GEOPHYSICAL CONSTRAINTS ON STRUCTURE AND TECTONICS OF THE EASTERN ARABIAN SEA AND THE ADJOINING WEST COAST OF INDIA WITH SPECIAL REFERENCE TO THE KERALA BASIN

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CERTIFICATE

I certify that the thesis, **"Geophysical constraints on Structure and Tectonics of the Eastern Arabian Sea and the adjoining West Coast of India with special reference to the Kerala Basin"** has been prepared by Arts K. Purushotham under my supervision and guidance in partial fulfilment of the requirements for the degree of Doctor of Philosophy and no part thereof has been submitted for any other degree.

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(DSS) profiles. Lines AA' through DD' show the location of regional traverses utilised for structural interpretation. P.F – Pseudo fault, T.C. – Transferred crust, DVP – Deccan Volcanic Province, CCR – Central Cratonic Region, SGT – Southern Granulite Terrain, SCB- Saurashtra Continental Block, GH – Girnar Horst, FL – Fermor Line.

Figure 4.2. Generalised geology showing various crustal blocks in the western Indian shield region. Dots are epicenters of major earthquakes listed in Mahadevan (1995). The available focal mechanism solutions of events compiled from 1. 1967 Koyna (Chandra, 1977); 2. 1980 Koyna (Rastogi, 1992); 3. 1983 Bhatsa (Rastogi, 1992); 4. 1986 Valsad (Rastogi, 1992); 5. 1970 Broach (Arora, 1970) are also shown. Trap thickness contours are adopted from Kaila (1988).

Figure 4.3. Gravity anomaly map of the eastern Arabian Sea and adjacent western Indian shield region. The contours shown are based on Bouguer anomalies (NGRI, 1978) on land and free – air anomalies (GEOSAT) in offshore areas (contour interval : 10 mgal). Data sources are cited in the text. The gravity traverses AA' through DD' shown in figure follow ship tracks in offshore areas. Wherever necessary, along profiles, ship track data have been extended in both shelf and deep sea areas by GEOSAT and ETOPO5 data. Details are discussed in the text.

Figure 4.4. Crustal seismic sections deciphering the main crustal units along regional gravity traverse (profiles AA') across the western margin considered in the present study. All available seismic information on crustal velocities, sediment and trap thickness and Moho information have been projected onto these sections. The continuous lines denote actual seismic information, while dashed lines indicate gaps in the seismic data. Thick hyphens on basement layer indicate control points obtained from published basement maps. Values in bracket refer to seismic

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CHAPTER I

INTRODUCTION

1.1 GENERAL INTRODUCTION

The Indian Ocean is bounded by the Africa, India, Australia and Antarctica continents which were formed after the break-up of Gondwanaland. The evolutionary history of the Indian Ocean lithosphere that originated due to sea floor spreading can be very well understood through a reconstruction of this original Gondwanaland super continent. The most important event of this reconstruction is the rifting and northward movement of India and subsequent collision of the Indian plate with the Eurasian plate as most of the major structural and tectonic features present in the northern Indian Ocean have been formed during the northward flight of India from the Gondwanaland. Unlike the Pacific Ocean, the Indian Ocean is devoid of any major ocean trenches, which means that most of the oceanic crust created in the Indian Ocean is still preserved. However, the existence of several submarine plateaus, interpreted either as uplifted oceanic crust or as continental fragments, makes the reconstruction very difficult, though study of fracture zones and magnetic lineaments and palaeomagnetic data, have rendered it possible to trace the movements of these continents and continental fragments and thus the evolution of the Indian Ocean.

The western Indian Ocean bounded by the India, Arabia, Africa and Antarctica has a varied and complex tectonic history as can be seen from the geomorphology. The region is dominated by the presence of active mid-oceanic ridges, a large number of aseismic ridges or ocean plateaus and seamounts, numerous islands, of which, some are considered continental fragments and others of volcanic origin (Figure 1.1). The Madagascar Island, the fourth largest island in the world, is considered to be a part of the Gondwanaland. All these topographic high features divide the region into a number of deep-sea basins. The Indus Fan which is one of the largest deep sea fans of the world is located in the northern part of the area.

The active mid-oceanic ridge system in the western Indian Ocean appears as three main branches that meet at ridge – ridge – ridge junction referred to as the Rodrigues Triple Junction. The northern branch comprises three segments, which from south to north are known as the Central Indian Ridge (CIR), the Carlsberg Ridge and the Sheba Ridge. The other two branches are known as South West Indian Ridge (SWIR) and the South East Indian Ridge (SEIR). These three branches of the mid-oceanic ridges form the boundaries between the Indian, Antarctic and African plates. The identification of linear magnetic anomalies in the western Indian Ocean on either side of these spreading ridges (Figure 1.2), has led to the understanding of sea floor spreading history of the region. The mantle plumes also played a significant role either during continental break up or during northward drift of India in the region. Apart from the active mid oceanic ridge system, the region also contains a number of prominent topographic features. A few of these topographic highs rise above sea level and emerge as islands. Most notable among these topographic features are, the Agulhas plateau, the Madagascar ridge, the Mozambique ridge, the Laxmi ridge,

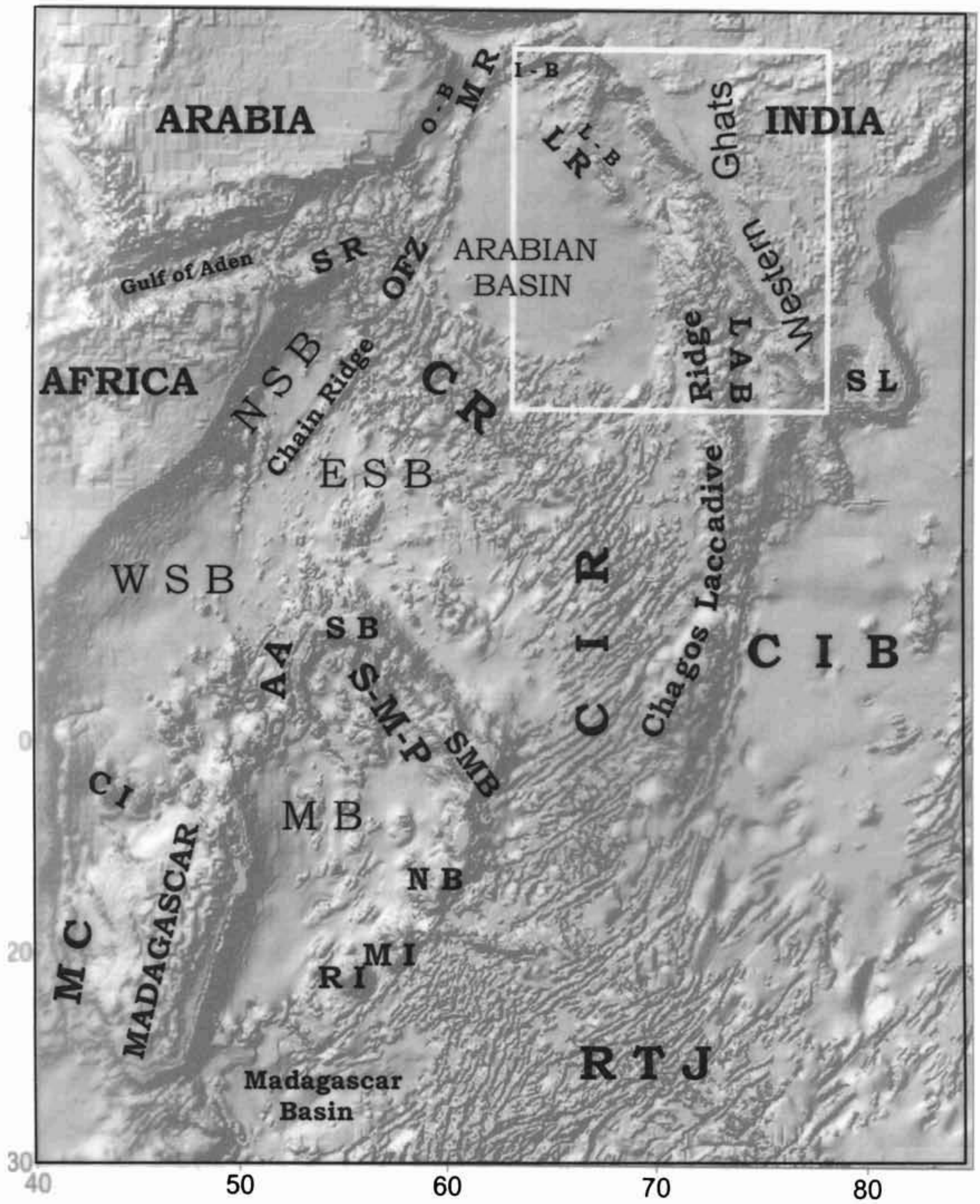

Figure 1.1 Shaded relief image of western Indian Ocean and the adjoining continents prepared based on ETOPO5 data base. Some of the prominent morphological and tectonic features are shown on the map. The area of present study is marked as rectangle (white). O-B: Owen basin, MR - Murray ridge, L-B: Laxmi basin, LR - Laxmi ridge, SR - Sheba ridge, OFZ - Owen fracture zone, NSB - Northern Somali basin, ESB - Eastern Somali basin, WSB - Western Somali basin, CR - Carlsberg ridge, CIB - Central Indian basin, AA - Amirante arc, SB - Seychelles bank, MB - Mascarene basin, S-M-P: Seychelles-Mascarene plateau complex, NB - Nazareth bank, MI - Mauritius island, RI - Reunion island, SMB - Saya de Malha bank, RTJ - Rodrigues triple junction

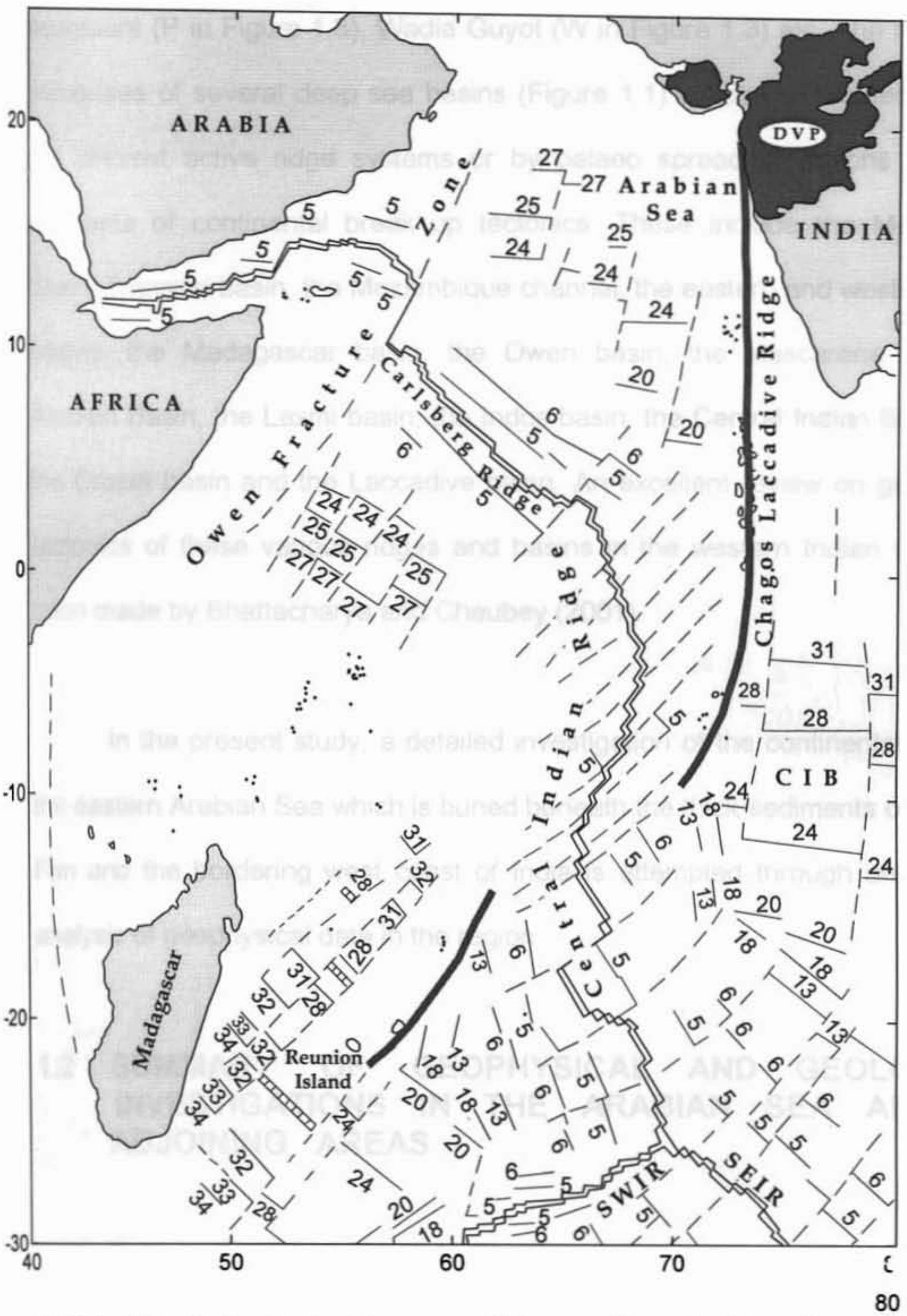

Figure 1.2 Tectonic sketch map of the w estern Indian Ocean up to 30 degree south redrawn after Royer et al. (1989). Dashed lines are fracture zones, continuous line with number are magnetic anomaly identifications, SWIR - Southwest Indian ridge, SEIR - South East Indian Ridge, dark marked area in India represents the Deccan Volcanic Province (DVP). The Reunion plume trail is shown as a thick line. CIB - Central

the Chagos-Laccadive Ridge (CLR), the Seychelles-Mascarene plateau complex and numerous seamounts like Raman seamount (R in Figure 1.3), Panikkar seamount (P in Figure 1.3), Wadia Guyot (W in Figure 1.3) etc. The region also comprises of several deep sea basins (Figure 1.1) which are created either by the present active ridge systems or by palaeo spreading regions or as the remnants of continental break up tectonics. These include the Mozambique basin, Transkei basin, the Mozambique channel, the eastern and western Somali basins, the Madagascar basin, the Owen basin, the Mascarene basin, the Arabian Basin, the Laxmi basin, the Indus basin, the Central Indian Basin (CIB), the Crozet basin and the Laccadive basin. An excellent review on geology and tectonics of these various ridges and basins in the western Indian Ocean has been made by Bhattacharya and Chaubey (2001).

In the present study, a detailed investigation of the continental margin of the eastern Arabian Sea which is buried beneath the thick sediments of the Indus Fan and the bordering west coast of India is attempted through an integrated analysis of geophysical data in the region.

1.2 SUMMARY OF GEOPHYSICAL AND GEOLOGICAL INVESTIGATIONS IN THE ARABIAN SEA AND THE ADJOINING AREAS

Prior to the International Indian Ocean Expedition (IIOE) programme in 1959, the Indian Ocean was very little studied as compared to other major oceans. During the IIOE (1959-1966) detailed geological and geophysical

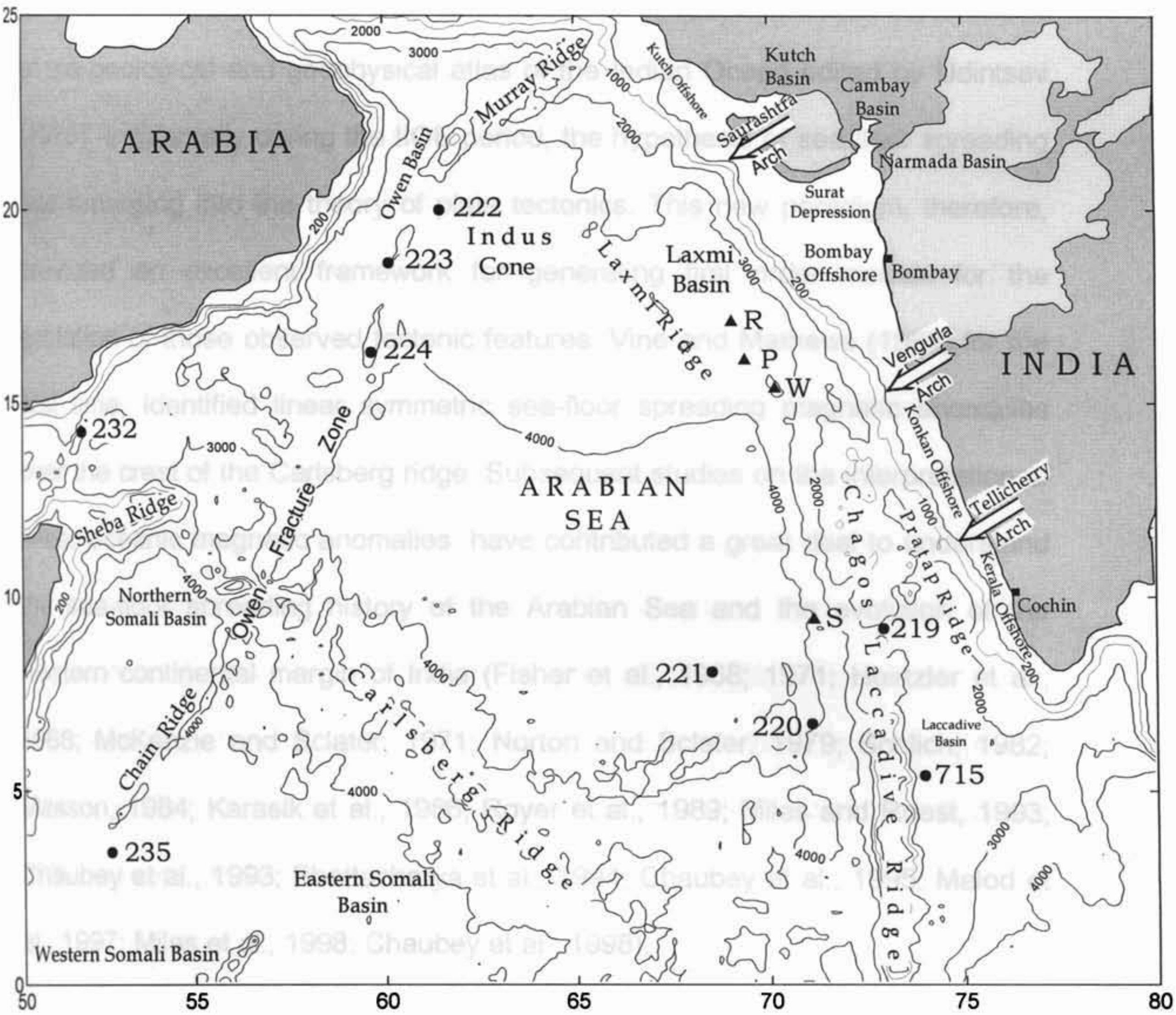

Figure 1.3 Major structural features in the Arabian Sea and the western continental margin of India along with selected bathymetric contours. The dots with number indicate the locations of scientific deep drilling (DSDP and ODP) sites. The various sub-basins and basement arches along the WCMI are shown from Biswas (2001). Solid triangles indicate seamounts. Details are given in text.

investigations were carried out. Heezen and Tharp (1964) prepared a detailed physiographic map of the Indian Ocean from the bathymetric and other geophysical data. The most significant contribution of the IIOE was the outcome of the geological and geophysical atlas of the Indian Ocean edited by Udintsev (1975). Incidentally during the IIOE period, the hypothesis of sea-floor spreading was emerging into the theory of plate tectonics. This new paradigm, therefore, provided an excellent framework for generating first order models for the evolution of those observed tectonic features. Vine and Mathews (1963) for the first time, identified linear symmetric sea-floor spreading magnetic anomalies over the crest of the Carlsberg ridge. Subsequent studies on the interpretation of linear oceanic magnetic anomalies have contributed a great deal to understand the sea-floor spreading history of the Arabian Sea and the evolution of the western continental margin of India (Fisher et al., 1968; 1971; Heirtzler et al., 1968; McKenzie and Sclater, 1971; Norton and Sclater, 1979; Schlich, 1982; Masson, 1984; Karasik et al., 1986; Royer et al., 1989; Miles and Roest, 1993; Chaubey et al., 1993; Bhattacharya et al., 1994; Chaubey et al., 1995; Malod et al., 1997; Miles et al., 1998; Chaubey et al., 1998).

Based on seismic data, several past studies discussed the sediment thickness distribution and the nature of the basement of the Indus Fan and the adjacent Indian continental margin (Neprochnov, 1961; Narain et al., 1968; Ewing et al., 1969; Closs et al., 1969; Rao, 1970; Harbison and Bassinger, 1973; Babenko et al., 1980; Bachman and Hamilton, 1980). These studies utilized data primarily from several single station refraction measurements. During 1974 and 1977, Lamont-Doherty Geological Observatory carried out detailed, multi-disciplinary geological-geophysical investigations in the Arabian Sea, including continuous seismic reflection profiling and wide-angle seismic reflection and refraction surveys. Based on these data, Naini and Kolla (1982) and Kolla and Coumes (1987) presented a detailed picture on the nature of sediment acoustics, sediment thickness distribution, and sedimentary processes in the Arabian Sea. Naini and Talwani (1982) published the sonobuoy refraction measurement data and presented a detailed picture on crustal structure variations and nature of the crust below the western continental margin and the Arabian Sea. Detailed sedimentary structure and tectonics and rifting history of western continental margin has been studied by Ramaswamy and Rao (1980); Biswas (1982;1987); Biswas and Singh (1988); Ghosh and Zhutshi (1989). The extension of several major onshore structural trends into the offshore areas have been inferred by several workers (Bhattacharya and Subrahmanyam, 1986; Kolla and Coumes, 1990; Subrahmanyam et al., 1995).

The first studies of surface gravity measurements in the Indian Ocean were based on pendulum observations aboard submarines (Vening Meinesz, 1948). Later submarine pendulum measurements have been carried out by Girdler and Harrison (1957) and Talwani (1962) aboard the British submarine H.M.S. Acheron. Subsequently, many organizations were involved in marine gravity measurements based on ship-borne gravity meters. The crustal structure, mass anomalies and rift tectonics of the western margin and the Arabian Sea has been studied from the ship-borne gravity measurements made during IIOE (Udintsev, 1975) and Lamont-Doherty cruises during 1974 – 1977 (Naini and Talwani, 1982) and several cruises of ORV Sagar Kanya by the National Institute of Oceanography, Goa (Subba Raju et al., 1990; Subrahmanyam et al., 1993; Subrahmanyam et al., 1995). More recent investigations on the structure and evolution of the western continental margin gave several valuable constraints on kinematic history of the region (Miles et al., 1998; Talwani and Reif, 1998; Todal and Eldholm, 1998; Chaubey et al., 2002).

1.3 MORPHOLOGICAL FEATURES IN THE ARABIAN SEA AND THE ADJOINING AREA

Major morphotectonic features in the Arabian Sea are believed to have been inherited from the breakup of the eastern Gondwanaland and the subsequent spreading of the Indian Ocean floor. The rifting and sea-floor spreading history of western India and the adjoining Arabian Sea has been known in general terms (McKenzie and Sclater, 1971; Whitmarsh, 1974; Norton and Sclater, 1979). Linear and symmetric pattern of magnetic anomalies were identified by Vine and Mathews (1963) for the first time over the crest of the Carlsberg ridge, which were interpreted in terms of sea-floor spreading and magnetic reversals. McKenzie and Sclater (1971) analyzed the available aeromagnetic and ship track magnetic data to study the evolution of the Indian Ocean since the late Cretaceous. They concluded that during 75 to 35 Ma, the movement of the Indian plate was very rapid (nearly 18 cm/year), and the movement was taken up by the Chagos Laccadive transform on the west and by the Ninety East ridge on the east.

Numerous regional structures and sedimentary basins are located along the continental margin of western India and the contiguous Arabian Sea. Most prominent among these are the Chagos Laccadive ridge, Laxmi ridge, Pratap ridge, Murray ridge, Owen fracture zone, Carlsberg ridge and the Indus Cone (Fan) of the Arabian Sea (Figure 1.3). The Indus Cone is bounded by the continental margin of India-Pakistan and the Chagos Laccadive ridge on the east, the Owen fracture zone and the Murray ridge on the west and north, and the Carlsberg ridge on the south. The fan is characterized by the presence of several valleys and channels through which the turbidity currents transported primarily the Indus river sediments into areas as far south as the Carlsberg ridge (Naini and Kolla, 1982). Apart from the Indus river which is the dominant supplier of sediments to the Arabian Sea, two other rivers, the Narmada and the Tapti also contribute sediments significantly to the eastern Arabian Sea. The region between the Chagos Laccadive ridge and the Indian margin south of about 16°N consists of a complex bathymetry with numerous topographic highs and lows. The shelf break occurs at an average depth of 200m along the margin with the width of the shelf varying from 150 km near Karachi and the Gulf of Kutch, 350 km off Bombay to 60 km towards south of Cochin (Naini and Kolla, 1982). Between Goa and Kathiawar, the continental slope-rise is normal whereas north of Kathiawar, the margin morphology has been modified by the presence of the Indus fan (Naini, 1980). However, between Goa and Cochin, numerous topographic highs complicate the nature of continental rise. The Pratap ridge is a prominent topographic feature between 7°N to 15°N latitudes paralleling the margin in this region. The Chagos Laccadive ridge extending from about 10°S to 15°N latitudes is an asymmetrical ridge with a steeper eastern flank. The ridge on an average is less than 1000m deep with occasional coral atolls and volcanic islands such as Laccadives. Prominent among numerous topographic features is the Laxmi ridge trending NW-SE located between 3000 and 3500m isobath in the Indus Cone – Arabian abyssal plain. Along the Indian margin, several basement highs (arches) trending perpendicular to the coast divide the shelf region into various thick sediment filled basins (Figure 1.3). They include Kutch, Saurashtra, Bombay, Konkan and Kerala basins. The southwesterly plunging Saurashtra arch separates Kutch from the Saurashtra basin in the south. The Bombay and Saurashtra basins are divided by Surat depression. The southwesterly plunging Vengurla arch separates the Bombay basin and the Konkan basin whereas the Tellicherry arch demarcates the Kerala and Konkan basins further south. Biswas (1988) presents a sequence of morphotectonic units that make up the margin which include the Kori-Comorin depression close to the coast, the Kori-Comorin ridge, the Laxmi-Laccadive depression and the Laxmi- Laccadive ridge. The shelfal horst-graben complex off Saurashtra and Bombay consists of three

Precambrian orogenic trends viz. the NNW-SSE Dharwar trend, the NE-SW Aravalli trend and the ENE-WSW Satpura trend (Biswas and Singh, 1988).

1.4 STUDY AREA

The eastern Arabian Sea and the adjoining west coast of India contain several structural features which have evolved mostly as a consequence of rifting and sea-floor spreading between India, Madagascar and Seychelles. Many of these structural and basement features have been inherited from the Precambrian structural grain of the western Indian shield. Therefore, in order to understand the rifting style, basement tectonics and early evolutionary history of the margin, it would be useful to integrate the geophysical data in the onshore as well as offshore along various segments of the margin. In the present study, the area starting from the western shield margin to the region covering the deep oceanic parts of the Arabian Sea which is bounded by Carlsberg and Central Indian ridges in the south, eastern part of the Indus Cone in the west and falling between 63°E and 80°E longitudes, and, 5°N – 24°N latitudes has been considered (Figure 1.1).

1.5 SCOPE OF THE PRESENT STUDY

The main objective of the present study is to model the gravity field in terms of lithospheric structure below the western continental margin of India, identify zones of crustal mass anomalies and attempt to infer the location of

Ocean Continent transition in the Arabian Sea. The vast amount of seismic reflection and refraction data in the form of crustal velocities, basement configuration and crustal thicknesses available for the west coast as well as the eastern Arabian Sea has been utilized for this purpose. For detailed basin scale modeling involving both onshore and offshore areas, close spaced data in the coastal areas is necessary. For this purpose, the Kerala basin covering both offshore as well as the coastal Kerala region has been considered for detailed data acquisition and interpretation in terms of crustal modeling. In order to fulfill the above-mentioned objectives, for the sake of convenience, the thesis is divided into six chapters.

Chapter I gives a brief introduction on the geotectonics of the region, historical background of various geophysical studies in the western Indian Ocean and various morphological features in the Arabian Sea. Based on these background informations, several outstanding problems that can be addressed in the present study also have been presented.

In Chapter II, a detailed account of the geotectonics, rifting history and tectonostratigraphic evolution of major sedimentary basins along the western continental margin of India is given. The nature of plume lithosphere interactions either during rifting or breakup of India – Madagascar at ~ 88 Ma or during India-Seychelles at ~ 65 Ma have been discussed. The development of major onshore and offshore sedimentary basins such as the Kutch, Cambay, Saurashtra, Bombay offshore and Konkan-Kerala basins during the India's northward drift after breakup from the Gondwanaland led to the deposition of thick pile of sediments in the margin. The structure and stratigraphic history of these basins in the light of rift tectonics has been discussed. The major topographic features in the eastern Arabian Sea mainly include the Chagos-Laccadive Ridge, the Pratap ridge and the Laxmi ridge. The nature of crust and their formation during the evolution of the Arabian Sea is still enigmatic. The nature of crust below the Laxmi basin in the NW part of the margin is also not clear. In order to address some of these problems, a detailed review on kinematic history of evolution for the eastern Arabian Sea has been presented in this chapter.

For interpretation of gravity anomalies in terms of crustal mass anomalies, rock density as well as crustal density information are essential. Such density information can either be obtained by direct determination of rock density from rock samples or inferred indirectly from the observed seismic velocities. The seismic data along the western continental margin of India and deep oceanic parts of the Arabian Sea include the wide-angle reflection and seismic refraction surveys carried out by many previous workers. Along the West Coast of India, deeper information on crust/mantle structure is available from seven refraction Deep Seismic Sounding Profiles. The available density data from surface sampling as given by previous workers is utilized for gravity modeling. The density values are inferred from Nafe-Drake relationship. These available seismic data for both West Coast and the adjoining oceanic areas have been utilized to infer an approximate density configuration for the crust in the region. The results have been enumerated in chapter III.

In chapter IV, a revised gravity anomaly map for the eastern Arabian Sea and the adjacent western shield margin has been prepared. The map shows that except in the inner shelf region, free-air anomalies are in general negative in the whole Arabian Sea. The bipolar edge effect anomalies i.e., a gravity high of +20 to +40 mGal in the inner shelf region and as low of as much as –60 mGal in the slope can be seen all along the western margin except between 12° - 16°N. Here the gravity field seems disturbed perhaps due to the presence of several basement ridges and isolated bathymetric features. The subdued and broadly varying gravity field in the deeper Arabian Sea is found to increase sharply on the Chagos-Laccadive Ridge. A NW- SE trending gravity low of more than –40 mGal correlates well with the Laxmi ridge. Four regional gravity traverses uniformly spaced across the western continental margin of India have been considered to interpret the 2D – lithospheric structure below the West Coast and the adjacent eastern Arabian Sea. The regional variations in mass distribution and crustal structure are discussed with an objective to supplement the geologic inference on the basic processes of crustal rifting and the crustal mass anomalies present below the eastern Arabian Sea and its underlying ridges.

The Kerala basin is a major onshore-offshore sedimentary basin observed along the western continental margin of India and is located in its southern part. Integrated interpretation of the geophysical data in the coastal as well as offshore areas of the Kerala basin has been made in order to delineate the structure and tectonics of the margin. For the purpose of preparing detailed gravity and magnetic maps in the coastal areas nearly 600 gravity station measurements utilizing a network of 28 new gravity base stations have been made in the onshore part of the basin. The analysis of gravity anomalies on the onshore part of the Kerala basin display faulted basement structure and also concealed intrusive bodies below the sedimentaries. The gravity derived crustal models along four profiles across the Kerala basin display areas of complex crustal configuration in the region. From the models, certain inferences on rift tectonics and margin evolution have been made. These results form the main component in chapter V.

Chapter VI presents the summary and conclusions of the gravity interpretation along the western continental margin of India.

CHAPTER II

REGIONAL GEOTECTONIC SETTING, BREAK UP AND EVOLUTIONARY HISTORY OF THE WESTERN CONTINENTAL MARGIN OF INDIA

2.1 INTRODUCTION

Geologic and geophysical studies of the Atlantic-type continental margins provide information on the basic processes of crustal rifting and tectonics in different stages in the evolution of the lithosphere in the region. The Western Continental Margin of India (WCMI) is one such Atlantic- type continental margin formed due to the rifting and drifting of India, Madagascar and the Seychelles since the early Cretaceous. During this period, the Deccan continental flood basalts erupted near the developing plate boundary, reflecting the impingement of the Deccan plume on the lithosphere. Several of the structural features observed in the shelf and further into the Arabian Sea have been formed during the margin development. Some of these structures have inherited the Precambrian structural grain of the western shield margin of India. Several workers identified extension of the few major onshore structures/lineaments into the offshore areas (Bhattacharya and Subrahmanyam, 1986; Kolla and Coumes, 1990).

2.2 INDIA, MADAGASCAR IN EASTERN GONDWANALAND, BREAK UP HISTORY AND PLUME LITHOSPHERE INTERACTIONS ALONG THE WCMI

India with many geologic systems was an important constituent of the eastern Gondwanaland (Powell et al., 1988). Its position in the reconstruction of eastern Gondwanaland has been studied by many workers (Katz and Premoli, 1979; Subba Rao and Sukheswala, 1981; Powell et al., 1988; Storey et al., 1995). Figure 2.1 shows the possible reconstruction of constituents of eastern

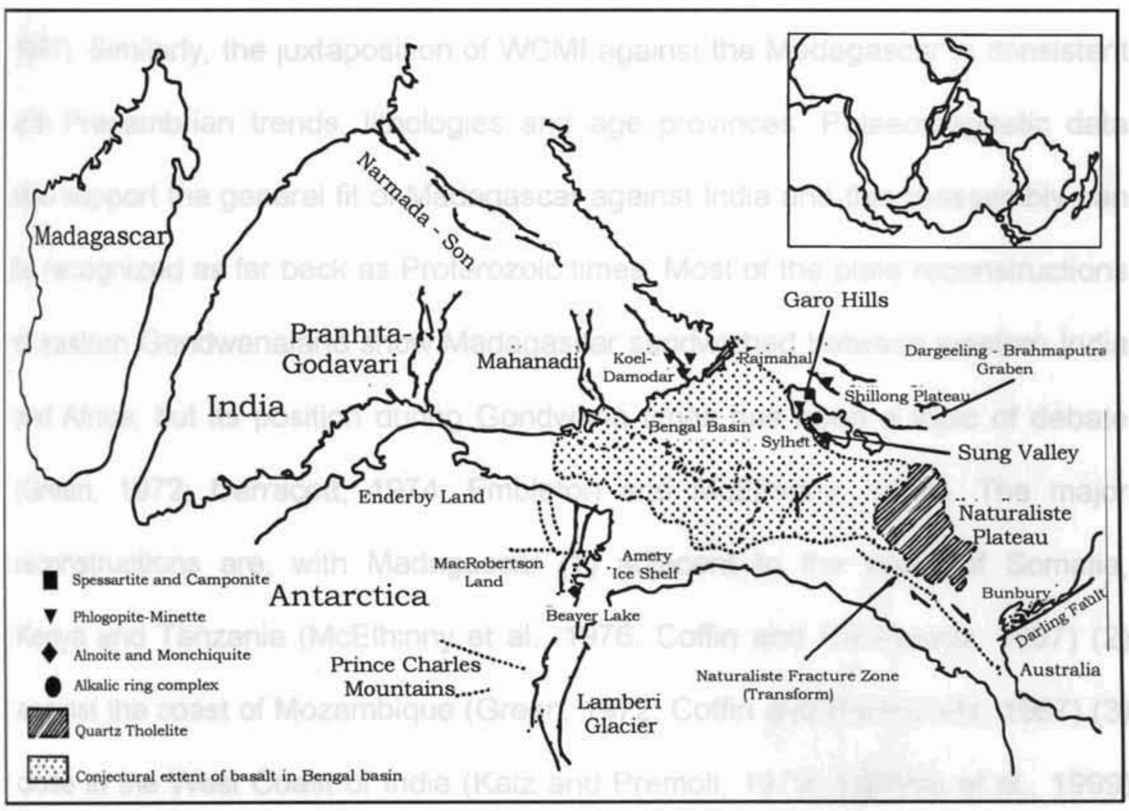

Figure 2.1 Reconstruction of India, east Antarctica and Madagascar in the Gondwana period (after Kent, 1991).

Gondwanaland. The present day continental margin of east Antarctica agrees well with the eastern continental margin for India along 200m bathymetry and this position has been strongly supported by magnetic lineations and structural lineaments traced into both continents (Johnson et al., 1976; Lawver et al., 1991). Similarly, the juxtaposition of WCMI against the Madagascar is consistent with Precambrian trends, lithologies and age provinces. Palaeomagnetic data also support the general fit of Madagascar against India and this reassembly can be recognized as far back as Proterozoic times. Most of the plate reconstructions of eastern Gondwanaland show Madagascar sandwiched between western India and Africa, but its position during Gondwana times has been a topic of debate (Green, 1972; Darracott, 1974; Embleton and McElhinny, 1975). The major reconstructions are, with Madagascar (1) adjacent to the coast of Somalia, Kenya and Tanzania (McElhinny et al., 1976; Coffin and Rabinowitz, 1987) (2) against the coast of Mozambique (Green, 1972; Coffin and Rabinowitz, 1987) (3) close to the West Coast of India (Katz and Premoli, 1979; Yoshida et al., 1999) (4) as a stationary island at the present position (Darracott, 1974). Comparisons between India and Madagascar (shown as Figure 2.2) have provided us with some similarities between them. It is found that the age of the southern Granulite zone of India (2.5-2.6 Ga) corresponds with the Madagascar granulite terrain. The shallow water Cretaceous fossils in the western India are reported to be closely akin to specimens from Madagascar (Stokes, 1965). Tectonically, the major lineaments in India are traced into Madagascar. The Narmada-Son lineament has been traced into the northern part of Madagascar by Crawford

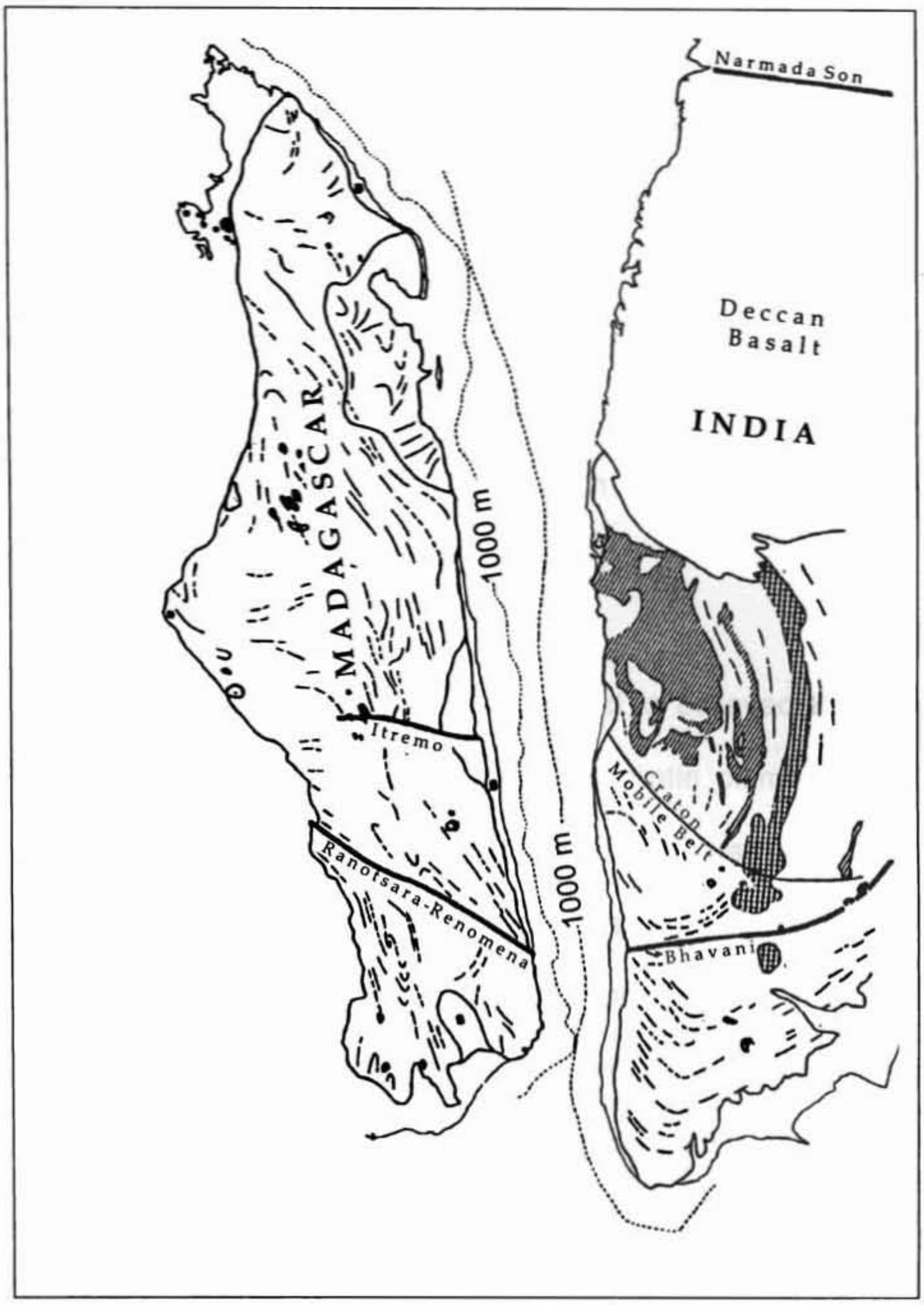

Figure 2.2 Reconstruction of India and Madagascar at 1000m isobath and matching of Precambrian structural trends (after Katz and Premoli, 1979).

(1978). The Bhavani lineament is traced to the Bongolava- Ranotsara lineament of Madagascar (Katz and Premoli, 1979). The presence of upper Cretaceous volcanic rocks and mafic dykes on the western margin of India (Subba Rao and Sukheshwala, 1981) and the eastern coast of Madagascar substantiate the rifting along these margins. Good correspondence of Magsat data and other geophysical and geologic evidence exists between Madagascar and the south Indian shield (Agarwal et al., 1992). The matching of 1000m isobath (Fig. 2.2), considerable thinning of the Moho, the presence of major faults and upper Cretaceous volcanic rocks, the escarpment structure on the eastern side of Madagascar and the nature of long wave length gravity anomalies on the two sides seem to confirm the idea of rifting between the east coast of Madagascar and the West Coast of India (Agarwal et al., 1992).

The continental breakup in Gondwanaland is believed to have resulted from the interaction of a series of hotspots or mantle plumes. The first such interaction that has relevance for the evolution of WCMI was when the combined Madagascar-Seychelles-India block came over the location of Marion hot spot (Figure 2.3a) approximately around 88 Ma resulting in the separation of Madagascar from Seychelles-India block (Storey et al., 1995; Besse and Courtillot, 1988). During the course of continued northward drift of India, around 65 Ma, just after the separation of Seychelles and India the region came under the influence of another hotspot, the Reunion hotspot (Figure 2.3b). This caused wide spread volcanism over the Indian landmass and created the continental

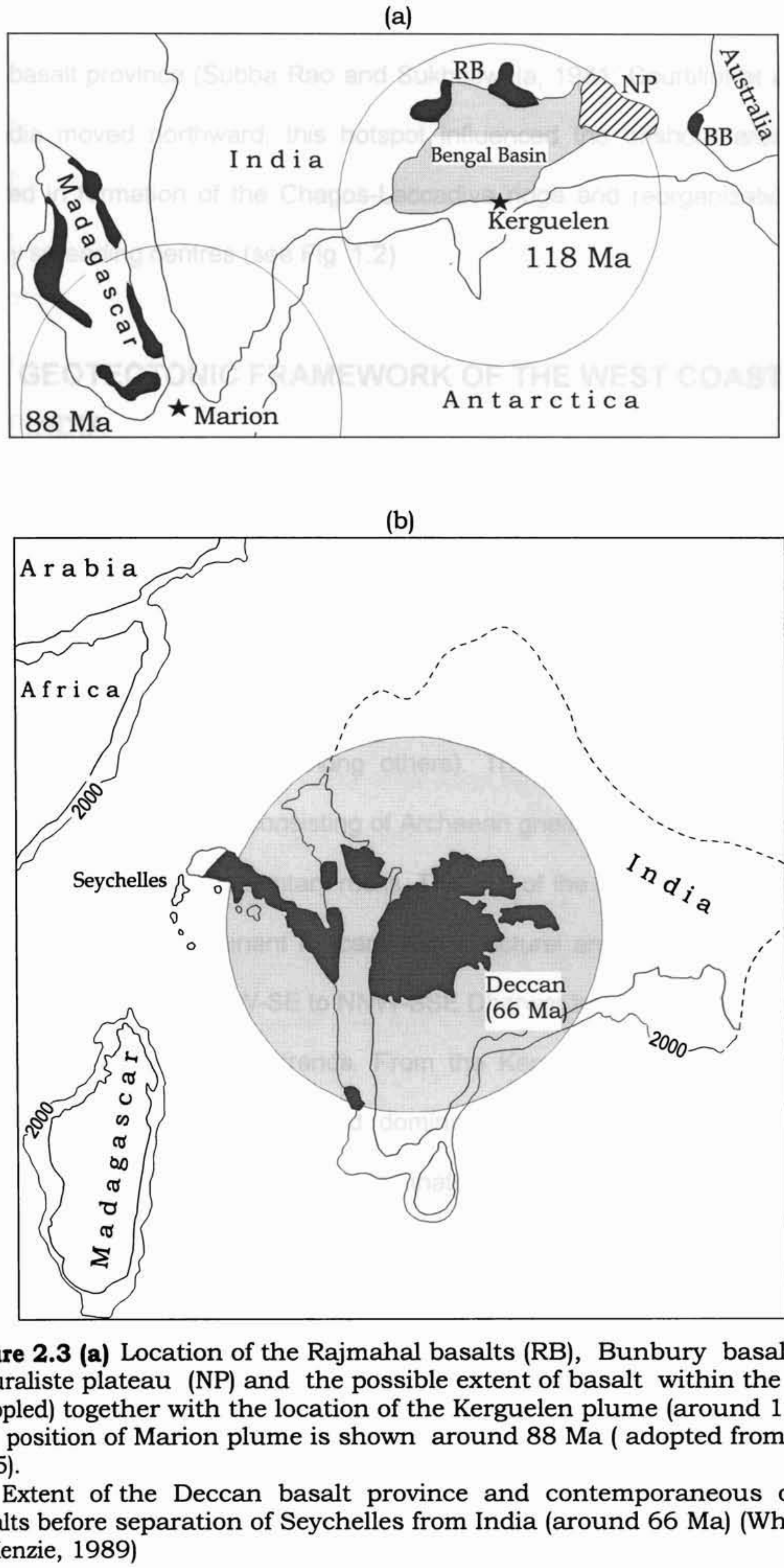

Figure 2.3 (a) Location of the Rajmahal basalts (RB), Bunbury basalts (BB), Naturaliste plateau (NP) and the possible extent of basalt within the Bengal (Stippled) together with the location of the Kerguelen plume (around 118 Ma). The position of Marion plume is shown around 88 Ma (adopted from Storey, 1995).

(b) Extent of the Deccan basalt province and contemporaneous offshore basalts before separation of Seychelles from India (around 66 Ma) (White and McKenzie, 1989) flood basalt province (Subba Rao and Sukheswala, 1981; Courtillot et al.,1986). As India moved northward, this hotspot influenced the offshore areas which resulted in formation of the Chagos-Laccadive ridge and reorganization of the nearby spreading centres (see Fig. 1.2).

2.3 GEOTECTONIC FRAMEWORK OF THE WEST COAST OF INDIA

The development of structural features of the Indian continental margin and associated igneous activities are related to the history of the Indian subcontinent, breakup from Gondwanaland, its northward movement and ultimate collision with the Asian plate (Norton and Sclater, 1979; Veevers et al., 1980; Subrahmanya, 1998; among others). The major portion of the Indian Peninsula is a shield area consisting of Archaean gneisses, schists, charnockites and metamorphosed sedimentary rocks. The rest of the Peninsula is covered by Deccan Traps. The dominant Precambrian structural and tectonic trends along the West Coast are the NW-SE to NNW-SSE Dharwar trend, NE-SW Aravalli and ENE-WSE to E-W Satpura trends. From the Kerala offshore to the Bombay offshore areas, the Dharwar trend dominates. To the north, in the Gulf of Cambay region, the Satpura trend dominates the structural style, while further north in the Kutch-Saurashtra region, the Aravalli-Delhi trends are predominant (Biswas, 1982). These Precambrian structural grain, according to Biswas (1982) has a bearing on the north to south sequential rifting of the Indian subcontinent during the breakup of Gondwanaland. North of Goa, the western Indian shield is completely buried under large cover of Deccan Traps (Das and Ray, 1976). The western margin of India has a long coastline bordered by coastal region of low elevation with width varying 30 to 50 km. The coastal region rises in small steps and suddenly there is a drastic change in altitude. This precipitous terrain to the east of coastal region forms the well-known Western Ghats. The escarpment is nearly parallel to the coastline over a length of 1500 km (Figure 2.4). The more or less wall-like feature facing the Arabian Sea is made of variety of rock types. These geomorphic features such as an elevated inland plateau, a huge erosionally controlled escarpment, a coast-parallel monoclinal flexure and a low lying coastal plain observed along the West Coast are similar to other rifted continental flood basalt provinces like Parana of Brazil, Karoo of SE Africa and Etendeka of SW Africa (Widdowson, 1997). The continental scale of drainage pattern is comparable to other continental flood basalt provinces like south Brazil and southeast Africa (Cox, 1989) which could be result of the dynamic plume uplift prior to continental rifting. The marginal uplift of Western Ghats along the West Coast has also been observed along several other passive margins of the world. The phenomena of uplift has been described by a number of workers which include the magmatic underplating (Cox, 1980; McKenzie, 1984); rift related mechanisms of crustal thinning (Royden and Keen, 1980; White and McKenzie, 1988); transient thermal effects (Cochran, 1983); secondary effects associated with extension (Buck, 1986) and flexural unloading (Weissel and Karner, 1989). The rifted margin upwarp is considered to be a consequence of differential denudation and flexural isostasy (Gilchrist and Summerfield, 1991).

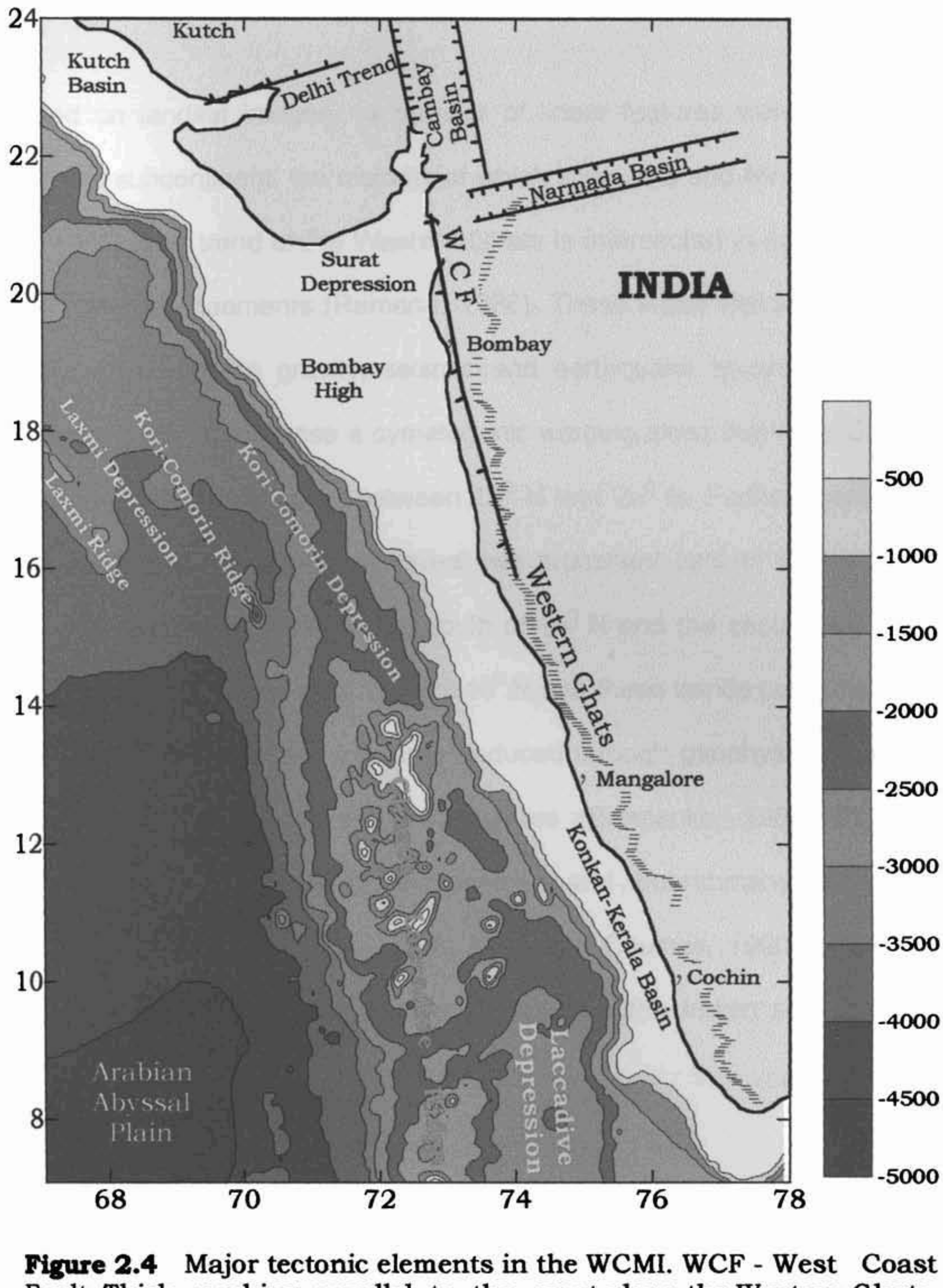

Figure 2.4 Major tectonic elements in the WCMI. WCF - West Coast Fault. Thick marking parallel to the coast along the Western Ghats indicate the location of Western Ghat scarp.

Apatite fission track analysis (Galleghar et al., 1998) indicates that the escarpments form by uplifting during rifting followed by a lateral retreat of an erosion (scarp retreat) across, may turn to hundreds of kilometers inland.

Based on landsat imagery, a number of linear features were identified over the Indian subcontinent, the majority of which show N-S and NW-SE trends (Qureshy, 1982). The trend of the Western Ghats is intersected in many places by NE-SW trending lineaments (Ramana, 1986). These linear features show a strong correlation with the gravity, seismic and earthquake epicentres which made Qureshy (1982) to propose a cymatogenic warping along the West Coast, with the axis parallel to the coast between 19^0 N and 20^0 N. Further, geologic, tectonic and geomorphological data reveal two prominent sets of linears, one with $320\text{-}340^0$ orientation over the area south of 16^0 N and the second set with $290\text{-}310^0$ orientation over the area north of 16^0 N and these trends correlate with the major subsurface faults and fractures deduced through geophysical studies (Chandrasekharam, 1985). Several investigators (Eremenko, 1968; Biswas, 1982; 1987; Gopala Rao, 1984; Bhattacharya and Subrahmanyam, 1986; Ramana, 1986; Biswas and Singh, 1988; Kolla and Coumes, 1990) proposed extension of these structural and tectonic trends from the Indian subcontinent into shelf areas of the western Indian margin.

2.4 STRUCTURE AND STRATIGRAPHY OF THE SEDIMENTARY BASINS ALONG THE WCMI

The western continental margin of India is divided into five major offshore sedimentary basins. These are Kutch, Saurashtra, Ratnagiri, Konkan and Kerala basins. All these five basins were divided by the transverse basement arches such as Saurashtra arch, Bombay high, Vengurla arch and the Tellicherry arch across the coast (Figure 1.3). Major rivers like the Indus, Narmada and Tapti are draining toward the northern part of this margin producing a very thick shelf sedimentary column. The shelf in the north is typically featured by longitudinal extensional faults giving rise to a series of narrow horst-graben structures. Such extensional faulting is responsible for widening of the shelf and the horst-graben structures created favourable habitat for hydrocarbon accumulation. The style of faulting is controlled by three major orogenic trends in the western part of the Indian shield margin; namely the NE-SW Aravalli, ENE-WSE Satpura and NNW-SSE Dharwar trends (Biswas, 1982). These trends have a bearing on the north to south sequential rifting of Indian subcontinent during the breakup of Gondwanaland (Biswas, 1982). Two major conjugate rift systems, Narmada and Cambay, cross each other south of Saurashtra peninsula in the Surat offshore region forming a deep depression. The Surat depression is considered by many as triple junction (Thomson, 1976; Bose, 1980; Powar, 1987). The shelf in the south, in the Konkan-Kerala basins, the structural styles are similar to north but of less intensity. Biswas and Singh (1988) identified six contiguous tectonic elements running N-S in the shelf and deep oceanic areas of the Arabian Sea along the WCMI (Figure 2.4). These are shelfal horst-graben complex, Kori-Comorin ridge, Laxmi-Laccadive depression, Kori-Comorin ridge, Laxmi-Laccadive ridge and the Arabian abyssal plain. Landward, the West Coast fault and its northward extension the east Cambay fault and the Nagar Parkar fault mark approximately the land ward limit of the WCMI. Seismic data shows that the WCMI has evolved through an early rift phase and post rift phase of divergent margin development separated by a prominent basin wide discontinuity (Biswas and Singh, 1988). The northern most part of the WCMI was the first to be subjected to continental rifting since the late Triassic giving rise to Mesozoic marginal basins in the onshore areas (Biswas, 1982). This gave rise to three intracratonic marginal basins such as Kutch, Narmada and Cambay basins on the northwest Coast. Later, the rifting and drifting of India since the break-up of Madagascar around 85-90 Ma gave rise to Pericratonic rift basins such as the Kutch, Saurashtra, Bombay (Ratnagiri), Konkan and Kerala basins.

A brief description of the structure, stratigraphy and tectonics of these various sedimentary basins is presented below:

2.4.1 MARGINAL RIFT BASINS

The northern part of the western continental margin is characterized by the presence of three important coastal basins namely the Kutch, Cambay and Narmada basins. These basins are pericratonic embayments rifted through grabens which have been formed from north to south, during different phases of rifting since the breakup of Greater India from Africa and its northward drift (Biswas, 1982). All three basins originated in different periods during the Mesozoic and have varying thickness of Mesozoic sediments. Table 2.1 presents the summary of generalized stratigraphy and history of these marginal rift basins.

2.4.1.1 KUTCH BASIN

The Kutch basin is bordered by the Nagar Parkar ridge in the north, the Radhanpur-Barmer arch in the east and the Kathiawar uplift in the south. This pericratonic rift basin is styled by three main uplifts along three master faults with interesting half-grabens (Biswas, 1980). The faulted margins of the uplifts are characterized by narrow linear zones of folding. The tilted blocks form a system of step faults, giving rise to a one-sided horst and half-grabens. A subsurface meridional high, crosses the basin at right angle to its axis in the middle.

The Kutch basin formed during the late Triassic. Its evolution and syn-rift sedimentation continued through Jurassic till early Cretaceous. Several unconformities and diastems have been recorded in the stratigraphy of the Kutch basin, each of which can be correlated with periods of uplift and erosion (Biswas, 1974). During the present compressive stage, the Radhanpur arch acts as a ramp for eastward movements along the principal deforming zones giving rise to the Kutch mainland active principal fault (Biswas, 2002).

Age	Kutch Basin			Cambay Basin			Narmada Basin		
	Lithology	Geological Environment	Events	Lithology	Geological Environment	Events	Lithology	Geological Environment	Events
Pliocene	S. St/ Conglomerate, Minor shale(1000ft)	Deltaic	Regression. Major tectonic movement	Sandstone/ Shale/ Conglomerate (3500 ft)	Fluvio-Deltaic to Marine	Regression, Major tectonic cycle			
E. Miocene	Shale/L.st/ Silt stone (660 ft)	Shallow Marine	Transgression						
Oligocene	L.st/Shale(126 ft)	Shallow Marine	Regression, Tectonic cycle, Transgression	Shale/S.st/L.st (600-900ft)					
L.Eocene									
M. Eocene	L.st/ Minor shale (185 ft)	Shallow Marine	Regression, Tectonic cycle. Transgression	S.st/silt stone/ Shale/coal (600-900ft)	Marine/Deltaic	Oscillatory, Transgression/ Regression cycles			
E. Eocene	Shale/L.st (135 ft)	Shallow Marine	Regression, Tectonic cycle, Transgression	Black shales (1500-4500ft)	Marine/Pro-Deltaic	Transgression		Terrestrial	Regression/ Uplift/ volcanicity Major. Tectonic cycle
Paleocene	Laterite/ Tuff/Fe Clay/S.st(163 ft)	Continental	Erosion/ Peneplanation	Volcanic Conglomerate/ Trap wash /Fe Clay stone (60-4000ft)	Fluvial/ Lacustrine	Graben formation Uplift/erosion/ volcanicity. Major tectonic cycle	Deccan traps (>3000ft) L.st/marl/ S.st(250 ft)	Marine	Transgression
L. Cretaceous	Deccan trap; Basalt flows(1500 ft)	Terrestrial	Major tectonic movement and volcanicity	Deccan traps (3000 ft)	Terrestrial	Rifting	S.st/Shale (300ft)	Deltaic/ Continental	Rifting
E. Cretaceous	S.st/Shale/Iron stone (3500 ft)	Deltaic	Regression	Feldspathic S.st (3000 ft)	Fluvial/ Deltaic				
U. Jurassic	S.st/Shale (2000 ft)	Shallow Marine							
E-M Jurassic	L.st/ Shale (2500 ft)								Uplift/Erosion
L. Triassic	Arkosic S.st (150 ft)	Shallow Marine Continental	Regression Transgression Rifting						
Pre-Mesozoic							S.st/shale/ L.st	Marine	Transgression
Precambrian Basement	Granite/Metamorphics			Granite			Metamorphics/ Granite		

Table 2.1. Generalised stratigraphy and history of marginal rift basins in the northwest Indian shield (after Biswas, 1987)

2.4.1.2 CAMBAY BASIN

The Cambay basin is an intracratonic graben bordered by the Radhanpur-Barmer arch separating it from the Kutch embayment and Kathiawar uplift on the west and by the Aravalli orogenic belt on the east. It is bounded by enechelon faults paralleling the Dharwar trend and cuts across the Aravalli and Narmada trends. The basin extends offshore to the south as a narrow graben parallel with the coast between Bombay high and the mainland (Biswas, 2001). The transverse faults segment the basin into six tectonic blocks, the Patan, Mehsana, Ahmedabad, Tarapur, Broach and the Narmada. Raju (1968) described the basin as an aulacogen and traced its evolution during Tertiary through four stages of development: formative, negative, oscillatory and positive. According to Biswas (1982), at least 1200m of Mesozoic sedimentaries are present below the Deccan trap flows, which form the floor of a Tertiary sequence of about 5000m thick.

2.4.1.3 NARMADA BASIN

The Narmada basin is the southern most of the three marginal basins embayed into a narrow graben along the Narmada-Son geofracture. The valley opened into a rift basin in late Cretaceous time and marine sediments were deposited in a progressively deepening environment until the end of the Cretaceous (Biswas, 2001). Among the three marginal basins, late Cretaceous marine sediments occur only in this basin indicating a subsidence while in the other two basins this was a period of non-deposition and volcanic activity

(Biswas, 1987). The sedimentation ended abruptly as a result of regional uplift followed by volcanic activity that deposited the Deccan traps in early Palaeocene (Biswas, 2001).

2.4.1.4 KERALA BASIN

The Kerala basin is a major onshore-offshore sedimentary basin observed along the western continental margin of India and is located in its southern most part. The Tertiary sedimentary formations in the onshore part of the basin unconformably overlie the Precambrians. Paulose and Narayanaswamy (1968) recognised two major basins of deposition, one in the south between Trivandrum and Ponnani and the other in the north between Cannanore and Kasaragod. The formations exposed on the southern part of the basin continue below the younger formations towards north Kerala (Bose and Kartha, 1977). Details on sediment thickness and lithology in the onshore part of the basin is available form regional geophysical investigations by Bose and Kartha (1977) and bore hole well data from Nair and Rao (1980). The Neogene sequences have a maximum thickness of 400m in the Ambalappuzha region. The tertiary sedimentary column is more than 600m in the region between Ambalappuzha and Alleppey, which has witnessed maximum subsidence during the Miocene.

2.4.2 OFFSHORE BASINS

The western offshore contain several deep water sedimentary basins extending from Kutch in the north to Cape Comorin in the south which encompasses a vast sedimentary track of 4,71,000 Km^2 upto the Exclusive Economic Zone (EEZ) (Thakur et al., 1999). The mechanism of formation of these pericratonic multiple rift basins owes much to the thermo-mechanical evolution of the continental margin since the breakup from Madagascar around 88 Ma (Strorey et al., 1995). Vast amount of seismic data in the offshore revealed a number of ridges and depressions continuously running parallel to the coast from Kutch to Cape Comorin (Mitra et al., 1983; Biswas and Singh, 1988). A number of basement arches running transverse to the coast divide the western offshore into five major offshore basins called Kutch, Saurashtra, Bombay (Ratnagiri), Konkan and Kerala basins. A brief description of structural and tectonic aspects of the major offshore basins are discussed below:

2.4.2.1 BOMBAY OFFSHORE

The Bombay offshore basin is the most important petroliferous basin so far discovered in the West Coast sedimentary province in India. It covers an area of 120,000 Km^2 up to 200m isobath. The basin is separated by Saurashtra arch in the north from the Kutch basin and the Vengurla arch in the south from the Konkan basin. (Rao and Talukdar, 1980; Mathur and Nair, 1993). The basin contains six major structural units each having several well-marked sub-units. The lithostratigraphic history of this offshore basin is given in Table 2.2. Some significant aspects on structure and sedimentation history of the basin are:

- the Surat depression is one the major basinal area with more than 3 km of clastic fill of Palaeocene-Eocene.
- the N-S trending Diu arch separates the Surat depression from the Saurashtra basin
- the Saurashtra and shelf margin basins, although formed in the Palaeocene, experienced maximum subsidence during late Oligocene to middle Miocene
- the NE trending Ratnagiri arch separates the Murud depression from the Rajapur depression and is traceable from the shelf area to the deep sea
- the Kori arch separating the shelf margin basin from the deep sea basin is a semi continuous regional arch.

2.4.2.2 KONKAN OFFSHORE

The offshore area between the Vengurla arch in the north and Tellicherry arch in the south along the central part of the West Coast of India forms the Konkan basin. The continental slope off Konkan has a gentle dip of about 2 to 5 degrees and drops off moderately to form a terrace like feature at a water depth of 1000m (Thakur et al., 1999). The ocean floor is having a relatively

Age	Saurashtra Basin	Surat Depression	Shelf Margin Basin	Shelf Margin Banks/ Reefs	Bombay Platform: DCS Area	Bombay Platform: Bombay High	Heera-Bassein Commp. Block	Ratnagiri Block	Transgression(T) Regression(R)
Middle Miocene-Holocene	Tarapur Formation				Tarapur Formation				T
	U	U	U						
Early - Middle Miocene	Shale With Limestone Bodies	Tapti Fm.	Vashi Fm. Shelf Margin Group	Angria Bank Group (Includes Many Unconformities)	DCS Group	Saurashtra Formation		Ratnagiri Fm.	R T
Early Miocene		Mahim Fm.				Bombay Fm.			R T
Late Oligocene-Early Miocene		Daman Fm.				Alibag Fm.			R T
Early OligoCene	Shale With Limestone Interbeds	Dhahanu Fm.					Bassein Fm.	Bassein Fm.	R T
Middle-Late Eocene									R T
Paleocene-Early Eocene	Panna Fm.			Panna Fm.	Panna Fm.		Panna Fm.		R T
	Deccan Trap				Deccan Trap			Deccan trap	
	Mesozoic Rocks				?	Absent	?	Mesozoic rocks	
	Precambrian Rocks								

Table 2.2. Generalised stratigraphy of various tectonic elements in the Bombay Offshore basin (modified after Mathur and Nair, 1993). DCS – Deep Continental Shelf.

corrugated topography in the southern part with a number of submarine topographic features aligned parallel to the present day coast (Subba Raju et al., 1990). Subrahmanyam et al. (1993,1994) delineated structural features such as the Pratap Ridge complex, the shelf margin basin, the mid-shelf basement ridge and the inner shelf graben within water depths of 30-2000m in the region. The tectono-sedimentation history of the margin (Thakur et al., 1999) reveals three sedimentary units belonging to pre-rift, syn-rift (Palaeocene-lower Eocene) and post rift (middle Eocene to recent) stages. The basin contains nearly 3 km of sediments. Table 2.3 presents a generalised stratigraphy of the basin showing various litho-units.

2.4.2.3 KERALA OFFSHORE

The Kerala offshore basin came into existence probably during middle to late Cretaceous as a result of an early phase of rifting between India and Madagascar. The basin in the offshore extends from Tellicherry arch in the north to Cape Comorin in the south. Two major depressions called the Cochin depression and the Cape Comorin depression characterize the shelfal horst-graben complex in which the Alleppey platform is a prominent tectonic element (Singh and Lal, 1993). Figure 2.5 shows various tectonic elements in the coast and within the shelfal horst-graben complex region of the basin. The marginal to shallow marine clastic fill encountered in two wells off Cochin belong to the late Cretaceous Cochin formation (Dirghangi et al., 2000). The base of the formation shows two dominant faults trends, a NNW-SSE trend parallel to the margin

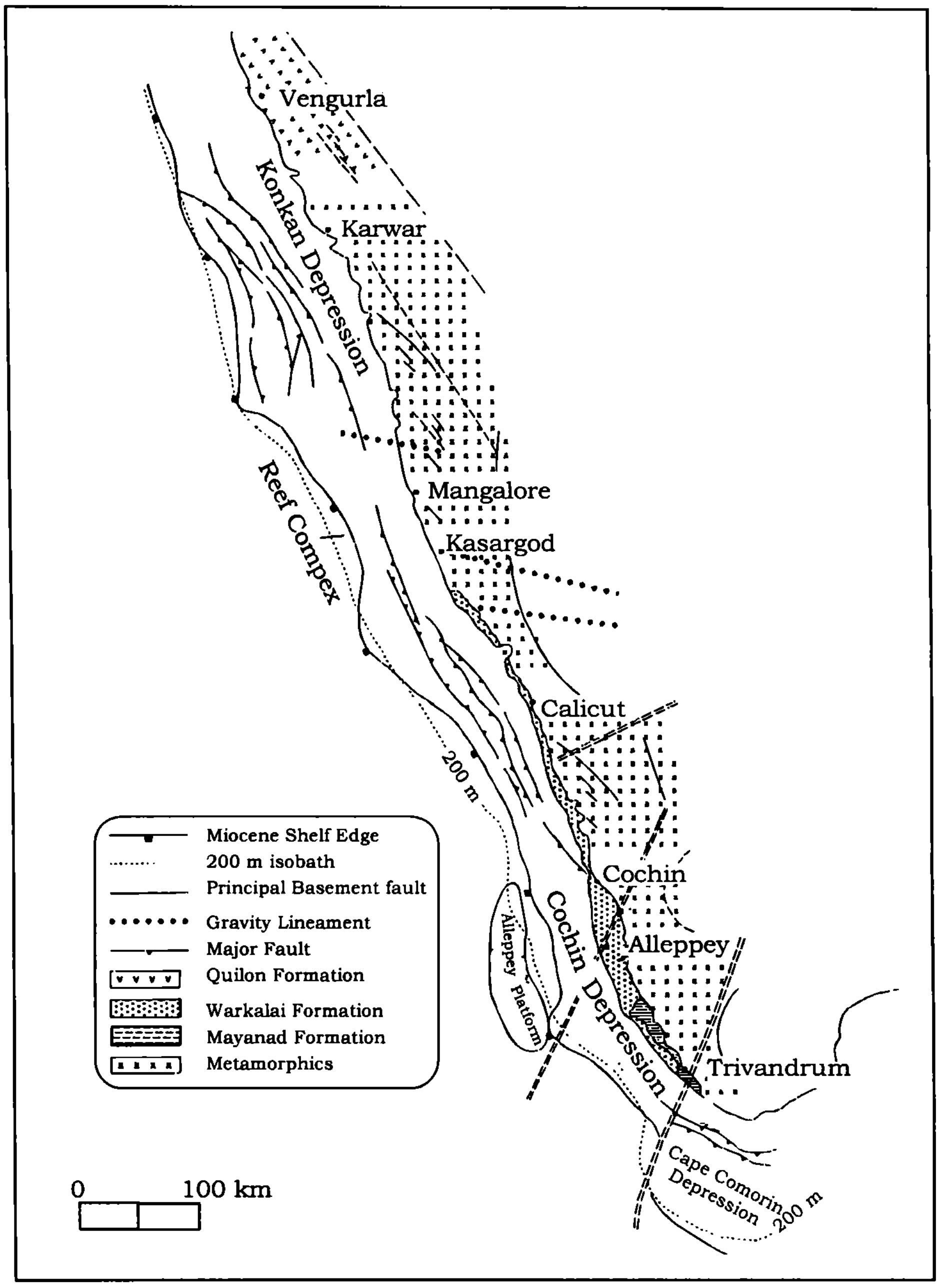

Figure 2.5 Tectonic features in the Konkan - Kerala coast and the adjoining shelfal horst - graben complex in the offshore (adopted from Singh and Lal, 1993)

Age		KARWAR -I		KASARGODE -I
Pleistocene to Recent		Clay:	Gy to Dk Gy., Soft plastic with shale fragments 299-34 (35m)	Clay/Claystone Pyritic, silty, Slightly calcareous 242-940 (690 m)
Pliocene		Claystone:	Gy., Pyritic, pebbly calcareous fossiliferous 334-599 (265m)	
Miocene	Late			
	Middle	Limestone	Lt.Gy.,micritic,chalky, dolomitic yellow minor shale 599-889 (90 m)	Limestone: Micritic to Biomicritic White,corals and shell fragments 940-1336(396 m)
		Limestone	Lt.Gy.,micritic,chalky dolomitic,yellow minor shale 689-997 (308m)	
	Early	Limestone	Lt.Gy.,micritic,chalky yellow , minor shale 997-1187(190 m)	
Basal Miocene		Limestone	Lt.Gy.,micritic,chalky dolomitic,yellow minor shale 1187-1318 (131 m)	Limestone: Chalky,micritic 1336-1470 (134 m)
Oligocene	Late			
	Middle	Dolomitic limestone with minor shale 1318-1408 (90 m)		Chalky micriticLimestone 1470-1540 (70 m)
	Early			
Eocene	Late			
	Middle	Dolomitic limestone with minor shale 1408-1504 (96 m)		Micritic, biomecritic marl and silt 1540-2300 (840 m)
	Early			
Palaeocene		? ? ?		? ?
Mesozoic				Sand :quartzose,poorly sorted Br,Gy.,Clay,limestone towards bottom 2380-3970(590 m)
Paleozoic				
Archaean				

Table 2.3. Generalised stratigraphy of the Konkan offshore basin as obtained from two offshore wells (after Singh and Lal, 1993).

representing the rift trend and a younger NNE-SSW shear faults (Dirghangi et al., 2000). A more detailed analysis in terms of structure and tectonics of this basin is presented in Chapter V.

2.5 KINEMATIC HISTORY OF EVOLUTION FOR THE EASTERN ARABIAN SEA- A GEOPHYSICAL PERSPECTIVE

The basic framework of the western continental margin of India was established by the end of Cretaceous (Biswas, 1987). The rifting and related processes along the margin as well as the seafloor spreading processes in the Arabian Sea should be very well understood for complete knowledge on kinematic history of evolution of the Arabian Sea. The Arabian sea is divided into several deep ocean basins by submarine plateaus, aseismic Laxmi and Laccadive ridges, the active spreading Carlsberg and Sheba ridges and the regionally extending Owen fracture zone. Evolution history of these basins has been deduced by various workers based on geophysical studies mainly magnetic anomalies and seismic data (McKenzie and Sclater, 1971; Whitmarsh, 1974; Norton and Sclater, 1979; Naini and Talwani, 1982, Schlich, 1982, Miles and Roest, 1993; Chaubey et al, 1993, 1995, 1998; Bhattacharya et al, 1994; Malod et al, 1997; Miles et al. 1998; Talwani and Reif, 1998; Todal and Eldholm, 1998; among others). Two major ridges, the Laxmi and Laccadive ridges divide the region into two broad crustal provinces namely the western Arabian basin and the eastern Arabian basin. The western Arabian basin and its conjugate eastern representing the rift trend and a younger NNE-SSW shear faults (Dirghangi et al., 2000). A more detailed analysis in terms of structure and tectonics of this basin is presented in Chapter V.

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Somali basin are definitely underlain by oceanic crust as they have crustal structure similar to a known oceanic crust and identifiable magnetic anomalies. Whereas, the crustal structure below the eastern Arabian basin lying between the Laxmi, Laccadive ridges and the western continental slope is enigmatic. Geophysical studies carried out have not so far made an unequivocal conclusion regarding the nature of crust in the region. However, Bhattacharya et al. (1994) inferred oceanic crust below the Laxmi basin, a small, portion within the eastern Arabian basin, based on magnetic anomaly identifications. The main ambiguity in the reconstruction history is on the actual timing of initiation of opening of the Arabian Sea. Considerable ambiguity on the oldest identifiable magnetic anomaly still exists. In fact, two important points remain equivocal, as far as tectonic history of the Arabian Sea is concerned i.e., the oldest sea floor spreading magnetic anomaly and the location of Ocean Continent Transition (OCT) along the margin. Another important factor that should be considered in the reconstruction is the role of Deccan plume activity during the continental break up and sea floor spreading. The continental flood basalts are known to have associated along some rifted margins with transient, large scale igneous activity during continental break up. However, in the case of western continental margin, the separation of Seychelles from India and the initial opening history of the Arabian Sea, eastern Somali basin are poorly known. Some recent works made in the Arabian Sea mainly focussed on these aspects (Bhattacharya et al., 1994; Malod et al., 1997; Miles et al., 1998; Talwani and Reif, 1998; Todal and Eldholm, 1998; Chaubey et al., 2002).

It is generally accepted that the sea floor spreading history of the Arabian Sea can be divided into two distinct phases. The first phase includes rifting between India and Madagascar during the Early Tertiary around 84-88 Ma. (Norton and Sclater, 1979; Besse and Courtillot, 1988; Storey et al., 1995). The sea floor spreading separated Madagascar from Seychelles-India block, which resulted in opening of the Mascarene basin. The relative motion between India and Madagascar took place just before emplacement of Chagos Laccadive archepelago along a transform fault (Whitmarsh. 1974) and up to middle Eocene the Indian plate moved rapidly northward towards Eurasia (Molnar et al., 1988).

During India's continued northward drift, around 69-65 Ma widespread volcanism took place due to Reunion hot spot that created the Deccan continental flood basalt province. Though several workers debate on the exact timing of this emplacement, it has been established that the traps were emplaced through a series of eruptions in a very short span of time (< 0.5 Ma) (Courtillot et al., 1986; Vandamme et. al., 1991; Venkatesan et al., 1993).

The most significant aspect that has wider implications on plate tectonic reconstruction of the Arabian Sea is the identification of sea floor spreading magnetic anomalies in the Laxmi basin by Bhattacharya et al. (1994). Based on this observation, Talwani and Reif (1998) proposed a reconstruction history shown in Figure 2.6 which moves Seychelles' original location closer to India and

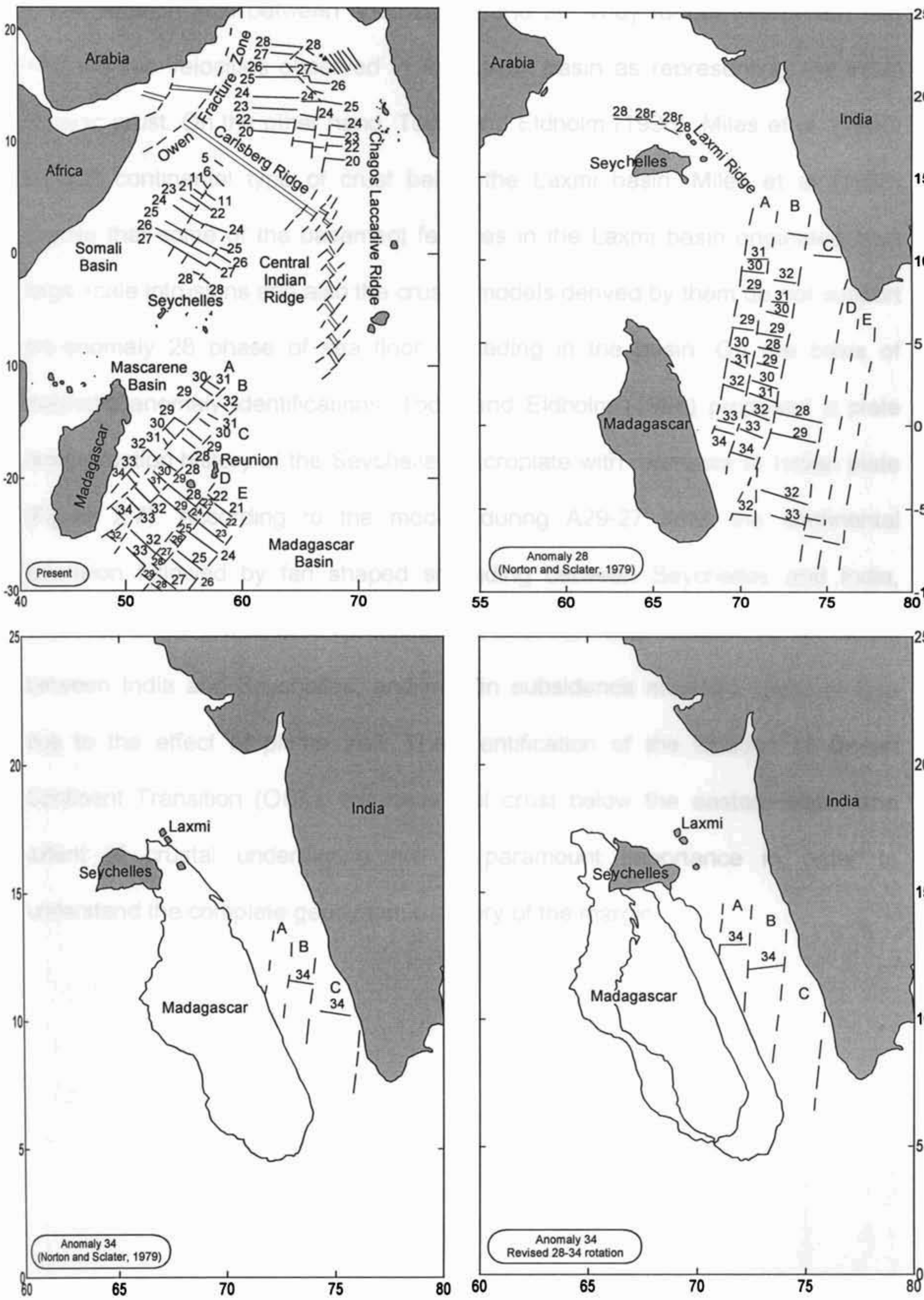


Figure 2.6 The reconstruction of India and Madagascar proposed by Talwani and Reif (1998) considering sea floor spreading anomalies in the Laxmi basin identified by Bhattacharya et al. (1994). A new rotation pole between anomaly 28 and 34 times has been used that ameliorite the space problem in the Mascarene basin.

a new rotation pole between anomaly 28 and 34. They further interpreted that >7.0 km/sec velocities observed in the Laxmi basin as representing the initial oceanic crust. On the other hand, Todal and Eldholm (1998), Miles et al. (1998) support continental type of crust below the Laxmi basin. Miles et al (1998) believe that some of the basement features in the Laxmi basin originated from large scale intrusions and also the crustal models derived by them do not support pre-anomaly 28 phase of sea floor spreading in the basin. On the basis of magnetic anomaly identifications, Todal and Eldholm (1998) proposed a plate reconstruction history of the Seychelles microplate with reference to Indian plate (Figure 2.7). According to the model, during A29-27 time, the continental extension followed by fan shaped spreading between Seychelles and India, cessation of the fan shaped spreading just after A27 time followed by spreading between India and Seychelles, and margin subsidence modified south of Goa due to the effect of plume trail. The identification of the location of Ocean Continent Transition (OCT), the nature of crust below the eastern basin and extent of crustal underplating are of paramount importance in order to understand the complete geodynamic history of the margin.

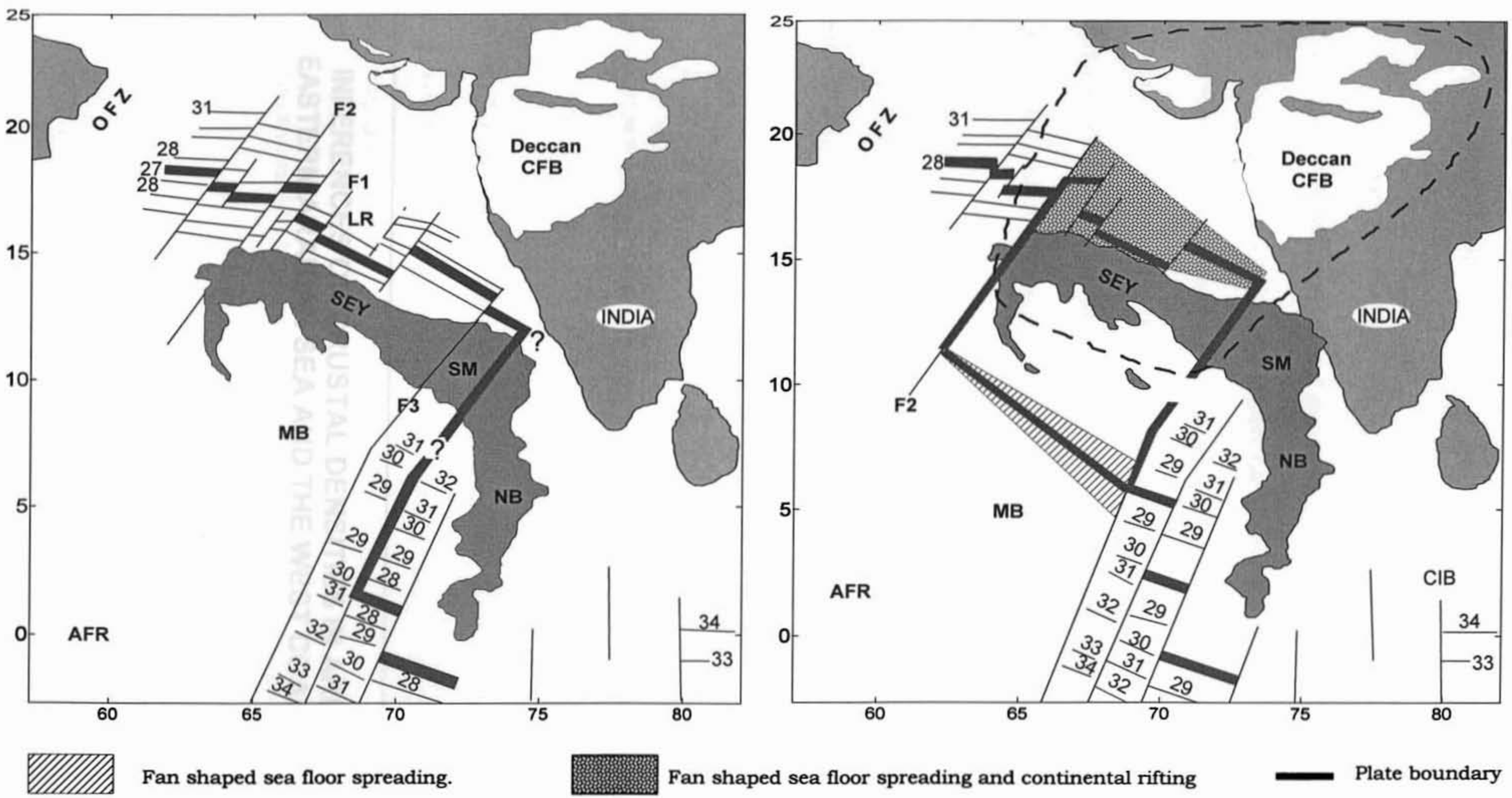


Figure 2.7 Plate reconstruction of Seychelles microplate (SEY) with reference to the Indian plate (IND). This reconstruction assumes Eastern basin as underlain by continental crust. AFR - African plate, OFZ - Owen fracture zone, MB - Mascarene basin, CIB - Central indian basin, NB- Nazareth bank, SM - Saya de Malha bank, LR - Laxmi ridge. Thick dashed line in the right diagram encircle the Deccan Large Igneous province (after Todal and Eldholm, 1998).

CHAPTER III

INFERENCES ON CRUSTAL DENSITIES IN AREAS OF THE EASTERN ARABIAN SEA AND THE WEST COAST OF INDIA

3.1 INTRODUCTION

For a meaningful interpretation of gravity anomalies in terms of crustal structure, the information on crustal densities are of very high significance. The densities of crustal rocks for any region can either be measured directly from surface rocks/cored rock samples or the values can be inferred based on seismic velocities obtained from seismic studies. In the present study, the crustal density information for the eastern Arabian Sea and the western Indian shield margin have been derived on the basis of following data :

(i) For the western Indian shield margin consisting of the Deccan Volcanic Province, Dharwar craton and the southern granulite terrain, the seismic velocity information available from the Deep Seismic Sounding (DSS) studies for indirect information on crustal densities particularly the deeper information.

(ii) Surface sampling of rocks and their measured densities for the high-grade granulite terrain, Dharwar craton and the Deccan traps along the west coast of India.

(iii) Sonobuoy refraction, wide-angle reflection and multichannel reflection data available for the Arabian Sea to infer density configuration for the eastern Arabian Sea crust.

The various data types utilized are diagrammatically shown in Figure 3.1.

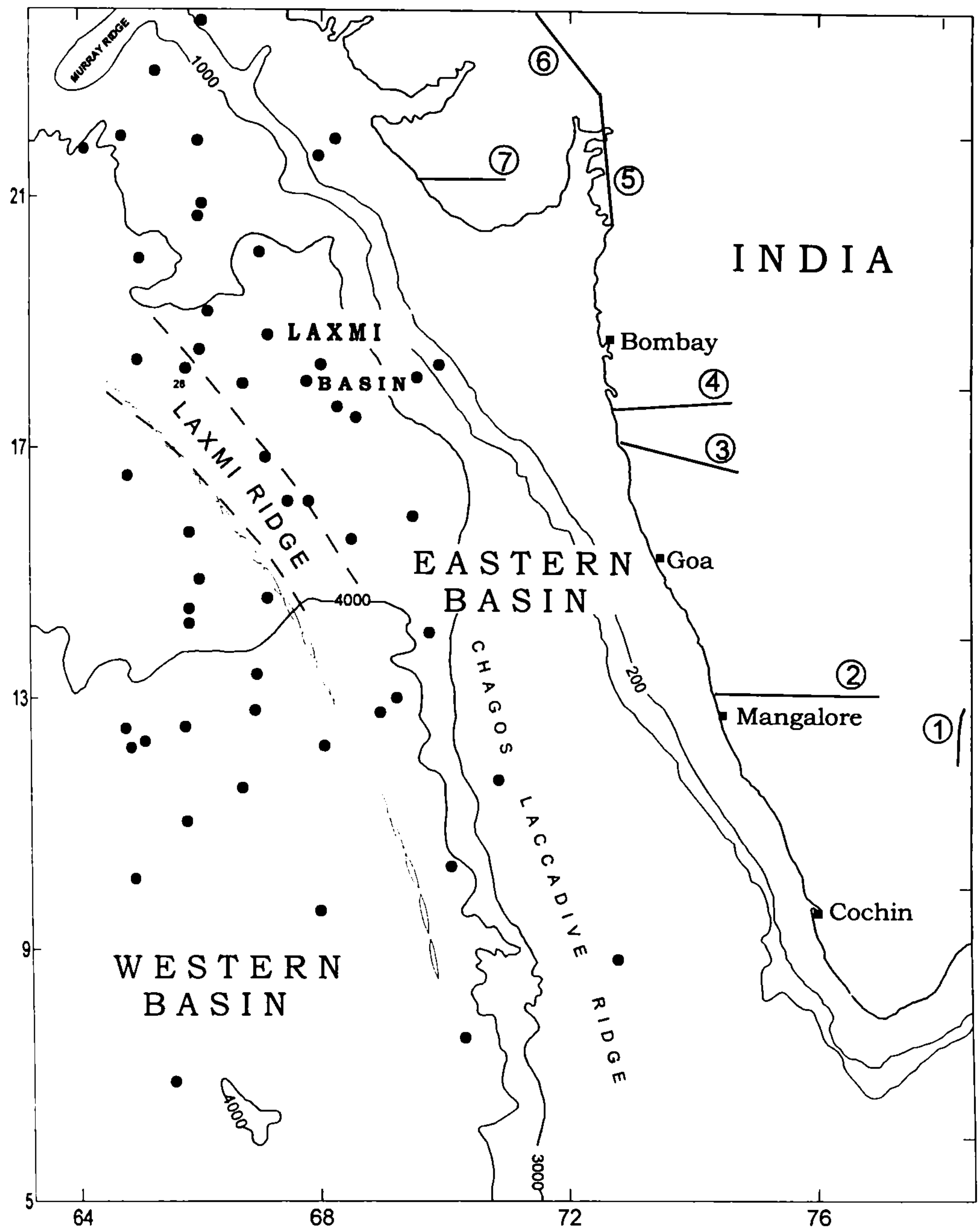


Figure 3.1 Showing location of DSS profiles in the western shield margin. Also shown are the location of refraction and wide angle seismic reflection stations in the eastern Arabian Sea considered in the present study (adopted from Naini and Talwani, 1982). The DSS profiles are I. Kuppam-Palani, 2. Kavali-Udipi, 3. Guhagar-Chorochi, 4. Kelsi-Loni, 5. Mehmadabad-Billimora, 6. Mehmadabad -Dharimanna, 7. Navibandar-Amreli.

3.2 SEISMIC REFRACTION RESULTS IN THE EASTERN ARABIAN SEA

The seismic data along the western continental margin of India and deep oceanic parts of the Arabian Sea include the wide angle reflection and sonobuoy refraction surveys carried out by Francis and Shor (1966), Rao (1970), Naini and Talwani (1982). Using several single station refraction measurements, many previous workers discussed the sediment thickness distribution and the nature of basement of the Indus fan and adjacent Indian margin (Neprochnov, 1961; Narain et al., 1968; Ewing et al., 1969; Closs et al., 1969; Rao, 1970; Harbison and Bassinger, 1973; Babenko et al., 1980). During 1974 and 1977 Lamont – Doherty Geological Observatory carried out detailed, continuous seismic reflection profiling, wide-angle seismic reflection and sonobuoy refraction surveys. The wide-angle seismic reflection and sonobuoy refraction techniques yield data on interval velocities and refraction velocities (LePichon et al., 1968), while interval velocities in general pertain to the sediments, refraction velocities pertain to the crust below the sediments. Based on the seismic velocity data on sediments and upper crustal layers, Naini and Talwani (1982) divided the eastern Arabian Sea into two provinces: the western basin and the eastern basin. These two basins are divided by the Laxmi ridge in the north and Laccadive ridge in the south. On the basis of these data, they concluded that the western basin is underlain by typical oceanic crust where well correlatable sea floor spreading magnetic anomalies are observed. The eastern basin is characterized by thick crust, which is thicker than the oceanic crust. According to them, the crust below the Laxmi ridge and the northern part of Chagos-Laccadive is also continental in nature. On the basis of seismic data on both the short range and long range sonobuoy refraction surveys as presented by Francis and Shor (1966); Closs et al. (1969); Naini and Talwani (1982) and Naini and Kolla (1982), details on velocity information for each one of these structural provinces is presented below:

3.2.1 WESTERN BASIN

The velocity-depth profiles obtained at various refraction stations in the western basin are plotted as shown in the Figure 3.2a. In this basin, water depths range between 3.4 to 4. km (with an average of 3.8 km (Naini and Talwani, 1982). The velocity depth profiles, however, are shown here with respect to the sea bottom at zero depth. The sediment depth ranges between 1.7 and 3.8 km/sec with thicknesses ranging from 1.3 km to 4.2 km which is underlain by the crust ranging in velocity between 5.0-7.0 km/sec. Two distinct velocity ranges have been observed, the top crustal layer showing a velocity range of 5.5 to 6.0 km/sec and the bottom crustal layer having velocities between 6.5 to 7.0 km/sec. Moho was observed at many refraction stations with velocities between 7.9-8.3 km/sec. The average depth to Moho is about 11.5 km.

3.2.2 EASTERN BASIN

The sediment velocities in the eastern basin show different ranges but mainly falling between 1.5-2.4 km/sec and 3.0-4.6 km/sec velocity ranges. The velocities of basal sediments in the eastern basin show a range of 4.0-5.0

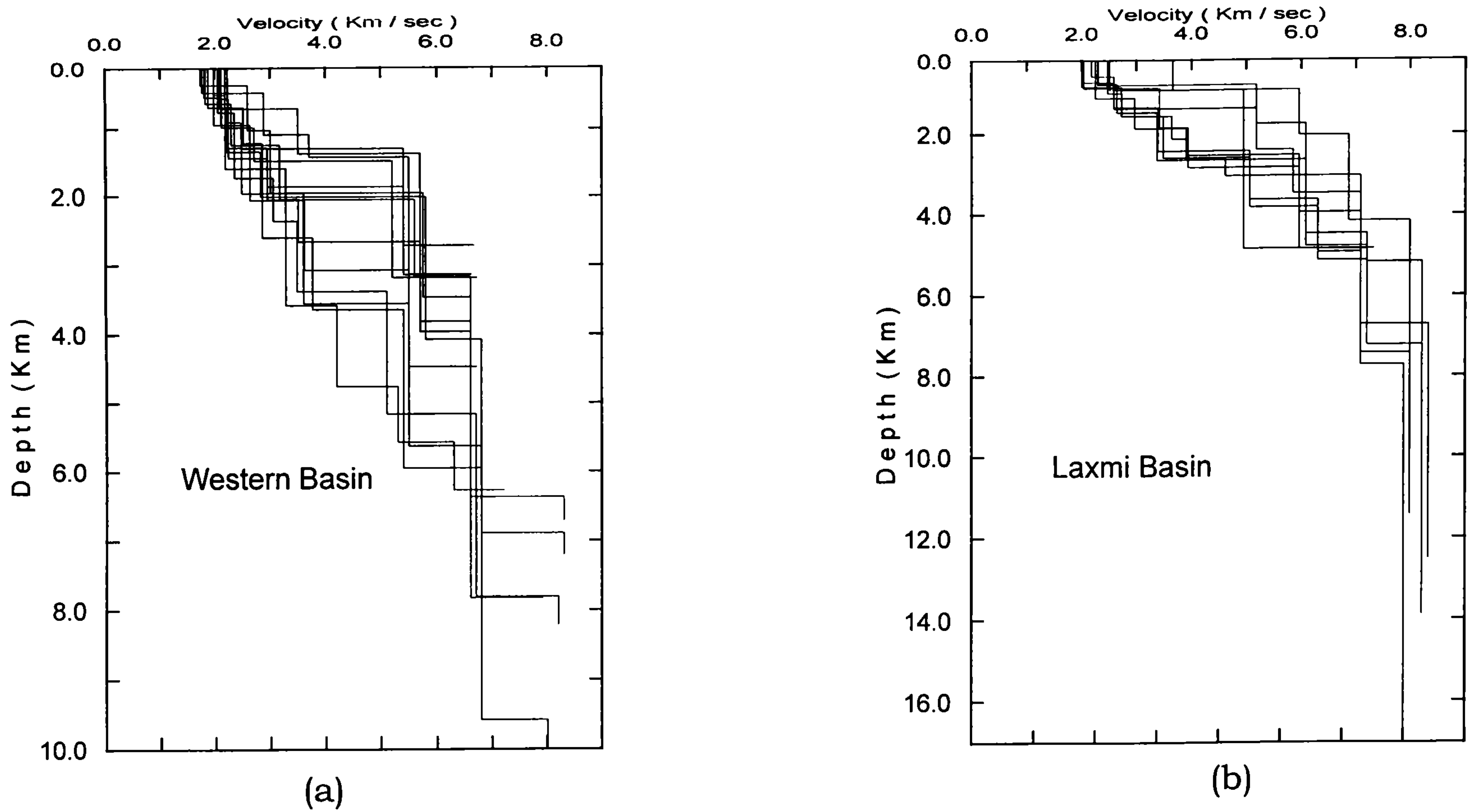


Figure 3.2 Velocity-depth profiles plotted for (a) Western basin and (b) Laxmi basin in the eastern Arabian Sea. The seismic refraction data given by Naini and Talwani (1982) have been utilised for this purpose. Details are discussed in the text.

km/sec. The crustal rocks below the sediments show velocities dominantly ranging between 5.4-5.6 km/sec, 6.2-6.4 km/sec and 7.2-7.4 km/sec. Moho has not been mapped anywhere below the eastern basin. By projecting the seismic velocities, Naini and Talwani (1982) estimated a minimum Moho depth of about 1.7 km. So, the crustal structure as obtained from the above data does not support the presence of normal oceanic crust below the eastern basin. However, recently Bhattacharya et al. (1994) identified sea-floor spreading magnetic anomalies in the Laxmi basin in the northern part of eastern basin. The velocity-depth profiles of all the refraction stations falling within the Laxmi basin are shown in Figure 3.2b which do not support the presence of normal oceanic crust below the Laxmi basin. Talwani and Reif (1998) refer these velocity structures to the presence of initial oceanic crust. The structural ambiguity and the geological implications of this extremely complex region are discussed in the next chapter.

3.2.3 LAXMI RIDGE

Laxmi ridge perhaps is the most intriguing tectonic feature in the Arabian *Sea due to the fact that it is a topographic high displaying negative gravity* anomalies over it (Naini and Talwani, 1982). Average sediment thickness over the ridge is about 500m with thicker ponded sediments. The velocity of sediments range between 1.7-3.9 km/sec. A basal sediment layer is also observed with velocity 4.3 km/sec. Three crustal layers below the sediments have been observed with velocities of 5.3 km/sec, 6.2 km/sec and 7.2 km/sec. Though Moho was not mapped beneath the ridge, the interpolated velocities by

Naini and Talwani (1982) suggests that the Moho could be at a depth of 21 km. The velocity-depth profiles obtained from various refraction stations over the ridge have been shown in Figure 3.3a considering sea bottom at zero depth. The velocity structure for the ridge indicates more continental affinity.

3.2.4 CHAGOS-LACCADIVE RIDGE

The velocity structure given by Francis and Shor (1966) for the Chagos-Maldives section reveal 4-5 km of top volcanic layer, 5-10 km of crustal material of velocity ranging from 6.1 to 6.7 km/sec. The Moho has been observed only at one location at a depth of 17 km. In the northern part, Naini and Talwani (1982) brings 1.6-2.1 km/sec, 4.2-4.4 km/sec, 5.6-5.7 km/sec and 7.2-7.3 km/sec layers. Narain et al. (1968) interpreted the ridge forming at the boundary of continent-ocean transition zone. The velocity-depth profiles from available refraction stations are shown in Figure 3.3b.

3.3 DENSITY INFORMATION DEDUCED FROM SEISMIC VELOCITIES IN THE EASTERN ARABIAN SEA

In order to obtain approximate density configuration for the various litho-units underlying the eastern Arabian Sea, the above seismic velocity information has been utilized. For the purpose of converting velocities to densities, the Nafe-Drake relationship has been used (Nafe and Drake, 1963). Despite limitations in correlating highly reflective seismic layers as density layer boundaries (Holliger and Kissling, 1992), this inferred densities would still be useful to derive a broad

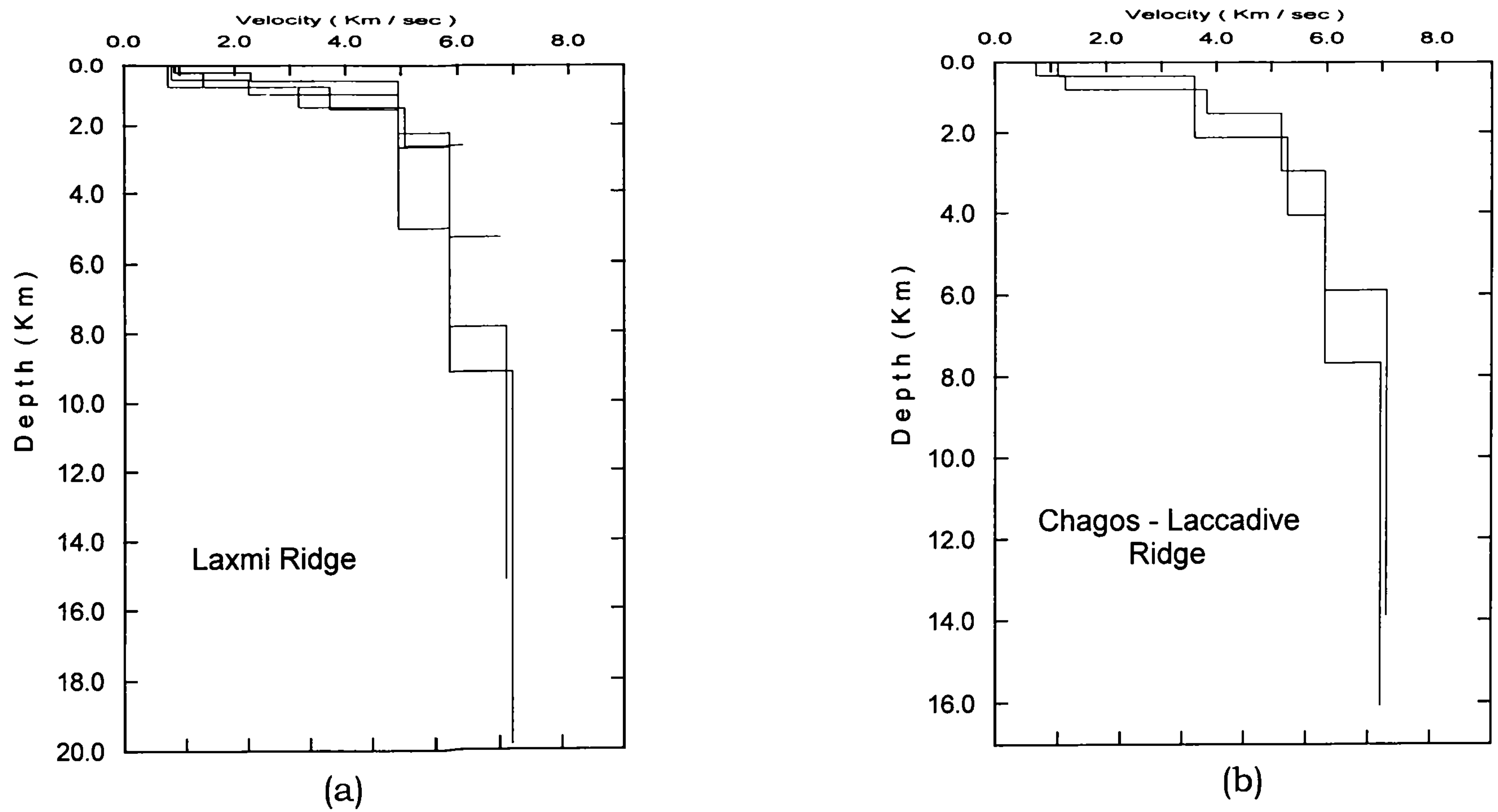


Figure 3.3 Velocity-depth profiles plotted for (a) Laxmi ridge and (b) Chagos Laccadive ridge in the eastern Arabian Sea. The seismic refraction data given by Naini and Talwani (1982) have been utilised for this purpose.

crustal density configuration. The sedimentary column, in general, is showing velocities of 1.7-2.8 km/sec (density of 2.1 g/cm^3) for the top unlithified sedimentaries and 2.9-5.0 km/sec (density of 2.3 g/cm^3) for the deeper compacted sediments. However, detailed layering pattern in terms of thickness variation of these two layers is not available. In the absence of such information a uniform value of 2.2 g/cm^3 for the whole sedimentary layer containing both sallow and deeper sediments has been assigned. A two-layered oceanic crust of 2.66 g/cm^3 for the top part (5.1-6.3 km/sec velocities) and 2.90 g/cm^3 for the bottom layer (6.4-7.0 km/sec velocities) has been assigned. The crustal structure below the Laxmi ridge is more of continental. A density of 2.67 g/cm^3 (5.2-6.3 km/sec) for the top layer and 2.84 g/cm^3 (6.4-7.0 km/sec) for the bottom layer have been assigned. The higher seismic velocities between 7.1-7.4 km/sec observed at many places occurring in the deeper crustal layer have been considered to represent a high density layer of 3.0 g/cm^3 at the crustal base. A uniform value of 3.3 g/cm^3 for the lithospheric mantle and 3.2 g/cm^3 for the Asthenosphere have been assumed. The seismic velocities and the inferred densities for the eastern Arabian Sea are tabulated in Table 3.1. The density configuration for the oceanic crust considered here is in agreement with the values inferred by Miles et al. (1998) and Todal and Eldholm (1998).

3.4 SYNTHESIS OF DEEP SEISMIC SOUNDING DATA FOR THE WESTERN INDIAN SHIELD MARGIN

Knowledge on deeper crust is essential for understanding the evolution of various structural features present in top part of the crust. The Deep Seismic

Oceanic Crust : Eastern Arabian Sea				Laxmi Ridge				Indian Shield : West Coast						
									DVP and CCR			SGT		
Layer	Velocity Range	Average Velocity Km/s	Density g/cm^3	Layer	Velocity Range	Average Velocity Km/s	Density g/cm^3	Layer	Velocity Range	Average Velocity Km/s	Density g/cm^3	Velocity Range	Average Velocity Km/s	Density g/cm^3
Sediments	1.7–5.0	3.0	2.20	Upper Crustal Layer	5.2-6.3	5.8	2.67	Upper Crustal Layer	5.8-6.5	6.1	2.67	6.1-6.5	6.3	2.75*
Oceanic Layer – 1	5.1–6.3	5.5	2.66											
Oceanic Layer – 2	6.4–7.0	6.7	2.90	Lower Crustal Layer	6.4-7.0	6.6	2.84	Lower Crustal Layer	6.6-7.0	6.7	2.85	6.6-7.0	6.7	2.85
High Velocity Layer	7.1–7.4	7.2	3.00	High Velocity Layer	7.1-7.4	7.2	3.00	High Velocity Layer	7.1-7.4	7.2	3.00			
Upper Mantle	7.9–8.2		3.30					Upper Mantle	8.0-8.4		3.30		8.3	3.30

Table 3.1. Crustal seismic velocities and inferred densities utilised for gravity modeling in the region. * indicates the density value for the exhumed mid-to-lower crustal rocks in the SGT.

Sounding (DSS) data provides valuable information on velocity distribution and geometry about the basement configuration and also for the crustal section down to the Moho or even for subcrustal areas. Prominent crustal discontinuities are generally reflected in the DSS data. Such velocity distribution and structural details help understanding the basic nature of the crust, density of crustal layers, which are of great significance in regional gravity and tectonic studies.

Since 1972, the National Geophysical Research Institute (NGRI), Hyderabad, has been collecting several DSS profiles over various geological settings in the Peninsular shield and the Himalayas. Both shallow and the deep crustal structure along these profiles have been delineated down to the Moho demarcating deep faults and fracture zones.

The DSS data available for the western Indian shield margin cover the areas of Dharwar craton, Western Ghats and other tectonic domains within the Deccan Volcanic Province. For the Southern Granulite Terrain (SGT), such data exists well into the continental interior (see Fig. 3.1 for location of these profiles). These DSS data provide valuable information on crust-mantle relationship for the western Indian shield near the west coast. For the present study, seven refraction DSS profiles collected by NGRI along the Kavali Udipi profile (Kaila et al., 1979; Reddy et al., 2000; Sarkar et al., 2001); Guhagar-Chorochi (Koyna-1) and Kelsi-Loni (Koyna- II) profiles in the Koyna region (Kaila et al., 1981a ; Kaila, 1982; Krishna et al., 1991), Mehmadabad-Billimora and Mehmadabad-Dharimanna profiles in Cambay basin (Kaila et al., 1981b; Kaila et al., 1990);

Navibander-Amreli profile in Saurashtra (Kaila et al., 1988) and Kuppam-Palani transect in the southern Granulite Terrrain (Reddy et al., 2002) have been considered. Mahadevan (1994) reviewed some of these profiles in terms of crustal models for the western India shield. The deeper crustal processes and their surface manifestations in various geotectonic domains have been presented by Mahadevan (1995) and Mahadevan and Subba Rao (1998). Some salient results obtained for each of these DSS profiles are presented below:

3.4.1 KAVALI-UDIPI PROFILE

The DSS studies were initiated in India by acquiring a 600 km long ENE-WSE profile near 14 ^{0} N latitude between Kavali and Udipi. The profile cuts across two major geological structures – the Dharwar schist belt and the Cuddapah basin in the peninsular shield. Kaila et al. (1979) have analysed the refraction and wide angle reflection data acquired along this profile and brought out a detailed crustal structure as shown in the Figure 3.4. As can be seen from the figure, the crust is cut-up into seventeen blocks by deep faults, which extend to the Moho. The crustal section is further complicated by large-scale movements along low angle thrust faults. Reddy et al (2000) and Sarkar et al. (2001) re-examined these data to refine the velocity structure obtained by Kaila et al. (1979). They obtained velocity structure for both western and eastern Dharwar craton. In the western Dharwar craton, the upper crust is 22-24 km thick, with a velocity between 6.0-6.2 km/sec. The lower crust with velocity increasing from 6.8-7.0 km/sec above the Moho. Moho is identified at an average depth of 40 km

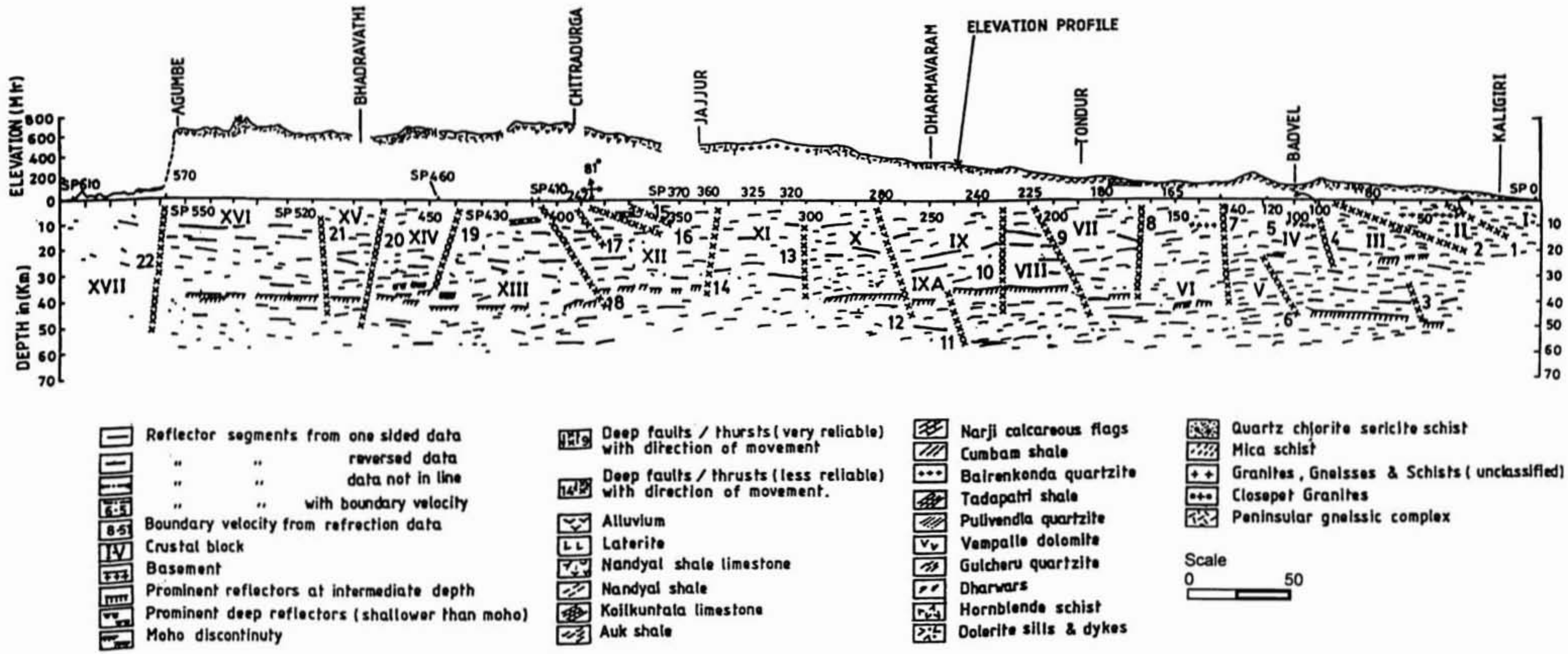


Figure 3.4 The crustal cross section along Kavali-Udipi profile obtained from DSS data (after Kaila et al., 1979)

with 8.4 km/sec velocity. On the other hand in the eastern Dharwar craton, the upper crust is 5-8 km thick with velocity increasing from 5.9-6.2 km/sec and the lower crust with velocity 6.7-7.0 km/sec. The Moho is observed at about 37 km with velocity of 7.8 km/sec.

3.4.2. KOYNA – I AND II PROFILES

The two DSS profiles' data collected for the Koyna project authority by NGRI during 1975-'78 in the Koyna region are along Guhagar-Chorochi (Koyna – I) in the south and Kelsi-Loni (Koyna-II) further north. These two profiles having a length of around 200 km have been made with an objective of delineating deeper crustal structure and to establish existence of any deep fault / fracture which is responsible for Koyna seismic activity (Kaila et al., 1981a; Krishna et al., 1991). The crustal depth sections along these two profiles are shown in Figure 3.5 and 3.6. The refraction data analysis along these two sections revealed a velocity of 4.7 to 4.9 km/sec for the traps, 5.9-6.1 km/sec for the pre-trap basement along Koyna I profile, and 4.8-5.0 km/sec velocities for traps, 6.0-6.15 km/sec for the pre-trap basement velocities along Koyna II profile (Kaila et al., 1981a; Kaila, 1982). The profiles show a number of reflection segments below the traps down to the Moho. A deep fault below the traps divide the entire cross-section into two crustal blocks. The Moho is at a depth of 39 km which appear to be shallowing towards the coast. Krishna et al. (1991) interpreted these two profiles using synthetic seismograms to obtain more refined velocity structure in the region. They interpreted that the upper crust is of 19-20 km thick and the

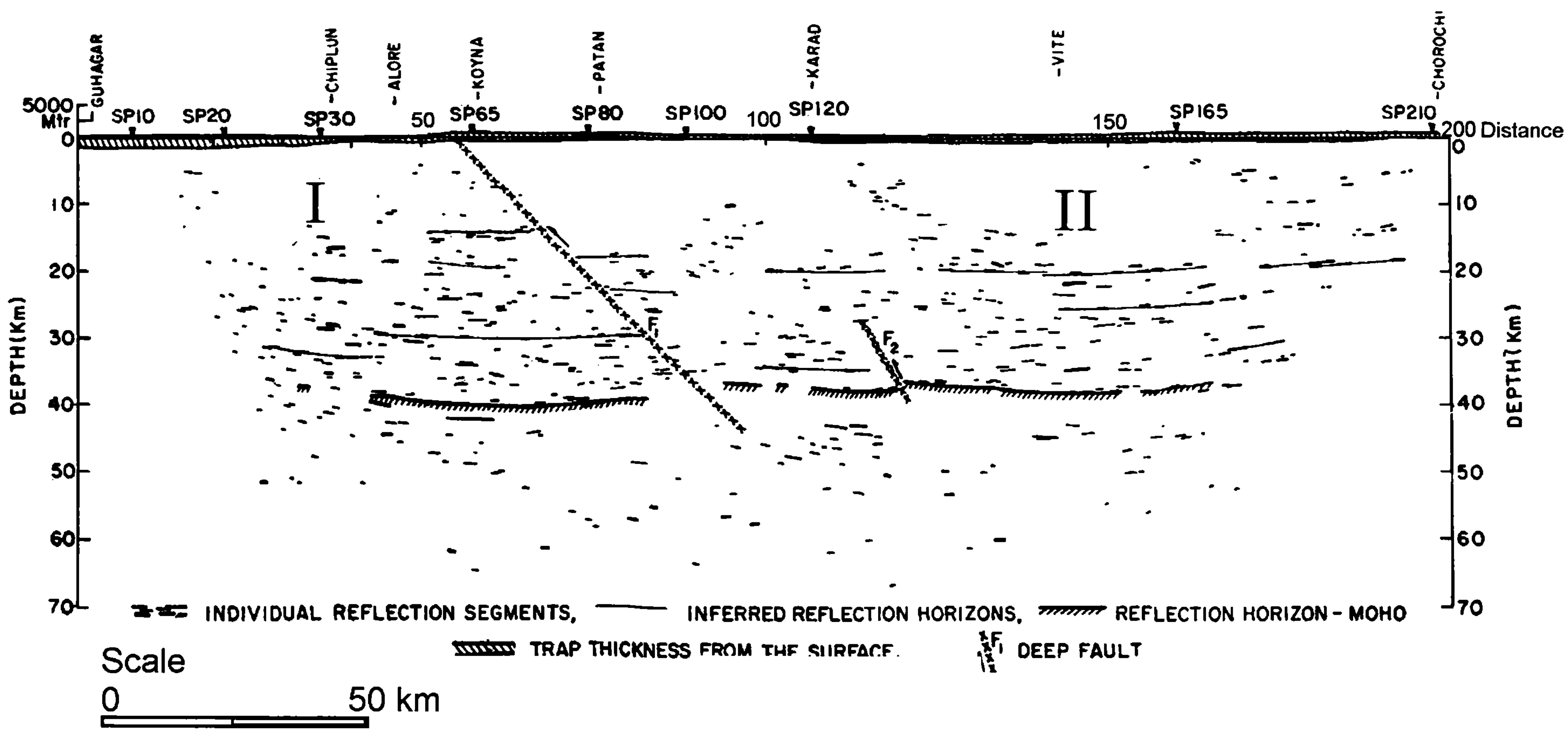


Figure 3.5 The crustal section along Koyna I (Guhagar - Chorochi) profile (after Kaila et. al., 1981a; Kaila, 1982)

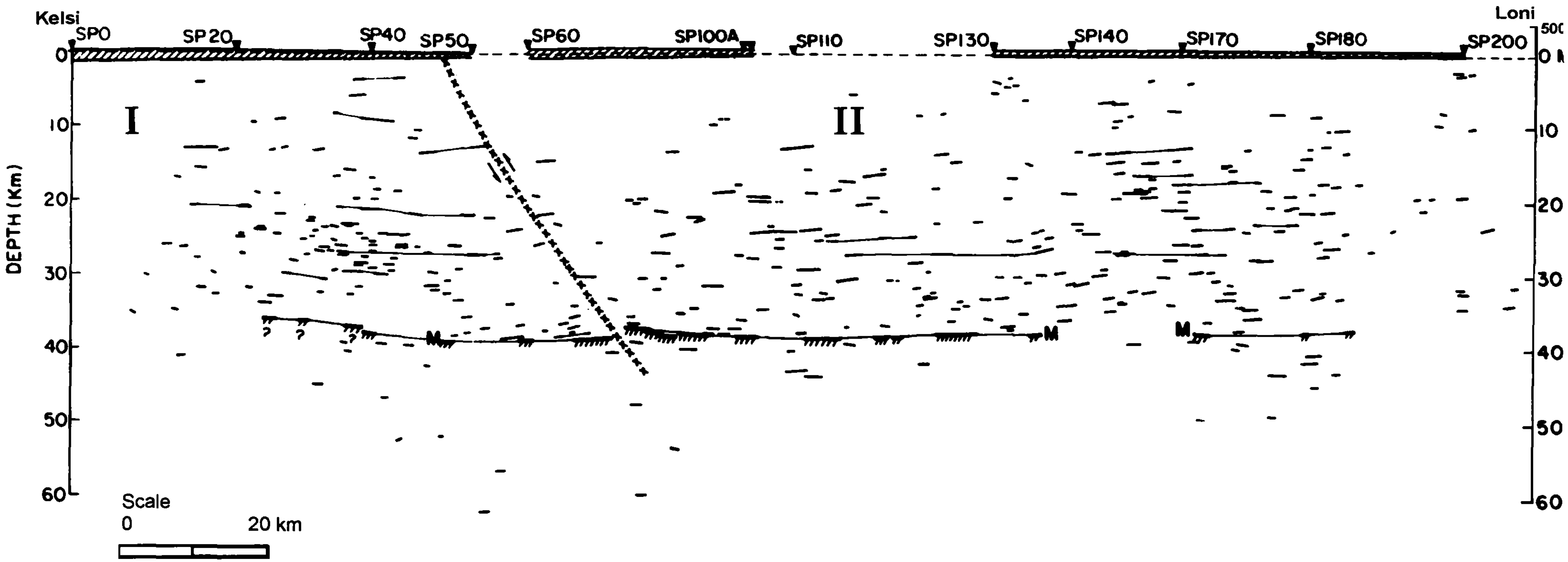


Figure 3.6 The crustal section across Koyna II (Kelsi-Loni) profile (after Kaila et al., 1981a)

Moho in this region as a transition zone of at least 2.0 km thickness from 35.5 km to 37.5 km depth.

3.4.3 CAMBAY BASIN PROFILES

Deep seismic sounding investigations carried out along two long N-S Profiles, one from Mehmadabad to Billimora and the other from Mehmadabad to Dharimanna in the Cambay basin revealed information pertaining to the deep structure of the crust and also shallow structural features (Kaila et al., 1981b; Kaila et al., 1990). The crustal depth sections shown in Figure 3.7 revealed that the basin is dissected into seven major crustal blocks in the N-S direction bounded by faults. The section reveals maximum crustal thickness of 38-40 km in the Jambussar – Broach block. The crustal depth section from Mehmadabad to Dharimanna shown in Figure 3.8 (Kaila et al.,1990) reveal the following features. The Deccan traps, which form the basement of the overlying sediments vary in thickness around 1.0 to 1.8 km with boundary velocities in the traps varying between 4.8 to 5.2 km/sec. The upper crust is around 15 km thick with velocity reaching 6.3 km/sec and the lower crust consisting of two layers of velocities 6.6 to 6.9 km/sec and 7.3-7.4 km/sec. The high velocities in the lower crust is observed at a depth of 23 km. The Moho lies at a depth of 31-33 km.

3.4.4 NAVIBANDAR-AMRELI PROFILE

Deep seismic sounding studies were carried out during 1977 along a 160 km long profile from Navibander to Amreli in the Saurashtra peninsula. The crustal seismic section along this profile is shown in Figure 3.9. The analysis of

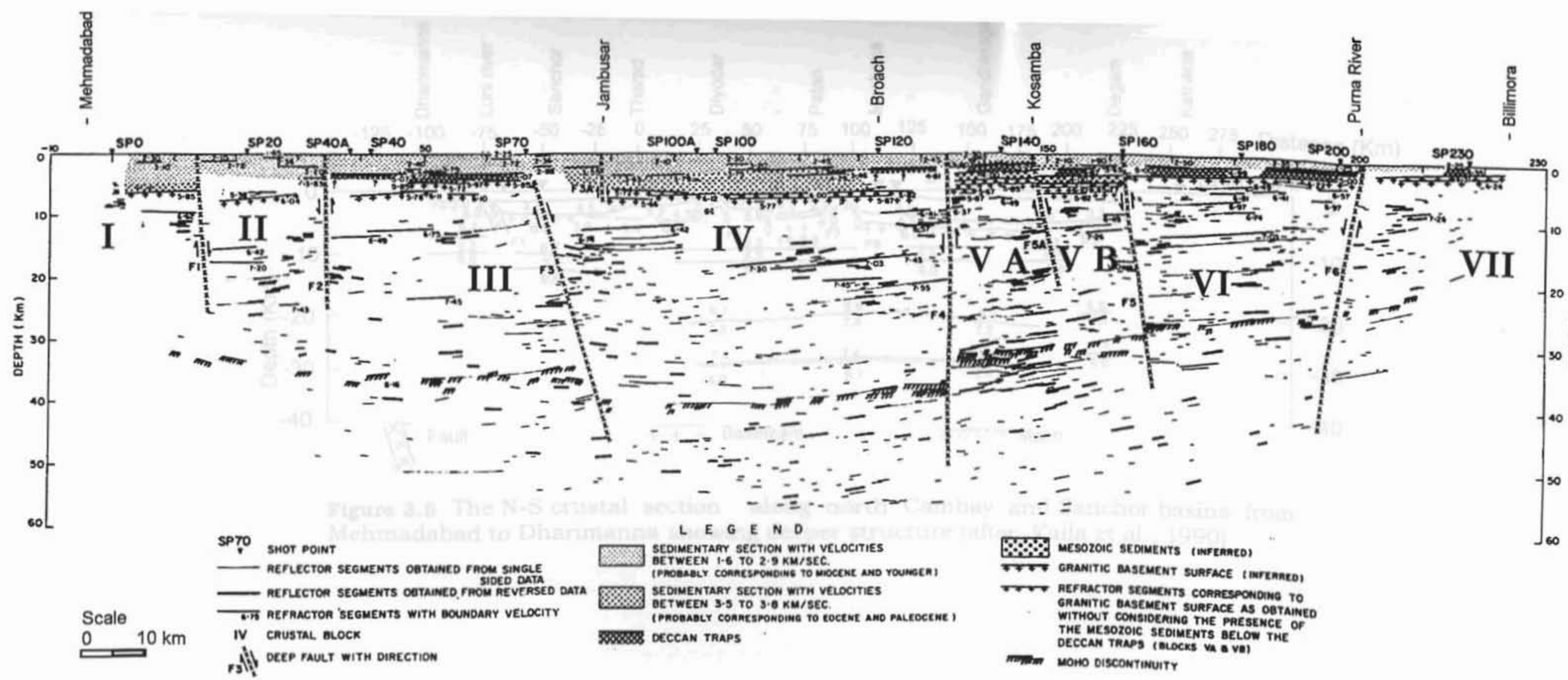


Figure 3.7 The N-S crustal section along Mehmadabad-Billimora profile in the Cambay basin (after kaila et al., 1981b).

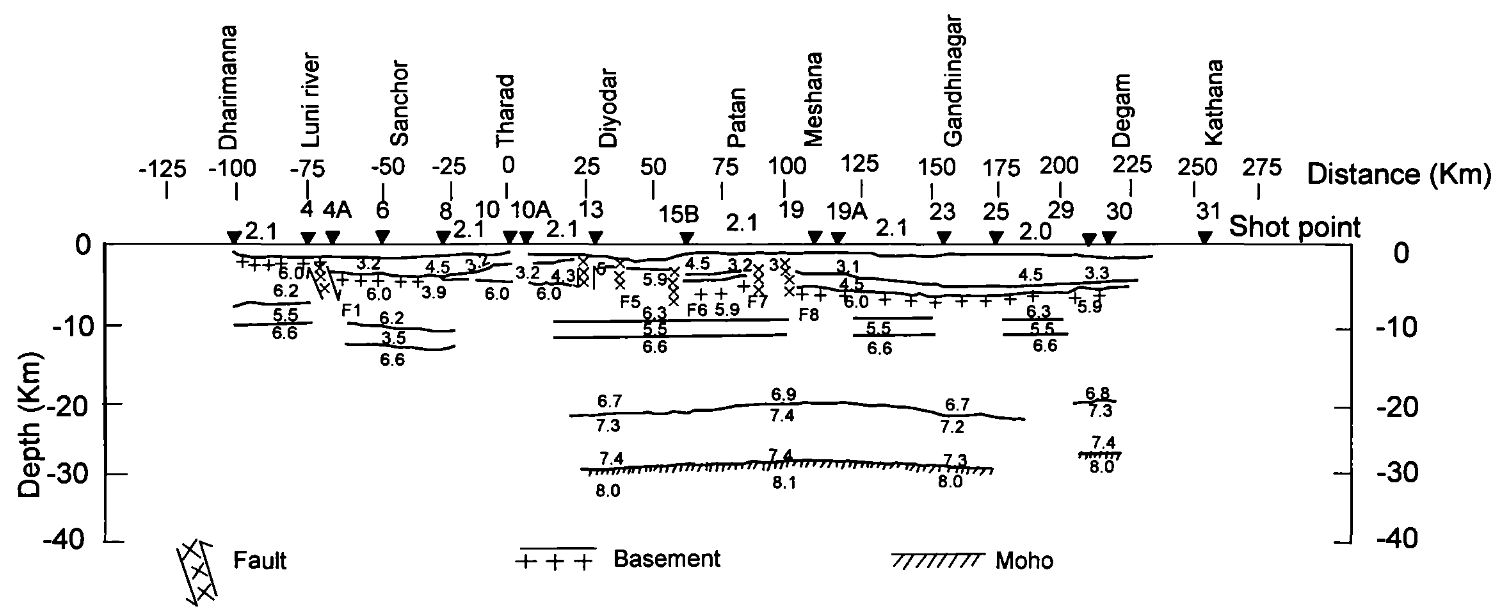


Figure 3.8 The N-S crustal section along north Cambay and Sanchor basins from Mehmadabad to Dharimanna showing deeper structure (after, Kaila et al., 1990)

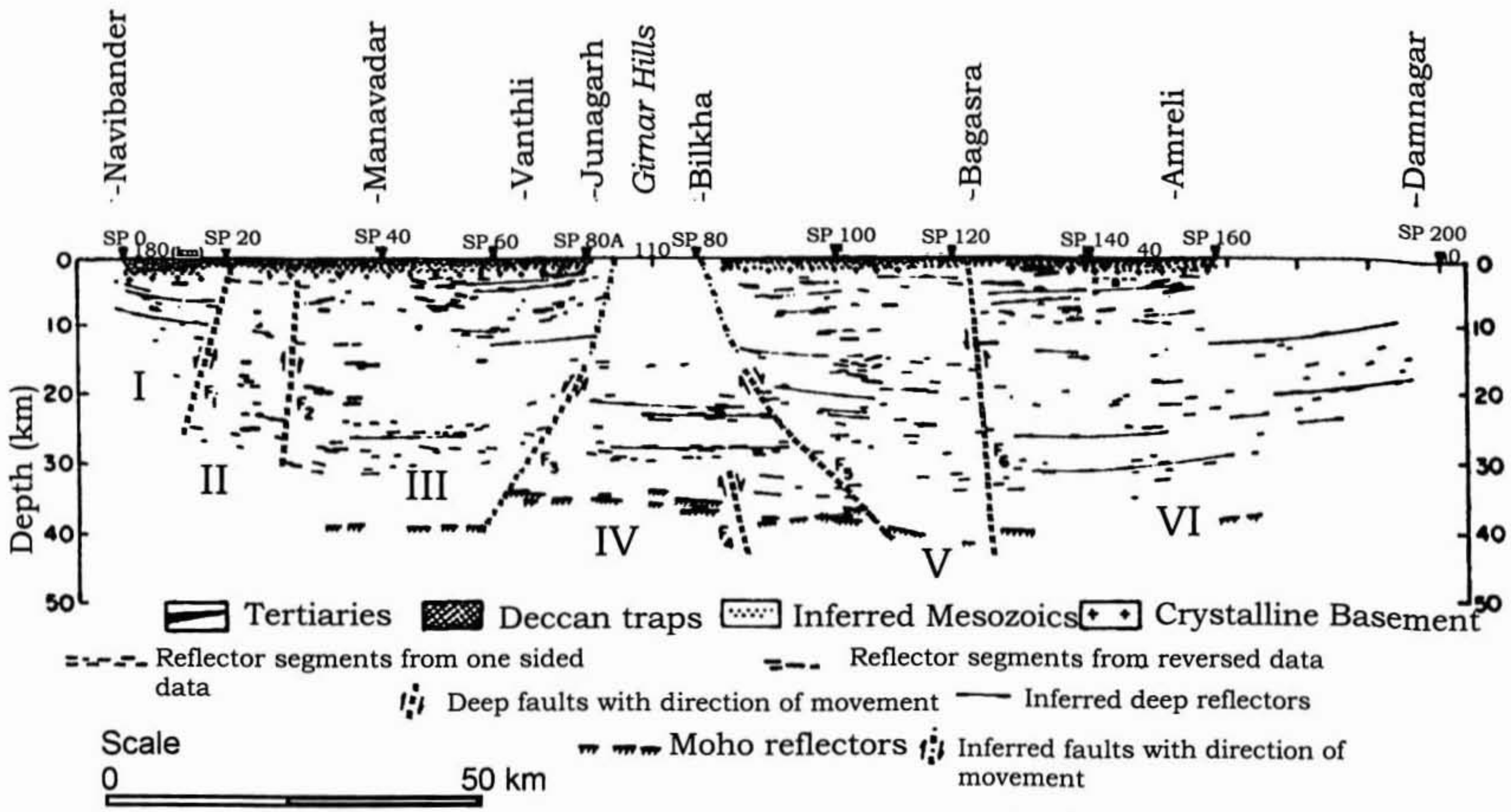


Figure 3.9 Crustal section along Navibander-Amreli profile in the Saurashtra peninsula (after Kaila et al., 1988)

seismic refraction and wide-angle reflection data along this profile (Kaila et al.,1988) indicate the following: the Deccan traps have velocities between 4.9-5.1 km/sec with thickness of traps varying from 0.4-1.5 km in the region, a low-velocity layer of 4.0 km/sec is observed below the traps, the crystalline basement shows velocities in the range of 5.9 to 6.0 km/sec. The deeper crust in this region display horst and graben structure with various crustal blocks bounded by deep faults. The main horst named the Girnar horst is very well marked on the seismic section. The depth to the Moho is estimated at 39 km at Bantava and continues upto Vanthil where the Moho is thrown upto 35 km by a fault. It again dips down to 37 km and further down faulted to a depth of 42 km by faults. The Conrad is mapped as a patchy reflector at 12-16km depth in this profile.

3.4.5 KUPPAM - PALANI PROFILE

The 300 km long DSS profile from Kuppam to Palani carried out recently provide the first ever models of velocity structure and reflectivity of the Southern Granulite Terrain. The crustal sections published by Reddy et al. (2002) between Kuppam-Bommidi and Kolathur-Palani are shown in Figure.3.10. The crustal section for Kuppam-Kumarapalayam segment reveals a four layered velocity structure characterised by a prominent 7-15 km thick mid-crustal low velocity layer. The Moho depths identified range from 41-45 km. The Kolathur-Palani segment running across Palghat-Cauvery shear zone also provided a four layered velocity model with a mid-crustal low velocity zone.

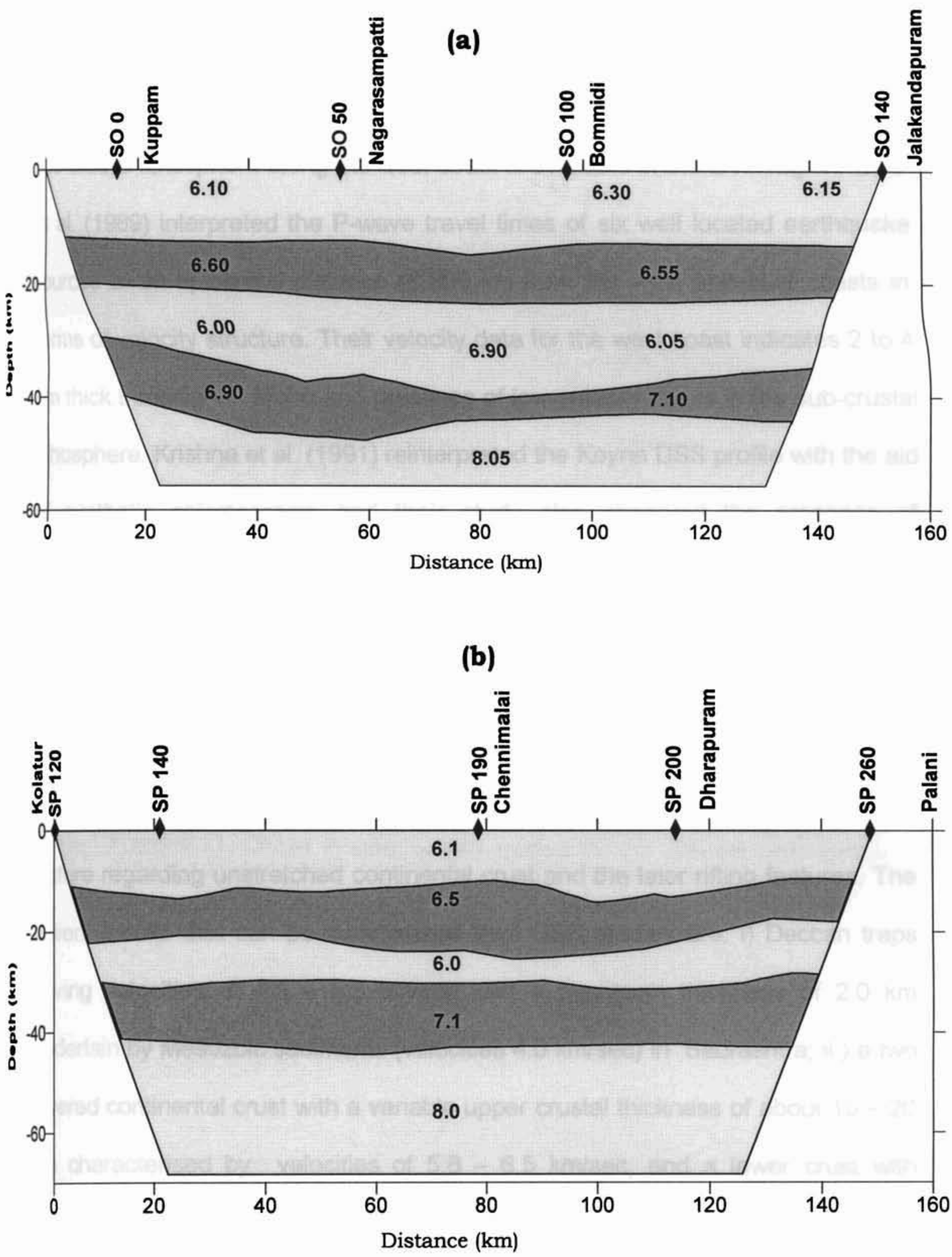


Figure 3.10 Crustal sections showing velocity layering along (a) Kuppam -Bommidi and (b) Kolathur-Palani DSS transects across the Southern Granulite Terrain (after Reddy et al., 2002).

3.4.6. CRUSTAL AND SUB-CRUSTAL VELOCITY MODELS

The interval velocity functions for the P-wave as determined from the above DSS profiles are shown in Figure 3.11. The velocity information on the sub-crustal lithosphere along the west coast is available in the DVP region. Gaur et al. (1989) interpreted the P-wave travel times of six well located earthquake sources at an epicentral distance of 800 km from the west and east coasts in terms of velocity structure. Their velocity data for the west coast indicates 2 to 4 km thick transitional Moho and presence of low velocity layers in the sub-crustal lithosphere. Krishna et al. (1991) reinterpreted the Koyna DSS profile with the aid of synthetic seismograms and their study also observed the presence of transitional Moho at a depth of 42 km and 62 km. The velocity-depth profiles obtained by these two workers is shown in Figure 3.12.

3.4.7. SALIENT RESULTS OF DSS INVESTIGATIONS ALONG THE WEST COAST

The DSS investigations in the western Indian shield bring out a clear picture regarding unstretched continental crust and the later rifting features. The salient results that can be summarized from DSS studies are: i) Deccan traps having velocities of 4.5 – 5.5 km/sec with a maximum thickness of 2.0 km underlain by Mesozoic sediments (velocities 4.0 km/sec) in Saurashtra; ii.) a two layered continental crust with a variable upper crustal thickness of about 10 – 20 km characterised by velocities of 5.8 – 6.5 km/sec, and a lower crust with velocities of 6.6 – 6.9 km/sec, with Moho observed at a depth of 38 – 42 km in the shield regions; iii.) general shallowing of Moho towards the coast; iv.) higher

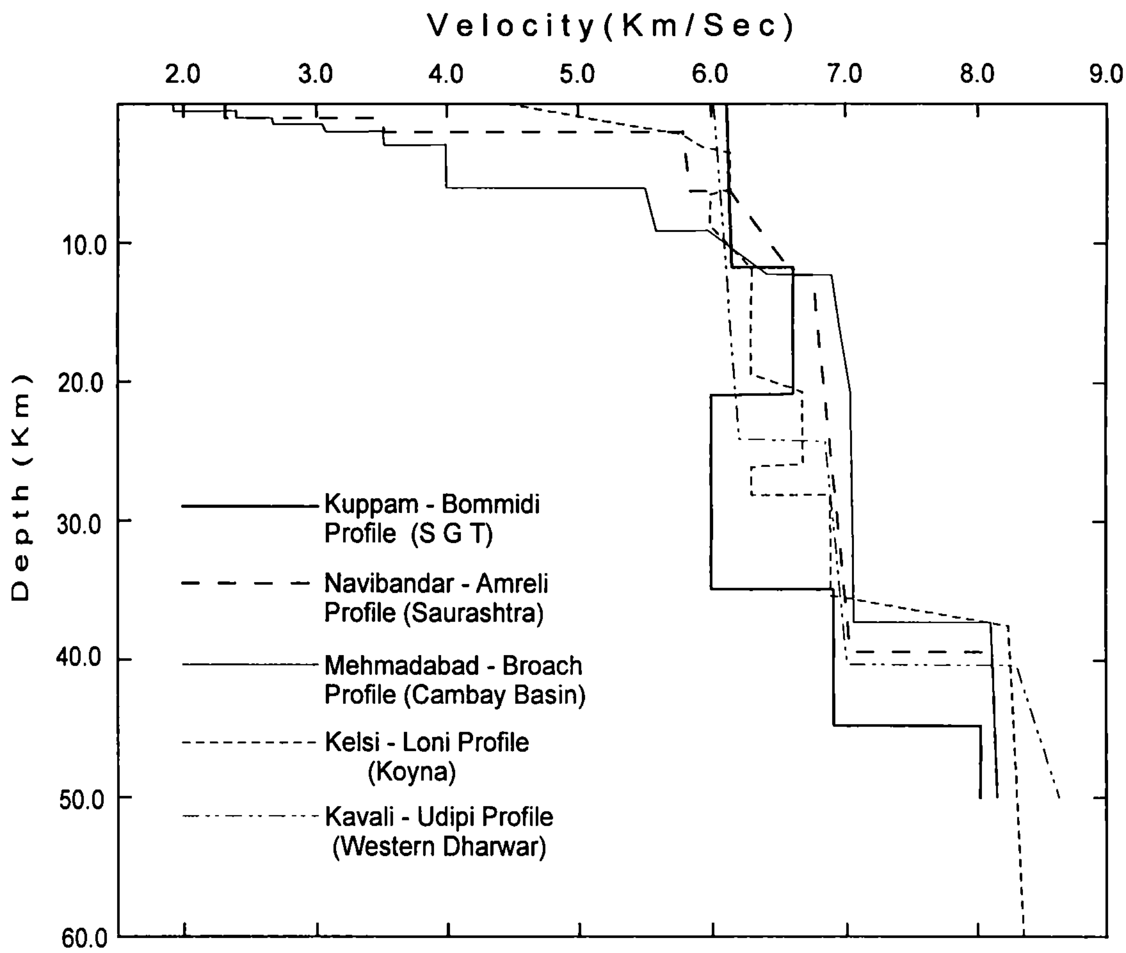


Figure 3.11 Crustal P-wave velocity models for the different DSS profiles along the western Indian shield region considered in the present study.

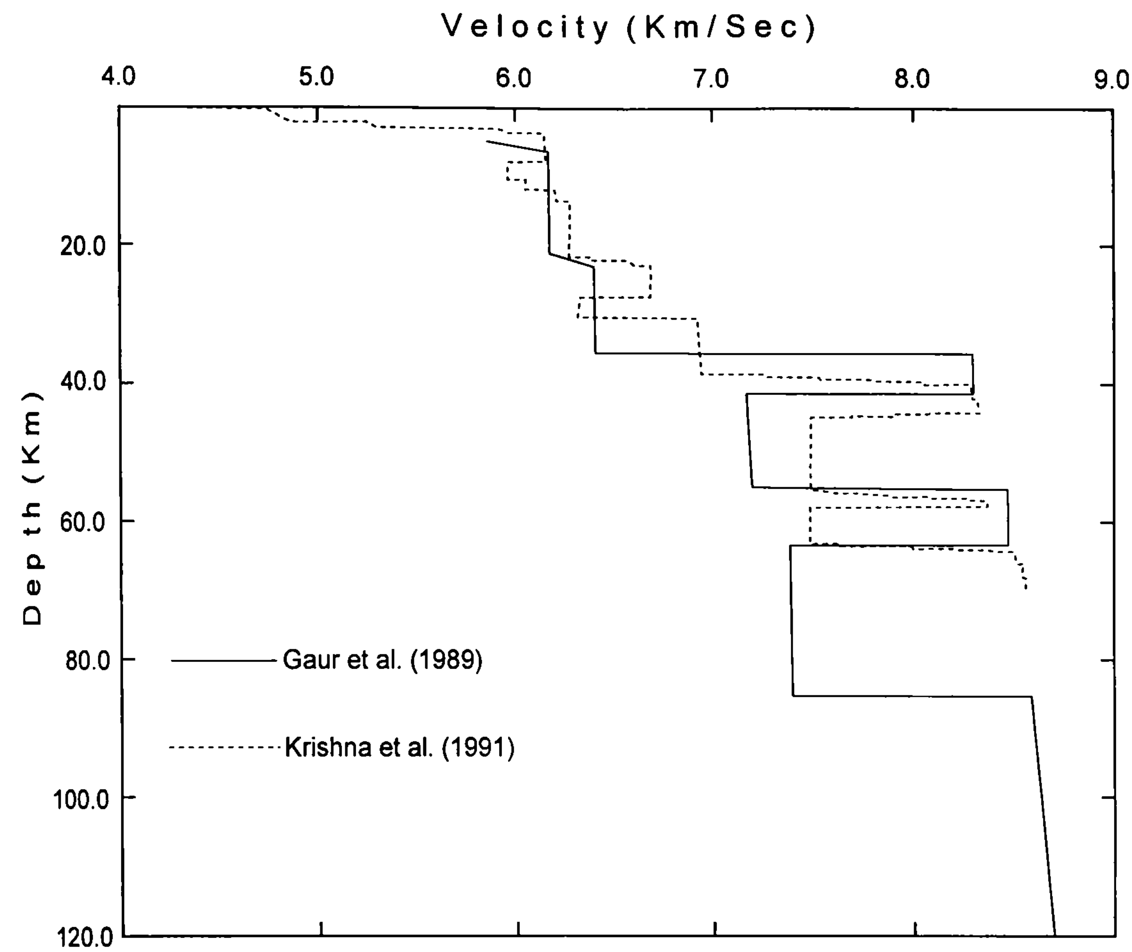


Figure 3.12 P-wave velocity models for the lithosphere below the West Coast in the Deccan Volcanic Province. The velocity model given by Gaur et al. (1989) is based on travel-time residuals of earthquakes and by Krishna et al. (1991) is based on synthetic seismogram modeling of Koyna DSS profiles.

lower crustal velocities at 23 – 25 km depth and a shallow Moho at a depth of 31 - 33 km below Cambay rift basin; v.) transitional Moho and low velocity layers in the Koyna region; and vi.) continental type of crust beneath Saurashtra Peninsula.

3.5 CRUSTAL DENSITY CONFIGURATION BASED ON SURFACE ROCK DENSITY MEASUREMENTS AND SEISMIC VELOCITIES

The seismic velocity distribution in the Indian shield crust as revealed through the DSS studies provide clear evidence for a two-layered crust with their individual seismic velocity characteristics. Wherever surface rock density data are available, an average density value of major country rocks of that region has been considered as representative density of upper crustal layer. The seismic velocities have been converted to density values using the Nafe-Drake velocity-density relationship. The inferred crustal density configuration under the western Indian shield is believed to represent only a gross and simplified pattern of the actual situation prevailing for the shield crust near the west coast which we consider for gravity modeling.

3.5.1 COMPILATION OF SURFACE ROCK DENSITIES FOR THE WESTERN SHIELD MARGIN

For meaningful interpretation of gravity data, the estimation of densities of exposed surface rocks would help in deciphering whether the anomalies result from the lateral variations in the densities and their subsurface extension or from the deep seated mass distribution or from a combination of both.

For the purpose of deriving gross density estimates for the major surface rocks along the west coast, three broad classifications in terms of geological history can be made. These are 1) the Southern Granulite Terrain (SGT) south of the Fermor Line, characterized by high-grade charnockitic rocks which have exhumation history form mid to lower crustal levels, 2) the Central Cratonic Region (CCR), consisting of Dharwar craton which are mainly of low-grade gneissic country rocks with belts of granite and schist, 3) the Deccan Volcanic Province (DVP), covering vast area of basaltic country rock with thickness as much as 1.5 km at certain locations. This basaltic layer is underlain by Peninsular gneiss throughout the province.

Surface rock density estimates for the Southern Granulite Terrain has been made by Kurian et al. (1999). The histograms of density estimated for various rock types in the region are shown in the Figure 3.13. The average density estimates of major rock types are 2.76 gm/cc for charnockites, 2.74 gm/cc for the gneisses giving an average value of 2.75 gm/cc for the exhumed mid-lower crustal layer in the SGT. The density estimates for the various rock types in the Dharwar crustal region were made by Subrahmanyam and Verma (1981). They suggested an average crustal density of 2.75 gm/cc for the Dharwar region considering the gneisses, granites, granodiorites and rocks from greenstone belt. However, the calculated densities for Peninsular gneissic rocks and granites together give rise to a density of 2.67 gm/cc. As the velocities for the upper crustal layer as *indicated by Kavali-Udupi profile in the region are in*

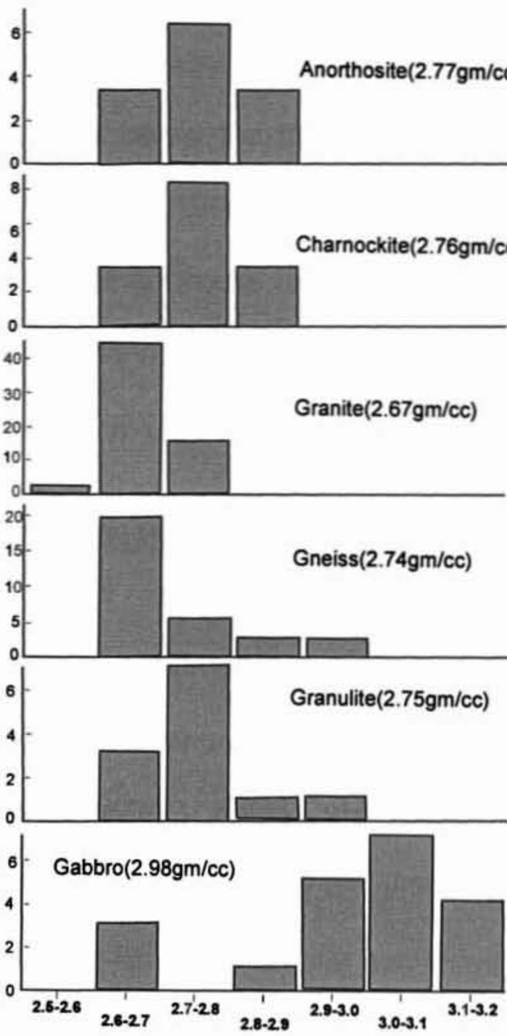


Figure 3.13 Histograms of density estimates for major rock types in the Southern Granulite Terrain (after Kurian et al., 1999)

the range of 5.9-6.2 km/sec, a density of 2.6 g/cm^3 would be more appropriate for surface rocks in the region. For the Deccan Volcanic Province, the density of 2.80 g/cm^3 for the top Deccan trap layer has been considered. The crystalline basement below the Deccan trap cover could be Dharwar formations or Precambrian granites and gneisses. A deep drill hole in the Latur region revealed a Peninsular gneissic rock below the traps (Gupta, 1994). The seismic velocities obtained for the crustal layer below the traps indicate velocities of 5.8 to 6.3 km/sec (Kaila et al. 1981a; 1988; 1990). A density value of 2.67 g/cm^3 for the upper crustal crystalline basement rocks has been considered based on these velocities. Further, a similar density value for upper crustal rocks (below traps) has been inferred by Tiwari et al. (1991) and Pandey et al. (1995).

3.5.2 DENSITIES OF CRUSTAL LAYERS

The seismic information obtained from DSS data give rise to velocities of 5.8-6.5 km/sec for the upper crustal layer in the Dharwar craton region and the Deccan Volcanic Province (DVP) below the traps. These velocities are representative of a layer with a density of 2.67 g/cm^3. Therefore, a density of 2.67 g/cm^3 has been adopted for upper crustal basement rocks in the Dharwar craton and the DVP regions. However, the SGT is characterized by exhumed lower to middle crustal rocks, which would imply that top crustal layers in this region have higher densities than the rest of the shield. This is also evidenced by the higher densities for the major crustal rocks in the region. Therefore, an average density value of 2.75 g/cm^3 for the exhumed mid-lower crustal layer in the SGT has been considered. In the DVP, the density of 2.80 gm/cc for basaltic traps has been considered. The lower crustal rocks show seismic velocities ranging between 6.6-6.9 km/sec giving rise to an average density of 2.85 gm/cc as density for the lower crust. The lower part of this lower crust, at some places, is characterized by the presence of high seismic velocities of 7.1-7.4 km/sec for which a density of 3.0 gm/cc has been assigned. The seismic velocities for sediments in the Cambay basin and the Mesozoic sediments lying below the Deccan traps give rise to a density of 2.40 gm/cc for these sediments. The seismic velocities and the inferred density values for the west coast have been tabulated in Table 3.1.

CHAPTER IV

INTERPRETATION OF GRAVITY ANOMALIES IN TERMS OF LITHOSPHERIC STRUCTURE BELOW THE WESTERN CONTINENTAL MARGIN OF INDIA (WCMI)

4.1 INTRODUCTION

The eastern Arabian Sea is the deep oceanic part of the western continental margin of India (WCMI). The WCMI contains several structural features which have evolved mostly as a consequence of rifting and sea floor spreading between India, Madagascar and Seychelles (McKenzie and Sclater, 1971; Whitmarsh, 1974; Naini and Talwani, 1982; Biswas, 1987). Therefore, a careful understanding of various structural and morphological features in this region would essentially form a major input into our knowledge on the evolutionary history of the western margin of India. The region comprises of several surface/subsurface structural features which include the Chagos-Laccadive ridge, Laxmi ridge, Pratap ridge and a belt of numerous horst-graben structure in the sediment filled basins bordering the West Coast of India. Figure 4.1 shows the major tectonic features in both onland and offshore along the WCMI.

Many previous workers suggested that the Eastern basin is characterised by thick transitional rift stage crust extending as far as the Laxmi and Laccadive ridge region (Harbison and Bassinger, 1973; Naini and Talwani, 1982; Kolla and Coumes, 1990; Subba Raju et al., 1990) and extension of Precambrian tectonic trends into deep oceanic areas (Bhattacharya and Subrahmanyam, 1986; Subrahmanyam et al., 1993). However, in the northern part of the Eastern basin, the Laxmi basin, Bhattacharya et al. (1994) and Malod et al. (1997) inferred oceanic crust from magnetic anomaly identifications. The presence of oceanic crust below the Laxmi basin necessitates a clearer understanding of break-up

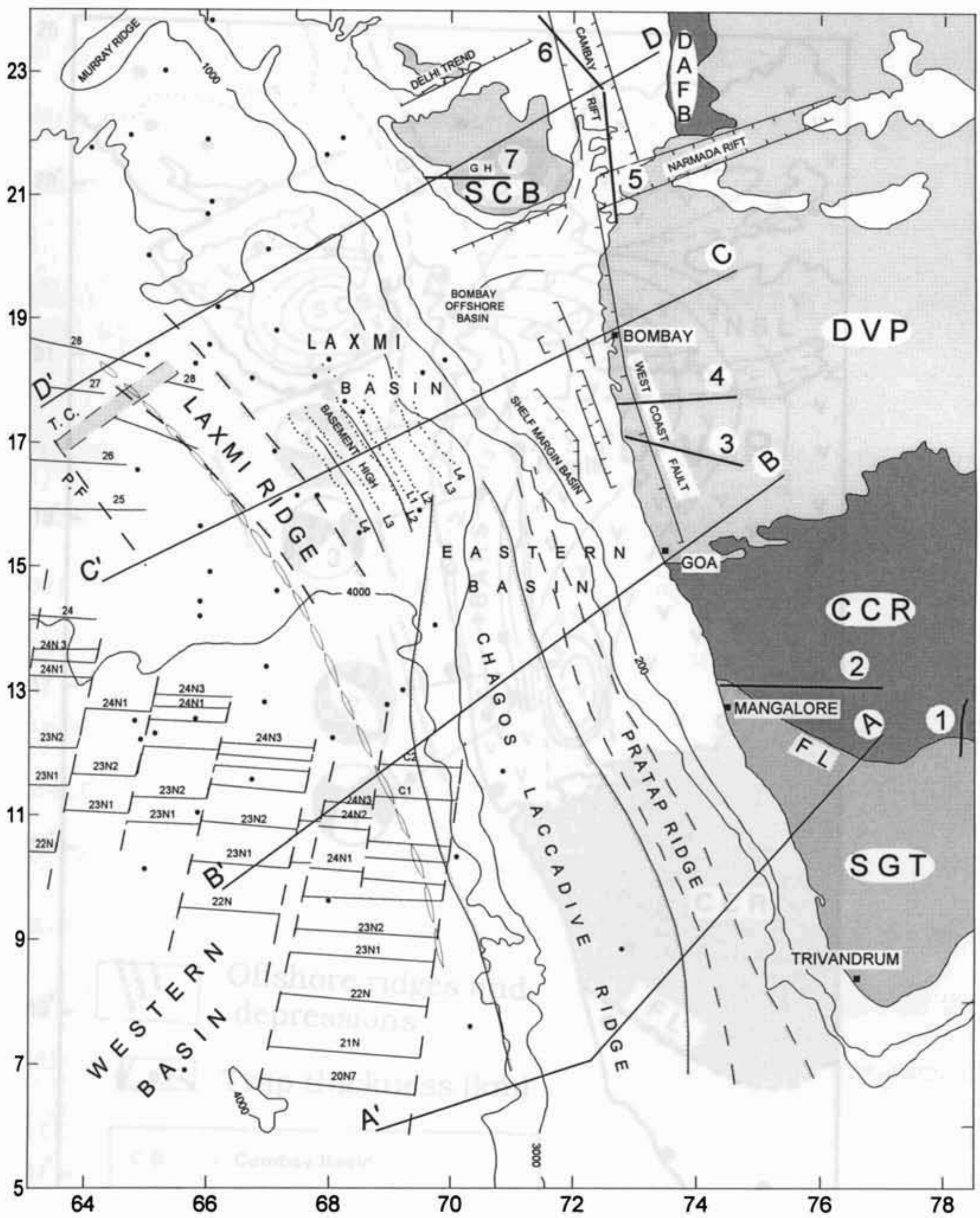


Figure 4.1 Tectonic and structural trend map of the eastern Arabian Sea and the adjoining west coast of India. Tectonic and structural details for the western Indian shield and the offshore areas are adopted from Biswas (1982, 1987) and Subrahmanyam et al. (1995). Lines with numbers in the Arabian Sea are magnetic anomaly identifications from Chaubey et al. (1995) and Miles et al. (1998). Dashed lines indicate fracture zones. Filled circles in the offshore areas show locations of seismic refraction stations from Francis and Shor (1966) and Naini and Talwani (1982). L1-L4 are magnetic lineations in Laxmi basin from Bhattacharya et al. (1994). Thick lines with numbers encircled along the West Coast show locations of seven Deep Seismic Sounding (DSS) profiles. Lines AA' through DD' show the location of regional traverses utilised for structural interpretations. P.F. - Pseudo fault; T.C. - Transferred crust; DVP - Deccan Volcanic Province; CCR - Central Cratonic Region; SGT - Southern Granulite Terrain; SCB - Saurashtra Continental Block; GH - Girnar Horst; FL - Fermor Line; DAFB - Delhi Araveli Fold Belt.

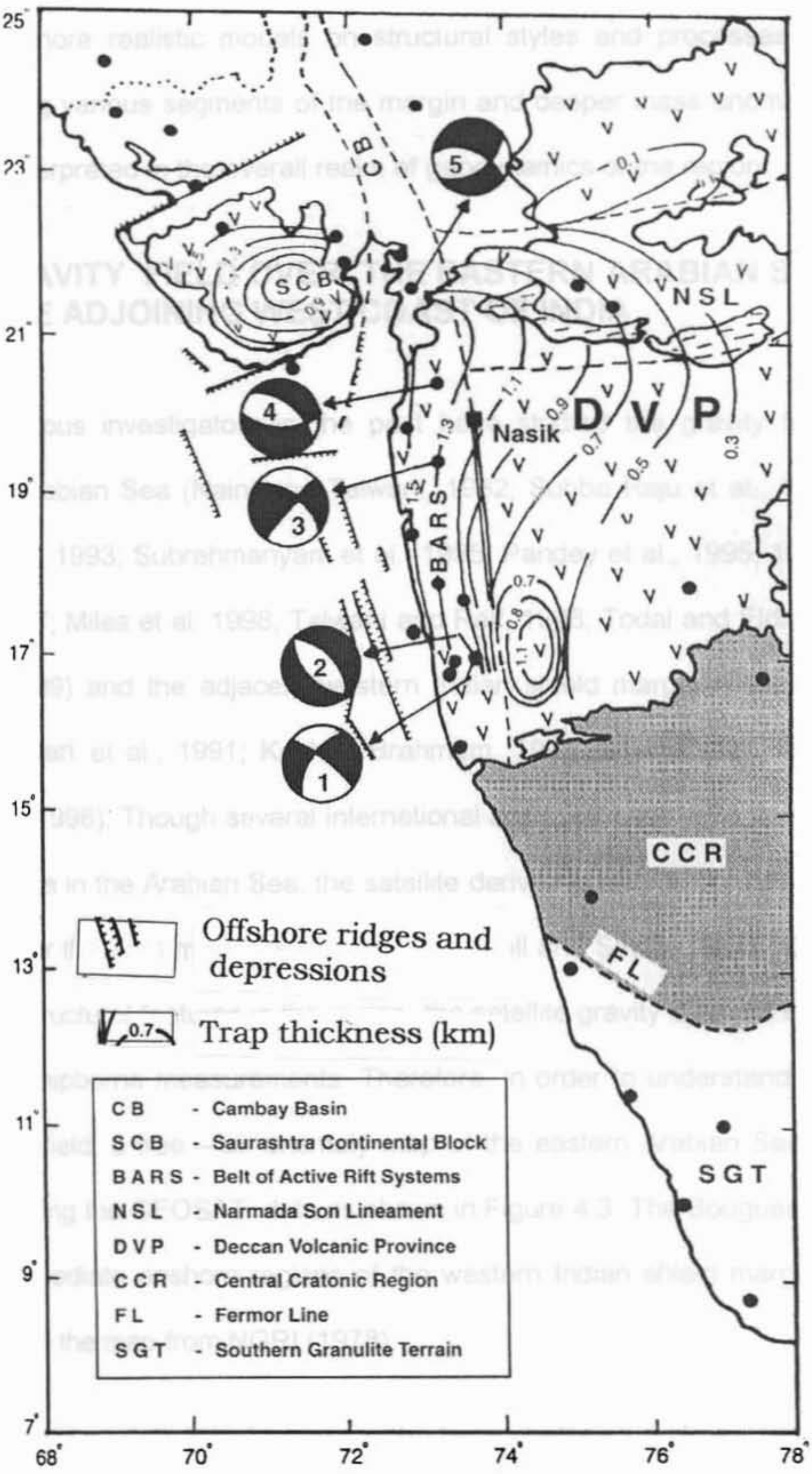


Figure 4.2. Generalised geology showing various crustal blocks in the western Indian shield region. Dots are epicenters of major earthquakes listed in Mahadevan (1995). The available focal mechanism solutions of events compiled from 1. 1967 Koyna (Chandra, 1977); 2. 1980 Koyna (Rastogi, 1992); 3. 1983 Bhatsa (Rastogi, 1992); 4. 1986 Valsad (Rastogi, 1992); 5. 1970 Broach (Arora, 1970) are also shown. Trap thickness contours are adopted from Kaila (1988).

generate more realistic models on structural styles and processes of crustal rifting along various segments of the margin and deeper mass anomalies which can be interpreted in the overall realm of geodynamics of the region.

4.2 GRAVITY FIELD OVER THE EASTERN ARABIAN SEA AND THE ADJOINING WEST COAST OF INDIA

Various investigators in the past have studied the gravity field of the eastern Arabian Sea (Naini and Talwani, 1982; Subba Raju et al., 1990; Miles and Roest, 1993; Subrahmanyam et al., 1995; Pandey et al., 1995, 1996; Malod et al., 1997; Miles et al. 1998; Talwani and Reif, 1998; Todal and Eldholm, 1998; Singh, 1999) and the adjacent western Indian shield margin (Kailasam et al., 1972; Tiwari et al., 1991; Krishna Brahmam, 1993;Balakrishnan, 1997; Singh and Mall, 1998). Though several international agencies have collected shipborne gravity data in the Arabian Sea, the satellite derived gravity anomalies (GEOSAT data) cover the area more completely (Sandwell and Smith, 1997). Also, for the scale of structural features in the region, the satellite gravity data are comparable with the shipborne measurements. Therefore, in order to understand the nature of gravity field, a free – air anomaly map of the eastern Arabian Sea has been utilized using the GEOSAT data as shown in Figure 4.3. The Bouguer anomalies in the immediate onshore regions of the western Indian shield margin are also included in the map from NGRI (1978).

The map shows that except in the inner shelf region, free – air anomalies are in general negative ranging from -10 to –60 mGal in the whole of eastern

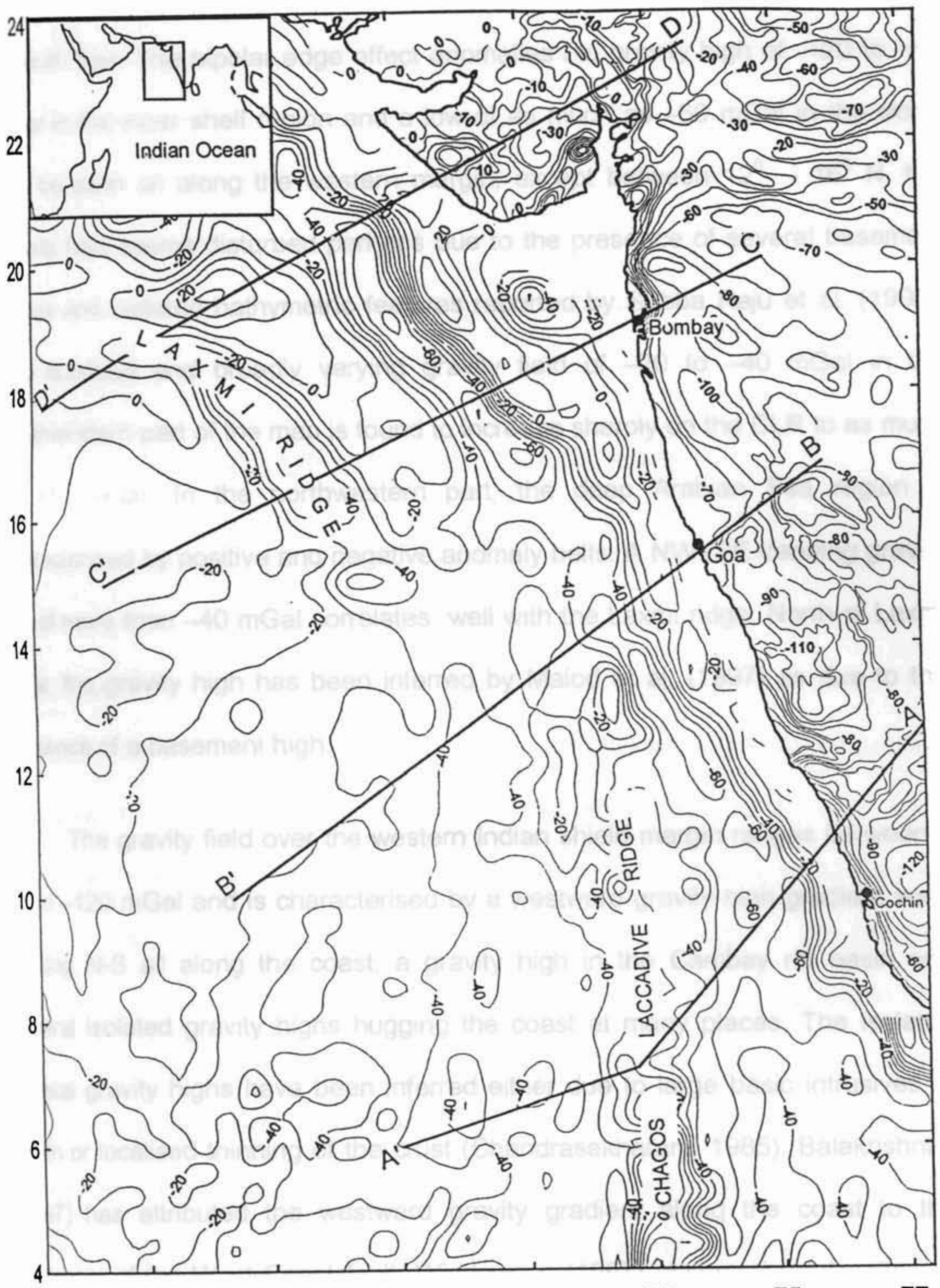


Figure 4.3. Gravity anomaly map of the eastern Arabian Sea and adjacent western Indian shield region. The contours shown are based on Bouguer anomalies (NGRI, 1978) on land and free - air anomalies (GEOSAT) in offshore areas (contour interval : 10 mgal). Data sources are cited in the text. The gravity traverses AA' through DD' shown in figure follow ship tracks in offshore areas. Wherever necessary, along profiles, ship track data have been extended in both shelf and deep sea areas by GEOSAT and ETOPO5 data. Details are discussed in the text.

Arabian Sea. The bipolar edge effect anomalies i.e. gravity high of +20 to +40 mGal in the inner shelf region and a low of as much as –60 mGal in the slope can be seen all along the western margin, except between 12^0 - 16^0 N, the gravity field seems disturbed perhaps due to the presence of several basement ridges and isolated bathymetric features reported by Subba Raju et al. (1990). The subdued and broadly varying gravity field of –20 to –40 mGal in the southwestern part of the map is found to increase sharply on the CLR to as much as +10 mGal. In the northwestern part, the deep Arabian Sea region is characterised by positive and negative anomaly belts. A NW- SE trending gravity low of more than –40 mGal correlates well with the Laxmi ridge. North of Laxmi ridge, the gravity high has been inferred by Malod et al. (1997) as due to the presence of a basement high.

The gravity field over the western Indian shield margin ranges between –20 to –120 mGal and is characterised by a westward gravity high gradient zone striking N-S all along the coast, a gravity high in the Cambay rift basin and several isolated gravity highs hugging the coast at many places. The isolated coastal gravity highs have been inferred either due to large basic intrusives at depth or localised thinning of the crust (Chandrasekharam, 1985). Balakrishnan (1997) has attributed the westward gravity gradient along the coast to the alignment of the West Coast fault. Widdowson (1997) observed the location of this fault much westward. Since the gravity gradient zone is almost 50 km. wide covering the entire coast, it could be explained by a crustal upwarp or lithospheric thinning (Qureshy, 1981; Mishra, 1989). The gravity high observed over the Cambay rift basin has been interpreted by several workers as due to large thickness of volcanic intrusives (Kailasam and Qureshy, 1964), shallowing of Moho (Sen Gupta, 1967), upper crustal intrusives (Verma et al., 1968), crustal thinning and high density underplated crust (Tewari et al., 1991). Singh and Mall (1998) observed high density underplated crust in the Koyna region based on gravity modeling.

4.3 PREPARATION OF CRUSTAL TRANSECTS

In the present study, four regional gravity traverses AA' through DD' uniformly located along the western continental margin of India (see Fig. 4.1 for profile location) have been considered to interpret 2D-lithosphere structure. The profiles are selected on the basis of availability of ship track gravity, bathymetry and seismic data. Wherever necessary, the ship track data have been complimented with GEOSAT and ETOPO5 data to fill the data gaps in the shelf region as well as in deep oceanic areas. In the onshore regions, the Bouguer anomalies have been considered along the traverses. All seismic refraction data points within half degree on either side of these profiles have been projected. The sediment thickness map compiled by Balakrishnan (1997) and basement depths inferred from magnetic anomalies by Subrahmanyam et al. (1993) along with the refraction data are used to obtain thickness of sediments along the profiles. The upper and lower crustal boundary as well as the Moho variations known from the DSS sections in the West Coast are projected onto the profiles.

This gives information on stretched as well as unstretched continental crust below the West Coast.

The crustal sections prepared along these profiles are shown in Figure 4.4 through 4.7. For profile AA', no DSS data for SGT is available in the coastal areas. The gross velocity structure obtained by Reddy et al.(2002) along nearby Kuppam-Bommidi profile in the interior of SGT together with regional crustal thickness estimates given by Rai et al.(1993) and Moho depth map of South India by Subba Rao(1987) have been considered. Profile BB' passes just outside the fringe of Central Cratonic Region(CCR), where small thickness of trap flows overlie the Dharwar crust. As the crustal structure along BB' is more characteristic of the CCR than the DVP, the crustal structure from the Kavali-Udipi DSS profile has been considered for profile BB' in preference to the Guhagar-Chorochi DSS profile(Koyna I) further north which presents a structure more characteristic of the DVP. For profile CC', the structure along the Kelsi-Loni DSS profile (Koyna II) has been considered. It may be noted that the ship-borne gravity data available for profile CC' was earlier modelled by Miles et al.(1998). Their derived crustal model confining only to the offshore areas indicates the presence of high density underplated crust below Laxmi ridge and Laxmi basin. For better understanding of the spatial extent of the underplated crust and also in view of additional seismic data available in the present study, we attempt to remodel by extending the profile onto the rifted collar of the continental crust further east in the DVP. The subcrustal LVL in the Koyna region of DVP (Fig.3.12) has been extended westward into the offshore areas below the

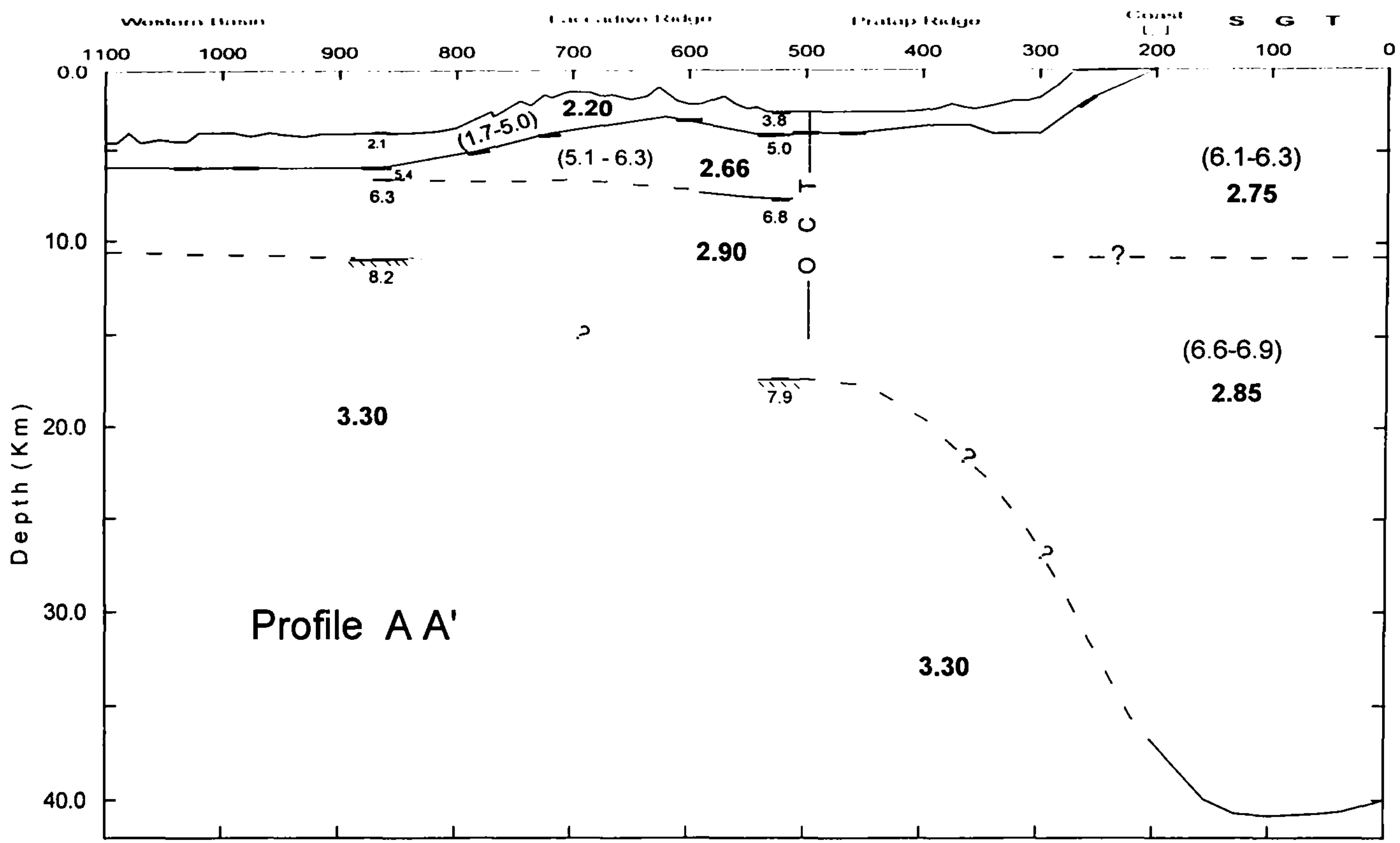


Figure 4.4 Crustal seismic sections deciphering the main crustal units along regional gravity traverse (profile AA') across the western margin considered in the present study. All available seismic information on crustal velocities, sediment and trap thickness and Moho information have been projected on to these sections. The continuous lines denote actual seismic information,while dashed lines indicate gaps in the seismic data. Thick hyphens on basement layer indicate control points obtained from published basement maps.Values in bracket refer to seismic velocities, while bold numbers indicate crustal densities. Details are discussed in the text.

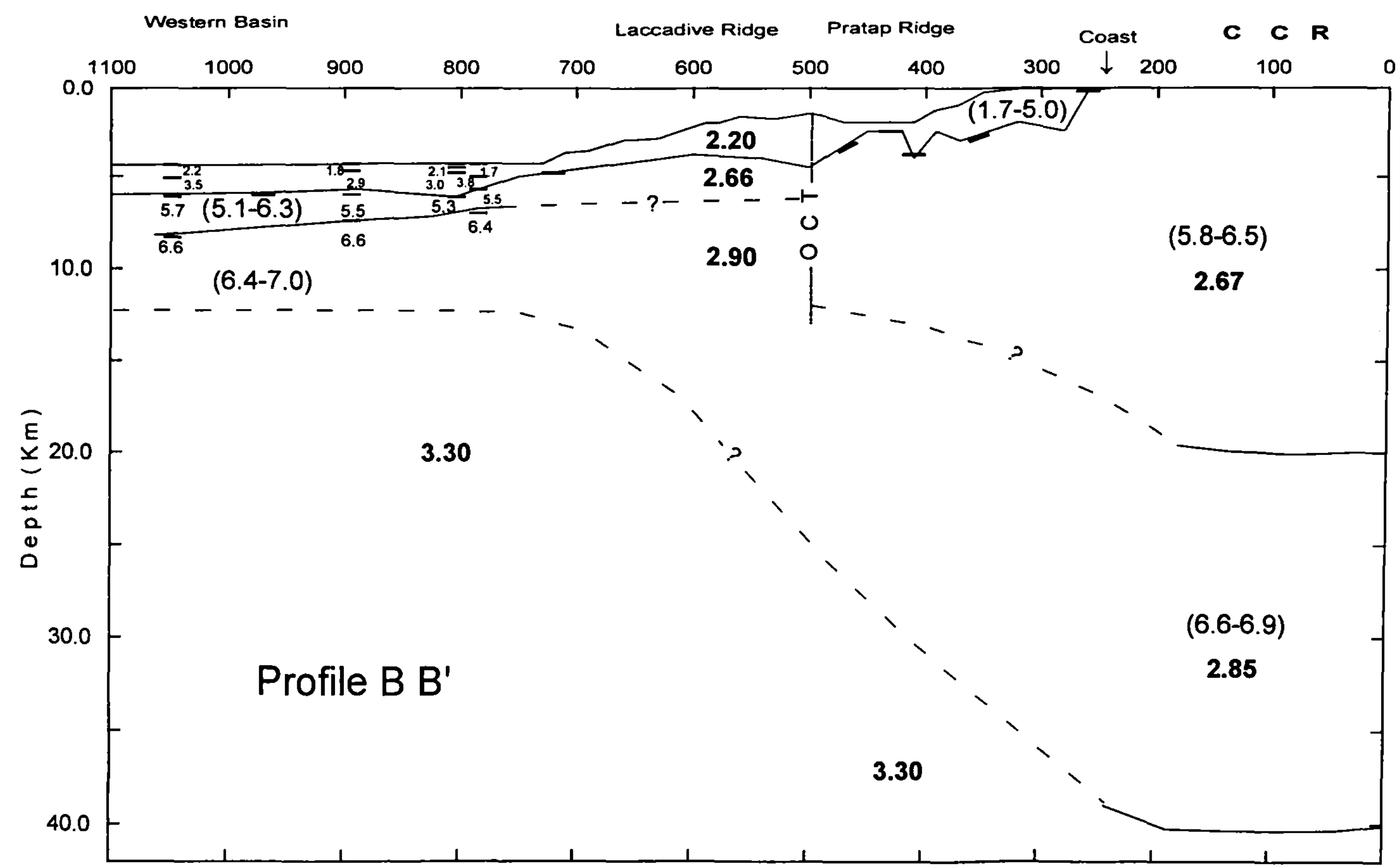


Figure 4.5 Crustal seismic section deciphering the main crustal units along profile BB' across the WCMI. Other details are as given in Figure 4.4.

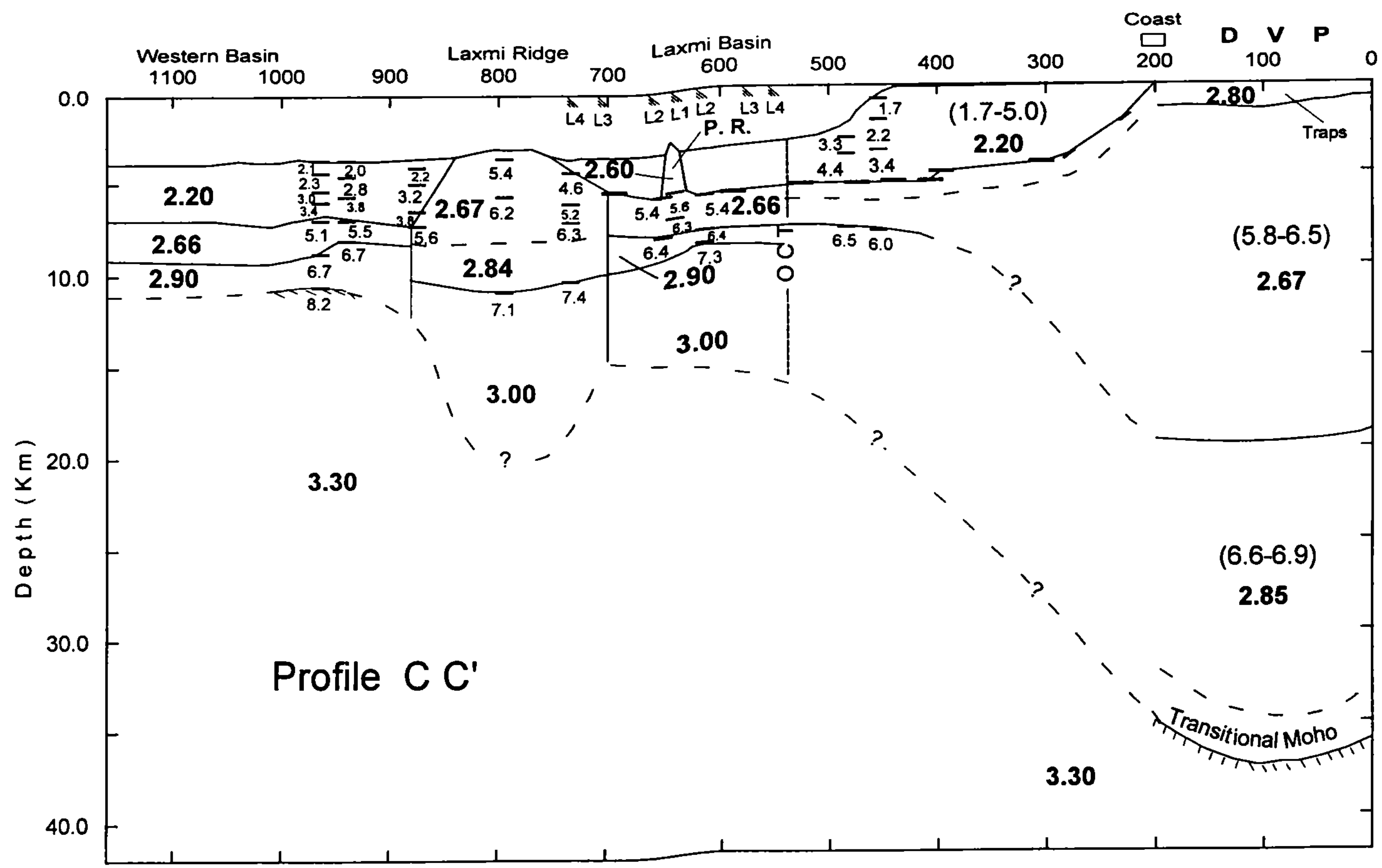


Figure 4.6 Crustal seismic section deciphering the main crustal units along profile CC' across the WCMI. Details are given in Figure 4.1 and 4.4. P.R - Panikkar Ridge

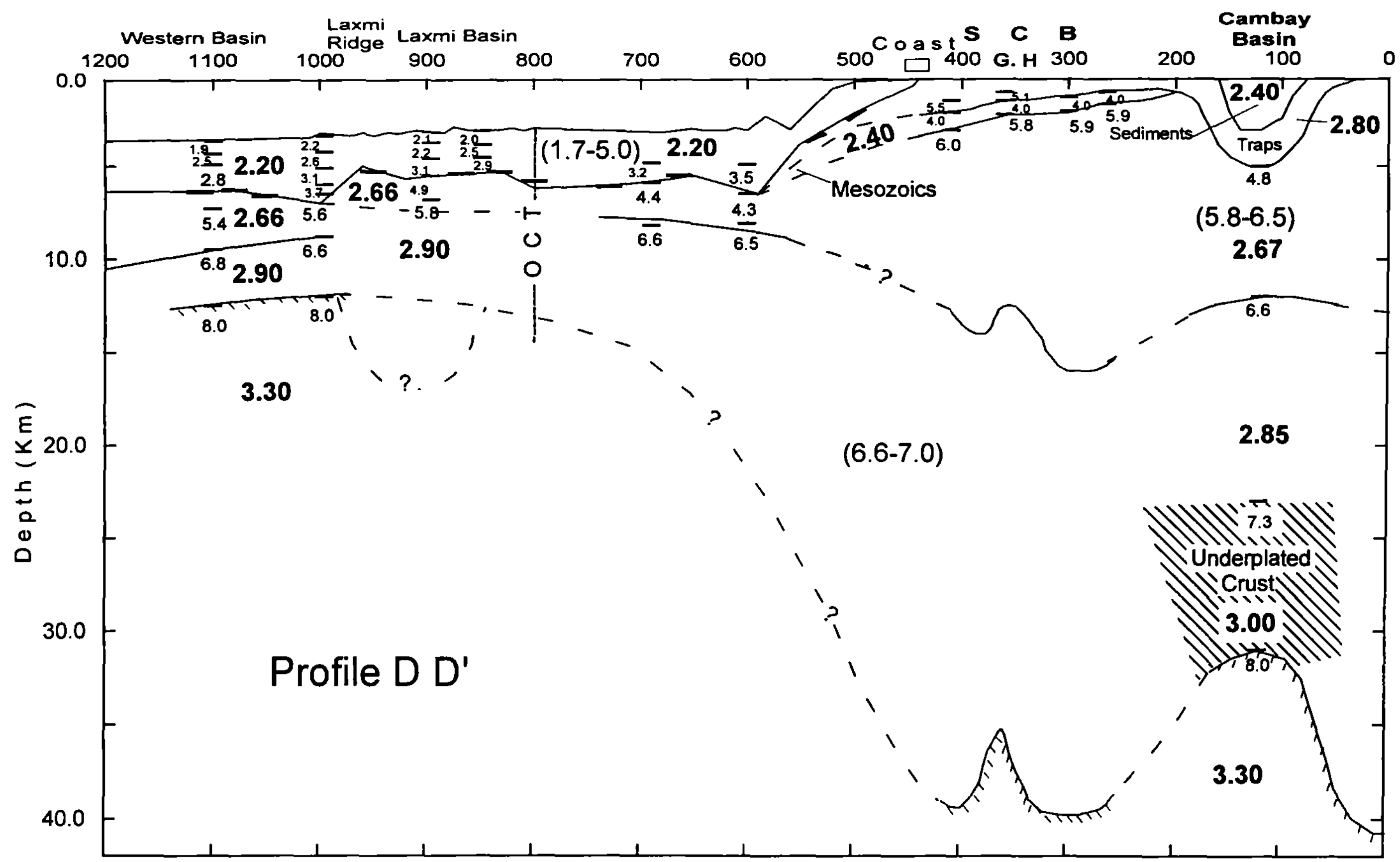


Figure 4.7 Crustal seismic sections deciphering the main crustal units along profile DD' across WCMI. Details are given in Figure 4.4.

Eastern basin by Pandey et al. (1996) for gravity modeling. Except in the Koyna region, the spatial extent of these LVL's along the West Coast and the adjoining oceanic areas is not known. So, incorporating such layers in the gravity modeling leads to more ambiguity and hence not considered here. But, if present, it would only enhance the modelled thickness and/or density of the underplated crust in the region. Profile DD' passes across the Cambay basin and Saurashtra Continental Block (SCB) in the West Coast where detailed velocity structure is known from Mehmadabad-Billimora, Mehmadabad- Dharimanna and Navibandar -Amreli DSS sections. For both CC' and DD' profiles, the thickness of traps is considered from Kaila(1988) in the DVP region and in the offshore areas from Gopala Rao(1990) and Dessai and Bertrand(1995). For all profiles, the lithosphere thickness of 70 km below the Arabian Sea(Singh, 1990) has been assumed.

4.4 GRAVITY MODELING

Utilizing the crustal seismic profiles shown in Figures 4.4 to 4.7, the gravity modeling has been carried out. Wherever seismic control is very high along these profiles, model parameters in that region are held fixed to infer the structure in the surrounding areas. The modeling is carried out by minimizing the misfit between observed and computed anomalies and the models presented here bring an r.m.s error of around 5 –8 mGal for all four profiles which is sufficient for regional gravity interpretation. The models are shown in Figures 4.8 to 4.11.

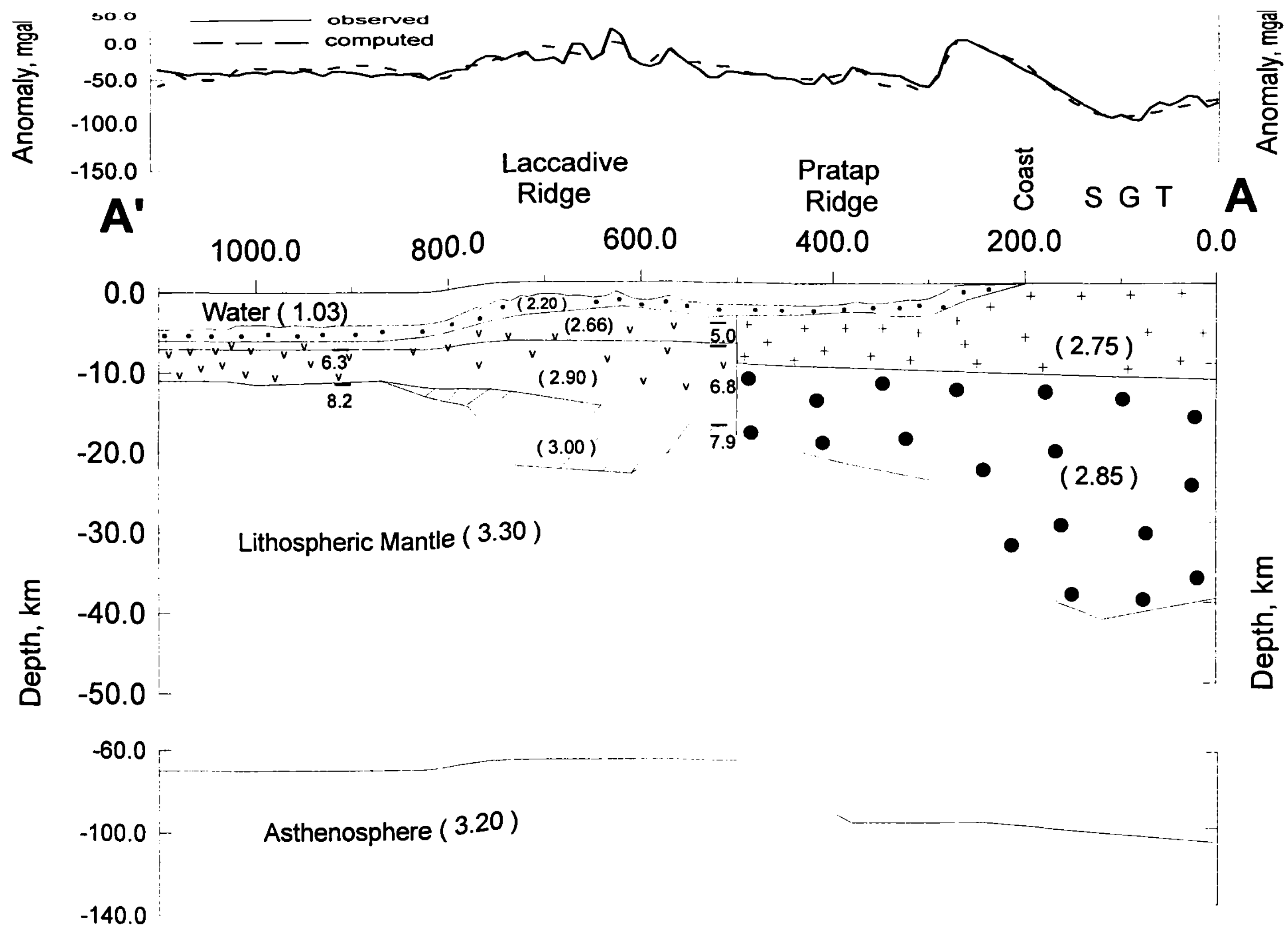


Figure 4.8 Profile AA' and the two-dimensional gravity model across the SW continental margin of India. The numbers with short bars refer to seismic velocities from refraction stations and the values in bracket refer to inferred densities as discussed in the text. Hatched region indicate underplated material of density 3.0 g/cc below the Laccadive ridge. SGT-Southern Granulite Terrain.

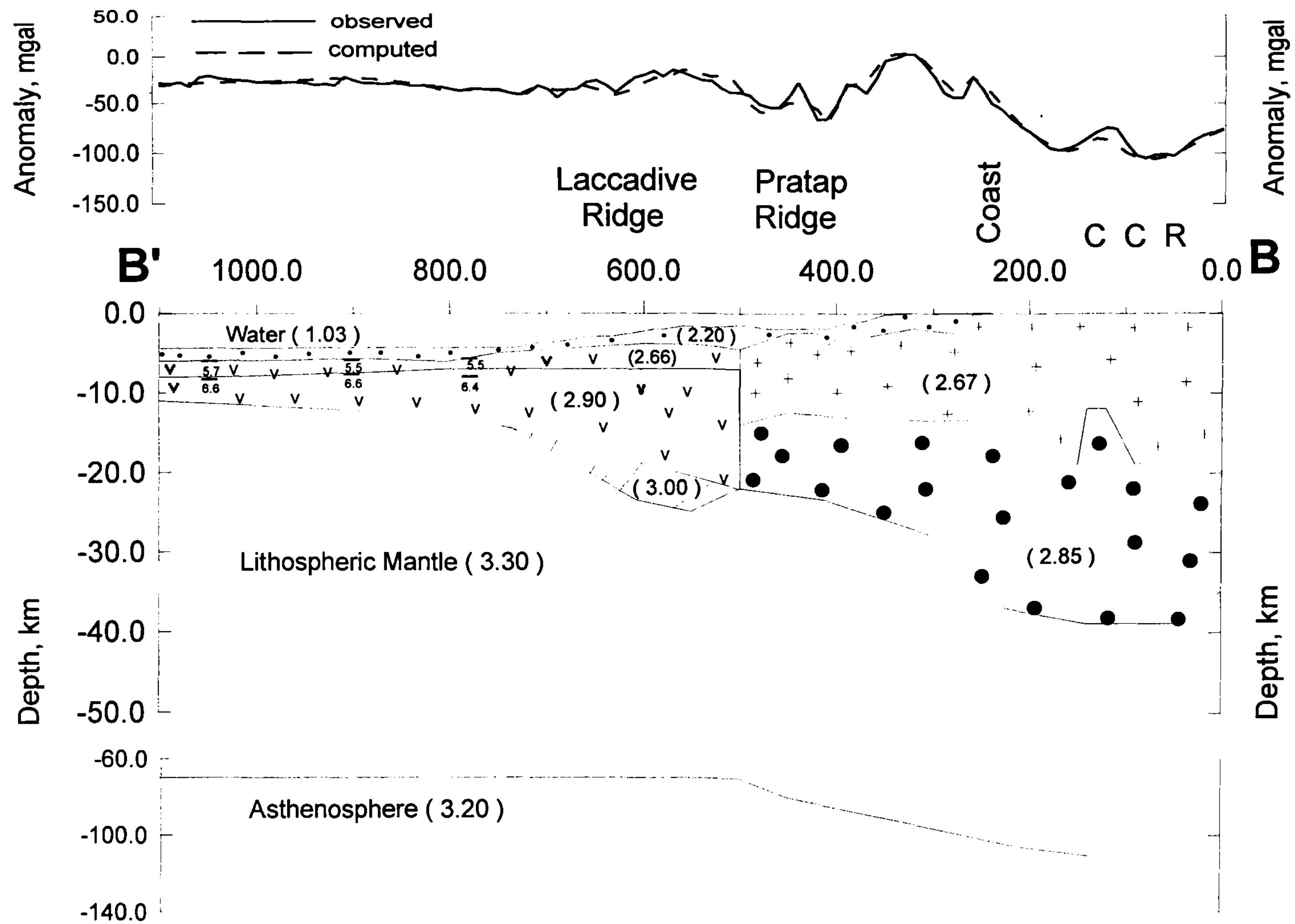


Figure 4.9 Profile BB' and the two-dimensional gravity model across the central West Coast of India. CCR - Central Cratonic Region. The notations are the same as in Fig 4.8.

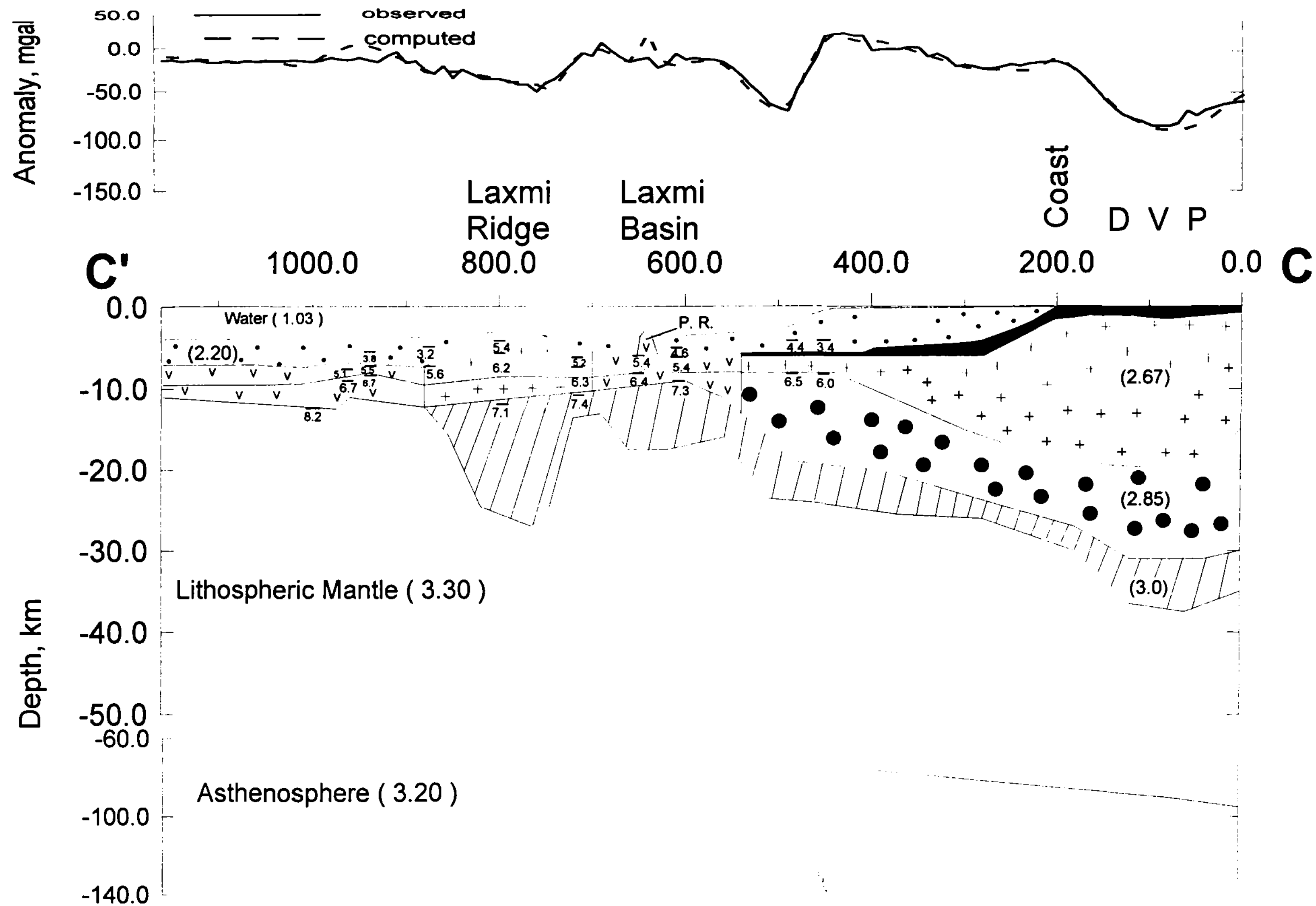


Figure 4.10 Profile CC' and the two-dimensional gravity model across the northwest coast of India within the Deccan Volcanic Province. Note the dark shaded region for the Deccan Traps. The hatched region indicates the high density material in the lower crust and is seen between West Coast and the Laxmi ridge. See text for more details. DVP - Deccan Volcanic Province.

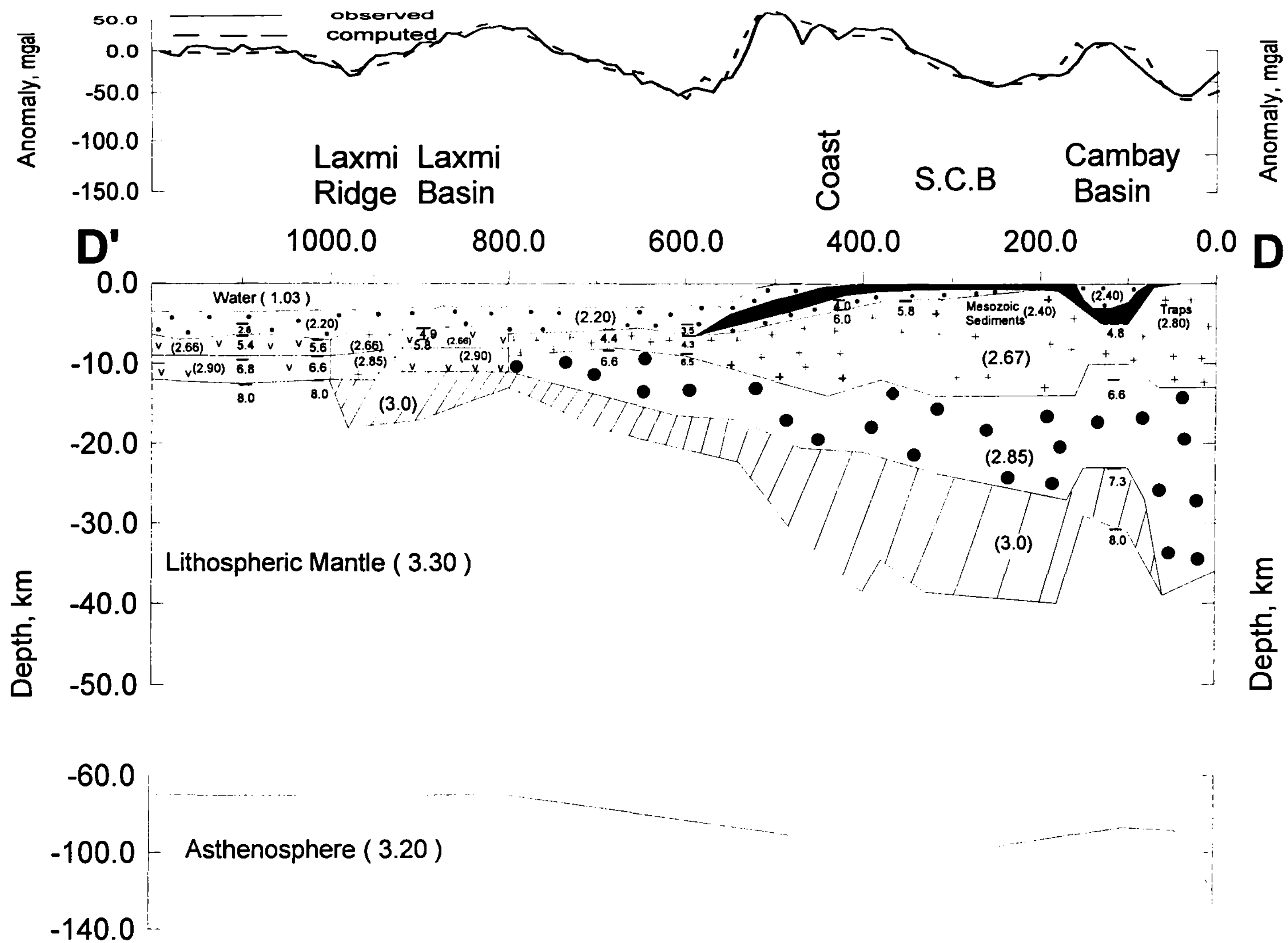


Figure 4.11 Profile DD' and the two dimensional gravity model across the northwest coast of India within the Deccan Volcanic Province. The dark shaded region represent the trap below which Mesozoic sediments are present. The notations and other details are as given in Fig. 4.8 and 4.10. SCB - Saurashtra Continental Block.

4.5 INTERPRETED MODELS AND IMPLICATIONS

The seismically constrained gravity models along profiles AA' through DD' throw some light on the probable lithospheric thickness variations in the region; extent of underplating influenced by episodic rifting and accompanying magmatism; rifting styles across the margin; and also partially helps to reconcile some of the existing models in the Arabian Sea. Some of the salient observations in the context of overall geodynamics of the region are presented below :

4.5.1 LITHOSPHERIC THICKNESS

The lithosphere fixed uniformly at a depth of 70km in the oceanic areas has been modelled here below the West Coast to fit the gravity anomalies. The models show considerable variation in lithospheric thickness along the western Indian shield margin.The thickness varies from 110 – 120 km observed in the southern and central part (profiles AA' and BB') to as much as 85 – 90 km in the northern part below Deccan plateau and Cambay rift basin (profile CC' and DD'). The shallowest part of the lithosphere is 85 km below the Cambay rift basin (profile DD') which sharply increases on either side to 120 km below the Aravallis and 90 – 110 km below the SCB.

4.5.2 CRUSTAL STRUCTURE BELOW WEST COAST AND THE EASTERN BASIN

The SCB is underlain by typical continental crust which appears to be highly faulted and fractured (profile DD'). The Girnar horst within the SCB seems to be due to localized crustal uplift deep from the Moho. The highly faulted nature of the crust might have resulted from successive rifting episodes and block movements beginning with the evolution of surrounding Mesozoic rift basins. The Cambay basin region further east is characterized by crustal thinning with the Moho shallowing to a depth of 31 km and presence of high density material (3.0 g/cm^3) between 22 – 31 km. The observed Moho depths of nearly 35-39 km below SCB (profile DD') and the region east of Bombay (profiles CC') require high density material at depth in order to explain the gravity anomalies. The continental crust varying in thickness between 38 – 42 km below the western Indian shield is thinning towards deep oceanic areas and can be seen to extend up to the eastern edge of Laccadive ridge in south (profiles AA' and BB'), whereas in north, thinned rift stage continental crust extends definitely up to east of Laxmi basin (profiles CC' and DD'). In the Laxmi basin, a large basement high feature can be seen in profile CC' which was identified by Gopala Rao et al.(1992) as Panikkar ridge. As mentioned earlier, there is considerable ambiguity regarding the nature of crust in the Laxmi basin region that has implications on the location of OCT as well as reconstruction history of the margin. An oceanic crust in this region has been proposed by Bhattacharya et al.(1994) and Malod et al.(1997)based on magnetic anomaly identifications. Talwani and Reif(1998) further support their idea stating that the region underlies the initial oceanic crust. This observation places the location of OCT below east of Eastern basin. Contrary to this, Miles et al.(1998) and Todal and Eldholm(1998) favour the presence of thinned continental crust in the Laxmi basin and OCT location south of the Laxmi ridge. While post- anomaly 28 sea floor spreading history proposed by Miles and Roest(1993) and Chaubey et al.(1998) in terms of complex propagating ridge sequences is generally accepted, the spreading anomalies older to anomaly 28 in the Laxmi basin proposed by Bhattacharya et al.(1994) and Malod et al.(1997) have been questioned by Miles et al.(1998) stating that the magnetic anomalies in this region could be explained as large scale intrusions into the thinned continental crust. Todal and Eldholm(1998) suggest the occurrence of massive Deccan volcanism under the late syn-rift tectonic setting and defined the region as part of Deccan Large Igneous Province. The gravity models in the present study neither resolve this issue nor can unequivocally identify the location of OCT as the density differences in the crust below Laxmi ridge and Laxmi basin are not sufficient to clearly distinguish the two through gravity modeling. However, it may be pointed out that the modelled thickness of underplated crust would be more if the Laxmi basin is underlain by continental crust in comparison to an oceanic crust. In order to obtain a lower bound on the thickness of the underplated crust, we invoke an oceanic crust in the modeling (profiles CC' and DD').

4.5.3 STRUCTURE BELOW LAXMI, LACCADIVE AND PRATAP RIDGES

Based on seismic velocity structure, Naini and Talwani (1982) inferred a thick continental type of crust below the Laxmi ridge. The continental nature of this ridge has also been widely accepted by many later workers though the nature and extent of underplated material below the ridge is debated (e.g. Miles and Roest, 1993; Bhattacharya et al., 1994; Malod et al., 1997; Miles et al., 1998; Talwani and Reif, 1998; Singh, 1999). Pandey et al.(1995) explained the low gravity anomaly due to thickened oceanic crust in terms of underplating while Todal and Eldholm (1998) described the ridge as a marginal high comprised of both continental and oceanic crust. The gravity models for Laxmi ridge in the present study (profiles CC' and DD') indicate that the ridge comprises of continental crust and a thick high density layer of 3.0 g/cm^3 extends from 11 – 12 km down to a maximum depth of 26 km.

It has been debated whether the formation of the Pratap ridge is related to the impact of Reunion hotspot along with the CLR (Krishna et al., 1992) or whether its evolution is influenced by a Precambrian fabric during the process of rifting (Subrahmanyam et al., 1995). From the gravity models (profiles AA' and BB'), it can be seen that the Pratap ridge is a shallow uncompensated basement high over thinned rifted continental crust which gives rise to the observed gravity high. So, the models are not consistent with a relation to the Reunion hotspot in its formation. Such basement highs could be related either to the formation of outer highs skirting the rifted crust at the OCT (Schuepbach and Vail, 1980) or to horst – graben tectonics within the upper crust during rifting (Curray, 1980).

The origin and emplacement of the Chagos-Laccadive Ridge (CLR) has been variously interpreted. It is viewed as oceanic in the north and continental in the south (Francis and Shor, 1966); as a former transform fault (Sclater and Fisher, 1974); as Reunion hotspot trace (Whitmarsh, 1974;Morgan, 1981;

Courtillot et al., 1986; Backman et al., 1987; Richards et al., 1989; Duncan, 1990); as an emplacement near a spreading centre-transform intersection (Ashalatha et al., 1991) and as a continental sliver in Laccadive islands region (Naini and Talwani, 1982). Chaubey et al. (1995) observed that magnetic anomalies identified in the southeastern Arabian Sea extend upto the western slopes of Laccadive ridge, but over the ridge the anomalies were obscured due to emplacement of volcanic material on the pre-existing oceanic crust. However, Chaubey et al. (2002) interpret the ridge to be continental in nature and rule out the possibility of plume generated volcanism. The gravity models (Profiles AA' to BB') across the CLR indicate a thick oceanic crust below the ridge which juxtaposes the continental crust along its eastern margin. The ridge is characterised by thickening of the crust to as much as 24 – 25 km by the presence of a high density material of 3.0 g/cm^3 below the ridge. Ashalatha et al.(1991) observed thick crustal roots beneath the ridge on the basis of admittance analysis. The presence of such thick high density material is consistent with the processes of underplating beneath the oceanic ridges along volcanic hotspot traces due to massive intrusions related to hotspot volcanism (Caress et al., 1995). Gravity models for the Ninetyeast ridge (Mukhopadhyay and Krishna, 1995) and for 85° E ridge (Subrahmanyam et al., 1999) in the northeastern Indian Ocean also indicate similar underplating due to hotspot related volcanism. Therefore, the models indicate the formation of the CLR due to Reunion hotspot at the edge of continental crust to the east.

4.5.4 UNDERPLATED CRUST

The modeling requires that in order to explain the gravity anomalies, a high density material of 3.0 g/cm^3 is required to be present at the base of the crust in the northern part of the study area covering the West Coast in the DVP and the adjoining oceanic areas as far as the Laxmi ridge (profiles CC' and DD'). The underplated crust seems to be enveloping the entire crust in the region. It is relevant to note here that the conjugate Seychelles margin has no evidence of crustal underplating (Francis and Shor, 1966; Mathews and Davies, 1966) which suggest that the underplated material present below the DVP and adjoining offshore areas is not completely due to rift related magmatism. The variation in the structure in terms of faulting of the crust, lithosphere thinning and widespread underplating between the northern part of the margin within DVP (profiles CC' and DD') and southern part outside the DVP(profile AA' and BB') can be clearly seen from the models. This difference could be due to the fact that the lithosphere experienced multiple rifting episodes and massive Deccan volcanism in the north. Though the layer appears to be underplating the whole region, its formation could be temporally related to processes such as rift related volcanism, oceanic crust generated in the initial break up and also large scale magmatism during the Deccan Volcanic episode.

4.5.5 IMPLICATIONS

The models may imply common crust-mantle processes to which both the oceanic and continental crust respond beneath the margin. The presence of regionally widespread high density underplated material at the base of lower crust below the NW continental margin of India agree well with the model for plume generated magmatism at volcanic rifted continental margins proposed by White and McKenzie (1989).

The models also indicate substantial density inhomogeneities due to faulting in the crust, large variations in lithosphere thickness and wide spread occurrence of underplated material in the lower crust within the Deccan Volcanic Province (DVP). Mandal and Singh (1996) observed that density inhomogeneities accentuate the stress field with DVP and are large enough at least to reactivate weak faults to failure. According to Zoback et al., (1996) model, the large thickness of high density underplated material below the DVP may also perturb the stress field giving rise to enhanced seismic activity in the region. Hence the rheological response of the whole lithosphere to the stress field should also be taken into account in understanding the seismogenesis of DVP.

4.6 CONCLUSIONS

Gravity modeling along the four regional traverses across the western continental margin of India highlights the large variation in crustal configuration between northern part of the margin within the DVP and the southern part outside the DVP. The lithosphere thickness below the West Coast in general varies from 110 – 120 km in the southern and central part (within SGT and CCR) to as much as 85-90 km in the Deccan plateau and Cambay rift basin. The crust below the SCB and Cambay rift appears to be highly faulted and the Girnar horst in the SCB is seen as a localised crustal uplift deep from the Moho. The Eastern basin is characterised by thinned continental crust which extends as far as Laxmi basin in the north and the CLR in the south. The modeling could not definitely identify the location of OCT in the Eastern basin. However, the models indicate a high density underplated crust of 3.0 g/cm^3 in the northern part of western margin covering the West Coast in the DVP and the adjoining oceanic areas as far as the Laxmi ridge. The models indicate the Pratap ridge as a shallow basement high over continental crust formed during rifting and formation of CLR due to Reunion hotspot at the edge of continental crust. The variation in lithospheric structure in terms of faulting of the crust, lithospheric thinning and widespread underplating observed in the northern part of the western margin within DVP can be attributed to multiple rifting episodes and massive Deccan volcanism in the region.

CHAPTER V

STRUCTURE AND TECTONICS OF THE KERALA BASIN, SOUTHWEST CONTINENTAL MARGIN OF INDIA BASED ON GRAVITY DATA

5.1 INTRODUCTION

The Kerala basin is a major onshore-offshore sedimentary basin observed along the western continental margin of India and is located in its southern most part. The basin in the onshore covers mostly the southern and central parts of the Kerala coast between 8.5°N – 10.5° N latitudes bounded by the Western Ghats in the east and the Arabian abyssal plain on the west. The basin is characterized by the presence of major surface / sub-surface structural features such as the Cochin depression, Cape Comorin depression, Pratap ridge and the Alleppey platform which have evolved during the rifting of India and Madagascar and subsequent sea-floor spreading between them (Biswas and Singh, 1988; Singh and Lal, 1993; Storey et al., 1995; Subrahmanyam et al., 1995). Apart from the horsts and grabens, in few places, igneous intrusives and volcanic flows are concealed below the thick sediments in the margin (Subrahmanyam et al., 1995; Chaubey et al., 2002). Many of these structural trends and basement features observed in the offshore areas throughout the western margin were inferred to have been controlled by the Precambrian structural grain of the Indian shield margin (Biswas, 1987; Kolla and Coumes, 1990; Subba Raju et al., 1990). Kolla and Coumes (1990) inferred that the onshore structural trends in the southwest coast extend into the offshore areas as far as the east of Laccadives (Figure 5.1), which suggests that the continental crust extends up to at least east of Laccadive islands. The aim of the present study is to delineate structure of this rifted continental crust and to study rift tectonics of the southwest margin by integrated analysis of both onshore and offshore gravity data.

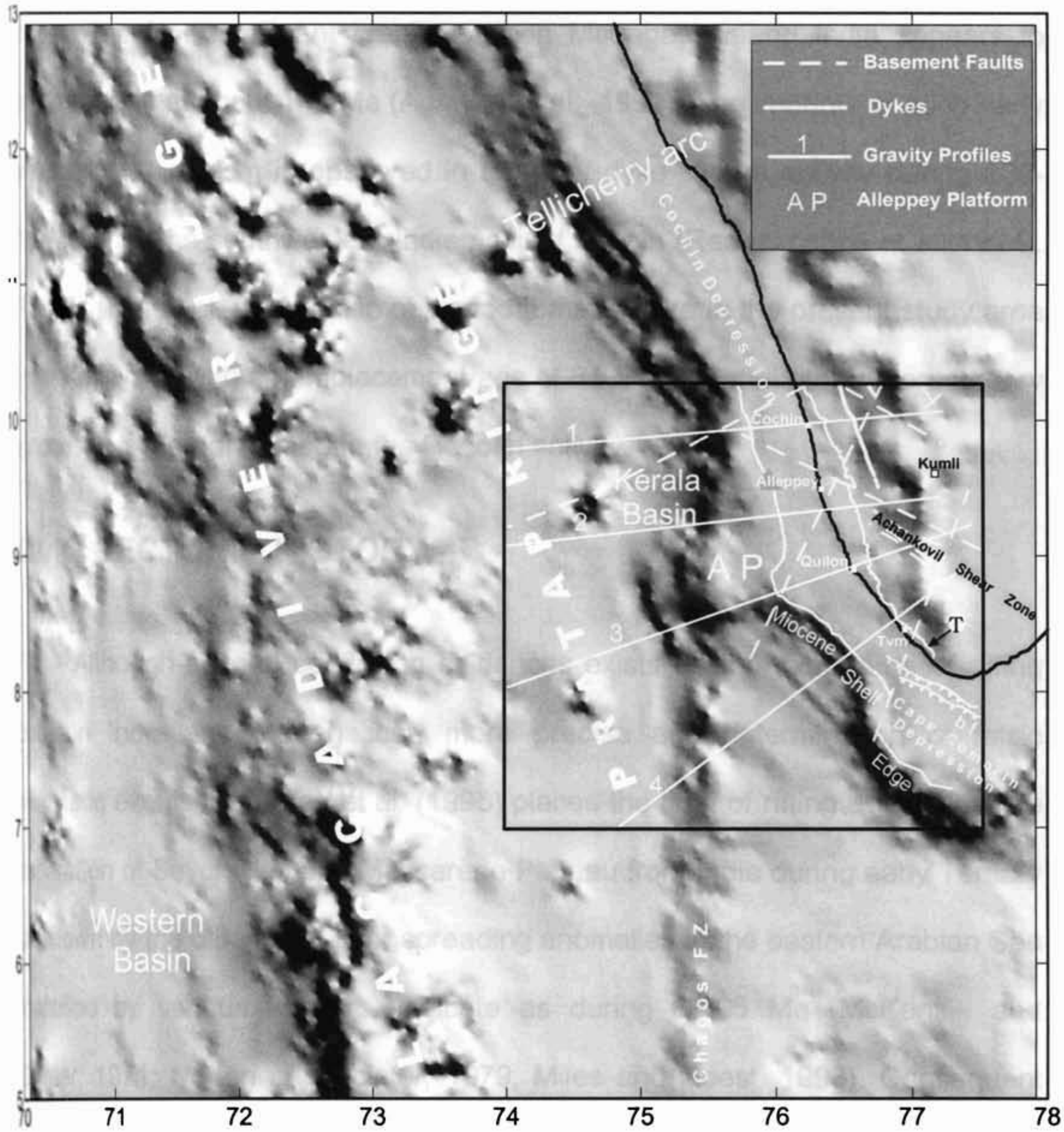


Figure 5.1 Shaded relief map of the southwestern shield and the adjoining offshore areas. Prominent structural features are marked on the map. The present study area is marked as a square. Major faults continuing into offshore are from Kolla and Coumes (1990), Biswas (1987). T - Tertiary boundary.

5.2 REGIONAL GEOLOGIC AND TECTONIC FRAMEWORK

The western continental margin of India has evolved through a number of stages. The first significant break between Madagascar and India appears to have occurred at about 140 Ma (Agarwal et al., 1992). The imprints of such early distensional tectonism is observed in terms of dyke swarm activity during 120-140 Ma along the southwestern Indian shield margin (Radhakrishna et al.,1994). Radhakrishna et al. (1994) also observed a major dyke in the present study area (near Kottayam) with an emplacement age of 81 Ma and attribute to a precursory igneous episode not related to the Deccan activity.

5.2.1 TECTONIC HISTORY

Although several conflicting evidences exists on the exact time of rifting between India and Madagascar, more precise age determination of felsic magmatic events by Storey et al. (1995) places the time of rifting at 88 Ma. The separation of Seychelles and Mascarene Plateau from India during early Tertiary as shown by the oldest sea-floor spreading anomalies in the eastern Arabian Sea identified by various workers, indicate as during 63-65 Ma (McKenzie and Sclater, 1971; Norton and Sclater, 1979; Miles and Roest, 1993). Consequent upon the rifting of Madagascar and Seychelles from India, the basement tectonics gave rise to the horst-graben morphology and formation of Kutch, Saurashtra, Bombay and Konkan-Kerala sedimentary basins (Katz and Premoli, 1979; Subrahmanyam et al., 1995).

5.2.2 STRUCTURE

5.2.2.1 ONSHORE

In the onshore regions, the Precambrian basement rocks have a general foliation strike in the NNW-SSE trend. Detailed structural analysis of these rocks revealed several phases of deformation. Several major/minor lineaments/faults with varied strike directions such as NW-SE, E-W and NE-SW occur along the Kerala coast from Landsat imageries (Varadarajan and Balakrishnan, 1980; Nair, 1990), of which the Achankovil – Thenmala shear system is the most prominent and major lineament zone in the study area. Narula et al. (2000) presented some of the most prominent and authentic set of lineaments/faults in the region. High-resolution topographic image obtained for the southwest coast (Figure. 5.2) suggests that many of these lineaments have a geomorphic expression. Evidences like the displacement of laterites and other geomorphological features indicate that movements have been taking place along some of the lineaments throughout Tertiary and well into the Quaternary period (Soman, 1997). Some of them show considerable seismic activity as evidenced by the epicentral location of earthquakes (Fig. 5.2) in the region (Tilak, 1980; Rajendran and Rajendran, 1995).

5.2.2.2 OFFSHORE

The major morphological regions of the southwest margin are the shelf, shelf margin basin, Alleppey platform in the shelf-slope region, Pratap ridge,

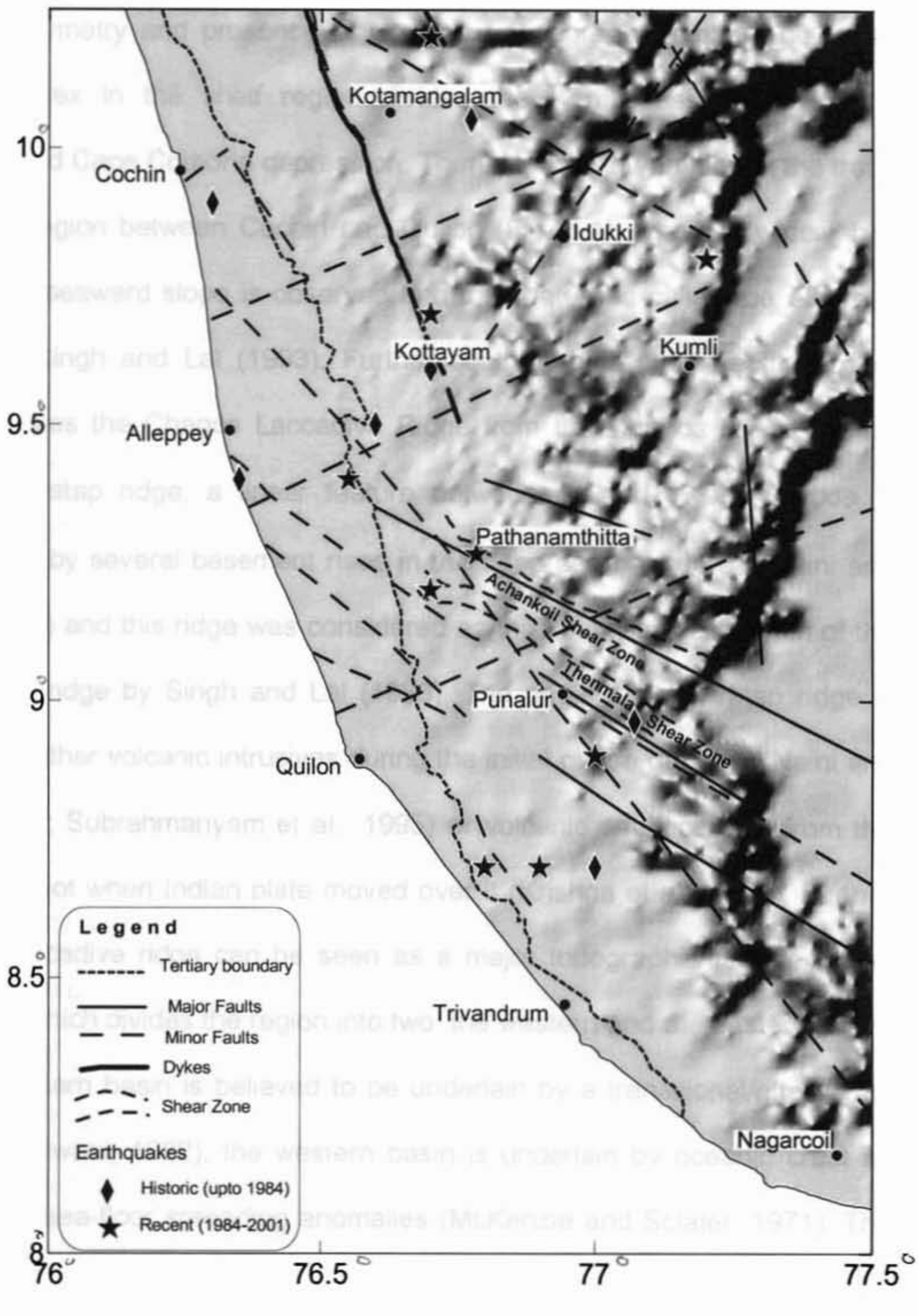


Figure 5.2 Morphotectonic map of the southwestern shield adjacent to the Kerala basin. The major/minor faults shown on the map are from Narula et al. (2000). The location of several moderate earthquakes in the region are shown. Details are discussed in the text.

Laccadive ridge and the western Arabian basin. The margin is characterised by complex bathymetry and presence of numerous topographic highs. The horst-graben complex in the shelf region divides the Kerala basin into Cochin depression and Cape Comorin depression. There is marked variation in the trend of the shelf region between Cochin and Quilon (Fig. 5.1), where a wider shelf with a gentle seaward slope is observed and this feature is called the Alleppey Platform by Singh and Lal (1993). Further south, the Chagos fracture zone, which separates the Chagos Laccadive Ridge from the Chagos basin can be seen. The Pratap ridge, a linear feature between 8° and 17° N latitude is characterised by several basement rises in the deep sea basin area (Naini and Talwani, 1982) and this ridge was considered as the southward extension of the Kori-Comorin ridge by Singh and Lal (1993). The origin of the Pratap ridge is attributed to either volcanic intrusives during the initial phase of rifting (Naini and Talwani, 1982; Subrahmanyam et al., 1995) or volcanic emplacement from the Reunion hotspot when Indian plate moved over it (Krishna et al., 1992). Further west, the Laccadive ridge can be seen as a major topographic feature in the Arabian sea which divides the region into two: the western and the eastern basin. While the eastern basin is believed to be underlain by a transitional/rifted crust (Naini and Talwani, 1982), the western basin is underlain by oceanic crust as evidenced by sea-floor spreading anomalies (McKenzie and Sclater, 1971). The origin and emplacement of the Laccadive ridge is still enigmatic.

5.3. GRAVITY DATA ACQUISITION IN THE ONSHORE KERALA BASIN ALONG SOUTH AND CENTRAL KERALA COAST

5.3.1 METHODOLOGY

The geotectonic nature of the southwest margin indicates that several of the observed structural/tectonic elements played a significant role in controlling the Kerala basin formation during pre- to post rift evolutionary history. Keeping this in mind, closely spaced gravity observations have been made in the near coastal areas of central basin area of the Kerala coast. For this purpose, a good network of gravity base stations are essential. The gravity base stations established by Singh et al. (1985) in the Palghat gap region and the bases established by Radha Krishna et al. (1998) in the Bavali shear and adjacent regions of northern Kerala are sufficient enough to conduct the regional gravity surveys north of the Palghat gap. However, in the region south of Palghat, very few stations are available. Many of the base stations setup by Woollard et al. (1969) are located at major railway stations, along the railway track and without any repetitions. Hence their accuracy for using them as reference stations in detailed gravity surveys is doubtful. Therefore, a network of 28 base stations were established by adopting forward looping technique and connected to the nearest available base at Vadakancheri established by Singh et al. (1985).

5.3.2. REFERENCE GRAVITY BASE

In the present study the nearest base station value of Vadakkancheri (observed gravity value – 978.12168 Gals) established by Singh et al. (1985) has been carried by forward looping method. This base was established with respect to Coimbatore airport gravity value of 978.0715 Gals (Qureshy and Krishna Brahmam, 1969). The Coimbatore airport base was, in turn, connected to the Bangalore airport value of 978.0386 Gals (Manghnani and Woollard, 1963). The Bangalore base corresponds to a value of 979.0640 Gals of the Indian National Gravity Base at Dehradun, which, in turn, corresponds to the Potsdam gravity value of 981.2740 Gals.

5.3.3. PLAN OF SURVEY

The base establishment was done initially for 22 stations with a Lacoste and Romberg gravimeter (model G-1042) having a world wide range of 7000mGals. For setting up additional 6 stations (Nos.23 to 28) in the far sourth, ie near around Trivandrum, a W.Sodin Gravimeter of scale value 0.24 mGal and 240 mGal range was employed. The base stations were established using the well known method of forward looping, the procedure being, to carry forward the gravity value from an already established base A to a new base B, by making a loop A-B-A. Well defined and permanent land marks such as verandhas of Rest House (RH), Guest Houses (GH), Inspection Bungalows (IB), Railway Stations (RS), Post Offices (PO) and other easily accessible locations were selected for locating the base stations. Elevation data was collected from spot heights, SOI toposheets and by using an American Paulin Altimeter. The locations of 28 gravity base stations established in the present study as shown in Figure. 5.3.

5.3.4. DESCRIPTION OF BASES

Description of gravity bases along with basic details such as the SOI toposheet number, height, latitude, longitude and observed value of the bases are given in the sketches of gravity base stations in Figures 5.4 – 5.9.

5.3.5. DYNAMIC DRIFT AND ACCURACY OF THE BASE VALUES

Drift rate in the individual base ties during the course of base establishment was calculated in order to ascertain the errors in the base values. The histogram of the dyanamic drift rate for the total number of base ties is shown in Figure 5.10. The dynamic drift was assumed to be linear during the survey and care was taken to close the individual base loops in 2-3hrs within the tidal cycle. As can be seen in Figure 5.10. most of the drift values fall within the range 0-0.002 mGal/min.

As mentioned earlier, in order to compare and check the accuracy of HIG base stations established in the central and south Kerala region by Woollard et al. (1969), we have reoccupied nearly 6 of their stations. The base values for these stations are given in Table 5.1. For comparison, the base values established in the present study are also shown in the Table. Though sketches for bases at Ettumannur and Chengannur Railway Stations are available but their

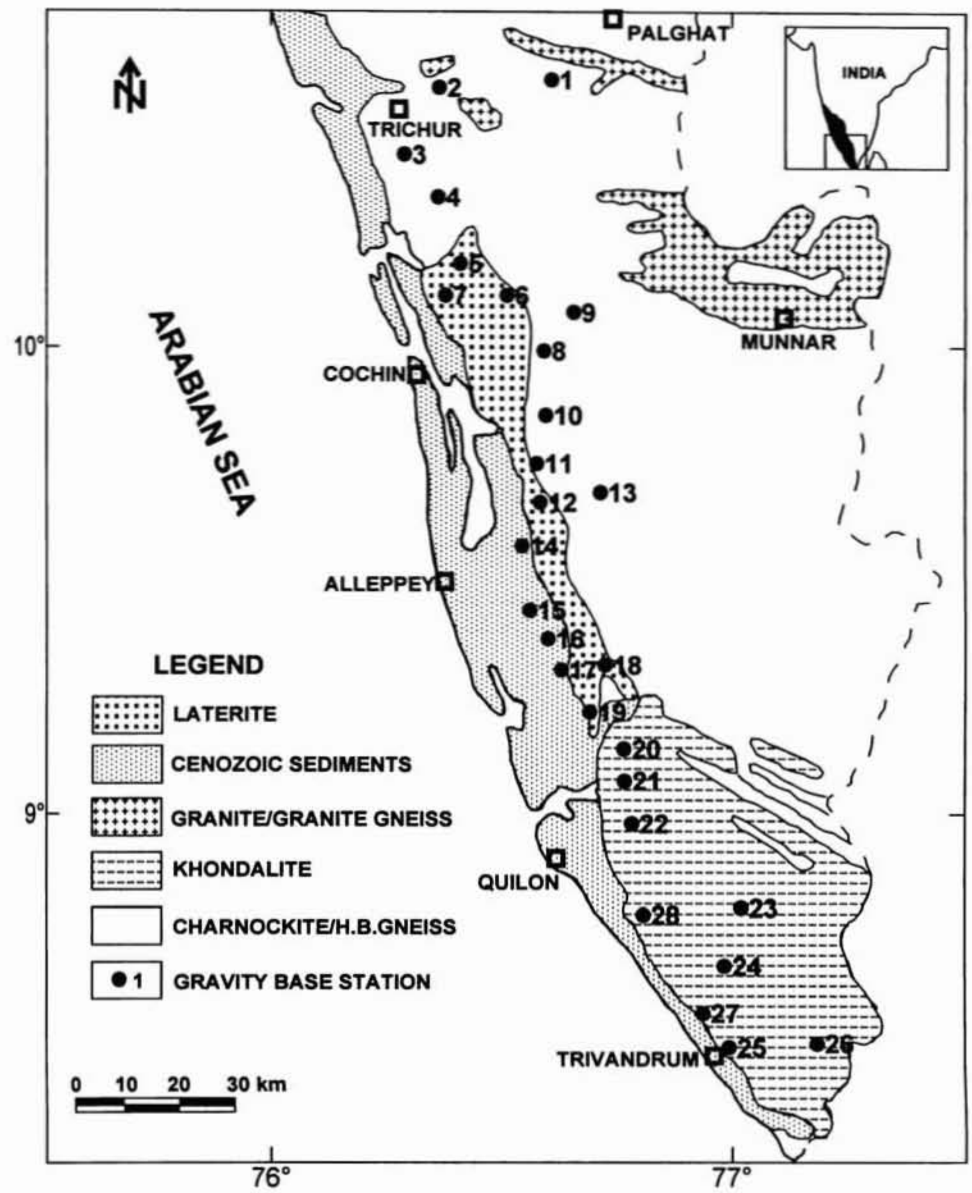


Figure 5.3 Map showing the distribution of 28 gravity base stations established in central and south Kerala region in the present study

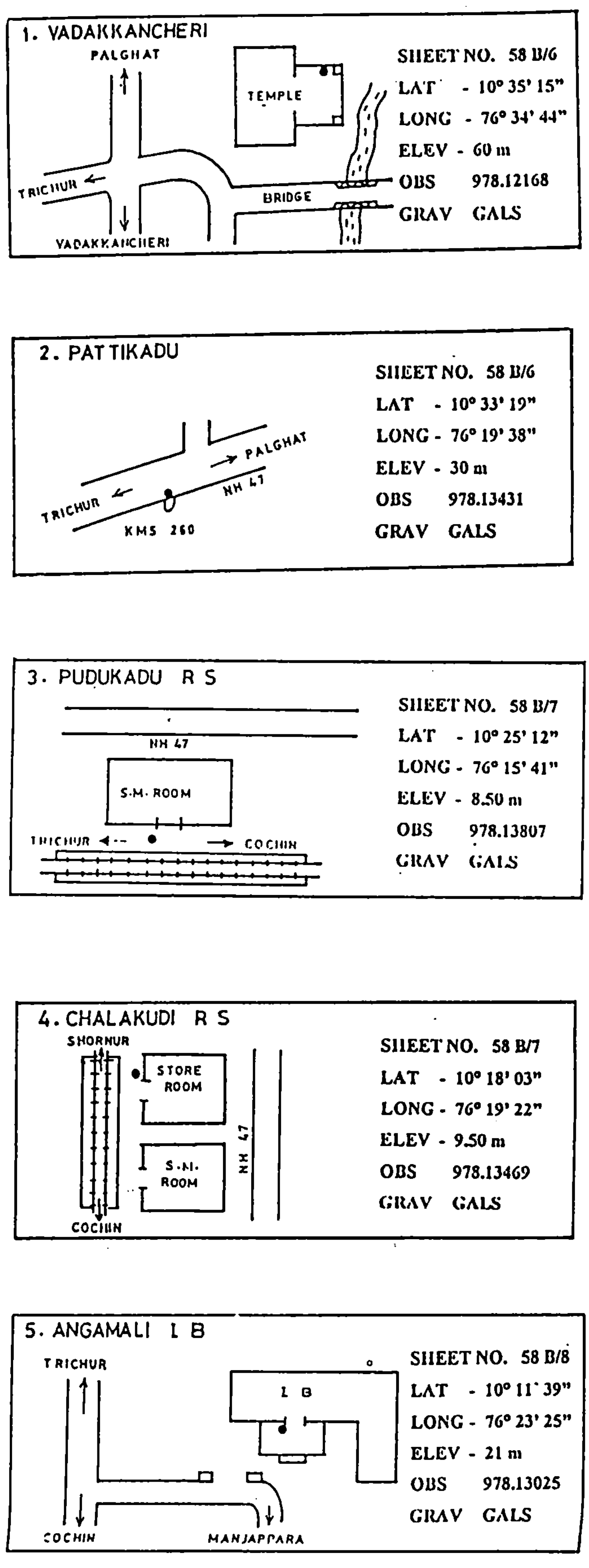
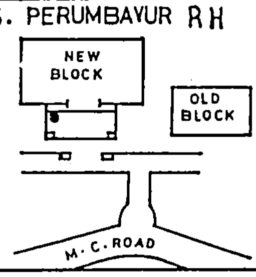


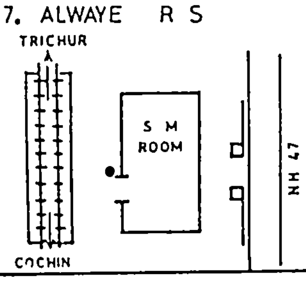
Figure 5.4. Sketches showing location of five permanent base stations. (nos. 1-5).

6. PERUMBAVUR R H



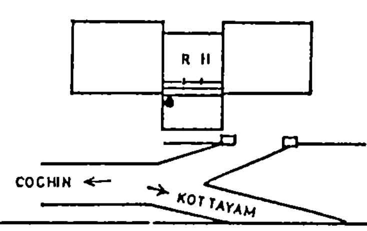
SHEET NO. 58 B/8
LAT - 10° 06' 57"
LONG - 76° 28' 15"
ELEV - 22 m
OBS 978.12438
GRAV GALS

7. ALWAYE R S



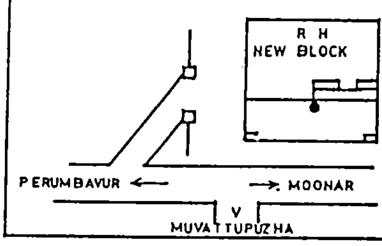
SHEET NO. 58 B/8
LAT - 10° 06' 25"
LONG - 76° 21' 26"
ELEV - 11.3 m
OBS 978.14238
GRAV GALS

8. MUVATTUPUZHA R H



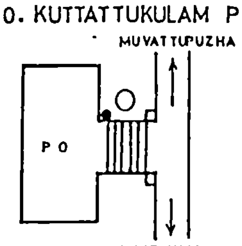
SHEET NO. 58 C/9
LAT - 09° 58' 50"
LONG - 76° 34' 55"
ELEV - 35 m
OBS 978.12069
GRAV GALS

9. KOTAMANGALAM R H



SHEET NO. 58 B/12
LAT - 10° 03' 51"
LONG - 76° 37' 19"
ELEV - 37 m
OBS 978.10900
GRAV GALS

10. KUTTATTUKULAM P O



SHEET NO. 58 C/9
LAT - 09° 51' 43"
LONG - 76° 35' 51"
ELEV - 30 m
OBS 978.12169
GRAV GALS

Figure 5.5. Sketches showing location of five permanent base stations. (nos. 6-10).

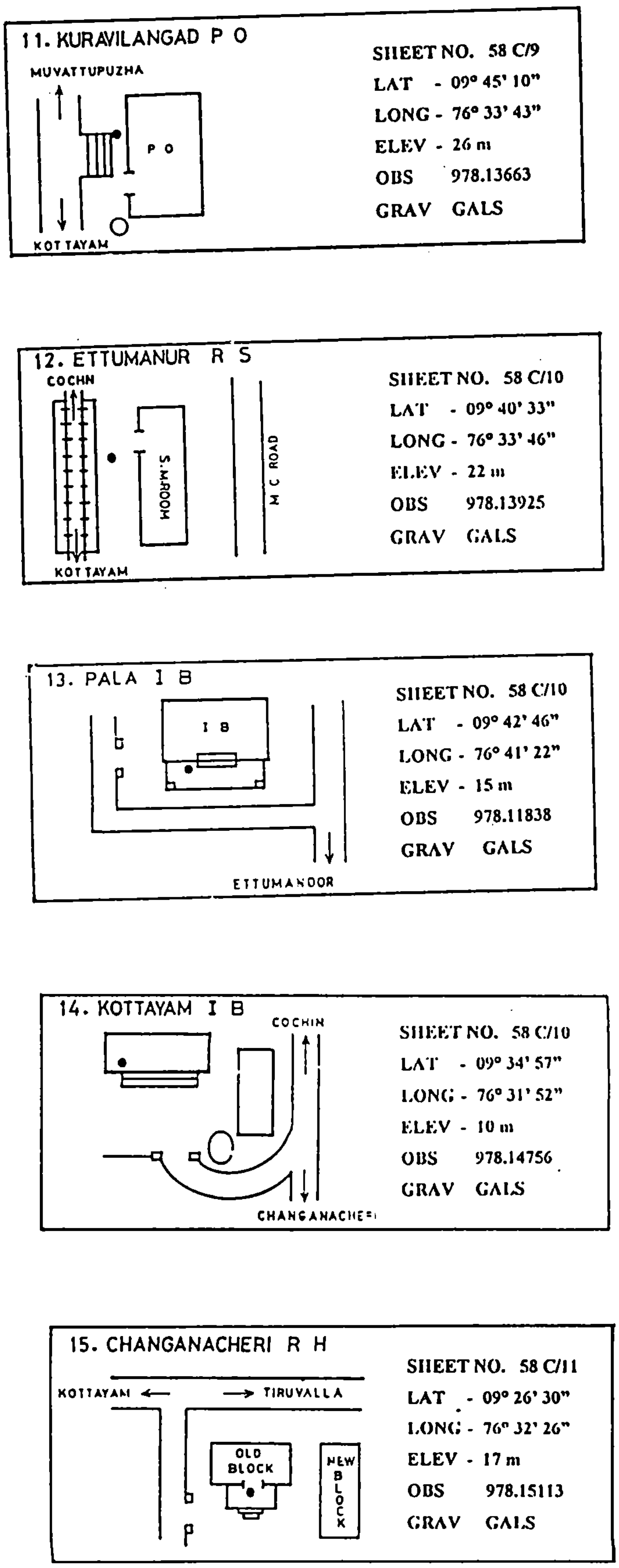


Figure 5.6. Sketches showing location of five permanent base stations. (nos. 11-15).

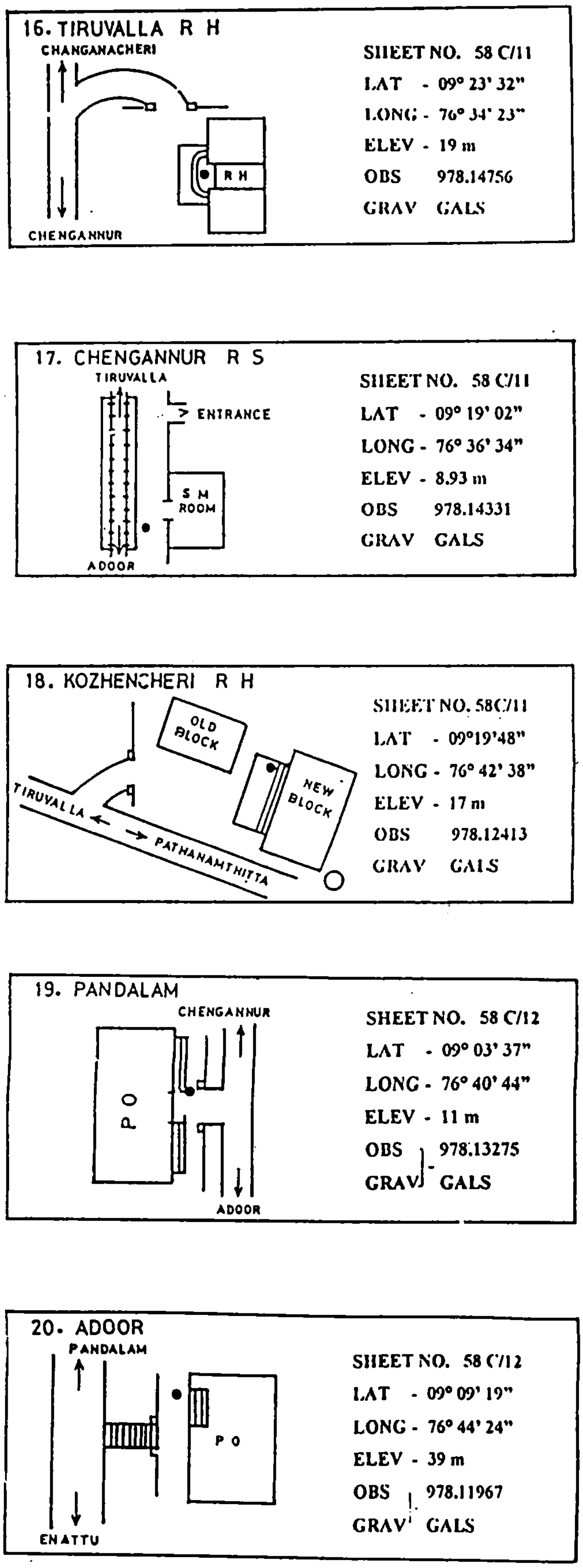
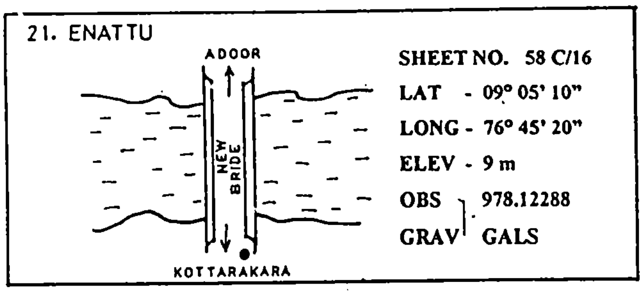
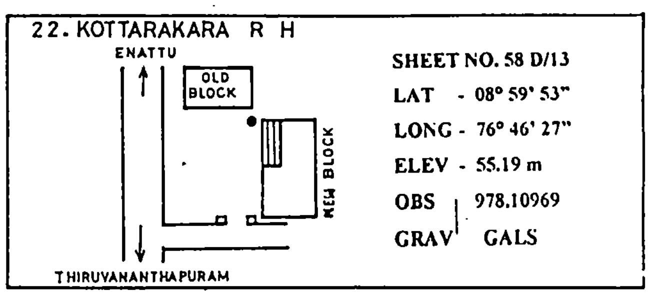
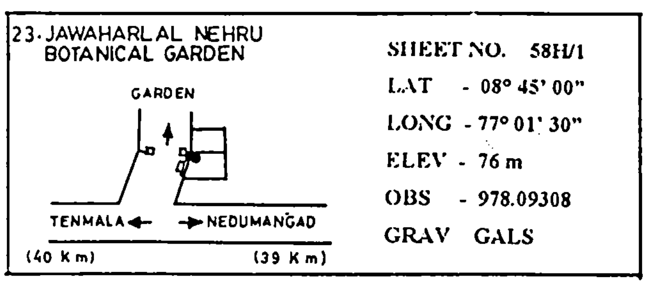
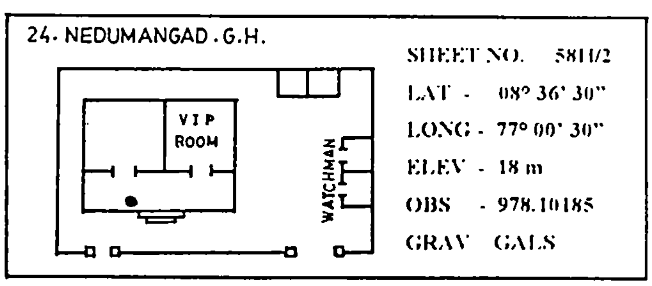


Figure 5.7. Sketches showing location of five permanent base stations. (nos. 16-20).









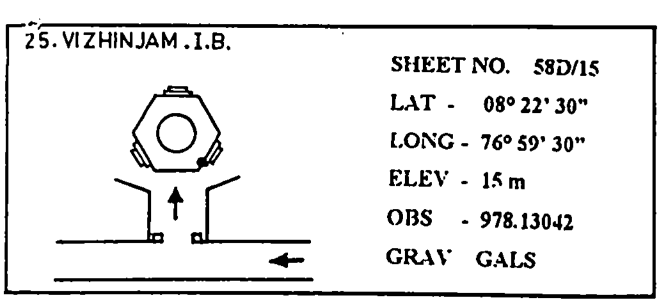
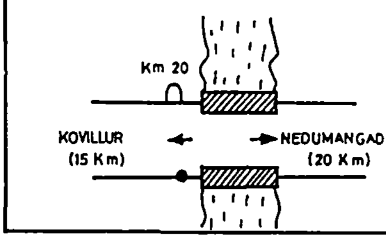


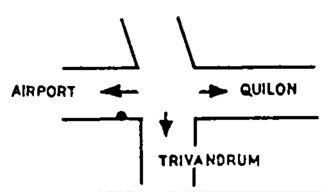
Figure 5.8. Sketches showing location of five permanent base stations. (nos. 21-25).

26.KMS 20



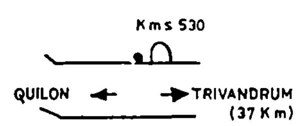
SHEET NO. 58H/2
LAT - 08° 31' 00"
LONG - 77° 08' 00"
ELEV - 30 m
OBS - 978.09932
GRAV GALS

27. TRIVANDRUM



SHEET NO. 58D/14
LAT - 08° 31' 30"
LONG - 76° 56' 00"
ELEV - 15 m
OBS - 978.11907
GRAV GALS

28. ATTINGAL



SHEET NO. 58D/14
LAT - 08° 43' 30"
LONG - 76° 49' 00"
ELEV - 30 m
OBS - 978.11448
GRAV GALS

●	GRAVITY BASE	GH	- GUEST HOUSE
+++	RAILWAY LINE	RH	- REST HOUSE
▭	STEPS	PO	- POST OFFICE
		RS	- RAILWAY STATION
m	METERS	IB	- INSPECTION BUNGLOW

LAT - LATITUDE
LONG - LONGITUDE
ELEV - ELEVATION
OBS } - OBSERVED
GRAV } GRAVITY

Figure 5.9. Sketches showing location of three permanent base stations (nos. 26-28). The legend describing the above base station data is given.

value were not reported in the volume of Woollard et al. (1969). Table 5.1 shows that the HIG values in general are higher and the difference between HIG and CUSAT values range approximately from 0.1-1.5 mGal. In view of this wide range in the HIG values, we conclude that the use of these base stations as reference base stations must be done with care in the detailed gravity surveys. The gravity bases presently reported here can be of help for routine gravity mapping of the region.

5.3.6. GRAVITY DATA

Utilizing this base network, a total of 600 gravity measurements were made using the Lacoste and Romberg gravimeter having a world wide range of 7000 mGal (model G1042) and W. Sodin gravimeter having 240 mGal range. The gravity data collected in this region by the National Geophysical Research Institute (NGRI, 1981) were also considered. The distribution of gravity measurement points are shown in Figure 5.11. Location of gravity stations were chosen in such a way that the topographic effects of undulating terrain and hills would be minimum and negligible. An American paulin altimeter was used along with benchmarks, spot heights and topographic contours from the Survey of India toposheets for obtaining elevation at each measuring point. The data has been reduced using 2.67 gm/cc as the average density of crustal rocks in order to calculate the Bouguer anomalies. The overall accuracy of the presently obtained Bouguer gravity anomalies is of the order of $\pm$ 1 mGal making them suitable for analysing along with the marine gravity data for deep crust and tectonics. In the

Sl. No.	Location	HIG value mGal	CUSAT value mGal	Difference mGal
1	Pudukkad R.S.	978138.13	978138.07	0.06
2	Chalakudi	978134.65	978134.69	-0.04
3	Alwaye R.S.	978143.92	978142.38	1.54
4	Ettumannur R.S	-	978139.25	-
5	Kottayam T.B.	978148.19	978147.56	0.64
6	Chengannur R.S	-	978143.31	-

Table 5.1. Comparison of the gravity base values established by Hawaii Institute of Geophysics and reoccupied by CUSAT. Note that base values for Ettumannur R.S and Chengannur R.S. were not given in HIG volume by Woollard et al. (1969)

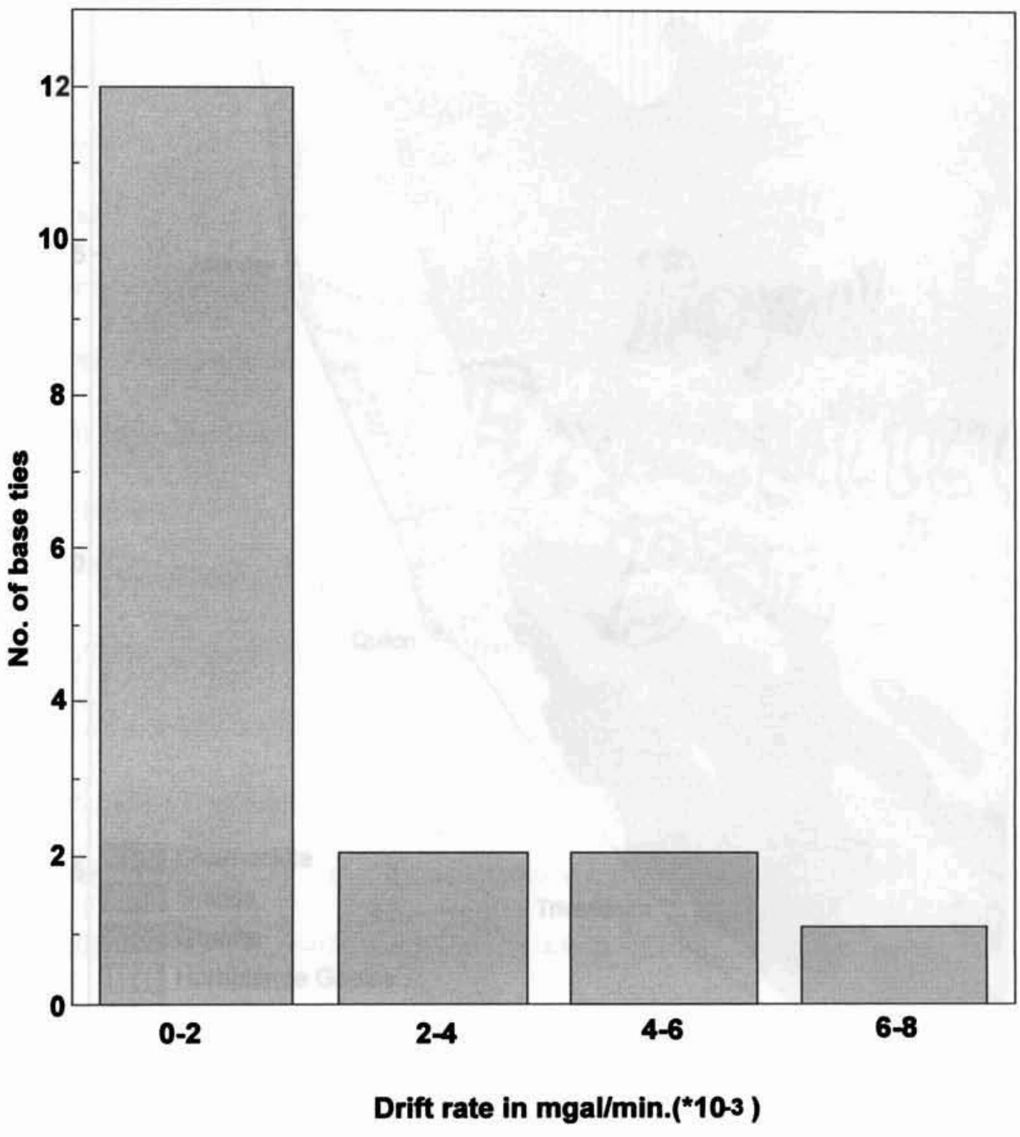


Figure 5.10 Histogram showing the number of base ties against dynamic drift during base establishment

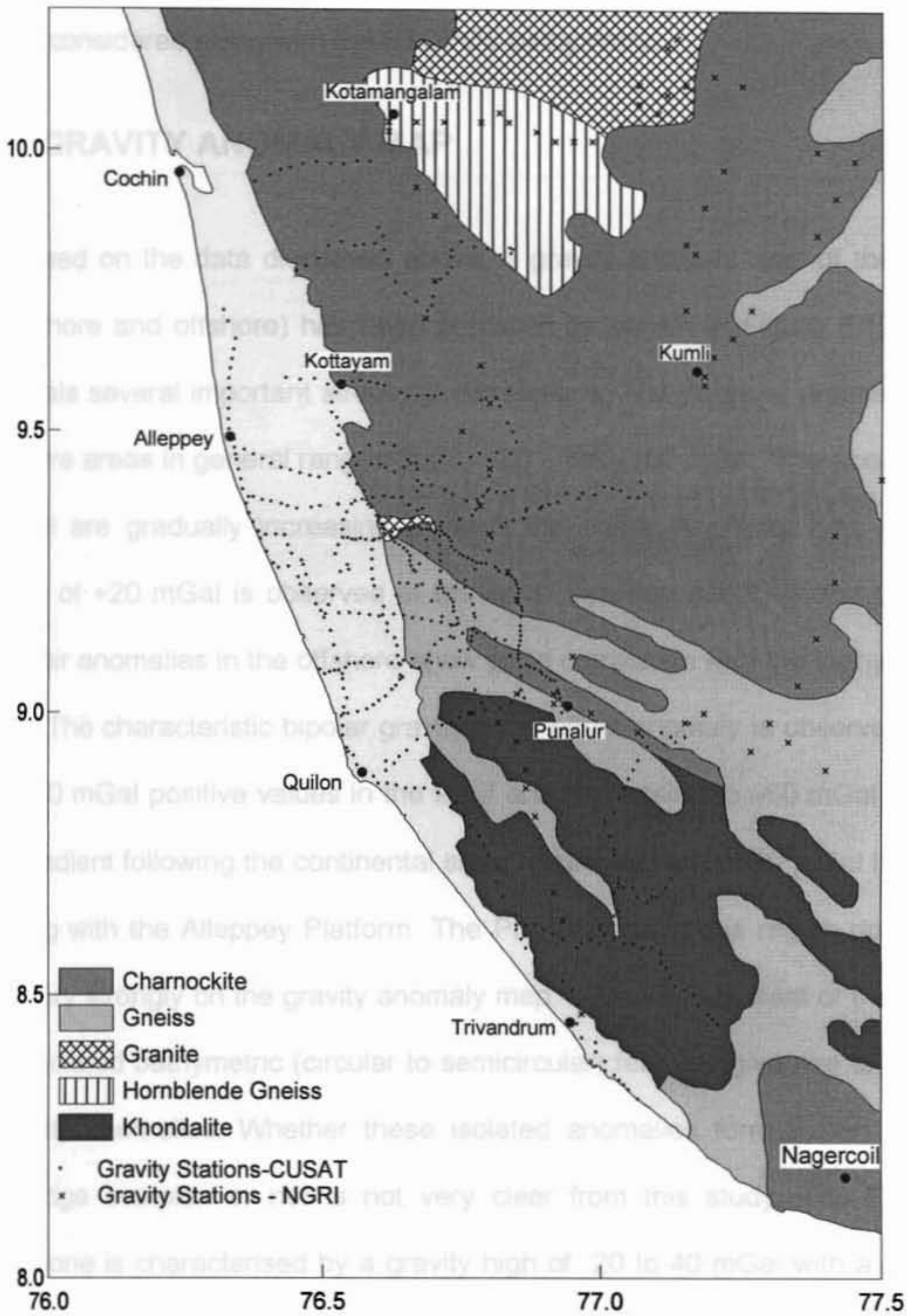


Figure 5.11 Map showing the distribution of gravity stations in the coastal Kerala and the adjoining shield area collected in the present study and also from NGRI (1981). Geology of the area is also shown.

offshore areas, the available GEOSAT gravity data (Sandwell and Smith, 1997) has been considered along with the ETOPO5 bathymetry.

5.4. GRAVITY ANOMALY MAP

Based on the data discussed above, a gravity anomaly map of the area (both onshore and offshore) has been prepared as shown in Figure 5.12. The map reveals several important structural correlations. The Bouguer anomalies in the onshore areas in general ranges from +20 to –100 mGal. The anomalies in general are gradually increasing towards the coast. A gravity high with a maximum of +20 mGal is observed at the coast between Alleppey and Quilon. The free air anomalies in the offshore show good correlation with the bathymetric features. The characteristic bipolar gravity edge effect anomaly is observed with +10 to +20 mGal positive values in the shelf and decreasing to –60 mGal with a strong gradient following the continental slope. A gravity high of 20 mGal is seen correlating with the Alleppey Platform. The Pratap ridge in this region does not appear very strongly on the gravity anomaly map. However, just east of the ridge several isolated bathymetric (circular to semicircular) features give rise to strong +ve gravity anomalies. Whether these isolated anomalies form a part of the Pratap ridge complex or not is not very clear from this study. The Chagos fracture zone is characterised by a gravity high of 20 to 40 mGal with a gravity low characterised by -50 mGal contour on either side. The anomalies in the Arabian basin, in general, vary from –40 to –50 mGal.

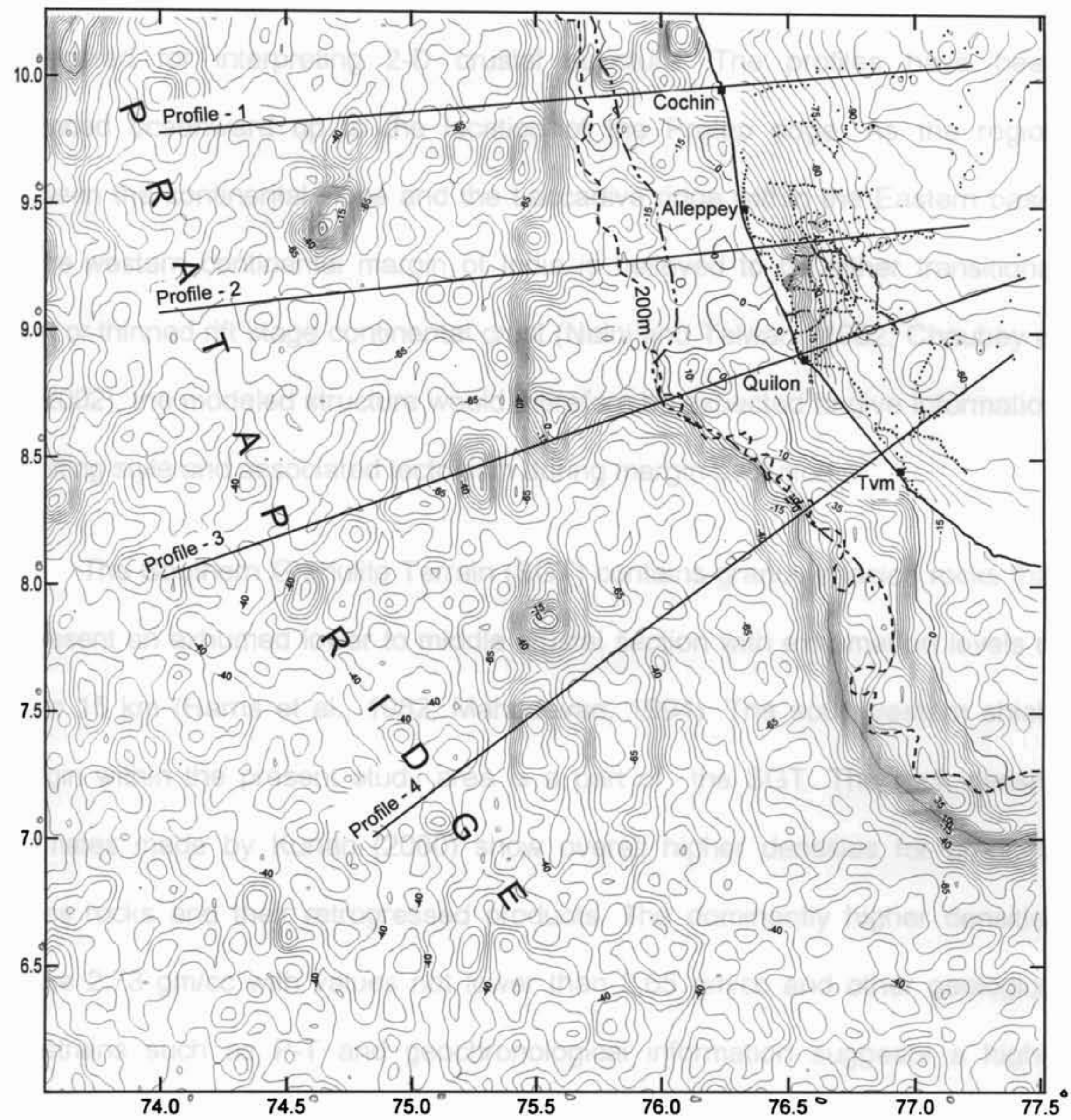


Figure 5.12 Gravity anomaly map of the Kerala basin and the surrounding area. Bouguer anomalies (contour interval : 5mGal) in the onshore and free air anomalies (contour interval : 5 mGal) in the offshore are shown. The thick lines indicate the location of four profiles (1-4) considered in the present study for gravity modeling. Tvm - Trivandrum. The present day shelf and the Miocene shelf edge has been indicated as dashed line in the offshore

5.5. GRAVITY MODELING

In the present study, gravity anomalies along four profiles (1-4) across the southwest continental margin of India covering the Kerala basin have been considered for interpreting 2-D crustal structure. The profiles have been extended oceanward up to the location of the Pratap ridge. As the region between the continental slope and the Laccadive ridge within the Eastern basin of the western continental margin of India is believed to be either transitional crust or thinned rift stage continental crust (Naini and Talwani, 1982; Chaubey et al., 2002), the modeled structure would therefore be expected to give information on rifting style and associated tectonism during margin evolution.

The Southern Granulite Terrain (SGT) contains granulite facies rocks that represent an exhumed lower to middle crustal section with exhumation levels of 10 to 15 km (Harris et al., 1982; Mahadevan, 1994). The southwestern shield margin within the present study area is a part of the SGT. The rock density estimates made by Kurian (2000) show overall higher densities for granulite facies rocks and their retrogressed products. The dominantly higher densities above 2.73 gm/cc with values not lower than 2.65 gm/cc and other geological constrains such as P-T and geochronological information suggests a highly exhumed crust. For the south Indian shield, Kaila and Bhatia (1981) generated a density profile along Kavali-Udipi DSS profile, where the deep lower crustal layer is of 2.85 gm/cc and the upper mantle has 3.3 gm/cc density. Considering the higher densities for granulite facies surface rocks in the region and the mid-to-lower crustal exhumation in the SGT, a generalized two-layer crustal density model for the SGT can be adopted as follows: an upper crustal layer having a density of 2.75 gm/cc (around 10 km), a lower crustal layer with a density of 2.85 gm/cc and the upper mantle with a density of 3.3 gm/cc. This two-layer density model for the crust is consistent with the simplified two-layer density model proposed for the SGT by Ramachandran (1992) based on velocity-density relations of major rock types.

The crustal thickness estimates were presented for the peninsular shield crust by Subba Rao (1987) based on gravity and Rai et al. (1993) based on seismic tomography. The thickness of the crust estimated by them along the southwest coast in the study area give rise to Moho depths of 35 – 37 km. A generalized thinning of the Moho towards the coast has been observed by both the workers. For the purpose of gravity modeling in the present study, Moho depth in the onshore regions has been adopted from the above data. Sediment thickness is also an important constraint in any gravity modeling of sedimentary basins. Bose et al. (1980) presented sediment thickness map of the coastal belt of Kerala based on detailed seismic refraction and electrical resistivity data. Their study reveal that the onshore part of the Kerala basin contains more than 600m of thick sediments in the deeper parts of the basin south of Alleppey. Based on the sediment facies distribution, Nair and Rao (1980) observed that the basin is divided into a southern and northern block by a NW trending line in the vicinity of Alleppey. In the offshore areas, sediment thickness information is available in the form of several published maps from (Naini and Kolla, 1982; Zutshi et al.,1995;

Balakrishnan, 1997). The generalised stratigraphy of sedimentary formations as revealed from the well data is presented in Table 5.2. These available information have been compiled to arrive at a composite basement configuration as shown in Figure 5.13. The basement data along the gravity profiles has been selected for modeling. Sediment thickness in general varies 3-5 km in the shelf region and 1-2 km in the deeper areas of the Kerala basin. Profile 1 covers northern part of the of the basin off Cochin, Profiles 2 and 3 in the central deep sedimentary part and Profile 4 passes through southern most part of the basin.

Apart form the effect of shallow sedimentaries, the gravity anomalies in the coastal and offshore areas are generated by deeper mass anomalies which include undulations in the crust-mantle boundary and the boundary separating upper part of the crust (2.75 gm/cc) from the lower part of the crust (2.85 gm/cc). However, both these boundaries cannot be arbitrarily changed unless and until the models are constrained by other geophysical data. In the absence of such data, in the present study, we adopted the following procedure. First, the crust-mantle boundary is modeled to fit the long wavelength anomalies and the remaining anomalies (shorter wavelength) have been explained by varying the density boundary within the crust.

5.6. GRAVITY MODELS AND IMPLICATIONS

The gravity derived crustal models have been presented along the four profiles (1-4) across the Kerala basin as shown in Figure 5.14. Since the basement along these profiles is seismically controlled, modeling mainly involved

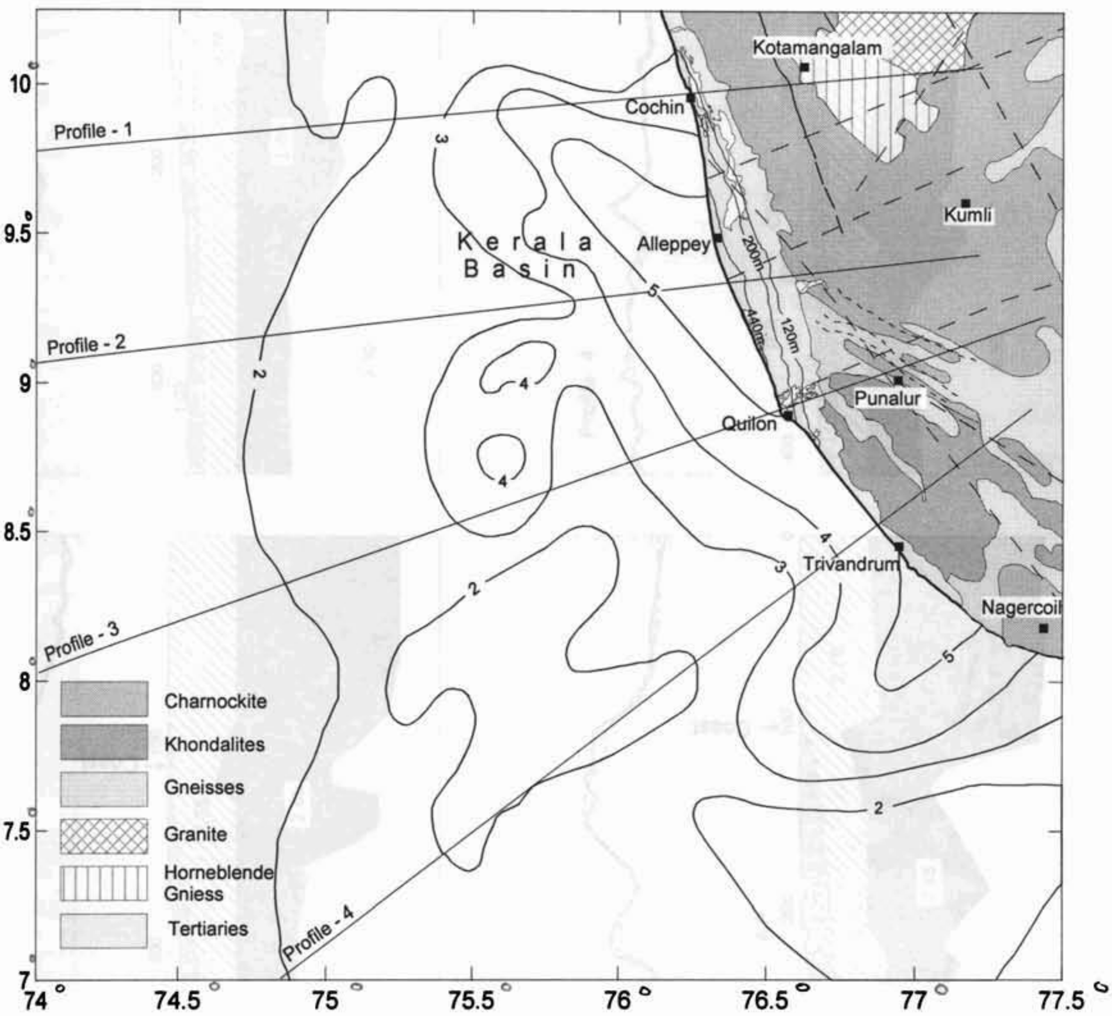


Figure 5.13 Contours showing sediment thickness in the Kerala basin region Details are discussed in the text. **Contour values are in kilometers**

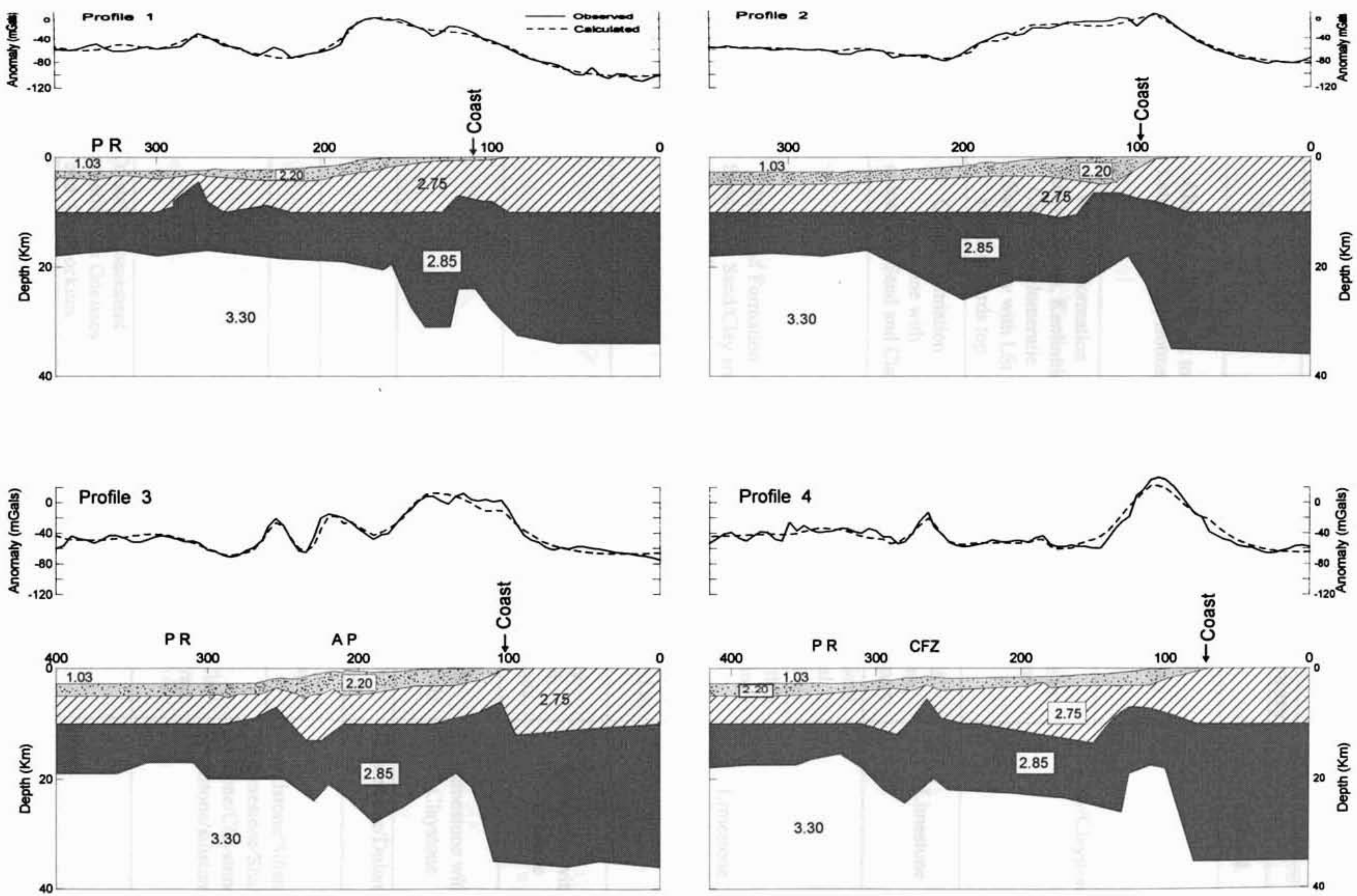


Figure 5.14 Gravity derived crustal models along four profiles (1-4) across the southwestern margin of India in the Kerala basin region. A. P - Alleppey platform; P. R - Pratap ridge; CFZ - Chagos Fracture Zone. Details are discussed in the text.

KERALA BASIN

Age	Onshore		Offshore K-1-1		Offshore CH-1-1
Pleistocene to Recent	Continental	Alluvial Clay, Black to Lateritic towards Bottom	Dominantly Coarse Sandstone		Clay/Claystone
Pliocene / Miocene Late	Continental	Warkalli Formation Arcose Sands, Kaolinitic Clay, Conglomeratic Sands, Shaly with LSt bands towards top	Shallow Marginal Marine	Dominantly fine to medium grained Sandstone	
Miocene Middle	Marine	Quilon Formation Limestone with calcareous Sand and Clay	Shallow Marginal Marine	Coarse grained, pebbly Sandstone, clayey in lower part	Limestone
Miocene Early	Continental to Deltaic	Mayanad Formation Sandstone, Sand/Clay and Peat	Shallow Marine	Clay/Sst alternations with occasional carbonaceous bands Carbonates with thin Sandstone and sandy Clay bands Sandstone with Clay bands and carbonaceous band in lower part	Limestone
Basal Miocene			Shallow Marginal Marine	Sandstone/Clay alternations with Lignitic Coal bands	Limestone with Claystone
Oligocene			Shallow Marine	Sandy Clays with thin carbonate bands	Limestone with Claystone
Eocene			Continental	Sandstone with Lignitic Coal bands Sandy Clay	Limestone/Dolomitic
Palaeocene			Continental	Clay/Shale, Trap derivatives	Sandstone/Siltstone Limestone/Shale Siltstone/Claystone Sandstone/siltstone/Sh
Mesozoiuc			Dominantly Fresh Water	Sandstone with Clay and weathered Trap	
Archean	Crystalline basement Garnetiferous Gneisses and Charnockites				

Table 5.2. Generalized stratigraphy of the Kerala basin as obtained from well data. Stratigraphy in the onshore adopted from Soman (1997) and in the offshore from Singh and Lal (1993)

variations in the upper crustal layer and the Moho. The models show that the crust, which is 35-36 km below the crystallines along the SW coast of India thins down to as much as 16 km in the deeper oceanic parts of the basin. Further, a steep rise in the Moho by 10 – 15 km is observed below the coast and shelf region. This rapid rise of the Moho is also associated with thinning of the upper crust seaward. Such characteristic crustal geometry across the rifted continental crust may possibly be an expression of the initial rift related faulting along the West Coast. The modeled Moho geometry based on the broad gravity anomalies in the four profiles studied here could be explained by invoking the southward extension of the West Coast fault (WCF) noticed by Balakrishnan (1977) based on gravity trends further north of the study area. However, possibilities of shearing movements through a system of transform faults in the NNE-SSW direction offsetting the primary faults oriented in NNW-SSE trend (cf. Ghosh and Zutshi, 1989; Dirghangi et al., 2000) render the picture of faulting more complex in the region. Therefore, more detailed and closer gravity data with better seismic constraints will be necessary before attempting to trace the primary rift related fault pattern in the region. In Profile-1, a gravity high of 30 mGal is observed right over the coast near Cochin. Similar gravity highs hugging the coast have been observed all along the western margin and interpreted either due to basic intrusions at depth (Takin, 1966) or due to the thinning of the crust (Chandrasekharam, 1985). In the deep oceanic areas, just east of the Pratap ridge, several minor topographic highs are associated with a gravity high of ~25 mGal. The models indicate that this could be due to local variations in the thickness of upper/lower crustal layers. As mentioned previously, whether these highs form part of the Pratap ridge complex or not is not clear. The gravity high observed over Alleppey platform, a distinct platformal feature in the outer shelf-slope region (Profiles 2 and 3) is explained as a minor basement high with variation in thickness of lower crustal layer characterized by a Moho rise below the platform. The Chagos Fracture Zone (CFZ) which separates the Chagos Laccadive Ridge from the Chagos basin is seen as a high at both upper crustal as well as Moho level with a steep Moho gradient (Profile 4) on its western flank. It is interesting to note that the Alleppey platform which appear as a northern continuation of the CFZ at the margin also displays similar crustal geometry (Profile 3). It has been suggested that northward motion of India has mainly taken up along the CFZ in the west and ninety east fracture zone in the east (Mckenzie and Sclater, 1971).The counterclockwise rotation of the Indian subcontinent during the early Tertiary period might have terminated the CFZ at the margin near Alleppey Platform (Singh and Lal, 1993). Subsequently, the motion along the CFZ also slowed down rapidly after the collision of Indian plate with Eurasian plate (McKenzie and Sclater, 1971) which might have resulted in extensive deposition of carbonate sequences over the Alleppey platform, causing the present day crustal geometry of this platformal structural feature.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The eastern Arabian Sea is the deep oceanic part of the western continental margin of India (WCMI). The region comprises of several surface / subsurface structural features which include the Chagos – Laccadive ridge(CLR), Laxmi ridge, Pratap ridge and a belt of numerous horst – graben structures in the sediment filled basins bordering the west coast of India. The Chagos Laccadive Ridge and Laxmi ridges divide the eastern Arabian sea into two provinces the Western and Eastern basins. While it is widely agreed that the Western basin is underlain by oceanic crust, the nature of crust below Eastern basin is debated. Many previous workers suggested that the Eastern basin is characterised by thick transitional rift stage crust extending as far as the Laxmi and Laccadive ridge region, some of them observed extension of Precambrian continental tectonic trends into deep oceanic areas of the Arabian Sea. The observed structural features have essentially evolved as a consequence of rifting and sea-floor spreading between India, Madagascar and Seychelles.

In order to understand the rifting style, basement tectonics and early evolutionary history of the margin, it would be useful to integrate the geophysical data in the onshore as well as offshore along various segments of the margin. The main objective of the present study is to model the gravity field in terms of lithosphere structure below the WCMI, identify zones of crustal mass anomalies and other rift related features across the margin. The vast amount of seismic reflection and refraction data in the form of crustal velocities, basement configuration and crustal thickness available for the west coast as well as the eastern Arabian Sea have been utilised. For this purpose, such integration of onshore and offshore data along the margin is expected to generate more realistic models on structural styles and processes of crustal rifting along various segments of the margin which can be interpreted in the overall realm of geodynamics of the region.

For interpretation of gravity anomalies in terms of crustal mass anomalies, surface rock density as well as crustal density data are essential. For this purpose, the crustal seismic velocities are useful to infer densities of deeper layers, whereas, the direct determination of surface rock densities are useful to infer the density of upper crustal layer. The seismic data along the WCMI and deep oceanic parts of the Arabian Sea include the wide angle reflection and refraction stations collected by various national and international agencies. For the West Coast of India, such deeper information on crust / mantle structure is available from refraction Deep Seismic Sounding profiles collected by the National Geophysical Research Institute.

The seismic data in the oceanic areas indicate that in sedimentary layers the velocities in general vary from 1.7 km/sec for top unlithified sediments to 4.9 km/sec for deeper layers above the acoustic basement. The velocities in the range of 4.0 – 4.9 km/sec observed mainly in the Eastern basin and Laxmi ridge region have been inferred as due to basal sedimentary layers related to early rifting. The acoustic basement can be inferred at a velocity of 5.0 km/sec. The crustal layers show a range of velocities between 5.2 – 7.3 km/sec (with predominantly 6.2 – 6.4 km/sec values). At few refraction stations in the Laxmi basin and Laxmi ridge, velocities >7.0 km/sec are observed in the lower crust. Moho velocities of 7.9 – 8.3 km/sec have been observed at several locations in the region at an average Moho depth of 11.5 km. The seismic data clearly indicate that the western basin is underlain by oceanic crust with Moho at 11-13km depth. Velocities observed along the Laxmi ridge indicate the continental affinity of the ridge, but, the nature of crust below the Laxmi basin is ambiguous from velocity data.

The DSS investigations in the western Indian shield bring out a clear picture regarding unstretched continental crust and the later rifting features. The inferences from DSS studies are: i) Deccan traps having velocities of 4.5 – 5.5 km/sec with a maximum thickness of 2.0 km underlain by Mesozoic sediments (velocities 4.0 km/sec) in Saurashtra; ii.) a two layered continental crust with a variable upper crustal thickness of about 10 – 20 km characterised by velocities of 5.8 – 6.5 km/sec, and a lower crust with velocities of 6.6 – 6.9 km/sec, with Moho observed at a depth of 38 – 42 km in the shield regions; iii.) general shallowing of Moho towards the coast; iv.) higher lower crustal velocities at 23 – 25 km depth and a shallow Moho at a depth of 31 – 33 km below Cambay rift basin; v.) transitional Moho and low velocity layers in the Koyna region; and vi.) continental type of crust beneath Saurashtra Peninsula.

The seismic information discussed above has been used to infer the density configuration for the continental as well as the oceanic crust based on the Nafe-Drake velocity-density relationship. In the oceanic areas, the 1.7 – 2.8

km/sec (density of 2.1 g/cm^3) and 2.9 – 5.0 km/sec (density of 2.3 g/cm^3) for shallow and deeper sediments were assigned a uniform value of 2.2 g/cm^3 for the sedimentary layer. A two layered oceanic crust of 2.66 g/cm^3 for the top part (5.1 – 6.3 km/sec velocities) and 2.90 g/cm^3 for the bottom layer (6.4 – 7.0 km/sec velocities) has been assigned. A uniform value of 3.3 g/cm^3 for the lithospheric mantle and 3.2 g/cm^3 for the Asthenosphere have been assumed. The velocity-density correlation of DSS in the western Indian shield margin gives rise to, a density value of 2.67 g/cm^3 for the upper crust (5.8 – 6.5 km/sec), 2.85 g/cm^3 for the lower crust (6.6 – 6.9 g/cm^3), 2.80 g/cm^3 for the Deccan traps, 2.40 g/cm^3 for sediments in the Cambay basin and the Mesozoic sediments lying below the Deccan traps. A density of 3.0 g/cm^3 has been assumed for the high velocity layer (7.1 – 7.4 km/sec) in the lower crust. However, the crust in the western Indian Shield south of 13 ^{0} N is characterised by exhumed lower to middle crustal rocks which would imply that top crustal layers in this region have higher densities than the rest of the shield. Therefore, an average density value of 2.75 g/cm^3 for the exhumed mid-lower crustal layer in the SGT has been inferred.

A revised gravity anomaly map considering free-air anomalies (GEOSAT data) in the oceanic areas and Bouguer anomalies in the land area has been prepared in order to understand nature of gravity field in the region. The map shows that except in the inner shelf region, free – air anomalies are in general negative ranging from -10 to -60 mGal in the whole of eastern Arabian Sea. The bipolar edge effect anomaly i.e. a gravity high of +20 to +40 mGal in the inner shelf region and a low of as much as –60 mGal in the slope can be seen all along the western margin, except between 12^0 - 16^0 N, the gravity field seems disturbed perhaps due to the presence of several basement ridges and isolated bathymetric features. The subdued and broadly varying gravity field of –20 to –40 mGal in the southwestern part of the map is found to increase sharply on the CLR to as much as +10 mGal. In the northwestern part, the deep Arabian Sea region is characterised by positive and negative anomaly belts. A NW- SE trending gravity low of more than –40 mGal correlates well with the Laxmi ridge.

The Bouguer anomalies over the western Indian shield margin range between –20 to –120 mGal and is characterised by a westward gravity high gradient zone striking N-S all along the coast, a gravity high in the Cambay rift basin and several isolated gravity highs hugging the coast at many places. The isolated coastal gravity highs have been inferred either due to large basic intrusives at depth or localised thinning of the crust.

Four uniformly spaced regional gravity traverses and the available seismic data across the WCMI, starting from the western Indian shield extending into the deep oceanic areas of the eastern Arabian Sea, have been utilized to delineate the lithospheric structure. The seismically constrained gravity models along these four traverses suggest that the crustal structure below the northern part of the margin within the Deccan Volcanic Province (DVP) is significantly different from the margin outside the DVP. This difference could be due to the fact that the lithosphere experienced multiple rifting episodes and massive Deccan volcanism in the north. The lithosphere thickness, in general, varies from 110 – 120 km in the central and southern part of the margin to as much as 85 – 90 km below the Deccan Plateau and Cambay rift basin in the north. The Eastern basin is characterised by thinned rift stage continental crust which extends as far as Laxmi basin in the north and the Laccadive ridge in the south. At the ocean – continent transition (OCT), crustal density differences between the Laxmi ridge and the Laxmi basin are not sufficient to distinguish continental as against an oceanic crust through gravity modeling. However, 5-6 km thick oceanic crust below the Laxmi basin is a consistent gravity option. Significantly, the models indicate the presence of a high density layer of 3.0 g/cm^3 in the lower crust in almost whole of the northern part of the region between the Laxmi ridge and the pericontinental northwest shield region in the DVP, and also below Laccadive ridge in the southern part. The Laxmi ridge is underlain by continental crust upto a depth of 11 km and a thick high density material (3.0 g/cm^3) between 11 – 26 km. The Pratap ridge is indicated as a shallow basement high in the upper part of the crust formed during rifting. The 15 –17 km thick oceanic crust below Laccadive ridge is seen further thickened by high density underplated material down to Moho depths of 24 – 25 km which indicate formation of the ridge along Reunion hotspot trace. The large variations in the lithosphere thickness and wide spread occurrence of under plated material in the lower crust in the DVP give rise to substantial density inhomogeneities which may accentuate the stress field within DVP giving rise to enhanced seismic activity in the region.

The WCMI is divided into five major sedimentary basins bounded by NE-SW trending basement arches. These basins have been developed during the rifting and sea-floor spreading between India, Madagascar and Seychelles. For detailed basin scale modeling on rift tectonics involving both onshore and offshore areas, close spaced data in the coastal areas is necessary. For this purpose, the Kerala basin covering both offshore as well as the coastal Kerala region has been considered for detailed data acquisition and interpretation in terms of crustal modeling. The data acquisition include establishment of 28 permanent gravity base stations and nearly 600 gravity measurement points in the coastal areas. A composite gravity anomaly map covering both onshore and offshore parts of the Kerala basin reveal several important structural correlations. The Bouguer anomalies in the onshore areas in general ranges from +20 to –100 mGal. The anomalies in general are gradually increasing towards the coast. A gravity high with a maximum of +20 mGal is observed at the coast between Alleppey and Quilon. The free air anomalies in the offshore show good correlation with the bathymetric features. The characteristic bipolar gravity edge effect anomaly is observed with +10 to +20 mGal positive values in the shelf and decreasing to –60 mGal with a strong gradient following the continental slope. A gravity high of 20 mGal is seen correlating with the Alleppey Platform. The Pratap ridge in this region does not appear very strongly on the gravity anomaly map. However, just east of the ridge several isolated bathymetric (circular to semicircular) features give rise to strong +ve gravity anomalies. Whether these isolated anomalies form a part of the Pratap ridge complex or not, is not very clear from this study. The

Chagos fracture zone is characterised by a gravity high of 20 to 40 mGal with a gravity low characterised by -50 mGal contour on either side. The anomalies in the Arabian basin, in general, vary from -40 to -50 mGal.

Gravity anomalies along four profiles across the Kerala basin have been considered for interpreting 2-D crustal structure. The models show that the crust, which is 35-36 km below the crystallines along the SW coast of India thins down to as much as 16 km in the deeper oceanic parts of the basin. Further, a steep rise in the Moho by 10 – 15 km is observed below the coast and shelf region. This rapid rise of the Moho is also associated with thinning of the crust seaward. Such characteristic crustal geometry across the rifted continental crust may possibly be an expression of the initial rift related faulting along the West Coast. The modeled Moho geometry based on the broad gravity anomalies in the four profiles studied here could be explained by invoking the southward extension of the West Coast fault (WCF). However, possibilities of shearing movements through a system of transform faults in the NNE-SSW direction offsetting the primary faults oriented in NNW-SSE trend render the picture of faulting more complex in the region. Therefore, more detailed and closer gravity data with better seismic constraints will be necessary before attempting to trace the primary rift related fault pattern in the region. The gravity high observed over Alleppey platform, a distinct platformal feature in the outer shelf-slope region is explained as a minor basement high with variation in thickness of lower crustal layer characterized by a Moho rise below the platform. The Chagos Fracture Zone (CFZ) which separates the Chagos Laccadive Ridge from the Chagos basin is seen as a high at both upper crustal as well as Moho level with a steep Moho gradient on its western flank. The counterclockwise rotation of the Indian subcontinent during the early Tertiary period might have terminated the CFZ at the margin near Alleppey Platform. Subsequently, the motion along the CFZ also slowed down rapidly after the collision of Indian plate with Eurasian plate which might have resulted in extensive deposition of carbonate sequences over the Alleppey platform, causing the present day crustal geometry of this platformal structural feature.

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