CHAPTER 1
Chapter - 1

GENERAL BACKGROUND

1.1 Introduction

The Indian mainland is bordered by the Arabian Sea in the west and the Bay of Bengal in the east. These two seas are part of the western and eastern regions of the Indian Ocean (Fig.1.1) respectively. The geographic limits of the Indian Ocean are Iran, Pakistan, India and Bangladesh in the north; Arabia and Africa in the west; Australia, Sunda subduction zone, Malaysian peninsula and Thailand in the east and the Antarctic continent in the south. The broad features of the Indian Ocean could be identified based on various geoscientific studies carried out during the International Indian Ocean Expedition (IIOE) in 1960s. The main physiographic features of the Indian Ocean region (Fig.1.1) are the active mid-oceanic ridge system, aseismic ridges, submarine plateaus, seamounts, islands, subduction zones and continental fragments. These features and the surrounding continents divide the Indian Ocean area into number of deep sea basins. The two largest deep sea fans - Indus cone and Bengal fan are also located in this ocean. Identification of these features and paleo-geographic reconstruction of surrounding continents allowed several workers to propose broad evolutionary history of the Indian Ocean in terms of plate tectonic and seafloor spreading framework. The broad understanding (McKenzie and Sclater, 1971; Norton and Sclater, 1979; Besse and Courtillot, 1988; Scotese et al., 1988) in this regard is that the Indian Ocean area evolved as a result of fragmentation and dispersal of the super
Fig. 1.1 Generalized physiography of the Indian Ocean along with selected (200 m, 1000 m, 2000 m and 3000 m) bathymetric contours. CR: Carlsberg Ridge; CIR: Central Indian Ridge; SEIR: Southeast Indian Ridge; SWIR: Southwest Indian Ridge; SMP: Seychelles-Mascarene Plateau.
continental assemblage of Gondwanaland, particularly the northward drift of India. However, the early opening history in the evolution of the Indian Ocean region is not yet fully unraveled. Key to understand this history appears to lie in the continental margins and adjacent deep sea basins surrounding the continents. The geological complexities and inadequate data may be the main hindrance to bridge this knowledge gap. The present study deals with a sector of continental margins and deep sea regions of the Indian Ocean which lies off the west coast of India and aims to enhance the knowledge about the structure and tectonics of the region.

Firstly, this chapter introduces the geographical entity of the study area and presents the objectives and scope of the study. Broadly speaking the study area falls in the Western Indian Ocean, therefore to put the study area in the broader perspective of the Western Indian Ocean, this chapter also provides a brief description of the main physiographic and structural features and the evolutionary history of the Western Indian Ocean.

1.2 Study area

The most prominent bathymetric features of the continental margin and deep sea regions adjacent to the west coast of India are the Laccadive-Chagos Ridge and the Laxmi Ridge. The intervening regions between these ridges and the continental shelf off India are identified as number of deep sea basins such as the Laccadive Basin, the Laxmi Basin and the Offshore Indus Basin. Westwards of these ridges lies the Arabian Basin. In context of this framework, the study area
(Fig. 1.2) broadly spans over a part of the continental slope and rise regions off the central west coast of India and covers a major portion of the Laxmi Basin, the northern extremity of Laccadive-Chagos Ridge, southern part of the Laxmi Ridge and the eastern fringes of the Arabian Basin. The study area assumes significance in the context of evolution of offshore regions off western India, as it appears to be a region of convergence of number of prominent but varied tectonic features, whose genesis and evolution yet remain to be well understood. Detailed description of these features along with different views regarding their genesis is presented in Chapter-2.

1.3 Objective and scope of the study

The present study is mainly aimed to decipher physiography, basement structure and disposition of sedimentary overburden in the study area and provide constraints to improve our understanding of the evolution of the continental margin and the deep sea region adjacent to the west coast of India. Towards achieving these objectives, a data set comprising of bathymetry and single channel seismic reflection were compiled and interpreted. This compilation includes the seismic and bathymetric data collected by the National Institute of Oceanography, Goa, as a part of its R&D program as well the bathymetric data collected by several international agencies, which are available with the National Geophysical Data Centre (NGDC), Boulder, Colorado, USA.
Fig. 1.2 Location of the study area.
1.4 Main features of the Western Indian Ocean

The Western Indian Ocean is defined (Bhattacharya and Chaubey, 2001) as that part of the Indian Ocean which broadly lies west of 80°E and north of 40°S (Fig. 1.3). The Western Indian Ocean floor contains mid-oceanic ridges, continental fragments, submarine plateaus, deep sea basins and one of the world's largest deep sea fans. A detailed account of these physiographic and tectonic features has been summarized by Laughton et al. (1970) and Schlich (1982). An updated information of the features in the Western Indian Ocean has been provided by Bhattacharya and Chaubey (2001).

Study of various publications indicated that for geographical reference to offshore areas, different researchers used different names. In the recent publication of Bhattacharya and Chaubey (2001) an attempt was made to compile the boundaries and most widely representative nomenclature of various geological zones in the Western Indian Ocean. The nomenclatures provided by them (Bhattacharya and Chaubey, 2001) has been used for ease of reference and for further discussion in this study.

1.4.1 Mid-oceanic ridge system

Three branches of the active mid-oceanic ridge system (spreading centers) are located in this area (Figs. 1.1 and 1.3). They converge near 25.5°S and 70°E as a ridge-ridge-ridge confluence to form a junction known as Rodriguez Triple Junction (RTJ). The northern branch of this system comprises of three segments of which the roughly north-south trending segment between RTJ and the equator is
known as the Central Indian Ridge (CIR). The NW-SE trending segment lying between equator and the Owen Fracture zone is known as the Carlsberg Ridge (CR) and nearly E-W trending Sheba Ridge (SR) is an offset extension of the Carlsberg Ridge in the Gulf of Aden. The other two branches of this mid-Indian Ocean ridge system are known as the Southwest Indian Ridge (SWIR) and the Southeast Indian Ridge (SEIR). These branches of the Indian Ocean ridge system form the divergent boundaries between the Indian, Antarctic and African plates.

The Owen Fracture Zone (OFZ) defines the major right lateral offset between the Carlsberg and the Sheba Ridges and forms a major transform boundary of the Indian Plate with Arabian and African plates. The NE-SW trending Southwest Indian Ridge (SWIR) starts from the RTJ and joins the southern part of the mid-Atlantic Ocean ridge system at the Bouvet Triple Junction (55°S, 1°W). The Southeast Indian Ridge (SEIR) is a NW-SE trending feature which starting from the RTJ extends in SE direction to join the Pacific-Antarctic mid-oceanic ridge system south of Australia.

1.4.2 Submarine plateaus and aseismic ridges

The Western Indian Ocean contains a number of topographic features (Fig.1.3), which protrude high above the ocean floor. Many of the features are elongated and wholly submarine, but few rise above sea level and emerge as islands. The main submarine plateaus are, the Agulhas Plateau, the Madagascar
Fig. 1.3 Locations of major ocean basins and other physiographic features of the Western Indian Ocean along with selected bathymetric contours. NV: Natal Valley; MC: Mozambique Channel; WSB: Western Somali Basin; NSB: Northern Somali Basin; IB: Indus Basin; L-R: Laxmi Ridge; LB: Laxmi Basin; LAB: Laccadive Basin; SR: Sheba Ridge; CR: Carlsberg Ridge; CIR: Central Indian Ridge; SEIR: Southeast Indian Ridge; SWIR: Southwest Indian Ridge. PG: Persian Gulf; GA: Gulf of Aden; RS: Red Sea; GO: Gulf of Oman.
Ridge, the Mozambique Ridge, the Laxmi Ridge, the Laccadive-Chagos Ridge and the Seychelles-Mascarene Plateau.

The Agulhas Plateau lies about 500 km SE of the Cape of Good Hope. The Madagascar Ridge, located south of Madagascar Island between 26° S and 36°S is a north-south elongated feature with a maximum width of 600 km. The Mozambique Ridge is a 2000 km long and 300 km wide elongated feature which lies roughly parallel to the coast of SE Africa between 25°S and 35°S. The Laxmi Ridge is an aseismic basement high feature located approximately 700 km west of Mumbai. The Laccadive-Chagos Ridge is a slightly arcuate, elongated aseismic ridge which extends for about 3000 km off the southwest coast of India approximately along 73°E between 14°N and 12°S. The Seychelles-Mascarene Plateau complex is 2600 km long arcuate system of wide, partially isolated shallow banks and small islands located in the areas between the Madagascar Island and the Central Indian – Carlsberg Ridge segments. Rodriguez Ridge is a narrow, linear 450 km long volcanic ridge which intersects the Seychelles-Mascarene Plateau complex perpendicularly about 200 km north of Mauritius.

1.4.3 Seamounts

Very few of the several seamounts (Fig.1.1) in the Western Indian Ocean area have been systematically studied and published information is meagre. Prominent among these seamounts are the Error seamount, Sagar Kanya seamount and a chain of seamounts located in the axial part of the Laxmi Basin (Bhattacharya and Chaubey, 2001). The Error seamount (Mathews, 1966; Ramana et al., 1987) is located approximately at the northwestern boundary of the
Carlsberg Ridge and appears to be a part of the system of features which constitute the Owen Fracture Zone. The Sagar Kanya seamount (Bhattacharya and Subrahmanyam, 1991) is a 2464 m high edifice located about 200 km west of the Laccadive Plateau. The Laxmi Basin seamount chain is located approximately in the axial part of the Laxmi basin (Bhattacharya et al., 1994b) and consists of the Raman Seamount, the Panikkar Seamount and the Wadia Guyot. This linear seamount chain is about 250 km long and trends nearly N30°W.

1.4.4 Deep sea basins

The Western Indian Ocean consists of several deep sea basins (Fig.1.3), some of which were created by the present system of mid-ocean spreading centers, where others were formed by extinct spreading regime or the remnants of the continental break-up stage tectonics. Prominent among these basins are the Natal Valley, the Transkei Basin, the Mozambique Basin, the Mozambique Channel, the Western Somali Basin, the Northern Somali Basin, the Owen Basin, the Gulf of Oman, the Gulf of Aden, the Madagascar Basin, the Mascarene Basin, the Eastern Somali Basin, the Arabian Basin, the offshore Indus Basin, the Laxmi Basin, the Laccadive Basin, the Central Indian Ocean Basin and the Crozet Basin.

The Natal Valley and the Transkei Basin are located adjacent to the SE continental margin of Africa. The Natal Valley is bounded in the west by the southwest African continental margin, in the north by a wide terrace that extends approximately along 30°S, in the east by the Mozambique Ridge and in the south it abuts the deep Transkei Basin. The small deep sea Transkei basin is bounded by the Agulhas Plateau in the south and its northern boundary can be considered to
be delineated by the southern extent of the Mozambique Ridge and the Natal Valley. The Mozambique Basin located SW of the Madagascar Island is approximately a 500 km wide basin which is bounded by the N-S trending Madagascar Ridge on the east and by the Mozambique Ridge in the west, by the Mozambique Channel in the north and by SWIR in the south. The Mozambique Channel lying between the Madagascar Island and the African mainland is a NNE-SSW trending basin, which extends from 12°S to 25°S. A major morphological feature, the N-S trending Davie Ridge dominates the morphology of this channel. The Western Somali Basin is bounded to the west and northwest by the east coast of Africa, the northern boundary is defined by a broad bathymetric high at 4°N which extends from African continental margin to the southern end of the Chain Ridge. The eastern and southern limits of this Western Somali Basin is considered to be defined by an irregular boundary commencing from the southern end of the Chain Ridge and passing through the western flank of the Seychelles Bank, the Amirante Arc, the northern tip of Madagascar and the Comoro islands. The Northern Somali Basin is a small oceanic basin, located approximately north of 4°N between the African continental margin and the Chain Ridge. The northern boundary of this basin is defined by a sub-merged spur of the African continent along 12° 30’ N and its southern boundary is defined by the bathymetric high which defines the northern limit of the Western Somali Basin. The Owen Basin is bounded to the east by the Owen Fracture Zone, to the west by the Oman continental margin, to the south by the Sheba Ridge and to the north it opens into the Gulf of Oman. The Persian Gulf and Gulf of Oman is a convergent region at
the northern margin of the Arabian Plate. The Gulf of Oman is bounded by the Makran ranges in the north and the Oman Mountains in the southwest. It is connected to the Persian Gulf by the narrow Strait of Hormuz. The Persian Gulf is an elongate depression located between the Zagros Mountains to the northeast and the Arabian Peninsula to the west, south and southeast.

The Madagascar Basin, located southeast of the Madagascar Island, is bounded on the southeast by the SWIR, in the northeast by southern section of the Central Indian Ridge, in the southwest by the Madagascar Ridge and in the northwest by the Mauritius Fracture Zone which is located west of the Mauritius Island. The Mascarene Basin, lying between the Madagascar Island and the Seychelles-Mascarene Plateau, corresponds to the northwest extension of the Madagascar Basin. Its southeasterly limit is considered to be defined by the Mauritius Fracture Zone. To the northwest, the basin is bounded by the irregular boundary passing through the Seychelles Bank, the Amirante Arc and the northern tip of the Madagascar Island. The Eastern Somali Basin is bounded in the north by the Carlsberg Ridge, in the south by northern part of the Seychelles-Mascarene Plateau, in the east by the Central Indian Ridge, and in the west by the Chain Ridge. The Arabian Basin is bounded in the west by the Owen Fracture Zone, in the east and northeast by the aseismic Laccadive-Chagos Ridge and the Laxmi Ridge respectively and the southern boundary is defined by the Carlsberg Ridge. The offshore Indus Basin is bounded by the E-W trending submarine Laxmi Ridge segment in the south, the Murray Ridge and the Owen Fracture Zone in the northwest, the continental shelf of India and Pakistan in the northeast. To the
southeast this basin opens into the Laxmi Basin. The Laxmi Basin is located between the Laxmi Ridge and the western continental shelf of India. The northern boundary of this basin is considered (Bhattacharya et al., 1994a) to be limited approximately along 21°N where the bathymetric contours of the adjacent continental slope of western India abruptly changes westerly. Towards south this basin abuts the northern extremity of the Laccadive-Chagos Ridge. The narrow triangular shaped the Laccadive Basin is located between the Laccadive-Chagos Ridge and the southwestern continental slope of India. The northern boundary of this basin lies approximately along 16°N where the northern extremity of the Laccadive-Chagos Ridge apparently meets the adjacent continental slope of western India. Towards south this basin opens into the Central Indian Basin.

The Central Indian Basin (Fig.1.1) is bounded in the west by the southern part of the Central Indian Ridge, the Chagos Bank and the Maldive Ridge; in the east by the Ninetyeast Ridge and in the south by SEIR. The Crozet Basin is referred to that area which is bounded in the northwest by the SWIR and in the northeast by SEIR and in the south by the Ob, Lena and Marion Dufresne seamount chain.

1.5 Broad evolutionary history of the Western Indian Ocean

The evolution of the Western Indian Ocean is a part of the evolution of the Indian Ocean. The only difference is in the detail and emphasis on those aspects, which have implications on the evolution of the deep offshore regions off the west coast of India. Various paleo-geographic reconstruction models have been proposed to depict the evolutionary history of the Indian Ocean. These models
were proposed based on the identification of seafloor spreading magnetic anomalies, fracture zone traces from magnetic, bathymetric and satellite altimetry data, and the paleo-magnetic studies of the continental rocks (McKenzie and Sclater, 1971; Norton and Sclater, 1979; Besse and Courtillot, 1988; Scotese et al., 1988; Royer et al., 1992). Following is a broad synthesis of the views of various authors regarding the evolution of the Indian Ocean with focus on Western Indian Ocean.

It is generally believed that the arrangement of continents, continental fragments and oceans – as we see today – was created by fragmentation and dispersal (Fig. 1.4a-f) of a supercontinent named the Pangea. The Pangea supercontinent consisting of almost all the continental landmasses was surrounded by the universal ocean “Panthalassa” (the ancestral Pacific) and eastern shores of Pangea were indented by a triangular sea called “Paleo-Tethys”. During Triassic a strip continent (known as Cimmerian strip continent) which comprised parts of present day Turkey, Iran, Afghanistan, Tibet, China and Indo-China rifted from Paleo-Tethyan margin and drifted towards north. This Cimmerian movement caused the closing of Paleo-Tethys and opening of a “Neo-Tethys” sea in its wake.

About 200 Ma the Pangean supercontinent began to split, first into a northern part (Laurasia) and a southern part (Gondwanaland). It is considered that the break-up of Gondwanaland also coincided with the commencement of closure of Neo-Tethys Sea by subduction under the Eurasian margin. This subduction gave rise to the development of an island arc system, named the Kohistan-Ladakh Island arc, which as will be described later was the zone of first contact
between the Indian and Eurasian plates. The unified Gondwanaland in the southern hemisphere was comprised of present day South America, Africa, Arabia, Madagascar, Sri Lanka, India, Australia and New Zealand. The origin of Indian Ocean is related to the fragmentation and dispersal of Gondwanaland. Main episodes of fragmentation and dispersal of Gondwanaland are summarized below:

Stage 1: A rifting episode initiated earlier than 152 Ma (Late Jurassic) began the break-up of the Gondwanaland. By about 152 Ma, commencement of seafloor spreading along short E-W trending spreading segments offset by long N-S trending transform faults divided the Gondwanaland into the west Gondwanaland consisting of Africa, Arabia and South America and the east Gondwanaland consisting of Antarctica, Australia, New Zealand, Madagascar, Seychelles, India-Sri Lanka. This was the stage during which the Mozambique, the Western Somali and probably the Northern Somali Basins began to form and mark opening of the Indian Ocean. After this break-up, east Gondwanaland moved south in comparison to west Gondwanaland.

Stage 2: Further break-up of eastern Gondwanaland began in Cretaceous. At about 133 Ma (Early Cretaceous) the conjoined Antarctica-Australia rifted from smaller Madagascar-Seychelles-India fragment.

Stage 3: Following separation of Madagascar-Seychelles-India block from Antarctica-Australia, the spreading of seafloor continued in a uniform fashion for about 15 My. Later, the spreading between Africa-Arabia and Madagascar-Seychelles-India blocks experienced change. The Madagascar-Seychelles-India block possibly came over the location of the Marion Hotspot around 88 Ma. Due to
Fig. 1.4 Cartoons depicting fragmentation and dispersal of PANGEA supercontinent since Late Permian. a) Late Permian (255 Ma), b) Middle Triassic (237 Ma), c) Early Jurassic (195 Ma); d) Mid-Cretaceous (94 Ma); e) Latest Cretaceous (94 Ma); and f) Eocene (50 Ma). Modified after Scotese (1997).
the influence of this hotspot, rifting was initiated and around 84 Ma (anomaly 34) due to seafloor spreading, the Madagascar separated from Seychelles-India block and got welded to the African Plate. This separation resulted in opening of the Mascarene and Madagascar Basins and establishment of a three plate system with a triple junction in the Western Indian Ocean. Most importantly this event probably marked the beginning of the tectonic events which resulted in shaping the present day deep offshore regions off the west coast of India. After separation, Seychelles-India block continued northward drift, and at the same time experienced a gradual anti-clockwise rotation.

Stage 4: While drifting northward, around 69-65 Ma (Late Cretaceous) wide spread volcanism took place over the Indian landmass and created the Deccan Trap continental flood basalt province which is related to the onset of the Reunion Hotspot activity. As India continued to move northward, the adjacent offshore areas came under the influence of the Reunion Hotspot. This resulted in commencement of formation of the Laccadive-Chagos Ridge and reorganization of the nearby spreading centers. Around ~63 Ma (Late Paleocene), spreading in the Mascarene Basin gradually ceased and jumped north of Seychelles, carving the Laxmi Ridge out of the Seychelles to form a new spreading center – the paleo-Carlsberg Ridge. The spreading along this paleo-Carlsberg Ridge caused the opening of the conjugate Arabian and Eastern Somali basins and welding of the Seychelles to the African Plate.

Stage 5: As the rapid northward movement of India continued, the Arabian and Eastern Somali basins continued to grow and simultaneously the Neo-Tethys
continued to be subducted. Finally around 50 Ma (Middle Eocene), the continental India came into contact with the Kohistan-Ladakh Island arc system and gradually closed the Neo-Tethys along the Indus-Zangbo suture zone. This event is termed as "soft collision" or the first contact between India and Asia. This resulted in slowing down of the spreading rates at the Carlsberg, Central Indian and Southeast Indian ridges. In response to the continued collision of India and Asia, the plate boundaries in the Indian Ocean area started re-organization. Along the paleo-Carlsberg Ridge spreading slowed to an imperceptible level from Anomaly 21 time (~47 Ma) onwards and probably by about 40 Ma the plate boundaries in the Indian Ocean began to assume the present day configuration.

**Stage 6:** The latest episode of spreading along the Carlsberg Ridge commenced around 34 Ma (Late Oligocene). Following this Late Oligocene reorganization, a new phase of accelerated spreading commenced in the Western Indian Ocean. During Late Miocene, shortly before the time of anomaly 5 (~11 Ma), the Carlsberg Ridge spreading center propagated westward as the Sheba Ridge and opened the Gulf of Aden. The accelerated spreading caused subduction of entire oceanic crust north of Indian Plate and brought continental crust of Indian and Eurasian plates into contact. This contact or the "hard collision" as it is known might probably have occurred during Middle Miocene (~16-11 Ma) and as a result of which the Himalayas emerged as a highland. The rapid rise of the Himalayas continued and by Late Miocene (~11-7.5 Ma), the Himalayas became a lofty mountain range. Consequent accelerated erosion of the Himalayas brought large volume of sediments in the Indus and Bengal fan area. At present the Carlsberg Ridge is
active and continue to accrete the Arabian and Eastern Somali basins at a rate of about 1.2 cm/year.