

# **Aseismic ridges of the northeastern Indian Ocean**

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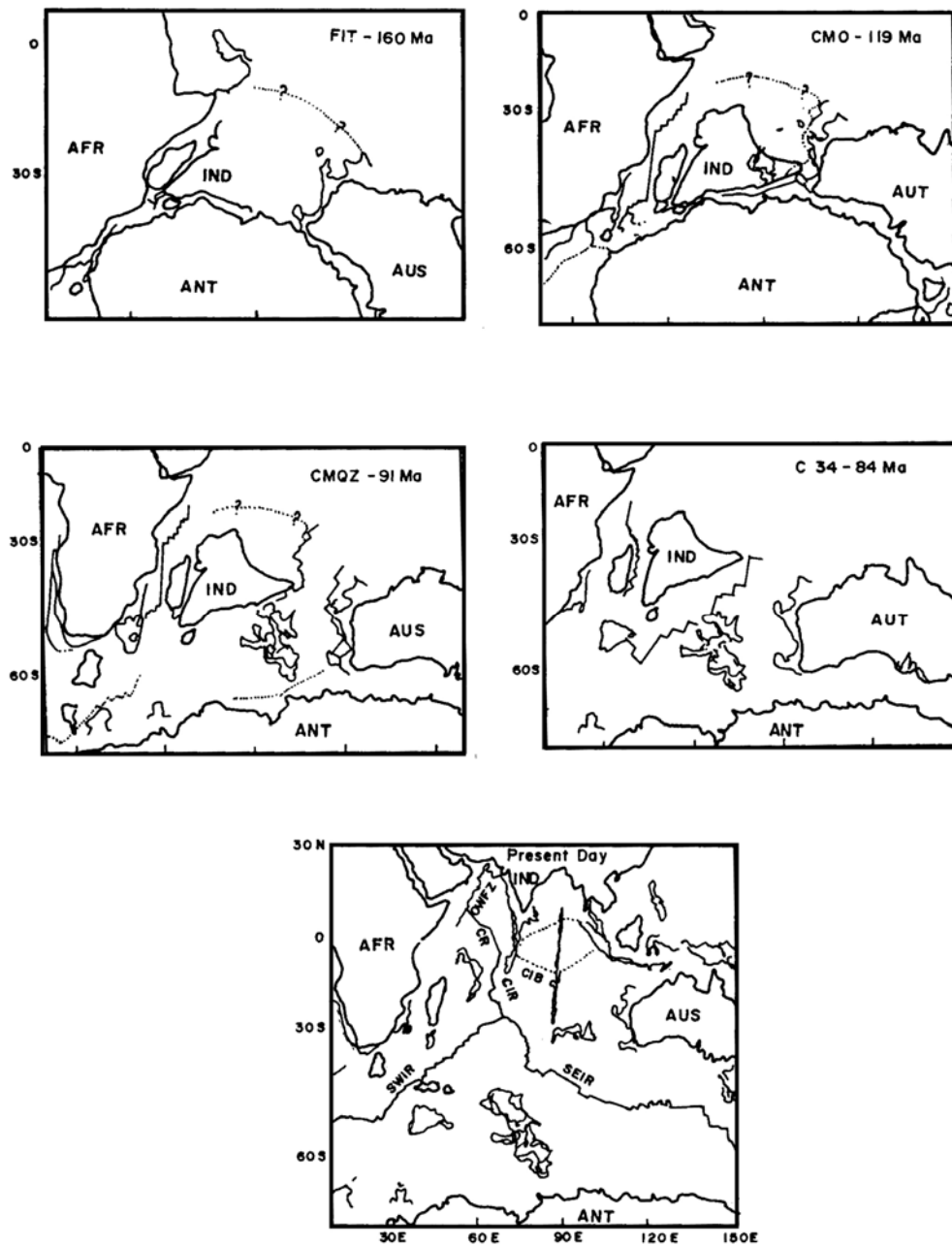
## **Aseismic ridges of the northeastern Indian Ocean**

### **2.1 Evolution of the Indian Ocean**

The initiation of the Indian Ocean commenced with the breakup of the Gondwanaland super-continent into two groups of continental masses during the Mesozoic period (Norton and Sclater, 1979). The first split of the Gondwanaland may possibly have associated with the Karoo mega-plume (Lawver and Gahagan, 1998). Followed by this rifting phase, during the late Jurassic, the Mozambique and Somali basins have formed by seafloor spreading activity of series of east-west trending ridge segments. Thus, the Gondwanaland super-continent divided into western and eastern continental blocks. The Western Gondwanaland consisted of Africa, Arabia and South America, whereas the East Gondwanaland consisted of Antarctica, Australia, New Zealand, Seychelles, Madagascar and India-Sri Lanka (Figure 2.1). After initial break-up, the East Gondwanaland moved southwards from the West Gondwanaland and led to gradual enlargement of the intervening seaways between them (Bhattacharya and Chaubey, 2001). Both West and East Gondwanaland masses have further sub-divided during the Cretaceous period. Approximate reconstructions of continental masses of the Gondwanaland from Jurassic to Present illustrating the aforesaid rifting events are shown in Figure 2.1 (Royer et al., 1992).

The opening of the western Indian Ocean started in early Cretaceous period with the rifting of Antarctica-Australia from Madagascar-Seychelles-India fragment at about 133 Ma (Holmes and Watkins, 1992). After about 15 Myr, followed by a major change in spreading pattern the Madagascar-Seychelles- India block again joined with the African plate (Besse et al., 1988). Thus, it is believed that the oldest oceanic crust of the Indian Ocean lies along the eastern margin of the African Continent.

The evolution of eastern Indian Ocean consists of three distinct phases of spreading and two major plate reorganizations. The first phase of spreading started during early Cretaceous in NW-SE direction resulting the drifting of Greater India from the Australia-Antarctica block (Curry et al., 1982; Gopala Rao et al., 1997; Gaina et al., 2003; Krishna



**Figure 2.1** Reconstruction of Gondwana super-continent blocks from Jurassic to Present (after Royer et al., 1992).

et al., 2009a). Subsequently, at about 120 Ma the Elan Bank, a micro-continent, which presently lies on the western margin of the Kerguelen Plateau in the southern Indian Ocean, separated from the present-day eastern margin of India (Gaina et al., 2003, 2007; Borissova et al., 2003; Krishna et al., 2009a). These breakup sequences suggest that most part of the oceanic crust in the Bay of Bengal was evolved during the Cretaceous Magnetic Quiet Period (120-83 Ma) as shown in Figure 2.1.

During the mid-Cretaceous, the second phase of spreading initiated approximately in north-south direction causing the first major plate organization in the Indian Ocean. Since then, India drifted northward from Antarctica continent (McKenzie and Slater, 1971), while Australia drifted away from Antarctica in NE direction by the spreading processes of Australia-Antarctica Ridge (Cande and Mutter, 1982; Veevers, 1986). During this period, spreading along India-Madagascar Ridge caused drifting of India from Madagascar-Seychelles (Norton and Sclater, 1979). These processes eventually led to the opening of Crozet, Wharton, Mascarene and Central Indian Basins (White and McKenzie, 1989; Storey et al., 1995) and establishment of a three-plate system: Antarctica, Africa and Indo-Australian, with a triple junction (Rodriguez Triple Junction) at a geographical position, 25°S latitude and 69°E longitude.

During the period close to the K-T boundary age, Seychelles rifted away from the Western India paving the way for the formation of the Carlsberg Ridge (McKenzie and Sclater, 1971; Norton and Sclater, 1979; Naini and Talwani, 1983; Royer et al., 2002; Chaubey et al., 2002). Concurrently, spreading along the Carlsberg Ridge led to the opening of conjugate Arabian and Eastern Somali basins. During this period the Indian and Arabian plates were moving along a fracture zone, the ancestor of Owen Fracture Zone, which connected the Carlsberg Ridge System and the Subduction zone in the Neo-Tethys region (Bhattacharya and Chaubey, 2001).

The northward flight of Greater India slowed down due to the collision of Indian Continent with southern Asian subduction zone in early Eocene. The first encounter, probably a soft collision between the greater India and an Island arch seaward of a marginal basin must

have occurred about 53 Ma (Curray et al., 1982). Subsequently at about 42 Ma, Wharton Spreading Ridge became inactive and jumped towards south (Liu et al., 1983; Krishna et al., 1995), and this led to the unification of India-Antarctica Ridge and Australia-Antarctica Ridge into the present day Southeast Indian Ridge (SEIR). In this process, Australian plate did merge with the Indian plate and formed a single Indo-Australian plate, resulting the second major plate reorganization in the Indian Ocean. The third phase of spreading (middle Eocene to Present) started in NE-SW direction along SEIR, which resulted the opening of Australian and Antarctic basins, north Crozet basin and southern part of the Central Indian Basin (Schilich, 1982).

After the India-Eurasia collision tectonics, the spreading centers in western Indian Ocean reorganized. Spreading along the Central Indian Ridge (CIR) and some ridge jumps during the early Oligocene resulted the separation of Chagos Bank from Nazareth Bank (Duncan, 1990). The continued spreading along CIR and Southwest Indian Ridge (SWIR) led to move the African plate towards northeast direction.

The next major event took place during the middle Miocene - the Carlsberg Spreading Ridge propagated westward as Sheba Ridge and led to the opening of the Gulf of Aden (Laughton et al., 1970). The oceanic crust north of the Indian subcontinent has largely subducted, as a result the Indian subcontinent collided with the Eurasian continent, generally referred as “Hard Collision”, which resulted the initial upliftment of the Himalayas (Curray et al., 1982). The rapid uplift and subsequent erosion of Himalayas resulted huge sediment deposition in both ocean regions: Bay of Bengal and Arabian Sea, adjoining the Indian continental regions. Within the central Indian Ocean, the collision tectonics and rapid upliftment of Himalayas accumulated compressional stresses leading to periodic deformation of oceanic lithosphere between India and Australia since about 15.4-13.9 Ma (Krishna et al., 1998, 2009b). The subduction of northeastern Indian plate below the South Asian plate resulted the Andaman Island Arch – trench system (Curray et al., 1982). The extrusive tectonics, rifting and seafloor spreading activity since 4 Ma resulted the formation of Andaman backarc basin (Kamesh Raju et al., 2004).

Several mantle plumes have significantly influenced the evolution of the Indian Ocean lithosphere at different geological ages. Initial plume head interaction with continental lithosphere caused Large Igneous Provinces (LIP), subsequently in oceanic region plume trails produced aseismic ridges, seamount chains and plateaus. Marion, Kerguelen and Reunion hotspots are the most prominent among the Indian Ocean hotspots, which had major role on the geodynamic history of the ocean. The locations of major hotspots along with tectonic and physiographic features of the Indian Ocean are shown in Figure 2.2.

The Marion hotspot is believed to be the most ancient one (over 184 m.y age) among the present day global hotspots and believed to have formed the Karoo flood basalts in South Africa (Morgan, 1981). During the late Cretaceous period the Marion hotspot was under India-Madagascar block and caused for wide spread volcanism in Madagascar and southwest India (Storey, 1995; Kumar et al., 2001). Further, it is generally believed that the Marion hotspot volcanism was a main cause for the India-Madagascar breakup and formation of Madagascar Ridge on African plate (Storey, 1995).

The Kerguelen hotspot activity started at around 130 m.y ago when the continental blocks of India-Australia-Antarctica were together. The hotspot has caused wide spread volcanism during the Cretaceous and Cenozoic period in continental as well as in oceanic regions (Duncan, 1978). The volcanic activity resulted the formation of large widespread igneous provinces of Rajmahal, Bunbury and lamprophyre dikes in Indian, Australian and Antarctic margins, and plateaus and aseismic ridges such as Kerguelen Plateau, Broken Ridge, Ninetyeast Ridge, recent expressions on Kerguelen Archipelago, Heard and McDonald Islands, etc. (Coffin et al., 2002). After the break up, the plates motion have dispersed the igneous rock complexes from their original site of emplacement to present locations (Müller et al., 1993).

The Reunion hotspot formed the Deccan Traps at about 69-65 Ma on northeastern Indian Shield (Duncan, 1990). The volcanic rocks of Seychelles Bank and adjacent Seychelles-Saya de Malha saddle area are also considered as the products of Deccan plume (Plummer and Belle, 1995). Subsequently India separated from Seychelles and moved northwards,

resulting in formation of the Laccadive-Maldives-Chagos Ridge and on African plate, the Seychelles-Mascarene ridge, Nazareth Bank and the island of Mauritius (O' Nail et al., 2003).

## **2.2 Major Aseismic Ridges**

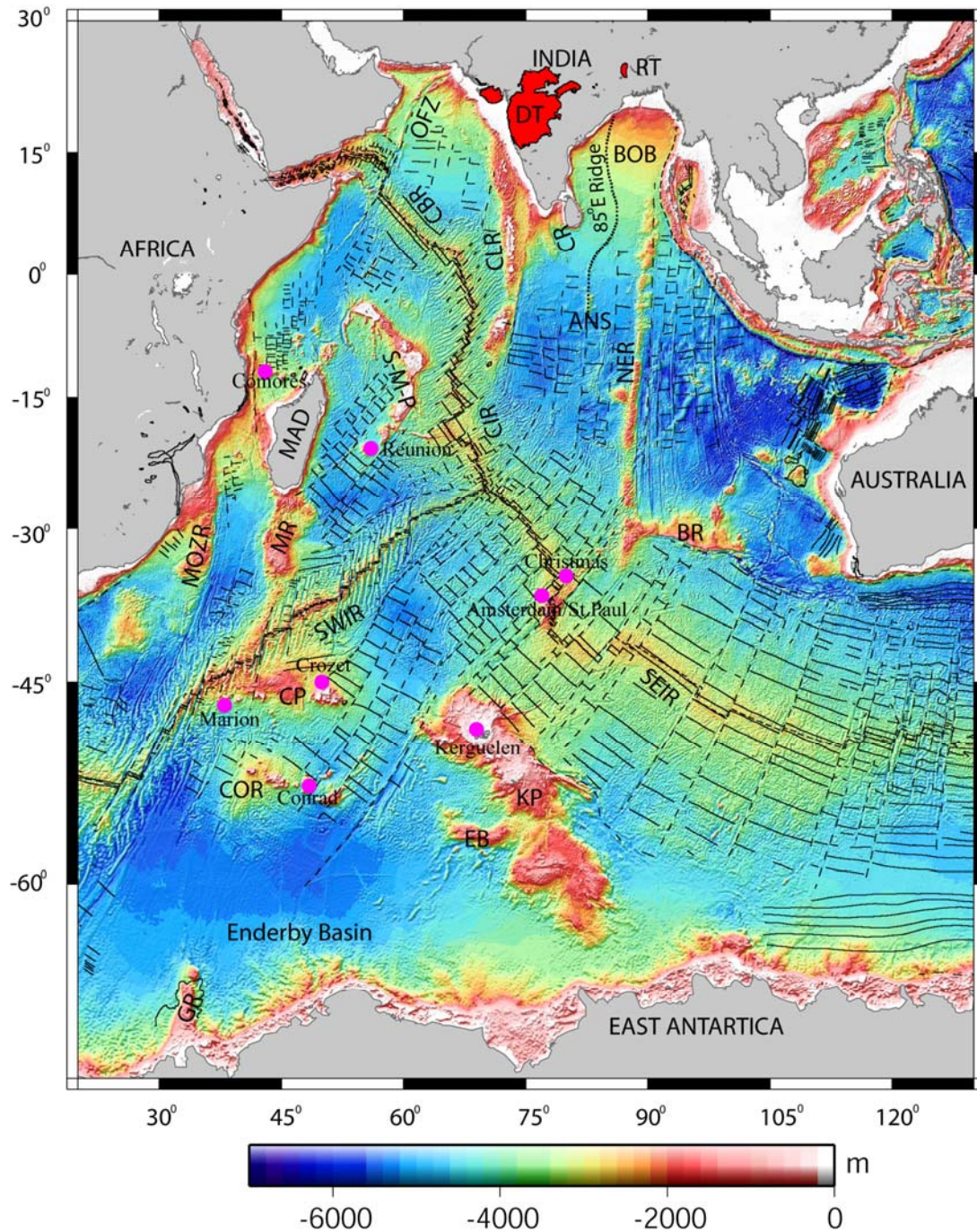
Aseismic ridges in the Indian Ocean were generally evolved either by volcanic activity or by continental fragmentation. In this section, a short description of some of the important aseismic ridges of the Indian Ocean is given. However, a detailed account of the structure, isostasy, geophysical signatures and evolutionary history of the Comorin, 85°E and Ninetyeast ridges are given in Chapters 4, 5 and 6, respectively.

### **2.2.1 The Ninetyeast Ridge**

The Ninetyeast Ridge is one of the longest linear aseismic ridges in the world oceans. It stretches for more than 5000 km in north-south direction from 17°N to 30°S in eastern Indian Ocean (Figure 2.2). The average elevation of the ridge is 2-3 km and width varies from 100 to 200 km. The southern part of the ridge (south of 15°S) is generally broader and wider than the northern part (Sclater and Fisher, 1974; Krishna et al., 1995). The northern portion of the Ninetyeast Ridge (north of 10°N) is buried under the Bengal Fan sediments (Curry et al., 1982; Gopala Rao et al., 1997; Micheal and Krishna, 2011), whereas the southern end of the ridge joins with the Broken Ridge.

### **2.2.2 The Chagos-Laccadive Ridge**

The Chagos-Laccadive ridge extends for about 2500 km from 14°N to 9°S along 73°E meridian in western Indian Ocean (Figure 2.2). The entire ridge system is broadly divided into three parts: the northern segment is referred as the Laccadive Ridge, the middle segment as Maldive Ridge and the southern segment as Chagos Bank. The Laccadive Ridge consists of a group of twenty islands and Banks, together known as Laccadive Islands. In general, this part of the ridge is associated with negative gravity signature with a belt of positive anomalies over the ridge crest (Naini and Talwani, 1983). The basement,



**Figure 2.2** General bathymetric map of Indian Ocean (ETOPO-1) showing mid-oceanic ridge system, aseismic ridges, plateaus, fracture zones, and magnetic lineations (after Royer et al., 1989; Müller et al., 1997). Locations Major hotspots are shown as pink dots. SWIR, Southwest Indian Ridge; SEIR, Southeast Indian Ridge; CIR, Central Indian Ridge; CBR, Carlsberg Ridge; NER, Ninetyeast Ridge; CR, Comorin Ridge; CLR, Chagos Laccadive Ridge; MR, Madagascar Ridge; S-M-P, Seychelles-Mascarene-Plateau; MOZR, Mozambic Ridge; BR, Broken Ridge; GR, Gunnerus Ridge; KP, Kerguelen Plateau; CP, Crozet Plateau; COR, Conrad Rise; EB, Elan Bank; OFZ, Owen Fracture Zone; RT, Rajmahal Traps; DT, Deccan Traps; ANS, Afanasy Nikitin seamount.



in general, forms a dome with several individual peaks. These peaks are devoid of sediments and some of them reach close to the sea surface. Seismic refraction results indicate that the Moho boundary lies at about 17-18 km and suggest an over thickened oceanic crust (Naini and Talwani, 1983). The Maldive Ridge lies between 7°N and 1°S is associated with subduded free-air gravity anomalies (Avraham and Bunce, 1977). A deep-water channel lying at a depth of about 4800 m separates Maldive Ridge from the Chagos Bank. The Chagos Bank is the southern part of the ridge system and lies south of 4°S. Free-air gravity anomaly over the bank is almost close to zero. Seismic and ODP results suggest volcanic crust with small sedimentary cover (Backman and Duncan, 1988).

Various theories have been proposed for the origin of the Chagos-Laccadive Ridge system, viz, leaky transform fault, continent-ocean boundary, hotspot trace, composed of structural elements of various origin, etc. (Bhattacharya and Chaubey, 2001; and references therein). The results of ODP Leg 115 suggested that the Chagos-Laccadive Ridge might have formed during the northward flight of the Indian plate over the Reunion hotspot (Whitmarsh, 1974; Duncan, 1981). However, the Laccadive Ridge segment is considered as continental fragment with volcanic intrusions (Chaubey et al., 2002; 2008).

### **2.2.3 The 85°E Ridge**

The 85°E Ridge stretches from the Mahanadi Basin (~19°N) to the Afanasy Nikitin seamount (4°S) in northeastern Indian Ocean (Figure 2.2). The northern part of the ridge in Bay of Bengal is completely buried under Bengal Fan sediments and associated with prominent negative gravity anomaly signature, whereas south of 7.5°S the ridge is partly exposed to the seafloor and associated with positive gravity anomaly signature. Seismic reflection studies reveal the presence of buried ridge in the Bay of Bengal and divide the region into two basins: the Western Basin lies between the ECMI and the 85°E Ridge, and the Central Basin lies between the 85°E and Ninetyeast ridges (Curry et al., 1982). The average width of the ridge is about 100 km with variable relief and morphology. It is generally believed that the ridge was emplaced by hotspot activity. However, there are

many contradicting views existing on the origin of the ridge. Detailed discussions regarding the origin of the 85°E Ridge are included in Chapter 5.

#### **2.2.4 The Comorin Ridge**

The Comorin Ridge trends in NNW-SSE direction in deep-water region of west of Sri Lanka and south of India, was named as Comorin Ridge because of its vicinity close to the place called Cape Comorin, southern tip of India (Figure 2.2). The ridge stretches for about 500 km with an average width of 50 km and relief of 1 km. In general, the ridge is associated with a subdued gravity anomaly, but no specific magnetic signature is noticed. Using marine geophysical data, Khale et al. (1982) suggested that the eastern edge of the Comorin Ridge might represent a continent-ocean boundary.

#### **2.2.5 The Broken Ridge**

The Broken Ridge in eastern Indian Ocean trends approximately in E-W direction and its western end joins the southern part of the Ninetyeast Ridge (Figure 2.2). The ridge stretches for about 1000 km with an average width of 100 km. Over the Broken Ridge the water depths are <2000 m and the southern edge of the ridge is steeper than the northern edge. The free-air gravity anomaly observed over the Broken Ridge suggests that the topography is basically uncompensated, in the sense that the Moho topography approximately follows the trend of the bathymetry. It is also suggested that Broken Ridge and central part of the Kerguelen Plateau were emplaced together due to intraplate volcanism during the mid-Cretaceous period and were separated during the middle Eocene (Weissel and Karner, 1989). The ODP Leg 121 results suggested that the Broken Ridge was formed initially above the sea level and subsequently subsided to the present position (Weissel and Karner, 1989).

### **2.3 Other Major Structural Features**

The Indian Ocean, besides aseismic ridges discussed above, possesses number of plateaus, seamounts, banks, etc. Most prominent among them are the Kerguelen Plateau, the

Mascarene Plateau, the Conrad Rise, the Nazareth Bank, the Elan Bank, the Afanasy Nikitin seamount, the Osborn Knoll, etc., (Figure 2.2). Some of the features relevant to the present research work are discussed below.

### **2.3.1 The Kerguelen Plateau**

The Kerguelen Plateau, an assemblage of several geological provinces, consists of Kerguelen-Gaussberg Ridge, sub-aerial Kerguelen Archipelago, Elan Bank, Skiff Bank, Heard Island (Frey et al., 2000). The plateau extends from 46°S to 64°S in a NNW-SSE direction with an average width of 450 km (Figure 2.2). The Kerguelen-Gaussberg Ridge is bounded north and east by the Crozet Basin, SW by the Enderby Basin, and SE by the Australia-Antarctic Basin. A trough with a depth of 3600 m, named as Challenger Channel (Vanney and Johnson, 1982), separates the Kerguelen-Heard Ridge from the Antarctic margins. The Kerguelen-Gaussberg Ridge is associated with low amplitude positive gravity anomalies, suggesting its structural compensation at deeper depths (Houtz et al., 1977). However seismic studies show that isostatic compensation is achieved by a low density mantle beneath the ridge. This scheme implies an upwelling of partially melted mantle. The magnetic anomaly pattern demonstrates that the Kerguelen-Gaussberg Ridge and Broken Ridge were joined prior to seafloor spreading anomaly 18 (40-42 Ma) and the present day separation between them is a result of the initial interplateau rifting followed by seafloor spreading since 42 Ma (Mutter and Cande, 1983; Royer and Sandwell, 1989)

### **2.3.2 The Elan Bank**

The Elan Bank, a relatively small elongated approximately E-W oriented feature, lies on the western margin of the Kerguelen Plateau (Figure 2.2). The ODP Leg 183 (Site 1137) results of the Elan Bank revealed that the bank consists of continental nature crust, therefore the bank is considered as a micro-continent (Frey et al., 2000). Using marine magnetic data, Gaina et al. (2003, 2007) and Krishna et al. (2009a) have suggested that the Elan Bank was separated from the present day Eastern Continental Margin of India at about 124 Ma. According to this interpretation, the seafloor spreading in the Enderby Basin ceased at about 124 Ma and the ridge segments jumped towards the Eastern

Continental Margin of India and caused for the detachment of the Elan Bank and its subsequent transfer to the Antarctic plate.

### **2.3.3 The Afanasy Nikitin seamount**

The Afanasy Nikitin seamount (ANS) stretches along 83°E between 2°S and 6°S with a relief of more than 2 km (Figure 2.2). The ANS is elongated for about 450 km in the north-south direction with an average width of 150 km. However, in the central part its width is narrower by ~50 km. The basement platform of the ANS rises to 3800 m water depth, on which a cluster of elongated peaks exists (Krishna, 2003). ANS is associated with positive but low amplitude free-air gravity anomaly. Plate reconstruction and magnetic studies have shown that the ANS is laying on 80-73 Ma aged oceanic crust (Müller et al., 1993; Krishna et al., 2011a). The magnetic anomalies over the ANS are low amplitude and short wavelength in nature, which are superimposed over the seafloor spreading anomalies.