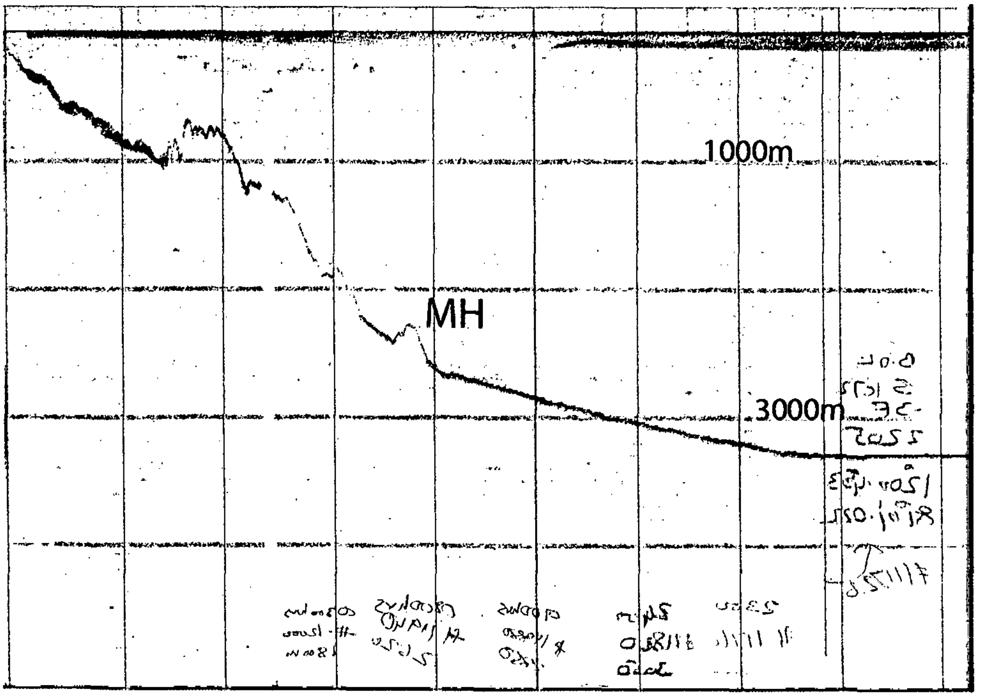




Figure 4-3 Echograms depicting the variations in topography along the continental slope and rise. MH: Marginal High

submarine canyon called the "Swatch of No Ground" (Curray and Moore, 1974). The multibeam swath bathymetry map and echograms (Cruise report SK100, 1995) of the "Swatch of No Ground" off Bengal coast depict its geomorphology across the southern region of the canyon (Figs 4-4 & 4-5). The "Swatch of No Ground" resembles a huge channel/deep valley running from the shelf to deep offshore. The canyon is deep (~900 m) in the shelf region (Fig. 4-5a), while further south, it is ~450 m deeper than the surrounding water depth of ~1000 m. Within the canyon, there exists another narrow valley like feature, which swings from NE-SW to N-S towards south (Fig. 4-5b). The width of the canyon (~14 km) is more or less constant throughout its length.

The seabed is covered with a thick sediment overburden in the Bay of Bengal, therefore the topography in general is smooth with few minor order undulations. Figure 4-6a depicts the smooth topography and the nature of the echo indicates the presence of stiff clays. This smooth topography is interrupted sporadically by micro topography undulations of the order of 10-500 m. These undulations may be in the form of low relief anticlines or turbidity channels flanked with levee wedges. The turbidity channels belong to a network of channel-levee system, which carries the terrigenous material from the submarine canyon, the 'Swatch of No Ground' right up to the southernmost tip of the distal Bengal Fan (Curray and Moore, 1971; Emmel and Curray, 1984). These channels exhibit either 'V' or 'U' shape. A pair of such channels about 70 m deep and 4-7 km wide are shown in figure 4-6b. The present-day active turbidity channel is connected to the

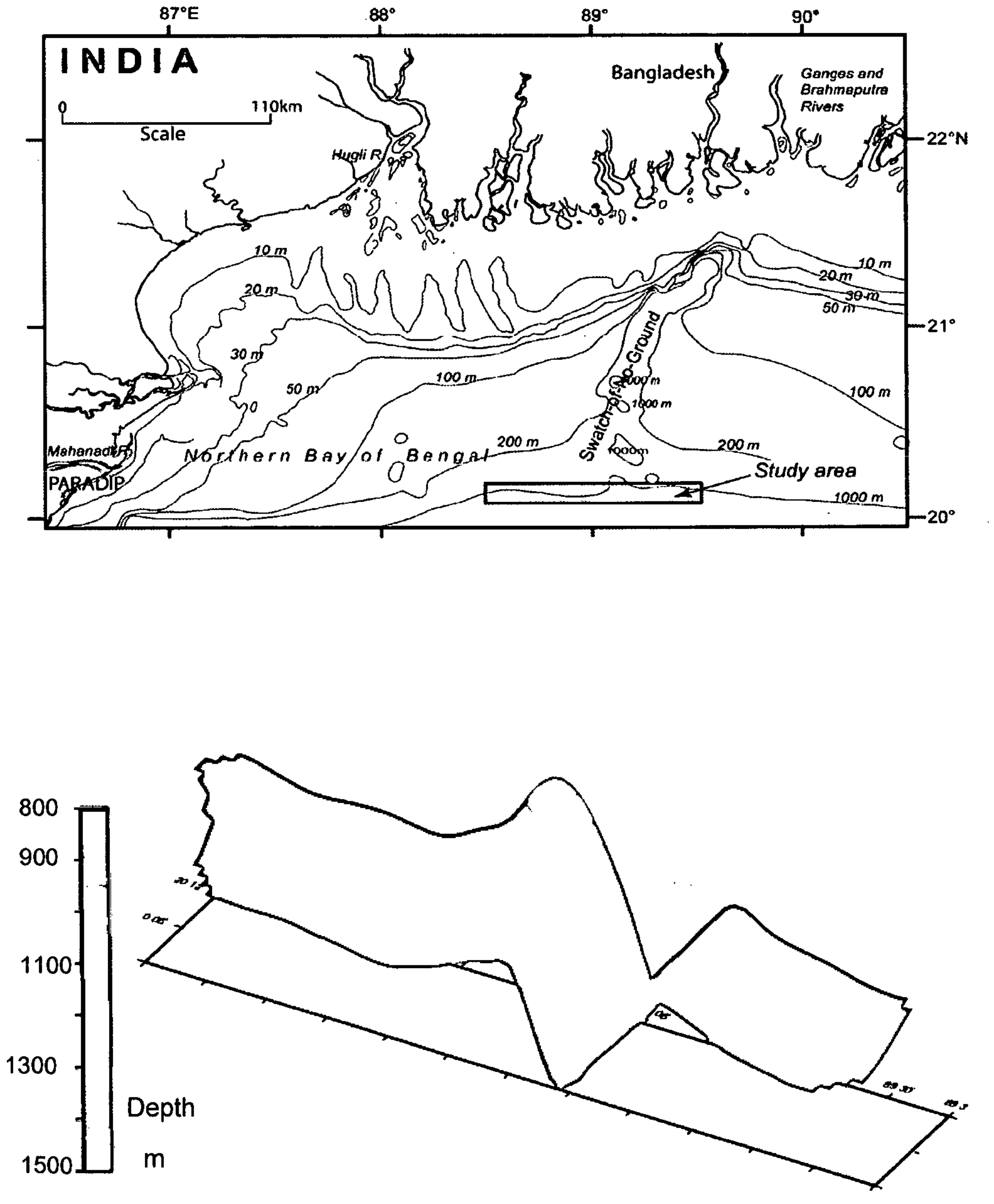



Figure 4-4 Detailed bathymetry map of the northernmost Bay of Bengal (above).
Shaded block denotes the area where geophysical data was collected during the 100th cruise of ORV Sagar Kanya across the Swatch of No Ground.
3D picture of the Swatch of No Ground inferred using multibeam bathymetry below).

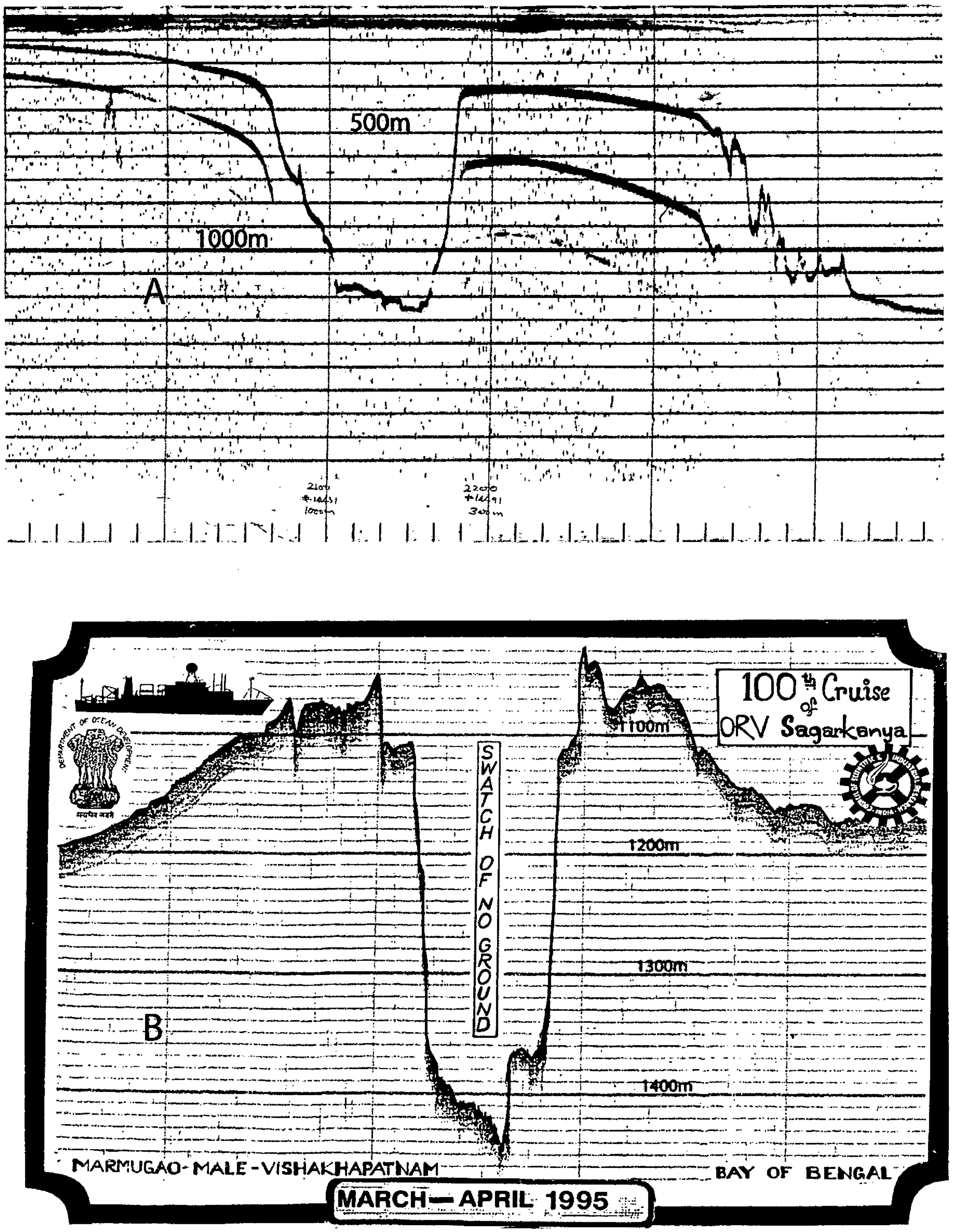



Figure 4-5 Echosounder records over the "Swatch of No Ground". A) in the shelf region, the canyon is about 800 m deep. B) Further offshore, the canyon is about 400 m deep

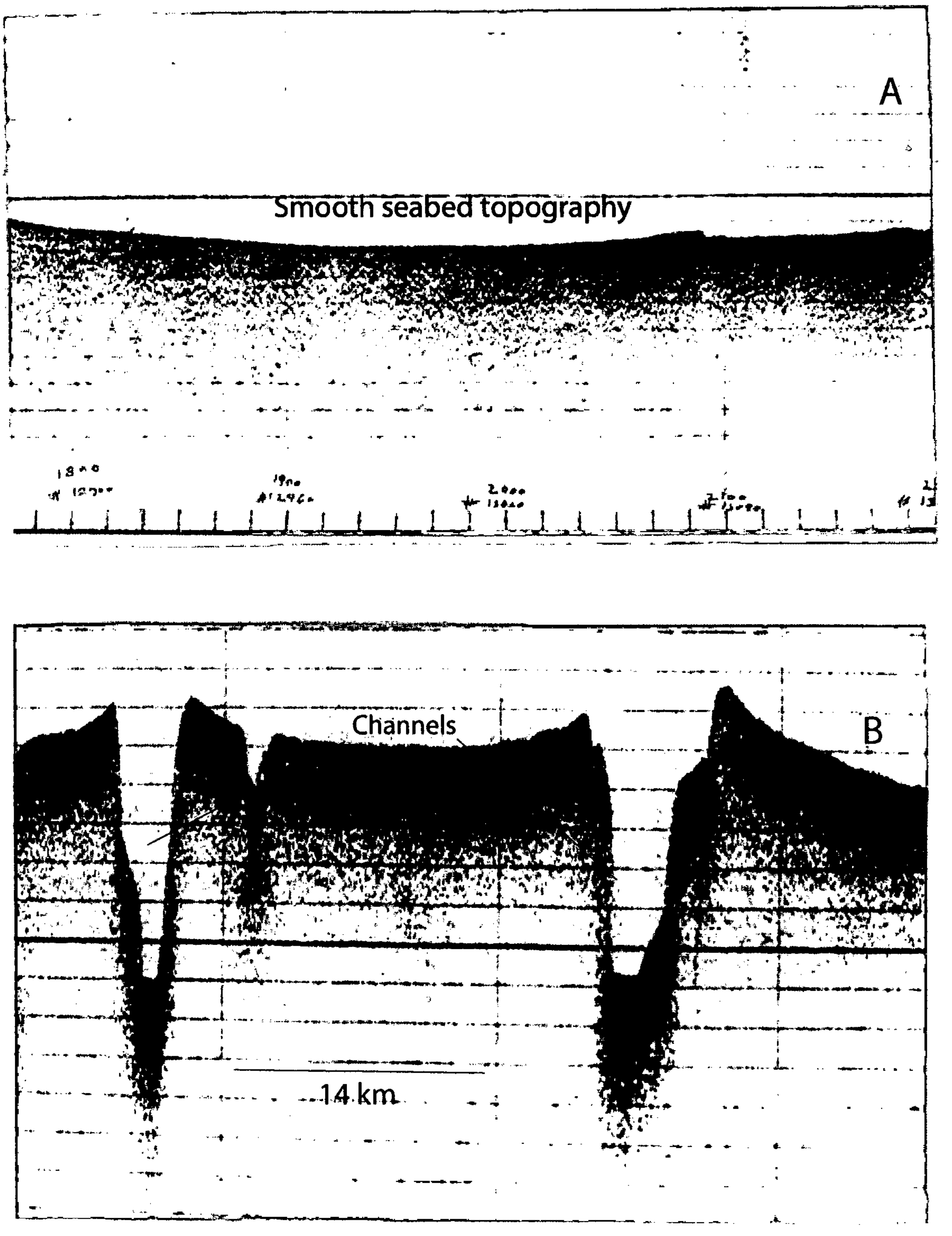



Figure 4-6 Echograms showing A) smooth topography in the Bay of Bengal. Pattern of the echo indicates the stiffness of the sediments. B) A pair of steeply cut channels about 70 m deep.

submarine canyon and has great continuity without any bifurcation (Fig. 2-2). Since active channels migrate over time, several abandoned and beheaded channels are formed. The observed channels with large natural levee complexes built on their flanks therefore may be either active or abandoned. Some channels are seen associated with slumping. Figure 4-7a is a small anticline like sedimentary feature 60 m high and 10 km wide. Figure 4-7b depicts a channel associated with slumping and a typical 'U' shaped channel. Figure 4-8a is another example of steeply cut channels with or without slumping. Figure 4-8b depicts a ~5 km wide and 600 m deep steep channel cutting through the seabed raised by about 40 m.

Linear positive bathymetry closures along the 90°E meridian correspond to the Ninetyeast Ridge and exhibit surface expression/relief upto 10°N latitude (Pierce, 1978; Pierce et al., 1989). The ridge is characterized by elongated highs with intermittent troughs comprising of a series of en echelon blocks of complex geomorphology. Isometric view of the ridge topography between 10°N and 5°S latitudes is shown in figure 4-9a. The ridge shallows to <2000 m from the surrounding bathymetry of ~3000 m in the north, while it rises to <3000 m from an average of 5000 m in the south. The eastern flank of the ridge appears relatively steeper and deeper than the western flank. A comparison of bathymetry along three N-S profiles, lying east, west and on the Ninetyeast Ridge, depicts the complex topography surrounding the Ninetyeast Ridge (Fig. 4-9b). The bathymetry along 91°E longitude (profile sk124-06) is more undulatory than the topography along 90°E longitude (profile dsdp22) on the ridge. This complex of narrow ridges and

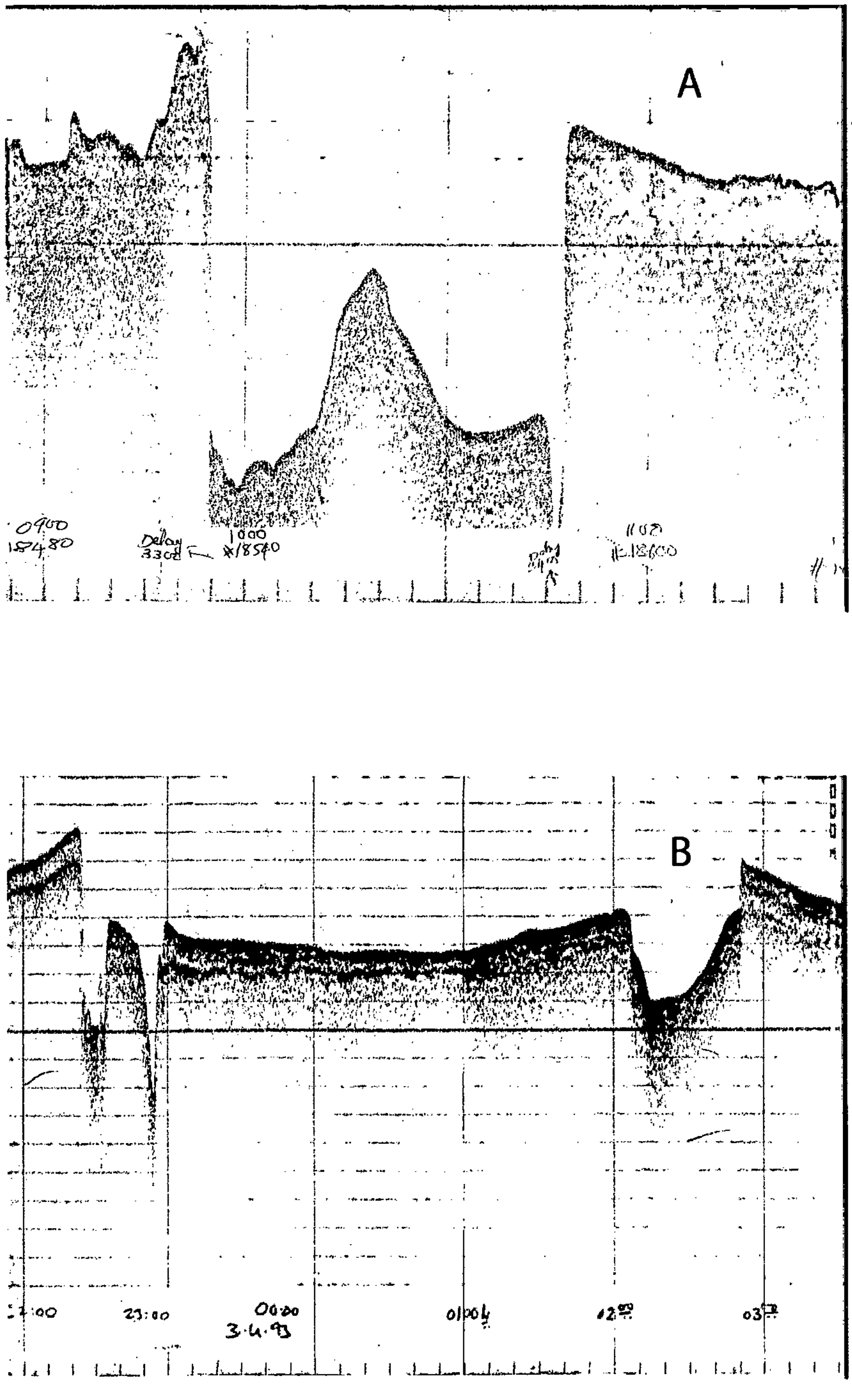



Figure 4-7 Echograms depicting minor order undulations in the seafloor topography, either as low relief anticlines or steeply cut channels

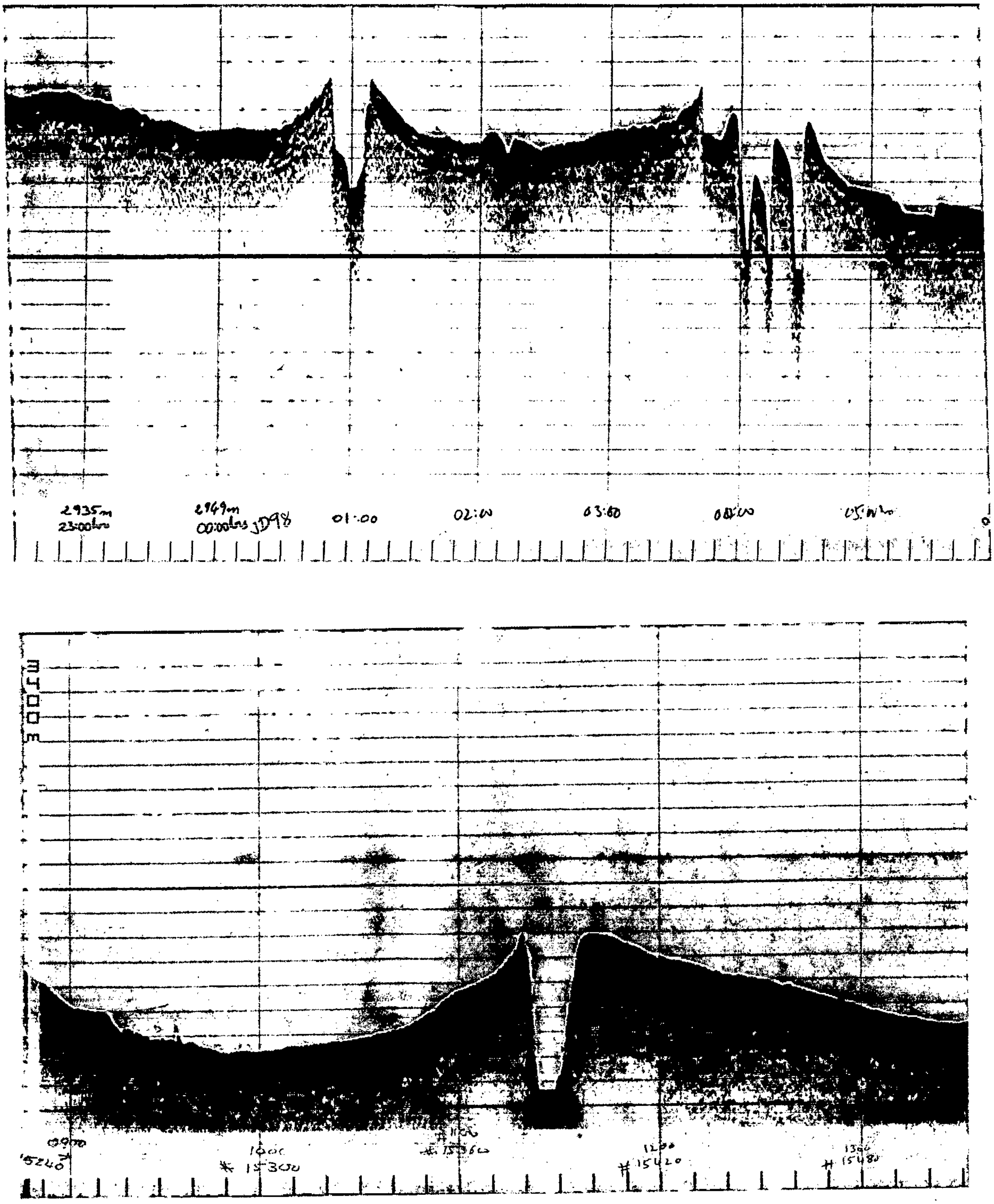



Figure 4-8 Echograms showing seafloor dotted with several channels flanked with levee wedges. Some channels are associated with slumping.

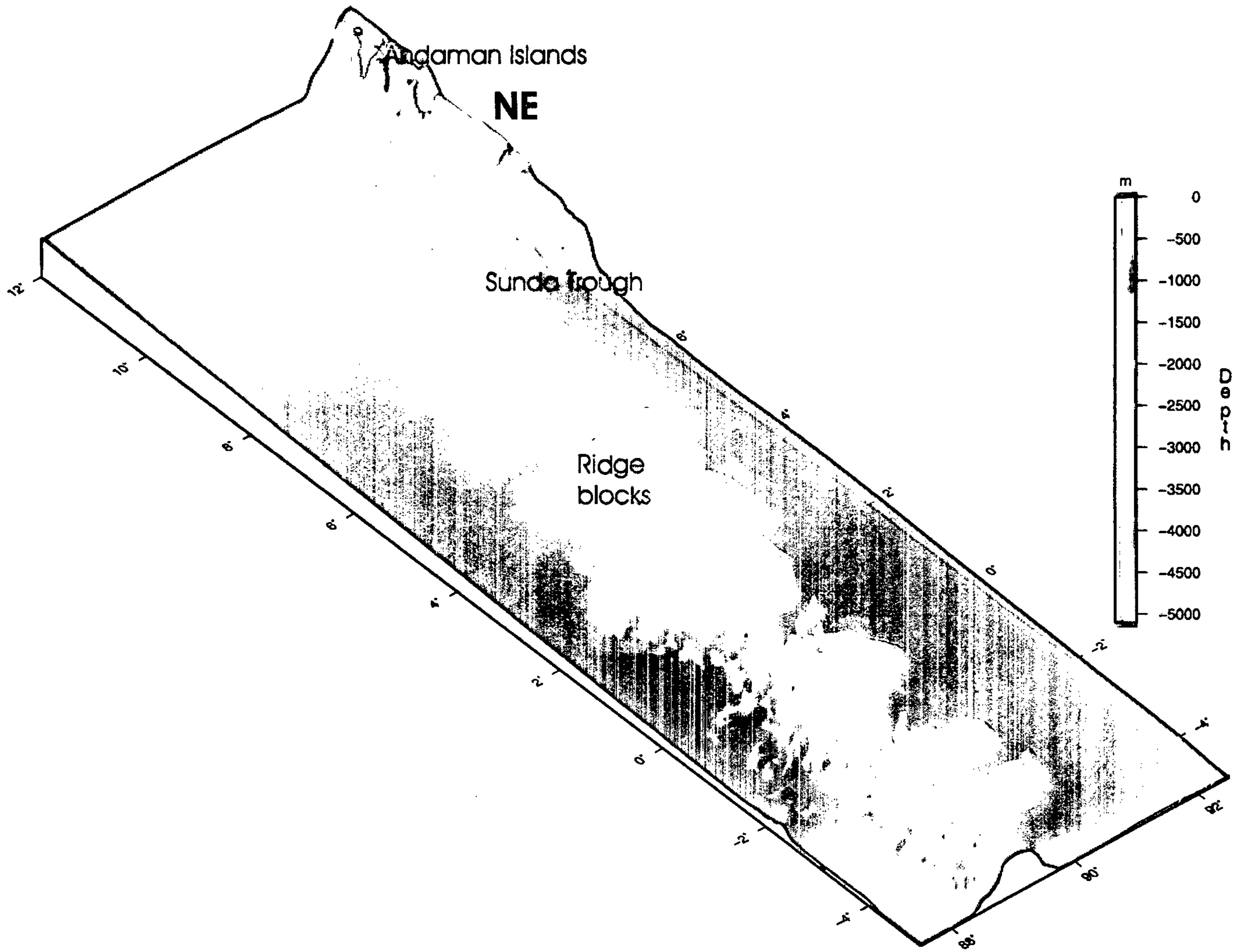



Figure 4-9a Isometric view of the Ninetyeast Ridge. Block like features are seen all along its length. Bathymetry initially deepens towards northeast (Sunda Trough) and then shallows to the Andaman group of islands.

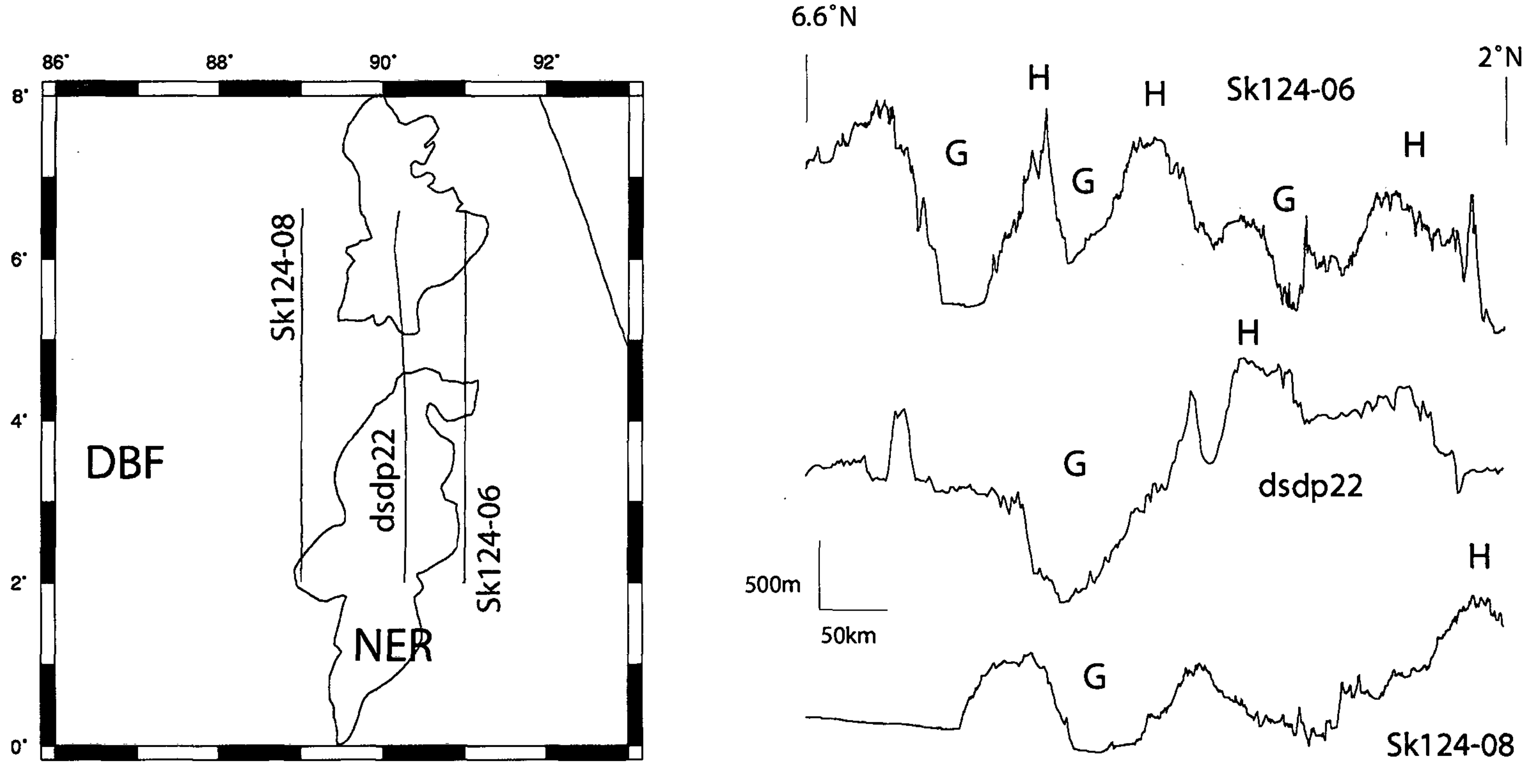



Figure 4-9b Bathymetry profiles along 89, 90 and 91°E longitudes between 2 and 6.6°N latitudes depicting complex nature of the Ninetyeast Ridge (NER). Horst (H) and graben (G) like features are seen. Topography is more rugged east of the ridge. Blue outlines depict the volcanic outcrops of NER. Green line denotes the Sunda Trough. DBF: Distal Bengal Fan

troughs seen east of the ridge has been interpreted as a transform fault between the Indian and Australian plates (Bowin, 1973).

Northeast of the Ninetyeast Ridge, dense linear bathymetric contours are observed extending in an arcuate shape (Fig. 4-1). These dense contours indicate the presence of a deep valley like feature, which is a part of the Sunda Trough. This trough rises immediately towards the Andaman group of Islands (Fig. 4-9a). The Sunda trough constitutes a destructive plate boundary (Emmel and Curray, 1984).

Some isolated seamounts are seen in the southern Bay of Bengal (Fig. 4-9c). These seamounts are characterized by considerable relief and width (Sarma et al., 2000[1]). It is interesting to see that these seamounts and partly buried hills occur along the arcuate zone of the subsurface 85°E Ridge which extends upto the Afanasy Nikitin seamount chain (ANS). The N-S elongated ANS rises from the surrounding water depth of ~4800 m to 3800 m. Several elongated peaks emerge from the basement, the shallowest peak rising to 1600 m in the north. In the south, the high is almost flat-topped with rises of 200-400 m relief (Krishna, 2003).

The region southwest of Sri Lanka between 2 and 6°N latitudes and 77-79°E longitudes is characterized by NNW-SSE trending irregular topography (Fig. 4-1).

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[1] *Sarma, K.V.L.N.S., Ramana, M.V., Subrahmanyam, V., Krishna, K.S., Ramprasad, T. and Desa, M., 2000. Morphological features in the Bay of Bengal, J. Indian Geophys. Union, 4: 185-190.*

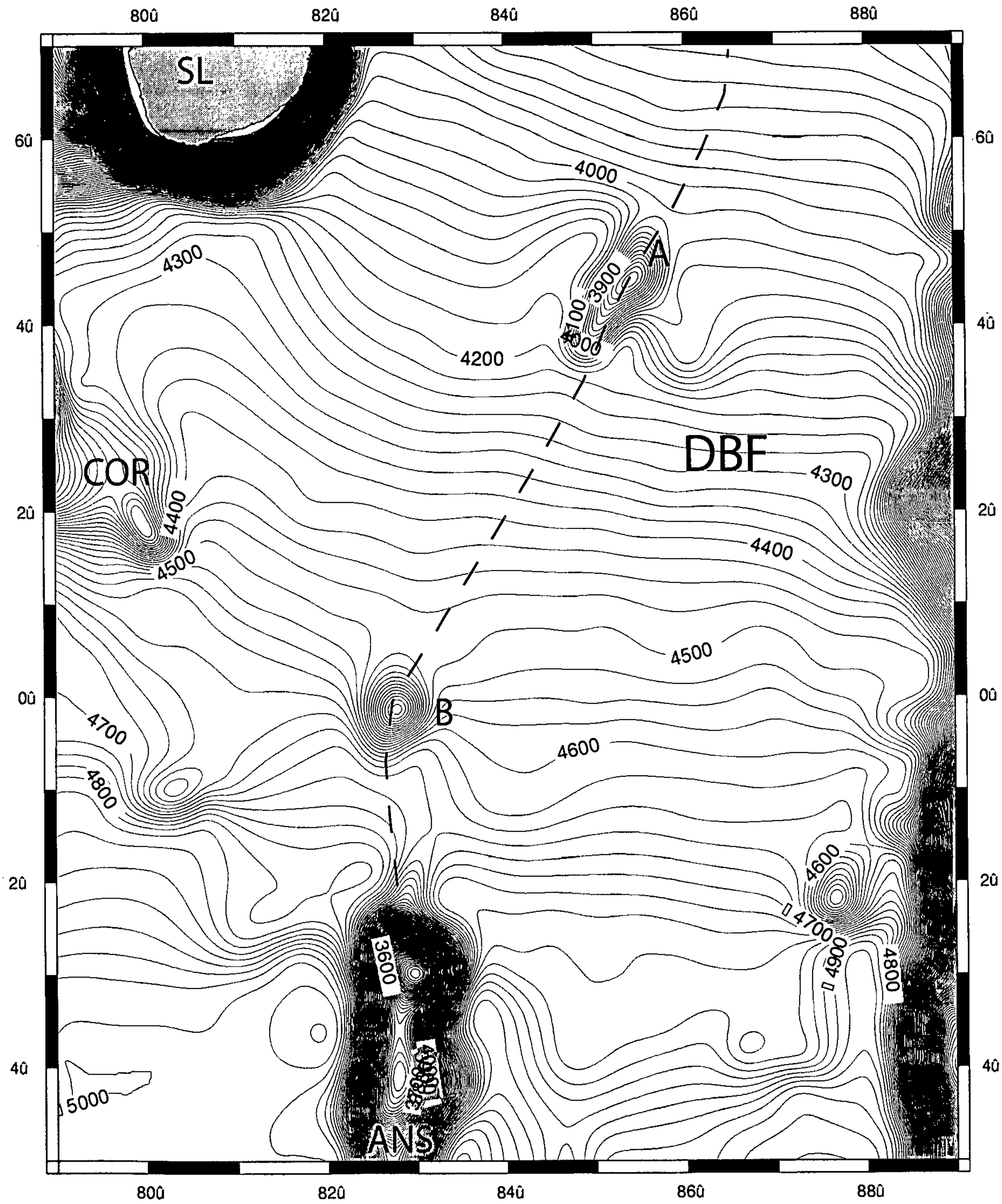


Figure 4-9c Detailed bathymetry of the distal Bengal Fan (DBF) with contour interval of 25 m. Positive bathymetry closures of considerable dimensions A and B are the outcrops of the subsurface 85°E Ridge. Dense contours around Sri Lanka indicate a steep slope. N-S contours towards east belong to the Ninetyeast Ridge. ANS: Afanasy Nikitin Seamount chain; COR: Comorin Ridge

This broad linear feature has been interpreted as the Comorin Ridge. The ridge has a relief of about 1000 m from the surrounding bathymetry of 3500 m. It is characterized by a steep scarp on the eastern side, while the gradient is relatively gentle on the western slope of the ridge. South and east of Sri Lanka, the continental shelf is narrow (~30 km) and the slope is steep (Fig. 4-1).

### 4.1.2 Subsurface geological configuration

The Bay of Bengal has been investigated and the primary subsurface configuration has been reported using multichannel and single channel seismics (refraction and reflection) techniques (Naini and Leyden, 1973; Curray and Moore, 1971; 1974; Curray et al., 1982). Some of the major inferences are: the subsurface 85°E Ridge and the unconformities, i.e. uppermost Miocene (M) and top of Paleocene (P). Subsequently, Pateria et al., (1992) identified four major sequences along two seismic lines shot across the Bay of Bengal, and Gopala Rao et al., (1994[2]) inferred 8 seismic sequences from the study of a single multichannel seismic reflection profile along 13°N latitude (Fig. 2-8). The above inferences are more pertinent to the sediment structure only and the basement configuration remains speculative due to limitations of the seismic systems.

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[2] *Gopala Rao, D., G.C. Bhattacharya, M.V. Ramana, V. Subrahmanyam, T. Ramprasad, K.S. Krishna, A.K. Chaubey, G.P.S. Murty, K. Srinivas, Maria Desa, S.I. Reddy, B. Ashalata, C. Subrahmanyam, G.S. Mittal, R.K. Drolia, S.N. Rai, S.K. Ghosh, R.N. Singh and R. Majumdar, Analysis of multichannel seismic reflection and magnetic data along 13°N latitude across the Bay of Bengal, Marine Geophys. Res., 16, 225-236, 1994.*

In order to have a comprehensive understanding of the subsurface features in the Bay of Bengal, multichannel seismic reflection data obtained from the Directorate General of Hydrocarbon (DGH), Ministry of Petroleum and Natural Gas, Government of India have been analyzed. The two seismic sections used in the present study are line KG-01 and line MN-01 (Fig. 3-3). Line KG-01 (397 km long) runs from the shelf to the abyssal depths in the Krishna-Godavari offshore. The upper slope is gentle upto 0.5 s TWT (~375 m). Thereafter, the water depth falls steeply upto 2.3 s TWT (~1725 m). The slope is followed by a gently deepening continental rise characterized by a marginal high, which continues into the abyssal plains (Fig. 4-10).

The other seismic line MN-01 (380 km long) in the Mahanadi offshore extends from 18°N latitude for about 20 km along the continental shelf and into the abyssal plains (Fig. 3-3). The slope beginning from 0.15 s TWT (~113 m) is steep upto 2 s TWT (~1500 m). The rise is comparatively less steep upto 3.3 s TWT (~2475 m) and is followed by gradually increasing abyssal depths (Fig. 4-11). The seismic sections were plotted and interpreted to understand the structure and thickness of the sedimentary column, and basement characteristics. Prominent horizons were picked based on the acoustic impedance contrast and nature of reflections. Eight horizons (H1 to H8) separating nine seismic sequences (A to I) were inferred within the sedimentary column overlying the basement. A brief description of the inferred seismic sequences along the seismic sections KG-01 and MN-01 are presented in Tables 4 and 5 respectively.

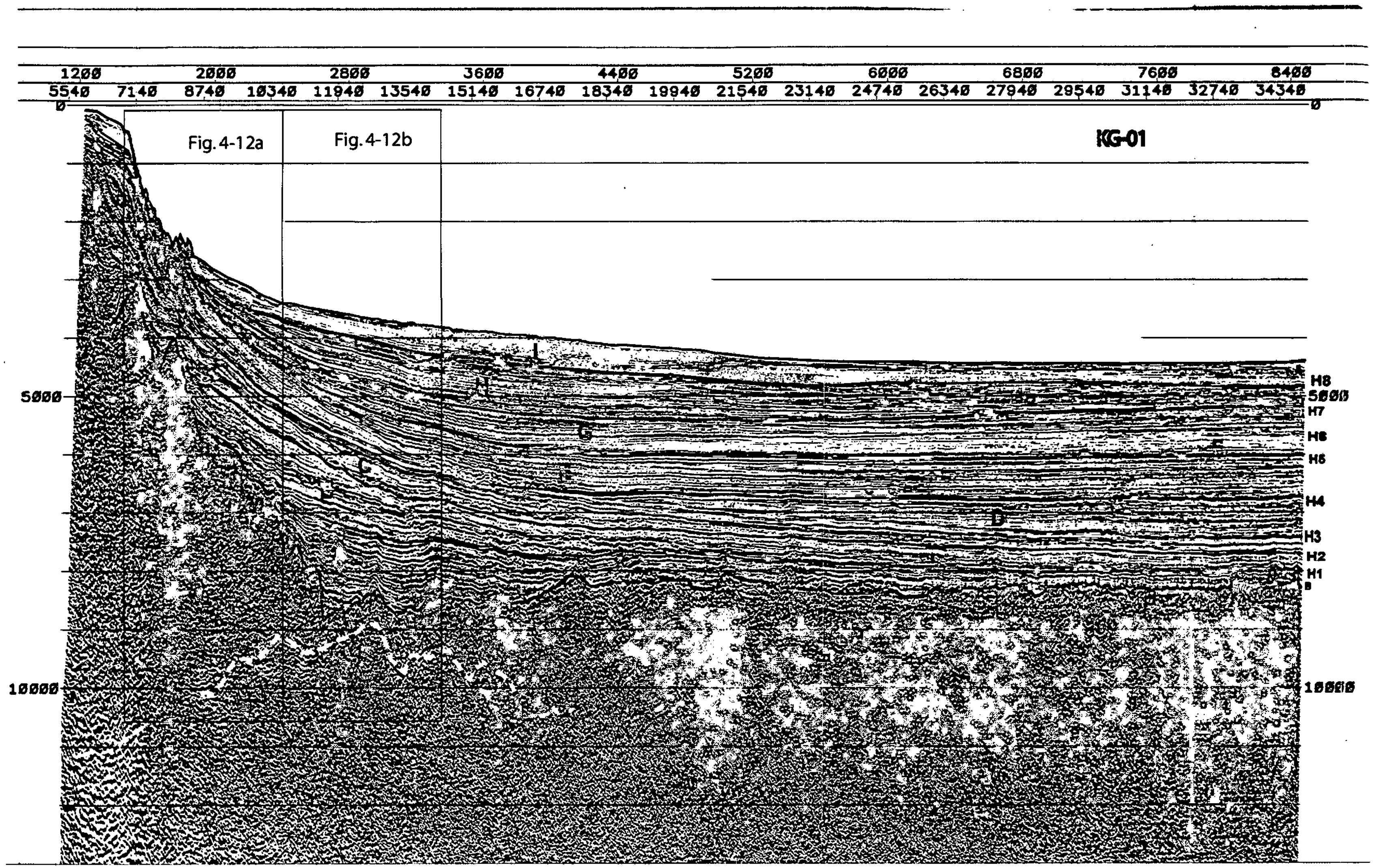


Figure 4-10 Multichannel seismic section along the profile KG-01 depicting 8 seismic horizons H1 to H8 and 9 seismic sequences A to I. Oceanic basement is shown as brown line, continental basement in blue and transition basement in pink. Moho below oceanic crust is shown as a blue dashed line, while base of transition/continental crust is shown as yellow dashed line. Blocks indicate the portions of the seismic section enlarged in the given figure number

Table 4: Description of seismic sequences inferred along Line KG-01

| Sequence/ corresponding unconformity | Description | Thickness |
|---|---|---|
| I<br>*H8* | Low amplitude, sub-parallel, transparent, discontinuous, mass transport complex | 0.25 to 0.5 secs TWT thick |
| H<br>*H7* | Continuous to discontinuous, sub-parallel to parallel, low amplitude | Upto 0.75 s TWT, decreasing towards offshore |
| G<br>*H6* | Continuous, parallel, low amplitude, | Upto 0.5 s TWT, increasing towards offshore |
| F<br>*H5* | Transparent sub-parallel discontinuous, onlapping and pinching out on sequence E | Upto 0.3 s TWT, increasing towards offshore |
| E<br>*H4* | Continuous, parallel to sub-parallel, high amplitude, | Around 0.75 s TWT all along the section |
| D<br>*H3* | Thinning towards coast, onlapping and pinching out on sequence C, discontinuous sub-parallel reflections, low amplitude | Upto 0.8 s TWT, increasing towards offshore |
| C<br>*H2* | Thinning towards offshore, discontinuous, sub-parallel reflections, high to low amplitude | Upto 0.5 s TWT, maximum at the continental rise |
| B<br>*H1* | Draping continental basement and onlapping sequence A, thinning towards offshore, discontinuous sub-parallel reflections, high to low amplitude | Upto 1.25 s TWT, maximum at the continental rise |
| A | Draping the basement, thinning towards offshore, low amplitude, discontinuous sub-parallel reflections | Upto 1.5 s TWT, maximum at the continental rise |

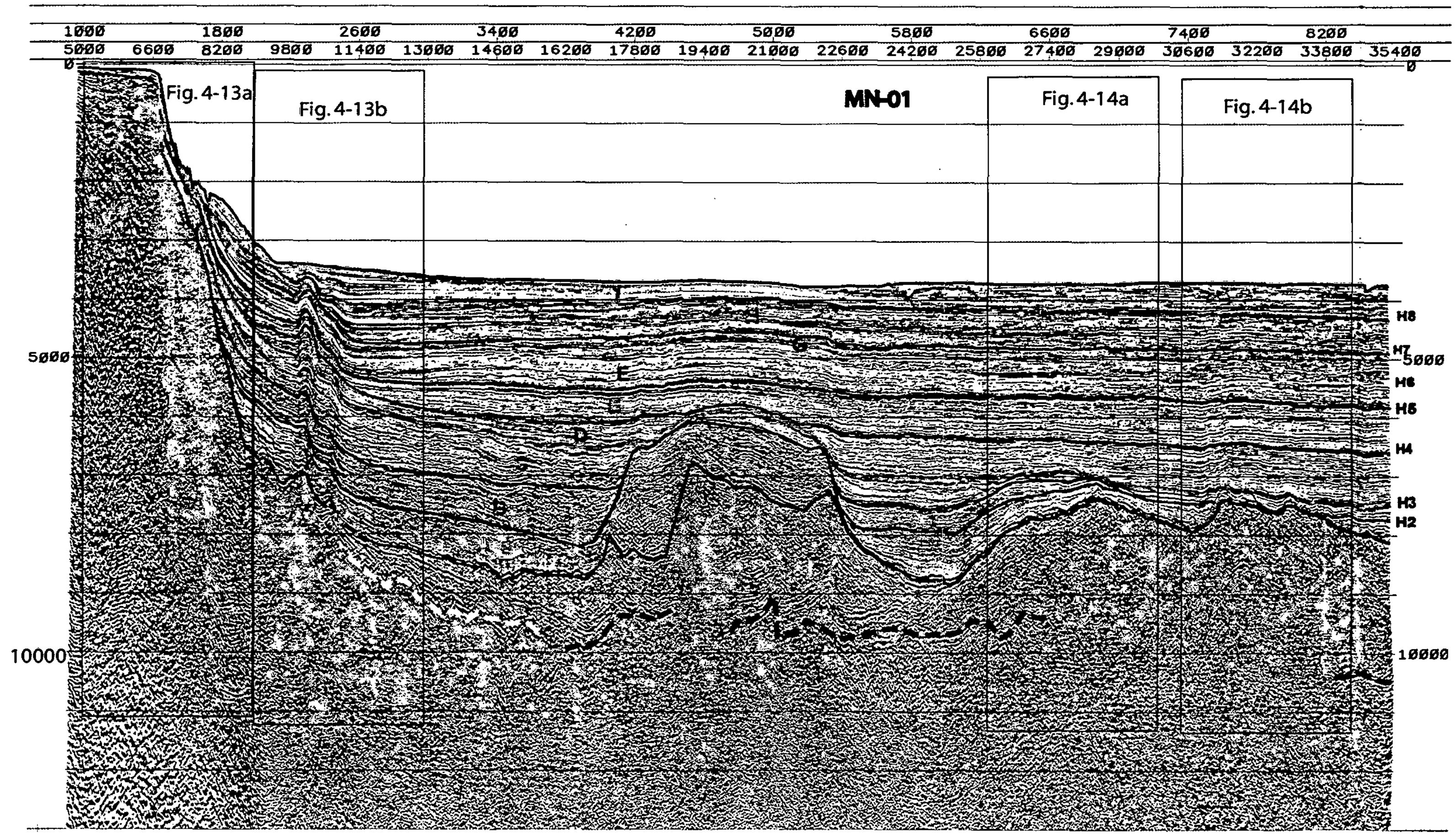


Figure 4-11 Multichannel seismic section along the profile MN-01 depicting 8 seismic horizons H1 to H8 and 9 seismic sequences A to I. Oceanic basement is shown as brown line, continental basement in blue and transition basement in pink. Moho below oceanic crust is shown as a blue dashed line, while base of transition crust is shown as yellow dashed line. The submerged basement high corresponds to the 85°E Ridge. The reflection pattern depicts its complex nature of evolution. Blocks indicate the portions of the seismic section enlarged in the given figure number

Table 5: Description of seismic sequences inferred along Line MN-01

| Sequence/ corresponding unconformity | Description | Thickness |
|---|---|---|
| I<br>*H8* | Low amplitude, sub-parallel, transparent, discontinuous, mass transport complex | 0.3 to 0.6 secs TWT thick |
| H<br>*H7* | Discontinuous, sub-parallel to parallel, low amplitude, thin near the coast | Around 0.7 s TWT in abyssal depths |
| G<br>*H6* | Continuous, parallel, low amplitude, thinning towards coast | Upto 0.5 s TWT, increasing towards offshore |
| F<br>*H5* | Sub-parallel discontinuous, fairly transparent, onlapping on sequence E | Around 0.4 s TWT all along the section |
| E<br>*H4* | Continuous, parallel to sub-parallel, high amplitude, thinning towards coast | Upto 0.8 s TWT increasing towards offshore |
| D<br>*H3* | thinning towards coast, onlapping on sequence C, discontinuous sub-parallel reflections, low amplitude | Upto 0.9 s TWT, increasing towards offshore |
| C<br>*H2* | Thinning towards offshore, discontinuous, sub-parallel reflections, high to low amplitude | Upto 0.9 s TWT, maximum at the continental rise |
| B<br>*H1* | Draping continental basement and onlapping sequence A, discontinuous sub-parallel reflections, high to low amplitude | Upto 1 s TWT, maximum west of 85°E Ridge |
| A | Draping the basement, thinning towards offshore, low amplitude, discontinuous sub-parallel reflections | Upto 0.8 s TWT, maximum at the continental rise |

Sequence A overlies the basement and constitutes the oldest sedimentary deposits. Sequences A to C thin towards offshore suggesting that their source is primarily the adjoining landmass. These sequences represent the typical continental rise type of sediments. The remaining top sequences either thicken towards offshore or maintain same thickness throughout the section. Sequences D and F pinch towards the coast, while the sequences E and G have a constant thickness along the section KG-01 (Fig. 4-10). In profile MN-01, the sequences D to G increase in thickness towards offshore (Fig. 4-11). The topmost sequence I has several transparent zones probably indicating either mass transport complex or the presence of homogenous material/gas. Total sediment thickness is more (>5 s TWT) near the coast, while it is relatively less towards offshore (~4.5 s TWT) along both the sections.

The bottommost horizon associated with high amplitude reflections corresponds to the acoustic basement, which represents the top of the crust. The underlying crust has been classified as continental, transitional and oceanic, based on the reflection pattern. The topography of the inferred continental crust is highly irregular with a relief of 500 to 3000 m. The continental crust extends offshore by >50 km from the shelf break. The marked tonal differences within the continental crust have been interpreted as massive intrusive bodies. These intrusions are the manifestations of rift-phase volcanism.

A 60 km wide transition zone has been inferred beyond the continental crust. This zone is characterized by an undulatory basement surface and a strong reflection akin to Moho, which shallows towards the continent. Beyond this transition zone, the crust is characterized by a strong reflection at 9.5 -10.5 s TWT. This reflection has been interpreted as the Moho and the overlying crust is oceanic.

Crustal thickness of about 1. – 2.2 s TWT has been inferred based on the identification of Moho and top of oceanic crust. The oceanic crust can be divided into two layers based on the reflection pattern, the upper layer (~500 m) is characterized by chaotic reflections, while the lower layer is reflection free.

In section KG-01 (Fig. 4-10), the continental type of basement is seen upto shot 2700 and the transition zone between shots 2700 and 3800. The Moho reflection is seen ascending from 11 s in the shelf region to 9 s in the transition zone. Thereafter, it descends to ~10 s beyond the transition zone. The basement surface is smooth to rough (0.1 to 0.2 s) beyond shot 4000 and is the top of the oceanic crust.

The enlarged seismic section between shots 1500 and 2500 (Fig. 4-12a) shows irregular topography on the seabed in the mid-slope region, which is due to slumping. The slumping in general has a relief of ~75 m and an amplitude of 1-1.5 km. The subsurface layers (~800 m) in this zone are mostly devoid of any regular pattern indicating that the paleoslope was not conducive for the deposition of sediments. Beyond shot 1875, regular depositional pattern is observed within the entire sedimentary column. This nature of deposition indicates the prevalence of low energy environment. The enlarged seismic section between shots 2500 and 3500 (Fig. 4-12b) depicts parallel and continuous reflections within the sedimentary column suggesting the deposition is continuous and systematic. The underlying

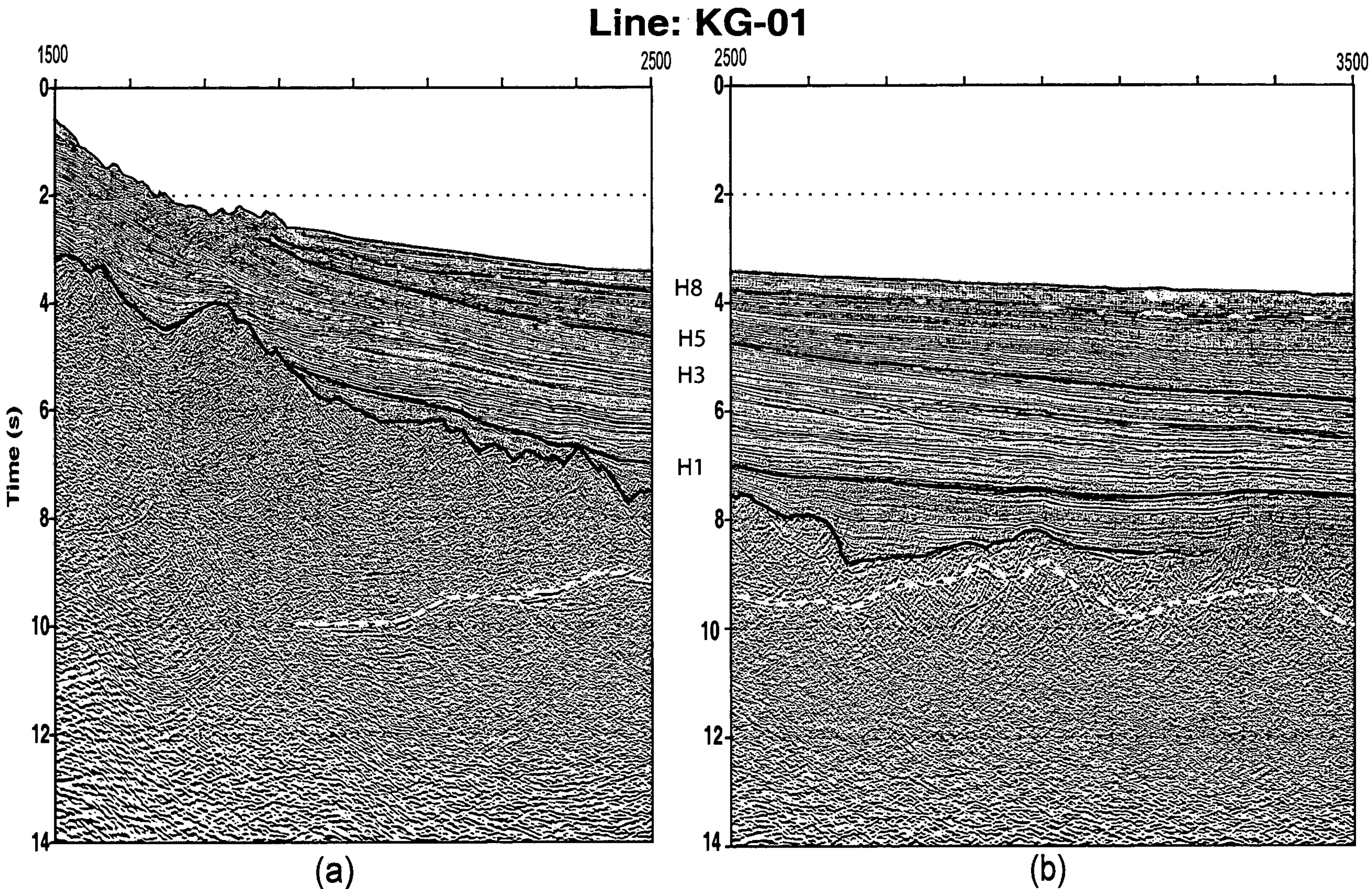


Figure 4-12 Enlarged seismic section from profile KG-01 (a) between shots 1500 and 2500, slumping signatures at the seafloor and underlying chaotic reflections are seen at the base of slope. Prominent unconformities such as top of Paleocene (H3), base of Early Cretaceous (H1) are marked. Moho deepening towards the coast; (b) between shots 2500 and 3500, showing systematic deposition pattern probably indicating prevalence of low energy environment. Basement is undulatory and Moho is shallow.

crust is transitional in nature and depicts chaotic type reflections. The thickness of the crust is also minimum.

In section MN-01 (Fig. 4-11), the continental type of basement is seen upto shot 2400 and the transition zone between shots 2400 and 3800. The image of the subsurface 85°E Ridge is seen as a basement high (~2 s TWT relief). The presence of sequence A (~1 s TWT thick) on the ridge, suggests that the ridge has uplifted along with the sequence after it was deposited. The sequences B to D truncate on either side of the ridge while the sequences C and D drape on it suggesting that ridge might have existed before the deposition of these sequences. All the younger sequences (E to I) seem to be slightly uplifted over the ridge indicating some recent activity/differential compaction. The Moho reflection is seen very prominently below and around the ridge at about 9.5 s TWT, except for a narrow zone (~13 km), which has a plume-like appearance. On either side of this plume like feature, the reflections suggest intermixing of the igneous material and existing basement. East of the 85°E Ridge, a small basin like feature is observed. Further east, the basement becomes shallow and undulatory over which the oldest sequences A to C either thin or disappear.

The enlarged seismic section (Fig. 4-13a) between shots 1000 and 2000 depicts the complex subsurface structure from the shelf to slope region. Slumping is seen on the seabed in the slope region in this section too. Vertical faulting is seen in the deeper portion of the shelf region. A massive intrusion has been inferred

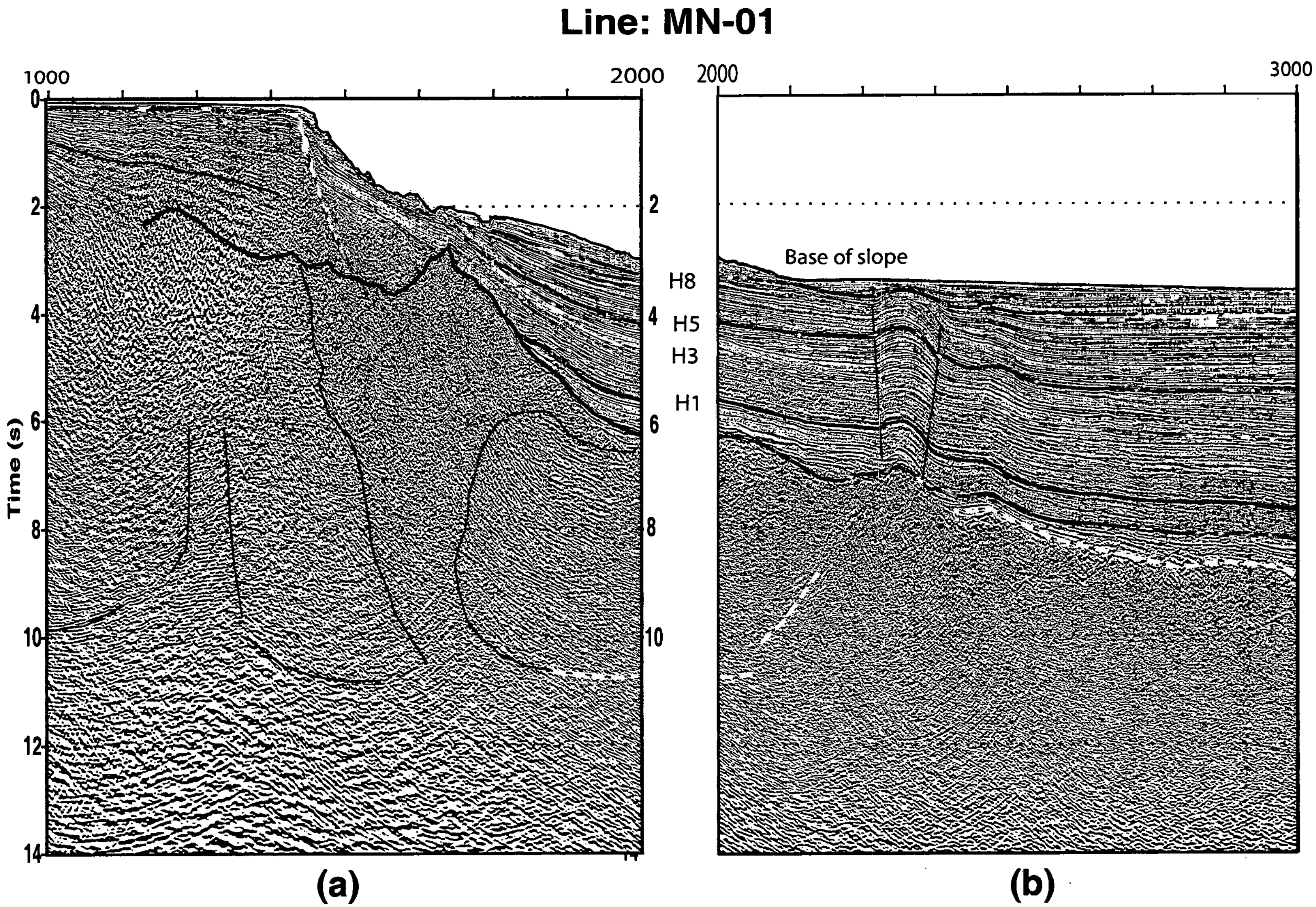


Figure 4-13 Detailed seismic section from profile MN-01 (a) between shots 1000 and 2000, slumping and erosion is seen in the slope region. The upper surface of the Precambrian basement is seen affected by massive mafic intrusions (b) between shots 2000 and 3000, sedimentary column depicts parallel and continuous reflection pattern with distinct unconformities. Basement deformation has created undulations in the sediment sequences upto horizon H8

below the slope region, which may have intruded into the pre-existing basement resulting in its doming and formation of a sill like body towards offshore. Detailed seismic section between shots 2000 and 3000 depict parallel to semi parallel and continuous reflectors uplifted between two faults beyond the continental slope (Fig. 4-13b). This divergent nature of the reflectors indicates a strong point source acted at the basement level. This is a manifestation of the deformation within the subcrustal layers, and the undulations within the sediments indicate that it is a recent activity.

Detailed seismic section (Fig. 4-14a) between shots 6250 and 7250 indicates slow and continuous deposition in a low energy environment. Bottom seismic sequences between 7 and 8.2 s TWT are thinning towards east. Moho reflection can be seen upto shot 6600 at ~9.5 s. Enlarged section between shots 7375 and 8375 indicates even, parallel and continuous sedimentation pattern (Fig. 4-14b). Upper surface of the crust is undulatory having relief of 200 to 1000 m and amplitude of 2 to 10 km. Bottommost reflector Moho is also associated with low relief undulations. The overlying sedimentary column (5-6 km) along with the crustal layer is seen faulted and is a manifestation of the uplift of the Moho, which can be attributed to intraplate deformation/reactivation.

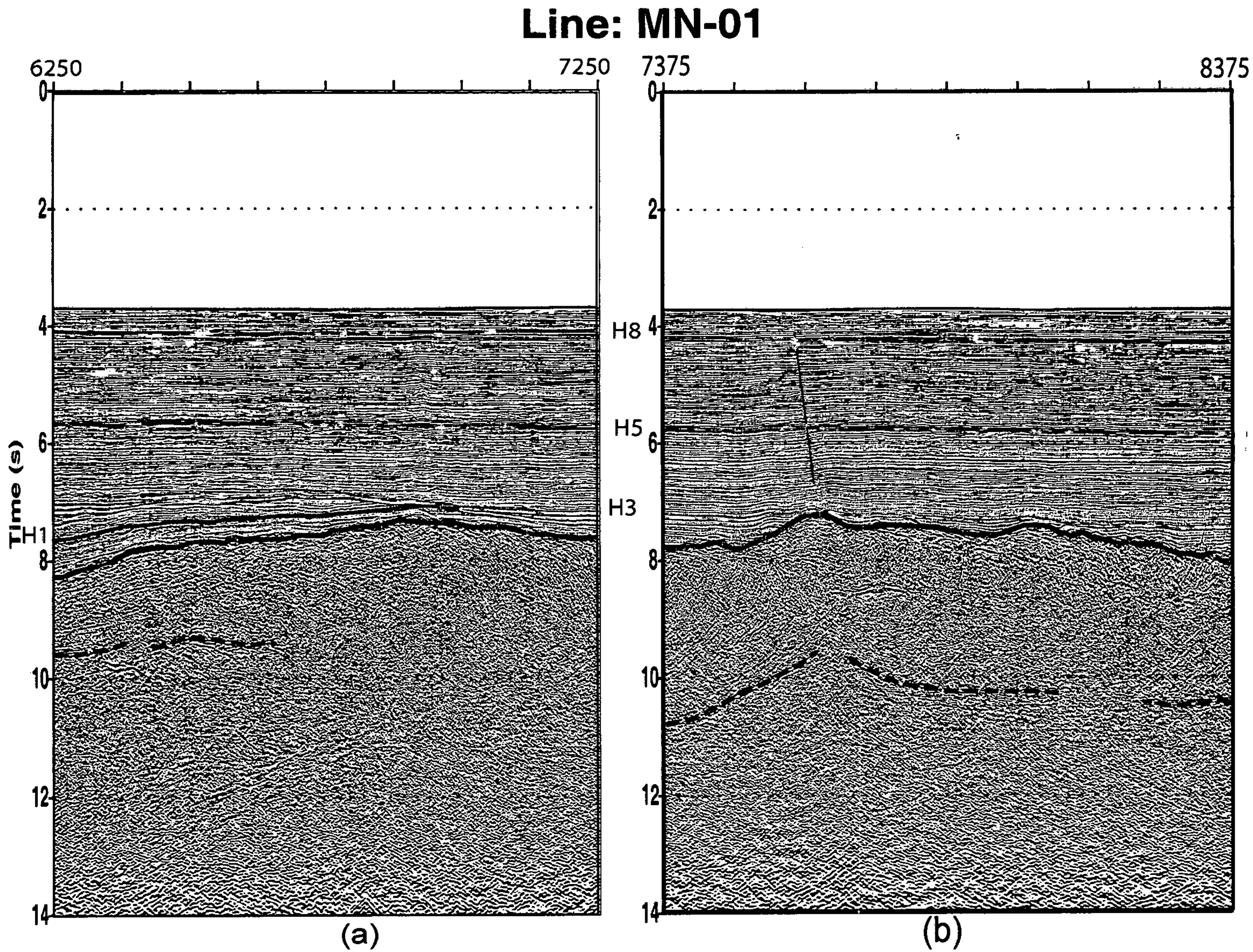


Figure 4-14 Detailed seismic section from profile MN-01 depicting parallel and continuous reflection pattern in sedimentary column, (a) between shots 6250 and 7250, lower sequences pinching towards offshore, basement with minor undulations and prominent Moho at ~10 s TWT (b) between shots 7375 and 8375, depicting undulatory basement and uplift where Moho is elevated causing faulting in the sedimentary column.

## 4.2 Enderby Basin

The Enderby Basin, the offshore extension of the East Antarctica continental margin being remotely located and ice covered, has not been densely covered for bathymetric investigations. Nevertheless, GEBCO provided a fairly good bathymetry map of the region (Fig. 4-15). Some recent investigations reveal the physiography of the continental margin and deep offshore (Johnson et al., 1982; Stagg et al., 2004; 2005). At the same time, the Kerguelen Plateau has been widely studied both for surface and subsurface structural configuration (Houtz et al., 1977; Schlich et al., 1987; Operto and Charvis, 1995 etc.).

The satellite derived free-air gravity mosaic obtained using the Topex Poseidon/ERS satellite systems (Sandwell and Smith, 1997) can be used to obtain the bathymetry. The bathymetric mosaic thus obtained is called the predicted topography and is highly reliable in the absence of dense geophysical data (Sandwell and McAdoo, 1988). In the present study, the predicted topography map of the Enderby Basin (Fig. 4-16) has been used to infer the geomorphic features. This map depicts fairly well the major structural features such as seamounts, ridges and plateaus as well as fine scale features such as fracture zones. The extent of the continental margin can also be discerned with a fair degree of accuracy.

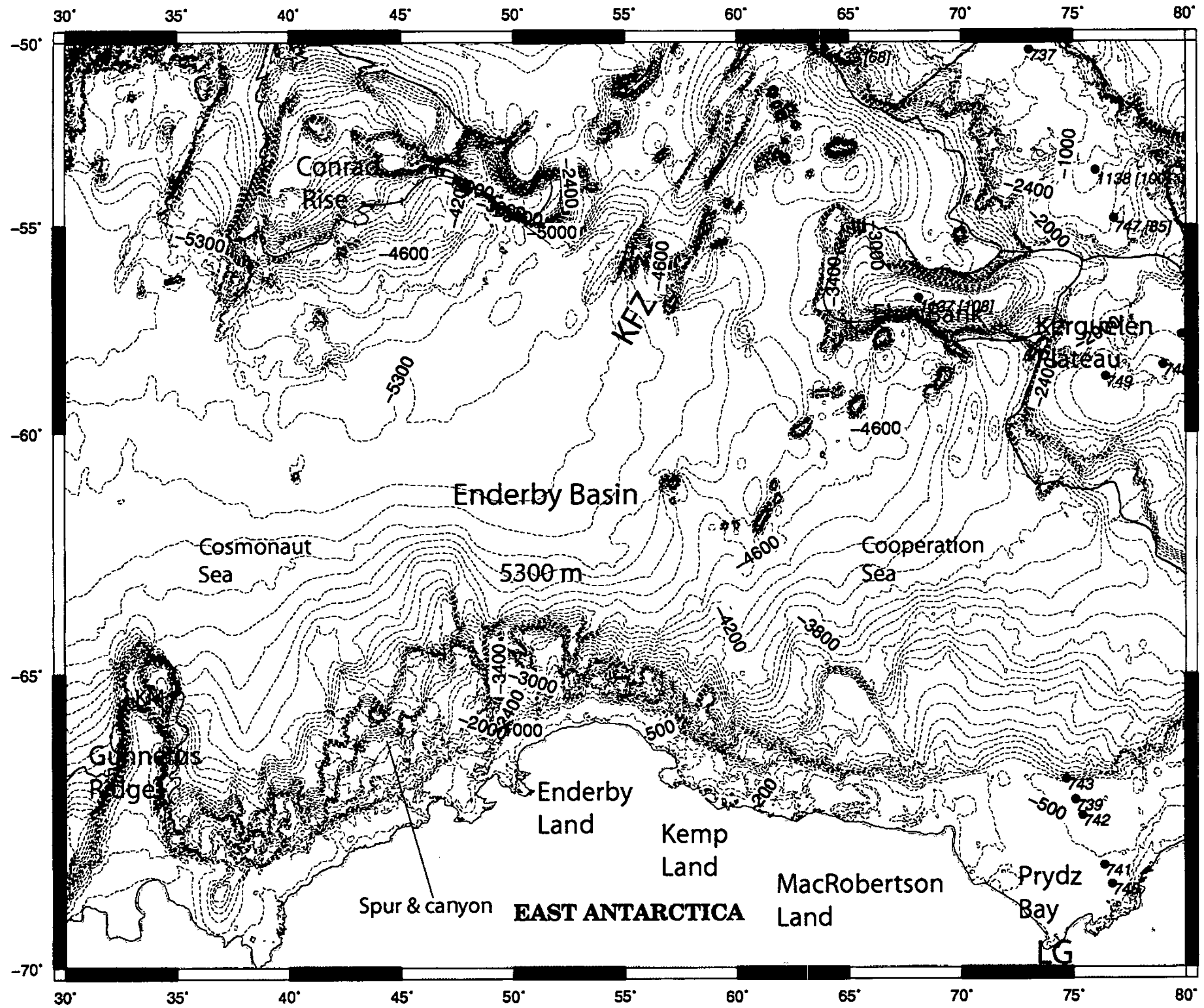


Figure 4-15 Detailed physiography of the Enderby Basin derived from GEBCO. Contour interval is variable. Northern Enderby Basin is associated with uneven topography belonging to the Kerguelen Plateau, Conrad Rise and Kerguelen Fracture zone (KFZ). Spur and canyon topography is seen along the continental margin. DSDP/ODP sites with its corresponding numbers are indicated as dots. LG: Lambert Graben; KM: Kainan Maru Seamount

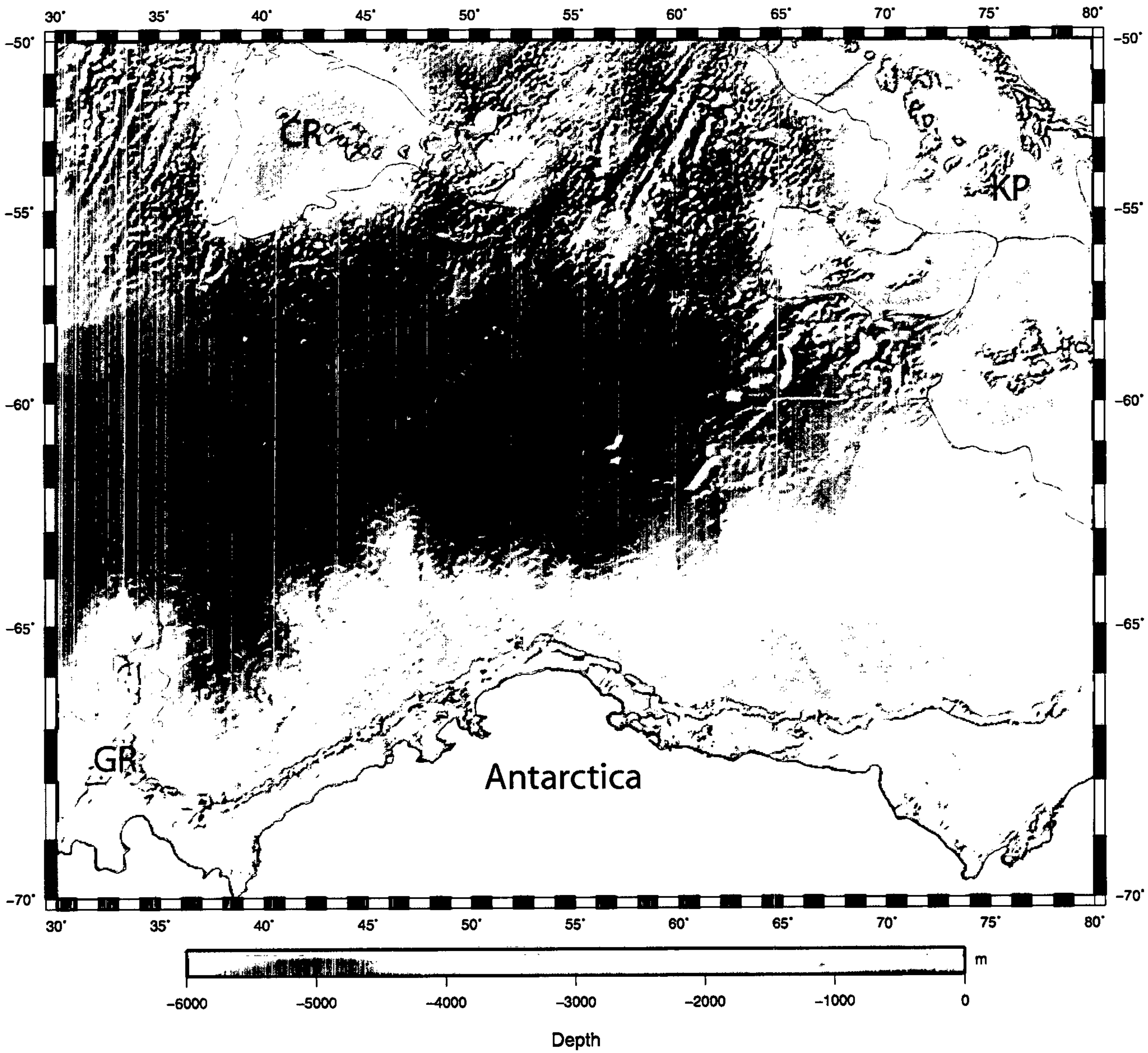


Figure 4-16 Predicted topography of the Enderby Basin (Sandwell and McAdoo, 1988). GR: Gunnerus Ridge; KP: Kerguelen Plateau; CR: Conrad Rise

### 4.2.1 Physiography

The Enderby Basin is characterized by complex topography as evidenced from the distribution of bathymetry contours (Fig. 4-15). The geomorphology/seabed topography of the East Antarctica continental margin is influenced by prolonged glaciation, which affected the depositional processes and shaped the seafloor. The average depth of the continental shelf is 500 m, eight times higher than the world average (Johnson et al., 1982). In general, the shelf is characterized by rugged topography. The continental margin has been divided into the eastern and western sectors based on the physiographic characteristics observed on its shelf, slope and rise.

The continental margin west of 60°E longitude has a narrow continental shelf (30-70 km wide) and is associated with several trough like features, which appear to extend from the present ice margin to the shelf edge. The 500-1000 m deep shelf edge is markedly sinuous, with bulges developing at the mouth of some of the troughs. The continental slope is dominated by spur and canyon topography for about 150-250 km oceanwards from the shelf edge. The gradient of the slope varies from ~10° in the western part near the Gunnerus Ridge to about 4° towards east. The foot of the slope occurs in water depths of ~2000 m. The upper rise topography is highly irregular and dominated by large canyons flanked by distinct sediment ridges. This irregular topography extends upto 4000 m, beyond which the seabed is relatively smooth (Fig. 4-16).

The continental margin east of 60°E longitude has a shelf of highly variable width (Fig. 4-15). It is <100 km off MacRobertson Land. Further east, i.e. in the Prydz Bay, the shelf width varies between >280 km in the central bay and ~180 km to its east. The major controlling factor of the margin morphology is the Lambert Glacier, the largest outlet ice stream of East Antarctica, which discharges through Prydz Bay (O'Brien, 1994). The Prydz Bay has a deep inner shelf (600-800 m) with shallow outer shelf banks (<200 m deep), i.e. the Four Ladies Bank in the eastern bay and Fram Bank in the western bay. The upper continental slope is steep down to about 3000 m water depths, while in the center the slope is more gentle (Stagg, 1985; Cooper et al., 1991).

Beyond the continental rise, the bathymetry is less undulatory (Fig. 4-15) except for the positive topography of the Conrad Rise and Kerguelen Plateau. Bathymetry is less than 5000 m in the eastern Enderby Basin south of Kerguelen Plateau, while it is the deepest (~5500 m) towards northwest. The northwestern Enderby Basin is characterized by the positive topography of the approximately WNW-ESE trending Conrad Rise consisting of the Ob, Lena and Marion Dufresne seamounts (Fig. 4-16). The Ob and Lena seamounts rise to ~250 m from the surrounding water depth of 4500 m. The Marion Dufresne seamount consists of two separate bathymetric highs, the summits of which culminate around 1300 m and 970 m below sealevel (Schlich, 1982). North of this seamount chain, the Crozet Basin is relatively shallower (~4500 m). East of the Conrad Rise, NE-SW trending narrow band of irregular topography belonging to the Kerguelen Fracture Zone is seen (Fig. 4-16).

The Gunnerus Ridge protruding from the western Enderby shelf region rises to <1000 m from the surrounding water depth of ~4500 m. It is bounded by steep slopes towards the east and west (Fig. 4-16). North of the Gunnerus Ridge, an oval shaped topography about 60 km wide and 120 km long is seen (Fig. 4-15). This topography belongs to the Kainan Maru seamount, which rises ~3500 m above the surrounding seafloor and has a gently sloping summit.

The northeastern Enderby Basin is characterized with complex positive topography of the Kerguelen Plateau (Fig. 4-15) wherein the bathymetry rises by ~1000-3500 m above the adjacent seafloor (Schlich et al., 1987). The northeastern flank of the plateau is extremely steep and linear (Rotstein et al., 1992). The southwestern flank of the plateau is much more complicated but shows a gentle slope, especially towards the south (Fig. 4-17).

The SKP is characterized with low relief topography averaging 1500-2000 m below the sealevel. It can be divided into several major morphological units, the most distinct one being the Banzare Bank. This bank is an E-W trending bathymetric feature (<1000 m) with a basement high (Houtz et al., 1977). To its east lies the Raggatt Basin, which is the largest sedimentary basin perched on the SKP. The CKP lies in water depths of <1000 to 2000 m (Fig. 4-17). The CKP is

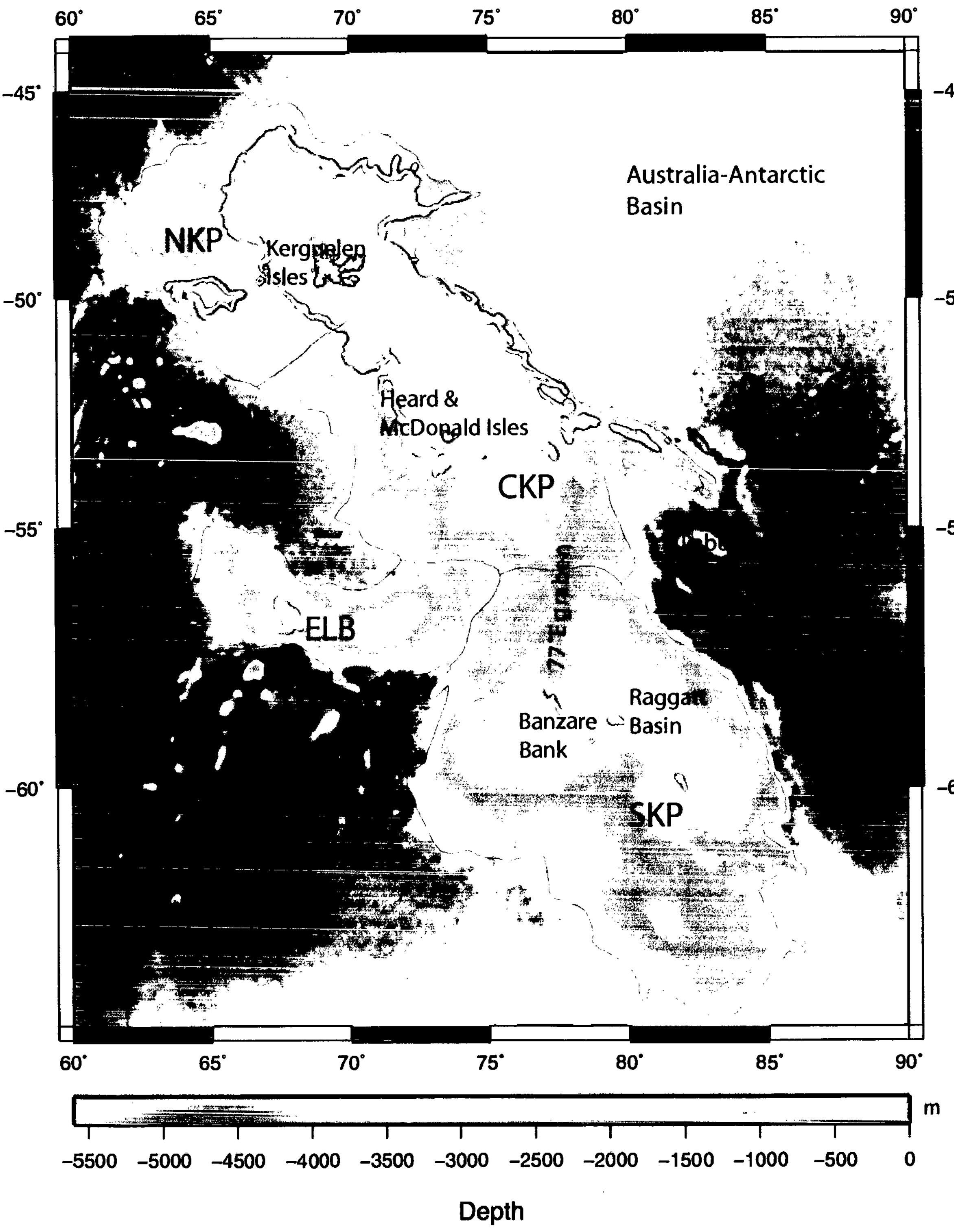


Figure 4-17 Predicted topography of the Kerguelen Plateau (Sandwell and McAdoo, 1988). ELB: Elan Bank; NKP: Northern Kerguelen Plateau; CKP: Central Kerguelen Plateau; SKP: Southern Kerguelen Plateau

characterized with two large rift zones associated with the 75° and 77°E grabens (Houtz et al., 1977). The 77°E Graben extends from the eastern flank of the plateau to the Banzare Bank for about 800 km (Munschy and Schlich, 1987). The NKP lies in average water depths of ~500 m and includes the Kerguelen Archipelago, and the Heard and McDonald Islands which are young, islolated volcanoes situated 500 km southeast of the archipelago (Fig. 4-17). A transition zone between the SKP and CKP from 54 to 58°S latitudes exhibits complex topography extending westward for about 600 km. This positive topography feature rises to <1000 m from the surrounding water depth of ~4500 m and belongs to the Elan Bank. The bank is characterized with a steep slope towards the south and fairly gentle slope towards north (Fig. 4-18).

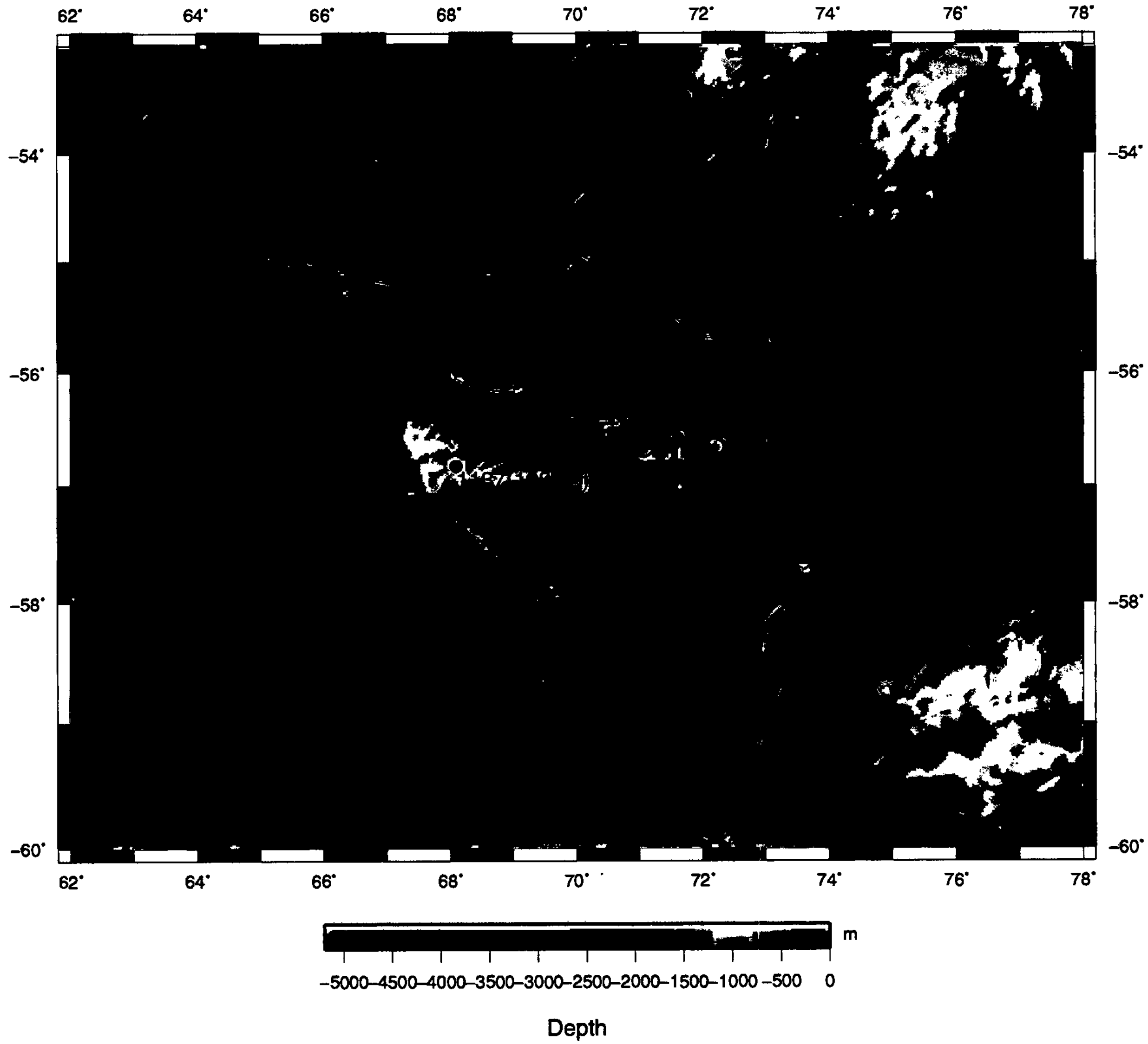


Figure 4-18 Predicted topography of and around the Elan Bank (Sandwell and McAdoo, 1988). ODP Drill site1137 location and age is indicated

# Chapter 5

# *Magnetics*

Magnetic anomalies provide important constraints in understanding the structure, tectonic framework, basement configuration and evolution of continental margins and ocean basins since the continental/oceanic rocks preserve the magnetization acquired during their formation. Once the continental margins are formed, new ocean basins grow in time and space due to seafloor spreading processes. Magnetic anomalies associated with these ocean basins are generally known as seafloor spreading type magnetic anomalies. Based on the characteristic magnetic anomaly pattern, the seafloor spreading anomalies can be identified and assigned ages using model studies, and thereby a complete evolutionary history of the ocean can be discerned.

According to the classical plate tectonic theory, new oceanic crust is generated discretely at the mid-oceanic ridges (MOR) and as the crust cools below the Curie point it gets magnetized in the direction of the prevailing Earth's magnetic field. Based on spreading rates (symmetric/asymmetric) and rate of magma outpouring, this crust pushes the already solidified old oceanic crust on either side and away from the axis of the MOR. The age and depth of the oceanic crust thus pushed increases as it moves away from the ridge axis. Parsons and Sclater (1977) have shown that the mean depth of the MOR is around 2500±300 m, and the MOR system subsides to 3000 m at ~2 m.y., 4000 m at ~20 m.y. and 5000 m at ~50 m.y. age. When a magnetic survey is conducted over an oceanic region, the observed magnetic anomaly depends on several parameters. Of these, the primary ones are the latitude of formation; the present day position; orientation of the source rock/body; direction of magnetization; magnetic susceptibility and remanence of the crust. Seafloor spreading magnetic anomalies exhibit characteristic shapes based on the factors mentioned above and are the manifestation of the reversals in the polarity of the earth's magnetic field, as hypothesized by Vine and Mathews (1963). These anomalies can be identified and proper formation ages can be assigned without much confusion using the geomagnetic polarity time scales.

## 5.1 Geomagnetic polarity time scales

Analysis of volcanic rocks revealed that some rocks are magnetized in a direction opposite to the present day earth's magnetic field, indicating that the earth's magnetic field may have reversed in the past. During the 1950s and 1960s, magnetic surveys across the oceans revealed patterns of regular and continuous stripes of alternating magnetic polarity, which were observed in all the oceans. These patterns of magnetic anomalies allow an estimation of the timing of creation of ocean floor. Paleomagnetic studies further indicated that the earth's magnetic field has reversed its polarity several times in the geological past and the rate of reversal varies randomly. During some periods of geologic time, the reversal rates occur very rapidly, even more than one reversal in a short span of 50,000 years. While at times, the Earth's magnetic field maintains a single orientation and does not depict much variation for several million years. These periods are termed magnetic quiet zones and are characterized by a smooth geomagnetic field with low amplitudes.

The Mesozoic era is associated with two long episodes wherein the geomagnetic field was fairly quiet and largely positive. The older one, i.e. the Jurassic Quiet Zone (M40 to M28; 165-155 Ma) and the later one, the Cretaceous Magnetic Quiet Zone (M0 to 34; 120-84 Ma) are considered as normal polarity superchrons. Roots and Srivatsava (1974) suggested several mechanisms for the occurrence of such quiet zones. These mechanisms include: i) period of non-reversal of the earth's magnetic field, ii) magnetization of the seafloor close to the magnetic equator, iii) very slow spreading, and/or iv) oblique spreading direction resulting in fragmentation of the ridge into short spreading segments.

The timings of the magnetic polarity reversals have been converted into a geomagnetic polarity time scale. Several geomagnetic polarity time scales have been generated and their accuracy has increased in recent times. These time scales have been generated for the Cenozoic and Mesozoic eras. The first marine magnetic anomaly based time scale was constructed by Heirtzler et al., (1968). The more recent Cenozoic time scales are that of Berggren et al., (1995) and Cande and Kent (1992; 1995). In these time scales, magnetic anomalies have been assigned anomaly numbers that increase with increasing age. The present-day magnetic anomaly is referred as '1n', where n corresponds to a normal chron. The last reversal was the Brunhes-Matuyama reversal approximately 780,000 years ago and termed '1r'. Within the chron '1n', many short term reversals termed events such as Jaramillo, Gilbert, etc. have taken place. The oldest crust (~65 m.y. old) belonging to the Cenozoic era bears anomaly number 29. The Late Cretaceous crust of age 84-65 Ma has been assigned magnetic anomaly numbers 34 to 30. The Cretaceous Magnetic Quiet Zone or KT Superchron occurs between120 and 84 Ma, i.e. between the anomaly 34 and the youngest Mesozoic magnetic anomaly M0. The Mesozoic time scales include those generated by Kent and Gradstein (1985); Gradstein et al., (1994); Channell et al., (1995) and Ogg (1995). The anomalies of the Mesozoic sequence are numbered with a prefix 'M' and range from M40 to M0 (165-120 Ma).

The geomagnetic polarity time scales have also been extended beyond the Mesozoic into the Paleozoic era (Ogg, 1995). Short-term variations in the geomagnetic field with polarity intervals of <10 Kyr have also been reported all around the world oceans. These are termed as cryptochrons and form tiny wiggles in the observed magnetic anomaly pattern (Bouligand et al., 2006). The geomagnetic time scales have been validated with geological data using isotope geochronology and geomathematics. These time scales are in extensive use while generating the synthetic seafloor spreading models, which facilitate in identification of the magnetic anomalies, in turn inferring the age of the crust and the seafloor spreading rate and direction. Paleogeographic reconstructions for the past can be achieved using the magnetic anomalies and time scales.

## 5.2 Mesozoic magnetic anomalies

The oceanic crust world over is not more than 200 m.y. old. The oldest magnetic anomaly identified so far is M40 (165 Ma) belonging to the Mesozoic era in the Central Atlantic Ocean (Bird et al., 2008). The youngest Mesozoic magnetic anomaly M0 corresponds to oceanic crust of 120 m.y. age. The Mesozoic anomalies M25 to M0 belong to the Early Cretaceous period, while the older sequence of Mesozoic anomalies (M26 to M40) belong to the Late Jurassic period. Since the present day continental configuration has evolved during the Mesozoic period, one can expect the oceanic crust characterized by Mesozoic magnetic anomalies to occur off the continental margins. Identification of these anomalies in general is difficult since the ocean floor has subsided to great depths and is overlain by thick sediment overburden. Most of these anomalies therefore, are subdued in nature. Also, since these anomalies were formed soon after continental breakup, they are usually characterized by slow spreading rates. These slow spreading rates may be another reason for the low amplitude of the magnetic anomalies. Conjugate Mesozoic crusts may be separated by thousands of kilometers (e.g. Mozambique Basin, off Africa and Dronning Maud Land, off Antarctica) and correlation of the corresponding magnetic anomalies is a difficult task. Nonetheless, some of these anomalies can be easily identified by their characteristic shapes. For example, Mesozoic anomaly M11 has a 'W' shape, while M8 is comprised of two positive peaks and M4 is a large positive anomaly in the southern hemisphere. These typical signatures were observed by Bergh (1977) while interpreting the magnetic anomalies off Dronning Maud Land, Antarctica. The magnetic anomalies generated during the Jurassic and Middle Cretaceous Long Normal polarity superchrons are weak and difficult to correlate. These low amplitude magnetic anomalies are characterized with rapid field fluctuations, which could be due to intensity or polarity changes (Tivey et al., 2006).

Presence of Mesozoic magnetic anomalies has been reported by several researchers in different ocean basins. Some examples are: i) Mesozoic magnetic anomalies M11 through M2 in the South Atlantic (Larson and Ladd, 1973), ii) off Western Australia (Larson, 1975; 1977), iii) off Northwest Africa (Hayes and Rabinowitz, 1975), iv) off Dronning Maud Land, Antarctica (Bergh, 1977) and v) Northern Mozambique Basin (Simpson et al., 1979). Further, Mesozoic crust represented by anomalies M4 through M0 has been inferred in the North Atlantic (Rohr and Twigt, 1980), and M12 through M0 in the southern Natal valley with HSR of 1.5 cm/yr (Goodlad et al., 1982). Ramana et al., (1994b[1]; 2001a[2]) inferred the presence of Mesozoic magnetic anomaly sequence M11 through M0 in the Bay of Bengal and its conjugate, the Enderby Basin. Fullerton et al., (1989) described the Late Jurassic to Early Cretaceous evolution of northwest Australia. Off Western Australia, magnetic anomalies M14 through M0 have been observed In the Cuvier

[1] *Ramana, M. V., Nair, R. R., Sarma, K. V. L. N. S., Ramprasad, T. Krishna, K. S., Subrahmanyam, V., D'Cruz, M., Subrahmanyam, C., Paul, J., Subrahmanyam, A. S. and Chandrasekhar, D. V., 1994b. Mesozoic anomalies in the Bay of Bengal, Earth Planet. Sci. Lett.* ***121****: 469-475.*

[2] *Ramana, M. V., Ramprasad, T. and Desa, M., 2001a. Seafloor spreading magnetic anomalies in the Enderby basin, East Antarctica, Earth Planet. Sci. Lett.,* ***191****: 241-255.*

Abyssal Plain, while younger anomalies M9 through M0 have been inferred in the Perth Abyssal Plain (Muller et al., 2000). Some examples of Mesozoic magnetic anomaly sequences in different ocean basins have been shown in figure 5-1.

## 5.3 Synthetic modeling results

In the present study, the magnetic anomalies have been identified using the seafloor spreading modeling technique. The geomagnetic polarity time scale of Gradstein et al., (1994) has been adopted to generate the synthetic magnetic anomaly model. Previous studies suggest that the Bay of Bengal is characterized by Mesozoic magnetic anomalies M11 through M0 (Ramana et al., 1994b) therefore similar model parameters have been used to generate the synthetic model. The models have been generated by assuming uniformly magnetized blocks of oceanic crust with an average thickness of 500 m and a remnant magnetization of 0.008 A/m. The best-fit models have been obtained with the paleo-spreading center in the vicinity of 50°S latitude.

### 5.3.1 Bay of Bengal

The magnetic data used in the present study in the Bay of Bengal have been collected during the cruises of ORV Sagar Kanya along tracks oriented in the N60°W direction (Table 1; Fig. 3-1). A few N-S lines are used to tie the data for quality control. Magnetic data extracted from the NGDC, Colorado, have been

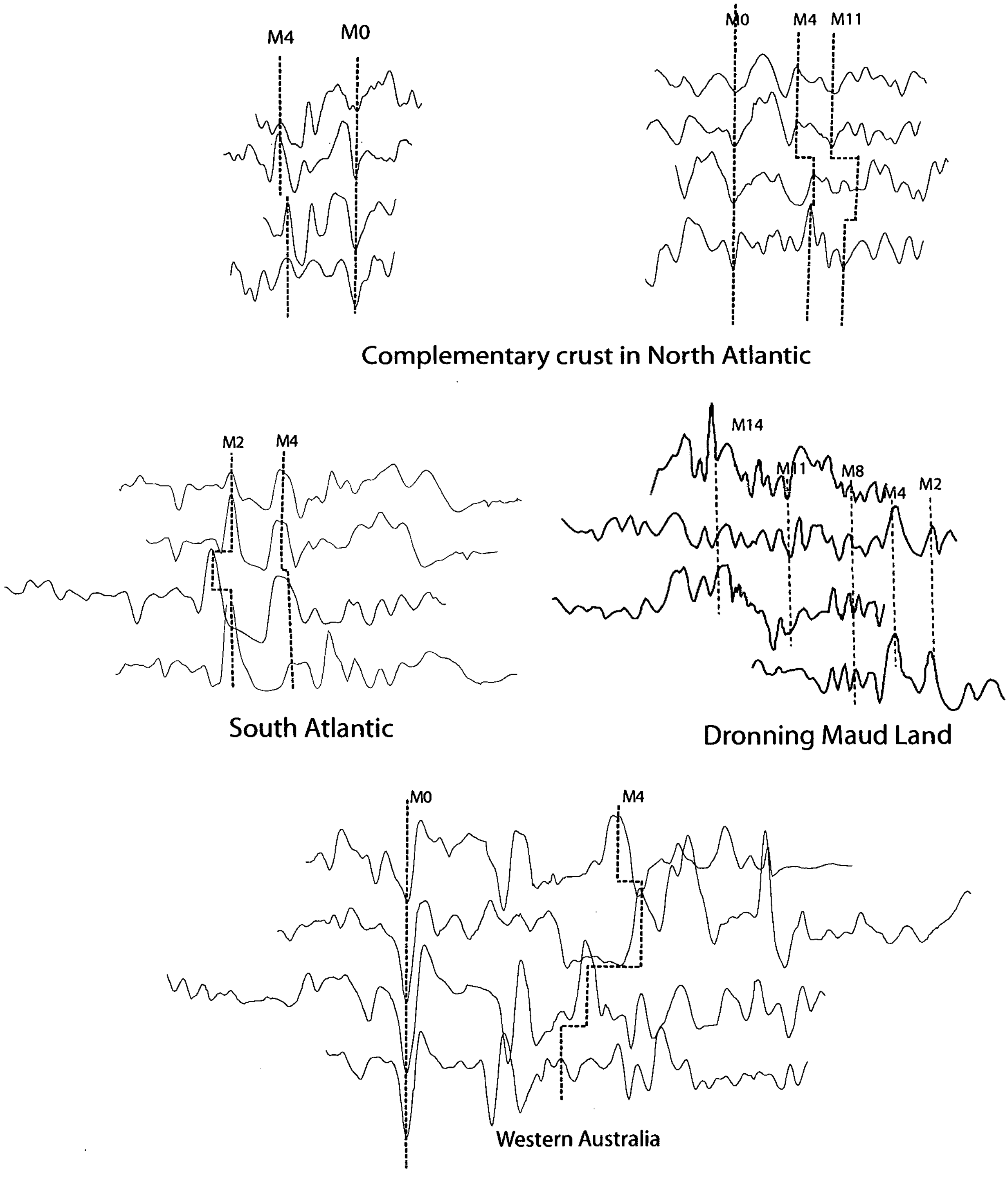


Figure 5-1 Examples of Mesozoic magnetic anomalies corresponding to Early Cretaceous crust in different ocean basins. Identified magnetic anomalies are numbered and indicated as dashed lines (Data source: NGDC; Royer et al., 1989)

included to increase the data density. An attempt has been made to interpret the magnetic data in the best possible way. Only the close grid data collected during the cruises SK72 and SK82 in the Central Bay of Bengal have been used for the magnetic model studies, since further north, the magnetic tracks of cruise SK100 are widely spaced.

The magnetic anomalies are in general subdued with amplitudes of <200 nT throughout the study area (Fig. 5-2). These magnetic anomalies are characterized with broad wavelength in the western and central basins. Towards the east, high frequency magnetic anomalies are seen along the 90°E meridian. Along the 85°E meridian, relatively high amplitude (upto 400 nT) magnetic anomalies are seen. The continental margin is characterized by alternate positive and negative magnetic anomalies (Fig. 2-4). However, the near shore areas are associated with high frequency large amplitude anomalies particularly around Chilka Lake.

The synthetic seafloor spreading model and the profile to profile anomaly correlation in the Bay of Bengal are shown in figure 5-3. Magnetic anomaly M11 has been identified with its typical 'W" shape on most of the profiles. Anomaly M10n follows M11 as a low towards the younger side of M11. Anomaly M8 is conspicuous as a broad positive anomaly with double peaks. Anomaly M4 also a broad positive anomaly has been identified on most of the profiles. The younger anomalies M2 and M0 are tentatively identified towards the far end of the profiles. All the profiles cross the subsurface 85°E Ridge obliquely and hence contain the

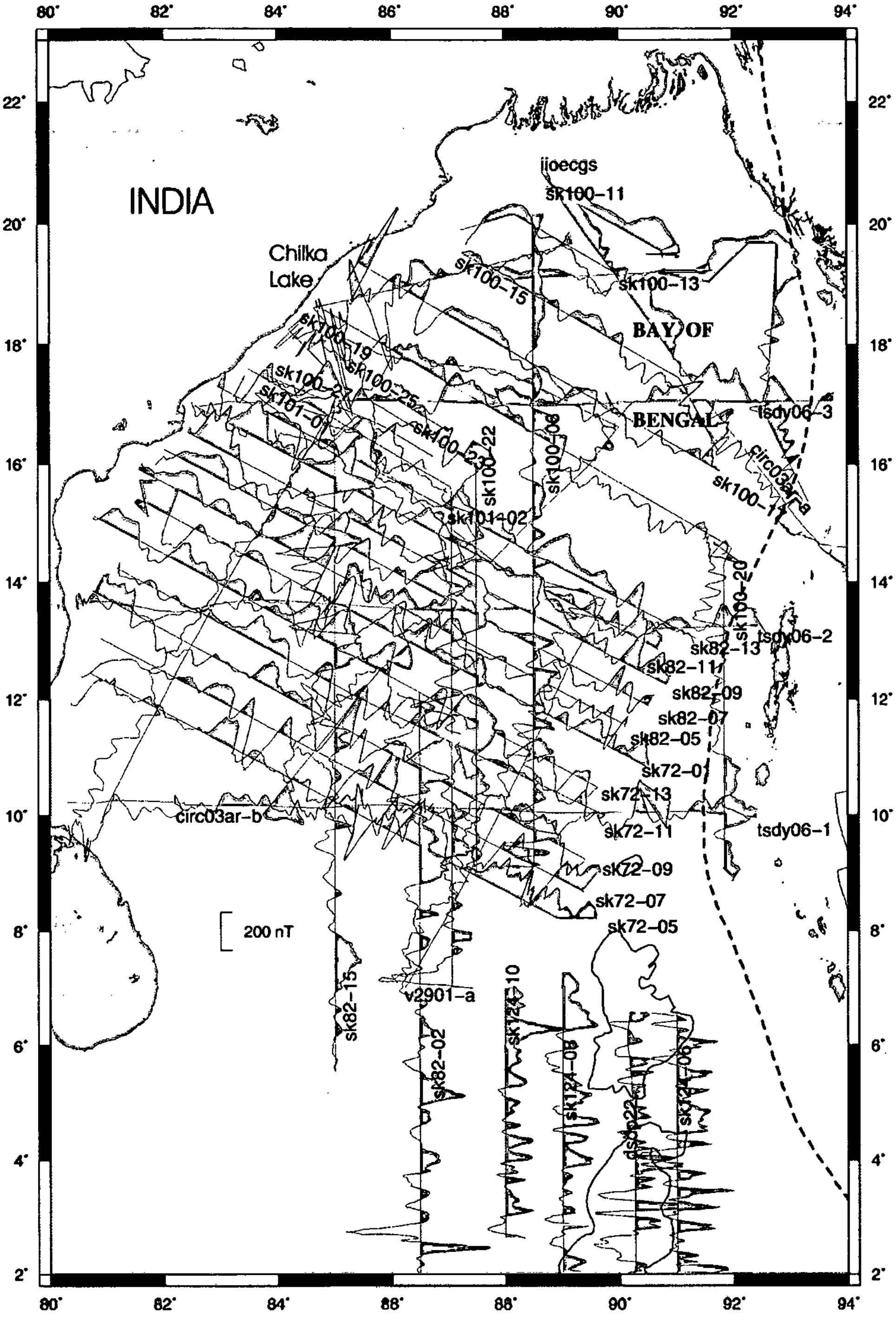


Figure 5-2 Magnetic anomalies plotted perpendicular to the cruise tracks in the Bay of Bengal. Positive anomalies are shaded gray. Dashed black curve depicts the Sunda Trough, while the blue curves belong to the volcanic outcrops of the Ninetyeast Ridge.

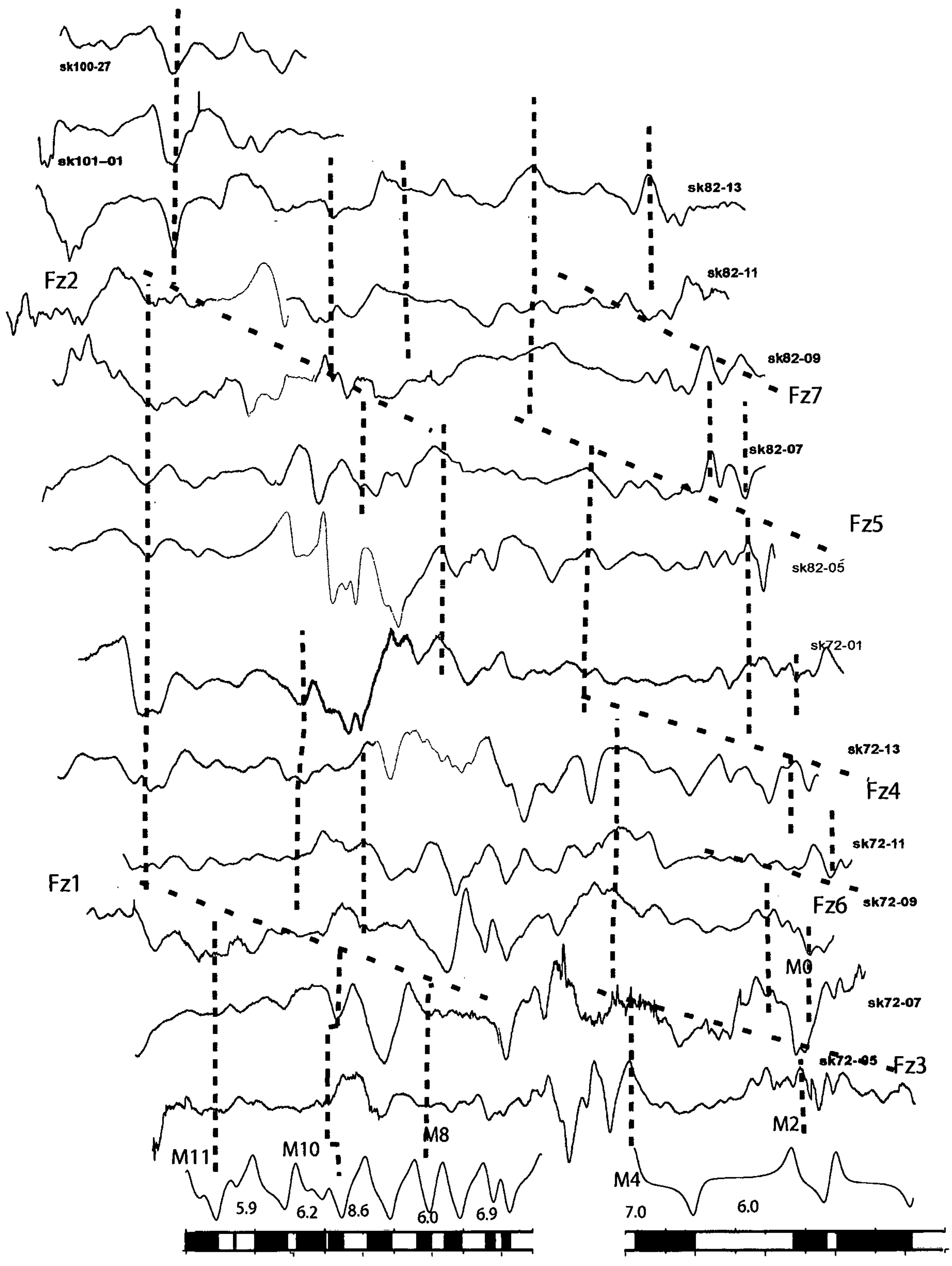


Figure 5-3 Magnetic profiles in the Central Bay of Bengal stacked along with the synthetic seafloor spreading model. Magnetic anomalies are identified with dashed lines of various colors. The extent of the 85°E Ridge inferred using satellite gravity is shaded in cream. HSRs are indicated in cm/yr. Dashed black lines indicate fracture zones inferred from the offsets in the magnetic anomalies.

magnetic signature of the ridge. Model studies suggest that the crust has evolved with half-spreading rates ranging from 5.9 to 8.6 cm/yr since breakup.

The identified magnetic anomaly isochrons have been plotted along the tracks to map the spatial distribution of the Early Cretaceous crust in the Bay of Bengal. The magnetic anomaly M11 occurs close to the east coast of India between 12 and 18°N latitudes (Fig. 5-4). This anomaly M11 is followed by the younger sequence of anomalies M10n through M8. The anomalies are seen offset at two locations. The offset is left lateral towards south, while, it is right lateral in the north. The disposition of successive magnetic anomalies indicates the presence of fracture zones. These fracture zones are designated as Fz1 and Fz2 in the present study. The orientation of these fracture zones has been constrained using the satellite derived free-air gravity mosaic (Fig. 2-7). The subsurface 85°E Ridge whose boundary is constrained using the satellite derived free-air gravity mosaic is associated with high amplitude magnetic anomalies, which have probably altered the original seafloor spreading signature and caused disposition of the magnetic anomalies M10 and M8. Between fracture zones Fz1 and Fz2, the ridge extent has right laterally offset these anomalies. The younger anomalies M4 to M0 occur east of the 85°E Ridge and are offset left laterally throughout the region. Based on the offsets between the anomalies, approximately NW-SE trending fracture zones (Fz3 to Fz7) have been inferred in this region. The distribution of Mesozoic magnetic anomalies M11 through M0 in the Central Bay of Bengal suggests the Early Cretaceous crust has evolved in a ~NW-SE direction (Fig. 5-4).

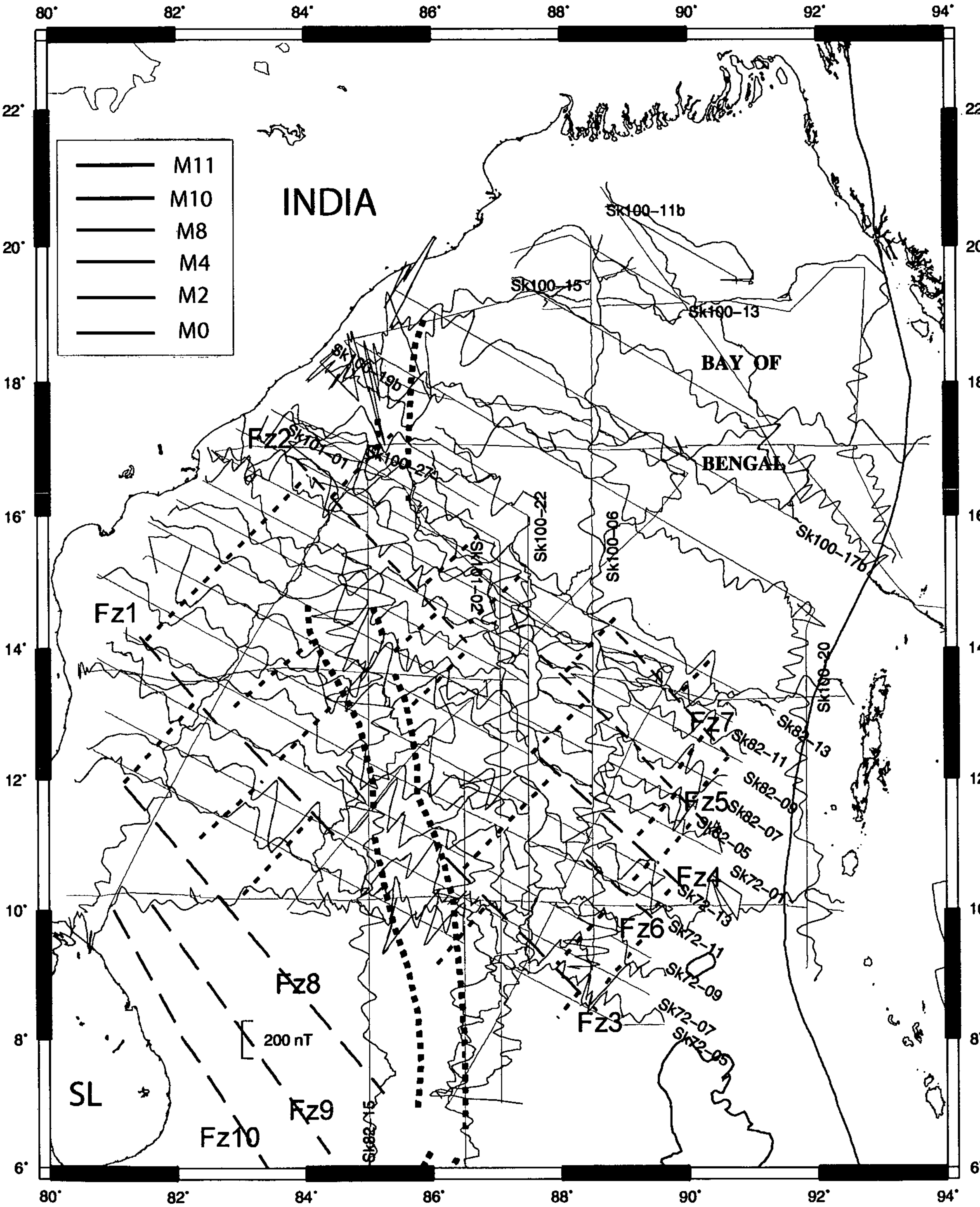


Figure 5-4 Map depicting the locations of the identified magnetic anomalies (color as per legend) in the Bay of Bengal. Fracture zones are numbered and indicated as thin black dashed lines. The extent of the 85°E Ridge inferred using satellite gravity is shown by thick black dashed lines. Green curve depicts the Sunda Trough, while the blue curves belong to the volcanic outcrops of the Ninetyeast Ridge

### 5.3.2 Enderby Basin

Magnetic data have been studied in the Enderby Basin, East Antarctica to confirm the identifications in the Bay of Bengal and understand the conjugate nature of both the basins. The magnetic data used in the Enderby Basin have been extracted from the NGDC, Colorado and shown in table 2. The cruise tracks bear various azimuths and the distribution of data is relatively inadequate. Therefore, interpretation of this sparse dataset has some limitations. However, some of the major anomalies like M11, M8, M6 and M4 have been recognized by their typical signatures despite the variations in their amplitudes due to rugged topography. The amplitude of the magnetic anomalies vary between <200 and >600 nT. Magnetic anomalies with large amplitudes and high frequencies are seen in the northern Enderby Basin (Fig. 5-5).

Model studies have been carried out and the best fit synthetic seafloor spreading model has been generated. The profile to profile anomaly correlation and the synthetic model in the Enderby Basin is shown in figure 5-6. There is a good correlation among the major anomalies. The magnetic anomaly M11 has been identified on lines GA228-06, rc1704-d, GA228/04-rc1704-c, rc1705-b and a2093. Anomalies M10 and M8 have been identified on all the profiles fairly confidently. Anomaly M4 is a prominent positive anomaly recognized on all the profiles. Anomalies M2 and M0 are tentatively identified on some of the profiles. Model studies also suggest that the oceanic crust represented by magnetic anomalies M11

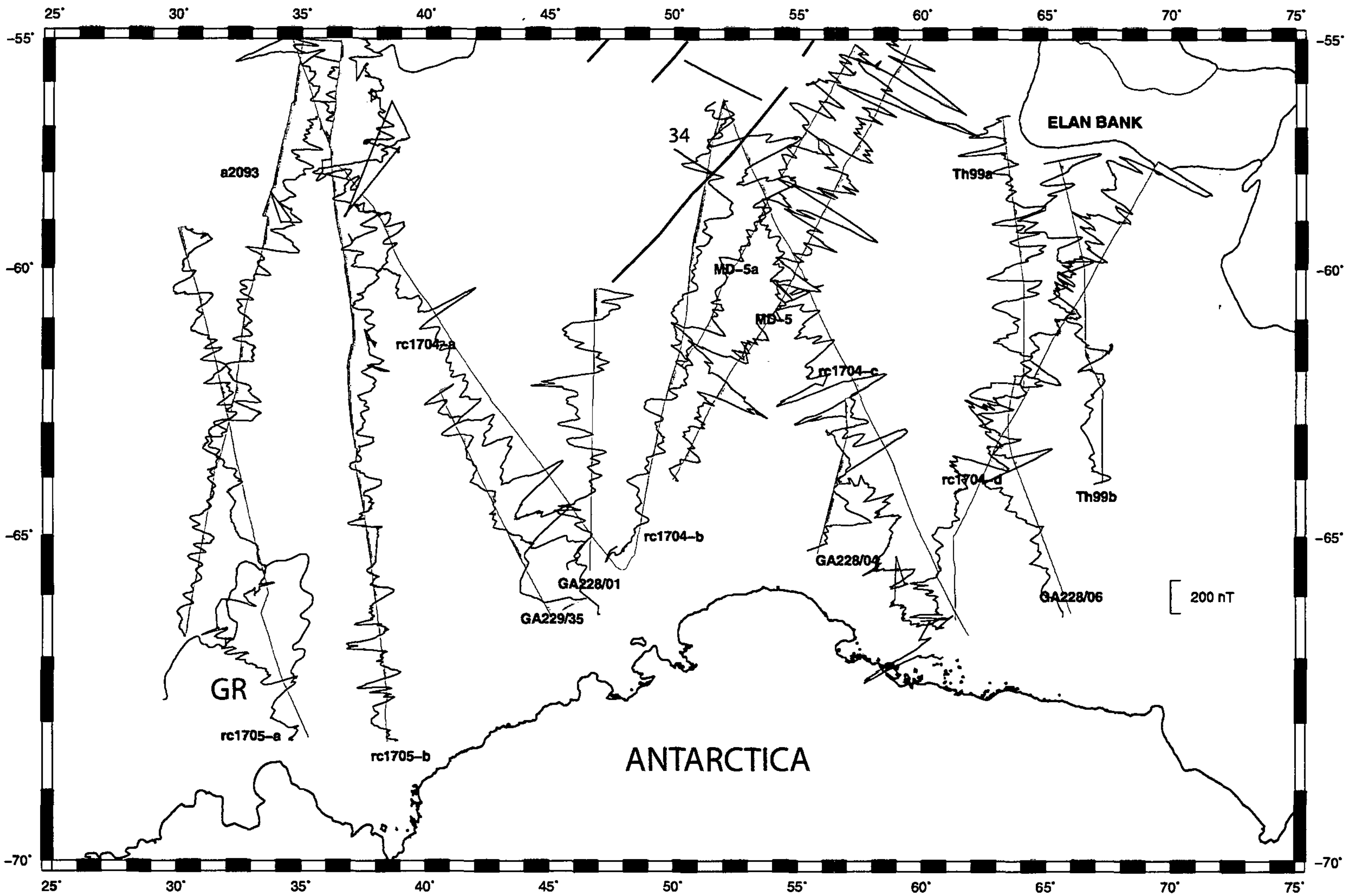


Figure 5-5 Magnetic anomalies plotted perpendicular to the cruise tracks in the Enderby Basin. Positive anomalies are shaded pink. The blue curves belong to the Large Igneous Provinces. Late Cretaceous magnetic anomalies (green line) and fracture zones (thick black line) are from Royer et al., (1989).

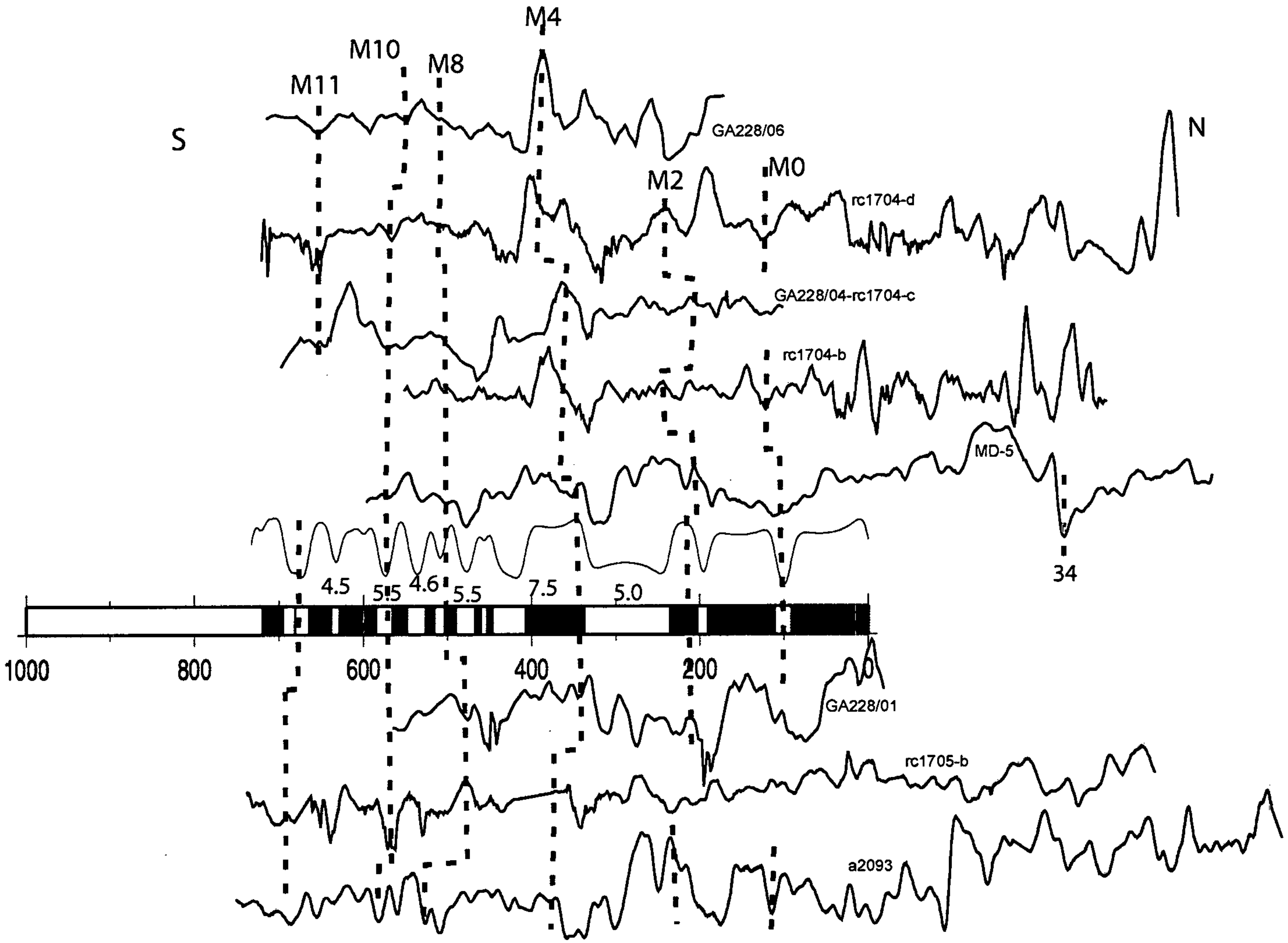


Figure 5-6 Magnetic profiles in the Enderby Basin stacked along with the synthetic seafloor spreading model. Magnetic anomalies are identified with dashed lines of various colors. HSRs are indicated in cm/yr.

through M0 has evolved with half-spreading rates varying between 4.5 and 7.5 cm/yr.

The identified magnetic anomaly isochrons were plotted along the tracks to map the spatial distribution of the Early Cretaceous crust in the Enderby Basin. As can be seen from the distribution of magnetic anomalies, the magnetic anomaly M11 occurs close to the Enderby coast (Fig. 5-7). Magnetic anomalies M10 through M0 occur further offshore in the Enderby Basin. Initially the fracture zones have been inferred from the disposition of the successive magnetic anomalies. However, the trend and location of these fracture zones have been constrained using the satellite derived free-air gravity mosaic (Fig. 2-10). West of Gunnerus Ridge, the Mesozoic magnetic anomaly sequence M11 through M0 is also seen. Figure 5-7 depicts the distribution of Mesozoic magnetic anomalies M11 through M0 in the Enderby Basin and indicates the continuous evolution of the Early Cretaceous crust in a N5-10°E direction.

## 5.4 Analytical signal results

The analytical signal technique was applied to the magnetic data in the Bay of Bengal and Enderby Basin. A sample output of this technique is shown in figure 3-6. The bell functions generated using the analytical signal technique along the lines sk72-13 and sk101-01 have been used in conjecture with multichannel seismic data to support the subsurface interpretation. The multichannel seismic section

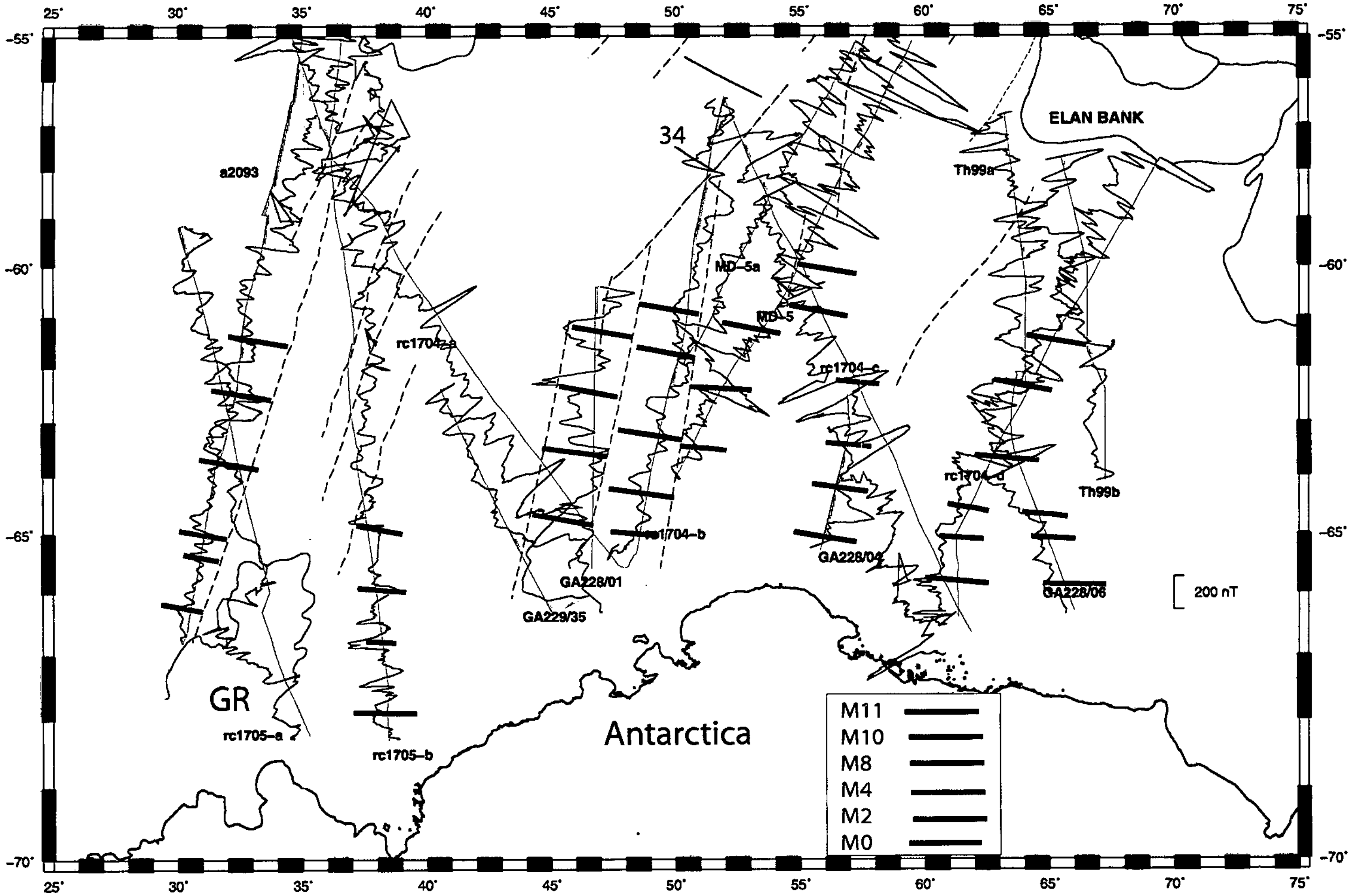


Figure 5-7 Map depicting the locations of the identified magnetic anomalies (color as per legend) in the Enderby Basin. Fracture zones whose trends are constrained using the satellite gravity mosaic are shown as thin dashed lines. Late Cretaceous magnetic anomalies are shown in green. The blue curves belong to the Large Igneous Provinces.

along the track KG-01 and the corresponding gravity, magnetic and interpreted analytical signal of profile sk72-13 are shown in figure 5-8. The gravity profile along this track shows an initial low 'A' indicating the probable seaward limit of the continental crust, and another typical low 'B' akin to the continent-ocean boundary. Analysis of the magnetic data along this track reveals that the occurrence of anomaly M11 just seawards of the inferred continent ocean boundary, which indicates that breakup of India from Antarctica, occurred prior to the formation of the magnetic anomaly M11. Seven prominent bell functions were observed along this profile, which depict the magnetic contrasts within and between the continental, transitional and oceanic crusts.

Multichannel seismic section MN-01 and the geophysical cruise track sk101-01 are coincident (Fig. 3-3). The magnetic, gravity and the corresponding bell function derived from the analytical signal method are stacked along with the seismic section to better appreciate the interrelationship of different geophysical parameters with the crustal configuration (Fig. 5-9). The gravity signature along the track shows a steep low 'A' indicating probable offshore limit of the continental crust. Two small broad lows 'B' and 'C' separated by a small high are seen on either side of the subsurface 85°E ridge.

Magnetic data analysis indicates that the continental shelf is associated with a prominent low with small undulations within the low. Further offshore, broad wavelength low amplitude magnetic anomalies prevail except for a prominent

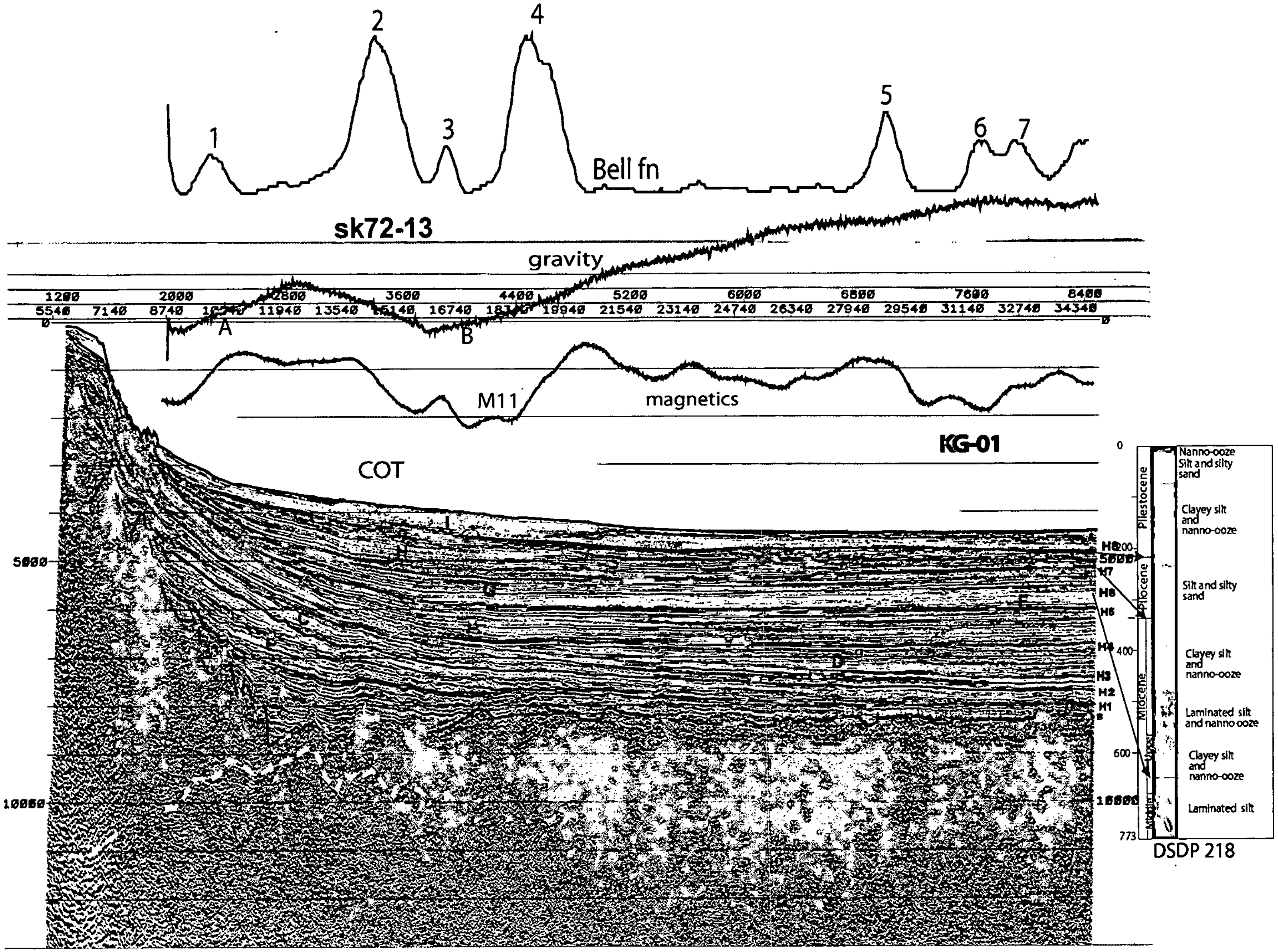


Figure 5-8 Bell functions generated using analytical signal technique along the profile sk72-13 in the Bay of Bengal superimposed on the gravity and magnetic signatures. Multichannel seismic section along coincident profile KG-01 is shown below with notations same as figure 4-10. Lithology of DSDP 218 is shown for comparison purpose.

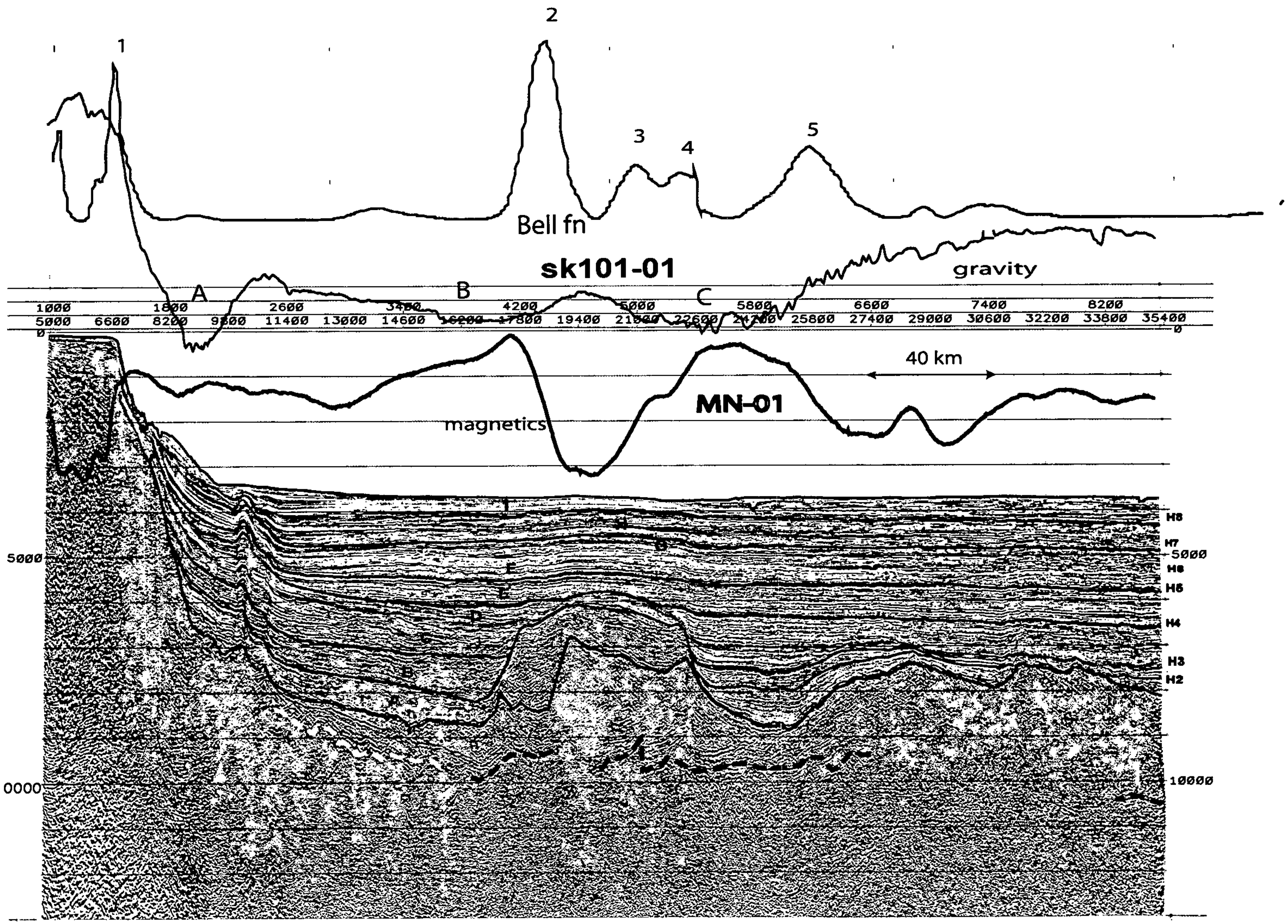


Figure 5-9 Bell functions generated using analytical signal technique along the profile sk101-01 in the Bay of Bengal superimposed on the gravity and magnetic signatures. Multichannel seismic section along coincident profile MN-01 is shown below with notations same as figure 4-11.

negative magnetic anomaly over the 85°E Ridge complex. Five significant bell functions are seen along this profile. The narrow bell function 1 is associated with the massive intrusion within the continental crust. Bell functions 2 to 4 are associated with basement and Moho undulations within the subsurface 85°E Ridge. Bell function 5 marks the termination of the deep basin after which the crust shallows significantly.

The bell functions resulting from the analytical signal technique indicate the probable locations of the edges of source rocks having appreciable magnetic contrast. The major structural boundaries such as the shelf-slope zone, continent-ocean transition zone, ridges and fracture zones have been discerned. The polarity boundaries due to seafloor spreading magnetic blocks have also been inferred along some profiles. Prominent bell functions prevail over the boundary of the 85°E Ridge. The intensity of occurrence of bell functions of variable amplitudes is attributed to complex tectonic setting/scenario in both the study areas.

## 5.5 Forward modeling results

Forward modeling has been carried out to infer the subsurface configuration along the two geophysical profiles sk72-13 and sk101-01 using sediment thickness, top of acoustic basement and Moho information from the multichannel seismic reflection profiles KG-01 and MN-01 respectively (Figs. 4-10 & 4-11). The sediment column has been divided into five layers (Q, Pl, M, OE and PC) whose thickness is constrained by the inferred seismic horizons. Variable density values and zero magnetization have been assigned to the sediments (Figs. 5-8 & 5-9). The underlying crust has been assigned susceptibility, remanent magnetization and density values based on its nature and location. The initial model thus generated has been refined by adjusting the input parameters until a best fit between the observed and calculated anomalies is obtained. The physical parameters of the various blocks inferred in the best fit models are given in table 6.

The continental crust has been divided into CC1 and CC2 having low susceptibility and densities 2.6 and 2.65 gm/cc respectively. The transitional crust is associated with dyke/mafic intrusive bodies whose density and magnetization vary significantly. Further, the oceanic crust has been subdivided into the uppermost layer 2A, the middle and lower crusts. The layer 2A with ~500 m thickness is split into several blocks of normal/reverse polarities for computing the seafloor spreading magnetic anomalies. The susceptibility of this layer is variable (0.001 to 0.01 cgs units), while the remnant magnetization ranges between 0.001 and 0.05 emu/cc with remnant inclination and declination of –67° (normal) and 310° respectively. Based on the reflection pattern on the MCS section, the thickness of the lower (LC) and middle (MC) crusts has been determined. It was found that these layers have least influence on the magnetic signature. The mantle with density 3.3 gm/cc occurs below the oceanic crust.

Profile sk72-13 and KG-01

The depth to the seabed along this profile varies between ~2 and 4.4 km (Fig. 5-10). Forward modeling indicates the presence of continental crust CC1 and CC2 that thins from 16 to 4.5 km towards offshore. The model further suggests the presence of transitional crust TC1 and TC2 with density 2.65 gm/cc and thickness around 5 km beyond the thinned continental crust. Model studies also suggest the presence of the higher density oceanic crust (2.9 gm/cc) seaward of this transitional crust. The density variation from the transitional (2.65 gm/cc) to oceanic crust (2.9 gm/cc) is reflected as a gravity low. This characteristic low represents the COB as inferred along other continental margins (Whitmarsh et al., 2001).

The continental rocks are associated with low susceptibility values ranging from 0.001 to 0.025 cgs units. These values indicate that the basement rocks are granitic in nature. The transitional crust has been assigned the susceptibility of 0.01 cgs units and remanent magnetization parameters of 0.003 to 0.005 emu/cc with inclination of –67° (normal polarity) to obtain the best fit between the observed and computed magnetic anomalies. Seaward of this transitional crust, Mesozoic magnetic anomaly M11 has been identified thereby confirming that the underlying crust is oceanic in nature. The layer 2A of ~500 m thickness comprises of alternate blocks of normal and reverse polarities, and the magnetic anomalies thus generated have been identified as the younger anomalies M10n through M9 (Fig. 5-3).

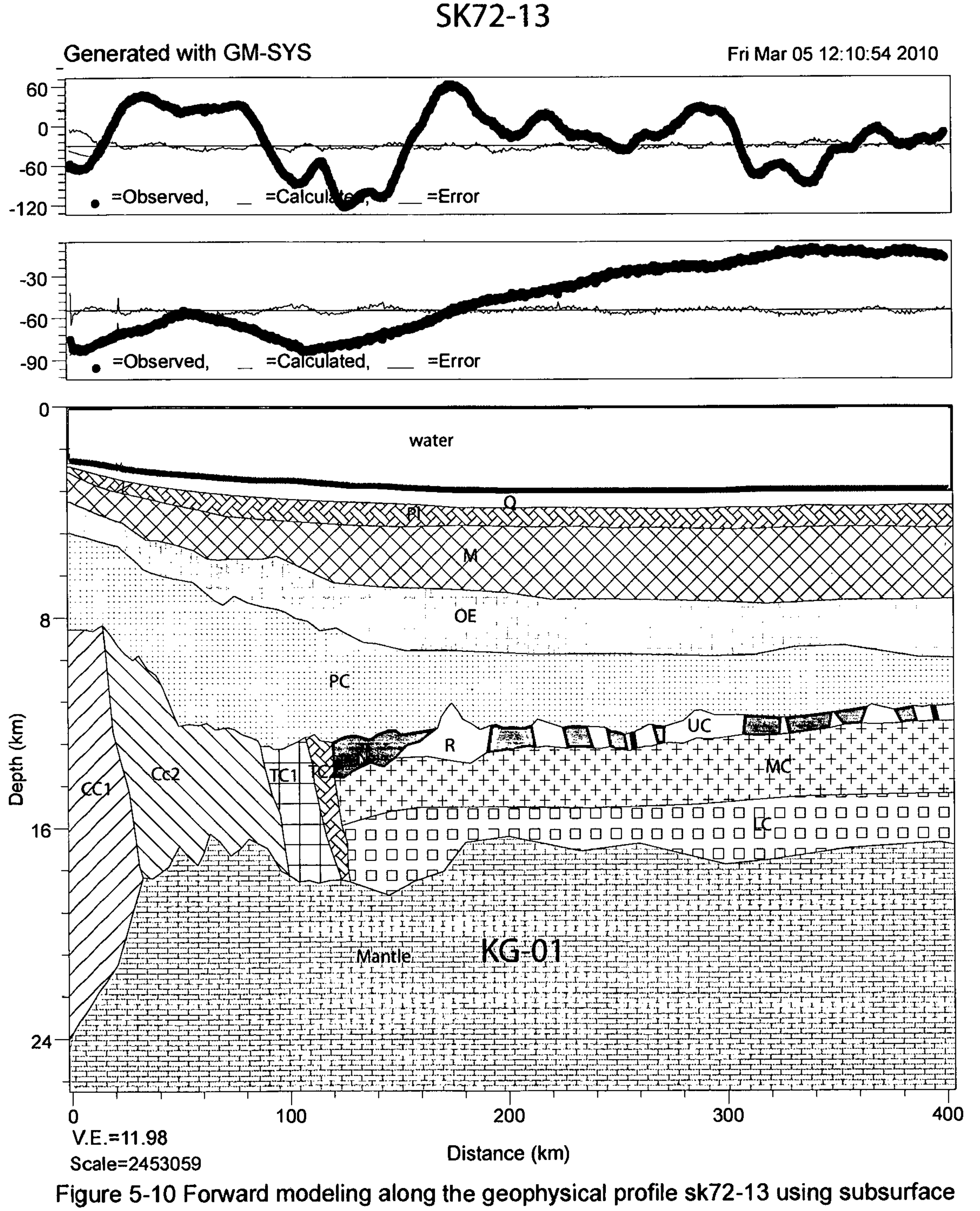


Figure 5-10 Forward modeling along the geophysical profile sk72-13 using subsurface constraints derived from the seismic section KG-01. Sedimentary column divided into 5 sequences (Q, Pl, M, OE and PC). Crust classified into continental, transitional and oceanic type. Densities and magnetic parameters of all bodies are indicated in table 6. Shaded and white zones in the upper oceanic crust denote normally and reversely magnetized crusts respectively.

Further, the model studies indicate that the oceanic crust is around 6 km thick along this profile.

Integrated model studies indicate the presence of upto 10 km thick sediments at the foot of the slope along this transect. The sediment thickness gradually decreases to ~8 km at the offshore end. An excellent fit between the observed and calculated potential field data under the constraints of multichannel seismic data prompted to infer that the model is geologically valid along this track.

Profile sk101-01 and MN-01

This profile (Fig. 5-11) runs across the shelf (<200 m water depth) to the abyssal plains (4000 m water depth). Multichannel seismic data along this profile reveals the presence of the subsurface 85°E Ridge and a thick sedimentary load. Potential field model studies reveal that the continental crust CC1 and CC2 shallows from 27 km below the shelf to ~21 km below the mid slope region. Further, the underlying crust changes its properties and shallows towards offshore. The presence of dyke intrusive like bodies (D1 to D5) having higher density values (3.1 to 3.25 gm/cc) are inferred in this zone, which constitutes the transitional crust.

Model studies suggest that the subsurface 85°E Ridge consists of low density material (2.45 gm/cc; RT) on the top. The lower portion has been subdivided into the western high density (3.1 gm/cc) block D6, the middle magmatic

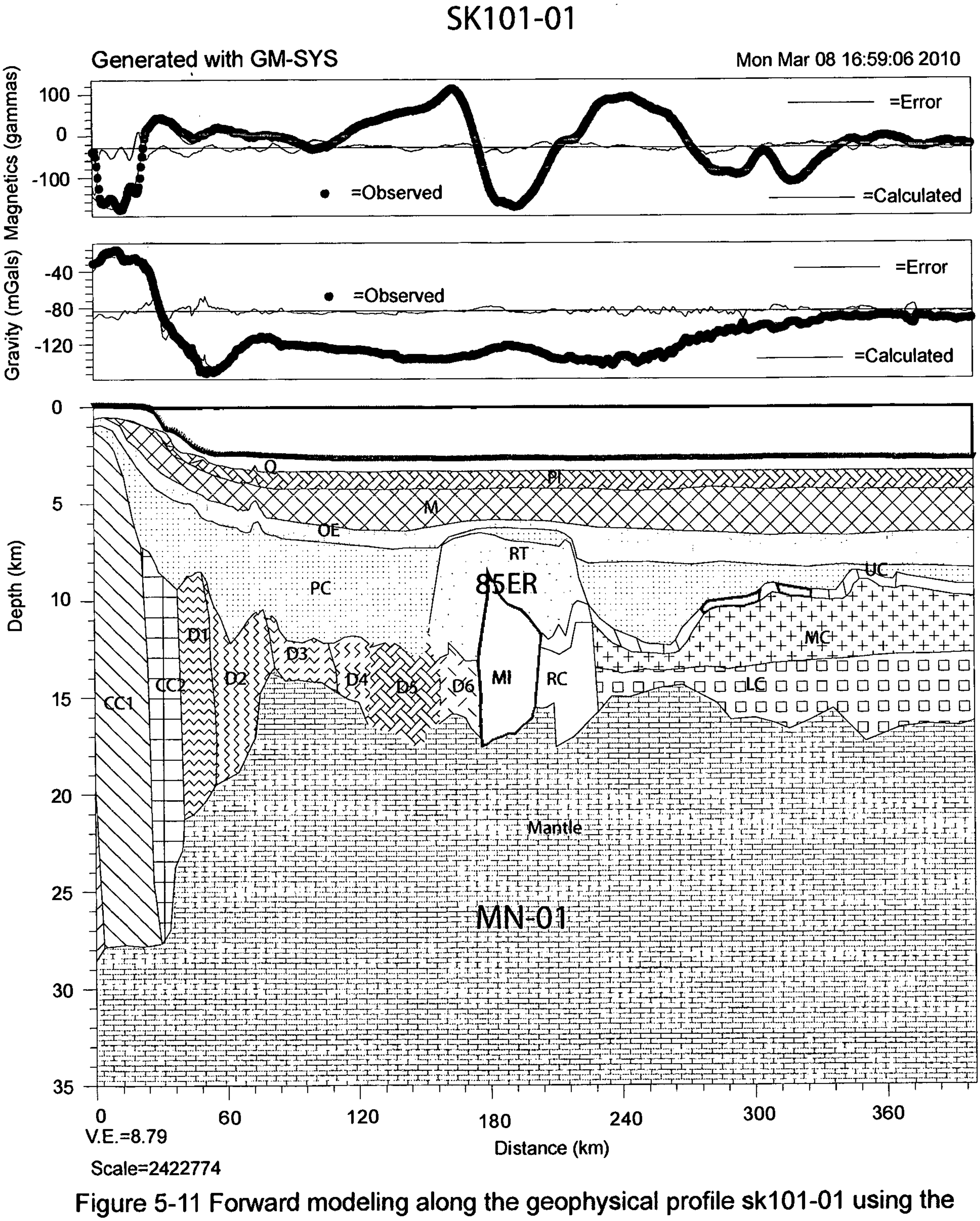


Figure 5-11 Forward modeling along the geophysical profile sk101-01 using the subsurface constraints derived from seismic profile MN-01. 85ER represents the subsurface 85°E Ridge. Further details and notations as per figure 5-10.

Table 6: Forward modeling parameters of various blocks

| Body | $V_p$ km/s | Density gm/cc | Polarity | Magnetisation emu/cc | Susceptibility cgs units |
|---|---|---|---|---|---|
| water | 1.5 | 1.03 | | | |
| Q | 1.8 | 1.6 | - | - | - |
| PI | 2.2 | 2.0 | - | - | - |
| M | 2.8 | 2.1 | - | - | - |
| OE | 4.0 | 2.2 | - | - | - |
| PC | 5.0 | 2.4 | - | - | - |
| CC1 | 6.0 | 2.6 | - | - | 0.001 |
| CC2 | 6.0 | 2.65 | - | - | 0.025 |
| UC (2A) | 7.0 | 2.7 | R | Varied | Varied |
| UC (2A) | 7.0 | 2.7 | N | Varied | Varied |
| MC | 7.5 | 2.9 | - | - | - |
| LC | 7.6 | 2.95 | - | - | - |
| Mantle | 8.0 | 3.3 | - | - | - |
| **KG-01** | | | | | |
| TC1 | 7.2 | 2.65 | N | 0.005 | 0.01 |
| TC2 | 7.2 | 2.65 | N | 0.003 | 0.02 |
| **MN-01** | | | | | |
| D1 | 8.0 | 3.1 | R | 0.001 | 0.01 |
| D2 | 8.0 | 3.2 | R | 0.005 | 0.01 |
| D3 | 8.0 | 3.25 | R | 0.015 | 0.01 |
| D4 | 8.0 | 3.25 | R | 0.01 | 0.025 |
| D5 | 8.0 | 3.2 | R | 0.008 | 0.01 |
| D6 | 8.0 | 3.1 | R | 0.01 | 0.02 |
| RT | 7.0 | 2.45 | - | - | 0.001 |
| MI | 8.0 | 2.85 | N | 0.002 | 0.01 |
| RC | 8.0 | 2.9 | - | - | 0.02 |

intrusion (MI) of density 2.85 gm/cc and the eastern oceanic type crust (RC; 2.9 gm/cc). Further east, the presence of oceanic crust has been inferred as indicated by the gentle gravity rise.

Forward modeling along this transect suggests that the continental crust is associated with low susceptibility values ranging from 0.001 to 0.025 cgs units, while the transitional crust in the form of dykes has susceptibilities ranging from 0.001 to 0.025 cgs units with remnant magnetization of 0.001 to 0.008 emu/cc and inclination of 67° (reversed polarity). The 85°E Ridge is characterized by a strong magnetic low, which may be attributed to the normally magnetized magmatic intrusion MI (Table 6). East of the 85°E Ridge, the model suggests the presence of ~8 km thick oceanic crust.

About 9 km thick sediments are inferred at the foot of the slope along this transect. The sediment thickness reduces to ~6 km at the offshore end. An excellent fit between the observed and calculated potential field data under the constraints of multichannel seismic data prompted to infer that the model is geologically plausible along this transect.

# Chapter 6

## *Discussion*

Antarctica landmass forms the core of Eastern Gondwanaland, as the position of Antarctica has not changed much with time (Tingey, 1991). Eastern Gondwanaland split into Greater India, Antarctica, Australia and Madagascar in the Late Jurassic thereby initiating the evolution of the Indian Ocean. Early seafloor spreading developed between Africa and Antarctica in the Late Jurassic (Bergh, 1977; Simpson et al., 1979; Jokat et al., 2003). Simultaneously, separation between Greater India and Australia began in the Argo Abyssal Plain (Heirtzler et al., 1978; Fullerton et al., 1989). This spreading ridge propagated southwestward resulting in seafloor spreading in the Cuvier and Perth Basins during the Early Cretaceous (Markl, 1974; Larson, 1977; Robb et al., 2005). Seafloor spreading thus commenced on either side of the conjoined India/East Antarctica landmass in the Late Jurassic as evidenced by the presence of older Mesozoic magnetic anomalies in the Mozambique, Dronning Maud Land and Argo, Cuvier and Perth Basins. Continental breakup mechanism between India and Antarctica can be traced by understanding the structure and tectonic framework of the respective continental margins. This is possible from the analysis of marine magnetic data, identification of seafloor spreading magnetic anomalies and inference of fracture zones from the distribution/displacement of magnetic anomalies.

The Early and Middle Cretaceous seafloor spreading history of the Indian Ocean remains speculative due to lack of magnetic anomaly identifications and adequate ground truth data like drilling results and dating of rocks. The Middle Cretaceous crust evolved during the Cretaceous Long Normal Polarity Epoch (120-84 Ma) is characterized by smooth magnetic field and the magnetic anomalies are difficult to either correlate or model. The first major plate reorganization associated with dramatic changes in spreading rates and directions coupled with spreading ridge jumps is known to have occurred during this period. The resultant changes in plate configuration are a major hindrance to demarcate the spatial extent and geometry of the Middle Cretaceous crust in the Indian Ocean.

The Early Cretaceous crust older to this Middle Cretaceous crust is plagued with even more severe problems. Geophysical and geological data that can describe the tectonic history between the plates (India and Antarctica) are sparsely distributed. Off Antarctica, the remoteness of the region and the thick ice cover for almost the entire year makes data acquisition cumbersome. These harsh conditions may be the reason for inadequate geophysical data with different profile azimuths. Further, the Early Cretaceous crust is relatively old (~140 Ma) and lies closest to the coasts. Therefore, this crust is subsided to deeper levels and the thick sediment column may obscure the geophysical signatures. For example, the huge sediment overburden in the Bay of Bengal, particularly the proximal Bengal Fan is the primary cause for the observed low amplitude magnetic anomalies. Thus, identification of magnetic anomalies, particularly the Mesozoic magnetic anomalies and mapping of fracture zones in this area become difficult. The Indian plate migrated northward several thousands of kilometers during the Late Cretaceous, and this migration caused skewness to the magnetic anomalies. In addition, the oceanic crust has been affected by emplacement of several seismic/aseismic ridges and large igneous provinces. Also, part of the Early to Middle Cretaceous crust of the Indian plate has been destroyed due to subduction in the Sunda Trough. As mentioned in previous chapters, different plate reconstruction models have been proposed for the early breakup of Eastern Gondwanaland based on the available inadequate datasets particularly in the Enderby Basin and Bay of Bengal (Ex: Powell et al., 1988; Royer and Sandwell, 1989, etc).

Integrated geophysical studies in the Bay of Bengal and Enderby Basin reveal a complex nature of the crust in both the conjugate margins. The Bay of Bengal is characterized by a very narrow continental shelf (<17 km) along the south and central east coast of India, while it widens to >200 km in the north. The continental slope is steep and narrow upto ~3000 m water depths. The abyssal plains are characterized by smooth topography due to thick sediment cover, except at a few isolated locations in the southern Bay of Bengal, and along the 90°E meridian corresponding to the Ninetyeast Ridge (Fig. 4-1). The sediment load brought in by the Ganges and Brahmaputra rivers is distributed through a network of turbidity channels from the proximal to distal Bengal Fan (Fig. 2-2). The presence of >21 km sediment load at the apex of the Bengal Fan (Fig. 2-3) is inferred based on various seismic experiments (Curray, 1994). Magnetic studies (Fig. 5-2) reveal the subdued nature of magnetic anomalies in the Bay of Bengal due to thick sediment overburden. The magnetic anomaly contour map along the ECMI shows high amplitude magnetic anomaly closures towards the north (Fig. 2-4). Shipborne gravity data and satellite derived free-air gravity mosaic (Figs. 2-6 & 2-7) reveal NNE-SSW to NE-SW trending gravity anomalies along the ECMI depicting the evolution of the seafloor. The subsurface 85°E Ridge is seen associated with negative gravity field, whereas the Ninetyeast Ridge depicts positive gravity. N-S trends representing fracture zones are prominent in the southern Bay of Bengal.

The Enderby Basin is characterized by a narrow continental shelf having an average water depth of 500 m (Johnson et al., 1982). The slope dominated by spur and canyon type of topography reaches to >2000 m water depth. The basin deepens towards the northwest (Figs. 4-15 & 4-16). Satellite derived free-air gravity mosaic show NNE-SSW to N-S trends in the southern Enderby Basin (Fig. 2-10). The Kerguelen Fracture Zone, Kerguelen Plateau, Gunnerus Ridge and Conrad Rise are some of the important geomorphic features well reflected on the mosaic. The sparse and irregularly oriented magnetic profiles (Fig. 5-5) depict low to high amplitude (<200 and >600 nT) magnetic anomalies in the basin indicating complex basement configuration.

## 6.1 Multichannel seismic data interpretation

### 6.1.1 Bay of Bengal

DSDP Site 218 drilled in the distal Bengal Fan revealed that the upper 200 m (0.25 s TWT) of the long core comprises Pleistocene sediments, while the sediment between 200 and 320 m is of Pliocene age. A major unconformity at 0.45 s TWT represents the top of Miocene, while the sediments between 320 and 773 m consists of Middle Miocene deposits (Von der Borch et al., 1974).

Two major unconformities, i.e. the uppermost Miocene (M) and the top of Paleocene (P) have been identified in the Bengal Fan. Further, it was inferred that the 85°E Ridge has been in existence prior to the P unconformity, and the thinning of the Tertiary section above it appears to be due to differential compaction and local erosion, rather than by continued uplift of the ridge (Curray et al., 1982). Sediment thickness of >8 km and similar crustal structure on both sides of the 85°E Ridge was inferred. The negative free-air gravity anomaly across the ridge has been interpreted in terms of formation of the ridge by emplacement of probable extrusive rocks when the underlying lithosphere was young (5-15 m.y. age) and low in flexural rigidity (Liu et al., 1982). The pre-Eocene sediments are considered to be the pre-fan, while the post-Paleocene sediments are considered as the post-fan sediments.

Subsequently, Pateria et al., (1992) inferred four major sequences along the regional seismic sections in the Bay of Bengal. The topmost sequence 4 consists of Recent to Miocene sediments, while the sequences 3 and 2 corresponding to Eocene-Oligocene and Paleocene sediments respectively thin towards the continental rise. The bottommost sequence 1 thickens towards the rise and is assigned Cretaceous age. The 85°E Ridge remained as a positive feature during the deposition of sequence 1 and a major part of sequence 2. Therefore, the ridge appears to be older than the oldest sediment deposited over the oceanic basement.

Multichannel seismic data (present study) along the two tracks KG-01 and MN-01 (Figs. 4-10 & 4-11) show the presence of upto 5 s TWT sediments in the Krishna-Godavari and Mahanadi offshores. The sedimentary column is comprised of nine (A to I) sequences separated by eight (H1 to H8) seismic horizons. The older sequences A to C thin towards offshore, while the younger sequences (D to I) either pinch out towards coast or maintain/increase their thickness. The inferred topmost seismic sequences E to I correspond to sequence 4 of Pateira et al., (1992), while D and C correspond to sequences 3 and 2 respectively. Similarly, the inferred sequences A and B correspond to sequence 1. The horizon H7 inferred in this study corresponds to top of Miocene (M), while H3 corresponds to top of Paleocene (P) of Curray et al., (1982).

Forward modeling of the potential field data suggests that sediment thickness of ~10 km at the foot of the continental slope decreases towards offshore (Figs. 5-10 & 5-11). The sequences Q, Pl, M, OE and PC represent the Quaternary, Pliocene, Miocene, Eocene-Oligocene and Paleocene-Cretaceous respectively under the constraints of published results. The ages of all the seismic horizons (Figs. 4-10 & 4-11) have been inferred along the profiles KG-01 and MN-01. The sediment thickness in TWT of all the sequences was converted to meters using the appropriate seismic velocities. The thickness and ages of these sequences facilitated in inferring the sedimentation rates. These rates as given in table 7 reflect the nature of the depositional environment in the geological past.

The rates of sedimentation inferred in the present study vary over time (Table 7). Initially, during rifting in the Early Cretaceous, the inferred rate is low

(~5 cm/Kyr). Thereafter, the rate increases to ~12 cm/Kyr in the Paleocene, when India was migrating at a fairly fast pace northwards. These constitute the normal pre-fan sediments and are about 4.7 km thick. Around Early Eocene, India began colliding with Asia, and the soft collision may have resulted in a marine transgression forming the shales, limestones, and sandstones of shallow marine environment. This was followed by Oligocene regression, which resulted in low sedimentation rate of 4.9 cm/Kyr. The hard collision during the Miocene resulted in the uplift of the Himalayas and was followed by the onset of intense Indian monsoon. The increased sediment flux resulted in the high sedimentation rate of >10 cm/Kyr during the entire Miocene period. During the Pliocene, sedimentation rate further increased to ~22 cm/Kyr. The Quaternary period is also characterized by high sedimentation rate (~25 cm/Kyr).

The abundance of turbidity current channels during the Pleistocene may be due to lowered sealevel, wherein all the sediment poured directly off the continental slope into the basin. During high sealevel as in the present, i.e. interglacial or interstadials, most of the sediments are trapped in deltas and little sediment passes to the fan. Turbidity current activity is therefore decreased. The post-fan sediments constitute the post-Paleocene deposits and are about 5 km thick.

Forward modeling results suggests the presence of a narrow (~60 km) transitional zone between the continental and oceanic crusts. This zone consists of normally magnetized low density crustal blocks TC1 and TC2 along profile KG-01 (Fig. 5-10). Along the profile MN-01, the transitional crust is characterized by dyke type intrusions D1 - D5 of high density (~3.2 gm/cc) and reverse magnetization (Fig. 5-11). The transitional crust therefore has non-volcanic normally magnetized nature in the Krishna-Godavari offshore and volcanic reversely magnetized character south of Mahanadi Basin (~18°N latitude). The distinct Moho reflection around 10 s TWT and the polarity reversals in the uppermost layer 2A confirms the presence of oceanic crust in the Bay of Bengal.

Table 7: Seismic sequence interpretation in terms of age and sedimentation rates in the Bay of Bengal

| Sequence and corresponding unconformity | Average thickness in sec TWT | Seismic velocity (km/s) | Average thickness in meters | Age | Sediment-ation rate in cm/Kyr |
|---|---|---|---|---|---|
| I<br>*H8* | 0.5 | 1.8 | 450 | Quaternary | 25 |
| H<br>*H7* | 0.7 | 2.2 | 770 | Pliocene | 22 |
| G<br>*H6* | 0.5 | 2.5 | 625 | Late Miocene | 10.4 |
| F<br>*H5* | 0.4 | 2.8 | 560 | Middle Miocene | 11.2 |
| E<br>*H4* | 0.8 | 3.0 | 1200 | Early Miocene | 15.3 |
| D<br>*H3* | 0.7 | 4.0 | 1400 | Eocene-Oligocene | 4.9 |
| C<br>*H2* | 0.5 | 4.8 | 1200 | Paleocene | 12 |
| B<br>*H1* | 0.7 | 5.0 | 1750 | Late Cretaceous | 9 |
| A | 0.7 | 5.2 | 1800 | Early to Middle Cretaceous | 5 |

Magnetic model studies in the Visakhapatnam-Paradip shelf region revealed its two stage evolution, i.e., (i) rift stage of intrusion/dyke in the inner shelf, and (ii) post-rift stage of vertical tectonics in the form of horst and graben like structures (Murthy et al., 1993). Similar studies along the 85°E longitude off Chilka Lake indicate intrusive rocks with high susceptibility contrast of 0.028 and 0.016 emu juxtaposed at shallow depths of 0.6-3.6 km respectively (Subrahmanyam et al., 1997).

### 6.1.2 The 85°E Ridge

Seismic data along the line MN-01 (Fig. 4-11) depicts that the 85°E Ridge is a basement rise of about 2 s TWT and 80 km width. The presence of sequence A on the basement rise indicates that ridge emplacement took place during the Middle Cretaceous on the pre-existing crust causing its uplift along with the overlying sequence A. The truncation of sequences B and C (Late Cretaceous to Paleocene) on either side of the ridge indicates the ridge has been in existence before these sequences were deposited. The discontinuity in the Moho reflection seen below the ridge at about 9.5 s TWT indicates the presence of a magmatic intrusion.

The 85°E Ridge is characterized by a negative free-air gravity anomaly throughout its length, and this low has been attributed to a depression in the Moho (Liu et al., 1982). On the contrary, the low gravity has been attributed to the presence of low-density material within the ridge (Ramana et al., 1997a[1]). Anand et al., (2009) suggested that the ridge is a geomorphological feature within the sediments above the basement north of 15°N latitude.

Multichannel seismic section MN-01 crosses the 85° E Ridge around 16.5°N latitude. This seismic section and forward modeling studies indicate that the ridge is a basement feature (Figs. 4-11 & 5-11). Further, the seismic section unambiguously indicates that there is no Moho depression below the ridge. Contrary to the inference that the ridge is associated with steep negative free-air gravity anomaly throughout its length, the gravity signature along this seismic section depicts a distinct positive anomaly of 20 mgals in an overall broad gravity low over the ridge (Fig. 5-9). This positive anomaly overlies that portion of the ridge where the Moho reflection is absent. Forward modeling along this profile suggests the presence of a magmatic body below this positive gravity anomaly. Model studies also reveal the presence of high density intrusives to its left and oceanic crust to its right (Fig. 5-11; Table 6).

The 85°E Ridge is also characterized by a strong negative magnetic anomaly flanked by positive peaks on either side (Fig. 5-9) along the seismic section MN-01. Modeling suggests the presence of reversely magnetized high density intrusives west of the ridge, while the magmatic intrusion within the ridge is normally magnetized (Table 6). Further, the prominent negative magnetic

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[1] *Ramana, M. V., Subrahmanyam, V., Chaubey, A. K., Ramprasad, T., Sarma, K.V.L.N.S, Krishna, K. S., Desa, M. and Murty, G.P.S., 1997a. Structure and origin of the 85°E Ridge, J. Geophys. Res.,* ***102:*** *17995-18012.*

anomaly over the ridge suggests the ridge was emplaced in the southern hemisphere when the earth's magnetic field was normal. This emplacement may have taken place during the Middle Cretaceous period when the geomagnetic field was largely positive on a pre-existing crust of Early Cretaceous age. This is in accordance with the suggestion that the emplacement took place over an already evolved young crust probably 5-15 m.y. old (Liu et al., 1982).

## 6.2 Magnetic Data interpretation

Synthetic seafloor spreading modeling technique has facilitated in the identification of Mesozoic magnetic anomaly sequence M11 through M0 in the two study areas viz., the Bay of Bengal and the Enderby Basin, East Antarctica. Half-spreading rates of 5.9 to 8.6 cm/yr are inferred in the Central Bay of Bengal (Fig. 5.3), while relatively lower spreading rates i.e., 4.5 to 7.5 cm/yr are estimated in the Enderby Basin (Fig. 5-6). This sort of unequal spreading rates are observed in all the major ocean basins and may be attributed to asymmetric crustal accretion (Muller et al., 1998). The position maps along with the identifications (Figs. 5-4 & 5-7) reveal that the breakup between these conjugate margins took place prior to the formation of magnetic anomaly M11 (~133 Ma) since the oldest anomaly M11 is identified close to the coasts in the Bay of Bengal as well as the Enderby Basin. Further north in the Bay of Bengal, the sparse data coverage and the subdued nature of the magnetic anomalies constrained any attempt for anomaly identification. Likewise, the region off

Prydz Bay in the eastern Enderby Basin has been affected by the Kerguelen mantle plume activity resulting in magnetic overprinting (Gohl et al., 2008). Hence identification of magnetic anomalies is difficult in this region. The present study suggests the presence of Early Cretaceous crust in both the conjugate margins.

### 6.2.1 Plate reconstruction models

Plate reconstruction models depict the paleo positions of continents either with reference to one another or some fixed frame (e.g. hotspot). Plate reconstruction modeling techniques include calculation of a rotation pole (Euler pole) using azimuths of oceanic fracture zones and magnetic anomaly identifications, and rotation of the continents. The resultant match in the positions of the chrons and trends of the fracture zones determine the accuracy of the pole parameters.

Several plate reconstruction models have been generated to trace the evolutionary history of the two study areas. For example, reconstruction models of Powell et al., (1988); Scotese et al., (1988); Royer and Sandwell, (1989), etc have provided the initial concept of the breakup of the continents (India from Antarctica) and evolution of ocean floor since their Early Cretaceous breakup. Initially, the datasets used for these reconstructions were sparse and scattered over large areas. As and when new datasets are available, these reconstructions are updated. For example, the plate reconstruction models of Royer and Coffin, (1992); Muller et al., (1993) and Gaina et al., (2003).

In the present study, the large volume of new datasets (marine magnetic and gravity) in the Bay of Bengal has been extensively used to refine the existing plate reconstruction models for different chrons starting from M29 to 34. Plate reconstruction models have been generated for various chrons either by using published pole parameters or calculated ones (Table 8). The PLACA software has been used to calculate the pole parameters. The identified magnetic anomalies and inferred fracture zones have been used as constraints to generate these models which trace the evolutionary history of the conjugate margins. Antarctica has been kept in its present day position, as this continent has not moved much in the geologic time. Greater India has been considered instead of the Indian subcontinent (Ali and Aitchison, 2005).

M29 reconstruction

The M29 reconstruction is the earliest reconstruction generated using the rotation poles (Table 8). This model is considered as the initial fit reconstruction. It depicts a good fit between the 2000 m isobaths surrounding India and Antarctica (Fig. 6-1). Sri Lanka has been placed close to India as suggested by earlier researchers (Powell et al., 1988; Scotese et al., 1988).

M11 reconstruction

M11 isochron is the oldest Mesozoic magnetic anomaly identified close to the coasts of both the conjugate margins, i.e., the Eastern continental margin of

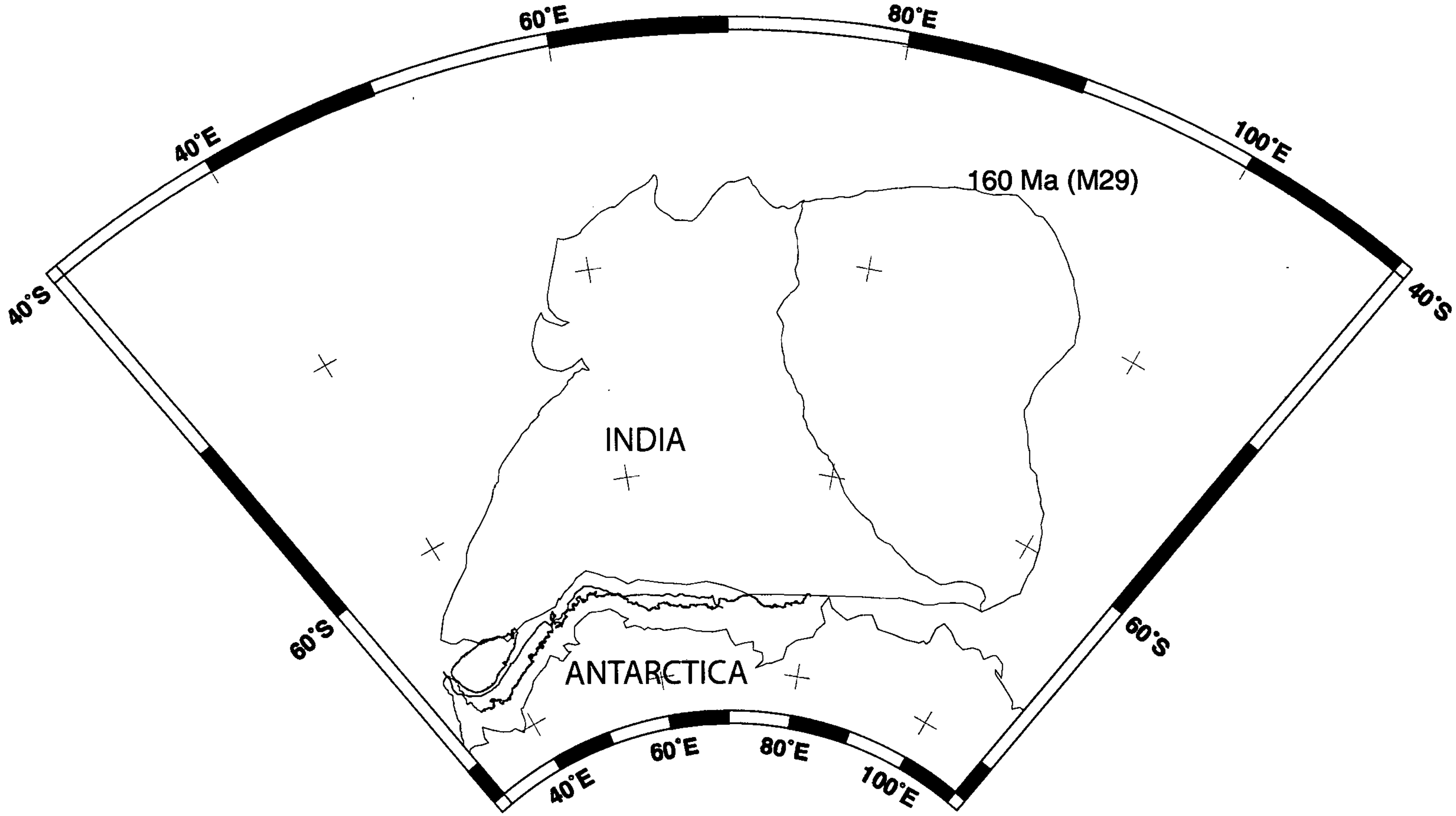


Figure 6-1 Plate reconstruction model depicting the palaeoposition of India relative to Antarctica at M29 time (160 Ma). Rotation pole parameters are as given in Table 8. Blue line represents the 2000 m isobath off Antarctica, while the red line represents the 2000 m isobath off India. Note the tight fit between the 2000 m isobaths off the two continents.

India and the Enderby margin, East Antarctica. In the Bay of Bengal, M11 isochron is identified from 14 to 17°N latitudes and on its either side with both left and right lateral offsets (Fig. 5-4). M11 isochrons are identified at three locations in the eastern Enderby Basin and at one location east and west of Gunnerus Ridge (Fig. 5-7). The M11 reconstruction generated using pole parameters (Table 8) is shown in figure 6-2. A good fit is seen between the M11 isochrons identified on the Indian and Antarctica plates. The fracture zones inferred using the satellite derived free-air gravity mosaic (Figs. 2-7 & 2-10) also match well and indicate that India moved away from Antarctica in ~NW-SE direction after breakup.

M8 reconstruction

This reconstruction is generated using the magnetic anomaly M8 identifications on both the conjugate margins (Fig. 6-3). It depicts the continuation of the ~NW-SE movement of India from Antarctica. A good fit is observed between the identified M8 isochrons and the inferred fracture zones on these conjugate margins.

M0 reconstruction

The M0 reconstruction has been generated using the magnetic anomaly M0 identifications on both the conjugate margins (Table 8). This reconstruction depicts the continuation of the Indian plate motion in ~NW-SE direction (Fig. 6-4). The fracture zones south of Sri Lanka have trends similar to those observed

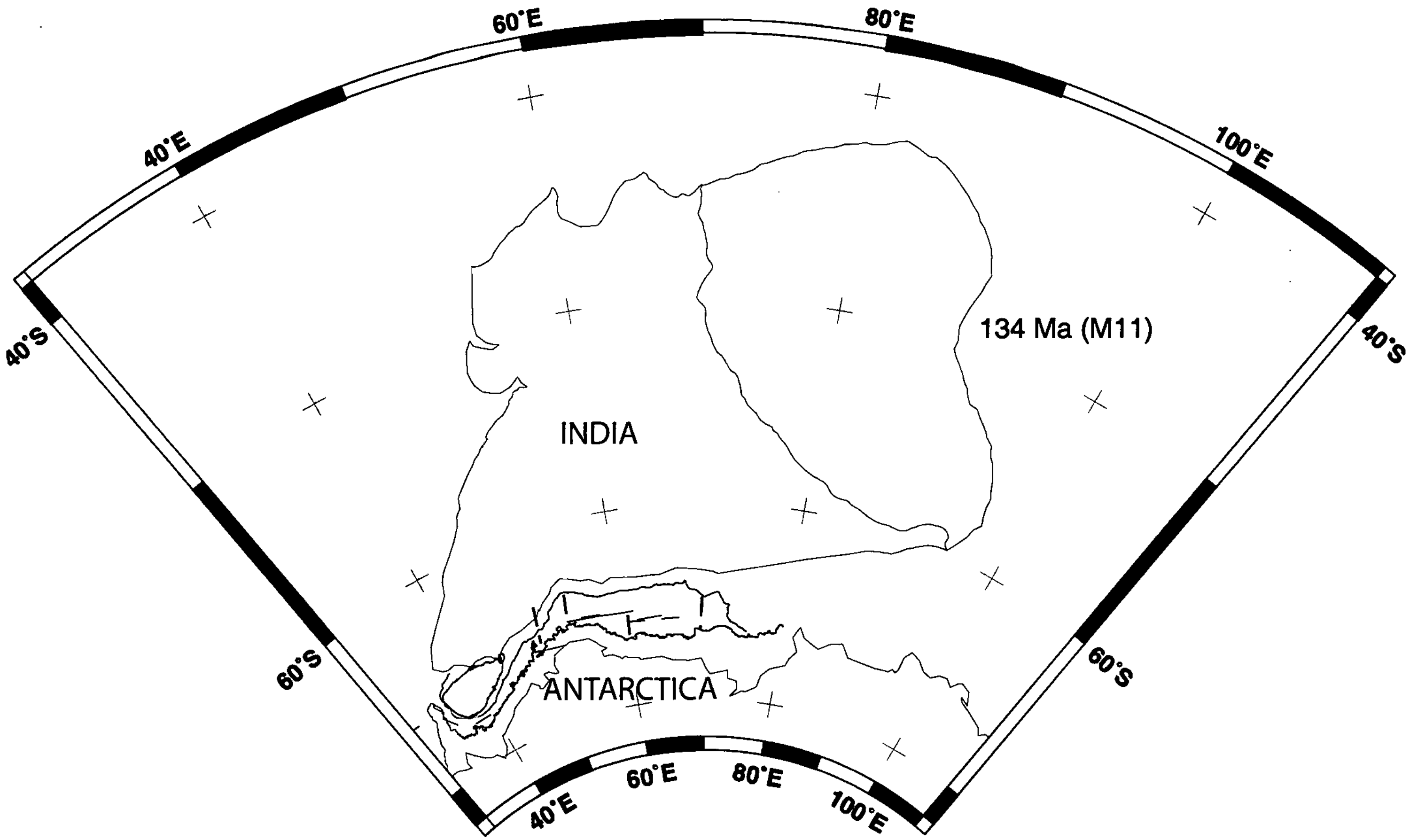


Figure 6-2 Plate reconstruction model depicting the palaeoposition of India relative to Antarctica at M11 time (134 Ma). M11 anomalies identified in the Bay of Bengal (pink) and Enderby Basin (red) show a good match. Remaining information as in figure 6-1. Fracture zones are shown as dashed lines.

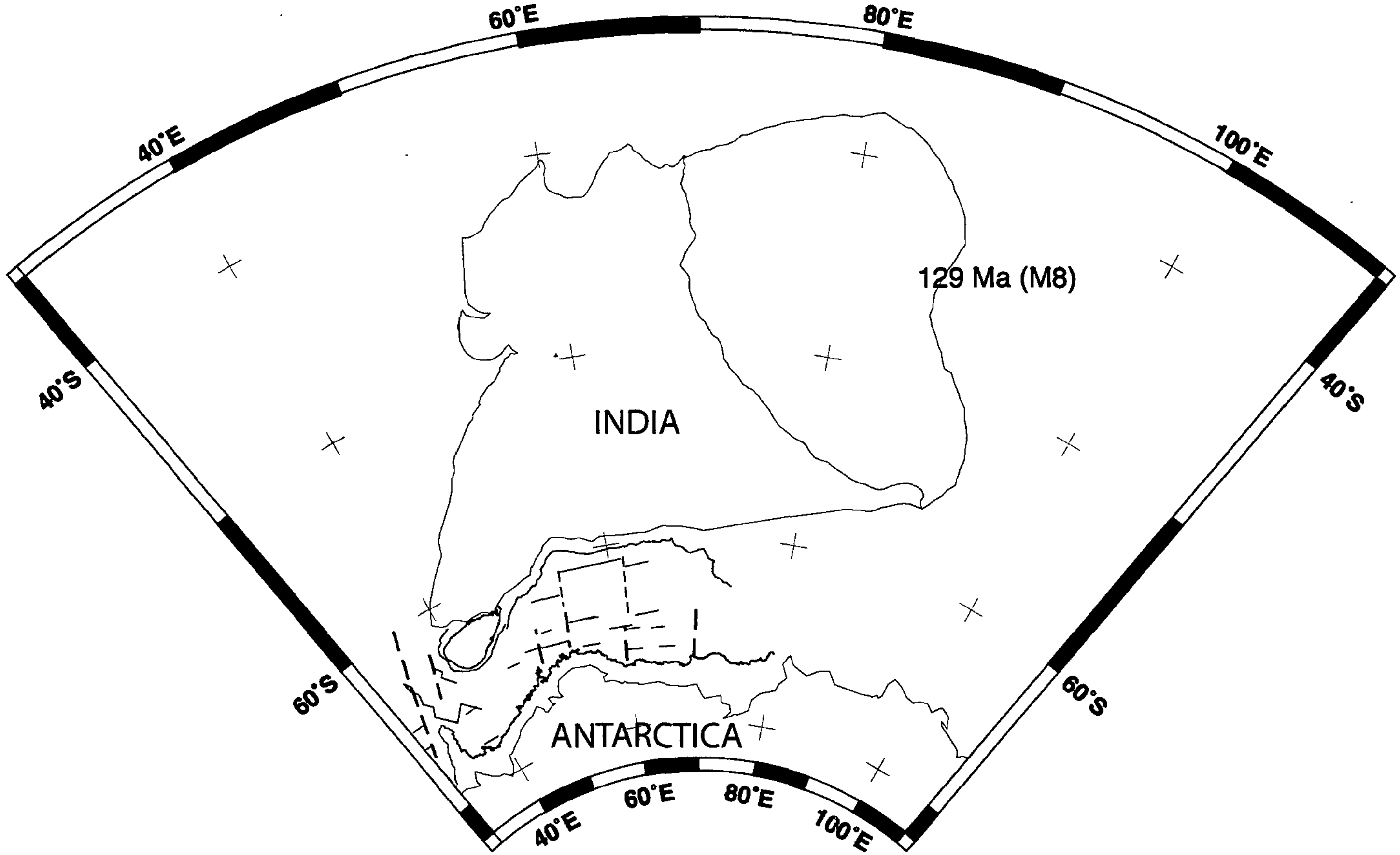


Figure 6-3 Plate reconstruction model depicting the palaeoposition of India relative to Antarctica at M8 time (129 Ma). Anomalies M8 (green) and M11 (pink) inferred in the Bay of Bengal, while M8 (blue) and M11 (red) in the Enderby Basin in the present study have been plotted. Remaining information as in figure 6-1. Fracture zones are shown as black dashed and continuous lines on the Antarctica and Indian plates respectively. A good match between the fracture zones and M8 anomaly identifications is conspicuous.

Table 8: Finite rotation pole parameters used for generating plate reconstruction models. Antarctica is kept in its present day position. Positive sign indicates northern latitude, east longitude and anticlockwise rotation.

| Age (Ma) | Chron | Latitude (°) | Longitude (°) | Angle (°) | References |
|---|---|---|---|---|---|
| India with reference to Antarctica | | | | | |
| 160 | M29 | -4.22 | 17.14 | -92.45 | Powell et al., (1988) |
| 133 | M11 | -1.6 | 13.0 | -88.7 | This study |
| 129 | M8 | 0.8 | 12.5 | -84.5 | This study |
| 120 | M0 | 6.0 | 11.8 | -76.0 | This study |
| 84 | 34 | 8.8 | 11.2 | -64.5 | Desa et al., (2009[2]) |
| Sri Lanka with reference to India | | | | | |
| 160 | M29 | 12 | 84.5 | -15 | Desa et al., (2006[3]) |
| 133 | M11 | 12 | 84.5 | -15 | Desa et al., (2006) |
| 129 | M8 | 12 | 84.5 | -15 | Desa et al., (2006) |
| 120 | M0 | 15 | 90 | -3 | Desa et al., (2006) |
| 84 | 34 | 0 | 0 | 0 | Present day position |

[2] *Desa, M., Ramana, M. V. and Ramprasad, T., 2009. Evolution of the late Cretaceous crust in the equatorial region of the Northern Indian Ocean and its implication in understanding the plate kinematics, Geophys. J. Int.,* ***177****:1265-1278.*

[3] *Desa, M., Ramana, M. V. and Ramprasad, T., 2006. Seafloor spreading magnetic anomalies south off Sri Lanka, Mar. Geol.,* ***229****: 227-240.*

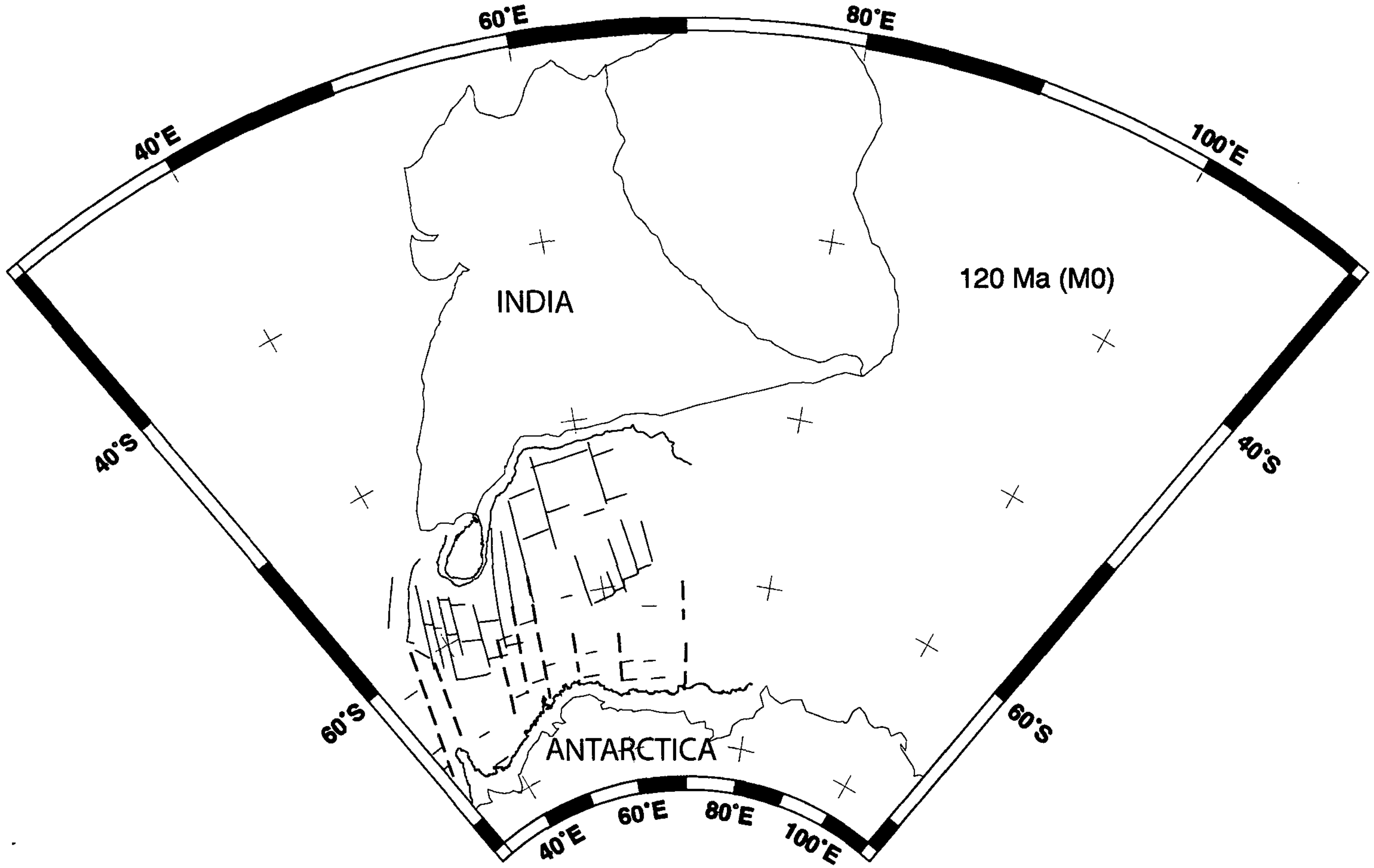


Figure 6-4 Plate reconstruction model depicting the palaeoposition of India relative to Antarctica at M0 time (120 Ma). Anomaly M0 in the Bay of Bengal (dark blue) and Enderby Basin (brown) identified in the present study show a fairly good match. Remaining information as in figure 6-3.

in the western Enderby Basin. The close match in the fracture zone orientations and the M0 isochrons suggests the reconstruction represents the actual tectonic scenario that existed since Early Cretaceous upto the formation of M0 anomaly.

34 reconstruction

The 34 reconstruction model is well constrained by a large number of chron 34 picks from the 3 plates viz., India, Antarctica and Australia (Table 8; Fig. 6-5). This model depicts the extent of the oceanic crust generated during the Early and Middle Cretaceous. The Mesozoic magnetic anomaly identifications M11 through M0 indicate the extent of the crust generated during the Early Cretaceous. The trends in the fracture zones indicate an initial ~NW-SE direction of the Indian plate motion from Antarctica. The reconstruction further depicts a change in the spreading direction between India and Antarctica during the Middle Cretaceous period. The unequal extent of the Middle Cretaceous crust between these conjugate margins is obvious. The Kerguelen Plateau consisting of the SKP, Elan Bank and CKP is seen in the reconstruction since these features were emplaced by chron 34 (Coffin et al., 2000). Another Large Igneous Province (LIP) the Conrad Rise, is also reflected in the reconstruction.

The plate reconstruction models generated for different magnetic chrons facilitated in tracing the complete evolutionary history of these conjugate margins from the Early to Late Cretaceous (Figs. 6-1 to 6-5). The validity of these reconstructions has been tested by plotting the positions of the Euler poles (Fig.

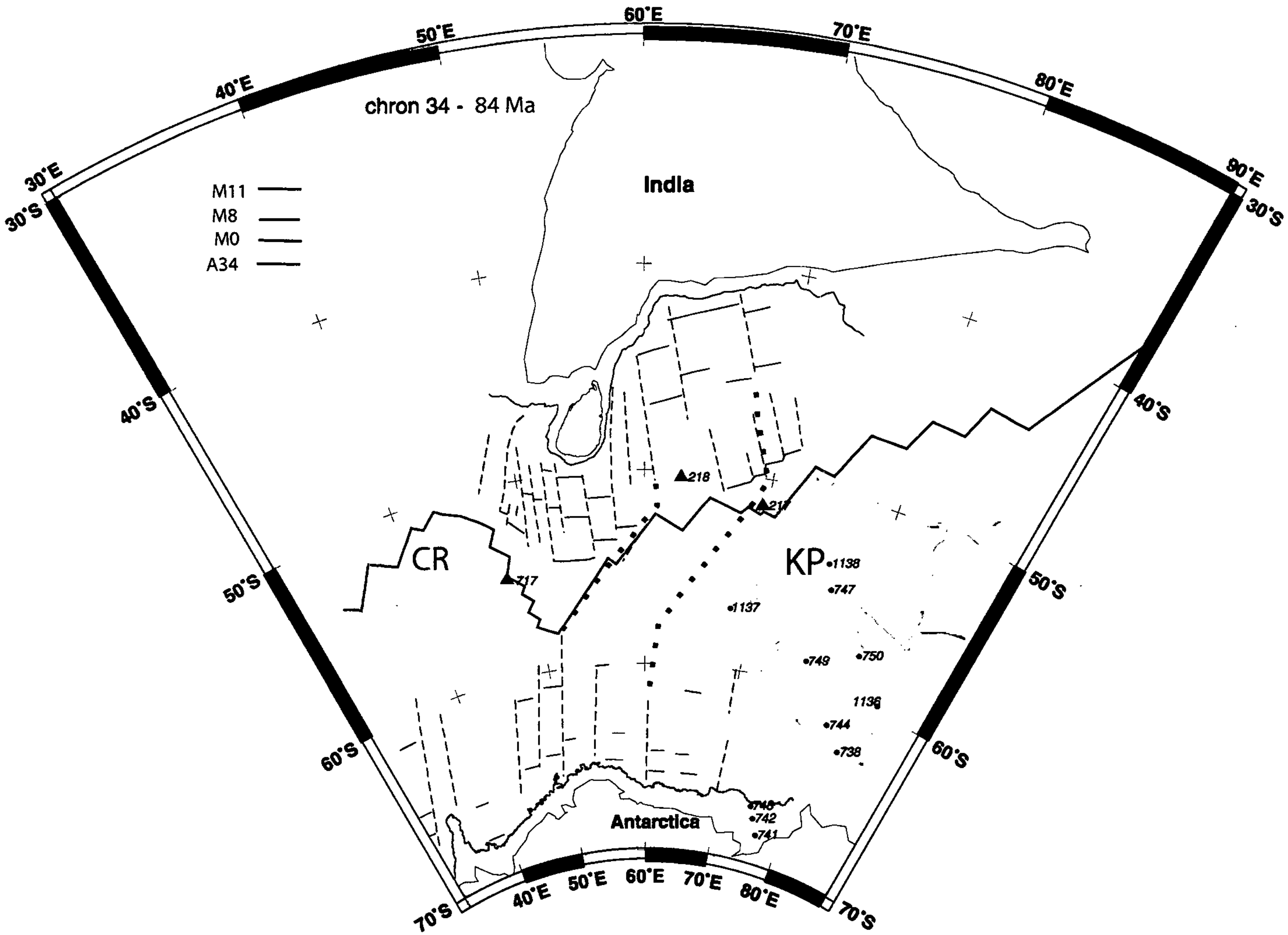


Figure 6-5 Plate reconstruction model depicting the palaeoposition of India relative to Antarctica at chron 34 time (84 Ma). Anomalies are shown as per the legend. ODP and DSDP sites are shown as triangles on the Indian plate and dots on the Antarctica plate. Star denotes the likely location of the Kerguelen hotspot. Pink continuous line represents the chron 34 boundary. Dashed lines represent fracture zones. Thick dotted lines are flow lines of plate motion. CR: Conrad Rise; KP: Kerguelen Plateau

6-6). The alignment of these poles suggests that the reconstructions made in this research work are highly reliable.

Figure 6-7 depicts the satellite derived free-air gravity mosaic grid reconstruction between India and Antarctica at chron 34 (Table 8). The extent of the oceanic crust generated during the Early and Middle Cretaceous is shown. The chron 34 boundary between the conjugate plates occurs above the Conrad Rise with left and right lateral offsets on either side. These right lateral offsets change to left lateral along the KFZ/86°E FZ with a large offset of about 900 km. The grid reconstruction shows good correspondence in the trends of the mosaic grains on both the plates. The trends on the Indian plate represent the flow lines of its motion during the Early Cretaceous. A prominent gravity low associated with the 85°E Ridge is seen suggesting that the ridge might have evolved prior to the formation of chron 34. On the Antarctica plate, N5-10°E trends are seen prominently northeast of the Gunnerus Ridge suggesting the initial seafloor spreading direction. In the eastern Enderby Basin, the trends in the mosaic grains are faint. The region south of Conrad Rise depicts cross trends terminating with the ~NE-SW trending Kerguelen fracture zone (KFZ). No particular trend in the mosaic grains is seen in the region east of the KFZ. Complex relatively positive gravity field of the Kerguelen Plateau is seen towards northeast.

The spatial extent of the Middle Cretaceous crust evolved during 120-84 Ma differs considerably on the Indian and Antarctica plates. The Middle Cretaceous crust on the Indian plate is a narrow zone, while it is broader on the

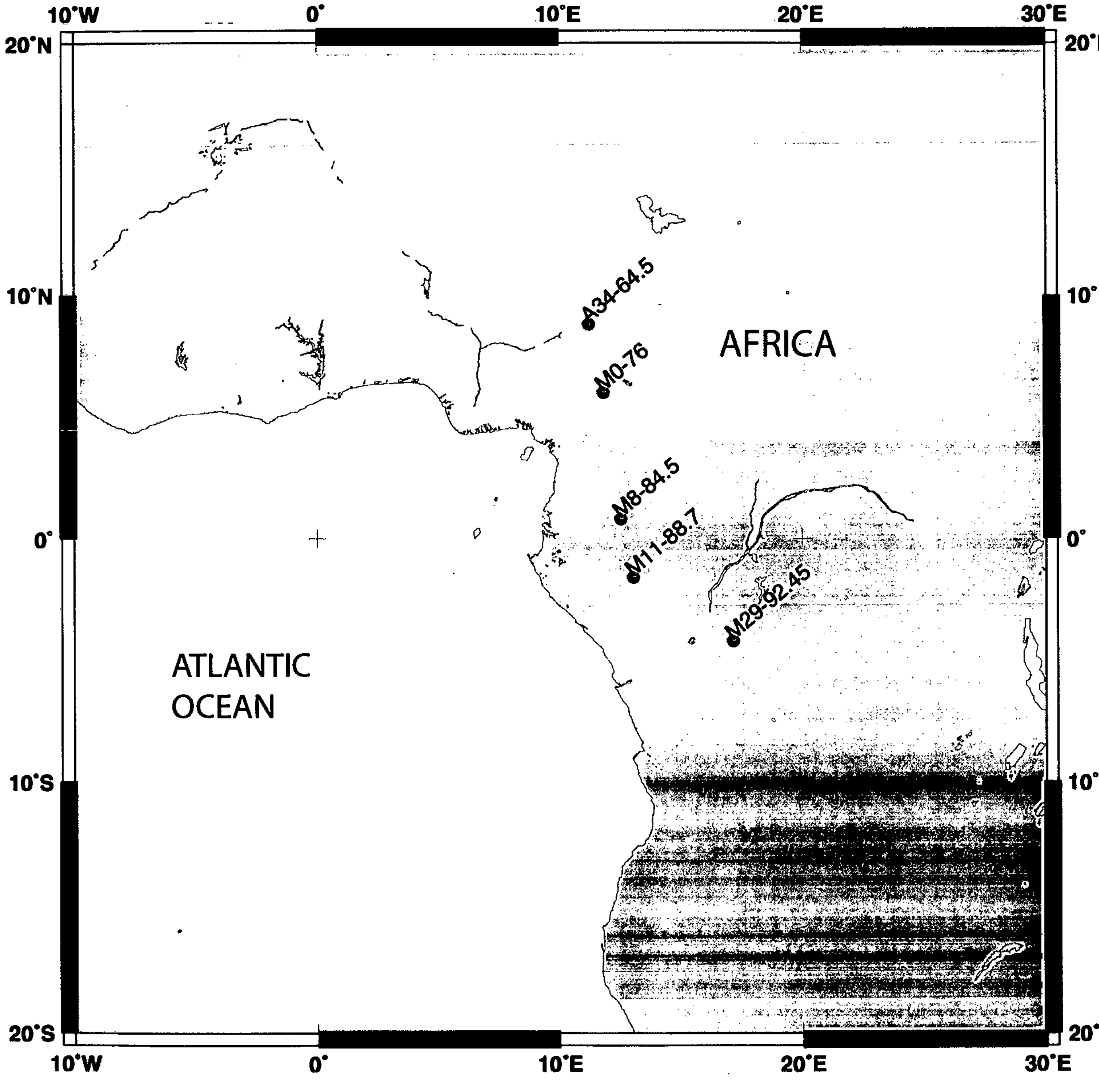


Figure 6-6 Map depicting the location of the finite rotation poles used for generating the India/Antarctica plate reconstruction models at various chrons (red dots). The annotation denotes the chron followed by the Euler angle.

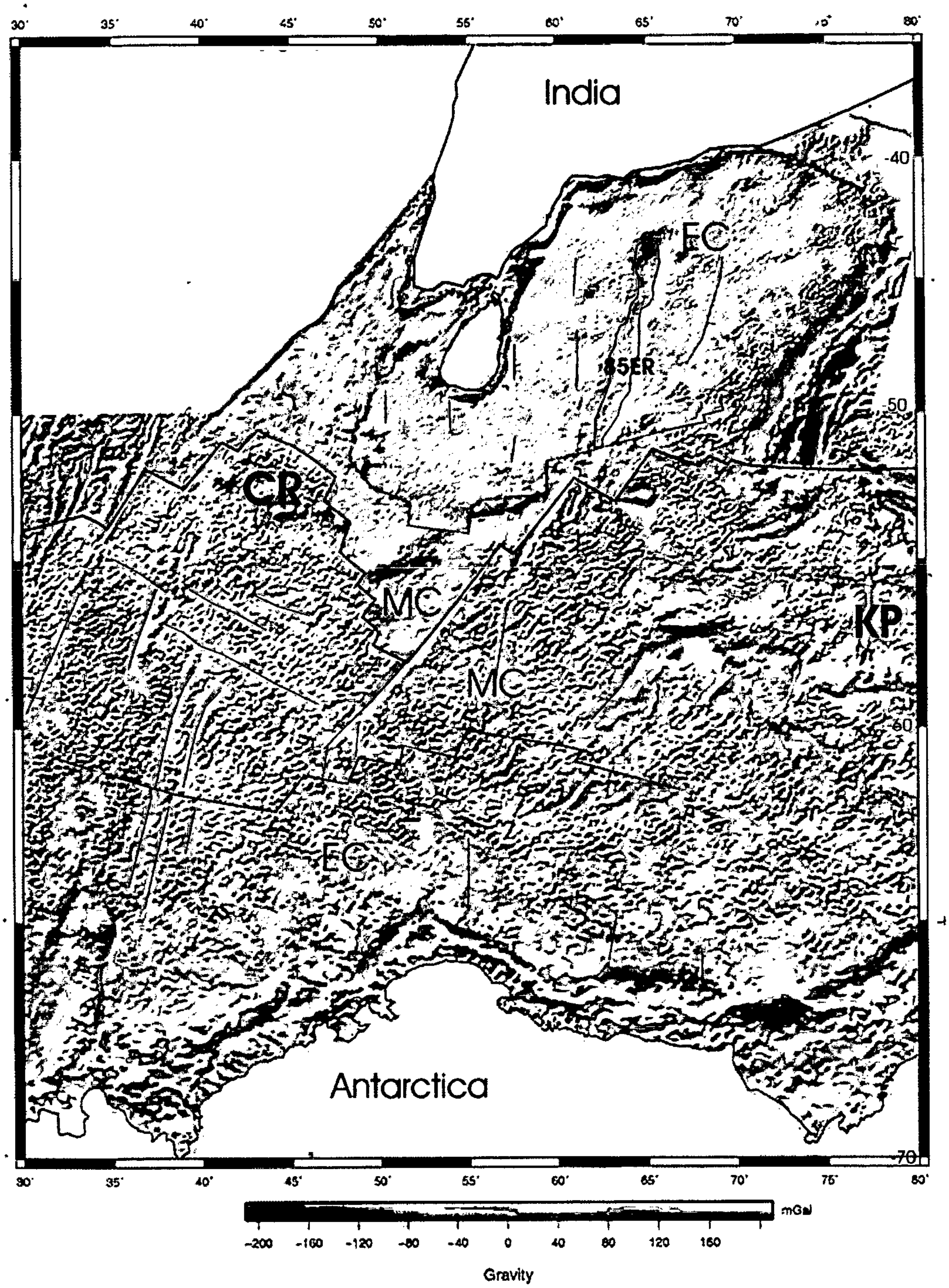


Figure 6-7 Satellite derived free-air gravity mosaic grid reconstruction of India and Antarctica at chron 34. The boundary between the Early (EC) and Middle (MC) Cretaceous crust is shown as a continuous red line based on the location of the M0 anomaly. Unequal extent of the Middle Cretaceous crust is seen. The KP (Kerguelen Plateau) and CR (Conrad Rise) lie within the Middle Cretaceous zone. Prominent lineations in the gravity mosaic are marked. The gravity low of the 85°E Ridge (85ER) is prominent

Antarctica plate (Fig. 6-7). This unequal extent of the Middle Cretaceous crust suggests the occurrence of asymmetric crustal accretion between the two plates. This asymmetry may be due to seafloor spreading changes and/or the transfer of oceanic crust from the Indian to the Antarctica plate by northward ridge jumps. This grid reconstruction endorses the complex evolution of these conjugate margins.

## 6.3 Oceanic crust provinces

The oceanic crust in the Bay of Bengal and Enderby Basin belongs to the Early, Middle and Late Cretaceous as deduced from the interpretation of geophysical and geological datasets. The Early Cretaceous crust formed between 133 and 120 Ma occurs closest to the continental margins and is represented by the Mesozoic magnetic anomalies M11 through M0. The extent of the Middle Cretaceous crust of 120 to 84 m.y. age, between the magnetic isochrons M0 and 34 is fairly well demarcated, but its evolution is ambiguous. The Late Cretaceous crust younger to chron 34 has been well established in both the conjugate basins.

### 6.3.1 Early Cretaceous Crust

Initially, several researchers have predicted the presence of Early Cretaceous crust in the Bay of Bengal and its conjugate, the Enderby Basin (Powell et al., 1988; Scotese et al., 1988) and generated plate reconstruction scenarios depicting the plates configuration prior to and after the breakup of Eastern Gondwanaland. Subsequently, Curray and Munasinghe, (1991) suspected the presence of Mesozoic magnetic anomalies M4 and M5 in the Bay of Bengal, and Ramana et al., (1994b[4]) for the first time reported the presence of complete sequence of Mesozoic magnetic anomalies M11 through M0 in the Central Bay of Bengal, though a part of oceanic crust is traversed by the subsurface ~N-S trending 85°E Ridge.

Interpretation of about 21,200 km of marine geophysical (magnetic, gravity and bathymetry) data south off Sri Lanka revealed the presence of Early Cretaceous crust of 133 to 120 Ma age associated with the Mesozoic magnetic anomalies M11 through M0 (Fig. 6-8). Synthetic seafloor spreading model studies revealed that the crust has evolved with variable half-spreading rates ranging from 5.5 to 1.53 cm/yr (Desa et al., 2006). The magnetic anomalies are offset by NNW-SSE and NW-SE trending fracture zones. The oldest magnetic anomaly M11 occurs 110-140 km away from the Sri Lankan coast indicating that the breakup of Eastern Gondwanaland has occurred prior to the formation of M11 chron (Desa et al., 2006).

Curray (1984) opined that the first rifting between India, Sri Lanka and Antarctica initiated along the Cauvery-Palk Strait-Gulf of Mannar zone but this rift did not progress into the seafloor spreading stage. Instead, the breakup took

[4] *Ramana, M. V., Nair, R. R., Sarma, K. V. L. N. S., Ramprasad, T. Krishna, K. S., Subrahmanyam, V., D'Cruz, M., Subrahmanyam, C., Paul, J., Subrahmanyam, A. S. and Chandrasekhar, D. V., 1994b. Mesozoic anomalies in the Bay of Bengal, Earth Planet. Sci. Lett.* ***121****: 469-475.*

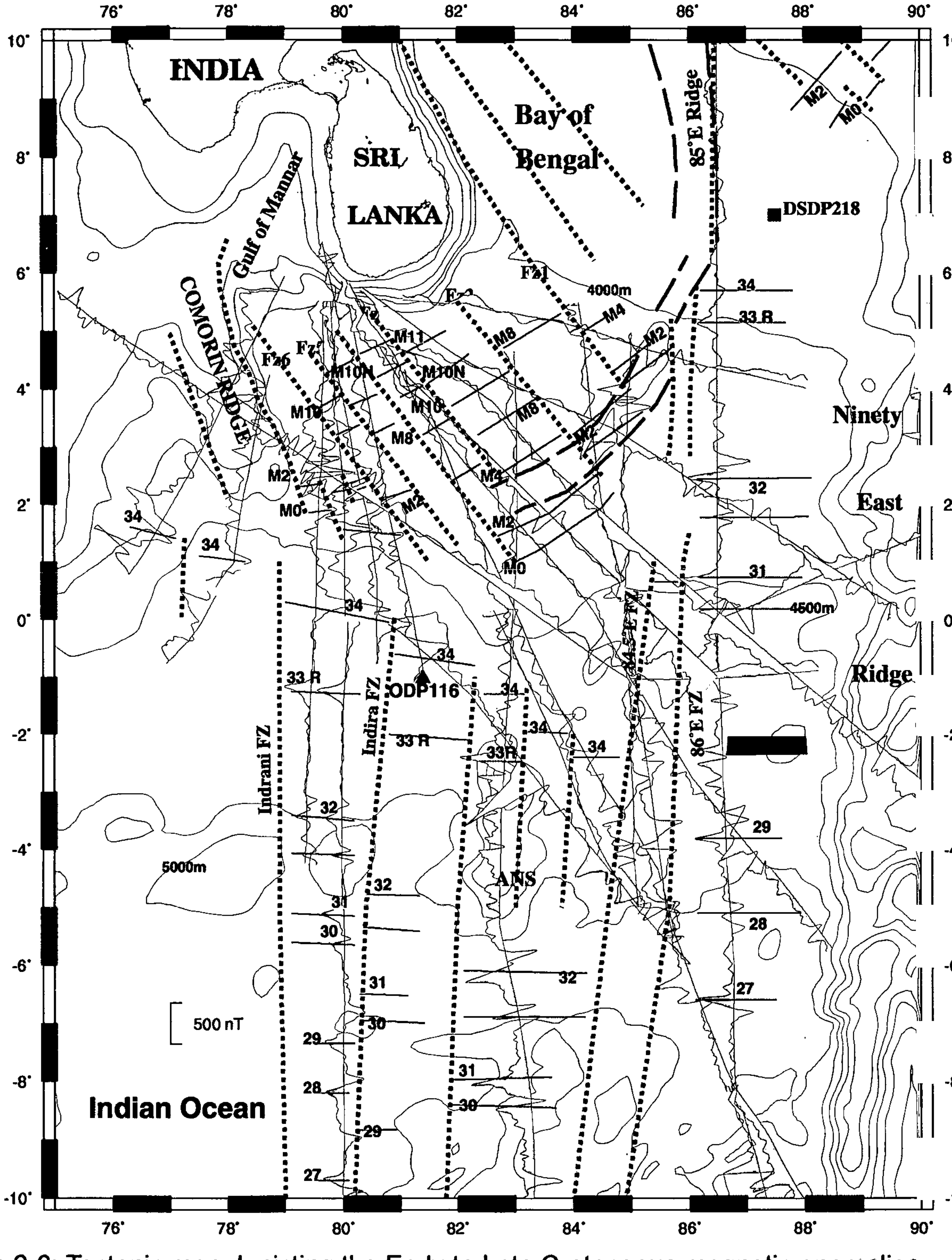


Figure 6-8: Tectonic map depicting the Early to Late Cretaceous magnetic anomalies (red) and fracture zones (black dashed) south off Sri Lanka (Desa et al., 2006). The trends of the fracture zones based on the offsets in successive magnetic anomalies are constrained by the satellite derived gravity mosaic. Bathymetric contours are shown as fine continuous lines. The southern extent of the 85°E Ridge is shown. Gray shaded box denotes a fossil spreading ridge (Royer et al., 1991).

place between Sri Lanka and Antarctica; and as a result, the Cauvery-Palk Strait-Gulf of Mannar Basin became a failed rift system. Curray (1984) further proposed that Sri Lanka acted as a mid-plate platelet moving slowly in a south-southeast direction relative to India during the Late Jurassic/Early Cretaceous. The NNW-SSE trending Comorin Ridge seen southwest of Sri Lanka has been interpreted as a structural crustal boundary (Kahle et al., 1981). The similarity in the trend of this ridge and seafloor spreading direction between India and Antarctica during the Early Cretaceous suggests that this ridge might have acted as a transform fault in the past.

The presence of Mesozoic magnetic anomalies was suspected in the Enderby Basin (Mizukoshi et al., 1986). Recently, several researchers (Ishihara et al., 2000; Joshima et al., 2001; Rotstein et al., 2001; Gandyukhin et al., 2002) have interpreted the presence of Mesozoic magnetic anomalies in the Enderby Basin. However, Ramana et al., (2001a[5]) based on a systematic analysis of marine magnetic data revealed the presence of Early Cretaceous crust in the Enderby Basin which is characterized by the Mesozoic magnetic anomalies M11 through M0. These anomalies evolved with half spreading rates varying between 6.5 and 2.8 cm/yr. More recently, an extinct spreading center with symmetric Mesozoic magnetic anomalies was inferred in a small corridor in the eastern Enderby Basin (Gaina et al., 2003). Stagg et al., (2004) extended the concept of the extinct spreading center to the western Enderby Basin. However,

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[5] *Ramana, M. V., Ramprasad, T. and Desa, M., 2001a. Seafloor spreading magnetic anomalies in the Enderby basin, East Antarctica, Earth Planet. Sci. Lett.,* ***191***: *241-255.*

Gaina et al., (2007) based on an updated database proposed that the extinct spreading center is limited only to the eastern Enderby Basin.

The present study indicates the presence of Early Cretaceous crust characterized by the Mesozoic magnetic anomalies M11 through M0 in the Central Bay of Bengal and the Enderby Basin. The presence of the entire Mesozoic sequence suggests that no ridge jump has occurred in these regions during the Early Cretaceous. Unequal spreading rates in these two basins have been attributed to asymmetric crustal accretion during this period.

**6.3.2 Middle Cretaceous Crust**

The spatial extent of the Middle Cretaceous crust can be seen between the location of the magnetic anomalies M0 and 34 (Fig. 6-7). The width of this crust is relatively small on the Indian plate than on its conjugate Antarctica plate. Ramana et al., (1997a) have inferred the presence of a magnetic quiet zone i.e. the crust formed during the Cretaceous long normal polarity super chron (120-84 Ma) in the southern Bay of Bengal. Desa et al., (2006) inferred the presence of Middle Cretaceous crust of ~170 km width, west of 80°E longitude, while towards east between 83 and 85°E longitudes, the width is ~500 km (Fig. 6-8). This Middle Cretaceous crust is estimated to have evolved with slower HSRs varying between 0.7 and 1.3 cm/yr.

The large left lateral offset of ~900 km of the chron 34 along 86°E longitude suggests that the 86°FZ/KFZ acted as a major transform fault during the Middle Cretaceous (Royer and Sandwell, 1989). In the western Enderby Basin, ridge reorganizations are inferred during the Cretaceous long normal polarity chron (Nogi and Kaminuma, 1999). The region south of Conrad Rise depicting cross trends in the satellite derived gravity mosaic (Fig. 6-7) belongs to this period. A change in spreading direction is obvious from these cross trends. Powell et al., (1988) predicted a change in spreading direction around 96 Ma in the form of northward ridge jumps. Thus, the unequal Middle Cretaceous crust between the two plates can be attributed to the occurrence of ridge jumps within this period.

### 6.3.3 Late Cretaceous Crust

Late Cretaceous-Cenozoic evolution of the Indian Ocean is well documented by interpretation of the seafloor spreading magnetic anomalies (Mckenzie and Sclater, 1971; Sclater and Fisher, 1974; Norton and Sclater, 1979; Curray et al., 1982; Schlich, 1982; Liu et al., 1983; Royer and Sandwell, 1989). This evolutionary phase began with the rapid movement of the Indian plate (>12 cm/yr) northwards till its collision with the Eurasian plate at ~54 Ma. This collision triggered the second major plate reorganization and resulted in formation of the present day mid-oceanic ridge system. Late Cretaceous to Tertiary magnetic anomalies 34 through 20 trend in an E-W direction and the anomalies are seen offset by several N-S trending fracture zones in the Central Indian Ocean Basin (McKenzie and Sclater, 1971; Schlich, 1982; Royer et al., 1989). The offsets are initially right lateral, west of the 86°E FZ, while along the

86°FZ, the magnetic anomalies 34 and younger are displaced left laterally by about 900 km (Sclater and Fisher, 1974).

Left laterally offset Late Cretaceous magnetic anomalies 32 and younger are interpreted in the Wharton Basin, east of the Ninetyeast Ridge (Liu et al., 1983). No magnetic anomaly identifications were made in the region, west of Ninetyeast Ridge and east of the 86°E FZ. However, recently, Desa et al., (2009) compiled geophysical data in the region between the 86°E FZ and Ninetyeast Ridge from 1°S to 9°N latitudes. Interpretation of marine magnetic data in this region revealed the presence of Late Cretaceous crust of age 84 and 68.7 Ma (chrons 34 through 31) evolved with variable and higher HSRs of 4.8 – 7.1 cm/yr. Model studies suggested the presence of fossil spreading ridge segments (FSR) and about 62-85 km extra oceanic crust. This extra crust is offset left laterally by N3°E trending FZs along with the adjacent oceanic crust (Fig. 6-9). Late Cretaceous magnetic anomalies 34 and younger are reported in Southern Crozet Basin, which is the conjugate of the Central Indian Ocean Basin (Schlich, 1975; 1982; Patriat, 1987; Royer and Sandwell, 1989). Several N28°E trending fracture zones offset these anomalies right laterally, while the major Kerguelen FZ offsets the anomalies left laterally by about 700 km. Seafloor spreading model studies suggested the absence of oceanic crust in some spreading corridors, equivalent to the amount transferred to the Indian plate (Desa et al., 2009).

The presence of a FSR and about 75 km extra crust on the Afanasy Nikitin seamount chain has been attributed to a southward ridge jump that

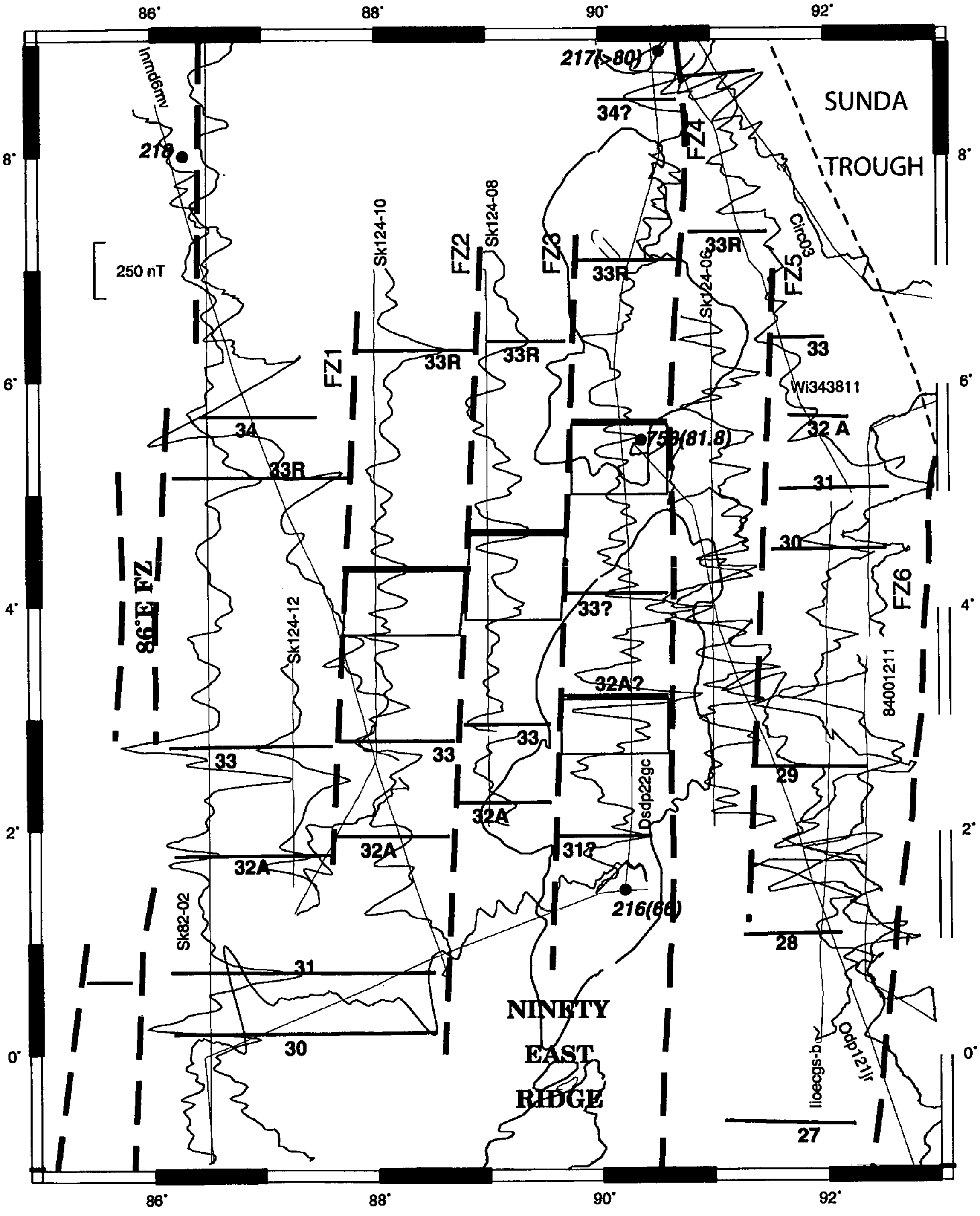


Figure 6-9 Tectonic map depicting the Late Cretaceous magnetic anomalies (continuous lines) in the region between the 86°E FZ and Ninetyeast Ridge (Desa et al., 2009). Fracture zones are shown as dashed lines. Continuous blue line depicts the 3000 m depth contour. Drill sites that reached and did not reach basement are indicated as black and red solid circles respectively. Age in m.y. of the oldest sediments/basement rocks is indicated in brackets. Thick black line represents the fossil spreading ridge segments, while light shaded box represents the inferred extra crust.

occurred around 75.8 Ma (Desa et al., 2009). The presence of extra crust and similar magnetic anomaly pattern on the Ninetyeast Ridge and Afanasy Nikitin seamount chain particularly between the chrons 33R and 33 strongly suggest a common evolution mechanism. The inferred extra crust has been captured from the Antarctica plate by southward ridge jumps as the spreading center tried to remain in the vicinity of the Kerguelen mantle plume during the northward motion of the Indian plate. Plume-ridge interaction is considered the main cause for the excess crustal accretion on the Indian plate during the Late Cretaceous.

## 6.4 The Kerguelen hotspot

The Kerguelen hotspot is one of the largest known volcanic source whose activity is recognized after the Early Cretaceous breakup between India and Antarctica (Colwell et al., 1994). Geophysical data and drilling results facilitated in the estimation of its magmatic output through time. The oldest lavas linked to the Kerguelen hotspot are basalt flows exposed at Bunbury, Western Australia (Frey et al., 1996). Coffin et al., (2002) provided $^{40}Ar/^{39}Ar$ data which suggest that the Bunbury lavas of ~85 m thickness were erupted in two phases, the first at ~130 Ma and the second at ~123 Ma. These ages are distinct from the ages of 100·6 ±1·2 Ma obtained from a basaltic andesite clast collected from the Naturaliste Plateau, located off Western Australia (Pyle et al., 1995). Thereafter, the lava pile of ~230 m thickness in the Rajmahal Hills, Jharkhand, and alkalic basalts in the Bengal Basin were emplaced at ~118 Ma (Kent et al., 2002). Magmatic activity in eastern India was contemporaneous with that on the

Southern Kerguelen Plateau (119–118 Ma). Lamprophyres emplaced southwest of the Rajmahal Hills and on the Antarctica margin appear to be ~2–3 m.y. younger than the Rajmahal Traps. Igneous material at Site 1137 on Elan Bank yielded an age of 110-105 Ma (Weis et al., 2001; Ingle et al., 2002). The Central Kerguelen Plateau (ODP Site 1138, ~100 Ma) and Broken Ridge (ODP Sites 1141/1142, ~95 Ma) were emplaced later (Frey et al., 2000; Duncan, 2002). Tholeiitic basalts from the Ninetyeast Ridge range in age from ~82 to ~37 Ma (Duncan, 1978). Basalt rocks drilled at site 1139 on Skiff Bank yielded ages of ~68 Ma (Coffin et al., 2002). An Oligocene age obtained by $^{40}Ar/^{39}Ar$ and biostratigraphic studies has been inferred for the Northern Kerguelen Plateau (ODP Site 1140, ~34 Ma). The most recent volcanism is observed on the Kerguelen Archipelago and the Heard and McDonald Islands (~29–0 Ma; Nicolaysen et al., 2000).

Volcanic provinces dot the Indian shield and their traces are found in the surrounding deep oceans (Curray and Munasinghe, 1991; Muller et al., 1993). Mantle plume activity has been reported in the Bengal Basin with the identification of underplated mantle material at the base of the continental crust. The NNW-SSE trending upwarp in Moho east of 87°E longitude maybe the probable trace of a plume in the northeastern continental margin of India (Mall et al., 1999). Mishra et al., (1999) inferred substantial rift magmatism in the coastal part of the Mahanadi Basin, India and Lambert Rift of Antarctica. Further, this magmatism is found absent in the Godavari basin, eastern India. Aeromagnetic study of the offshore Mahanadi Basin implies the presence of buried Cretaceous volcanic sequence directly over the Precambrian basement and magmatic underplating within the basement (Nayak and Rama Rao, 2002). Behera et al., (2004) reported the presence of a ~10 km thick, high velocity (7.5 km/s), high density (3.05 gm/cc) layer at the base of the crust in the Mahanadi delta. The observed Moho upwarping suggests basaltic underplating due to hotspot activity. These findings indicate that the northern region of the Eastern Continental margin of India has been influenced by hotspot activity of the Kerguelen mantle plume.

The Kerguelen hotspot was positioned far north before the dispersal of Eastern Gondwanaland continental fragments. After breakup, India moved in a northwesterly direction towards the Kerguelen hotspot during the Early Cretaceous. The arrival of the Kerguelen mantle plume below the Indian plate might have caused the eruption of a flood basalt most of which appears to be buried under the thick fill of the Indo-Gangetic plains and the Himalayan front, while the basalts of the Rajmahal and Sylhet Traps remain exposed. With continued movement in the same direction, the hotspot moved offshore from India into the Northeastern Bay of Bengal. Since the India-Antarctica spreading center was migrating northward in the absolute sense (Muller et al., 1998), over time it got centered on the Kerguelen hotspot causing a complex redistribution of the plume material along the spreading ridge segments. In short, a major plate reorganization took place accompanied by changes in spreading directions and rates. With the onset of north-south spreading, the hotspot moved southward away from the spreading center, but constant southward ridge jumps kept the spreading center in the vicinity of the hotspot. Finally, the hotspot jumped from the Indian plate to the Antarctica plate.

Northward ridge jumps have been inferred right from northwest Australia to the Elan Bank during the Early Cretaceous. Off northwest Australia, ridge jumps have been inferred after M8 time, while in southwest Australia, jumps have been inferred after M2 time (Robb et al., 2005). Two major ridge propagation events have been inferred during the Middle Cretaceous period in the Perth Basin (Muller et al., 2000). In the Princess Elizabeth Trough, ridge jumps have been inferred after M6 time (Gohl et al., 2008). Likewise, south of Elan Bank, a ridge jump has been inferred after M2 time (Gaina et al., 2003). All these ridge jumps have probably occurred under the influence of the Kerguelen mantle plume. Rotstein et al., (2001) suggested that during the Early Cretaceous, a triple junction may have existed at the location where the Kerguelen plateau was emplaced under the influence of the Kerguelen mantle plume.

## 6.5 Plate kinematics

### 6.5.1 AFR-ANT Scenario

A refined model for the Mesozoic breakup of Gondwanaland has been presented (Konig and Jokat, 2006). In Late Jurassic, seafloor spreading began between Africa and Antarctica in the Riiser-Larsen Sea-Mozambique Basin and Somali Basin after a long phase of extension and rifting. A strong positive anomaly of about 600 nT marks the onset of about 200 km wide transitional or rifted continental crust. Mesozoic magnetic anomaly sequence M24n (155 Ma) through M0 were identified based on aeromagnetic data in the Riiser-Larsen Sea (Jokat et al., 2003). The anomalies are offset left laterally by several NNE-SSW trending fracture zones. Inferred half-spreading rates range from 2.5 to 1 cm/yr since initial breakup to chron M0 (Fig. 6-10). This region is conjugate to the Mozambique Basin where Mesozoic magnetic anomalies M22 through M2 have been identified (Simpson et al., 1979).

The southern Astrid Ridge and the Gunnerus Ridge together with the Kainan Maru Seamount are continental fragments, which delimit the oceanic crust of the Riiser-Larsen Sea off Dronning Maud Land (Bergh, 1987). These ridges may have been highly stretched for at least 20 m.y. before breakup. It is clear that in the Africa-Antarctica corridor, there was a long period of continental thinning and differential extension, resulting in a broad zone of transitional crust on the Antarctica side before the onset of seafloor spreading. This transitional crust zone is relatively narrow on the African side probably suggesting crustal accretion asymmetry in the initial stages itself. This asymmetry could be due to the limited motion of the Antarctica plate in any direction on account of its boundaries being divergent in nature. These inferences suggest that continental breakup depends on variations in the strength of the lithosphere. The Gunnerus Ridge, Madagascar Ridge and other similar ridges of continental nature may owe their existence to this circumstance and/or detachment by strike-slip motion (Roeser et al., 1996).

### 6.5.2 IND-AUST Scenario

The Argo and Gascoyne Abyssal Plains in the easternmost Indian Ocean mark the last stages of eastern Tethys evolution before the breakup of Eastern Gondwanaland. With the identification of M25 as the oldest magnetic anomaly in the Argo and northern Gascoyne Abyssal Plains, continental breakup between Australia and an unknown landmass started in the Oxfordian (Larson, 1975; Heine and Muller, 2005). Continental breakup followed by NW-SE seafloor spreading and southwestward propagation of the spreading ridge between Greater India and Australia was inferred (Larson, 1977; Johnson et al., 1980; Powell et al., 1988). Integrated analysis of magnetic, gravity and seismic data suggested that continental breakup in the Cuvier Abyssal Plain started around 136 Ma (M14) and was followed by two rift propagation events: (i) between M10n and M4, and (ii) between M2 and M0, which transferred portions of the Indian plate to the Australian plate (Veevers et al., 1985; Mihut and Muller, 1998). Further, it was believed that these propagation events may have been caused by ridge-plume interaction, or, in a non-plume scenario, the spreading ridge may have abutted the Indian continental crust between breakup and chron M0 time. HSRs averaging to 4.0 cm/yr on the Australian plate, with slightly higher HSR of 4.6 cm/yr on the Indian plate between chrons M14 to M5 were calculated in the Cuvier Abyssal Plain. Lower HSRs, i.e. 3.2 –2.2 cm/yr were reported between chrons M5 and M1-r on the Australian plate.

The oldest magnetic anomaly identified in the Perth abyssal plain is M8 and two major ridge propagation events during the Middle Cretaceous period accreted large segments of the Indian Plate to the Australian Plate (Muller et al., 2000). The most likely cause for these ridge propagation events is the Kerguelen hotspot and the resultant hotspot-ridge interaction. Several stretched and subsided continental platforms such as the Exmouth Plateau, Wallaby Plateau, Zenith Plateau, Naturaliste Plateau, etc. are distributed off Western Australia. Some of these plateaus are underlain by volcanic basement, while some are characterized with continental rocks. Several fracture zones such as the Cape Range, Perth, Naturaliste and Leeuwin FZs belong to the Mesozoic seafloor spreading system (Rotstein et al., 2001). Further, it is inferred that the onset of seafloor spreading in the Enderby Basin occurred simultaneously to that in the Perth Basin.

### 6.5.3 IND-ANT Scenario

Eastern Gondwanaland started fragmenting in the Late Jurassic with Greater India separating from Australia since chron M25 in a NW-SE direction. Simultaneously, early seafloor spreading initiated between Africa and Antarctica on the west since chron M24. Continental breakup and subsequent seafloor spreading between India and Antarctica occurred as a westward extension of the same ridge that separated Greater India from Australia, and was devoid of intense volcanic activity (Johnson et al., 1980). Further, Rotstein et al., (2001) suggested that the breakup between Greater India, Australia and Antarctica may have been a three-plate system in the Early Cretaceous in the NW-SE direction and the triple junction may have existed at the location of the Kerguelen plateau (Fig. 6-10).

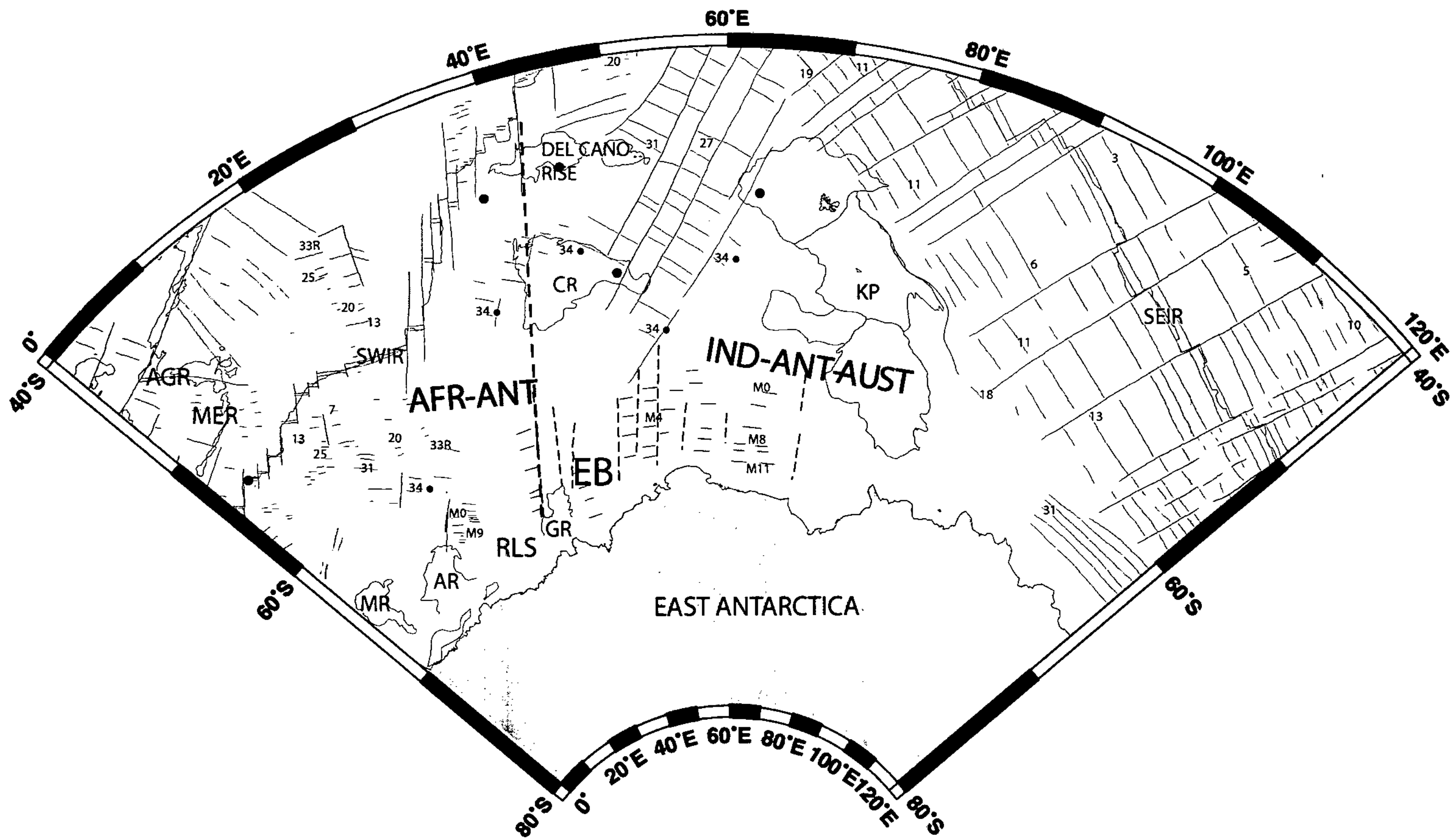


Figure 6-10 Tectonic map off East Antarctica depicting the breakup and seafloor spreading scenario between Africa/Antarctica and India/Antarctica/Australia. Identified magnetic anomalies are shown in red with some numbered. Fracture zones are marked as black lines (Royer et al., 1989). Magnetic anomalies and fracture zones inferred in the present study are shown as pink and dashed lines respectively. Spreading corridors are indicated. EB: Enderby Basin; MR: Maud Rise; AR: Astrid Rise; CR: Conrad Rise; KP: Kerguelen Plateau; SWIR: Southwest Indian Ridge; SEIR: Southeast Indian Ridge; MER: Meteor Rise; AGR: Agulhas Ridge; RLS: Riiser-Larsen Sea; GR: Gunnerus Ridge

The presence of Mesozoic magnetic anomalies was suggested in the Bay of Bengal (Curray and Munasinghe, 1991). The Mesozoic magnetic anomaly sequence M11 through M0 was identified in the Central Bay of Bengal (Ramana et al., 1994b) and south of Sri Lanka (Desa et al., 2006). Different Mesozoic magnetic anomaly identifications were made in the Enderby Basin (Fig. 2-13; Ishihara et al., 2000; Joshima et al., 2001; Rotstein et al., 2001; Ramana et al., 2001a; Gandyukhin et al., 2002; Stagg et al., 2004). Gaina et al., (2003) suggested the presence of magnetic anomalies M9 to M2 symmetric about an extinct spreading center in a narrow corridor south of Elan Bank in the eastern Enderby Basin.

Recent plate reconstruction models place the Elan Bank against the East coast of India between the Krishna-Godavari and Mahanadi offshores and postulate that a northward ridge jump around chron M2 transferred it along with the Mesozoic crust of the Bay of Bengal to the Antarctica plate (Gaina et al., 2003). Further, Gaina et al., (2007) based on an updated geophysical database proposed an alternative model for the evolution of the Enderby Basin. The model suggested that the northward ridge jump was limited to the Elan Bank region, whereas normal seafloor spreading continued in the western Enderby Basin. The Mesozoic magnetic anomaly sequence M9 through M0 were inferred in the western Enderby Basin, while in the eastern Enderby Basin, symmetric sets of magnetic anomalies M9 through M2 were inferred. Thus, it was ascertained that not all the Mesozoic crust from the Indian plate has been transferred to the Antarctica plate.

The interpretations (magnetic anomalies and fracture zones) made in the present study are plotted onto the position maps of the Bay of Bengal and Enderby Basin (Figs. 5-4 & 5-7). The fracture zones represent the flow lines along which the plates moved after breakup, while the magnetic anomalies indicate the ages of the underlying crust. The interpretation based on the synthesis of all the results indicates that the breakup of India from Antarctica occurred prior to the formation of anomaly M11. Figure 6-11 depicts the extent of the Mesozoic (Early to Late Cretaceous) crust in the Central Bay of Bengal and off Sri Lanka. The fracture zone orientations indicate the ~NW-SE direction of the Indian plate motion during the Early Cretaceous. The unequal width of the Middle Cretaceous crust suggests the occurrence of a major plate reorganization with changes in spreading rates and directions and/or ridge jumps. The E-W trending Late Cretaceous magnetic anomalies suggest the northward motion of the Indian plate from Antarctica.

The presence of the Mesozoic magnetic anomaly sequence M11 through M0 in the Bay of Bengal endorse the fact that not all the Mesozoic crust from the Indian plate has been transferred to the Antarctica plate (Fig. 6-11). Since the complete Mesozoic magnetic anomaly sequence M11 through M0 is present in both the Enderby Basin and Central Bay of Bengal, it is also evident that no ridge jump has occurred prior to the formation of magnetic anomaly M0 (Figs. 5-4 & 5-7). Further, the Kerguelen Plateau along with the Elan Bank lies north of the M0 chrons identified in the present study (Fig. 5-7). Hence, if any ridge jump has occurred to separate Elan Bank from India, it may have occurred during the

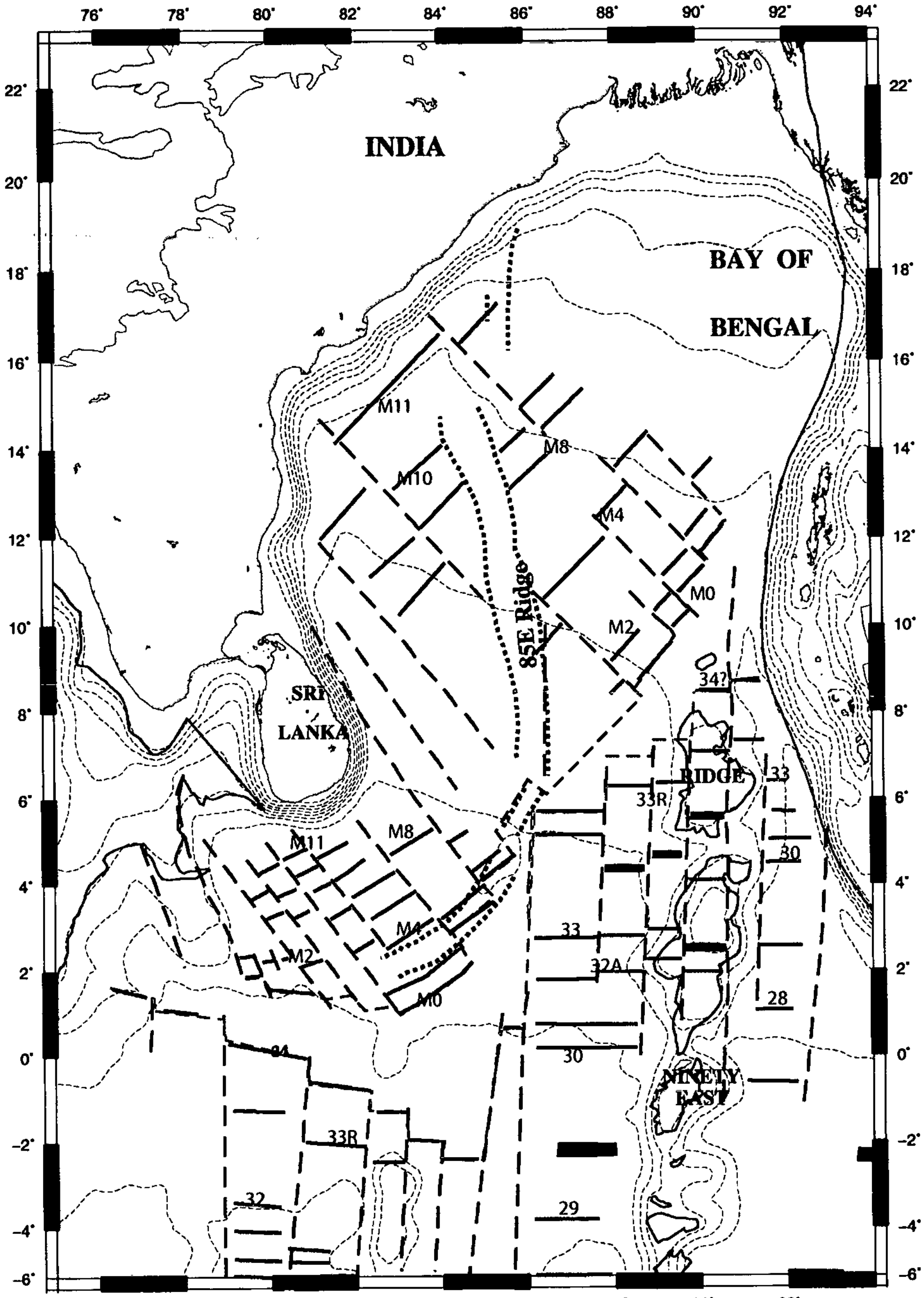


Figure 6-11 Combined tectonic summary chart of the Bay of Bengal inferred from the present study and earlier works (Ramana et al., 1994b; 2001a; Sclater and Fisher, 1974; Royer et al., 1989; 1991; Desa et al., 2006; 2009). Fossil spreading ridges are shown as gray boxes. Fracture zones and magnetic anomalies are shown as dashed and red lines respectively. Sunda Trough is shown as green line. The boundaries between Early and Middle Cretaceous crusts, and Middle and Late Cretaceous crusts are shown in blue and pink respectively.

Middle Cretaceous time. Plate reconstruction models (Figs. 6-1 to 6-5) suggest that Elan Bank may have evolved from a location situated north of 17°N latitude along the ECMI, and not between the Krishna-Godavari and Mahanadi offshores. The crust on the Indian plate conjugate to the crust south of Elan Bank might have subducted beneath the Sunda Trough.

The magnetic anomalies and fracture zones inferred in the present study have been used to define the plate boundaries and motions during different ages. The extent of the oceanic crust provinces bearing different ages on these conjugate margins has been traced and shown in figures 6-12 & 6-13. Figure 6-12 depicts the presence of Early to Late Cretaceous crust in the Central Bay of Bengal. Magnetic anomaly M11 is the oldest anomaly occurring off the Eastern Continental margin of India. Thereafter, the younger Mesozoic magnetic anomalies upto M0 are seen offset by ~NW-SE trending fracture zones. The subsurface 85°E Ridge traverses through the Early Cretaceous crust and may have contributed 100-150 km to the ~800 km extent of the Early Cretaceous crust in the Bay of Bengal. This may be one of the reasons for the inferred relatively high (~6 cm/yr) half spreading rates during the Early Cretaceous. The extent of the Late Cretaceous crust is seen towards the southeast in the Bay of Bengal. This crust has evolved in a N-S direction and its oldest boundary represented by the 34 chron depicts left lateral offsets. Further east, the oceanic crust appears to be subducting into the Sunda Trough. The Middle Cretaceous crust sandwiched between the Early and Late Cretaceous crusts is a narrow zone characterized with variable width.

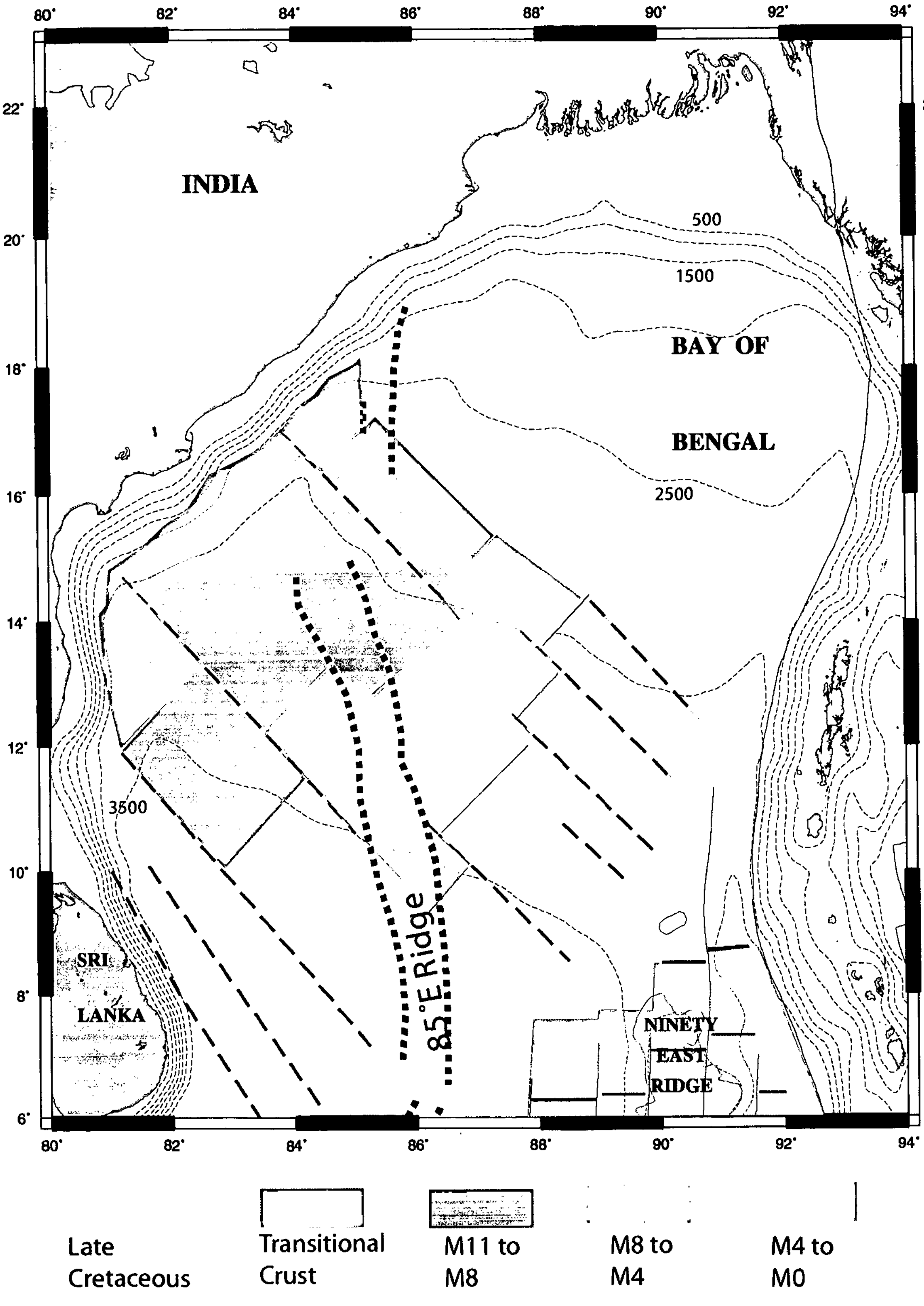


Figure 6-12: Age provinces as derived from the integrated interpretation of geophysical data in the Bay of Bengal as per given colour code. Fracture zones are shown as thin dashed lines. The extent of the 85°E Ridge is shown with a pair of thick dashed lines. Bathymetry contours with interval 500 m are shown as very thin dashed curves.

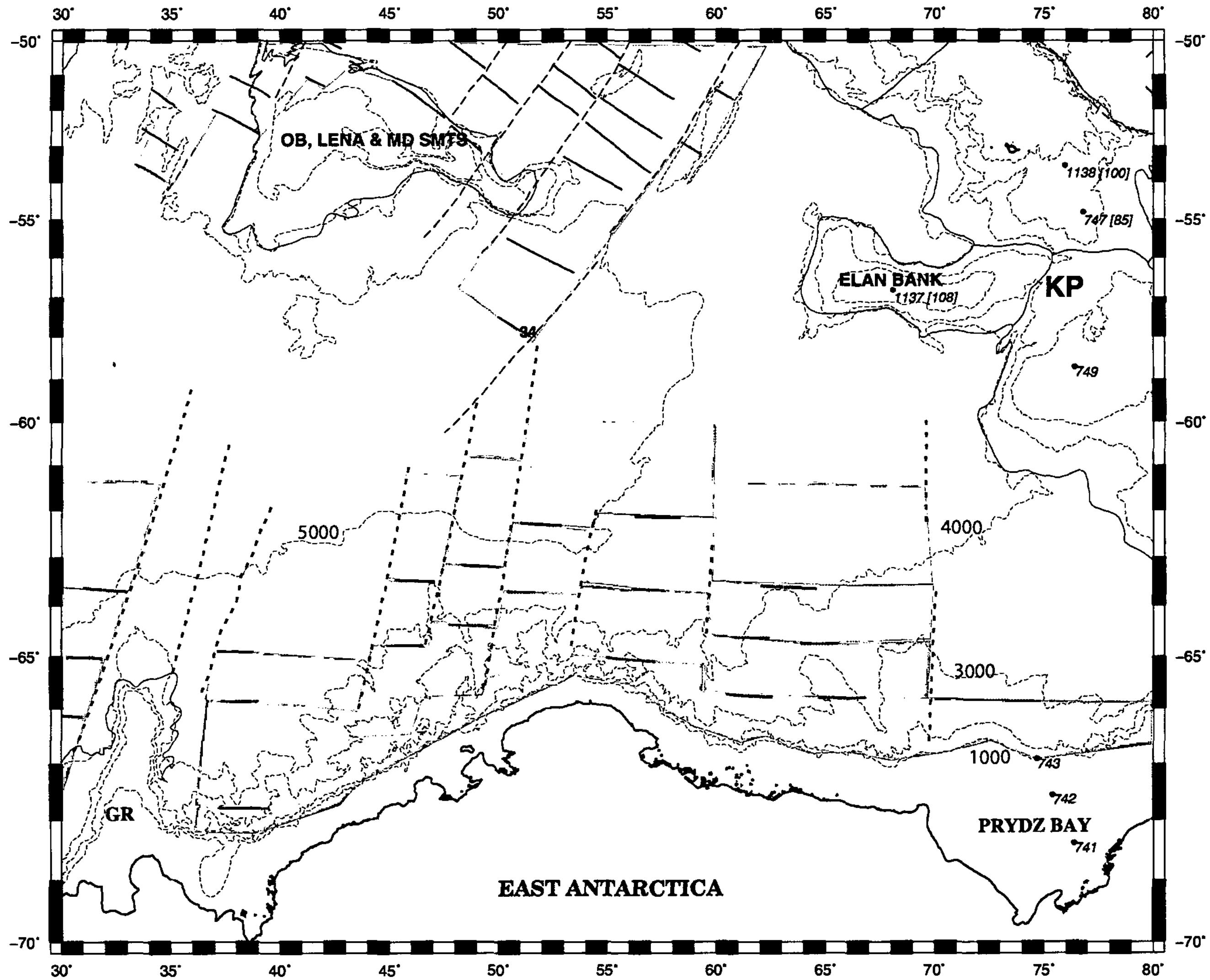


Figure 6-13: Age provinces as derived from the integrated interpretation of geophysical data in the Enderby Basin. Colour code as shown in figure 6-12. Fracture zones are denoted as thin dashed lines. Bathymetry contours with interval 1000 m are shown as very thin dashed curves. Drill sites are indicated as black dots with numbers and basement age. GR: Gunnerus Ridge; KP: Kerguelen Plateau

Figure 6-13 depicts the presence of Early to Late Cretaceous crust in the Enderby Basin. Magnetic anomaly M11 is the oldest anomaly occurring closest to the coast followed by the younger Mesozoic magnetic anomalies upto M0 offset by N5-10°E trending fracture zones. About 550 km crust of Early Cretaceous age is generated at slightly lower half spreading rates (~5 cm/yr) as compared to its conjugate, the Bay of Bengal. Late Cretaceous crust occurs in the northwestern Enderby Basin and the oldest anomaly 34 lies just north of the Ob, Lena and Marion Dufresne seamount chain. This crust has been generated in a N28°E seafloor spreading direction as indicated by the trend in the fracture zones. The Middle Cretaceous crust sandwiched between the Early and Late Cretaceous crusts is of variable extent suggesting that this period was characterized by changes in seafloor spreading rates and directions, and /or occurrence of ridge jumps.

Detailed analyses of geophysical data in the two study areas (Bay of Bengal and Enderby Basin) therefore suggest that the early breakup between the two plates (India and Antarctica) occurred prior to the formation of magnetic anomaly M11. The Indian plate moved in the NW-SE direction away from the contiguous Antarctica-Australian plate from chron M11 to M0 time. During the Middle Cretaceous, the first major plate reorganization took place in the form of changes in seafloor spreading rates and directions, and/or occurrence of ridge jumps. This reorganization resulted in unequal widths of the Middle Cretaceous crust in the conjugate basins. The Kerguelen Plateau and Conrad Rise were emplaced on the Antarctica plate, and the subsurface 85°E Ridge on the Indian plate during this period. In the Late Cretaceous, the Indian plate moved in a N-S direction away from Antarctica till it collided with the Eurasian plate. This collision triggered the second major plate reorganization wherein spreading rates and directions changed. A new mid-oceanic ridge system was formed with seafloor spreading in a NE-SW direction, which prevails to date. Refined plate reconstruction models presented in this thesis traced the evolutionary history of the conjugate basins, Bay of Bengal and Enderby Basin in time and space.

# Chapter 7

# *Conclusions*

Detailed analyses of ~47,000 km of bathymetry, magnetic and gravity data under the constraints of multichannel seismic reflection and satellite derived gravity data in the Bay of Bengal and Enderby Basin revealed the following significant conclusions.

## 7.1 Geophysical signatures

### 7.1.1 Bathymetry

The depth to the seabed varies between <200 m (shelf/upper slope) in the Eastern continental margin of India and ~5000 m in the distal Bengal Fan (Fig. 4-1). The continental shelf is narrow and its width ranges between 17 km off Karaikal and 200 km off Bengal coast. The continental slope is steep in the southern ECMI, whereas it is gentle in the north (Fig. 4-2). The seabed topography in general is relatively smooth, except for the sporadic presence of micro topography undulations of the order 10-500 m (Figs. 4-6 to 4-8). These undulations are mostly in the form of turbidity channels with levee wedges responsible for the sediment transport from the apex to the distal Bengal Fan. The elongated positive bathymetry along the 90°E longitude south of 10°N latitude corresponds to the Ninetyeast Ridge (Fig. 4-9a). Few topographic rises are seen in the distal Bengal Fan, the most prominent one belonging to the Afanasy Nikitin seamount chain (Fig. 4-9c).

Study of bathymetry data along the geophysical tracks, GEBCO database and predicted topography derived from satellite gravity data in the Enderby Basin reveals that the entire East Antarctica offshore is characterized with irregular topography (Figs. 4-15 to 4-18). The continental shelf has variable width and an average depth of 500 m. The slope is not well defined and is characterized with spur and canyon topography. The depth to the seabed attains >5000 m in the northwestern side of the basin, while it is <2000 m on the Kerguelen Plateau, Conrad Rise and the Gunnerus Ridge.

### 7.1.2 Gravity

A steep gradient free-air gravity anomaly running almost parallel to the coast is observed along the Eastern Continental margin of India and may represent the Continent-Ocean Boundary. The NNE-SSW to NE-SW trending gravity anomalies of the ECMI depict the alignment of the paleo-spreading ridge and growth of the seafloor. The large negative free-air gravity anomaly observed along the 85°E longitude corresponds to the subsurface 85°E Ridge (Figs. 2-6 & 2-7). The axis of the gravity low takes an arcuate shape southeast of Sri Lanka and appears to be abut with the northern extension of Afanasy Nikitin Seamount chain. The Ninetyeast Ridge, a trace of Kerguelen hotspot is characterized with positive gravity field. N-S trending lineations representing fracture zones are seen in the southern Bay of Bengal.

The satellite derived free-air gravity mosaic shows distinctly the subsurface crustal characteristics of the Enderby Basin (Fig. 2-10). The steep gradient gravity anomaly beyond shelf break appears to represent the COB. Several N5-10°E trending lineations representing fracture zones are prominent in the western Enderby Basin. The eastern Enderby Basin lacks such fracture zone imprints due to the presence of a thick sediment overburden. The Kerguelen Plateau and Conrad Rise are associated with positive gravity signatures, while the ~NE-SW trending Kerguelen Fracture zone is seen with a strong negative gravity signature.

### 7.1.3 Subsurface configuration

Analysis of multichannel seismic reflection sections in the Bay of Bengal reveals the presence of nine seismic sequences and eight prominent unconformities (Figs. 4-10 & 4-11). The uppermost sequences (D to I) attain maximum thickness towards offshore and comprise the sediments brought in predominantly by the Ganges and Brahmaputra rivers that drain the Himalayas. These sediment sequences are known as the post-fan sediments. The lower sequences (A to C) are typical continental rise sediments, which thicken towards the coast and are termed the pre-fan sediments. The bottommost reflector represents the acoustic basement and has been categorized based on the reflection characteristics as continental, transitional and oceanic. A narrow continent-ocean transition zone characterized by intrusives is seen beyond the continental shelf. The oceanic crust is identified based on the prominent reflection of the Moho at ~10 s TWT. The thick

(~10 km) sediment overburden indicates that the underlying crust is very old. An Early Cretaceous age has been inferred for the oceanic crust based on the interpretation of magnetic data. Forward modeling of the potential data suggests that the transition zone is comprised of low density material along the section KG-01 in the Krishna-Godavari offshore and some mafic intrusives along the section MN-01 situated further north (Figs. 5-10 & 5-11).

Seismic section MN-01 across the subsurface 85°E Ridge shows that it is a complex basement high which might have developed by several episodes of magmatic material expulsion (Fig. 5-9). The uplift of sequence A and the truncation of sediment sequences B and C suggest that the ridge was emplaced on the pre-existing crust of 5-15 m.y. age, probably during the Middle Cretaceous. The Moho reflector is undulatory and occurs at ~9.5 s TWT in the vicinity of the ridge. Modeling of potential field data suggests that the magmatic intrusion within the ridge is normally magnetized and characterized with density of 2.85 gm/cc (Fig. 5-11). The ridge is adjoined by high density intrusive bodies to its west and oceanic crust to its east.

Seismic studies in the Enderby Basin reveal the presence of a thick pile of sediments on the continental shelf. The shelf edge and upper slope are underlain by a major fault controlled basin. Beyond the slope, the basement downfaults by at least 6 km (Stagg et al., 2004). The continent-ocean transition zone of <100 km width in the west broadens to >300 km in the east at ~58°E longitude. The transitional crust has been divided into two types ecot1 and ecot2 based on the degree of faulting (Stagg et al., 2005). The oceanic crust in the Enderby Basin has been classified into several distinct types (ebo1 to ebo10). The continental margin and corresponding offshore regions of the Enderby Basin have been divided into 3 zones (west of 52°E; 52-58°E, and 58-76°E longitudes) based on seismic results and geophysical signatures.

### 7.1.4 Magnetic analysis

Magnetic anomalies observed in the Bay of Bengal in general are subdued and characterized by broad wavelength. The Ninetyeast Ridge is seen associated with irregular and high frequency magnetic anomalies, while the 85°E Ridge is characterized with high amplitude and large wavelength magnetic anomalies (Fig. 5-2). Synthetic seafloor spreading model studies suggest that the best fit between the observed data and synthetic model can be obtained with a paleolatitude of 50°S. Model studies further facilitated the identification of Mesozoic magnetic anomaly sequence M11 through M0 in the Bay of Bengal (Fig. 5-3). The Mesozoic magnetic anomaly M11 is seen just off the ECMI between latitudes 12 to 18°N (Fig. 5-4). This magnetic anomaly is followed by the entire younger sequence upto M0 in the Central Bay of Bengal. The Early Cretaceous crust has evolved with variable half-spreading rates, which vary from 5.9 to 8.6 cm/yr. A part of the Early Cretaceous crust is interrupted by the subsurface 85°E Ridge. The presence of oceanic fracture zones Fz1 to Fz7 has been inferred from the offsets in the successive magnetic anomaly isochrons. The inferred NW-SE trend of these fracture zones has been constrained by the satellite derived gravity mosaic.

Seafloor spreading model studies carried out in the Enderby Basin, East Antarctica suggest the presence of Mesozoic magnetic anomalies (M11 through M0) similar to those inferred in the Bay of Bengal. In this basin also, the oldest magnetic anomaly M11 occurs close to the coast (Figs. 5-6 & 5-7). Magnetic model studies further suggest that the oceanic crust was evolved with half-spreading rates of 4.5 to 7.5 cm/yr during the Early Cretaceous. Oceanic fracture zones have been inferred from the observed offsets in the successive magnetic anomaly isochrons. A N5-10°E trend of these fracture zones has been constrained using the satellite derived gravity mosaic.

## 7.2 Evolution of conjugate basins

Plate reconstruction models have been generated for different chrons using the new constraints. i.e. oceanic fracture zones and magnetic anomaly lineations identified in this study (Figs. 6-1 to 6-5). A good correspondence of the inferred fracture zones and anomaly locations strongly suggests that the generated models represent the scenarios prevailing during the evolution of these conjugate margins, the Bay of Bengal and Enderby Basin. These reconstruction models facilitated in tracing the complete breakup and evolutionary history of these margins since the Early Cretaceous.

The present study suggests that continental breakup between India and the contiguous Antarctica-Australia began in the Early Cretaceous before 133 Ma since magnetic anomaly M11 is the oldest chron occurring close to the Eastern Continental margin of India and Enderby offshore. Greater India moved away from Antarctica in a NW-SE direction and this movement continued till 120 Ma. The presence of the complete Mesozoic magnetic anomaly sequence M11 through M0 in the Central Bay of Bengal and its conjugate, the Enderby Basin suggests that no ridge jump has occurred in these regions during the Early Cretaceous period.

Thereafter, the first major plate reorganization took place during the Middle Cretaceous. This period was characterized by very slow spreading and ridge jumps resulting in the generation of unequal oceanic crust on either side of the spreading center. The Conrad Rise and the Kerguelen Plateau might have emplaced during this period. The Indian plate motion changed from the initial ~NW-SE during the Early Cretaceous to N-S in the Late Cretaceous (Fig. 6-7). The rapid northward movement of the Indian plate from Antarctica slowed with the collision between the Indian and Eurasian plates, which triggered the second major plate reorganization. The resultant changes in seafloor spreading and ridge jump occurrences culminated into the formation of the present day mid-oceanic ridge system.

The magnetic anomaly identifications and fracture zone inferences facilitated in defining the different age crustal provinces in the conjugate basins (Figs. 6-12 &

6-13). Refined plate reconstruction models presented in this thesis traced the evolutionary history of these conjugate margins in time and space.

## 7.3 Limitations and future scope of work

Inadequate geophysical data in the Enderby Basin has constrained the interpretation in the present study to a certain extent. However, the satellite derived gravity field facilitated in deriving trends and boundaries of the structural features such as fracture zones, ridges, etc. in both the conjugate margins. Dense coverage of geophysical data with the appropriate orientation is required in the Enderby Basin to update the existing database. Interpretation of an updated database would have resolved unambiguously the timing of separation of India from the contiguous Antarctica-Australia and validated the proposition of the existence of a fossil spreading ridge in the Enderby Basin.

The magnetic interpretation in the Bay of Bengal has been confined to the Central region only. Additional magnetic data along closely spaced tracks in the Northern Bay of Bengal would facilitate in unraveling the evolution of the entire Bay of Bengal. Additional multichannel seismic data in the Bay of Bengal and its interpretation is essential to derive the micro tectonics and evolution of these conjugate margins. The understanding of the subsurface 85°E Ridge can be greatly improved by an integrated geophysical approach.

Lack of ground truth data in the form of geochronology of the basement/oceanic rocks remains a critical limitation to confirm the ages deduced from magnetic anomalies in the Bay of Bengal and Enderby Basin. Thus, it is vital to obtain the ground truth data by deep drilling to solve the long pending issue of age and nature of the underlying crust in these conjugate margins.

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## List of Publications of Maria Ana Desa


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