Chapter-1

GENERAL BACKGROUND
1.1 Introduction

The Indian Ocean, the third largest of the world's oceans, is a storehouse of diverse and complex tectonic and sedimentary features. The Arabian Sea and the Bay of Bengal, which border Indian peninsula west and east respectively, form the northwestern and northeastern parts of the Indian Ocean. Geological and geophysical studies in the Indian Ocean revealed several major tectonic and structural features of the ocean, as well as basement ages of part of the ocean basins. However there are unexplored regions in the Indian Ocean which require systematic study on their tectonic and sedimentological evolution. Evidences of the early opening history of the Indian Ocean lie in the continental margins and adjacent deep sea basins surrounding the continents.

The passive continental margins, to which the western continental margin of India belongs, are considered as the places where the breakup and rifting of continents took place. The passive margins are subsequently covered by a thick pile of synrift and postrift sediments which may provide the source of significant natural resources. Detailed geological and geophysical investigations of western continental margin of India have been mostly confined to the continental shelf for the purpose of commercial exploration of natural resources. The likelihood of further prospects in the adjacent deeper parts necessitated better understanding of ongoing geological and tectonic processes, and evolutionary history of the western continental margins of India. The present study aims to enhance knowledge of stratigraphy, sedimentation history, and tectonics of the southwest continental margin of India. Knowledge of crustal structure, tectonics and sedimentation will not only improve scientific understanding but also be crucial to the future wealth and well-being of the nation.

In this introductory chapter the Western Continental Margin of India (WCMI) is briefly described along with the geographical entity of the study area. Further the chapter presents objectives and scope of the present study. Finally, a brief
description of various types of continental margins with special emphasis on passive margins is presented.

1.2 Western continental margin of India

The Western Continental Margin of India (WCMI) extends NW-SE from Kutch in the north to Cape Comorin in the south (Figure 1.1). It has evolved after the break-up of Madagascar in the Late-Cretaceous and Seychelles micro-continent in the Early Tertiary from India (McKenzie and Sclater, 1971; Norton and Sclater, 1979; Schlich, 1982; Besse and Courtillot, 1988; Patriat and Segoufin, 1988; Scotese et al., 1988; Royer et al., 1989; White and McKenzie, 1989; Storey et al., 1995; Reeves and de Wit, 2000; Reeves and Leven, 2001; Royer et al., 2002). The break-ups were associated with massive extrusive and intrusive magmatism due to interaction of hotspots (Richards et al., 1989; White and McKenzie, 1989; Duncan, 1990; Storey, 1995; Storey et al., 1995; Courtillot et al., 1999). The tectonic and structural features classify the WCMI under the category of passive continental margins (Biswas, 1982; Chandrasekharam, 1985). The WCMI is characterized by i) a NW-SE trending continental shelf limited by the shelf edge at about 200 m isobath, ii) a continental slope bounded between 200 and 2000 m isobath, iii) deep offshore sedimentary basins, and iv) basement ridges more or less parallel to the continental shelf edge. The continental shelf widens more than 300 km off Kutch-Saurashtra and gradually narrows down southward to about 50 km off Cochin. In contrast, the continental slope is narrow in the north but widens towards south (Biswas, 1982, 1987, 1988).

The continental shelf separated by southwesterly plunging basement highs is comprised mainly of four shelfal basins, namely Kutch, Saurashtra, Ratnagiri and Kerala-Konkan basins (Biswas, 1988). The margin hosts a number of deep-seated faults, rift systems, basement highs, numerous NW-SE trending structural features such as Laccadive Ridge, Laxmi Ridge, Prathap Ridge Complex, Panikkar Ridge (seamount chain comprising Raman Seamount, Panikkar Seamount and Wadia Guyot), which are mostly buried under the Indus Fan sediments. Three major deep offshore sedimentary basins - Indus Basin, Laxmi Basin and Laccadive Basin - are located between the continental slope and the Laxmi-Laccadive
ridges. The Arabian Basin is located west of the Laxmi and Laccadive ridges and continues up to the Carlsberg Ridge. Several onshore structural lineaments of the Indian subcontinent extend to a considerable distance into the offshore region (Kolla and Coumes, 1990). The host-graben structures, basement arches and fault patterns of the shelf areas, mainly parallel to the Dharwar (NW-SE to NNW-SSE) and Eastern Ghat (NE-SW) trends, are formed due to rifting and movements along the ancient Precambrian structural trends (Biswas, 1987). The WCMI consists of modified and attenuated continental crust, with Archaean granitic basement juxtaposed with oceanic crust, which underlies the abyssal plain of the adjacent Arabian Basin. Major structural and tectonic features of the WCMI are concealed under thick sedimentary cover and volcanic flows impeding the initial configuration of the margin. A large continental flood basalt province - Deccan Trap - emplaced by the Réunion hotspot (68.5-62 Ma) is found on central western Indian shield along WCMI as well as on the Praslin Island in the Seychelles microcontinent (Devey and Stephens, 1991). The Deccan Trap is the largest known continental flood basalt province formed by series of eruptions (Courtillot et al., 1986; Vandamme et al., 1991; Venkatesan et al., 1993; Bhattacharji et al., 1996). As a result of continued interaction of the Réunion hotspot with the northward moving Indian Plate, the adjacent offshore areas came under the influence of the Réunion hotspot that resulted in magmatic intrusions within the western continental margin of India (Shipboard scientific party, 1988; Richards et al., 1989; Duncan, 1990, Pandey et al., 1996; Singh, 2002) and built the northern part of the Chagos-Laccadive Ridge on the rifted lithospheric crust of India.

1.3 Study area

Study area is located between the latitudes 6°-16°N and longitudes 66°-78°E on the southern part of the western continental margin of India, approximately south of Goa (Figure 1.1). The major geological domains of the study area are (i) narrow shelf comprised of Kerala-Konkan Basin formed by horst-graben structures, (ii) wide continental slope bounded between 200 and 2000 m isobath (iii) shelf margin sedimentary basin known as the Laccadive Basin, (iv) the Prathap Ridge, (v) the Laccadive Ridge, and (vi) the deep Arabian Basin west of the Laccadive
Figure 1.1 Generalized map of Western Continental Margin of India (WCMI) and adjacent regions. Study area is shown within rectangle. DSDP drill sites (Whitmarsh et al., 1974) are represented by solid annotated stars; GEBCO bathymetry contours are shown by annotated thin lines; solid thick dashed lines represents computer-modeled Réunion hotspot track; numbers along the hotspot track are predicted ages in My (Shipboard Scientific Party, 1988); SW trending arrows in the continental shelf represent strike of basement arches (Biswas, 1987). SGT: Southern Granulite Terrain; GR: Godavari Rift; NSR: Narmada Sone Rift; LBSC: Laxmi Basin Seamount Chain; W: Wadia Guyot; R, P: Raman, Panikkar seamounts respectively.
Ridge. The study area assumes significance in the context of evolution of southwest continental margin of India as it contains numerous prominent and varied geologic features whose genesis and evolution are not yet well understood. Detailed description of these features and present understanding of their genesis are presented in chapter-2.

1.4 Scope and objectives of the study

The western continental margin of India is considered as a typical passive rifted margin (Biswas, 1982; Chandrasekaram, 1985). Despite the fact that the India-Madagascar breakup produced an extensive volcanic province along eastern Madagascar and numerous volcanic flows and intrusives in the southwest Indian shield, southwest continental margin of India is generally considered as a non volcanic passive margin. Whereas the northwest continental margin of India, developed during the breakup between Laxmi Ridge-India and Seychelles, is considered as a volcanic passive margin due to contemporaneous outbursts of the Deccan volcanics. In view of the above facts, nature of southwest continental margin of India remains poorly understood and therefore warrants detailed investigation.

Southwest Continental Margin of India (SWCMI) is characterized by a number of structural and tectonic features which were formed due to extensional tectonics during India-Madagascar breakup under influence of the Marion hotspot, magmatic episodes of the Rùunion hotspot and subsequent evolution of the margin. The major structural features include present- and paleo-shelf breaks, Kerala-Konkan Basin, Shelf Margin High, Laccadive Basin, Prathap Ridge and Laccadive Ridge. The lateral extent of some of the structural features was demarcated earlier based on physiographic expressions and seismic reflection data (Naini and Talwani, 1983; Biswas and Singh, 1988). Since considerable parts of the features are concealed under thick sediment cover and volcanic flows, their extent yet to be demarcated based on crustal structure obtained from integrated interpretation of geophysical data. It is believed that the Marion and Rùunion hotspots related magmatism had a profound influence on crustal evolution of the
SWCMI concealing pre-existing geology and crustal structure. Therefore, reported crustal structure of this complex margin is equivocal. Radhakrishna et al. (2002) inferred a thick under-plated oceanic crust below the Laccadive Ridge and Continent-Ocean Boundary (COB) to the east of the ridge based on the analysis of seismic and free-air gravity data. Whereas Chaubey et al. (2002b), in their 2-D crustal model based on integrated interpretation of gravity and magnetic data, depicted a heavily intruded continental crust for the Laccadive Ridge with an inferred continent-ocean boundary to the west of the ridge. The results of these studies are equivocal in resolving the crustal nature of the Laccadive Ridge and COB along SWCMI. In order to address the impact of hotspot on the SWCMI, crustal structure, continent-ocean boundary/transition and anomalous basement depths needs to be investigated.

Most of the earlier investigations on the stratigraphy and sedimentation pattern of the margin, were focussed on the continental shelf and slope region in connection with hydrocarbon exploration (Nair and Rao, 1980; Raju et al., 1981, Rao and Srivastava, 1981, 1984; Raha et al., 1983; Singh and Lal, 1993, 2001; Pandey and Dave, 1998; Thakur et al., 1999; Gunnel, 2001; Chaubey et al., 2002b; Rao et al., 2002; Campanile et al., 2008). Studies are very sparse in the deep offshore region of SWCMI. Therefore, understanding of the sedimentation history of various geological domains of the SWCMI is still limited.

The present study is primarily aimed at deciphering sedimentation, crustal architecture and Continent-Ocean Transition (COT) along the SWCMI, and to provide constraints to improve the understanding of tectonics of the margin. Specific objectives of the study are formulated as:

➢ Identification and mapping of detailed structural and tectonic features to understand nature of the margin.
➢ Identification of seismic sequences and their correlation with litho- and chrono-stratigraphy to understand the sedimentation history.
➢ Computation of basement depth anomalies to understand Réunion Hotspot interaction with the SWCMI.
Elucidation of crustal structure across the margin to delineate the continent-ocean transition and the nature of crust of the margin.

Implications of identified structural and tectonic features in the tectonics of the margin.

In order to achieve these objectives, multi-channel seismic reflection data supplemented by shipborne as well as satellite altimetry derived free-air gravity anomaly data are analyzed. Bathymetric, drill-well and seismic refraction information are also utilized to constrain the results of the present study.

Since the present study is focused on the southwest continental margin of India which is classified as a passive continental margin, a brief account on the concept of continental margin (Symonds et al., 2000 and references therein) is presented in the following sections.

1.5 Continental margins

Two major types of morphological features dominating the Earth's surface are continents and oceans. The oceans cover about 71% of the total Earth's surface. The continents and oceans are separated by the coastline, which is a transitory boundary. A much more fundamental subdivision of the Earth's surface is in terms of geological provinces composed of either continental or oceanic crust. Continental margins are a zone between the thin, dense, oceanic crust and the thicker, lighter, chemically different continental crust. Continental margins occupy about 28% of the total area of the oceans and about 20% of the continental crust lies beneath the oceans (Kennett, 1982). The geomorphological and geologic characteristics of a continental margin are a function of its tectonic, magmatic, and sedimentation history. The transition from continental to oceanic crust commonly occurs beneath the outer part of continental margins. Important province boundaries are continent-ocean boundary/continent-ocean transition. They are difficult to define because of their complexity and transitional nature.

There are three main types of continental margins which are differentiated based on their relationship to plates, plate boundaries, and presence or absence of
seismic and volcanic activities. They are referred to in a variety of ways in scientific literature. They are:

(i) Divergent / rifted / passive / aseismic or Atlantic type
(ii) Convergent / active / seismic or Pacific type
(iii) Transform / translational or sheared type

Transform margins can occur in both divergent and convergent tectonic settings.

1.5.1 Divergent continental margins

The divergent continental margins are formed by rifting and drifting of continental lithosphere. An intracontinental rift system evolves into a continental margin when the two diverging pieces of lithosphere are separated by seafloor spreading centers. The continental rifting process marks the zone where active divergent plate tectonic processes commence. Although divergent margins initially form at divergent plate boundaries, they move away from these boundaries, progressively cool, subside and accumulate sediments in the fault grabens. Thus, divergent margins, located within a plate on the transition from continental to oceanic crust characterized by extensional tectonics, are commonly called 'Passive margins'. Divergent margins are tectonically active for a few million years during their formation, but they become inactive soon after the continent breaks into two parts and the oceanic spreading center retreats from the margins. There are two important classes of passive margins:

i) Non-volcanic passive margins

ii) Volcanic passive margins

1.5.1.1 Non-volcanic passive margins

In the non-volcanic passive margins (Figure 1.2a) magmatism is either absent or incidental (e.g., west Iberia margin). They are characterized by a zone of synrift sediments deposited in the rift system overlain by a broad zone of post rift or post breakup sediments deposited following the initiation of seafloor spreading.
Lithospheric deformation on a nonvolcanic margin is dominated by block faulting related to brittle deformation in the upper crust and ductile deformation in the lower crust and upper mantle, producing a broad extensional crust. Magmatism does occur but is probably confined to the deeper parts of the lithosphere, with only minor volcanism in the upper crust. Rifting is commonly viewed as progressing from an intercontinental rift to an active rifted margin. Along the non-volcanic passive margins COB can be distinguished in the narrow zones of initial dyke injection and by abrupt change from continental to oceanic basement. The final morphology of the margin is heavily controlled by the amount of post breakup sediment deposition. On sediment-poor margins, the original rift architecture will have a significant influence on margin morphology, but it will be overwhelmed by sediment depositional processes on sediment-rich margins.

1.5.1.2 Volcanic passive margins

Volcanic passive margins (Figure 1.2b) are characterized by extensive extrusive constructions emplaced during continental breakup and the initial phase of seafloor spreading. These constructions commonly include formations which appear as Seaward Dipping Reflector (SDR) sequences in the seismic record (Hinz, 1981; Coffin and Eldholm, 1992). The volcanic passive margins, together with continental flood basalts, oceanic plateaus and ocean basin flood basalts have been defined as sites of voluminous emplacements of predominantly mafic rocks which do not originate at normal seafloor spreading centers (Coffin and Eldholm, 1992). The episodic, massive melting associated with large igneous provinces is commonly related to hotspot activity or thermal plume rising from deep within the earth. The magmatic activity is manifested by extensive volcanism, producing lavas from numerous feeders, volcanoes, and fissures, both above sea level and in shallow waters. The volcanism is centered along the line of continental breakup. However, the basaltic lavas may flow for long distances and cover large areas of the neighboring continents. The magmatic activity which takes place during both the final phase of continental thinning and the initial period of seafloor spreading are short-lived (few million years) on a geological time scale. As the excess volcanism abates, the main feeder system subsides to become a mid-oceanic ridge that produces new oceanic crust. As the ocean matures, the
volcanic complexes on the conjugate continental margins subside and are gradually buried below the sediments. Many of the volcanic passive margins are also characterized by thicker than normal oceanic crust beneath the extrusive complex, including a high velocity (7.1 - 7.7 km/sec.) Lower Crustal Body (LCB). On volcanic passive margins, the definition of COB is complex, and the use of the term COT is probably more appropriate. Because, the early stage subaerial or submarine basaltic lava flows may spread over the broad preexisting rift zone basement disguising the location of the COB forming a wide COT. However, a complex COT may result if the start of spreading is slow, episodic with low magma supply and jumps around within the rift system.

Figure 1.2 Schematic diagrams of (a) non-volcanic and (b) volcanic passive margins.

Volcanic or non-volcanic nature of the margin, is not directly evident from bathymetric and geomorphic features. Volcanic passive margins exist both in regular shelf-slope-rise settings, as well as in settings where the slope is interrupted by a marginal high bounded by an upper and a lower slope. Whereas on non-volcanic passive margins marginal highs may be poorly developed or even absent. The main factors governing volcanic passive margin architecture, including the construction of buried marginal highs and marginal plateaus are
(i) style and distribution of structural deformation since onset of rifting, (ii) volume and rate of magma production and geological environment during breakup; and (iii) subsidence and sedimentation history since breakup. Differences in these factors can result in a range of morphological and structural configurations and great variation in volcanic margin architecture.

1.5.2 Convergent continental margins

Convergent continental margins are generally defined as the broad area between the active subduction zone and the continental land mass (National Research council, 1979). This definition includes the trench, accretionary prism, forearc and backarc basins, volcanic arc, remnant arcs, island arcs and collision complex within the convergent margin terrain. Convergent continental margins mark the boundaries between continental and oceanic plates or two converging, continental or oceanic plates. The convergent continental margins are associated with deformation and subduction of continental and oceanic crusts. The interaction of continental and oceanic plates creates deep-sea trenches, volcanic arcs, remnant arcs and forearc basins (Figure 1.3a; e.g., west coast of Indonesia and Sumatra). Collision between two oceanic plates (Figure 1.3b; e.g., South Sandwich Islands, South Georgia) forms island arcs, trenches, forearc and backarc basins. Whereas the collision between two continental plates is characterized by orogenic mountain ranges at their margins (Figure 1.3c; e.g., Himalayan ranges). The convergent continental margins are sometimes referred to as active or seismic margins because they are often marked by shallow to deep-seated earth quakes, volcanism, crustal deformation and metamorphism. They form much of the margin around the Pacific Ocean, as well as parts of the southern Atlantic Ocean and the northeast Indian Ocean. The transition from continent to oceanic crust on convergent continental margin is generally much more complex than the divergent continental margins. The morphology of a typical Pacific active convergent margin consists of a continental shelf and slope bounded on the seaward side by a trough or trench. Sediment accumulations on the slope appear to be less, compared to divergent margins, and continental rises are generally absent since the continental slope bottoms in a deep trench.
Figure 1.3 Schematic diagrams of (a) continent-ocean collision, (b) oceanic-oceanic collision and (c) continent-continent collision.

1.5.3 Transform margins

Plate tectonic motion that is more or less perpendicular to the rift system and the locus of breakup creates divergent rifted margins. In some places, these rifted margin segments are linked by margins where the locus of breakup is more or less parallel to the initial plate motions between parting continents. Such margins
are called transform (rift-transform, translational, sheared) margins (Figure 1.4; Mascle and Blarez, 1987). They evolve within a thermomechanical regime that includes significant components of strike-slip shear as well as extensional strain deformation owing to sharp contrast for their morphological, crustal and sedimentary characteristics between the continental domain and the nearby younger oceanic crust. Most of the structural characteristics of transform margins develop during their early intracontinental stage, when the two continents progressively slide past each other. During this stage syn-sedimentary and syn-diagenetic deformation characterizes a wide, linear zone located between the two parting continents in association with severe tectonism, structural inversion and erosion (Mascle et al., 1998). These processes lead to the development of incipient marginal ridge features. Transform margins exhibit distinctive morphological characteristics such as strong linearity, declivity and large scale margin parallel ridges called marginal ridges. The transform margin slopes representing geologic scars resulting from the transcurrent movement between the separating continents. The distribution of sediments across transform margin is strongly dependent on their tectonic evolution and related morphostructural features. The steep continental slopes preclude substantial deposition. At transform margins the transition from continent to oceanic crust appears quite abrupt. The COT is quite narrow (<10 km) and correlates with an abrupt seaward shallowing of the Moho. Even though some of the transform margins appear to be a sharp and simple juxtaposition of continental and oceanic crust, with no evidences of magmatic activity, there are transform margins with complexities related to continental crust contamination, magmatic intrusions and underplating.

Figure 1.4 Schematic diagram of a transform margin.