Seismic reflection and bathymetric study over deep offshore regions off the central west coast of India

Thesis submitted to

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For the Degree of

DOCTOR OF PHILOSOPHY

in

Geology

by

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M.Sc

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Certified that all the corrections have been incorporated in the thesis

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to

mother,
brother &
hassan naseem siddiquie (HNS)

who continue to inspire me even in their physical absence……..

STATEMENT

As required by the University Ordinance 0.19.8 (ii), I state that the present thesis entitled " ***Seismic reflection and bathymetric study over deep offshore regions off the central west coast of India*** " is my original contribution and same has not been submitted on any previous occasion for any other degree or Diploma of this University or any other University/Institute. To the best of my knowledge, the present study is the first comprehensive work of its kind from the area mentioned. The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

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CERTIFICATE

As required by the University Ordinance 0.19.8 (vi), this is to certify that the thesis entitled "***Seismic reflection and bathymetric study over deep offshore regions off the central west coast of India*** " submitted by **Mr. K. Srinivas** for the award of the degree of Doctorate of Philosophy in Geology is based on the original and independent work carried out by him during the period of study under our supervision.

The thesis or any part thereof has not been previously submitted for any other Degree or Diploma in any University or Institute. The material obtained from other sources has been duly acknowledged.

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PREFACE

Indian Ocean was formed as a result of fragmentation and dispersal of various continental blocks of the super continental assemblage of Gondwanaland. The Arabian Sea and the Bay of Bengal region which borders Indian mainland is part of this Indian Ocean. The various geo-scientific studies carried out since 1960s in the Indian Ocean region have enabled development of its broad evolutionary history. However, many geological complexities of this area, particularly the early opening history of various ocean basins remains inadequately understood. Scarcity of detailed studies particularly pertaining to the structure, tectonics and evolution of the bordering continental margins appear to be one of the reasons for this knowledge gap, the geological complexity may be the other reason.

In the Arabian Sea, the Arabian and its conjugate eastern Somali Basins are believed to have been formed by seafloor spreading process along Carlsberg Ridge since early Tertiary time. According to this model, in the deep offshore regions off western India, the Laxmi and Laccadive Ridges broadly mark the shoreward boundary of this early Tertiary Oceanic crust. However, there exists a deep offshore region between Laxmi-Laccadive Ridges and the continental slope of western India whose genesis and evolution remains to be confidently established.

The present study deals with a sector of continental slope, rise and deep offshore region between Laxmi-Laccadive Ridges off the central west coast of India. Broadly the study covers major portion of the Laxmi Basin, northern extremity of submarine Laccadive Plateau and the southeastern part of the Laxmi Ridge. The aim of the study is to obtain various constraints from physiography, basement structure and disposition of sedimentary overburden which may help in improving our understanding of the evolutionary history of this area.

About 49000 km of conventional bathymetry data, about 2800 km of seismic reflection data forms the main data set for this study. In addition, some published swath-bathymetric data have also been used to supplement the conventional bathymetric data. The main contents of the study are presented in seven chapters in the following manner.

Chapter 1 briefly presents the broad evolutionary history of the Indian Ocean in general and Arabian Sea region in particular while introducing the geographical entity of the study area along with objectives and scope of the present study.

Chapter 2 presents a review of pertinent previous publications over and adjacent to the study area and synthesis the available knowledge about the structure, tectonics and overall geological framework of the western Indian offshore in general and the study area in particular. Further this chapter also presents a brief account of various proposed models about the genesis and evolution of the study area.

Chapter 3 presents a brief description of the types of data used for the present study and methodology adopted for their interpretation. The description of methodology adopted for interpretation includes processing, interpretation of data and presentation of various interpretative figures.

Chapter 4 deals with analyses of bathymetric data presented in the form of sections and contour maps. The updated bathymetric contour map was prepared by including the available conventional bathymetric data as well as detailed swath-bathymetric data over four seamounts within the study area. The bathymetric data allowed mapping the extent and trend of physiographic features over larger aerial extent, and also in inferring some tectonic clues.

Chapter 5 deals with the analyses of seismic reflection data. The interpreted seismic data are presented in the form of line drawing sections and contour maps. The observed basement features and sedimentary units in terms of acoustic stratigraphy have been described along each line. The aerial extent and interrelationship of various basement and sedimentary features have been described using depth to the basement map, structural trends map and isopachs of identified sedimentary units.

Chapter 6 presents the interpretation of integrated bathymetric and seismic reflection data with an aim to understand the basement tectonics and depositional pattern of sedimentary units to provide new information for a better understanding of the evolution of the study area.

Chapter 7 presents a summary of the study and highlights the important results obtained from the study. This chapter further includes some suggestions for further studies.

Finally a detailed list of references cited in the text. The references quoted are arranged in alphabetical order and is included at the end of the thesis.

CHAPTER 1

Chapter – 1

GENERAL BACKGROUND

1.1 Introduction

The Indian mainland is bordered by the Arabian Sea in the west and the Bay of Bengal in the east. These two seas are part of the western and eastern regions of the Indian Ocean (Fig.1.1) respectively. The geographic limits of the Indian Ocean are Iran, Pakistan, India and Bangladesh in the north; Arabia and Africa in the west; Australia, Sunda subduction zone, Malaysian peninsula and Thailand in the east and the Antarctic continent in the south. The broad features of the Indian Ocean could be identified based on various geoscientific studies carried out during the International Indian Ocean Expedition (IIOE) in 1960s. The main physiographic features of the Indian Ocean region (Fig.1.1) are the active mid-oceanic ridge system, aseismic ridges, submarine plateaus, seamounts, islands, subduction zones and continental fragments. These features and the surrounding continents divide the Indian Ocean area into number of deep sea basins. The two largest deep sea fans - Indus cone and Bengal fan are also located in this ocean. Identification of these features and paleo-geographic reconstruction of surrounding continents allowed several workers to propose broad evolutionary history of the Indian Ocean in terms of plate tectonic and seafloor spreading framework. The broad understanding (McKenzie and Sclater, 1971; Norton and Sclater, 1979; Besse and Courtillot, 1988; Scotese et al., 1988) in this regard is that the Indian Ocean area evolved as a result of fragmentation and dispersal of the super

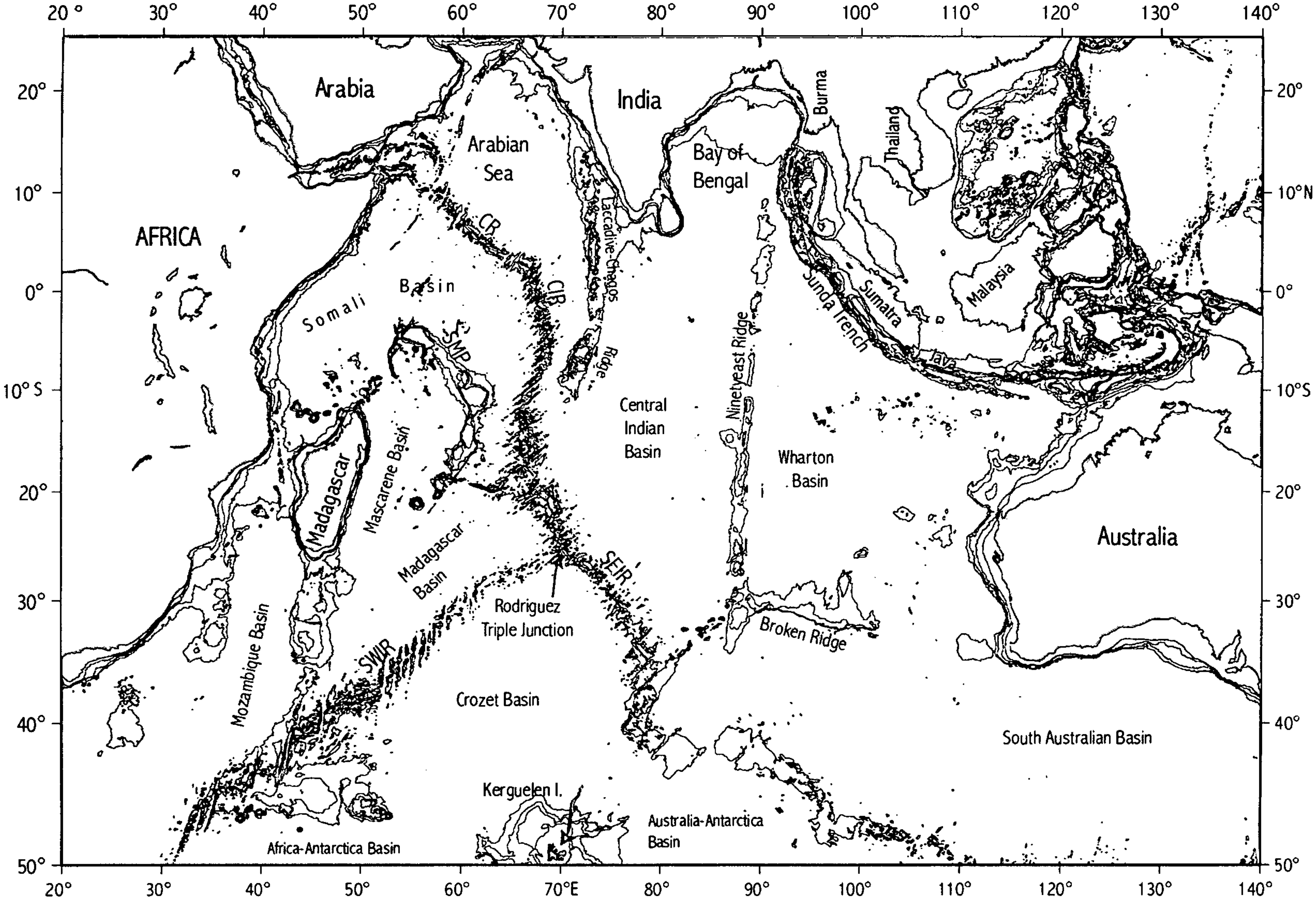


Fig. 1.1 Generalized physiography of the Indian Ocean along with selected (200 m, 1000 m, 2000 m and 3000 m) bathymetric contours. CR: Carlsberg Ridge; CIR: Central Indian Ridge; SEIR: Southeast Indian Ridge; SWIR: Southwest Indian Ridge; SMP: Seychelles-Mascarene Plateau.

continental assemblage of Gondwanaland, particularly the northward drift of India. However, the early opening history in the evolution of the Indian Ocean region is not yet fully unraveled. Key to understand this history appears to lie in the continental margins and adjacent deep sea basins surrounding the continents. The geological complexities and inadequate data may be the main hindrance to bridge this knowledge gap. The present study deals with a sector of continental margins and deep sea regions of the Indian Ocean which lies off the west coast of India and aims to enhance the knowledge about the structure and tectonics of the region.

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

1.2 Study area

The most prominent bathymetric features of the continental margin and deep sea regions adjacent to the west coast of India are the Laccadive-Chagos Ridge and the Laxmi Ridge. The intervening regions between these ridges and the continental shelf off India are identified as number of deep sea basins such as the Laccadive Basin, the Laxmi Basin and the Offshore Indus Basin. Westwards of these ridges lies the Arabian Basin. In context of this framework, the study area

(Fig. 1.2) broadly spans over a part of the continental slope and rise regions off the central west coast of India and covers a major portion of the Laxmi Basin, the northern extremity of Laccadive-Chagos Ridge, southern part of the Laxmi Ridge and the eastern fringes of the Arabian Basin. The study area assumes significance in the context of evolution of offshore regions off western India, as it appears to be a region of convergence of number of prominent but varied tectonic features, whose genesis and evolution yet remain to be well understood. Detailed description of these features along with different views regarding their genesis is presented in Chapter-2.

1.3 Objective and scope of the study

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

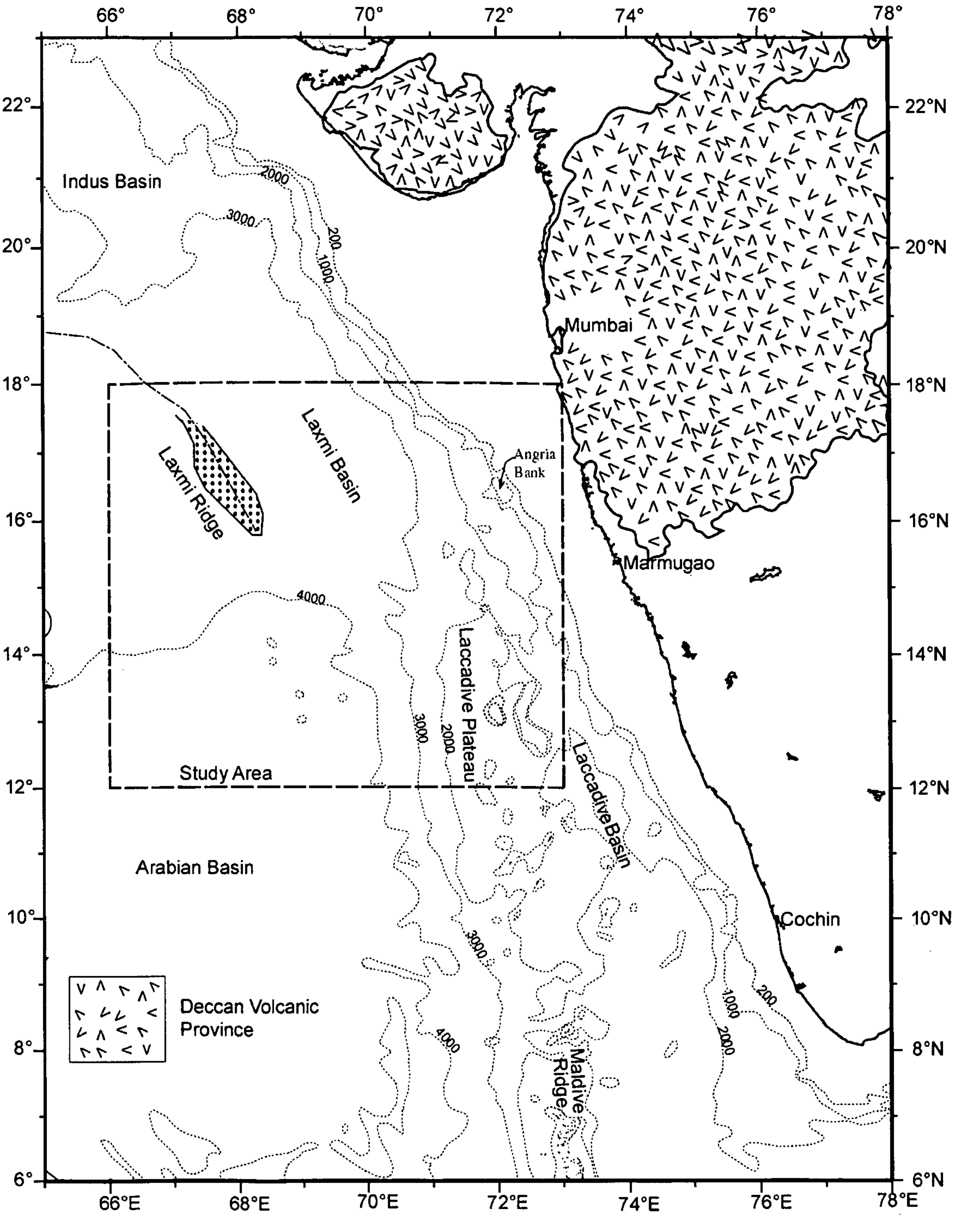


Fig. 1.2 Location of the study area.

1.4 Main features of the Western Indian Ocean

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

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

1.4.1 *Mid-oceanic ridge system*

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

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

1.4.2 *Submarine plateaus and aseismic ridges*

The Western Indian Ocean contains a number of topographic features (Fig.1.3), which protrude high above the ocean floor. Many of the features are elongated and wholly submarine, but few rise above sea level and emerge as islands. The main submarine plateaus are, the Agulhas Plateau, the Madagascar

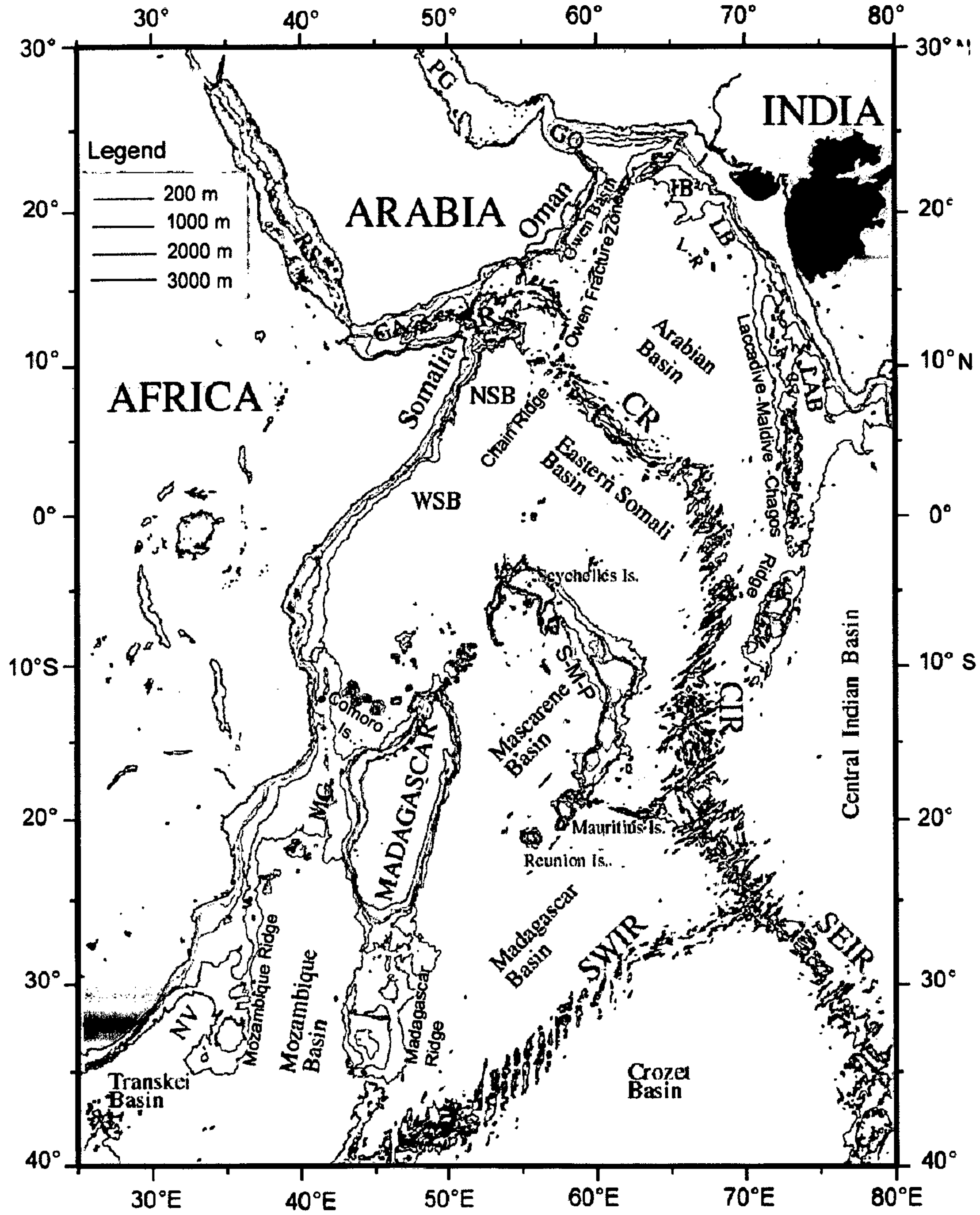


Fig. 1.3 Locations of major ocean basins and other physiographic features of the Western Indian Ocean along with selected bathymetric contours. NV: Natal Valley; MC: Mozambique Channel; WSB: Western Somali Basin; NSB: Northern Somali Basin; IB: Indus Basin; L-R: Laxmi Ridge; LB: Laxmi Basin; LAB: Laccadive Basin; SR: Sheba Ridge; CR: Carlsberg Ridge; CIR: Central Indian Ridge; SEIR: Southeast Indian Ridge; SWIR: Southwest Indian Ridge. PG: Persian Gulf; GA: Gulf of Aden; RS: Red Sea; GO: Gulf of Oman.

Ridge, the Mozambique Ridge, the Laxmi Ridge, the Laccadive-Chagos Ridge and the Seychelles-Mascarene Plateau.

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

1.4.3 *Seamounts*

Very few of the several seamounts (Fig.1.1) in the Western Indian Ocean area have been systematically studied and published information is meagre. Prominent among these seamounts are the Error seamount, Sagar Kanya seamount and a chain of seamounts located in the axial part of the Laxmi Basin (Bhattacharya and Chaubey, 2001). The Error seamount (Mathews, 1966; Ramana et al., 1987) is located approximately at the northwestern boundary of the

Carlsberg Ridge and appears to be a part of the system of features which constitute the Owen Fracture Zone. The Sagar Kanya seamount (Bhattacharya and Subrahmanyam, 1991) is a 2464 m high edifice located about 200 km west of the Laccadive Plateau. The Laxmi Basin seamount chain is located approximately in the axial part of the Laxmi basin (Bhattacharya et al., 1994b) and consists of the Raman Seamount, the Panikkar Seamount and the Wadia Guyot. This linear seamount chain is about 250 km long and trends nearly N30°W.

1.4.4 *Deep sea basins*

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

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

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

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

1.5 Broad evolutionary history of the Western Indian Ocean

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

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

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

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

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

Stage 3: Following separation of Madagascar-Seychelles-India block from Antarctica-Australia, the spreading of seafloor continued in a uniform fashion for about 15 My. Later, the spreading between Africa-Arabia and Madagascar-Seychelles-India blocks experienced change. The Madagascar-Seychelles-India block possibly came over the location of the Marion Hotspot around 88 Ma. Due to

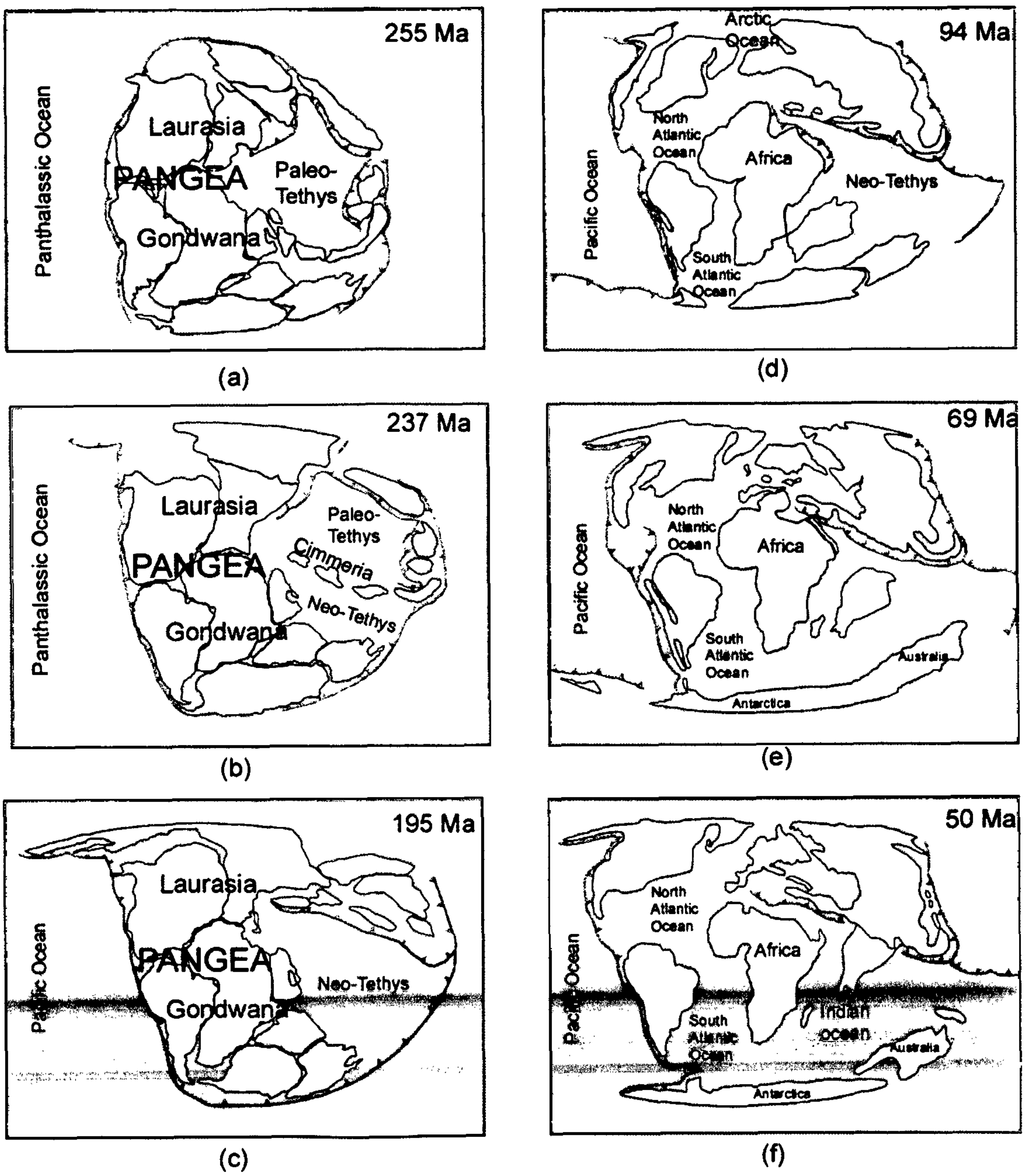


Fig.1.4 Cartoons depicting fragmentation and dispersal of PANGEA supercontinent since Late Permian. a) Late Permian (255 Ma), b) Middle Triassic (237 Ma), c) Early Jurassic (195 Ma); d) Mid-Cretaceous (94 Ma); e) Latest Cretaceous (94 Ma); and f) Eocene (50 Ma). Modified after Scotese (1997).

the influence of this hotspot, rifting was initiated and around 84 Ma (anomaly 34) due to seafloor spreading, the Madagascar separated from Seychelles-India block and got welded to the African Plate. This separation resulted in opening of the Mascarene and Madagascar Basins and establishment of a three plate system with a triple junction in the Western Indian Ocean. Most importantly this event probably marked the beginning of the tectonic events which resulted in shaping the present day deep offshore regions off the west coast of India. After separation, Seychelles-India block continued northward drift, and at the same time experienced a gradual anti-clockwise rotation.

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

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

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

active and continue to accrete the Arabian and Eastern Somali basins at a rate of about 1.2 cm/year.

CHAPTER 2

Chapter – 2

GEOLOGICAL FRAMEWORK

2.1 Introduction

The continental margin and adjacent deep offshore regions off west coast of India have evolved by rifting and drifting of India away from Madagascar and Seychelles. The present day geological scenario of the deep offshore region off west coast of India, thus, is a consequence of this rift, drift and subsequent tectonic and sedimentary evolution. Various studies carried out in this area have unraveled several structural and sedimentary features and allowed proposing various models of evolution. In order to be able to interpret the results of the present study, which covers a segment of this deep offshore region, in a broader geological perspective, available information about structure and tectonics of various features in and around the study area have been collated in this chapter. Further, as the western continental margin of India was classified as a passive continental margin (Biswas, 1982, 1987), therefore in order to appreciate the passive continental margin setting, a brief account of the concept of continental margin in general and passive continental margin in particular have also been presented in this chapter.

2.2 Prominent features in and around the study area

Marine geoscientific investigations on the continental shelf, slope and deep offshore regions off west coast of India have so far revealed the existence of several physiographic, sedimentary and basement features. Many parts of the continental shelf have been investigated in detail in connection with hydrocarbon exploration but most of these results are not available in public domain, whereas, not much studies were carried out in the deep offshore regions. The features described below are regional features and information about them is based on literature available in public domain.

2.2.1. *Features on the western part of the Indian mainland*

The geological formations on the western part of Indian mainland range in age from Archaean to Recent. Archaean formations, which are the oldest, consists of gneisses (~2600-2950 Ma), granulites, schists and supracrustals (~2900-3200 Ma), occur between Cape Comorin and Kasargod. Between Kasargod and north of Goa, the Dharwarian meta-sedimentary formations (~2100-2950 Ma) appear to overlie the Archaean basement and predominate the geological formations (Radhakrishna and Vasudev, 1977).

A major portion of the deeper geology of western India lie hidden under the Deccan Traps (Fig 2.1) which are one of the largest known continental flood basalt (CFB) provinces on the earth. The Deccan Trap CFB extend over nearly 500,000 sq. km and lie flat as horizontal sheets and are believed to have erupted sub-aerially through fissures in the earth's crust (Kumar, 1986). A large thermal anomaly, generated by a deep mantle plume (Reunion Hotspot) is commonly postulated to explain the genesis of the Deccan Trap CFB event (Morgan, 1972, 1981; Courtillot et al., 1986; White and McKenzie, 1989; Duncan, 1990; Baksi and Farrar, 1991; Basu et al., 1993). The timing and duration of this volcanic

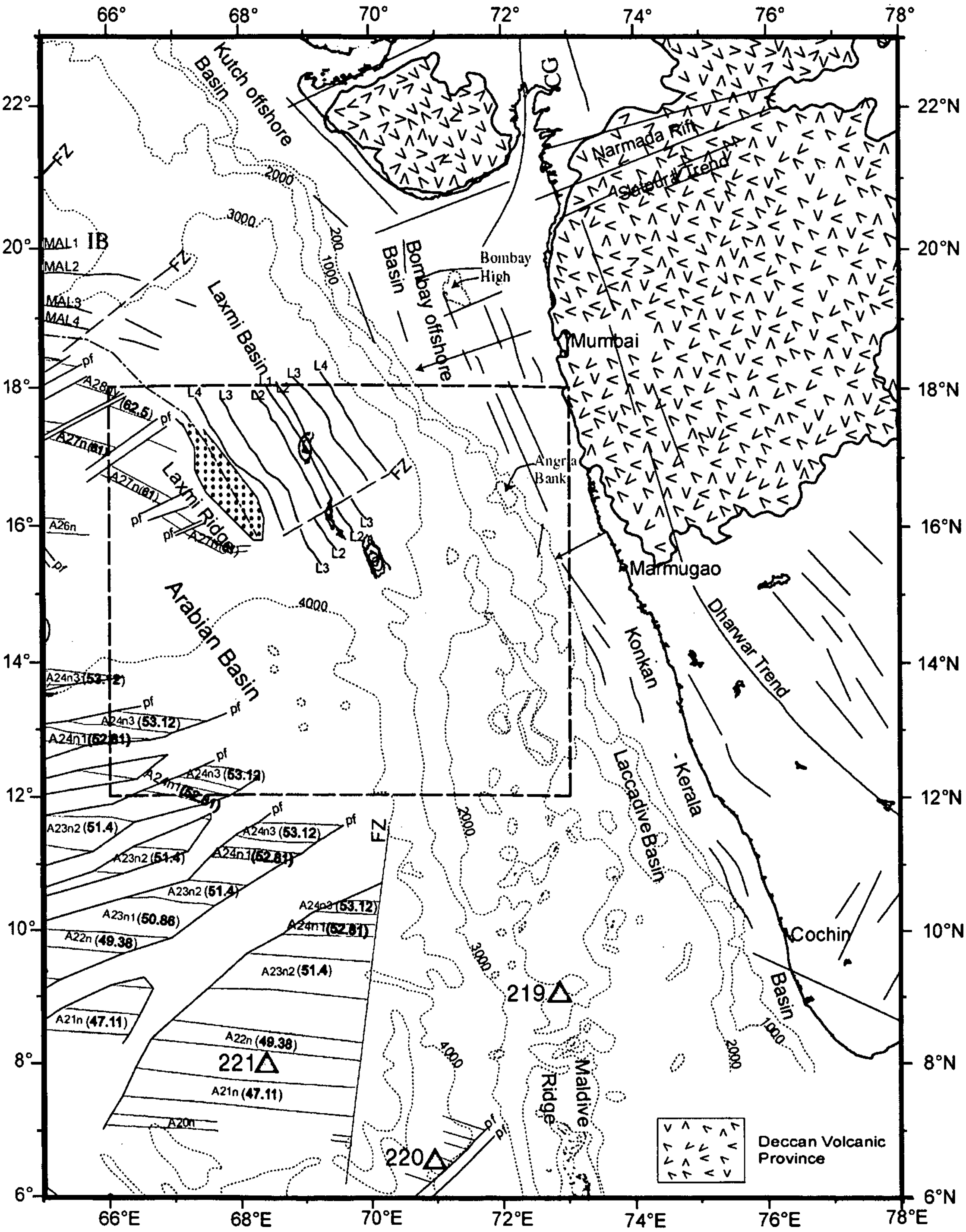


Fig. 2.1 Major structural and tectonic trends within and adjacent to the study area (box). Thin dotted lines are selected bathymetric contours (in meters). Solid annotated triangles are DSDP drill sites with site numbers. Inferred magnetic lineations: L1-L4 in the Laxmi Basin and MAL1-MAL4 in the offshore Indus Basin. Identified magnetic isochrons with anomaly number (anomalies A28 through A20) and corresponding age in Ma [e.g. A24n3 (53.12)]. FZ: Fracture Zone; pf: pseudofaults; R: Raman Seamount; P: Panikkar Seamount; W: Wadia Guyot. Modified after Biswas (1988), Singh and Lal (1993), Bhattacharya et al. (1994a, 1994b), Malod et al., (1997) and Chaubey et al. (2002).

event over the Indian peninsula have been a subject of considerable debate (Alvarez et al., 1980; Baksi, 1988, 1994; Courtillot et al., 1988; Duncan and Pyle, 1988; Rampino and Stothers, 1988; Acton and Gordon, 1989; Vandamme et al, 1991; Negi et al., 1993; Basu et al., 1993) and various postulated ages ranges between 62-72 Ma. However, views appear to converge on a short duration (1 Ma) peak volcanism around 65 Ma (Courtillot et al. 1986; Vandamme et al. 1991; Hofmann et al., 2000).

Three orogenic trends predominate the Precambrian basement grains of the western part of the Indian peninsula. These are, the Dharwar trend, the Delhi-Aravalli fold trend and the Satpura trend (Fig. 2.1). The generally NNW oriented Dharwar trend is the dominant basement grain in the western peninsular India (Biswas, 1982). It is expected that Dharwar trend continues below much of the area now covered by Deccan Trap CFB (Das and Ray, 1976; Krishnan, 1968; Biswas, 1982; Gombos et al., 1995). The NE-SW oriented Delhi-Aravalli trend bifurcates into two branches at its southwest end: the Delhi trend swings E-W into the Kuchch region, and NE-SW trending Aravalli trend continues across the Cambay graben into the Kathiawar Peninsula. The ENE-WSW Satpura trend along the Narmada-Son lineament is the other dominant structural fabric of the western India (Biswas, 1982). These three major trends, resulting from orogenesis dating back more than 2000 Ma, were the zones of deformed and weakened crust along which later Phanerozoic rifting was facilitated (Biswas, 1982, 1987; Gombos et al., 1995).

One of the major geomorphic features in the western peninsular India adjacent to the study area is the Western Ghats escarpment, which forms the western edge of the mountainous Sahyadri Range. This spectacular Western Ghat escarpment, has more than 700 m drop at places (Valdiya, 2001). This feature appears to be interesting in connection with the evolution of the western continental margin because some researchers believe that this feature relates to the formation of a new continental edge at the time of break-up of the Gondwanaland (Ollier and Powar, 1985; Subrahmanya, 1998a). Some other researchers believe that this feature was formed at the time of rifting of Seychelles from India (~65 Ma) and subsequently retreated by about 120-180 km (Widdowson, 1997; Widdowson and Gunnell, 1999).

2.2.2. *Continental shelf and slope*

The western continental shelf of India (Fig.2.1) is considered to be limited by 200 m isobath. Towards north, the shelf is relatively wider, reaching a width of more than 300 km in the areas north off Mumbai coast, whereas towards south the width of the shelf gradually narrows down and off Kerala coast it becomes about 50 km. In contrast to this, the continental slope is narrow in the north but widens towards south (Biswas, 1989).

A series of narrow regional and local horsts, graben structures formed by longitudinal extension faults characterizes the basement trends of the shelf area. The style of faulting is controlled by three major orogenic trends of western part of the Indian mainland. From Kerala offshore to Bombay offshore, the Dharwarian trend (NNW-SSE) predominates, to the north, in the Gulf of Cambay region – the Satpura trend (ENE-WSW) dominates the structural style while further north in Kutch-Saurashtra region – the Aravalli-Delhi trend (NE-SW) are predominant (Biswas, 1989).

Various publications (Harbison and Bassinger, 1973; Ramaswamy and Rao, 1980; Chauhan and Almeida, 1993) reported the presence of several physiographic highs in the mid-slope region. The northern part of the slope region is also characterized by slumping and its related features (Hussain and Guptha, 1985; Rao, et al., 1988; Rao, 1989; Chauhan and Almeida, 1993). The typical shelf-slope morphology of the western continental shelf of India thus appears to be modified at places by the presence of mid-slope basement highs or by slumping and related features.

The western continental shelf sedimentary basins appear to have been divided into several sub-basins delimited by transverse basement arches or fault bounded highs and identified as various zones by different researchers (Ramaswamy and Rao, 1980; Biswas, 1989; Nair et al., 1992; Singh and Lal, 1993; Raju et al., 1999). The information regarding the sedimentation pattern over these shelfal sedimentary basins as inferred from analysis of several drill well samples have been summarized as follows: In the continental shelf areas off Konkan-Kerala coast (i.e. in the areas south of Vengurla) in a well drilled to about 1760 m, the sedimentary succession was found to be the following; i) the lower most sediments are coarse clastics deposited in continental to bathyal conditions during Late Cretaceous to Paleocene; ii) the overlying middle part of the succession is Eocene to Middle Miocene limestone and shales; and (iii) the upper part of the succession is Late Miocene to Holocene shale and claystone (Mitra et al., 1983; Singh and Lal, 1993). To the north, in the Bombay Offshore Basin, the Tertiary sediments were laid down at places over Deccan Trap basaltic floor of Paleocene age (Mohan, 1985; Pandey, 1986; Raiverman, 1986; Nair et al. 1992) and at other places, specially over structural highs, the sediments directly overlie Precambrian basement (Ramaswamy and Rao, 1980; Rao, 1994). In the continental shelf area between off Saurashtra peninsula and the regions south of Bombay, there were three phases of clastic sedimentation and two phases of carbonate sedimentation. The oldest phase which took place during Late Paleocene-Early Eocene times resulting the deposition of shales and minor sands in the subsiding depressions and grabens. During Middle Eocene to Early Oligocene, the first phase of carbonate deposition took place in most parts of the basin except Bombay High. During Late Oligocene-Middle Miocene the second phase of clastic sedimentation took place over shelf margin and Saurashtra Basin. During Late Oligocene to Middle Miocene the second phase of carbonate deposition occurred mostly in the areas of Bombay High and neighbourhood, During Late Miocene – Holocene was the third and last phase of clastic sedimentation which covered the entire region and shelf prograded by varying distances (Nair et al., 1992). Information from a well drilled through about 2600 m sediments in the continental shelf area off Kutch, suggests that during Paleocene to Middle Miocene limestones were deposited, while during Middle Miocene to Pleistocene the sands were deposited (Ramaswamy and Rao,1980).

2.2.3. *Laccadive-Chagos Ridge*

The Laccadive-Chagos Ridge is one of the most prominent physiographic and aseismic features of the Indian Ocean (Fig.1.1). This linear nearly north-south ridge is considered to extend for over 3000 km between 12°S and about 14°N. A considerable length of the crest of this ridge is composed of shoals, banks and coral reefs at a depths less than 1500 m. This elongated ridge is slightly arcuate and its western side is concave (Heezen and Tharp, 1965; Whitmarsh et al., 1974; Avraham and Bunce, 1977). This ridge appears to be divided into three main segments by breaches in its topographic continuity by several relatively deep saddle-like features (Bhattacharya and Chaubey, 2001). In literature, these three segments are referred by various names. The northern segment is referred as the Laccadive Islands (Lakshadweep) or Laccadive Plateau, the middle segment as Maldive Islands or the Maldive Ridge, and the southern segment as Chagos Archipelago or Chagos Bank. Following Bhattacharya and Chaubey (2001) these three segments of Laccadive-Chagos Ridge are being referred from north to south as the Laccadive Plateau, the Maldive Ridge and the Chagos Bank.

In this perspective, the present study area covers northern part of the Laccadive Plateau (Fig.2.1) which lies approximately north of 10°N and contains about twenty islands and banks. Overall, these islands and banks depict a N-S lineament, which corresponds to the general N-S trend of the Laccadive-Chagos Ridge complex. However, according to Eremenko and Datta (1968) the individual islands and banks depict a fairly definite pattern of orientations. Gravity data in this region indicates that the Free-air gravity anomaly, in general, is negative and subdued. However, a belt of relative positive anomalies was observed approximately over the crestal region (Talwani and Kahle, 1975; Avraham and Bunce, 1977; Naini, 1980; Naini and Talwani, 1982). The magnetic anomalies over the eastern half of the Laccadive Plateau are reported (Naini and Talwani, 1982; Gopala Rao et al., 1987) to be subdued, whereas its western half in contrast, appears to be associated with several prominent high amplitude anomalies. Seismic reflection studies suggest that the basement in general is in the form of a broad bulge, over which at places sharp peaks are present. These peaks are devoid of sediment cover and some of them reach very close to the sea surface. In the areas north of 12°N, the basement appears to consist of smaller blocks that drop in a step-like fashion to the west (Naini, 1980; Naini and Talwani, 1982; Reddy et al., 1988).

A number of workers have postulated that the Laccadive-Chagos Ridge is an inactive and subsided part of a linear volcanic feature formed during the northward motion of the Indian plate over the Reunion Hotspot. The linearity of this ridge and the north-south age progression of the volcanic rocks along the trace of the ridge are considered as strong evidences for such a hotspot model (Francis and Shor, 1966; Dietz and Holden, 1970; Whitmarsh, 1974; Morgan, 1981; Duncan, 1981; Duncan and Hargraves, 1990; Verzhbitsky, 2003). However, a number of alternate models were also forwarded to explain the origin of this ridge. Particularly, it appears that many observations and inferences do favour a non-hotspot model of origin for the Laccadive Plateau region. For example, based on seismic refraction studies Babenko et al. (1981) inferred that the Moho in this region lies at a depth of about 18-19 km, which suggests that the thickness of the crust in the Laccadive Plateau region is higher than the normal oceanic crust. Higher than normal oceanic crust thickness was also inferred by Naini and Talwani (1982) from analysis of seismic refraction data and by Chaubey et al. (2002) from two-dimensional modeling of gravity and magnetic data. Based on identification of several rotated fault blocks from multichannel seismic reflection data, Murty et al. (1999) inferred existence of continental ribbon (or continental fragment) structure over the Laccadive Plateau region. The lack of appreciable magnetic anomalies led Gopala Rao et al. (1987) to infer continental origin for the Laccadive Plateau region. Based on two-dimensional modeling of magnetic data, Satyanarayana et al. (1997) inferred that the basement of the Laccadive Plateau region is of volcanic in nature. Narain et al. (1968), based on seismic refraction results of Francis and Shor (1966), have opined that the Laccadive Plateau region forms a transition between oceanic crust to the west and continental crust to the east. Fisher et al. (1971) have suggested that the Laccadive-Chagos Ridge was build up over an old transform fault during India's northward movement. By considering the refraction velocities over Laccadive-Chagos Ridge (Francis and Shor, 1966) and plate reconstruction models, McKenzie and Sclater (1971) opined that the Laccadive-Chagos Ridge was formed due to volcanism since Upper Cretaceous. Avraham and Bunce (1977) suggested that the Laccadive-Chagos Ridge is composed of structural elements of multiple origin. They suggested that the ridge consists in part of several north-south fracture zones and in parts of volcanic features formed either by leaky transform faults or by the passage of Indian plate over a hotspot.

2.2.4. *Laxmi Ridge*

Apart from the Laccadive-Chagos Ridge, another prominent physiographic feature that exists in the deep offshore regions off west coast of India is the Laxmi Ridge (Fig.2.1). The presence of this physiographic feature was first observed during RV Conrad cruises in the form of isolated structures (Naini and Talwani, 1977). These isolated features were suspected by Naini and Talwani (1982) to be part of a continuous structural feature and was named as "Laxmi Ridge". It appears that the name "Fedynsky Ridge" was given to the same physiographic feature by Babenko et al. (1981).

The Laxmi Ridge is an aseismic basement high feature, mostly buried under sediment cover. The average water depth over the ridge is about 2.8 km and has a basement relief of about 2 km (Naini and Talwani, 1982; Droz and Bellaiche, 1991). The Laxmi Ridge is a northwestward plunging system of ridges and downwarps (Shaynurov and Terekhov, 1991). Sediment cover over the ridge appears to vary between 0.5 km over basement high regions (Naini and Talwani, 1982) and about 2.5 km in the basement troughs (Shaynurov and Terekhov, 1991). Even though a positive basement feature, this ridge, interestingly was observed (Naini and Talwani, 1982) to be associated with a broad free-air negative (-50 mGal) gravity anomaly. It is expressed as NW-SE trending topographic high in the southern end, while its topographic expression is not discernible northward beyond 18°30'N. However, based on associated characteristic gravity low and the adjacent magnetic anomalies, it was deduced that around 65°30'E this ridge turns WNW-ESE and extends westwards at least up to 63°40'E (Miles and Roest, 1993).

The southward extension of the physiographic expression of the NW-SE trending segment of the Laxmi Ridge appears to terminate abruptly against an oceanic crust containing east-west trending magnetic lineations (Bhattacharya and Chaubey, 2001).

In absence of direct evidences like drill well information, various authors have inferred nature of the basement of the Laxmi Ridge based on geophysical data. Based on gravity, magnetic and seismic refractions studies Naini (1980) and Naini and Talwani (1982) suggested that the Laxmi Ridge is a continental sliver. Malod et al. (1997) reported to have observed stratified horizons below the acoustic basement reflector, which according to them is indicative of continental nature of the Laxmi Ridge basement. Talwani and Reif (1998) have modeled the ridge as a continental fragment lying between the oceanic crust of Arabian basin in the west and oceanic crust of the Laxmi Basin in the east. Based on modeling of gravity data, paleogeographic reconstruction and analysis of seismic refraction data Todal and Eldholm (1998) explained the Laxmi Ridge as a complex rifted marginal high comprised of both continental and oceanic crust where inner part of the ridge is underlain by faulted continental blocks.

2.2.5. *Laccadive Basin*

The Laccadive Basin – a narrow triangular shaped basin – is located between the Laccadive Plateau in the west and the southwestern continental slope of India in the east (Fig.2.1). The northern boundary of the basin lies approximately near 16°N where the northern extremity of the Laccadive Plateau apparently meets the adjacent continental slope of western India. In the south, this basin opens into the

Central Indian Basin. For geographical reference to this area, different researchers used different nomenclatures. In the present study this area is being referred as "Laccadive Basin", a name which was used for the first time in published literature by Whitmarsh (1974). The water depth in this basin varies from ~2000 m in the north to ~2800 m in the south (Bhattacharya and Chaubey, 2001). Based on limited magnetic and seismic reflection data Rao and Bhattacharya (1975) inferred that the underlying basement in this area is block faulted. The seismic reflection studies (Ramaswamy and Rao, 1980; Naini and Talwani, 1982; Rao and Srivastava, 1984) suggest that the sediment thickness in this basin is about 2.5 sec (TWT) in the southern part which gradually increases to about 3.5 sec (TWT) towards the northern part of the basin. The underlying basement widens and deepens towards south and is characterized by several basement high features, which form an approximately NNW-SSE trending lineament which was named by Naini and Talwani (1982) as the "Prathap Ridge".

The Laccadive Basin is reported to be associated with broad low to subdued magnetic anomaly, and generally low Free-air gravity anomaly (Rao and Bhattacharya 1977; Naini and Talwani, 1982; Gopala Rao et al., 1987; Subrahmanyam et al., 1995). However, these geophysical signatures are locally modified due to the presence of Prathap Ridge, which is associated with relative Free-air gravity high. Based on gravity studies, Subrahmanyam et al. (1995) opined that the Prathap Ridge is offset along pre-exiting ENE-WSW trending Precambrian fault trends extending from adjacent Indian mainland and was formed during the separation of India from Madagascar. The Prathap Ridge is mostly buried below sediments and divides the basin in two parts. Based on widely spaced seismic reflection profiles, Gopala Rao et al. (1987) inferred that the ridge is depicted as a single peak basement high in the north, and multiple peaks in the south. Based on the magnetic data and seismic reflection studies Krishna et al., (1992) interpreted that, the Prathap Ridge consists of basement having variable magnetic signatures, and formed due to Reunion Hotspot activity. By identifying rotated fault blocks representing half-grabens, which are equidistance from a central basement high (Prathap Ridge) in the Laccadive Basin, Chaubey et al. (2002) suggest that the basin formed as a result of failed rift and volcanism of the stretched continental regime.

2.2.6. *Laxmi Basin*

Naini and Talwani (1982) divided the deep offshore regions off western continental margin into two provinces viz., the Easterm Basin and the Western Basin. The dividing line between these two provinces was considered to coincide approximately along the western limit of the Laxmi Ridge and the Laccadive Plateau. Bhattacharya et al. (1994a) considered a part of this Eastern Basin as a distinct entity and named that part as the "Laxmi Basin" (Fig.2.1). The Laxmi Basin was considered to be bounded in the west by the Laxmi Ridge, in the south by the northern extremity of the Laccadive Plateau, and in the east by the continental slope of India respectively. The northern limit of the basin is formed off Saurashtra by the bathymetric contours whose trend changes abruptly from NW-SE to E-W. It may be noted that the deep-sea basin region eastward of the Laxmi Ridge and the Laccadive Plateau was referred by Biswas and Singh (1988) as the "Laxmi-

Laccadive depression." In this context the Laxmi Basin represents a part of this Laxmi-Laccadive depression. The major portion of the study area covers the southern Laxmi Basin area. Approximately along the axial part of this basin, a NNW-trending seamount chain is present (Bhattacharya et al., 1994b). Apart from these seamounts, the water depths in the Laxmi Basin area range between 3000 and 3750 m and seafloor gently dips southwestward (Bhattacharya and Chaubey, 2001). In this region, the sediment thickness is minimum over the seamounts and the adjacent Laxmi Ridge, where as in rest of the basin, it attains a maximum thickness of about 2.0 km (Naini, 1980).

The seismic refraction and gravity studies (Naini, 1980; Naini and Talwani, 1982) in this region suggest that; i) the crustal thickness is about 17 Km, which implies that the underlying crust is thicker than normal oceanic basin crust and nearly half that of a standard continental crust and ii) the basin is characterized by a low amplitude (~20 mGal) short wavelength (~60 km) free-air gravity low superimposed on a long wavelength (~350 km) gravity high. Based on a study of closely spaced magnetic and gravity profiles, Bhattacharya et al. (1994a) mapped the existence of well-correlatable NNW-trending magnetic anomalies in this basin. The magnetic lineations are symmetric about a central negative magnetic anomaly and the axis of symmetry coincides with a characteristic short-wavelength Free-air gravity low. The magnetic lineations are contiguous and parallel to the adjacent segment of the Laxmi Ridge in the west and the continental shelf in the east. It was inferred (Bhattacharya et al., 1994a) that the Laxmi Basin magnetic lineations record a two-limbed seafloor spreading anomaly sequence (Fig.2.1) probably representing anomalies 33 (~79 My, Late Cretaceous) through 28 (~62 My, Late Paleocene). In the axial part of the Laxmi Basin, Naini (1980) observed a well defined basement peak in one of the seismic profiles. This feature is about 30 km wide and rises by about 3.0 sec TWT above the adjacent basement. Basement rises were also observed (Naini, 1980) in the neighbouring seismic profiles, but they are much subdued and sub-surface. Together these features were considered (Naini, 1980) to represent a basement high zone. Based on analysis of additional seismic profiles in the neighbourhood, Gopala Rao et al. (1992) inferred that this basement high zone to represent a 360 km long linear feature and named it as the Panikkar Ridge. This basement high zone approximately coincides with the reported axis of symmetry of two-limbed seafloor spreading magnetic anomalies, which Bhattacharya et al. (1994a) inferred to represent an extinct spreading centre. As it will be shown in the next paragraph, this basement high zone or extinct spreading centre also coincides with the Laxmi Basin seamount chain (Fig. 2.1).

As mentioned earlier, in the axial part of the Laxmi Basin, Bhattacharya et al. (1994b) have reported existence of a NNW-trending linear seamount chain. The seamount chain consists of three main edifices which from north to south are the Raman and Panikkar Seamounts and the Wadia Guyot (Figs. 2.1, 2.2). This seamount chain happened to be the first one in the Arabian Sea whose bathymetry has been established using swath bathymetric survey. The three seamount features together form a nearly N30°W trending 250 km long linear seamount chain.

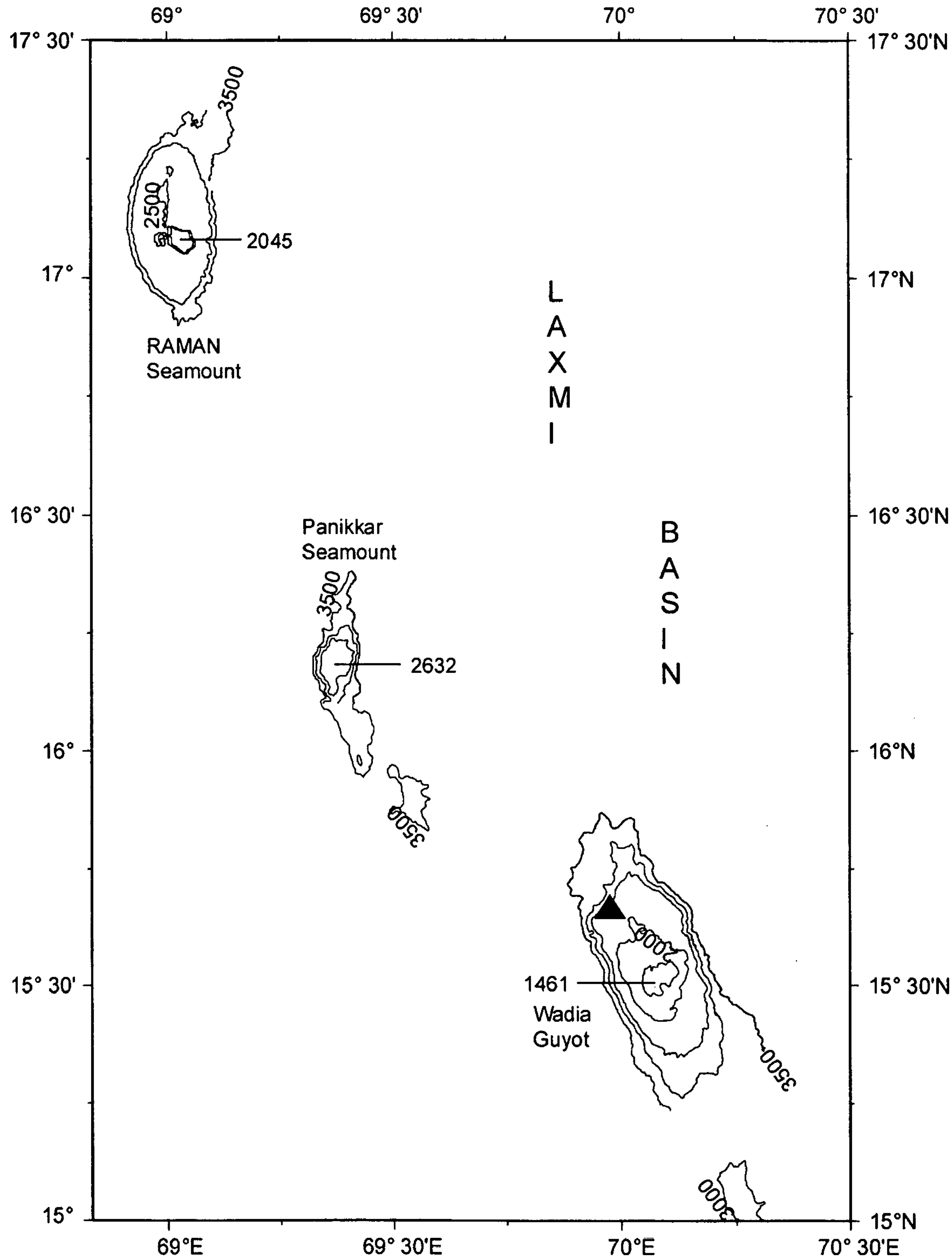


Fig. 2.2 Bathymetric map of the Laxmi Basin seamount chain with location of sediment core sample. Contour interval 500 meters. Minimum water depths (in meters) recorded over the summit area of each seamount is labelled. Solid triangle is the location of core sample over the Wadia Guyot as discussed in the text. Modified after Bhattacharya et al., (1994b).

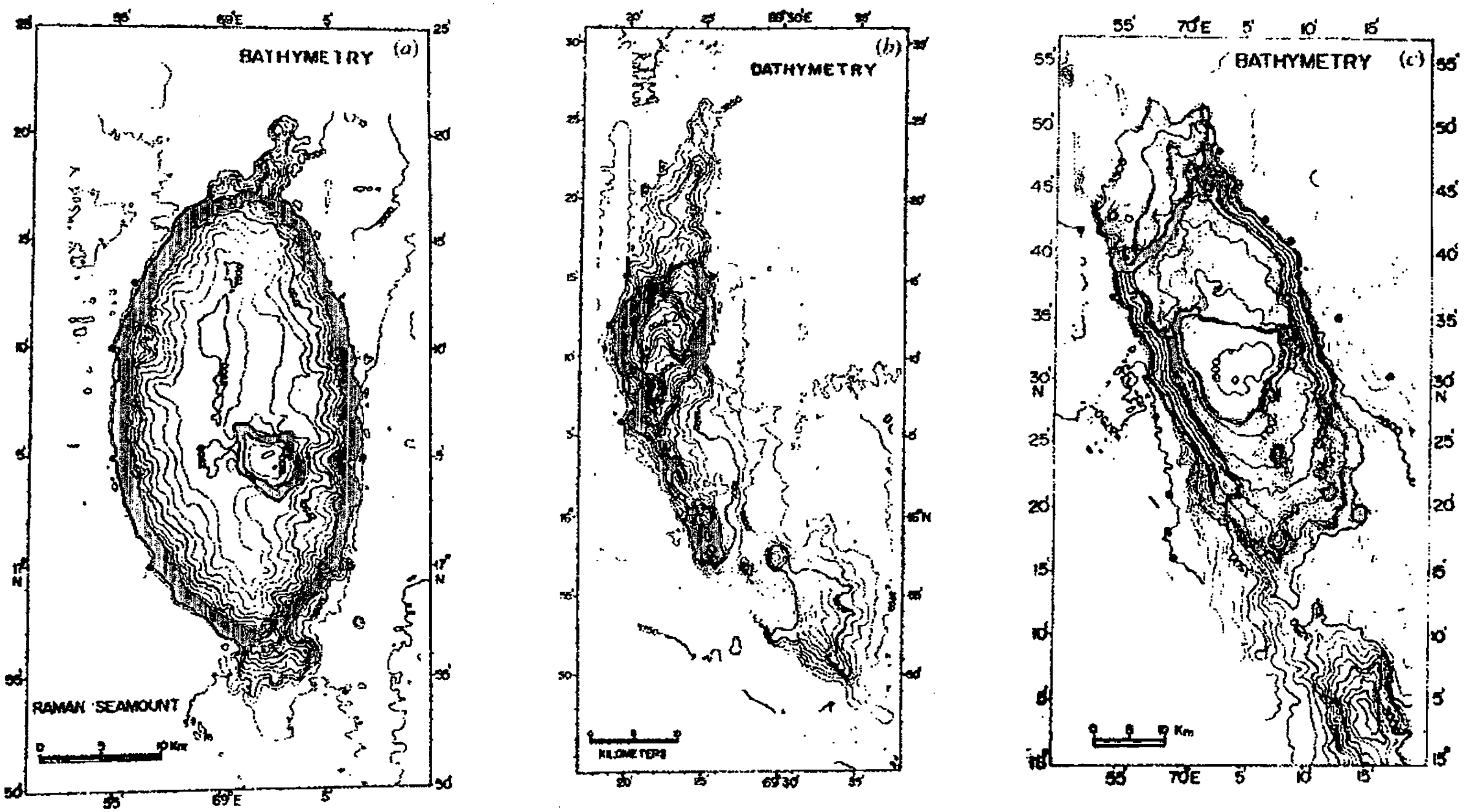


Fig.2.3 Detailed bathymetric map of the Laxmi Basin seamounts as derived from multibeam (Hydrosweep) swath-bathymetric investigations. Contour interval is 50 meters. a) Raman Seamount (reduced from original 1:110,000 scale map); b) Panikkar Seamount (reduced from original 1:150,000 scale maps) and c) Wadia Guyot (reduced from 1:200,000 scale map). Modified after Bhattacharya et al. (1994b)

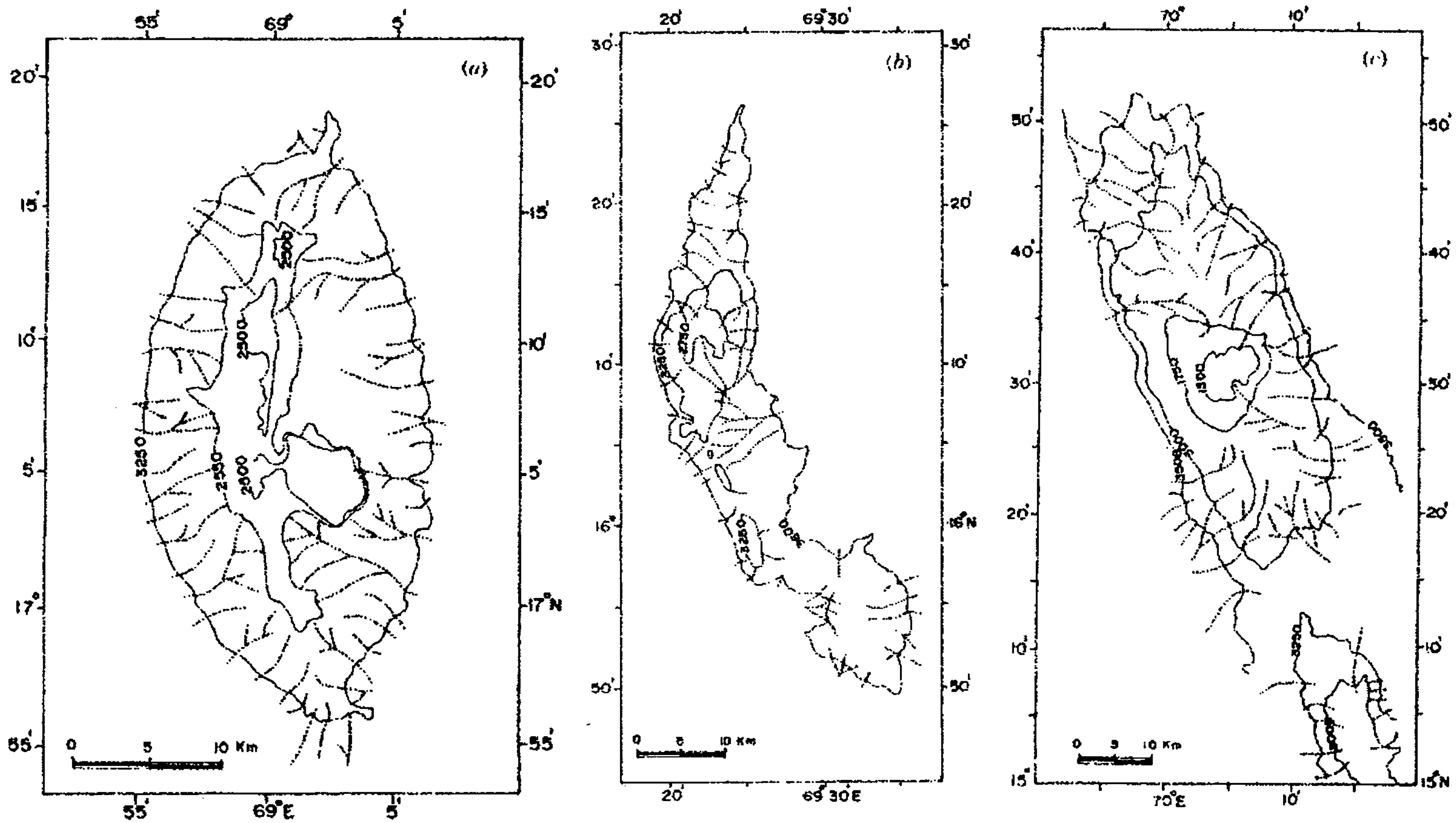


Fig. 2.4 Interpreted gully pattern (thin dashed line) over the a) Raman Seamount, b) Panikkar Seamount and c) Wadia Guyot. Continuous lines represents selected bathymetric contours (in meters). Modified after Bhattacharya et al., (1994b).

The swath bathymetric map clearly depicted that the Raman Seamount (Fig. 2.3a) which is the northern most seamount of the chain and is remarkably elliptical in plan. The overall elongation of the feature is approximately NS and has a basal area of about 660 sq. km. The seamount rises by about 1000 m from the surrounding seafloor and forms a relatively flat plateau area. A secondary peak having a basal area of about 28 sq. km is present over this plateau. The least depth of 2045 m encountered over this secondary peak gives a total height of the seamount edifice as 1505 m. The contour map (Fig. 2.4a) revealed numerous gullies intersecting the upper and lower flank slopes of the seamount. Most of these gullies can be traced downwards up to the exposed base of the seamount. Some of the gullies appear to have developed into a dendritic pattern.

The swath bathymetric map of the Panikkar Seamount (Fig. 2.3b) reveals that the seamount is an arcuate elongated feature that contains multiple peaks on a single base. In plan view this seamount appears like a curved spindle. The basal area of this feature is about 300 sq. km. From the surrounding seafloor of about 3700 m the entire platform base of this seamount has been built as a single feature approximately up to 3350 m whereupon several individual peaks have formed. The major peak (near 16°13'N) has a relatively flat, crescent –shaped summit, whereas the other peaks are conical. The least depth over the largest of the peaks is about 2632 m giving rise to a maximum height of the this seamount of about 1068 m. To the immediate southeast of the seamount there is a smaller hill whose maximum relief is about 350 m. The slopes of this seamount also are dissected by numerous gullies (Fig.2.4b), some of which developed headward into a dendritic pattern. The gullies appear to spread sidewise from a higher axial zone all along the seamount. Most of the gullies can be traced from the highest regions of this axial zone to the base of the seamount.

The Wadia Guyot is the southern most and the biggest edifice of the Laxmi Basin seamount chain (Fig. 2.3c). The swath bathymetric map revealed that in plan view the Wadia Guyot is approximately rhomboid in shape and covers a basal area of about 1210 sq. km. The elongation direction (N25°W) of this guyot is almost the same as that of the overall trend of the seamount chain. Along the long axis its length is about 72 km, whereas its maximum width is about 25 km. The top of the guyot is a summit plateau (slope <2°) that covers an area of about 108 sq. km. The least depth recorded over the summit plateau is 1461 m, which yields the maximum relief of the edifice to be about 2240 m. Like the other two seamounts, the Wadia Guyot is also dissected by numerous gullies (Fig.2.4c) that appear to radiate from the central highlands and many of them develop headward into dendritic pattern. Most of these gullies can be traced from the summit plateau up to the exposed base or even over the apron areas near the base. Toward the southeast of this guyot, another 550 m high small hill like feature, trending approximately in the same direction as that of the Wadia Guyot, was also reported (Bhattacharya et al., 1994b).

Towards evolution of the Laxmi Basin, earlier workers proposed various models and difference of opinion exists regarding the nature of the crust underlying the Laxmi Basin. Based on semi-oceanic crustal thickness and lack of identifiable seafloor spreading type magnetic anomalies, Naini and Talwani (1982) believed that the crust underlying this region is transitional between oceanic and continental crusts. Based on identification of hyperbolic reflection pattern typical of an oceanic crust in multichannel seismic reflection data in the deep offshore regions off Ratnagiri coast, Biswas (1989) and Biswas and Singh (1988) favoured an oceanic nature of the basement in this area. As mentioned earlier, based on identifying seafloor spreading type magnetic anomalies Bhattacharya et al. (1994a) concluded that the Laxmi Basin is underlain by oceanic crust of an extinct spreading episode. Based on interpretation of gravity data it was believed that this area is an underplated normal oceanic crust (Pandey et al., 1995; Singh, 1999). Based on observation of structural and tectonic grains parallel to the ancient Precambrian structural grain of the adjacent western part of the Indian subcontinent, Kolla and Coumes (1990) inferred that the Laxmi Basin area represents rifted transitional crust. Studying ship-borne and satellite gravity and magnetic data, Miles et al. (1998) concluded that the crust in the Laxmi Basin is rifted and underplated continental crust. It may be mentioned here, that areas north and northwest of the Laxmi Basin, i.e. in the areas northward of Laxmi Ridge, Malod et al. (1997) inferred the existence of oceanic type of crust, which evolved during magnetic anomalies 29R-29 (about 66-64 My, early Paleocene, Fig.2.1). Mainly based on gravity and magnetic data and paleogeographic reconstructions, Todal and Eldholm (1998) opined that the crust underlying the Laxmi Basin is of continental in nature. Talwani and Reif (1998) on the other hand favoured oceanic nature of the crust underlying the Laxmi Basin.

2.2.7. *Arabian Basin*

The Arabian Basin is bounded to the west by the Owen Fracture Zone (Fig.1.3), which demarcates the transform boundary between Indian and the Arabian plates. The uneven topography of the NW-SE trending active Carlsberg Ridge, which separates the Indian and African plates, forms the southern boundary of the basin. The aseismic Laxmi Ridge and the Laccadive Plateau bound most of the northern and eastern limit of this basin. The basin is covered by Indus fan sediments, which determine the submarine topography. The water depth in this basin varies from 3400 m in the north to about 4400 m in the south, and the relatively smooth, sediment covered seafloor, in general, dips southward. Existence of well developed magnetic lineation in this basin was established from various studies. In earlier studies (McKenzie and Sclater, 1971; Whitmarsh, 1974; Norton and Sclater, 1979; Naini and Talwani, 1982; Bhattacharya et al., 1992; Chaubey et al., 1993; Chaubey et al., 1995) the observed magnetic anomaly offsets were accommodated by invoking the presence of a number of fracture zones in terms of a classical linear magnetic anomalies and orthogonal fracture zone model. Recent detailed studies of closely spaced magnetic profiles (Miles and Roest, 1993; Chaubey et al., 1998; Dyment, 1998; Chaubey et al., 1998, 2002; Royer et al., 2002) have indicated that the magnetic lineations 28 through 20 are obliquely offset (Fig. 2.1). The oblique offsets were considered to represent the pseudofaults associated with paleo-propagating ridges. These ridge propagation events commenced around anomaly 28 time (~63 Ma; Late Paleocene) and continued at least until anomaly 23 time (~51 Ma; Middle Eocene). As a result of this ridge propagation, about 65% of the crust formed at the paleo-Carlsberg Ridge between anomalies 26 and 25 was accreted to the African plate, while more than 75% of the crust formed between anomalies 24 and 20 was accreted to the Indian Plate (Dyment, 1998). The pre-anomaly 24 period was characterized by ridge reorientation, whereas such a phenomenon was not apparent during the post-anomaly 24 period. The accretionary process of the Early Tertiary oceanic crust in the Arabian Sea, thus, appears to have been greatly influenced by the propagating ridges (Bhattacharya and Chaubey, 2001). Seismic refraction study (Naini, 1980; Naini and Talwani, 1982) in this basin suggests presence of sediments whose thickness vary between 1.3 and 4.2 km. Underlying the sediments are two crustal layers. The upper crustal layer, whose upper bound coincides with the acoustic basement identified in reflection profiles, has an average velocity and thickness of about 5.51 km/sec and 1.69 km respectively. The lower crustal layer has an average velocity and thickness of about 6.67 km/sec and 3.0 km respectively. The Moho was observed to lie at about 11.5 km below sea level. The crustal structure of the Arabian Basin was considered to be similar to that of the typical ocean basin.

Two DSDP drill sites (Site 220 and Site 221) were located (Fig. 2.1) in the southeastern part of this basin. The micro-paleontological age of the oldest sediment overlying the basaltic basement at Site 221 was inferred to be Middle Eocene. The recent magnetic anomaly identification (Chaubey et al., 1995) suggests that Site 221 was located on the reversely magnetized oceanic crust between confidently identifiable anomalies 22 and 21, which provide a reliable age constraint of ~48 Ma for the oceanic crust at this site. Unlike DSDP Site 221 (48 Ma), so far no confidently identifiable magnetic lineations have been identified near DSDP Site 220, which is located further east of DSDP Site 221. However, analysis of DSDP core samples (Whitmarsh et al., 1974) suggest that DSDP Site 220 area most probably is also underlain by oceanic crust and the oldest sediment overlying the basaltic basement is of Early Eocene age. Further, Whitmarsh et al. (1974) suggested that, considering the rate of seafloor spreading at that time and the distance between DSDP Site 221 and DSDP Site 220, the basement at DSDP Site 220 is atleast 10 My older than the basement at DSDP Site 221. It is believed that the Arabian Basin was created by seafloor spreading in two distinct phases. The spreading during the older of these two phases commenced sometime during the time of anomaly 28 (~63 Ma, Early Paleocene). This older phase of spreading possibly ceased or became very slow sometime after the formation of anomaly 20 (~43 Ma, Middle Eocene). The spreading of the later phase possibly commenced in its present geometry shortly before anomaly 11 (30 Ma, Late Oligocene) and is continuing until today (Bhattacharya and Chaubey, 2001).

2.2.8 *Offshore Indus Basin*

The offshore Indus Basin (Miles et al., 1998) is located in the upper Indus Fan region and is bounded (Fig. 1.2) by the east-west trending buried Laxmi Ridge to the south, the Murray Ridge and the Owen Fracture Zone in the northwest and the continental shelf off India and Pakistan in the northeast. In the southeast, the basin's boundary lies approximately along 3000 m isobath, where the basin merges with the northern boundary of the Laxmi Basin. The water depths in this basin range from 1400-1600 m at the foot of the continental slope to about 3400 m near the east-west trending buried Laxmi Ridge (Bhattacharya and Chaubey, 2001). The maximum sediment thickness in the basin is about 6 sec TWT, of which the fan-type sediment thickness may exceed 3 sec TWT. These sediments are interpreted to have been deposited since the Cretaceous period, but the fan type (turbidites) sediment deposition appears to be continuing since the Middle Oligocene to the Early Miocene (Kolla and Coumes, 1987). The tectonic structure of the basement comprised of east-west trending horst and graben with several northeast-southwest trending basement faults. The underlying basement was inferred by some researchers (Naini and Talwani, 1982; Kolla and Coumes, 1987; Miles et al., 1998) as transitional to continental, while others (Malod et al., 1997) inferred it as oceanic type, which evolved during magnetic anomalies 29R-29 (about 66-64 My, Early Paleocene).

2.3 Sedimentation source in and around the study area

At the time of rifting from Madagascar and Seychelles, India was in the southern hemisphere, from where it has moved to the present position. During the course of its journey, India passed over warm latitudes, collided with Eurasian Plate and while passing over the Reunion Hotspot caused an uplift of the western part of the peninsula which reoriented the fluvial system (due to which the west flowing rivers became east flowing rivers) in the sub-continent (Gombos et al., 1995). These three factors appear to have pronounced effect on the source of sedimentation in the western offshore regions at different times. The sedimentation in the western offshore basins appears to have started since Cretaceous, but most of the results document sedimentation history only since Paleocene (Ramaswamy and Rao, 1980; Raju et . al., 1981; Mitra et al., 1983; Mohan, 1985; Pandey, 1986; Raiverman, 1986; Nair et al. 1992; Rao, 1994; Pandey and Dave, 1998).

The studies of sediments from drill wells over the continental shelf region suggest that after Early-Middle Miocene, the western margin as a whole experienced heavy influx of terrigenous clastic sediments resulting in the development of monotonous shale/clay sequence (Singh and Lal, 1993). Summarizing the drill hole information presented in Fig.6 of Pandey and Dave (1998), it appears that prior to Early-Mid Miocene, broadly speaking the continental shelf witnessed dominant carbonate sedimentation. In fact, the depositional conditions were conducive for carbonate development over western continental margin of India since the time of its break–up from Madagascar and Seychelles till about Early-Mid Miocene. This is because of India's position during this period was in warm latitude belt and terrigenous influx was very low due to re-orientation of drainage patterns on the Indian shield. The post Mid Miocene onset of terrigenous influx appears to coincide with emergence of Himalaya as a lofty mountain range (Late Miocene) and onset of Indian monsoon system (Valdiya, 1999). As a consequence of these two developments in Miocene, accelerated weathering and erosion of the Indian landmass as well as Himalayan mountain range have brought terrigenous influx in the Indus Fan and continental shelf area. Based on the studies carried out on geological samples available from DSDP Site 221 (site located in the southern most part of the Indus Fan), over the lower Indus Basin on land and over the offshore shelf, Kolla and Coumes (1987), suggested that the fan sedimentation in the offshore areas commenced probably since Middle Oligocene to Early Miocene. Whereas, Davies et al. (1995) inferred that the Indus fan sedimentation initiated during Late Oligocene or Early Miocene.

Regarding the present day sedimentation over the shelf and deep offshore regions off western India, the studies of Kolla et al. (1981) provides a broad framework. Kolla et al. (1981) observed occurrence of very high (>60%) percentage of mineral Smectite in the present day sediments over the northwestern, and southwestern parts of western Indian continental shelf and a high percentage (40-50%) of Smectite over rest of the western continental shelf. Based on this observation they concluded that the Narmada and Tapti rivers which are the only two major rivers that drain in the western Peninsular India are the source of sediment in the western continental shelf region in general. In the southwest, some sediments probably are being brought in by relatively fresh surface water currents from western Bay of Bengal. Based on the observation of high percentages of Illite in most parts of the deep offshore regions, they concluded that probably at present the main source of sedimentation in this region is the Indus Fan.

The present day terrigenous sedimentation is dominant over the shelf, slope region and even in deeper areas by slumping. In the deep sea basins, the terrigenous sediments are reaching through Indus Fan sedimentation. However, the physiographic highs within the deep sea basins such as the Laccadive Plateau etc. at present appear to be under pelagic sedimentation regime. This conclusion appears to be supported by the results of drill hole samples at DSDP Site 219

(Shipboard Scientific Party, 1972) located over the Laccadive Plateau. Analysis of the drill hole at this Site suggests that the Site received pelagic sedimentation almost since Eocene times and the post-Early Miocene unit consists of nanno oozes. Further, the analysis carried out on a recently cored sample (sample courtesy S.W.A. Naqvi, NIO) over the summit area of the Wadia Guyot (Fig.2.2) located in the Laxmi Basin area revealed that the sediments contain about 80% carbonate (C. Prakash Babu, NIO, personal communication) suggesting dominant pelagic sedimentation regime over the seamount.

2.4 Inferred subsidence of the region

On the basis of reported results based on drill well sample analyses and other reported indirect evidences, it appears that the regions in and around the study area have undergone considerable amount of subsidence. Following are some inferences in this regard from published literature.

The oldest Paleocene sediments recovered at DSDP Site 219 (Fig. 2.1) drilled over the Laccadive Plateau, is considered as conclusive evidence that they were deposited in shallow waters (Shipboard Scientific Party, 1972). Based on presence of benthonic foraminifera, this depth of deposition was estimated to be about 100 m. Additional indicators, like recovered samples of glauconite, cross lamination, fragments of pelecypods, red algae, coarsely ornamented ostracods, bryozoans and echinoids also considered to represent shallow water deposition at this Site. At present, this site (DSDP Site 219) lies at 1764 m of water depth. Since the depth of deposition of oldest sediments recovered from this site was 100 m, and because the sediments are now found 411 m below the seafloor, the seafloor at this site has thus sunk by 2075 m since Early-Late Paleocene time. (Shipboard Scientific Party, 1972).

The studies carried out from the samples in Bombay High region suggest that the sea transgressed onto the Bombay High platform probably during the Late Oligocene or early part of Miocene under shallow water conditions of 20-30 m bathymetry (Raju et al., 1999). The geological depth section across Bombay High (Fig.2 of Roychoudhury and Deshpande, 1982) suggests that the basement of Bombay High at present lies at about 2 km below the seafloor. Thus, it can be surmised that the Bombay High basement subsided by about 1.98 km at least since Oligocene.

In a well (GKS-A) drilled in the Kutch offshore region, the benthic foraminiferal assemblages consisting of M. miscella, Assilina dandotica and Discocyclina seunesi in the formations of Limestones and shale intercalations. The benthic foraminiferal assemblage (Late Paleocene age) is an indicative of shallow water sedimentation of approximately between 25-50 m (inner shelf) water depths and the sequences at present lie at a depth between 3600 m – 3520 m (Bhandari et al., 1996 and references there in) suggesting that this area subsided by about 3500 m, at least from Late Paleocene onwards.

An indirect evidence of subsidence of the Laxmi Basin area was provided by Bhattacharya et al. (1994b) from their swath bathymetric study of the Laxmi Basin seamount chain. The swath-bathymetric data over these seamount edifices showed presence of extensive pattern of gully like features (Fig. 2.4), some of which grew headward into dendritic pattern. These observed gullies with their dendritic pattern was inferred to closely resemble a relict drainage pattern of subaerial erosional origin. This observation led Bhattacharya et al. (1994b) to infer a subsidence of the Laxmi Basin region to the tune of atleast 3700 m.

2.5 Dated volcanism around the study area

In Table 2.1, available estimated ages of volcanic formations around the study area have been compiled. This age estimates are of volcanic rock samples recovered from drill wells over the continental shelf area, volcanic rocks exposed in the coastal belt, oceanic basement sampled at DSDP Site 221 and volcanic rock recovered from a drill hole over the Laccadive Plateau (Fig. 2.5). Apart from these estimated ages, an idea about the basement ages of western part of the study area as determined from identified seafloor spreading magnetic anomalies were also depicted in Fig 2.5. The compiled data shows occurrence of volcanic rocks of broadly three age groups. The rock samples around 65 Ma of age, onland and offshore were related to Deccan Trap basalts (Rathore et al., 1997; Hofmann et al., 2000). The rocks older than 85 Ma perhaps represent Indo-Madagascar separation related volcanism or even older events. The volcanic rocks younger than 65 Ma, perhaps represents those formed by passage of India over Reunion Hotspot. The evidence of two episodes of volcanism over Laccadive Plateau (Padua Bank in Fig. 2.5) and the estimated ages of 102 Ma and 60 Ma for those events (Kothari et al., 2001) appears to be interesting. The 60 Ma age corresponds well with the ages

Table 2.1 Estimated ages of volcanic rocks from selected locations over the western part of the Indian mainland and offshore regions as compiled from various publications. Where the position locations are not given in the publication, they were digitized from respective figures.

ID*	Latitude (N)	Longitude (E)	Rock type and sample locale	Age of rock (My)	Reference
A	19° 00'	71° 33'	Basalts, continental shelf off Bombay	65	Rathore et al. (1997)
B	17° 55'	73° 38'	Deccan Trap basalts Mahabaleshwar,	65	Hofmann et al., (2000)
C	15° 30'	73° 44'	Dykes, Goa coast	63	Widdowson et al. (2000)
D	13° 27'	72° 32'	Basalts, Padua Bank, Laccadive Plateau	102+	Kothari et al. (2001)
E	13° 21'	74° 39'	Volcanic rocks, St.Mary Islands, northwest off Mangalore	93##	Valsangkar et al. (1981)
F	12° 22'	75° 16'	Dykes, Kerala Coast	114	Radhakrishna et al. (1999)
G	11° 56'	75° 28'	Dykes, Kerala Coast	99	Radhakrishna et al. (1999)
H	11° 56'	75° 30'	Dykes, Kerala Coast	54	Radhakrishna et al. (1999)
I	11° 53'	75° 45'	Dykes, Kerala Coast	129	Radhakrishna et al. (1999)
J	11° 27'	75° 47'	Dykes, Kerala Coast	61	Radhakrishna et al. (1999)
K	11° 18'	75° 53'	Dykes, Kerala Coast	83	Radhakrishna et al. (1999)
L	7° 58'	68° 24	Oceanic Basalt, DSDP Site 221, Arabian Basin	48	Shipboard Scientific Party, 1972

ID*: Identification of the locations as given in Fig.2.5.

+ : In this area age of basalts in different flows range between 60 and 102 Ma

##: In this area Torsvik et al. (2000) dated some rocks at ~91 Ma and Pandey et al. (2001) at ~85 Ma.

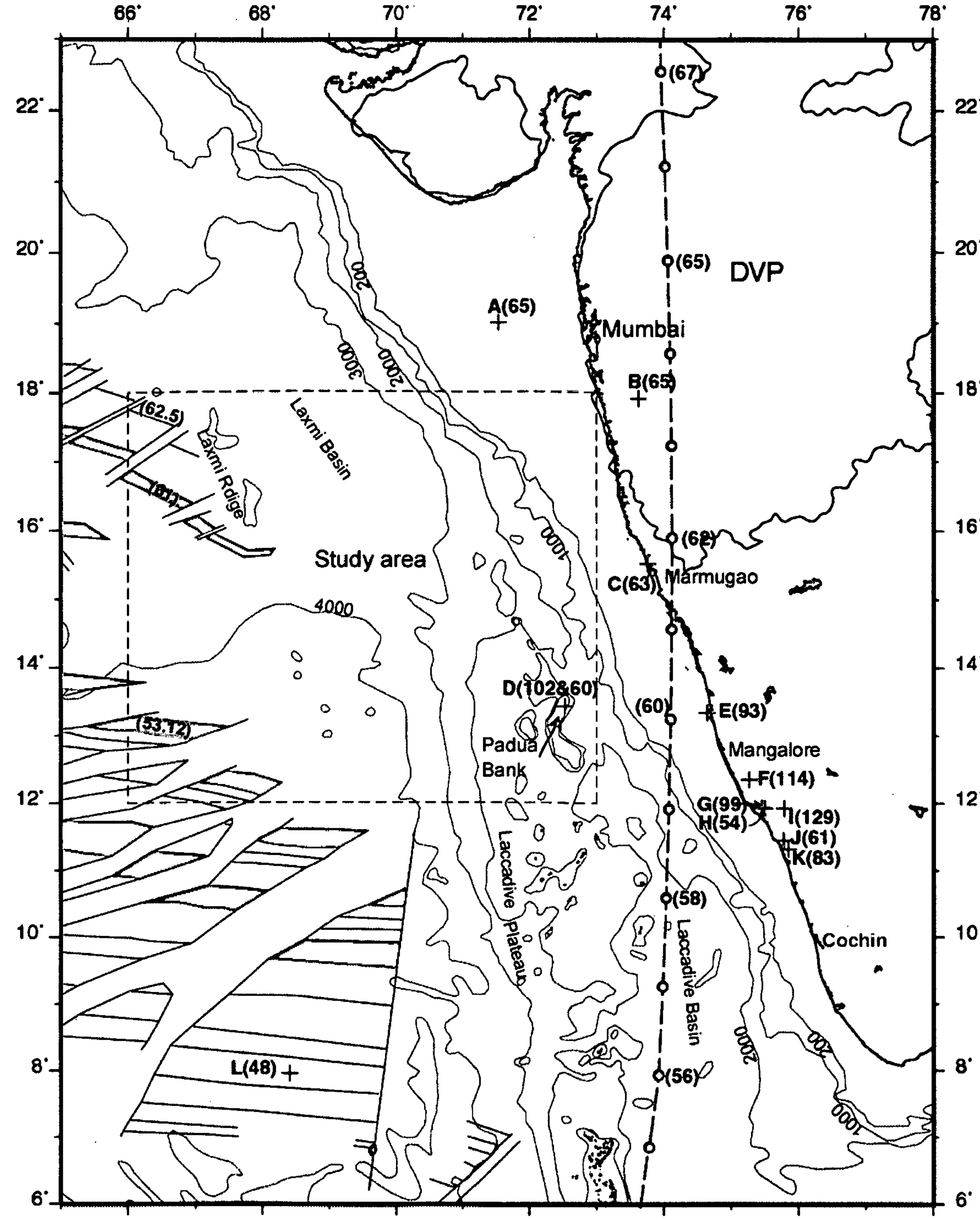


Fig. 2.5 Locations of selected volcanic formations in and around the study area with their estimated ages of emplacement. Ages (in Ma) of formations at locations are given within parenthesis. +: Locations where volcanic formations were dated in laboratory; filled circles: locations of estimated ages along the reconstructed track of the Reunion Hotspot (track courtesy V. Yatheesh, NIO); ages over identified magnetic isochrons (colour shaded blocks and thin lines) are after Chaubey et al., (2002). DVP: Deccan Volcanic Province. Details of age compilation are presented in Table. 2.1.

along the predicted track of Reunion Hotspot, so it could be related to the hotspot volcanism. However, the 102 Ma age volcanism appears to be surprising due to the fact that the Laccadive Plateau is considered by many as a trail of Reunion Hotspot implying that all volcanism over the Laccadive Plateau should be same or younger than 65 Ma. May be the presence of 102 Ma age volcanic rocks over the Laccadive Plateau indicates that this plateau region is a continental fragment which was in existence even before the India-Madagascar separation.

2.6 Concept of passive continental margin

Broadly speaking the continental margins are the regions of transition between continent and deep ocean. The continental margins world wide differ greatly in characteristics and they have been broadly categorized into, 1) Atlantic (or passive) type and 2) Pacific (or active) type. The Atlantic type margins usually have wide continental shelf and an extensive continental rise at the foot of the slope. These Atlantic type margins are devoid of significant concentration of seismic and volcanic activity and develop while continents rift apart and form new ocean. Therefore, in case of Atlantic type of margin, the continent and adjacent ocean floor are part of the same plate. The Pacific type of margins typically have a trench at the foot of the continental slope instead of a continental rise, and are usually seismically very active. They form where an oceanic plate being consumed beneath a continental plate at subduction zone and therefore, in case of Pacific type margin the continent and adjacent ocean floor belongs to different plates (Seibold and Berger, 1993; Open University Course Team, 1995).

As mentioned earlier, the western continental margin of India was classified (Biswas, 1982, 1987) as a passive continental margin. Therefore, in the following paragraphs the generalized scheme of passive margin evolution has been briefly presented. However, the studies carried out world wide indicated that the passive margins often exhibit complex structural pattern, revealing a great variety in structural style as well as depositional regime.

The origin of the margins is to be understood in the context of seafloor spreading and ocean basin formation (Fig.2.6). The continental rifting process commonly is the first event in the formation of a major ocean basin; the continental margin marks the zone where active, divergent plate tectonic processes commence from which the ocean basin grows. Although passive margins formed at divergent plate boundary following the break-up of continent, they move away from these boundaries while progressively cooling, subsiding and accumulating sediments. Passive margin therefore is not a plate margin but it marks the juxtaposition of continental and oceanic lithospheres within the plate interiors (Bott, 1995; Symonds et al., 2000). They border most of the Atlantic, Indian and Arctic Oceans, which increase in size by seafloor spreading as the continents drift apart. They are also located along the Antarctic edge of the closing Pacific Ocean and occur within some marginal seas such as the Mediterranean. Passive margins are divisible into rifted and sheared (offset) types. Rifted margins form where the initial plate separation is approximately perpendicular to the rupture. They show a gradational transition, and their morphology can be sub-divided into continental shelf, continental slope and continental rise. Sheared margins form when initial

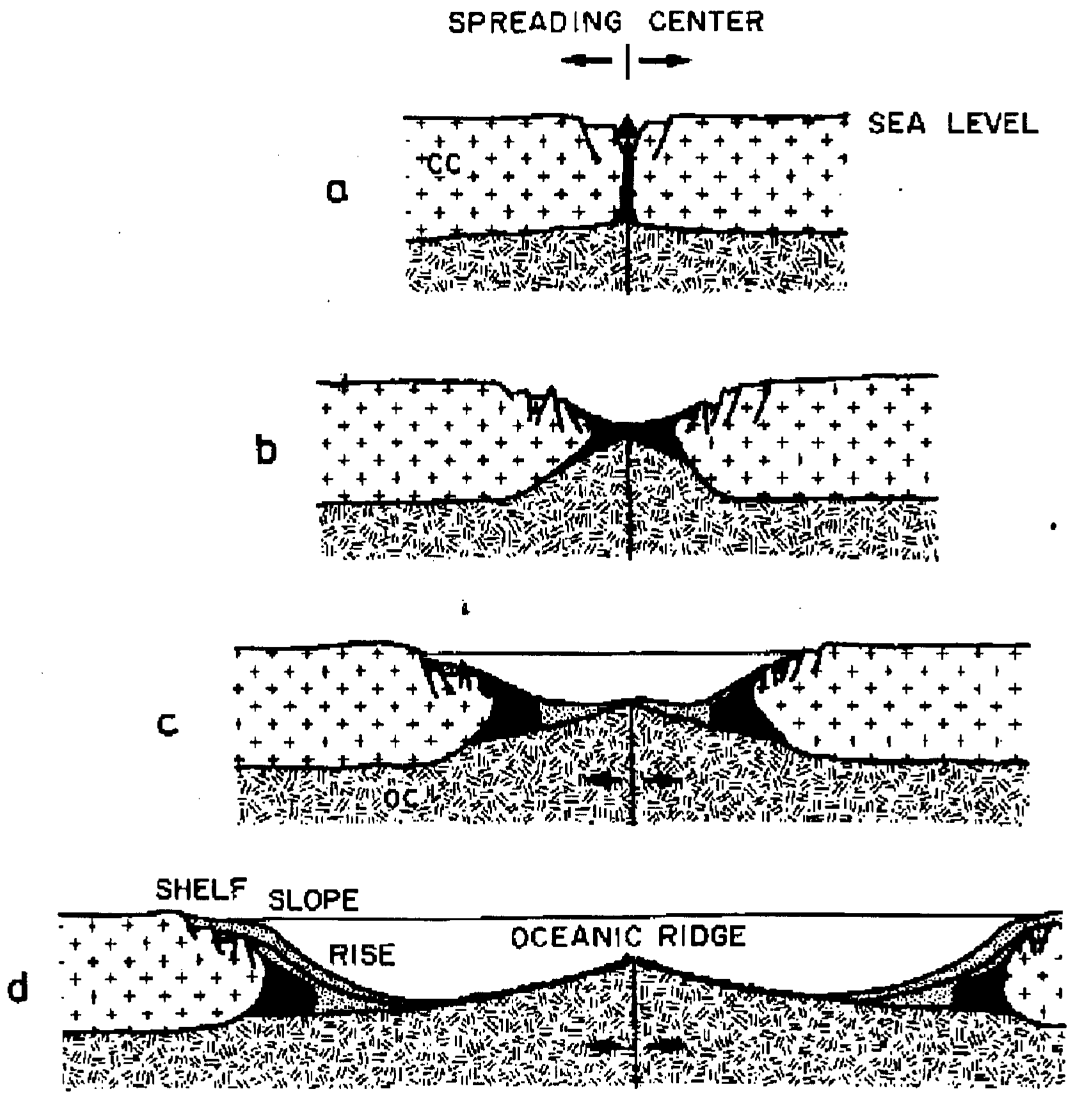


Fig. 2.6 Schematic representation of the concept of passive continental margin development at successive stages. Stage a: initiation of breaking of a continental mass along a weak zone; Stage b: crustal thinning, rifting and initiation of seafloor spreading; Stage c: continents drift away as seafloor spreading continues and Stage d: subsiding continental landmasses as they drift away under the load of sedimentation giving rise to shelf, slope and rise configuration. After Seibold and Berger (1993).

split is along a transform fault; they generally show a much sharper transition, and much smaller thickness of sediments (Bott, 1995).

Rifted passive margins are underlain by stretched continental crust formed prior to the final continental break-up. The stretched upper crust is rifted and often forms a region of highly extended terrain. Some segments of passive margins display intense flood basalt volcanism at about the time of break-up and just before it. Passive margins have also been categorized as non-volcanic or volcanic. Margins in which magmatism seems to have been absent or incidental leading to breakup are known as non-volcanic rifted margins and margins in which magmatism has dominated the breakup processes are known as volcanic rifted margins (Symonds et al., 2000). Normally passive margins are characterized by thick piles of sediment, however, there are a few starved margins where sediments are thin or absent due to lack of supply of sediments during their development. In general, the sedimentary rocks found at passive margins had been formed during three successive stages (Fig.2.7). First, the continental basement may be overlained by the pre-rift sediments, i.e. the sediments deposited prior to rifting. Second, syn-rift sediments of the rifting stage of margin development may be deposited at the time of initial rifting and continental stretching. Third, post-rift sediments of the drifting stage are deposited subsequent to continental break-up and onset of seafloor spreading. They are separated from the underlain syn-rift sediments by the post-rift or break-up unconformity. The post-rift sediments are generally un-faulted (except for growth faults at the slope) indicating a quiet tectonic environment apart from slow but persistent subsidence at an exponentially decreasing rate. Syn-rift sediments are typically deposited in half-grabens formed by intense stretching and thinning of the continental crust and lithosphere (Bott, 1995).

The kind of material accumulating on sinking continental margins depends on the geologic setting of the region. In the tropics, and where no large rivers bring sediment or fresh water, reef carbonates can grow. Elsewhere, mixtures of lagoonal or riverine sediments may gradually be buried by offshore deposits – mainly hemipelagic mud, rich in the shells of planktonic and benthic organisms. In places, the sediments can become extraordinary thick. The end result of rifting, then are the continental margins consisting of thick sediment stacks piled on the sinking blocks of a continental edge (Seibold and Berger, 1993). Understanding the evolution of a passive continental margin is necessary as these margins were considered to be of wide spread economic importance as a source of oil and gas (Bott, 1995).

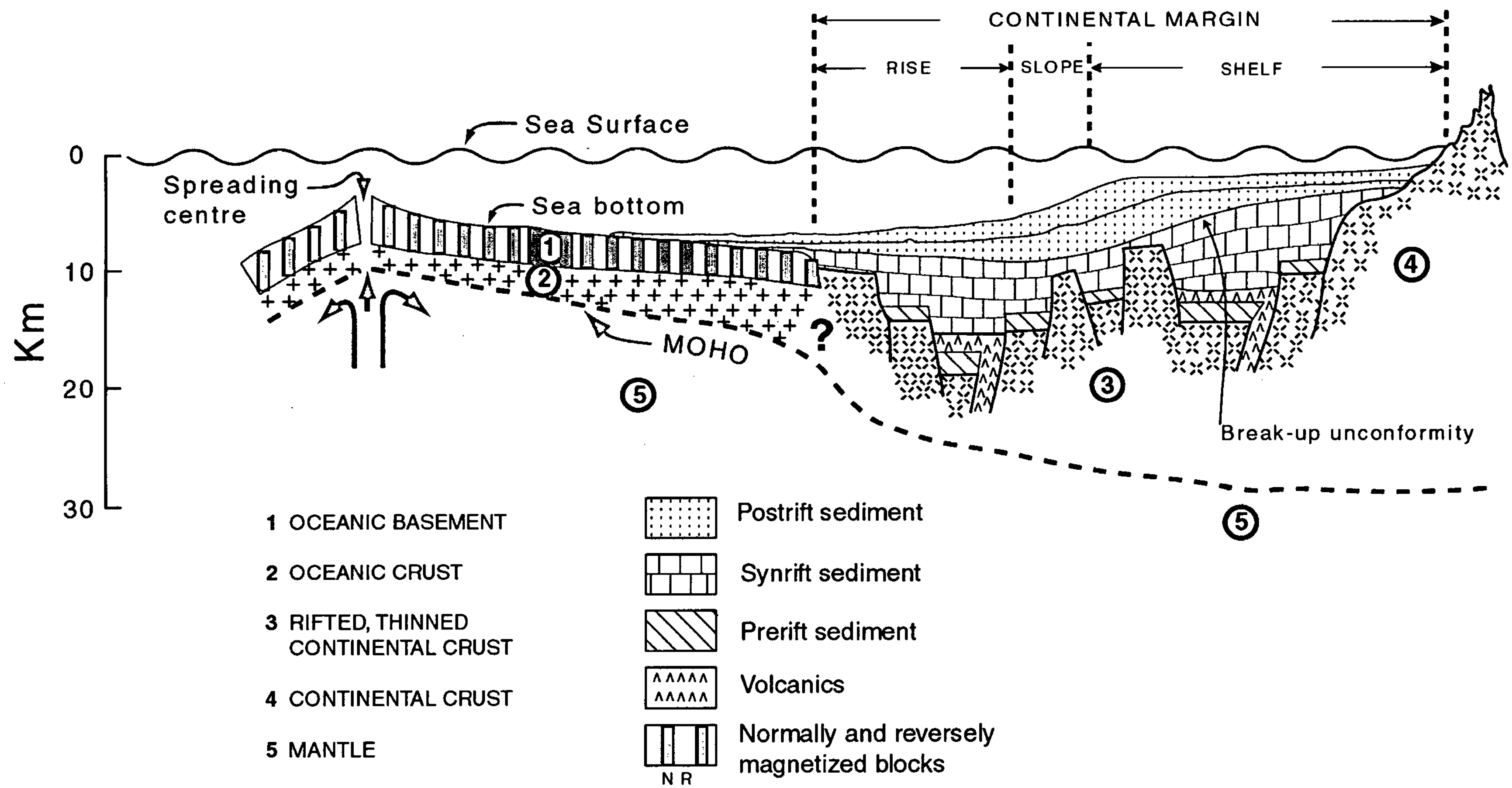


Fig. 2.7 Schematic representation of a crustal section across a passive continental margin with depiction of the sequence of sediments deposited during pre-rift, syn-rift and post-rift stages of a passive continental margin evolution. Figure courtesy G.C. Bhattacharya, NIO.

CHAPTER 3

Chapter - 3

DATA AND METHODOLOGY

3.1 Introduction

The main data set for this study comprises of about 49000 km of conventional bathymetry data and about 2800 km of seismic reflection data. In addition, some published swath-bathymetric data have also been used to augment the conventional bathymetry data. In this chapter, sources of these data, equipments used for their acquisition, methodology adopted for processing, presentation and interpretation have been described.

3.2 Types and sources of data

The data being used and presented in this work were collected during various cruises of Indian and foreign research vessels. The Indian bathymetry data were acquired during various cruises of ORV Sagar Kanya, belonging to the Department of Ocean Development, New Delhi. To augment the Indian bathymetry data set, additional bathymetry data in and around the study area were extracted from the CD ROM database entitled “Marine Geological and Geophysical data from NGDC”, which was obtained from the National Geophysical Data Centre (NGDC), Boulder, Colorado, USA. The NGDC database is a compilation of data generated by various international organizations from time to time. The seismic reflection data used in this study mainly comprises of seven transects of single channel seismic reflection data acquired by the National Institute of Oceanography, Goa; onboard chartered vessel AAS Sidorenko. The summary of cruise identifications and types of data used from the cruises is presented in Table 3.1. The cruise tracks along which the bathymetry and seismic reflection data used in the present study were acquired, are shown in Fig. 3.1 and Fig. 3.2 respectively.

3.3 Methodology used for data acquisition

The methodology of acquisition of bathymetry and seismic reflection data in the oceanic areas are briefly described below.

3.3.1 Conventional and swath bathymetry data

a) Conventional bathymetry data

The bathymetry data were acquired along the ships tracks using echosounders. The echosounders have been the conventional equipment to measure the depth to the seafloor and map the seafloor topography. The echosounder, records the time taken for a sound pulse to travel from the transducer to the seafloor and back again. The depth to the seafloor is then half the product of this two way travel time and the mean sound velocity in the water column. The working principle of an echosounder is shown in Fig. 3.3.

b) Swath bathymetry data

In addition to conventional echosounding data, some published swath-bathymetric data in the study area have also been compiled to augment the bathymetry data set. This swath-bathymetry data were collected onboard ORV Sagar Kanya using Hydrosweep system. The swath-bathymetry system is a multi-beam echosounder, which measures depths simultaneously over a corridor of seafloor (swath) from a series of beams on either side of the ship.

Table 3.1: Cruise identification and types of data used in the present study. Wherever information is available, the main method for obtaining primary position during data acquisition in the deep water areas have been mentioned under the column 'Primary navigation'.

Vessel	Cruise Id.	Year	Types of data used			Primary navigation
			Depth	Seismic reflection	Swath-bathymetry	
A) Data Acquired by the National Institute of Oceanography (NIO), Goa, India						
ORV Sagar Kanya	SK-05	1983	Y	-----	-----	INS with TS
ORV Sagar Kanya	SK-12	1984	Y	-----	-----	INS with TS
ORV Sagar Kanya	SK-22	1986	Y	-----	-----	INS with TS
ORV Sagar Kanya	SK-50	1989	Y	-----	-----	INS with TS
ORV Sagar Kanya	SK-64	1991	Y	-----	-----	GPS
ORV Sagar Kanya	SK-79	1992	Y	-----	Y	GPS
AAS Sidorenko	AAS-09	1995	Y	Y	-----	GPS
B) Data obtained from databases of National Geophysical Data Centre (NGDC), Boulder, Colorado, USA						
RV Atlantis-II	A2008	1963	Y	-----	-----	-----
RV Robert D. Conrad	C0910	1965	Y	-----	-----	-----
RV Robert D. Conrad	C1707	1974	Y	-----	-----	GPS, TS
RV Robert D. Conrad	C1708	1974	Y	-----	-----	GPS, TS
RV Robert D. Conrad	C2704+	1986	Y	-----	-----	GPS, TS
RV Umita Kamaru	UM68+	1968	Y	-----	-----	-----
HMS Shackleton	SHACK475	1975	Y	-----	-----	TS
RV Atlantis-II	A2093L7	1977	Y	-----	-----	-----
RV Vema	V3306	1976	Y	-----	-----	TS
RV Vema	V3307	1976	Y	-----	-----	TS
RV Vema	V3407	1977	Y	-----	-----	TS
RV Vema	V3408	1977	Y	-----	-----	TS
RV Vema	V3617	1980	Y	-----	-----	TS
RV Vema	V3502	1978	Y	-----	-----	TS
R/V Jean Charcot	838008911	1984	Y	-----	-----	-----
HMS Charles Darwin	CD2087	1987	Y	-----	-----	GPS, TS
HMS Charles Darwin	CD2787	1987	Y	-----	-----	GPS, TS
HMS OWEN	OWEN61	1961	Y	-----	-----	Celestial
HMV Britannia	19910014	1988	Y	-----	-----	TS
HMS Invincible	19920157+	1992	Y	-----	-----	GPS, TS

INS: Integrated Navigation System; TS : Transit satellite; GPS: Global Positioning System: +: Profiles not considered/removed for contouring after carrying out mistie

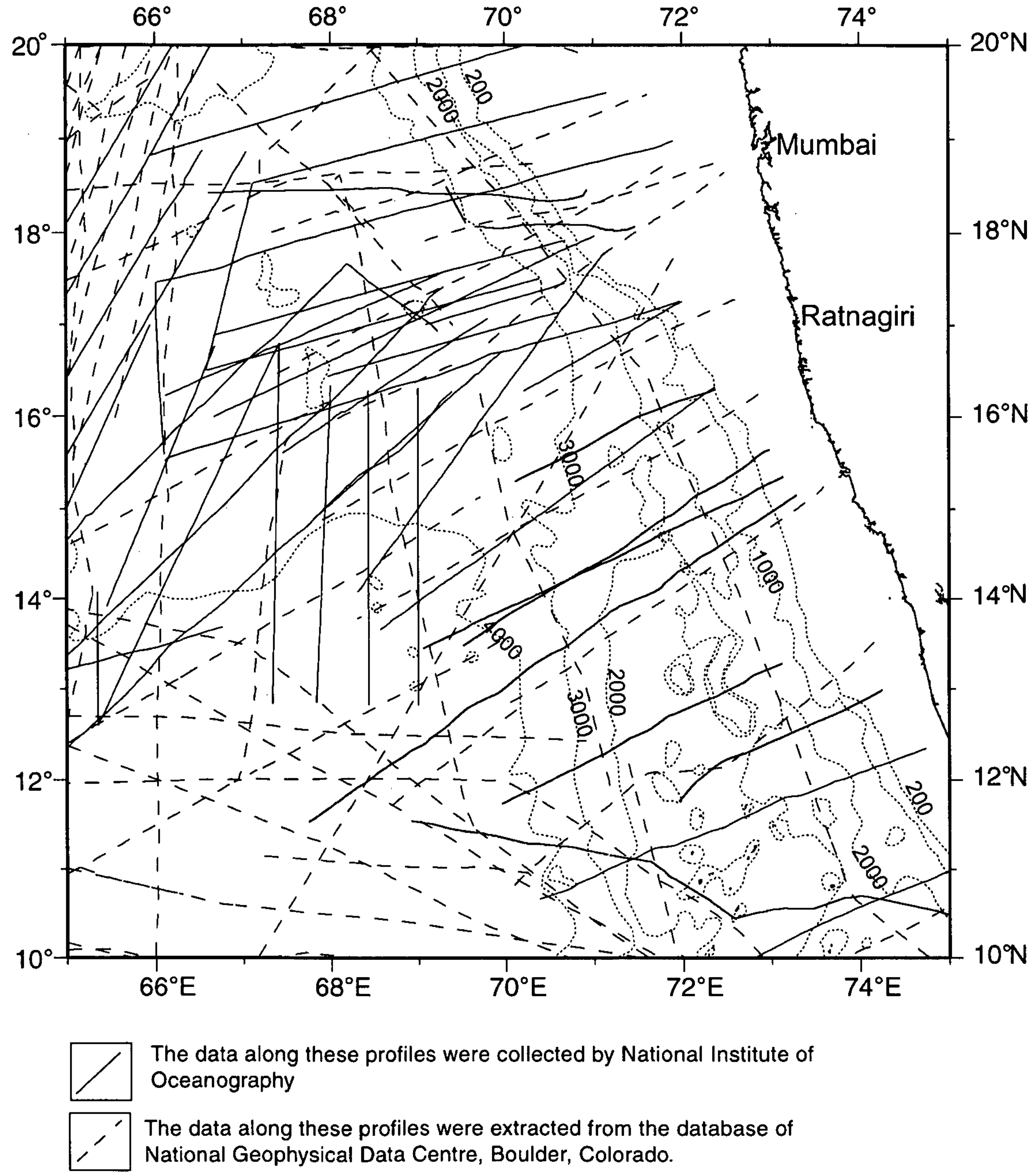


Fig.3.1 Cruise tracks along which the bathymetry data have been extracted and used in the present study. Details regarding the ships and cruises are presented in Table 3.1. Thin dotted lines are bathymetric contours adopted from Naval Hydrographic Chart (Chart No.7705).

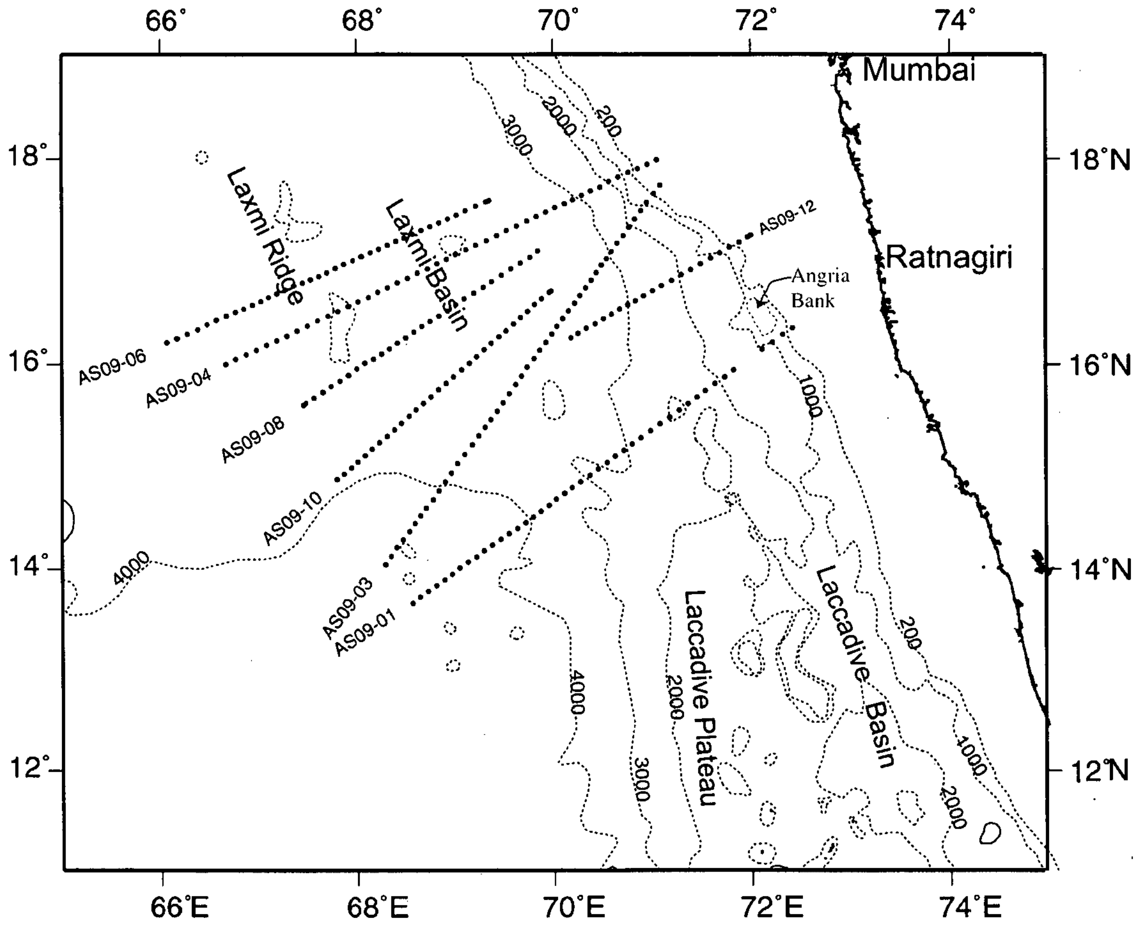
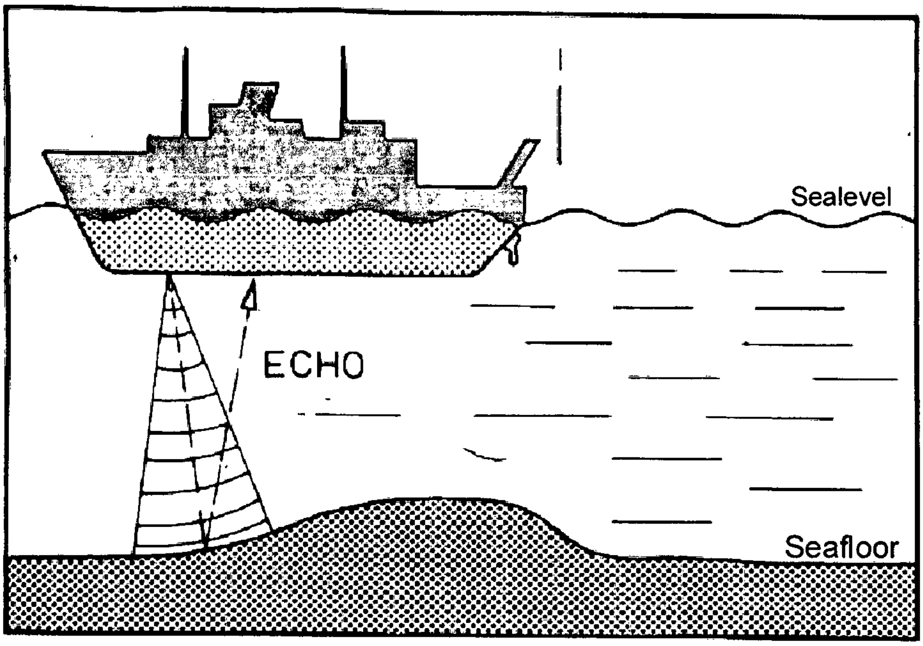
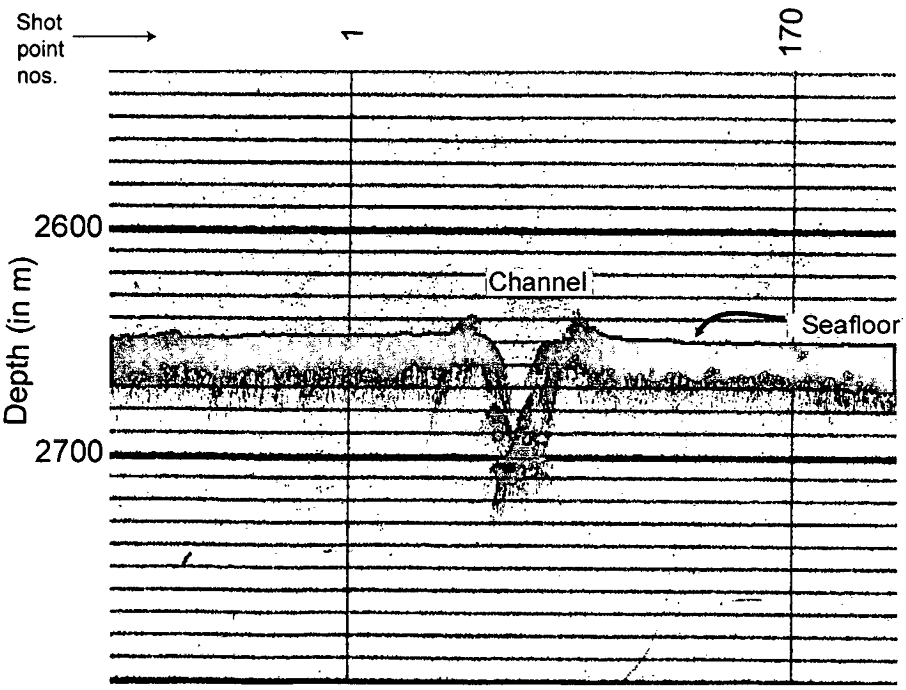


Fig. 3.2 Locations of seismic reflection profiles used in the present study.



(a)



(b)

Fig.3.3 Schematic representation of the principle of echosounding. (a) Echosounding technique, (b) sample echogram Horizontal lines are the depth lines at every 10 m. Vertical lines represent position reference shot point marks.

The "Hydrosweep System" (manufactured by M/s. Krupp Atlas Electronik, Germany) 45 degree on either side of the ship by a fan of 59 beams and can achieve a coverage on the seafloor equalling to twice the water depths. This coverage is known as swath width (Grant and Schreiber, 1990). Operator's console, which is a part of the Hydrosweep system facilitates to monitor the data collection. The data is processed to generate firstly, track-coverage maps. Secondly, the data from different tracks are merged to create depth contour maps (Kodagali, 1990, 1992).

3.3.2 Seismic reflection data

The seismic reflection data were acquired onboard AAS Sidorenko with a single channel seismic reflection data acquisition system. This data acquisition system consists of three basic subsystems: the acoustic source, the receiving unit, and the recording system. The concept of single channel seismic reflection data acquisition system is shown in Fig. 3.4. Onboard AAS Sidorenko a single channel seismic reflection system with an airgun as acoustic source was used. Following are the system specifications and acquisition parameters used onboard AAS Sidorenko for seismic reflection data acquisition.

A) Source

Type of Source	Airgun
Volume	3 Litres
Number of guns	1
Pressure	120 (atm/v)
Airgun depth below sea surface	3 meters
Towing distance astern of ship	40 meters

B) Receiver streamer

Type of Streamer	Piezoelectric single channel
Group length	45 m
No. of hydrophones	46

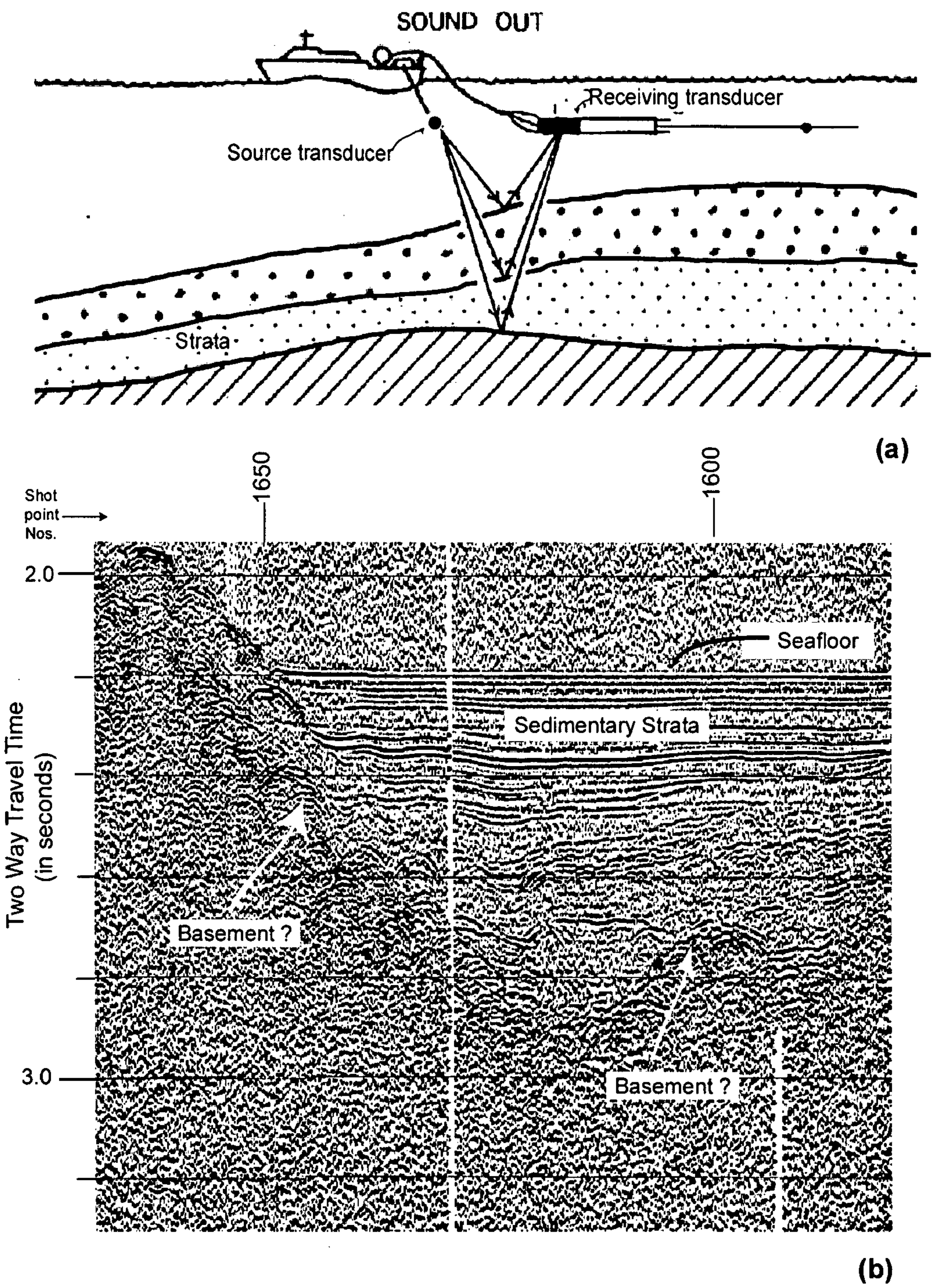


Fig.3.4 Schematic representation of the seismic reflection data acquisition: (a) Seismic data acquisition technique, (b) sample record of a marine seismic reflection section. In the section, vertical axis show the depth in terms of Two Way Travel Time (TWT), and the horizontal axis shows position reference shot points marks.

Towing depth below sea surface	7 m
Source receiver offset distance	320 m

C) Recording

Length of data recording	8 sec
Data sampling interval	0.5 msec
Filter (Bandpass)	20 – 500 Hz

The navigation during data acquisition on board AAS Sidorenko was provided with a Global Positioning System (GPS) and shots were fired in time mode with a shot point interval of nearly 50 m.

3.4 Methodology adopted for processing and presentation of data

3.4.1 Bathymetry data

The digital bathymetry data collected during the cruises were archived in NIO and NGDC databases in various formats. For the purpose of easy handling all the required data falling within and adjacent to the study area were extracted using available suitable softwares and were stored in a common format. The extracted information includes vessel, cruise identification, date and time of data acquisition, position of the depth measurement (latitude and longitude) and corrected depth values in meters. The extracted data were then plotted to know the trends of tracks of each cruise. The tracks were then divided into separate straight line segments and stored as separate data files with easily identifiable file identifications. The purpose of dividing each cruise data into relatively straight line segments was for easy handling and display as profile sections. Subsequently each profile data were displayed on monitor and visually checked for quality control. It was observed that at times the profiles contain erroneous spikes. The erroneous or spiked data may be due to a variety of reasons, e.g.

resulting due to instrument errors, rough sea conditions during data collection. The spiked data were identified from the profiles and edited / removed from the database. It was observed that the depth values in NGDC database are available as corrected depth, i.e. corrected for transducer depth and variation of sound velocity in seawater. However the depth values in NIO database were available as uncorrected measured depths. Therefore, the depth data extracted from NIO database were then corrected for transducer correction and velocity of sound in seawater using available software. To correct the measured depth values for variation of the sound velocity in seawater, the software uses the correction factor provided in Mathew's Tables (Carter, 1980).

The bathymetric data compiled in the present study is collected nearly over three decades onboard different vessels and using various types of echosounders. It was observed that many profiles cross each other at various points. A point of intersection between two segments of ship's tracks is defined as a "crossover point" (Verhoef et al.,1991). According to Verhoef et al., (1991), all factors being equal, observations along the two intersecting segments should agree at the point of intersection, but rarely coincides. This problem is more evident and obvious when the data are collected using various equipment and over long periods. They further opined that a crossover analysis of data helps in understanding the internal consistency of the data being handled. Therefore in order to achieve an "internally consistent" bathymetry dataset, crossover analysis was carried out on the bathymetry data compiled in the present study. For the purpose of calculating difference in the values at crossover points (mistie values) available software was used. The computed crossover mistie values were examined critically to identify the profiles, which consistently show mismatch with other profiles at crossover points and give rise to large mistie values. After evaluation, all the profiles which are inconsistent or "bad tracks" (Verhoef et al., 1991) with other profiles were identified and removed from the dataset. The dataset after removing the bad tracks were again subjected to crossover analysis. It was observed that in the total dataset at about 84% crossover points, the mistie was within 50 m (i.e. 25 to –25 m). The dataset after removal of bad tracks have shown that at about 91% crossover points, the mistie is within 50 m. It thus, appears that the internal consistency even for the total dataset was quite good and it has further improved after removal of bad tracks. The dense distribution of crossover points of the bathymetric profiles is shown in Fig. 3.5. The results of the crossover analysis of dataset before and after removal of bad tracks are given in Table 3.2 and as histogram in Fig. 3.6a & 3.6b. The corrected (i.e. bad track removed), bathymetry dataset was used for preparation of profiles and contour maps used for interpretation in this study.

The bathymetry data analysed in this study are presented as profiles and contour maps. The contour map was prepared to represent the generalized physiographic expression of the seafloor. For preparing bathymetric contour maps, first of all annotated depth maps have been prepared at a scale of 1:1,500,000 and that annotated map was contoured manually. A small segment of this annotated depth map has been presented in Fig.3.7 as an example. Subsequently the manually prepared depth contours were digitised using ARC/info GIS and stored as digital bathymetry contour data files. Separate files were created for each contour value. The final contour maps were plotted in desired scales using GMT software (Wessel and Smith, 1995).

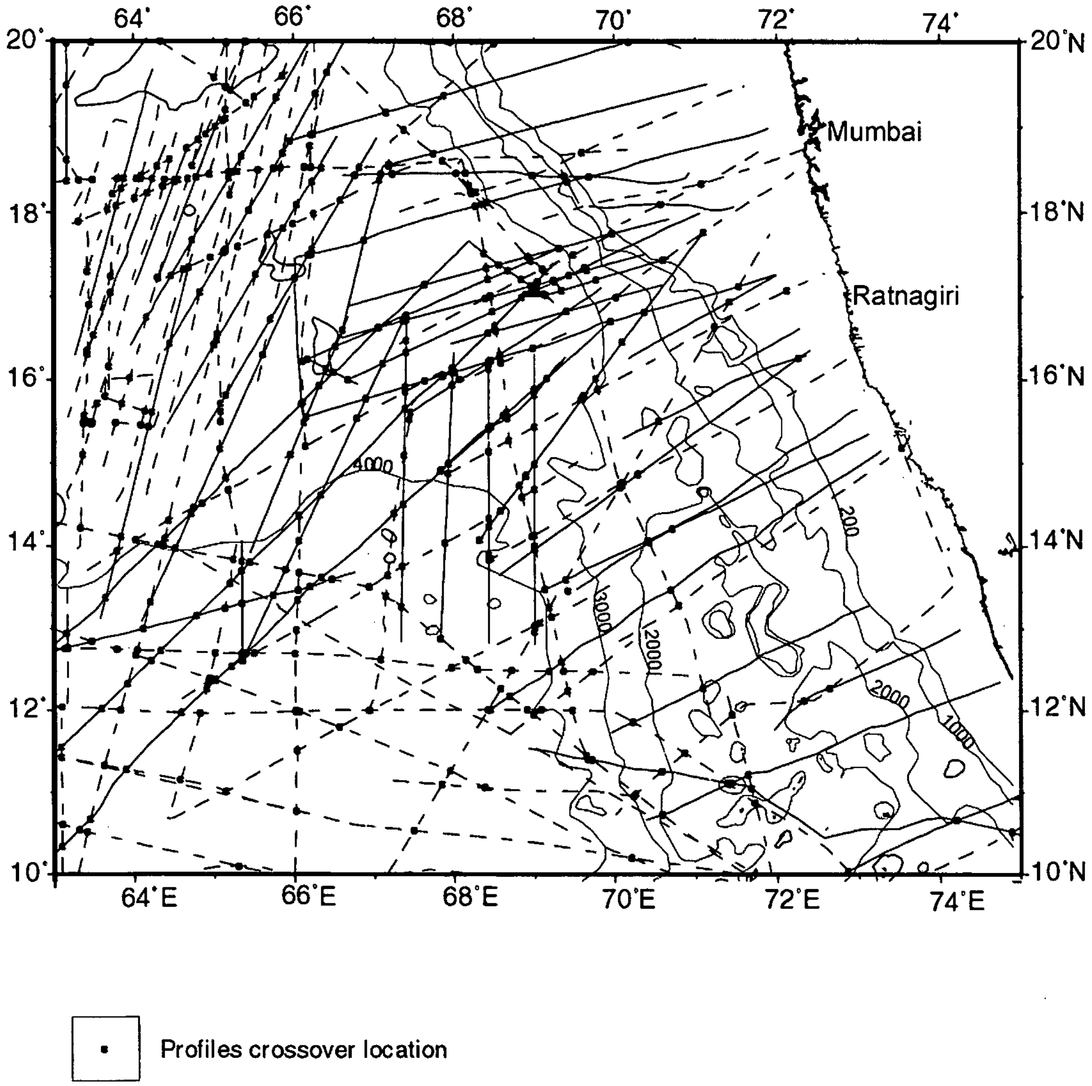


Fig. 3.5 Locations of crossover points of bathymetric data traverses used in the present study.

Table 3.2 Results of cross-over analysis of bathymetric dataset

Mistie of depth values. Range (meters)		Number of cross over points	
		Total dataset as retrieved	Dataset as compiled after removal of bad tracks
(376)	– (425)	1	0
(326)	– (375)	0	0
(276)	– (325)	1	0
(226)	– (275)	0	0
(176)	– (225)	2	1
(126)	– (175)	4	2
(76)	– (125)	15	2
(26)	– (75)	17	12
(25)	– (-25)	425	414
(-26)	– (-75)	20	16
(-76)	– (-126)	15	6
(-126)	– (-175)	1	0
(-176)	– (-225)	0	0
(-226)	– (-275)	0	0
(-276)	– (-325)	0	0
(-326)	– (-375)	0	0
(-376)	– (-425)	0	0
Total number of cross points		501	453

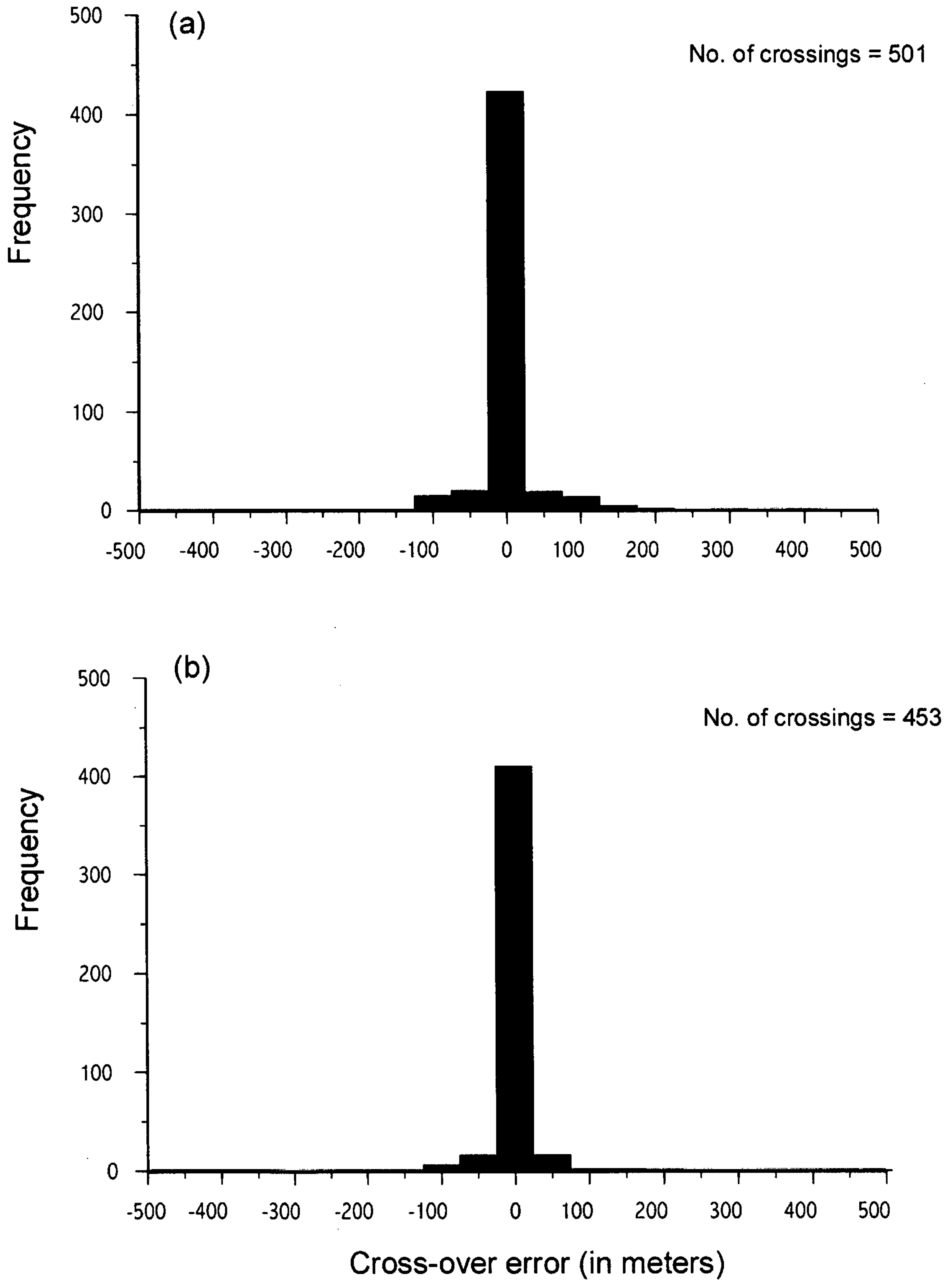


Fig.3.6 Histogram depicting results of cross-over analysis of the bathymetric data: a) original data set, b) data set after removal of bad profiles.

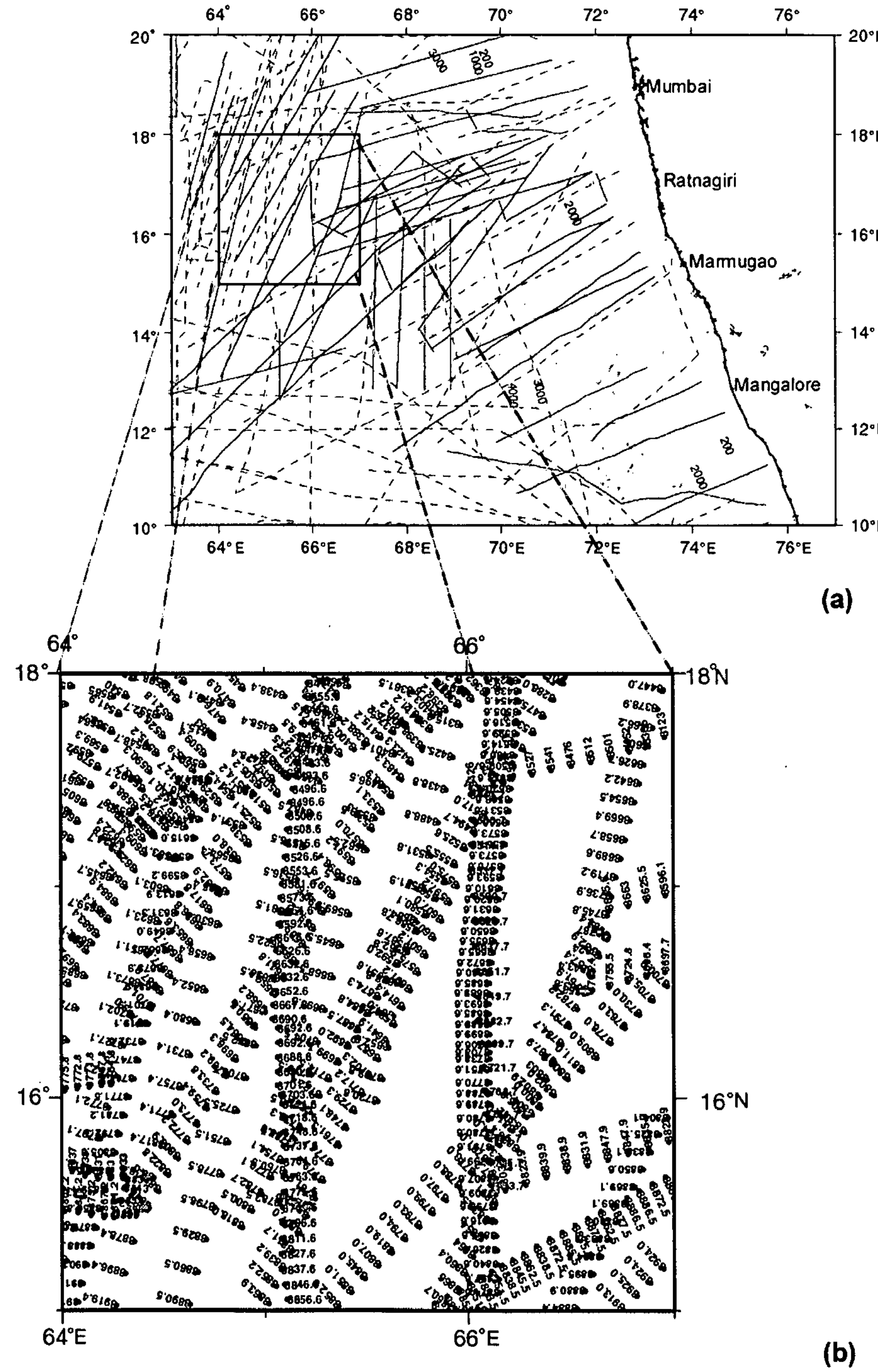


Fig. 3.7 Example of annotated bathymetric map used to prepare depth contour: (a) inset shows the area for which annotated plot have been presented in (b).

3.4.2 Seismic reflection data

During acquisition the seismic data recorded in magnetic tapes was processed by the acquiring agency onboard AAS Sidorenko. While processing, the data were re-sampled at 1 msec. A bandpass filter (frequency range 30-100 Hz) was applied on the dataset before final printing of the seismic sections. The final hard copy seismic sections were generated with an approximate horizontal scale of 1 cm = 1 km and vertical scale of about 1 cm = 70.4 msec of TWT. The interpretation was carried out onshore using the hard copy seismic sections. While interpreting, the basement, overlying sedimentary units and the intra-sedimentary features (such as faults, channel-levee etc.) were identified using the seismic sequence analysis approach. The interpreted sequence boundaries, horizons, faults etc. on seismic sections were manually digitised with reference to time mark on the seismic section. The digitised horizon values were incorporated in the position data file at appropriate shot point location and stored as a seismic horizon database. The seismic horizon database thus consists of position (latitude, longitude), time information at every shot point and depth value from the sea level (in TWT msec) to the interpreted horizons at respective shot points. The digitised data were used to plot interpretative line drawings of seismic sections using GMT Software. Prior to plotting, the distance between two successive shot points were calculated from the position information and appended to horizon database as cumulative distance in kilometres from the beginning of profile. In the interpretative line drawing sections, the distance is plotted along the X-axis and depth to the seafloor and sub-surface features in Two Way Travel Time (TWT) along Y-axis.

The seismic reflection data are presented as interpretative line drawing sections. Original seismic record sections, in which interpretations were carried out are of highly enlarged nature (Vertical scale:1cm = 0.1 sec TWT; Horizontal scale: 1cm = ~1.0 km). The interpreted line drawings were plotted in various scales as required for analysis and synthesis.

3.5 Details of presented maps

In the present study, all the interpretative maps (bathymetry) and seismic reflection) are generated in Mercator Projection. In general, the maps presented along with the text in the thesis are in the scale either 1:8,500,000 (or 1 cm = 85 km) or in the scale of 1:1,500,000 (or 1 cm = 15 km). The 1:8,500,000 scale maps were generated with reference latitude of 0° N, and 1:1,500,000 scale maps were generated with reference latitude of 17°N. The location map showing the tracks along which seismic reflection data were collected is presented in 1:3,500,00 scale with reference latitude of 22° 30'N.

CHAPTER 4

Chapter – 4

BATHYMETRIC STUDY

4.1 Introduction

The compiled bathymetry data have been used to prepare an updated bathymetry contour map of the study area. The sources of data and procedure followed for data correction and compilation is given in Chapter-3. The main data source for contouring was the digital depth data along the profiles. As mentioned earlier, almost a decade back, existence of a prominent seamount chain (consisting of three large seamounts) was reported (Bhattacharya et al., 1994b) in the axial part of the Laxmi Basin. However, the bathymetry maps of this area published subsequently depict only two seamounts, but do neither include the third seamount nor provide the detail bathymetry of the seamounts as revealed by the swath bathymetric investigations. In order to mitigate this inadequacy, the updated contour map prepared in this study integrates the detailed bathymetric contours of three seamounts located in the axial part of the Laxmi Basin. The data has been presented as profiles and contour map. In general the contours are drawn at an interval of 500 meters, however over the Laxmi Ridge, they are drawn with 250 meters interval and an additional 200 meters contour was drawn over the shelf area. Over the shelf, 200 meters contour was drawn with an aim to approximately define the extent of average shelf break in this region following Naini and Talwani (1982). Over the Laxmi Ridge, the contours were drawn at 250 meters interval, as it was felt necessary to use this contour interval for depicting gross morphology of the Laxmi Ridge more clearly. The contours from published hydrographic chart (chart No.7705, Indian Naval Hydrographic Office) are taken into consideration while contouring for reference. Wherever additional data points warranted modification, the contours given in the hydrographic chart were modified. In other places (i.e. wherever additional control depth values are not available), the contours given in the hydrographic chart were adopted to complete the contours. The bathymetry contours of the published hydrographic chart are presented in Fig. 4.1 as an example of bathymetry contours of this area prior to the present study and the updated bathymetry contour map prepared in this study is given in Fig. 4.2. In order to depict the sectional view of major physiographic features, few bathymetry profiles running across the study area have been selected and presented as stacked bathymetry profiles. The cruise tracks of these selected bathymetry profiles are given in Fig.4.3 and stack of those bathymetric profiles is presented in Fig.4.4. The main aim of studying bathymetry data is to define the physiographic expression of the major structural features more clearly. This chapter presents a description of the important physiographic features depicted from the profiles and contour map.

4.2 Major physiographic features of the study area

4.2.1. *Shelf and slope*

The shelf area as defined by 200 m contour has variable width (Fig. 4.2). South of Ratnagiri, the shelf is narrow (about 100 km) till at least up to Mangalore. Further south the shelf is still narrower. North of Ratnagiri, the shelf gradually

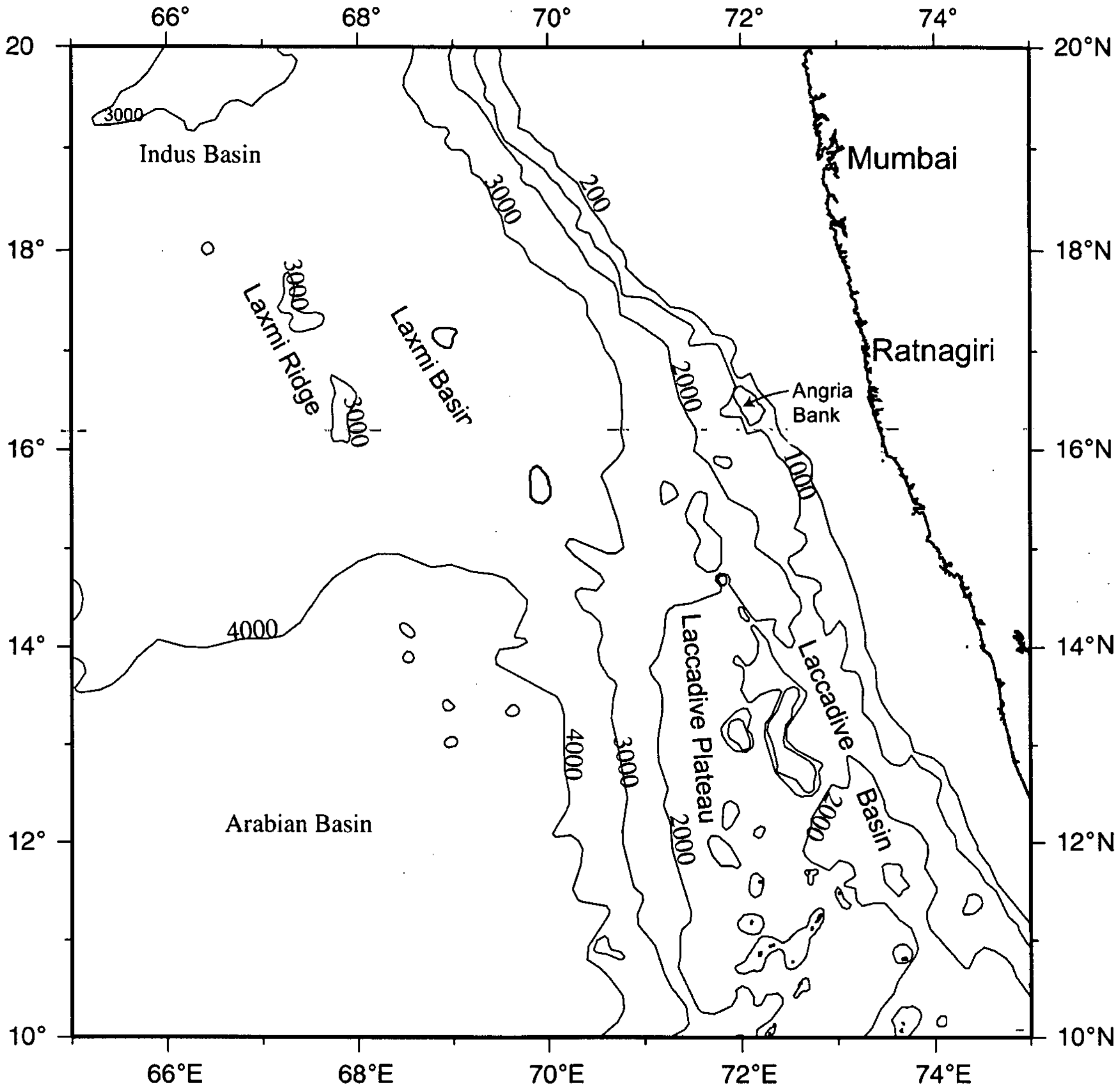


Fig.4.1 Bathymetry contours of the study area from the published hydrographic chart (chart No.7705, Indian Naval Hydrographic Office).

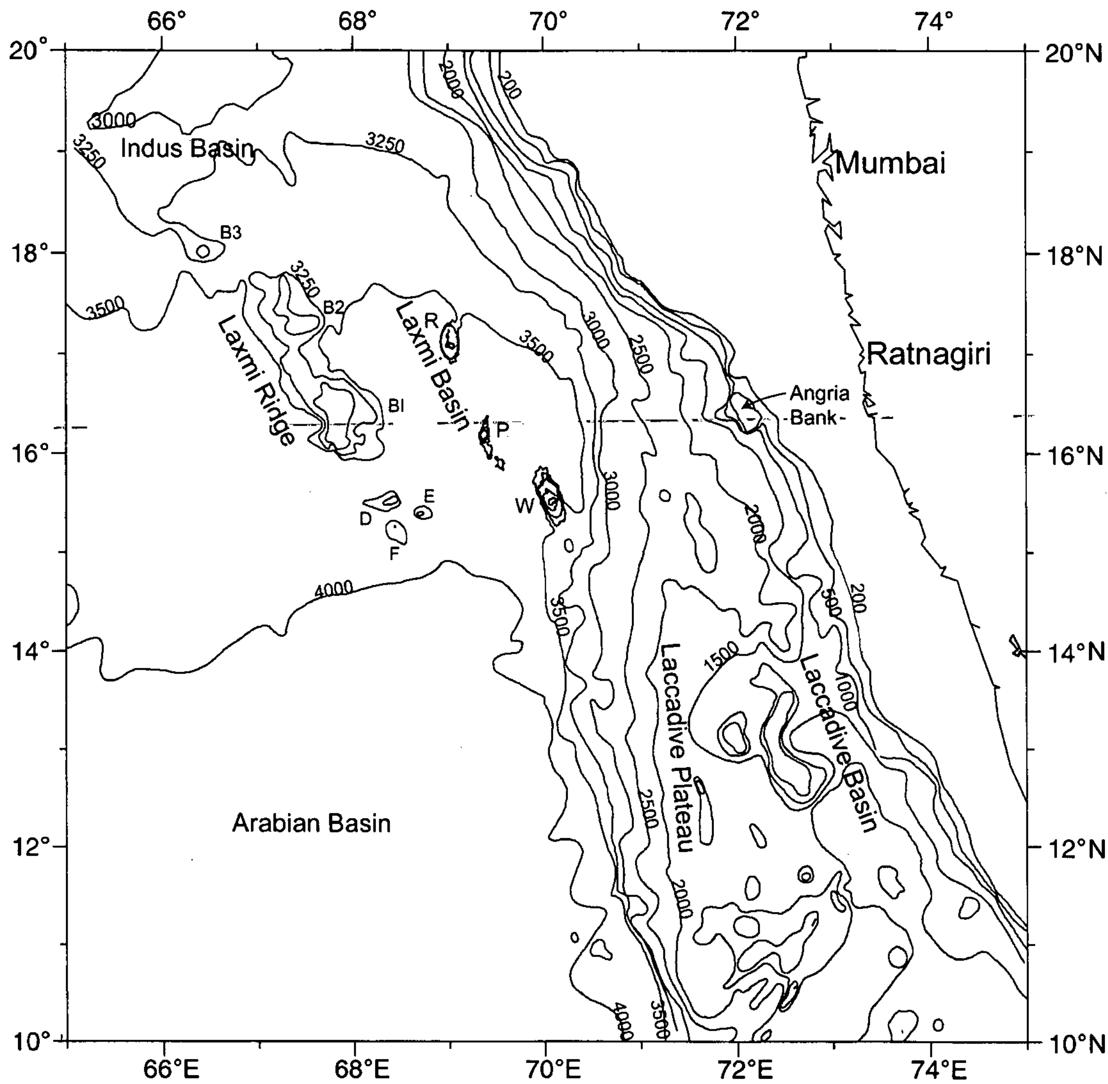


Fig.4.2 Updated bathymetric contour map prepared in the present study. Cruise tracks along which the data used to prepare this contour map are presented in Fig. 3.1. In general the contour interval is 500 m, however, over the Laxmi Ridge the contour interval is 250 m, and an additional 200 m contour over shelf area is presented. B1, B2, B3: blocks in the summit region of the Laxmi Ridge. R: Raman Seamount; P: Panikkar Seamount; W: Wadia Guyot. D, E and F: isolated hill like features southeast of the Laxmi Ridge as defined by 3750 m contour.

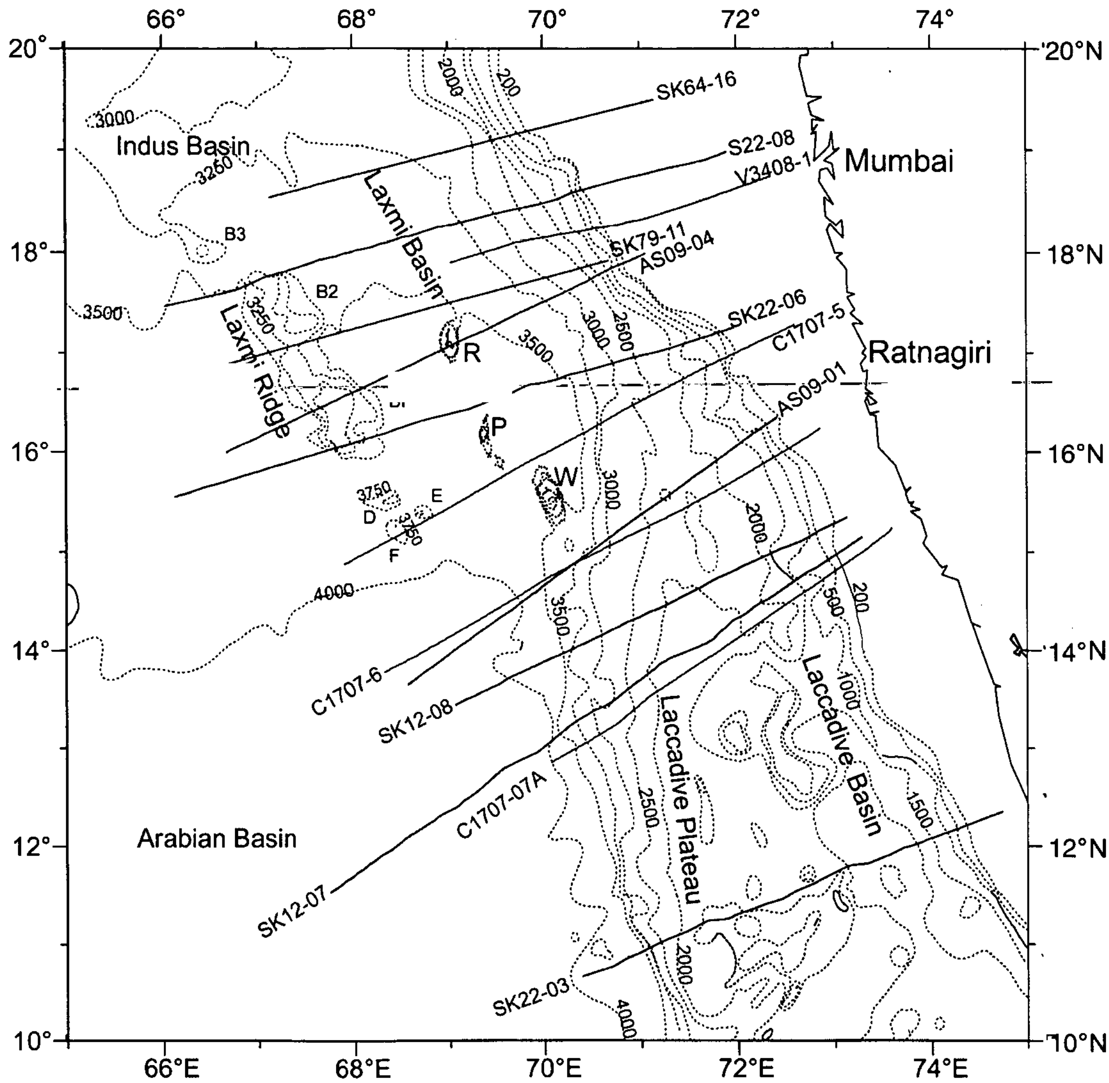


Fig.4.3 Map showing location of selected bathymetry profiles along which sectional views have been presented in Fig.4.4. Annotations along the tracks are profile identifiers. Thin dotted lines are the bathymetric contours prepared in the present study. Contour intervals and other details are as in Fig.4.2.

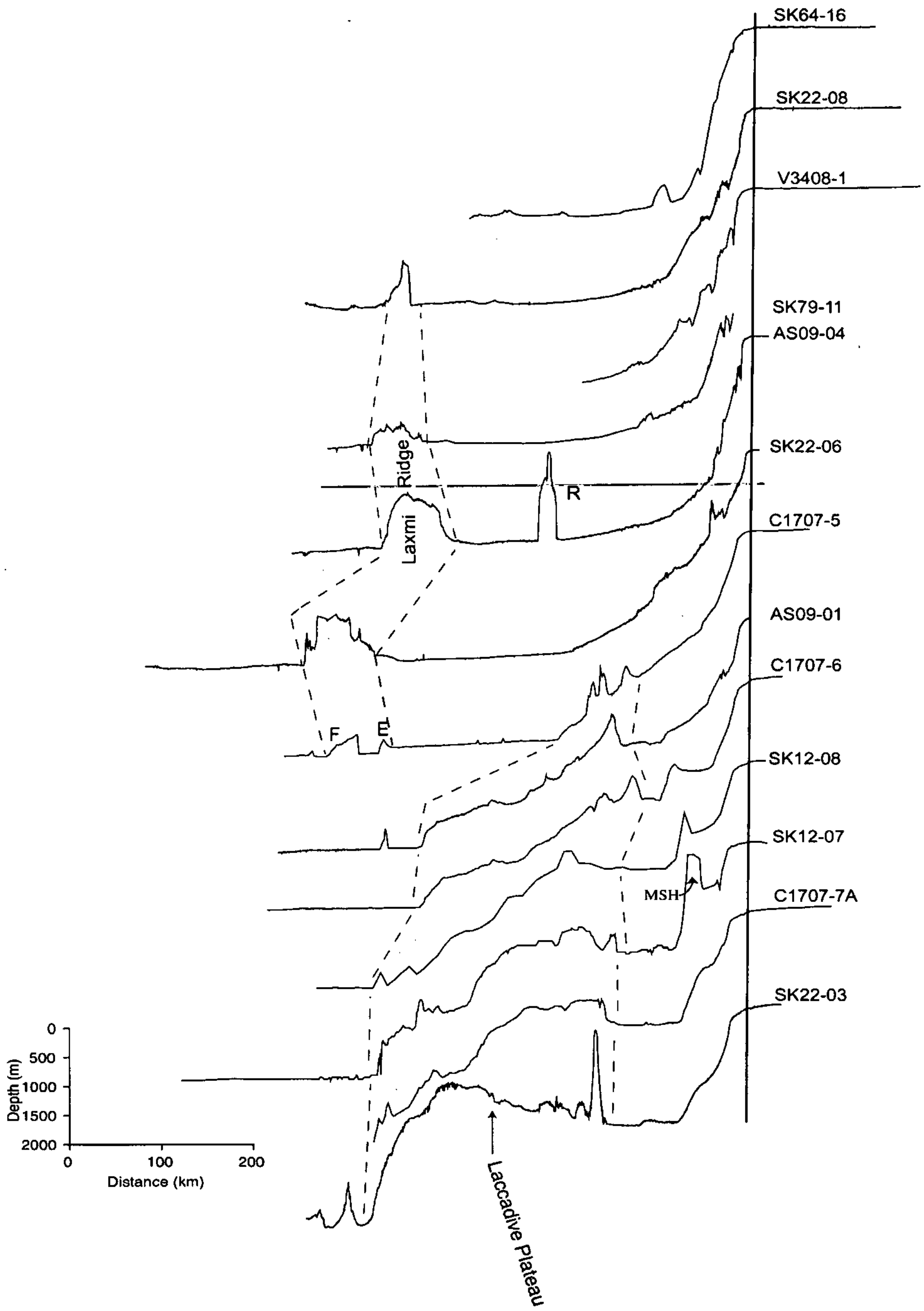


Fig.4.4 Selected bathymetric profiles across the study area showing the sectional view of various major physiographic features. Location of these profiles is presented in Fig. 4.3. The profiles are stacked from north to south aligning approximately with the shelf edge (thick line). The limits of major structural features are marked with thin dashed line and labeled. R: Raman Seamount. MSH: Mid slope high (off Goa). Annotations adjacent to profiles are profile identifiers as given in Fig. 4.3.

widens to the north and in the regions off Mumbai attains a maximum width of about 300 km. The normal continental slope and rise configuration is relatively well pronounced in the areas north of 17°N, whereas in the areas south of 17°N the configuration is not clearly depicted due to presence of several isolated highs and the Laccadive Plateau. One of such highs observed off Goa (along profile SK12-07 in Fig. 4.4) attains a height of ~1600 m from the adjacent sea floor on the west. The bathymetry profiles north of 16°N (Figs. 4.3 and 4.4) display a characteristic rugged slope. The extent of this rugged slope topography matches well with the zone of slumping mapped by various workers based on analysis of surface sediment samples (Chauhan and Almeida, 1993; Rao et al., 2003; Guptha et al., 2002). In general, beyond the slope the seafloor is smooth till the eastern face of the physiographic highs (Laccadive Plateau, Seamounts, Laxmi Ridge) are reached.

4.2.2 *The Laccadive Plateau*

The Laccadive Plateau (Fig. 4.2) is the most prominent physiographic feature in the deep offshore regions of western India. The Laccadive Plateau as mentioned earlier is the northern segment of the Laccadive-Chagos Ridge. It is considered (Bhattacharya and Chaubey, 2001) that the Laccadive Plateau extends northward from about 10°N. However the present study covers only the northern part of this plateau that lies north of 12°N. In this study area too the Laccadive Plateau appears to maintain its general N-S trend. Towards the southern part it is broad and gradually narrows towards north. Based on the contour pattern, the physiographic expression of the Laccadive Plateau do not appear to extend beyond 16° 50' N. The Laccadive Plateau appears to be an asymmetric feature (Fig. 4.4) with a gently dipping western limb and relatively steeper eastern limb. Towards west the gentle flat seafloor (~4000 m) of the abyssal plain abuts against the western limit of the plateau. In some profiles, the western limit of the plateau coincides with a scarp face wherein other profiles, the western limit is a gradual transition to the abyssal plain. Over the plateau the shallow banks and islands having their individual trends rise from a broad platform whose aerial extent can be defined by the 2000 m contour. The Wadia Guyot (W) appear to abut (Fig. 4.2) against the gently northwestward plunging Laccadive Plateau approximately near 15°N, 70° 15'E and appears as a spur like feature of the plateau.

4.2.3 *The Laxmi Ridge*

The other prominent physiographic feature in the study area is the Laxmi Ridge. The ridge (Fig.4.2) is a NW-SE trending linear feature located on the gently southward dipping abyssal plain region and extends between 16°N and 18°N. Saddle like features appear to divide the physiographic expression of the summit region of the ridge into three blocks. The shallow contours over the individual blocks appear to trend N-S. For the ease of discussion in this study these blocks are referred from south to north as block B1 (centered around 16°20'N, 68°10'E), block B2 (centered around 17°20'N, 67°15'E) and block B3 (centered around18°N, 66°25'E).

The block B1 is encompassed by 3500 m contour in south, east and west directions. However, the average water depths around the block are in the range of 3600 m except at southwestern side, where the water depths increase to more than 3800 m. Further, the bathymetry data suggests that eastern limb is gentler as compared to the western limb, whereas the southwestern limit of the Laxmi Ridge is in the form of a relatively steeper scarp face. The shallowest depth over this block is observed to be about 2805 m, which gives the total height of about 950 m to this block. A saddle like feature (at around 17°N and 67°22.5' E) separates this block from block B2 at the level of about 3250 m. The block B2 appears to rise from a surrounding water depth of 3500 m. In absence of any profile crossing the shallow summit regions of the block, the shallow depths could not be ascertained correctly, however, based on the 3000 m contour published in hydrographic chart, it appears that the minimum height of the block should be of the order of 500-600 m. From the contour pattern it appears that the block B2 has more symmetrically dipping flanks as compared to southerly block BI. This block B2 is separated from block B3 by a saddle like feature at the level of 3250 m contour. The block B3 is the northernmost (Fig.4.2) block and is surrounded by 3250 m contour. The western face of the block is relatively steeper as compared to its gently dipping eastern face. Overall within the study area, the total length of the Laxmi Ridge is about 327 km and the width varies from a maximum of about 74 km to a minimum of about 17 km.

4.2.4 *Isolated hills southeast of the Laxmi Ridge*

Three small hill like features were mapped about 50 km southeast of the Laxmi Ridge edifice. It is observed that the existence of these features was not reported in any earlier publications or hydrographic charts. These features have been marked as D, E and F in Fig. 4.2. The hill D is bigger, rhomboidal in shape, 436 m in height, about 42 km in width and trends approximately in an E-W direction. The hill E is elliptical in nature, about 400 m in height, about 22 km in width and trends approximately in an E-W direction. The hill F is also elliptical in shape, about 200 m in height, about 25 km in width and trends approximately in a NW-SE direction.

4.2.5. *The Laxmi Basin seamount chain*

Along the axial part of the Laxmi Basin lies a prominent linear chain of seamounts consisting of three major edifices namely Raman Seamount, Panikkar Seamount and Wadia Guyot (Fig. 4.2). These three seamounts together form nearly N30°W trending linear seamount chain of about 250 km length and extends from 15°N,70°15'E to 17°20'N, 69°E. These seamounts appear to be the first one in the Arabian Sea whose bathymetry has been established in details using the swath-bathymetric investigations (Bhattacharya et al., 1994b). These seamounts are relatively steep sided and as mentioned earlier are of large dimensions. The Raman seamount, which is the northernmost seamount having a basal area of about 660 sq. km and height of about 1505 m rises from surrounding seafloor of average depth of 3550 m. The Panikkar Seamount, which is the middle edifice of the seamount chain, have a basal area of about 300 sq. km and height of about 1068 m rises from a surrounding water depths of 3700 m. The third and the largest of the edifices of the seamount chain, the Wadia Guyot is having a basal area of about 1210 sq. km and height of about 2240 m. The bathymetric contour prepared in the present study (Fig. 4.2) clearly indicates that this Wadia guyot abuts against the northwestern plunging the Laccadive Plateau.

4.2.6. *The Arabian basin*

The study area covers only northeastern portion of the Arabian Basin (Fig.4.2). It appears that its eastern and northern limit are bounded by the Laxmi Ridge and the Laccadive Plateau. The water depths of the Arabian Basin in the study area extends from 3500 m to a maximum of about 4400 m towards the southwestern part of the study area (Fig.4.2). In general the physiography is smooth but details in the bathymetric profiles suggest that at places the smooth topography is modified by the presence of channels and associated depositional features probably of turbidity channel sedimentation origin. However, the contour interval does not allow to depict the relatively minor features like turbidity channels.

4.2.7. *Southern part of the offshore Indus Basin*

A small portion of the offshore Indus basin is covered in the present study. The water depths in that area generally ranges between 3000-3500 m. The topography in this basin appears to be affected and modified by the turbidity channels and associated depositional features.

CHAPTER 5

Chapter – 5

SEISMIC REFLECTION STUDIES

5.1 Introduction

In the present chapter, seismic reflection data is described along each profile with the help of interpretative line drawing sections. The locations of seismic lines are shown in Fig. 5.1. The data being single channel did not provide any velocity information within the sedimentary layers, therefore the depths to the horizons were measured and presented in msec of TWT (Two Way Travel time). Each profile has been described individually and the description is carried out from shelf to deep sea and from southern profiles to northern profiles. Before proceeding to describe individual profiles, the various seismic units identified in the study area have been described briefly.

5.2 Various seismic units identified in the study area

The seismic data have been interpreted using seismic stratigraphic technique. Broadly speaking, this process involves dividing the seismic record section into significantly different components, termed "seismic units", that are characterized by their internal reflection pattern, boundary geometry and structure. These seismic units are considered to represent different depositional regimes in an area. Within the study area fifteen gross seismic units have been identified. Brief description of these various seismic units have been provided with the help of segments of original seismic record section (Figs.5.2 to 5.6). The colour codes and nomen-

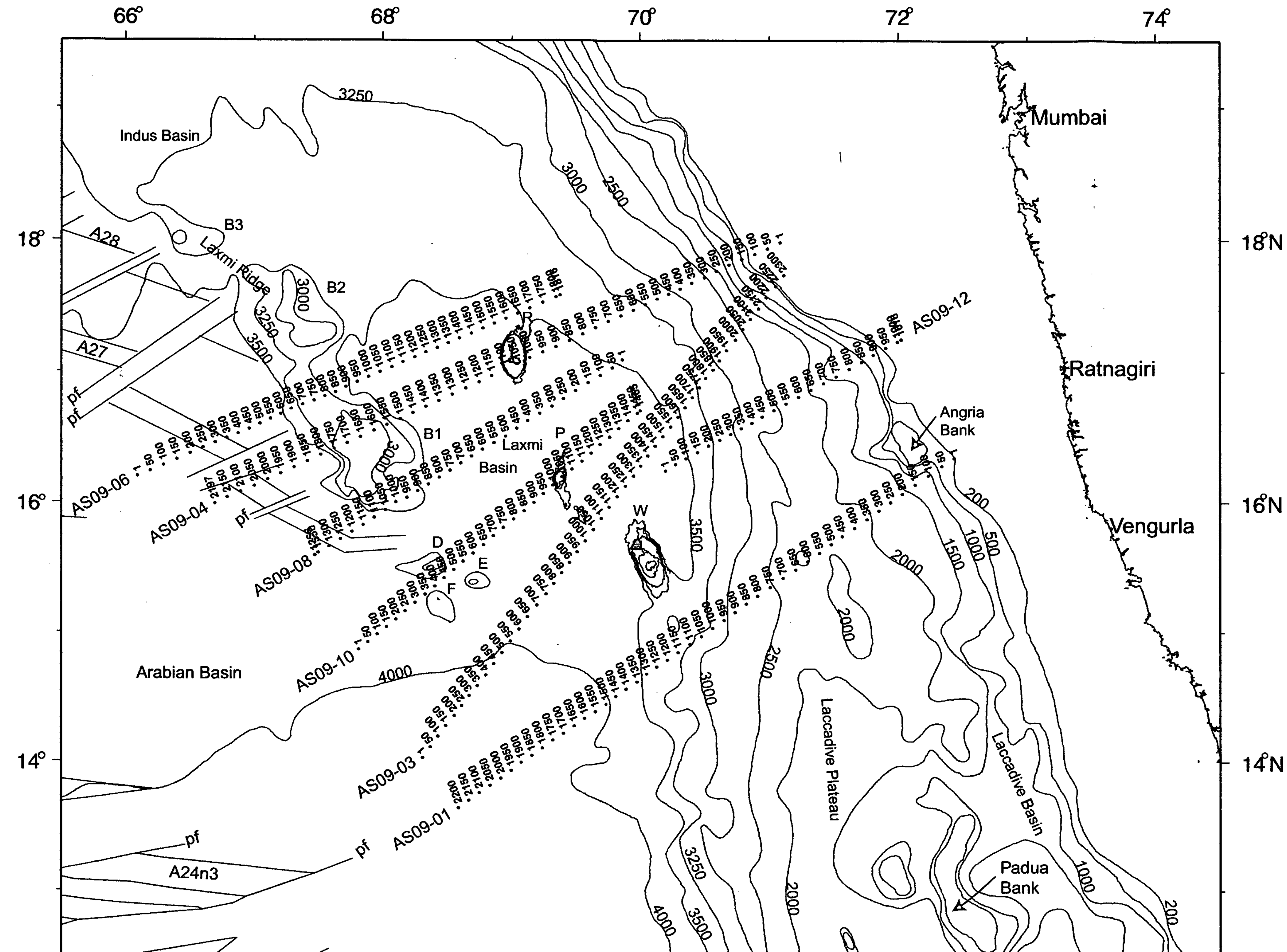


Fig.5.1. Location of seismic profiles used in the present study with shot point numbers annotated perpendicular to the track. Profiles are labelled with profile number. Selected bathymetric contours as prepared in the present study. Straight lines separated by pseudofaults (pf) are published seafloor spreading magnetic lineations labelled with anomaly numbers. Solid square over Wadia Guyot (W) is the location of core sample discussed in the text. Other features are as in Fig.4.2.

clature used for various seismic units are given in Table 5.1. While naming the units, an attempt is made to associate the unit name with the area where those units were found to occur most conspicuously. It has been observed that along the profiles a varying combination / juxtaposition of these seismic units occur at different locations. Following are the brief description of these seismic units.

a) Acoustic basement (Unit ACB and Unit OACB)

In a seismic reflection section, the sedimentary succession is usually characterized by presence of well defined parallel reflectors resulting from the bedded sedimentary sequence. Sometimes the sedimentary succession also are characterized by reflection free zones or by very weak, continuous to discontinuous reflectors. The base of the sedimentary succession is usually identified in the seismic record as a rugged strong reflector or the deepest observed reflector below which no other reflectors are seen (Ewing and Tirey, 1961; Kumar, 1978; Droz and Bellaiche, 1991). When this reflector depict a rugged surface and give rise to hyperbolic acoustic returns, it is considered to represent the igneous or crystalline basement or top of Layer 2 of oceanic crust (Naini, 1980). The basement rocks represent a sharp increase in seismic velocities and give a high acoustic impedance contrast relative to the overlying sediments, thus, the basement surface is usually depicted as a strong reflection event. Wherever velocity information is available (for example, in multi-channel seismic surveys) the basement can be recognized by sudden increase in the velocity. However, in some cases, due to limitations of the acoustic energy used or large thickness of the

Table 5.1 : Legend of various seismic units identified in the present study along with their brief description

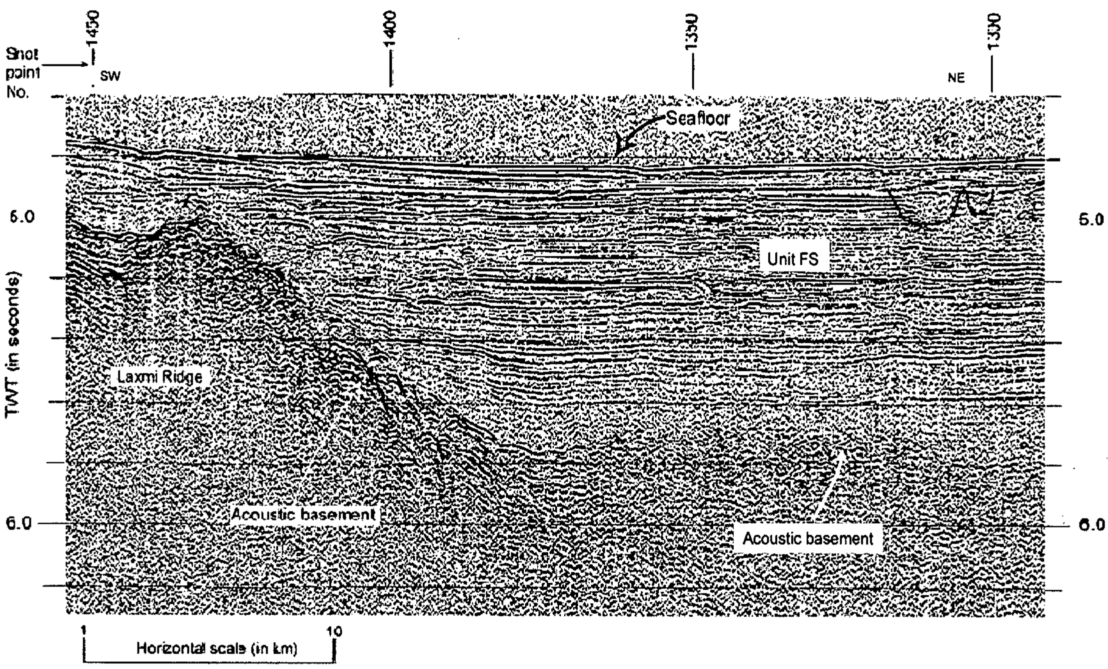
	Unit - SL	Sediments of the slope region
	Unit - FS	Indus fan sediments
	Unit - ARPFU	Upper pre-fan sediments of the Arabian Basin
	Unit - ARPFL	Lower pre-fan sediments of the Arabian Basin
	Unit - LRPR	Faulted sediments of the Laxmi Ridge
	Unit - ATLLX	Acoustically transparent layer of the Laxmi Basin.
	Unit - LPIL	Intervening layered sediments of the Laccadive Plateau
	Unit - MSIL	Intervening layered sediments of the midslope regions
	Unit - ATLLP	Basal transparent layer of the Laccadive Plateau
	Unit - LCBU	Upper sedimentary unit of the Laccadive Basin
	Unit - LCBL	Basal sediments of the Laccadive Basin
	Unit - OACB	Acoustic basement in the areas of identified oceanic crust.
	Unit - ACB	Acoustic basement

Carbonate buildup (?)

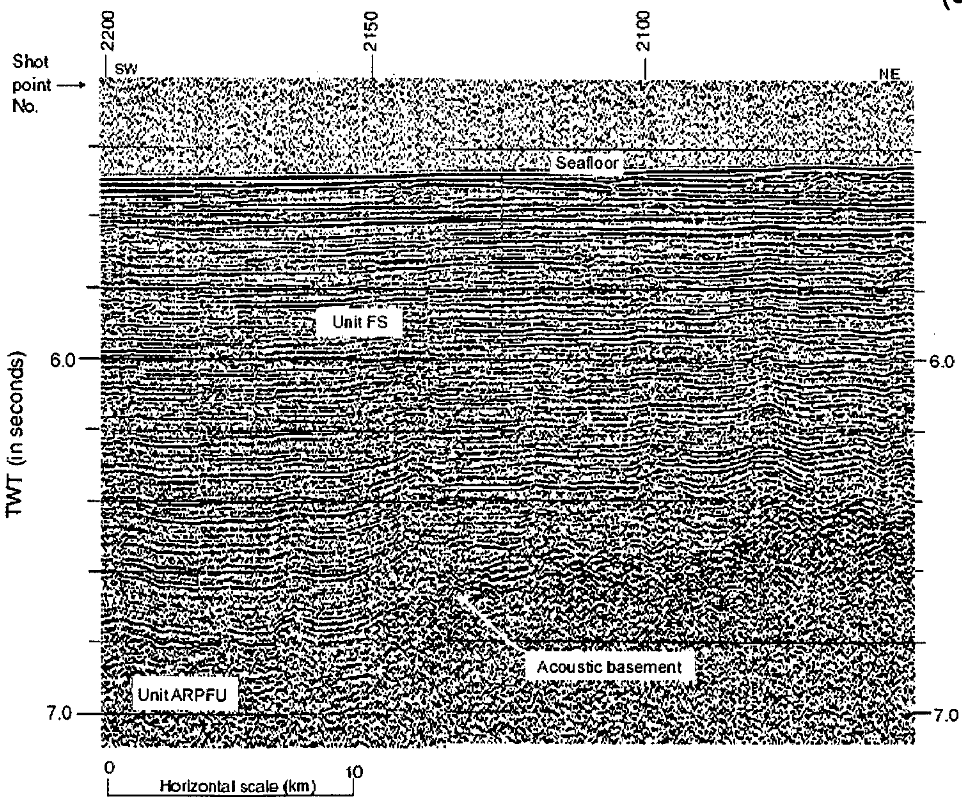
Diapiric structure

Sedimentary overburden or geological complexities, the sound pulse may not penetrate through the entire sedimentary succession and get reflected from the underlying basement surface. In such cases, a term "acoustic basement" is commonly used in seismic parlance to define a reflecting horizon below which no underlying reflectors are mappable using a particular seismic system.

In the present study, the term basement is used to define the seismic reflector which represents the acoustic basement. At places this acoustic basement and the crystalline basement appears to be the same (for example Fig. 5.2a), in other places it represents the lower most identifiable reflector as mentioned above (Fig. 5.2b). It is also noted that in the neighbourhood of the study area (over the identified oceanic crust or over the Laccadive Plateau), the drilling results (DSDP Sites 219 and 221) indicated that the acoustic basement identified in the seismic section represents the top of thin veneer of strongly reflective cherts or lava flows (Naini, 1980; Shipboard Scientific Party, 1972) which overlie the deeper basement. Based on identification of seafloor spreading magnetic anomalies in some areas of the Arabian Basin, the oceanic nature of the underlying crust was inferred. The acoustic basement of the profiles in such areas is considered to represent the oceanic basement that may be overlain by such a chert layer.



(a)



(b)

Fig 5.2 Part of the seismic reflection records depicting the Acoustic basement, Unit ARPFU and Unit FS. a) record along profile AS09-04 (SP 1300 - SP 1450) and b) record along profileAS09-01 (approximately from SP 1450 - SP 1300).

b) Faulted sediments of the Laxmi Ridge (Unit LRPR)

This unit is present mainly over the basement high regions and adjacent basinward dipping flanks of the Laxmi Ridge (Fig. 5.3a). This unit is characterized by moderate amplitude, continuous, sub-parallel reflections and is inferred to represent well stratified sediments. On the apex region of the Laxmi Ridge, an acoustically transparent layer overlies this unit, whereas, on the slopes of the Laxmi Ridge, the younger sequences onlap over this unit. This unit occurs over the basement highs and troughs of the Laxmi Ridge and adjacent slope regions. Based on well defined truncation of the reflectors in association with the apparent faulted surface of the basement, it appears that this unit was also faulted along with the basement.

c) Acoustically transparent layers of the western deep offshore (Unit ATLLP and Unit ATLLX)

In the study area, wide spread occurrence of acoustically transparent to very weakly laminated seismic unit was observed. In basinal areas, this unit overlies the basement, and in the basement high regions it drapes over the basement highs. In absence of any significant internal reflection pattern, it is difficult to infer whether this acoustically transparent unit represents one sedimentary package or different packages in the entire study area. However, based on the bounding surface and the presence of intervening layers, it appears that at least two different acoustically transparent units are present in the study area. These two units are named as following;

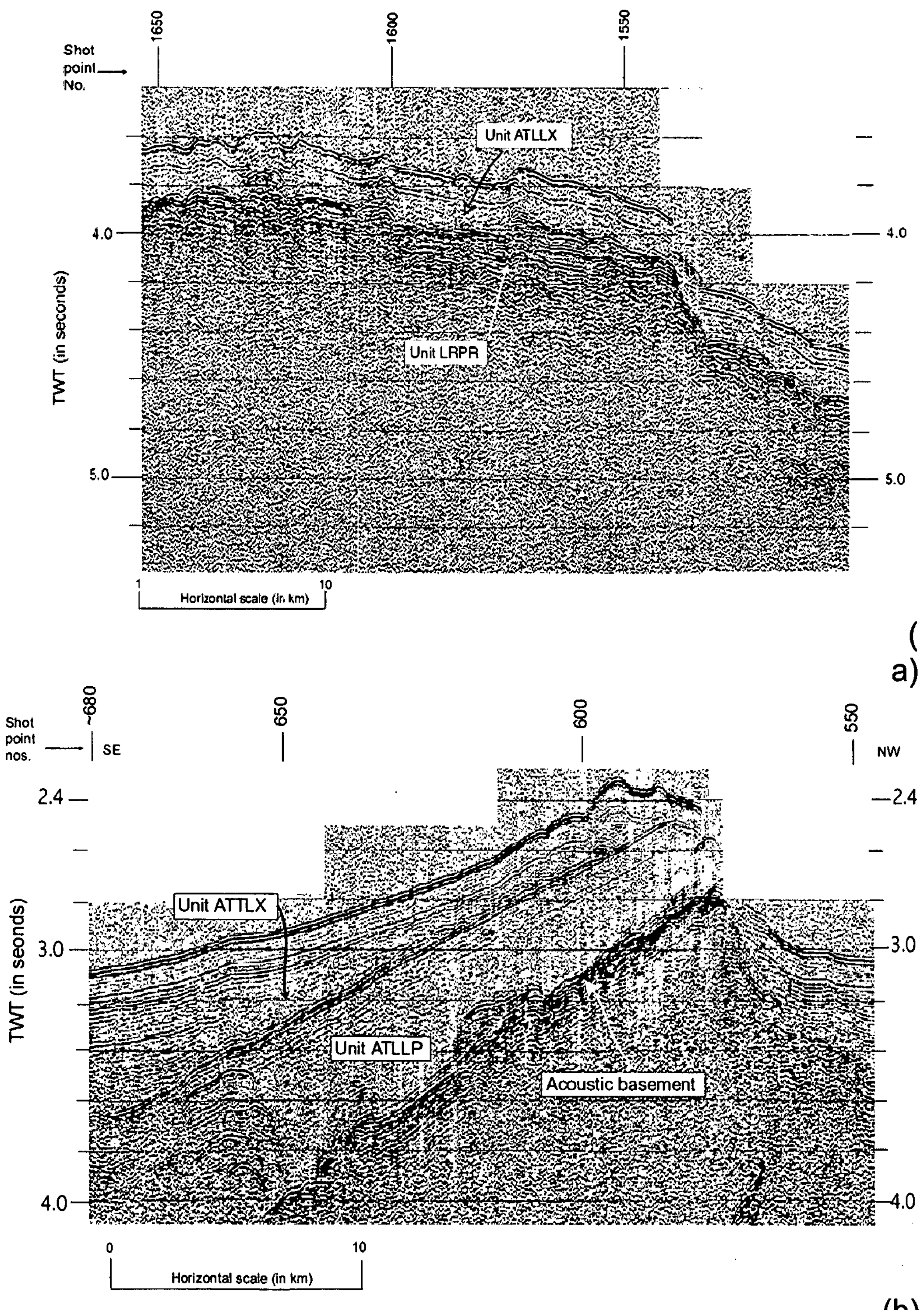


Fig.5.3 Part of the seismic reflection records depicting Acoustic basement, unit LRPR, Unit ATLLP and unit ATTLX. a) record along profile AS09-04 (approximately from SP 1500 - SP 1650) and b) record along profile AS09-01 (approximately from SP 975 - SP 1100).

i) Basal transparent layer of the Laccadive Plateau (Unit ATLLP)

ii) Acoustically transparent layer of the Laxmi Basin (Unit ATLLX).

The unit ATLLP is present over the Laccadive Plateau region and is clearly distinguishable along seismic profile AS09-01. Most part of this unit is characterized by absence of any internal reflections. It overlies the basement, follows the basement trend and appears to have been titled along with the tilting of the basement. Its upper boundary clearly represents a surface of unconformity over which the upper acoustically transparent unit ATLLX onlaps (Fig.5.3b).

The acoustically transparent unit ATLLX is widespread and forms the basal unit in the Laxmi Basin area and in the Laccadive Plateau region onlaps on to the lower unit ATLLP. At places, this unit contains very weak, incoherent and discontinuous reflectors. In the basinal parts, this unit is overlain by younger sedimentary sequences and its upper surface forms an unconformity. This unit drapes over the positive bathymetric features of the Laccadive Plateau, the Laxmi Ridge and at many places the unit outcrops at the seafloor level. Similar acoustic transparent layer appears to be present atop the summit region of the seamounts.

d) Layered sedimentary unit over Laccadive (Unit LPIL)

The unit LPIL occurs as an intervening unit between the acoustically transparent units ATTLP and ATLLX. This unit is characterized by closely spaced acoustic laminations and fairly continuous, moderate amplitude reflection pattern (Fig.5.4a). Its occurrence is localized on the flanks of a basement high zone which extends along the axial part of the Laccadive Plateau and the Laxmi Basin. This unit appears to thicken towards the basement high zone and wedges out outwards. The upper sedimentary units conformably overlie this unit.

e) Basal sediments of the Laccadive Basin (Unit LCBL)

The unit is present in the Laccadive Basin and overlies the acoustic basement. This unit is characterized by moderately continuous, parallel reflectors whose amplitudes are relatively stronger than the overlying unit (Fig.5.5a). The upper sedimentary unit conformably overlies this unit.

f) Upper sedimentary unit of the Laccadive Basin (Unit LCBU)

The unit LCBU (Fig. 5.5a) is present in the Laccadive basin. This unit is characterized by fairly continuous, widely separated, parallel reflectors whose amplitudes are relatively weaker than the underlying unit (unit LCBL). This unit conformably overlies the underlying unit LCBL and continues up to the seafloor. Further, at places this unit appears to contain evidences of slumping and at some slump scars, where the older sediments of this unit are exposed.

g) Intervening layered sediments of the mid-slope regions (Unit MSIL)

The unit MSIL is observed to be present as a localized intervening (Fig. 5.5b) thin layer within the acoustically transparent unit of the mid-slope regions along profile AS09-12. The unit is characterized by fairly continuous reflectors having relatively strong amplitude reflection.

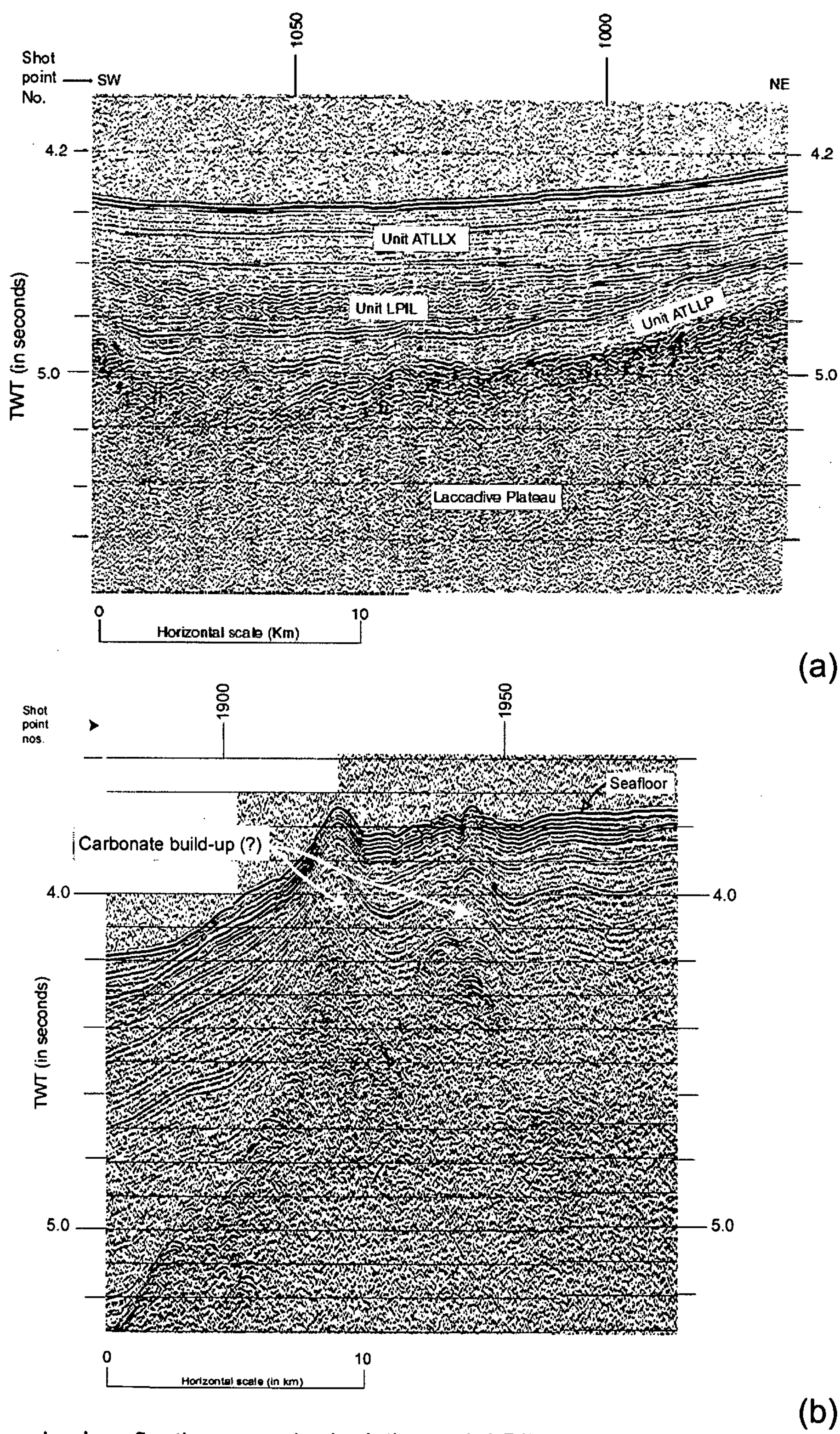


Fig.5.4 Part of the seismic reflection records depicting unit LPIL, unit ATLLP, unit ATLLX and Carbonate build-up (?). (a) record along profile AS09-01 (approximately from SP 980 to SP 1100) and (b) record along profile AS09-03 (approximately SP 1980 and SP 1870).

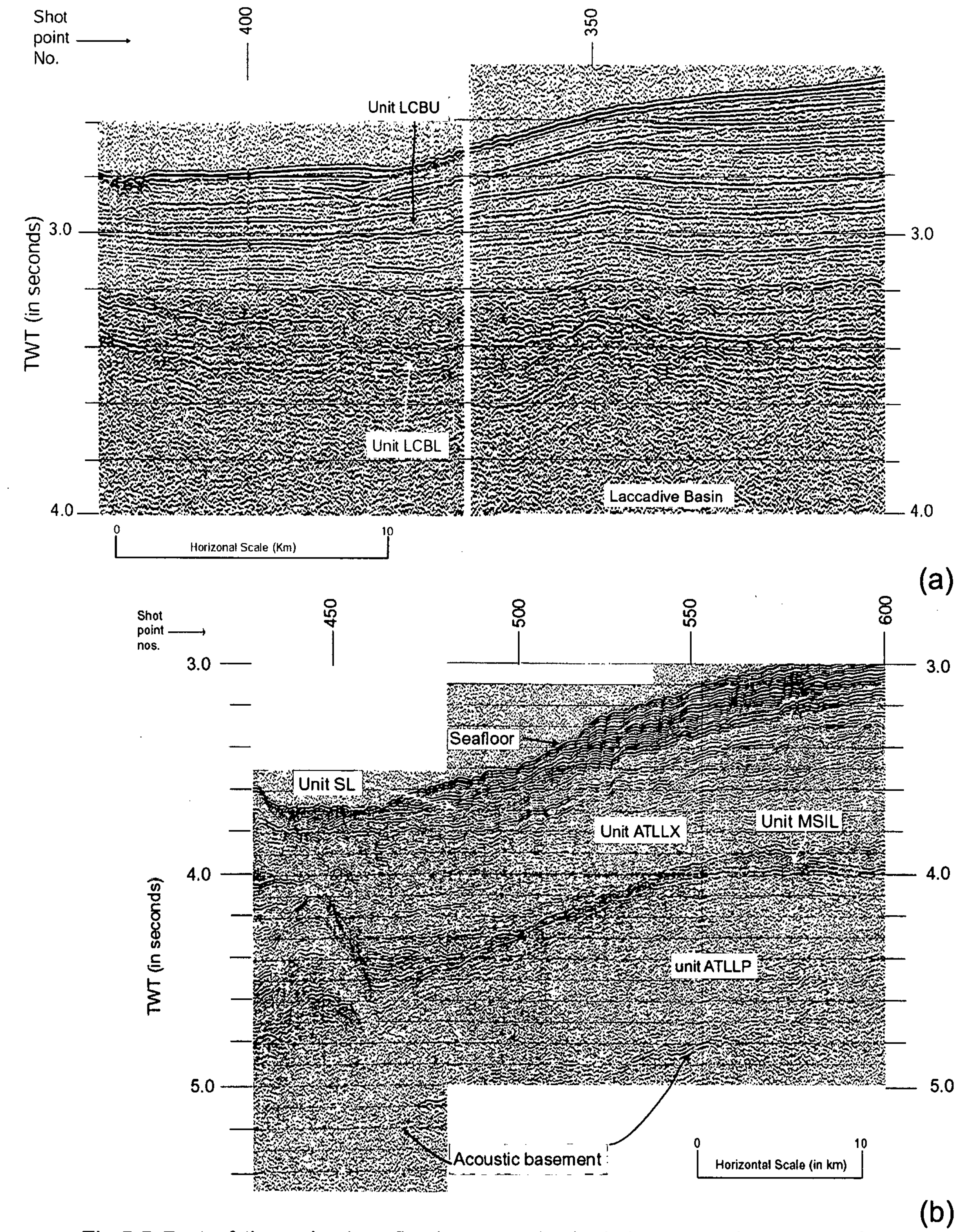


Fig.5.5 Part of the seismic reflection records depicting unit LCBL, unit LCBU, unit ATLLX, unit ATLLP with an intervening unit MSIL and unit SL. (a) record along profile AS09-01 (approximately from SP 300 - SP 425) and (b) record along profile AS09-12 (approximately between SP 600 and SP 430).

h) Pre-fan sedimentary units of the Arabian Basin (Unit ARPFL and Unit ARPFU)

The profiles of the present study cross a shorter distance over the Arabian Basin. Mainly, the upper thicker sedimentary unit in this area depict closely spaced, fairly continuous, large thickness sedimentary package of the Indus Fan sedimentation. However, between these unit and the acoustic basement lies a zone of relatively reflection free sedimentary package. This package appears to be divisible into a lower unit ARPFL and upper unit ARPFU. The thicknesses of these units are very less. Mostly these units could be mapped in the relatively flatter basement regions west of the Laxmi Ridge and the Laccadive Plateau. It may be worthwhile to mention that at places, these flatter basement regions were identified to be underlain by oceanic crust. The lower unit ARPFL appears to be relatively thinner and localized in nature, whereas the upper unit ARPFU (Fig.5.2b) is observed to be present in all the profiles.

i) Sediments of the slope region (Unit SL)

In almost all the profiles of the study area, the upper sedimentary package of the slope regions depict the presence of an acoustic unit, which is characterized by fairly continuous, closely spaced dipping reflectors of moderately high amplitude. The reflectors of this unit dip from the shelf region towards the deep sea and stand as conspicuous dipping events as compared to the monotonous flat reflectors of the upper sedimentary package of the abyssal plains. This dipping reflectors package of the slope region is termed as sediments of the slope region or unit SL

(Fig. 5.5b). This unit also depicts at places evidences of gentle folding, faulting, slumping and pockets of chaotic reflection zones. The zone of contact between this unit and the abyssal plain sedimentary unit appears to be easily detectable by the presence of conspicuous wavy structure of this unit.

j) Indus Fan area sedimentary unit (Unit FS)

The profiles of the present study cross a shorter distance over the Arabian Basin. The upper thick sedimentary unit in this region is termed as the Indus Fan sedimentary unit (unit FS). This unit depicts very conspicuous, closely spaced, parallel to sub-parallel, continuous to highly continuous horizontal reflections (Figs. 5.2a and 5.2b). At places this unit contains highly continuous reflections, at other places it shows presence of channels and levee structures which are characteristic of fan sedimentation. In several studies in the adjacent region (Droz and Bellaiche, 1991; Malod et al., 1997; Gaedicke et al., 2002), the sedimentary package of the Indus Fan area was considered to represent mainly the terrigenous deposits supplied by the Indus River. The presence of channel-levee complexes was inferred to represent the Indus Fan sedimentation. Based on the close proximity of the regions and resemblance of the acoustic characteristics of the sedimentary package observed in the present study and those presented in the earlier studies, this unit is considered to represent the Indus River derived sedimentation. The short length of the seismic profiles in the Indus Fan area do not allow to distinguish different sub-units of the Indus River derived sediment package very clearly. This unit is the most wide spread in the basinal part of the study area, onlaps over the pre-existing layers and forms the present day flat seafloor in most of the parts.

Towards the slope, the unit is in conspicuous contact with the slope sedimentary unit.

k) Carbonate build-up and diapiric structures

Apart from the above described major seismic units, some minor and localized seismic units also were noticed to be present in the study area. The first among them is interpreted to represent carbonate build-up structures (reef growth?), which are observed over the sub-cropping basement high structures and are depicted as localized, reflection free mounds within the surrounding sediments (Fig. 5.4b).

The other minor seismic units observed in the study area are interpreted as diapiric structures (Fig. 5.6). These are depicted as acoustically transparent unit piercing through the surrounding layered sequence and are associated with upward bending of the reflectors, which abut against its boundary.

5.3 Description of seismic profiles

It has been observed that the basement structure and seismic stratigraphic units varied along each line. Non-availability of tie lines prevented precise aerial correlation of units. However, proximity of profiles allowed reasonable identification of zones of similar structural style and equable acoustic stratigraphic units from line to line on the regional scale. Following are the description of individual profiles. The depths to the seafloor along each profile wherever mentioned are read from the bathymetry data.

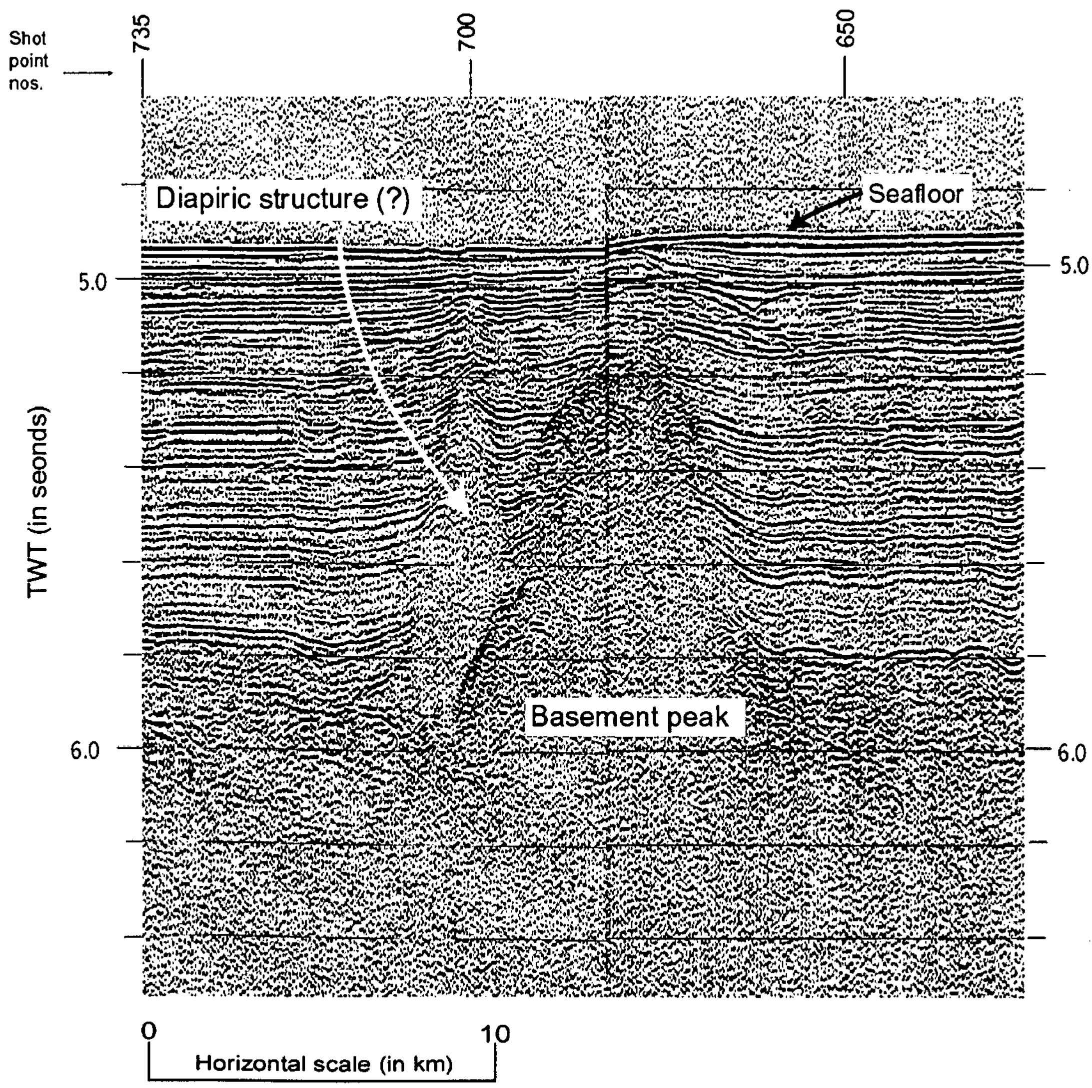


Fig.5.6 Part of the seismic reflection records depicting diapiric structure and adjacent basement peak along profile AS09-08 (approximately from SP 635 - SP 735).

5.3.1. *Seismic profile* **AS09-01**

This approximately NE-SW oriented profile AS09-01 (Fig. 5.1) is about 510 km long and crosses the shelf, slope, Laccadive Basin, Laccadive Plateau and a short distance within the abyssal plains of the Arabian Basin. The interpreted line drawing of the seismic reflection data along this profile is shown in Fig. 5.7. The depth to the seafloor in the easterly end of the section is about 190 m and at the westerly end it is about 4100 m. The seafloor topography, configuration of the underlying basement and disposition of seismic units warrant the description of profile in terms of four zones whose boundaries are defined by the closest shot point (SP) numbers indicated in the interpretative line drawings. The zones identified and described are 1) the shelf and slope (from SP 1 to SP 170); 2) the Laccadive Basin (from SP 210 to SP 540); 3) the Laccadive Plateau (from SP 540 to SP1485) and 4) abyssal plain of the Arabian Basin (SP 1485-SP 2200).

The shelf and slope zone as identified lie between SP 1 and SP 170. Within these boundaries the seafloor dips gently from the beginning of the profile till shelf break i.e. till about SP 25. From this point the slope dips comparatively steeper up to SP 100 where the slope morphology is modified by a small topographic high centered at SP 120. The topographic high has a low relief of about 150 msec. Further west of SP 170 a change in the dip of the seafloor is observed. The basement within major part of the zone could not be identified except between SP 130 and SP 170. In the shelf region due to the presence of multiples, only about

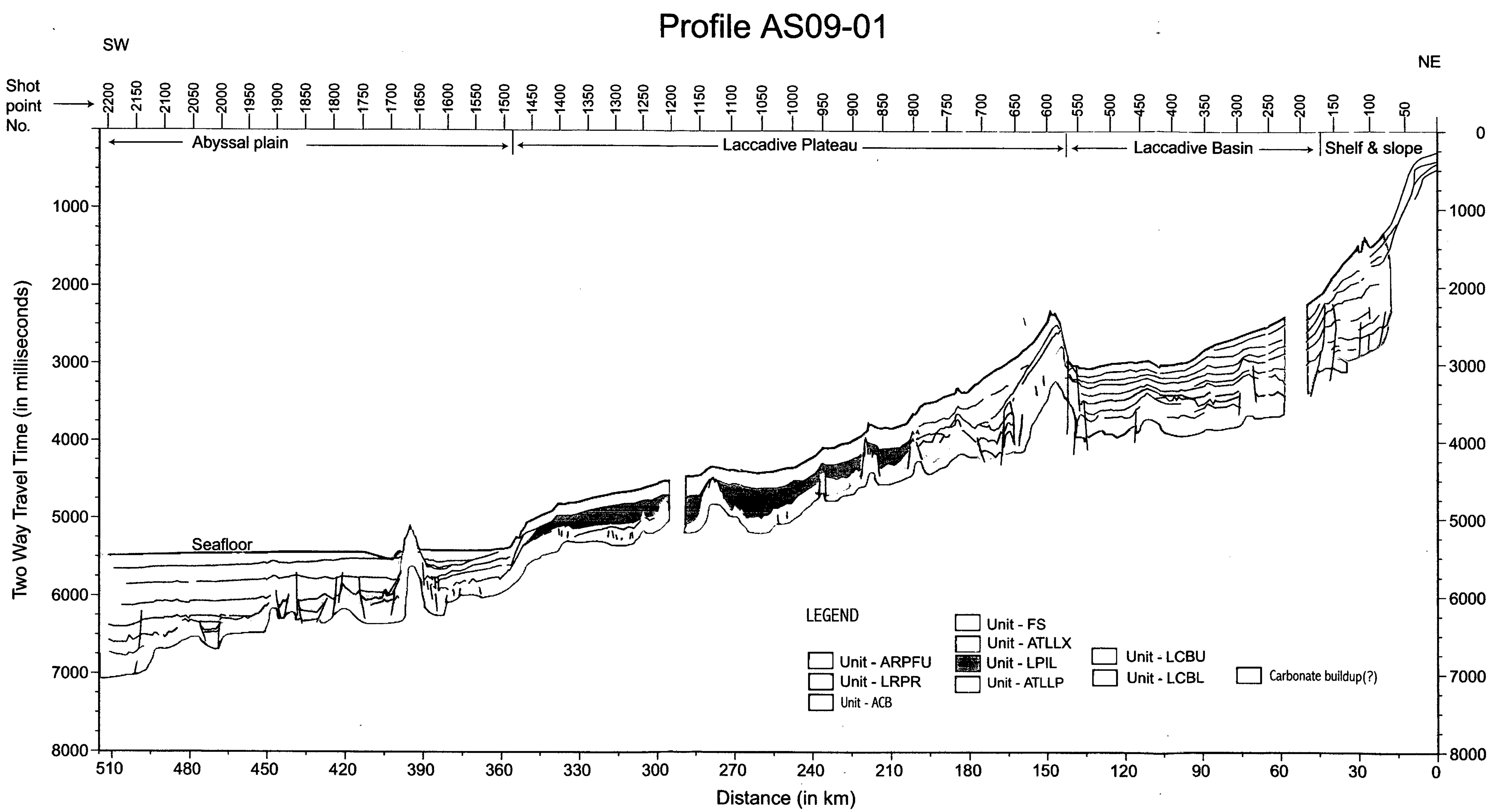


Fig. 5.7. Line drawing of interpreted seismic reflection profile AS09-01. Location of the profile is given in Fig. 5.1.

250 msec thick sediments could be interpreted, however the actual sediment thickness could be considerably more. In the slope region near SP 100 about 1300 msec thick sediment could be measured.

This profile crosses the Laccadive Basin between SP 170 and SP 540, which indicate a width of about 90 km of the Laccadive Basin in this zone. Within this zone, the seafloor in general gently dips westwards and the water depths ranges from about 1500 m to 2250 m. Within this gently westward dipping seafloor a broad topographic low is present between SP 350 and SP 440. The low is about 22 km wide and 112 m deep from the adjacent seafloor and appears as a wide channel like feature. In this Laccadive Basin area, the basement could be observed only between SP 225 and SP 470. The basement could not be identified between SP 180 and SP 225 due to data gap. Between SP 470 and SP 540 the basement could not be mapped and disposition of sedimentary layers suggests existence of a narrow fault bound graben like structure over here. Based on the depth to the lower most reflector identified, the basement appear to lie deeper than 4000 msec. The basement in this zone appear to be composed of several basement peaks and troughs which attains a maximum relief of about 550 msec. Within this basin, the sediment overburden thickness varies between about 500 msec and 1000 msec. However, based on the reflection pattern, the sedimentary column above the basement is divided into two seismic units. The lower unit LCBL overlie the basement. This unit fills up the irregularities in the basement. The reflectors of this unit abut against the eastern scarp face of a high (near SP 540) that marks the eastern limit of the Laccadive Plateau. The unit LCBL is apparently present and confined in the deepest parts of the basin and its thickness gradually decreases towards east. The upper unit LCBU lies conformably over the unit LCBL. It is observed that thickness of the unit LCBU increases eastwards towards the slope. The reflectors within the unit are fairly continuous. Towards the slope the unit appear to have affected by down to the basement faults. As mentioned earlier, existence of a narrow fault bound graben was inferred between SP 470 and SP 540. The sedimentary horizons of sequences LCBL and LCBU appear to be thickening slightly towards the axis of this narrow graben, which may suggest that the graben remained tectonically active (subsiding) throughout the deposition of the sedimentary column.

The profile crosses a broad elevated topographic region between SP 540 and SP 1485. Location wise this topographic high falls within the Laccadive Plateau region. Incidentally, the topographic high also coincides with the relatively elevated basement complex (Fig. 5.7) underneath. The basement could be identified in most part of this zone. The basement rises steeply from 4000 msec near SP 540 to 2750 msec near SP 575 and descends to about 4000 msec near SP 650. This change in basement depths gives rise to a 25 km wide basement high (centered around SP 575). Presence of two down thrown basement blocks (near SP 550 and SP 545) on the eastern flank of this high suggests a faulted eastern boundary of this high. With relatively steep eastern flank and gently dipping western flank this basement high appears like a tilted fault block. In general from SP 650 to SP 1485 the basement gently dips west and have alternate peaks and troughs like features. The basement between SP 900 and SP 1350 appears as a broad (100 km) low and along the axial part of this broad low, lies a pair of large basement peaks. The larger of this pair of peaks is centered around SP 1135, has about 500 msec relief, 30 km width, and appear to be capped by reef. Similarly, the other peak of this pair is centered around SP 1210 has about 300 msec relief, 7 km width, also appear to be capped by reef. From the location (Fig.5.1) on the seismic profiles, these two peaks appear to be the sub-surface southward continuation of the smaller hill lying southeast of the Wadia Guyot. The basement depth is about 5375 msec near SP 1450, whereas near SP 1540 the depth is about 6000 msec. This gives a total drop in the basement depths of the order of 625 msec around SP1485. The drop in the basement in this region is also reflected in a drop in the levels of seafloor by about 350 msec. The sedimentary column over the elevated topographic high region of the Laccadive Plateau appears to be composed of two acoustically transparent units and an intervening relatively stratified unit. The presence of two acoustically transparent units is inferred from two considerations. The lower acoustically transparent unit ATLLP, is relatively thin, overlies the basement and follows the basement trend. The upper acoustically transparent unit ATLLX which continues till the seafloor, appears to be in unconformable contact with the lower unit ATLLP. This unconformity contact is conspicuous towards east between SP575 and SP700. Further, the unit ATLLP in this region also appears to be dipping towards west in the same attitude as the underlying basement block. Secondly, between SP800 and SP1450 presence of an intervening unit LPIL have been inferred. This unit LPIL is thicker near the previously mentioned basement high pair (between SP 1070 and SP 1250) and wedges out on either side. Westward of SP 1485, both the acoustically transparent units appear to be in conformable contact. The westward extent of these acoustically transparent units appears to be restricted by the basement high (centered around SP 1655).

As mentioned earlier between SP 1485 and SP 2200, the profile runs in abyssal plains of the Arabian Basin. In this zone the seafloor in general is smooth. In this zone the basement gently dips westward and is characterized by the presence of number of faults and fault bound basement blocks. The most prominent among these blocks, is the peak centered at around SP 1655, is expressed as an outcrop in the seafloor. Westward of this peak till at least SP 2100 presence of a weakly stratified unit LRPR is identified. This unit LRPR consists of reflectors that are continuous within the basement troughs and follow the basement trend. At places the reflectors of the unit LRPR appear to have been affected by faults. Near SP2120, one more conspicuous drop in the basement is identified, westward of which the short segment of the profile depicts a flat lying basement.

The upper most sedimentary unit west of SP1500 is identified as the fan sequence (unit FS). The unit FS gradually onlaps over a clearly identifiable unconformity surface which defines the top of unit LRPR and basement highs (between SP1690 and SP2100). This unit FS continues eastwards of the basement outcrop (centered around SP1655) and onlaps over a unconformity surface, which defines the top of the acoustically transparent unit ATLLX in this region. West of the previously mentioned basement drop (at around SP 2120) the unit FS appears to lie conformably over a relatively reflection free unit ARPF.

5.3.2 *Seismic profile* **AS09-12**

This approximately NE-SW oriented profile AS09-12 (Fig. 5.1) is 215 km long. The easterly and westerly end of the profile traverses the shelf and the Laxmi Basin respectively for short distances, while the central and major portion of the profile lies over the slope regions. The interpreted line drawing of the seismic reflection data along this profile is shown in Fig. 5.8. The depth to the seafloor in the easterly end of the section is about 180 m and at the westerly end is about 3700 m. The shelf is flat from beginning of the profile till it breaks at SP 940. From SP 940 to SP 90, the seafloor is characterized by broad undulations. At places over these broad undulations, the seafloor depicts wavy features (e.g. around SP 725, and around SP 550). Westward of SP 90 till end of the profile the seafloor is nearly flat.

The basement along this profile particularly the western part consists of series of basement peaks and intervening troughs. In the shelf region between SP 980 and SP 920, the identifiable lower most reflector appear as a high having a relief of about 800 msec. Westward between SP920 and SP820 the basement could not be identified. Between SP820 and SP 625, depicted as a broad basement high of about 45 km width and a relief of about 1500 msec. The eastern limit of this high appears to be marked by a fault, whereas its western limb dips

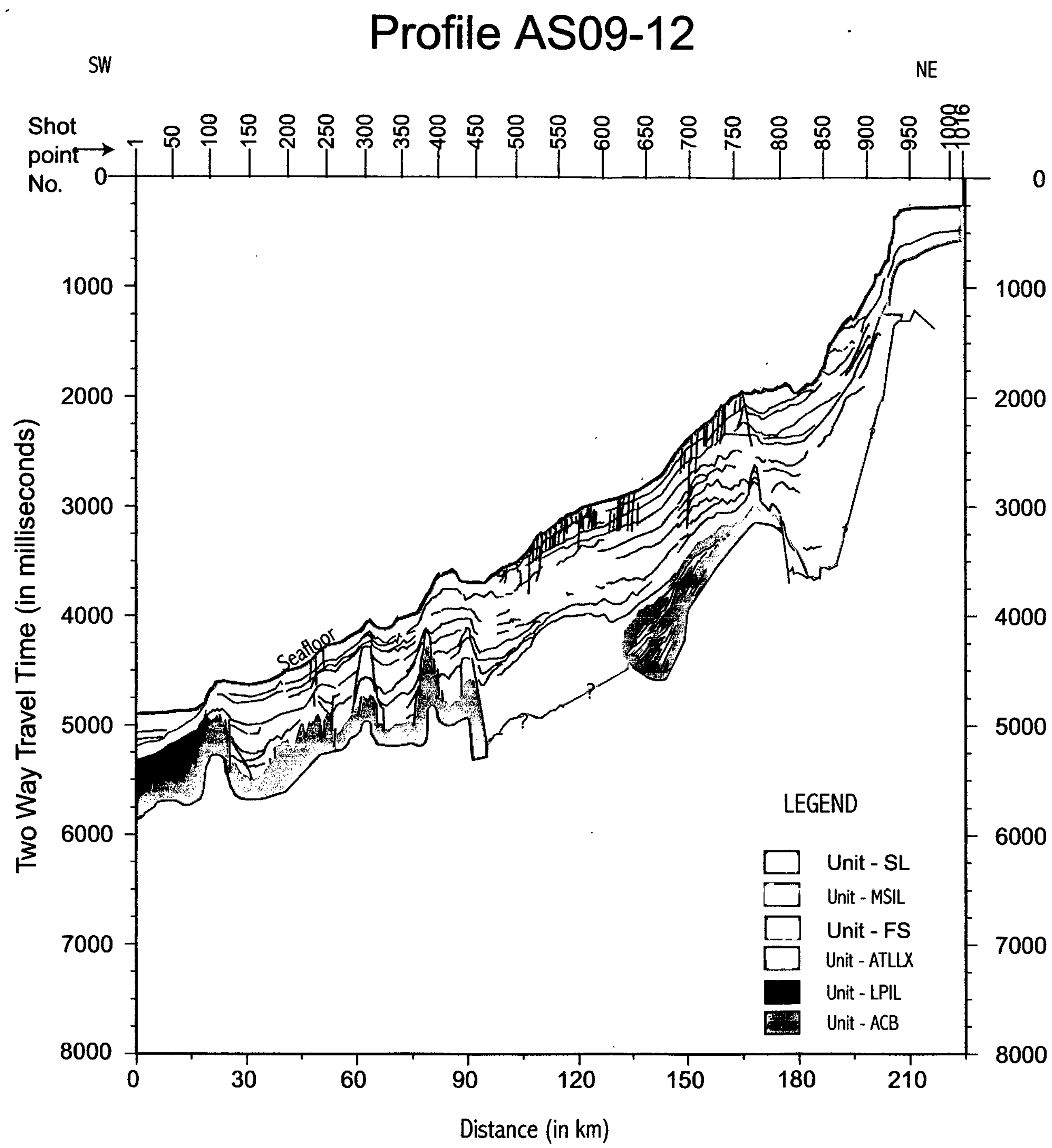


Fig.5.8. Line drawing of interpreted seismic reflection profile AS09-12. Location of the profile is given in Fig.5.1.

gently westward. A set of westward dipping reflectors appears to exist within the acoustic basement between SP 730 and SP 630. Between SP 630 and SP 465, the basement could not be identified. Between SP 470 and SP1, the basement dips gradually westward and consists of several prominent peaks and intervening troughs. At places, the peaks attain a relief of about 700 msec (e.g. peak centered at SP 390) and width of about 15 km (e.g. peak centered around SP 100). The intervening troughs attain a maximum width of about 15 km (e.g. the trough centered around SP 155).

The interpretable sediment overburden over the shelf is at least about 250 msec. Since the basement could not be clearly mapped, the actual sediment thickness in the shelf area could be more. In rest of the profile, the sediment overburden thickness is variable and ranges between a minimum of 400 msec over the basement peak near SP 100 to at least about 2000 msec in the troughs (near SP 850).

The sediment overburden between SP 1016 and SP 100 consists of three units. The most predominant is the acoustically transparent layer of the Laxmi Basin (unit ATTLX), which overlies the acoustic basement and drapes over the basement highs and attains a maximum thickness of about 1450 msec. Along this profile between SP 775 and SP 450 within the acoustically transparent unit, presence of an intervening thin layer of acoustically well laminated unit was observed. This intervening unit was named as unit MSIL and was found to occur only along this profile. The sediments of the slope region (unit SL), which form the uppermost unit in this area, appears to conformably overly the unit ATLLX. The unit SL appears to have been affected by slumping and at places the older sedimentary layers are exposed due to erosion or slump related activity.

The unit ATLLX appear to thicken towards east whereas, towards west the basement peaks appear to have restricted its westward continuation as thick layer. However, after filling the basement troughs, the younger upper layers of this unit appear to have crossed the basement barrier (at around SP 100) as a drape and continued further westward as a thin layer. The draped high (near SP 100) appears to have acted as a barrier for the westward continuation of slope sediments. Towards west, between SP 100 and SP 1, the unit (about 400 msec thick) representing intervening layered sediments of the Laccadive Plateau (unit LPIL) overlies and parallels the west dipping basement. A thin layer of acoustically transparent unit ATLLX conformably overlies the unit LPIL over which the unit FS onlaps.

5.3.3 *Seismic profile* **AS09-03**

This approximately NE-SW oriented line AS09-03 (Fig. 5.1) is about 515 km long and traverses the shelf, slope and the relatively flat seafloor regions of the Laxmi Basin and a short distance in the Arabian abyssal plains. The interpreted line drawing of the seismic reflection data along this profile is shown in Fig. 5.9. The depth to the seafloor in the easterly end of the section is about 172 m and at the westerly end is about 4050 m.

From the beginning of the profile in the east (SP 2327), the flat shelf continues till the shelf break at SP 2270 from where begins the relatively steeper

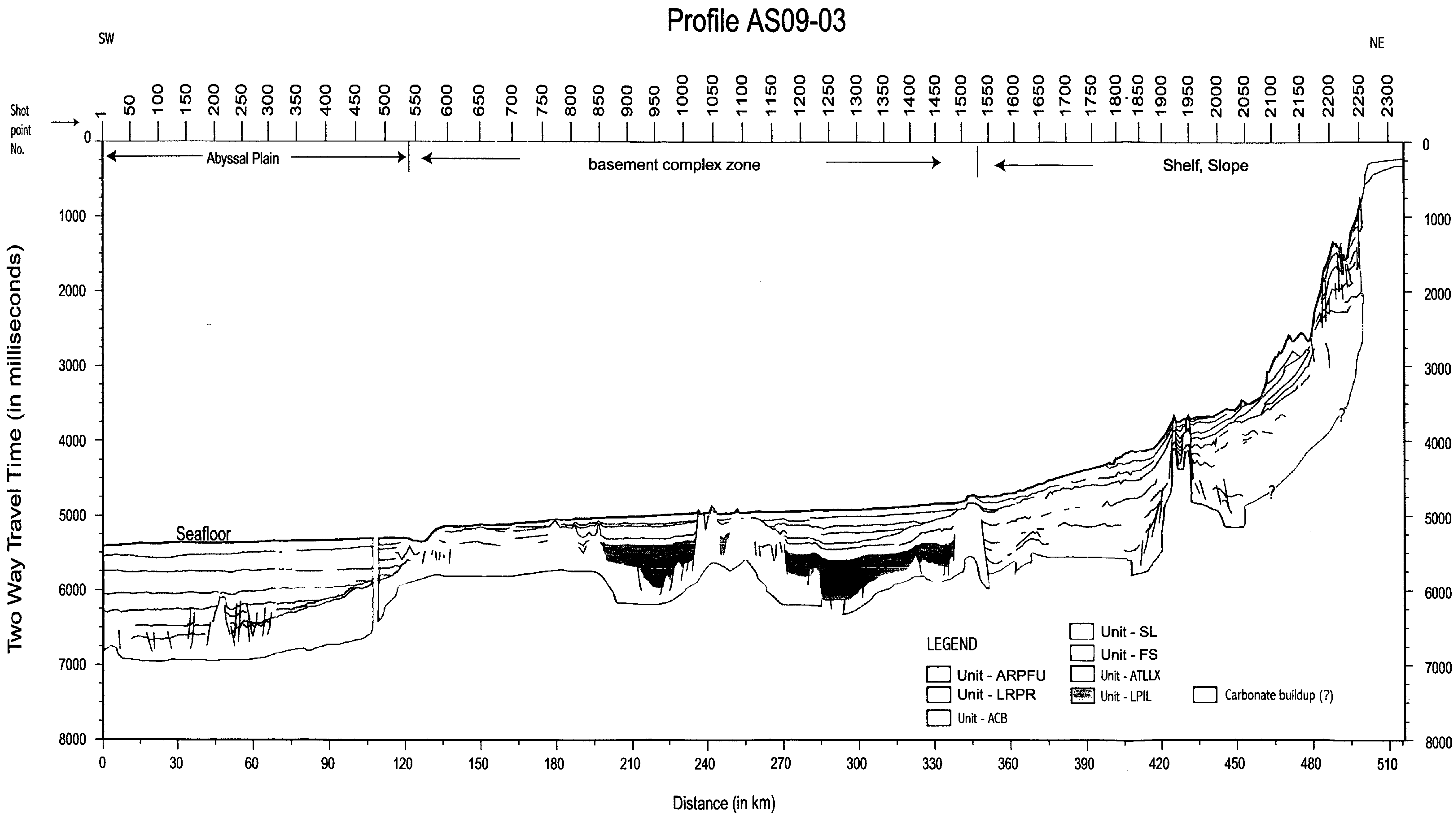


Fig.5.9 Line drawing of interpreted seismic reflection profile AS09-03. Location of the profile is given in FIg.5.1

slope and rise region which continue till at least SP 1500 until it meets the relatively gentle seafloor of the Laxmi Basin at about 3500 m water depths. In this zone, two topographic highs having a relief of about 750 msec (centered at around SP 2200, SP 2125 respectively) modify the slope morphology. Within this zone the most prominent basement feature is a broad basement high (between SP 2050 and SP 1850) having a width of about 40 km, and a relief of about 1500 msec. The flanks of this basement high appear to consist of series of down thrown fault blocks. The summit region of the basement high is observed as two reef capped(?) basement peaks which are separated by a narrow, thick sediment filled graben. The basement high appears to divide this region into two thick sediment filled basins. The base of the basin lying eastwards of this high could not be mapped. The other basin (between SP 1925 and SP 1550) which lies west of this high is about 75 km wide and 1500 msec deep.

The sedimentary overburden in the shelf, slope and rise regions bears similarity with the southern profile AS09-12. In the shelf region due to the presence of multiples, only about 100 msec thick sediments could be interpreted, however the actual sediment thickness could be more. The sedimentary overburden in the two basins flanking the basement high (centered around SP 1925) is interpreted to consist of two units. The lower unit is the acoustically transparent layer of the Laxmi Basin (unit ATLLX) and the upper unit is the sediments of slope region (unit SL). It appears that both the units, unit ATLLX and unit SL thicken towards east. Further, the thickness of the unit SL appears to be different on both sides of the basement high (centered around SP 1925), this thickness is more towards east of the high as compared to west of the high which perhaps suggest that the high acted as a barrier for deposition of sediments of unit SL for a longer period.

The draped layers of the unit ATLLX over another basement high (centered around SP 1525) acted as another barrier for restricting the westward continuity of unit SL and west of SP 1525, the unit FS of the Laxmi Basin appears to constitute the seafloor.

Towards further west, the region between SP1525 and SP 530 appears to consist of multiple basement units and intervening basins. In general, the seafloor is nearly smooth with only few very low relief (maximum of about 50 msec) topographic highs (at SP1515, SP1100, SP1040) present at places. The depth to the seafloor varies between 3500 m in east and about 3900 m in the west. Towards the western end of the zone, a drop of about 200 msec (at around SP 580) is observed in the levels of seafloor.

The configuration of the basement between SP 1500 and SP 850 is observed as a broad basement high zone (centered around SP 1060) flanked by two half-graben like structures. This basement high zone is about 70 km wide having a relief of about 1000 msec. The basin on the eastern flanks of this high zone is about 68 km wide and the basin on the western flank is about 36 km wide. It is observed that the flanks of the basement high zone is contains numerous faults which continue at least into the overlying sedimentary unit LPIL and the thickness of this unit LPIL thickens towards the basement high zone. Westward of the western half-graben, between SP 955 and SP 525 the basement is depicted as a 105 km wide broad platform. Some minor relief secondary basement high structures are present on the periphery of this platform.

The interpreted sedimentary overburden in the zone between SP 1500 and SP 530, is divided into three seismic units. The unit LPIL is about 500 msec thick and restricted to the floor the half-grabens, whereas the acoustically transparent layer (unit ATLLX) overlies the unit LPIL and drapes over the basement high zone and the broad basement platform. In this zone, the unit FS appears to unconformably overly the unit ATLLX.

Towards west of SP 530, the profile crosses the abyssal plains of the Arabian Basin. In this zone, the seafloor is generally flat and the depths to the seafloor varies between 3975 m in the east and about 4050 m in the west. In this zone, in general the basement gently dips west, however, between SP 300 and SP 100 the basement is highly fractured. Within this fractured zone, a basement high of 11 km width and 400 msec relief is present. This high appears to be capped by carbonate growth. The sedimentary overburden in this zone is interpreted to consist of three units; i.e. unit LRPR, unit ARPFU and unit FS. The unit LRPR is the lowermost unit that overly and parallels the basement. The acoustically transparent unit ARPFU and the overlying unit FS onlaps the unit LRPR.

5.3.4 *Seismic profile* AS09-10

This approximately NE-SW oriented 315 km long profile AS09-10 (Fig. 5.1) crosses a part of the Laxmi Basin and a short distance in the Arabian Basin abyssal plains. The interpreted line drawing of the profile is shown in Fig.5.10. The

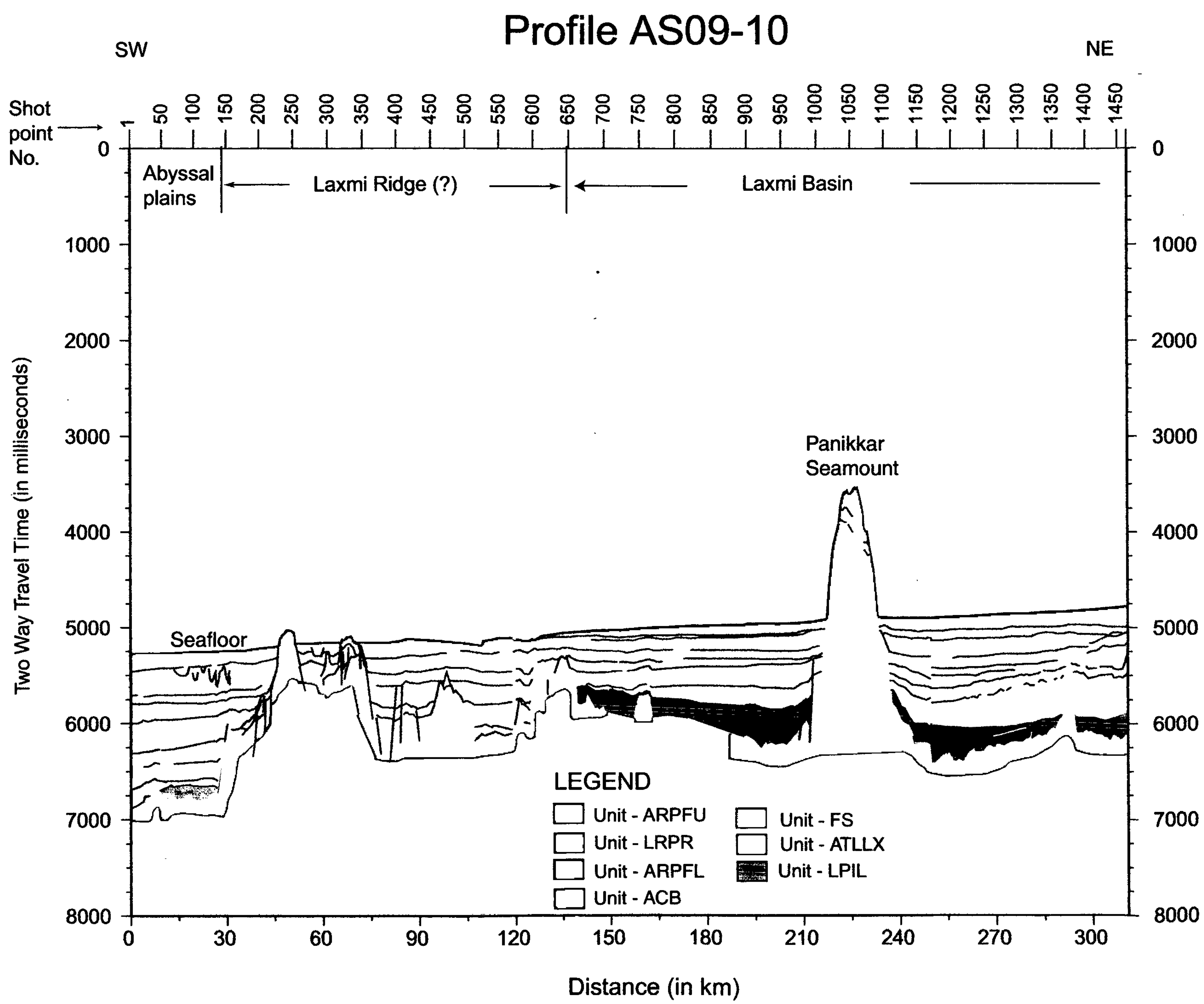


Fig.5.10 Line drawing of interpreted seismic reflection profile AS09-10. Location of the profile is given in Fig.5.1.

configuration of the basement and overlying sediment overburden warrant to describe the profile in terms of three zones whose boundaries are defined by the closest shot point (SP) numbers in the interpretative line drawing.

Along the profile, depths to the seafloor vary between about 3600 m in the east and about 3975 m in the west. The gently west dipping seafloor is punctuated by a 15 km wide and about 1400 msec high conspicuous topographic high (centered at around SP 1050). The geographical location of this basement high suggests that it is a part of the Panikkar Seamount identified earlier by Bhattacharya et al. (1994b). Along this profile, the summit of the seamount is about 6 km wide and appears to contain a low relief depression. In the seafloor, in addition to the Panikkar Seamount, low relief (about 125 msec) topographic highs (at around SP 330, SP 250) and channel like features (about 60 msec, at around SP 600, SP520) are also observed.

In the 165 km wide zone lying between SP 1462 and SP 700, the basement appears as two basins flanking the basement high zone of the Panikkar Seamount. The base of the seamount is about 40 km wide and it attains a total relief of about 2750 msec. In the summit area of the seamount, the basement appears as a secondary basement peak. This secondary basement peak has a relief of about 550 msec and at its base it is about 6 km wide. In this zone, the basement flanking the seamounts appears to deepen towards the seamount. The maximum thickness of the sedimentary overburden in this zone is about 1550 msec and is interpreted to consist of three seismic units. The basal unit LPIL has a maximum thickness of about 450 msec and appears to thicken towards the seamount. The acoustically transparent unit ATLLX conformably overlies the unit LPIL. It is observed that the thickness and characteristic of this unit is somewhat different in both the flanks of the seamount. Towards east at least its upper package is weakly laminated, it is thicker and attains a maximum thickness of about 800 msec. Whereas towards west of the seamount, this unit is devoid of any laminations and is of considerable reduced thickness which finally wedges out at around SP 675. Over the Panikkar Seamount, similar acoustically transparent layer is also observed to be present. The topmost sedimentary package in this area is the unit FS which overly the unit ATLLX unconformably.

In the second, 125 km wide zone between SP700 and SP 140, the basement is characterized by a complex zone consisting of number of large basement blocks and intervening basins of varied dimensions. The biggest of these blocks (centered at around SP 275) is about 50 km width and has a relief of about 1600 msec. These basement blocks appear to be bounded by steep fault faces. Some of these faults appear to cause large offsets in the basement levels, for example at around SP 150, the displacement along the western steep scarp face of bigger peak is about 750 msec. The sedimentary overburden in this zone is interpreted to consist of three seismic units (i.e. unit LRPR, unit ATLLX and the unit FS). The unit LRPR is observed to be present over the basement highs and appears to have been offset along with the basement faults. Over some of the basement highs, restricted occurrence of the acoustically transparent unit ATLLX was also observed as growth and drape structure. The topmost and most predominant sedimentary unit of this region is the unit FS which attains a maximum thickness of about 1200 msec.

The zone between SP 140 and SP 1 is characterized by westward dipping basement except for a small basement peak (centered at around SP 50). The 1700 msec thick overlying sedimentary overburden is interpreted to consists of three seismic units (i.e. unit ARPFL, unit ARPFU and unit FS). The unit ARPFL is the basal layer over which unit ARPFU lies conformably. The maximum thickness of unit ARPFL and unit ARPFU together is about 150 msec. The uppermost sedimentary package is the unit FS which is about 1550 msec thick and lies conformably over unit ARPFU.

5.3.5 *Seismic profile* **AS09-08**

This approximately NE-SW oriented 310 km long profile AS09-08 (Fig. 5.1) crosses a part of the Laxmi Basin, the Laxmi Ridge and a short distance in the abyssal plains of the Arabian basin. Along the profile, the depths to the seafloor in the easterly end is about 3470 m and at the westerly end is about 3840 m. The interpreted line drawing of the profile is shown in Fig.5.11. The configuration of seafloor topography and basement warrant description of the profile in terms of three zones whose boundaries are defined by the closest shot point (SP) numbers in the interpretative line drawing. The structure and configuration of the sedimentary units appears to be similar to that of immediate southern profile AS09-10.

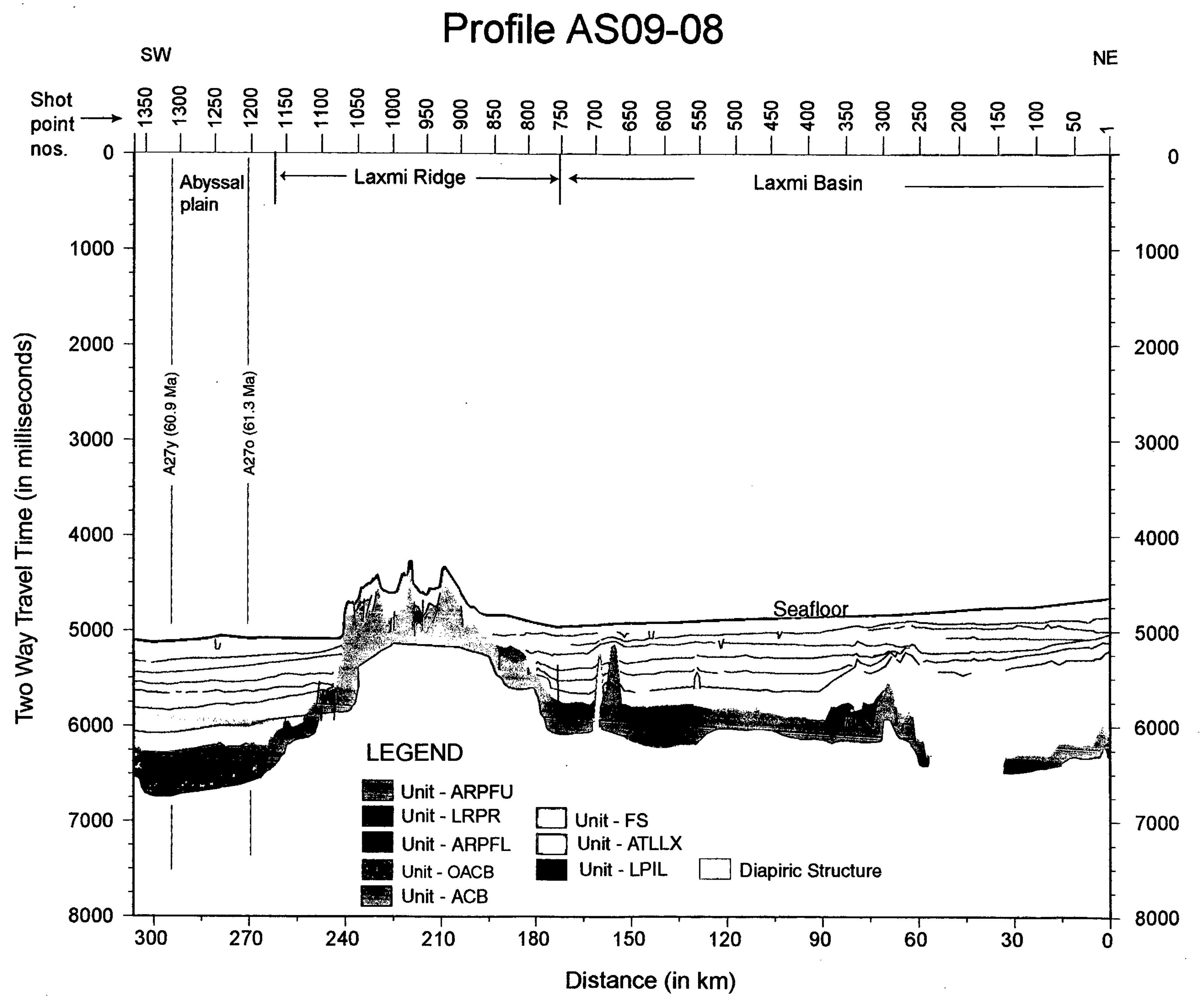


Fig. 5.11 Line drawing of interpreted seismic reflection profile AS09-08. Areas where the seismic section crosses the identified seafloor spreding magnetic lineations (Fig5.1) have been marked by vertical dashed lines labelled with correspnding magnetic anomaly number and age.

The zone between SP1 and SP750 is identified to be a part of the Laxmi Basin. In this zone, in general the seafloor is nearly flat and smooth. In most parts of this zone, basement could be identified. Except for the presence of two basement high zones, the basement in rest of the area is relatively featureless. One of these two basement high zones is, a 30 km wide and 950 msec high (centered at around SP 290). Towards east of this high, basement is observed to be deeper at a depth of about 6300 msec, whereas towards west of this high, it is shallower. The second basement high feature is a nearly 10 km wide basement peak with a relief of about 800 msec (centered at around SP 675). Slightly westward of this feature another peak of similar dimensions is also present, however, on closer examination of the reflection pattern suggests that, this feature is characterized by acoustically transparent unit and probably caused by a diapiric intrusion.

In this region, the sedimentary overburden is thick and attains a maximum thickness of about 1500 msec. The sedimentary overburden is interpreted to consist of three seismic units (unit LPIL, unit ATLLX and unit FS). The basal unit LPIL is observed to be present over the western flank of the basement high zone lying between SP240 and SP 355 and over both the flanks of basement peak centered around SP 675. The unit LPIL is overlain by acoustically transparent unit ATTLX. The unit ATLLX is observed to be thicker (maximum about 1100 msec) in the areas east of the basement high zone (centered around SP 290) whereas this thickness reduces to about 150 msec towards west of the basement high zone. Possibly the basement high zone (centered around SP 290) might have acted as a barrier for westward continuation of unit ATLLX. Further, it also appear that some weak acoustic laminations in the upper sedimentary package of the unit ATLLX in the areas eastward of the basement high zone. The upper surface of the unit ATLLX forms a well defined unconformity surface over which the uppermost unit FS onlaps. The thickness of the unit FS is observed to increase from the east (about 300 msec) to the west (about 800 msec).

The zone between SP 750 and SP 1175, is identified as a part of the Laxmi Ridge. In this zone, the seafloor rises gently from ~3700 m to ~3200 m water depths and then falls to about 3800 m that gives rise to a 40 km wide and 700 m high topographic expression of the Laxmi Ridge. Along the western end of the topographic expression of the Laxmi Ridge, a sharp drop in the sea levels by about 300 m is observed. Topographically the summit region of the ridge appears to consist of multiple peaks and intervening depressions. The bigger of these depressions centered around SP 950 is about 7.5 km wide.

Along the profile, the basement high zone associated with the Laxmi Ridge appears to be about 74 km wide and have a maximum relief of about 1750 msec. The ridge's eastern limb is relatively gentle and shallower than its western limb. The basement in the summit part of the Laxmi Ridge appears to consist of three peaks and intervening narrow grabens. One of these basement peaks is observed to attain a maximum relief of about 650 msec (centered around SP 975) and widest of the peaks is 14 km wide (centered around SP 1040). The intervening grabens have a depth of the order of about 620 msec. The basement along the western limb of the ridge (near SP 1075) appears to have been down faulted by about 950 msec and this fault face is appears to have reflected in the physiography. The summit regions of the Laxmi Ridge is topped by about 400 msec thick sedimentary package that consists of two seismic units (unit LRPR and unit ATLLX), however, on the flanks the situation is different. The basal unit LRPR is observed to be present over the basement highs and appears to have been offset along with the basement faults. The eastern flank and the summit region of the Laxmi Ridge are observed to be draped by acoustically transparent unit ATLLX which is exposed over the summit regions of the ridge. It was also noted that the unit ATLLX do not continue westward of the Laxmi Ridge. In this region, the uppermost unit is the Indus Fan sediments. This unit, i.e. unit FS is about 1200 msec thick and appear to onlap the unit ATLLX over the eastern flank of the ridge, and is in contact with the basement over western flank of the ridge.

The zone between SP1175 and SP1366 is characterized by westward dipping basement, which towards end of the profile appears to rise as a basement high of about 300 msec relief. Based on identified magnetic lineations (Chaubey et al., 1998, 2002) in this region, this part of the Arabian Basin appears to be underlain by oceanic crust (Fig.5.1) formed due to seafloor spreading since anomaly 27 time. In view of this it may be reasonable to assume that the acoustic basement identified in this zone may represent the top of oceanic crust. The sedimentary overburden which attains a maximum thickness of about 1500 msec is interpreted to consist of three seismic units (unit ARPFL, unit ARPFU and unit FS). The unit ARPFL is the basal layer over which unit ARPFU lies conformably. The maximum thickness of unit ARPFL and unit ARPFU is together is only about

250 msec. The uppermost sedimentary package is the unit FS which attains a maximum thickness of about 1250 msec, lies conformably over unit ARPFU.

5.3.6 *Seismic profile* AS09-04

This approximately NE-SW oriented 515 km long profile AS09-04 (Fig. 5.1) traverses across the shelf, slope, the Laxmi Basin, the Laxmi Ridge and a short distance in the abyssal plains of the Arabian Basin. The interpreted line drawing of the seismic reflection record along this profile is presented in Fig. 5.12. The depth to the seafloor in the easterly end of the section is about 169 m and at the westerly end is about 3800 m. The seafloor topography, configuration of the underlying basement and disposition of seismic sequences warrant the description of profile in terms of four zones whose boundaries are defined by the closest shot point (SP) numbers indicated in the interpretative line drawings.

The zone between SP1 and SP740 represents the shelf, slope and continental rise regions. The gradient of the seafloor in the shelf area of this zone is gentle till the shelf break at SP110. The gradient of the seafloor is relatively steep in slope region. The seafloor topography appears to be modified by presence of multiple low relief (a maximum of 150-200 msec) topographic features, which are present till at least SP 740. In the region, between SP 135 and SP 250 the topographic features are more prominent. In this zone, basement could not be identified from the beginning of the profile till at least up to SP250. From SP 250 and SP740 the basement appear as a series of faulted basement blocks. Over the shelf, at least about 300 msec maximum thick sediments could be interpreted

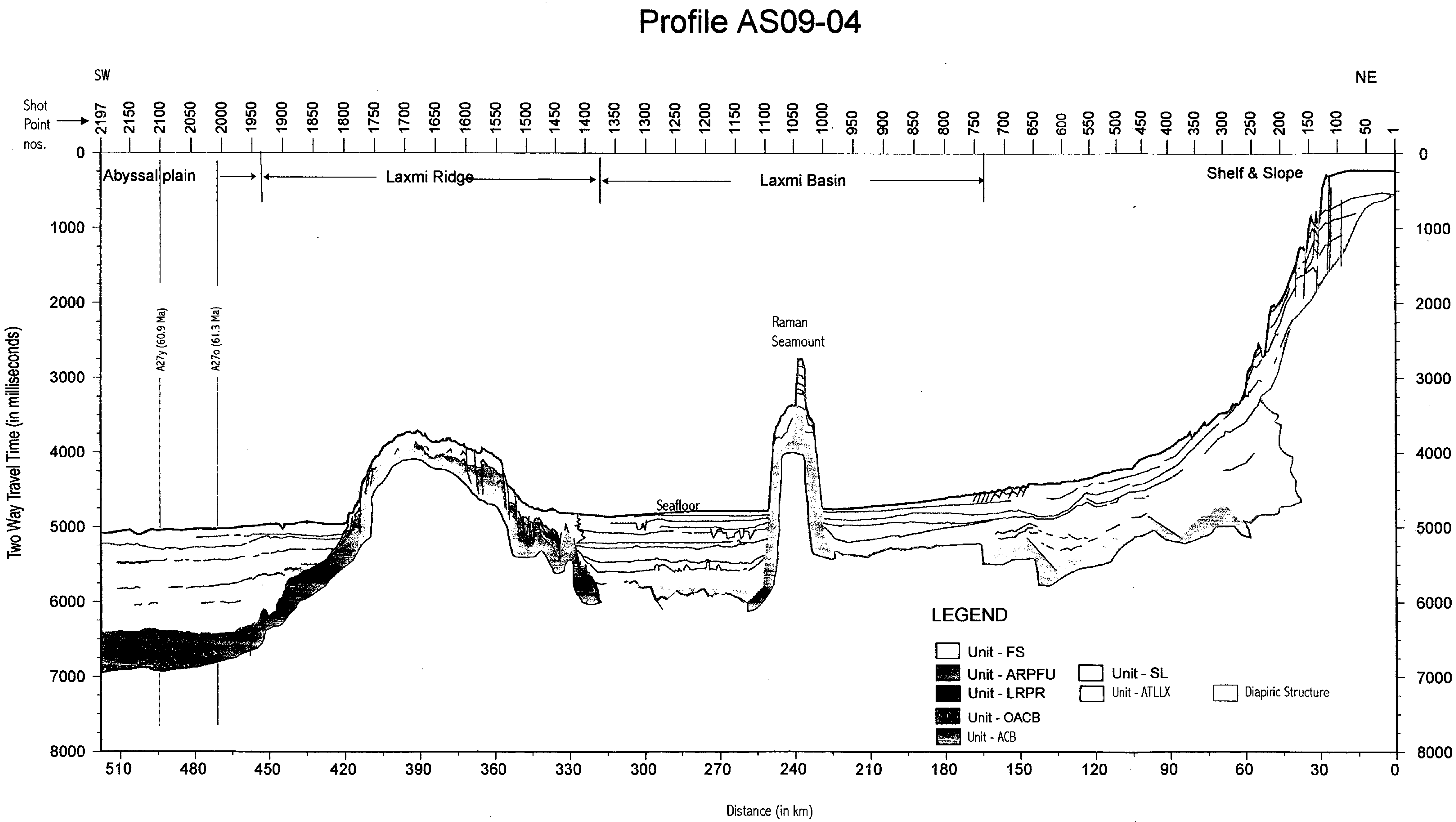


Fig. 5.12 Line drawing of interpreted seismic reflection profile AS09-08. Areas where the seismic section crosses the identified seafloor spreding magnetic lineations (Fig5.1) have been marked by vertical dashed lines labelled with correspnding magnetic anomaly number and age.

however, the actual thickness could be more. In the region, where the basement could be identified (between SP 250 and SP 740), the maximum interpretable sediment overburden is about 2400 msec and is interpreted to consist of two seismic units (unit ATLLX and unit SL). The basal unit ATLLX thickens towards east and is overlain by unit SL conformably. The corrugated relief of the seafloor near SP 750 perhaps represents the zone of contact between the slope sediments and the sedimentary unit (unit FS) of the abyssal plains.

The zone west of SP 740 till the eastern flank of the Laxmi Ridge (near SP 1375) appears to depict a 155 km wide basin. In this zone, depths to the seafloor in the easterly end is about 3300 m and westerly end is about 3600 m. Over the gentle westward dipping seafloor, a large topographic high (centered around SP 1000) is observed. Based on the published literature (Bhattacharya et al., 1994b), this topographic high represents a part of the RAMAN Seamount. Topographically, the seamount is 1550 m high and 23 km wide. The summit region of the seamount is observed to be about 15 km wide. The base of the seamount is about 36 km wide, and maximum relief of the seamount is about 2200 msec. In summit regions of the seamount, presence of a secondary basement peak, having a relief of about 325 msec and 4 km width is observed. The acoustic basement in the regions eastwards of the RAMAN Seamount appears to be shallower than the same in the western part. In this zone, the sedimentary overburden is interpreted to consist of two seismic units (unit ATLLX and unit FS). The basal unit ATLLX appear to be thicker in the regions west of the seamount as compared to the thickness of the same unit in the regions east of the seamount. The unit FS onlaps the unit ATLLX and its thickness also appear to reduce towards east. The summit region of the seamount is also covered by about 500 msec thick acoustically transparent sediment.

The profile traverses a basement high zone between SP1375 and SP1940, and position wise this represents a part of the Laxmi Ridge. Along this profile, topographically the ridge appears to be about 77 km wide with a maximum relief of about 1100 msec. It is observed that towards east of the ridge, seafloor is relatively shallower by about 150 m as compared to the depth to seafloor in the region west of the ridge. At the base level, the ridge appears to be about 140 km wide and attains a maximum relief of about 2300 msec. The eastern flank of this ridge is relatively gentler than the western flank. The eastern flank of the ridge appears to be highly faulted. The interpretable sediment overburden in the summit area of the ridge is about 450 msec. The basement of the ridge appears to be overlain by unit LRPR which also have been faulted along the faulting of the basement blocks. In the topographic regions of the ridge the uppermost seismic unit is the unit ATLLX which appears to drape over the underlying units and gives rise to an undulating seafloor whose attitude nearly parallel to the relief of the underlying basement. Towards the western flank of the ridge, the unit ATLLX thins out and do not appear to continue west of SP 1800, whereas the underlying basal unit LRPR continues further west till at least up to SP 1900.

In the zone between SP1940 and SP2197, the basement and the overburden structure appears to be similar to that of immediate southern line (profile AS09-08). Here also based on identified magnetic lineations (Chaubey et al., 1998, 2002) the acoustic basement may represent the top of oceanic crust. The sedimentary overburden, which attains a maximum thickness of about 2000 msec is interpreted to consist of two seismic units (unit ARPFU and unit FS). The unit ARPFU is the basal layer and its maximum thickness in this region is about 400 msec. The uppermost sedimentary package is the unit FS which attains a maximum thickness of about 1600 msec and overlies the unit ARPFU conformably and gradually onlaps the unit LRPR over the western flank of the Laxmi Ridge.

5.3.7 *Seismic profile* **AS09-06**

This approximately NE-SW oriented 383 km long profile AS09-06 (Fig. 5.1) is the northern most profile in the study area that traverses a part of the Laxmi Basin, the Laxmi Ridge and a short distance in abyssal plains of the Arabian Basin. The interpreted line drawing of the seismic reflection data along this profile is presented in Fig. 5.13. The depth to the seafloor in the easterly end of the section is about 3450 m and at the westerly end is about 3700 m. The topographic relief of the outcropping summit area of the Laxmi Ridge is the most conspicuous physiographic feature along this profile. This topographic expression of the Laxmi Ridge is about 60 km in width and has a maximum relief of about 600 m. It is observed that, along this profile, the topographic expression of the Ridge is more symmetrical than that of a southern profile AS09-04. At places, particularly westward of the Laxmi Ridge the seafloor is dissected by a number of channel like features. Towards of the east of the Laxmi Ridge topographic relief the seafloor is in the form of a very broad depression.

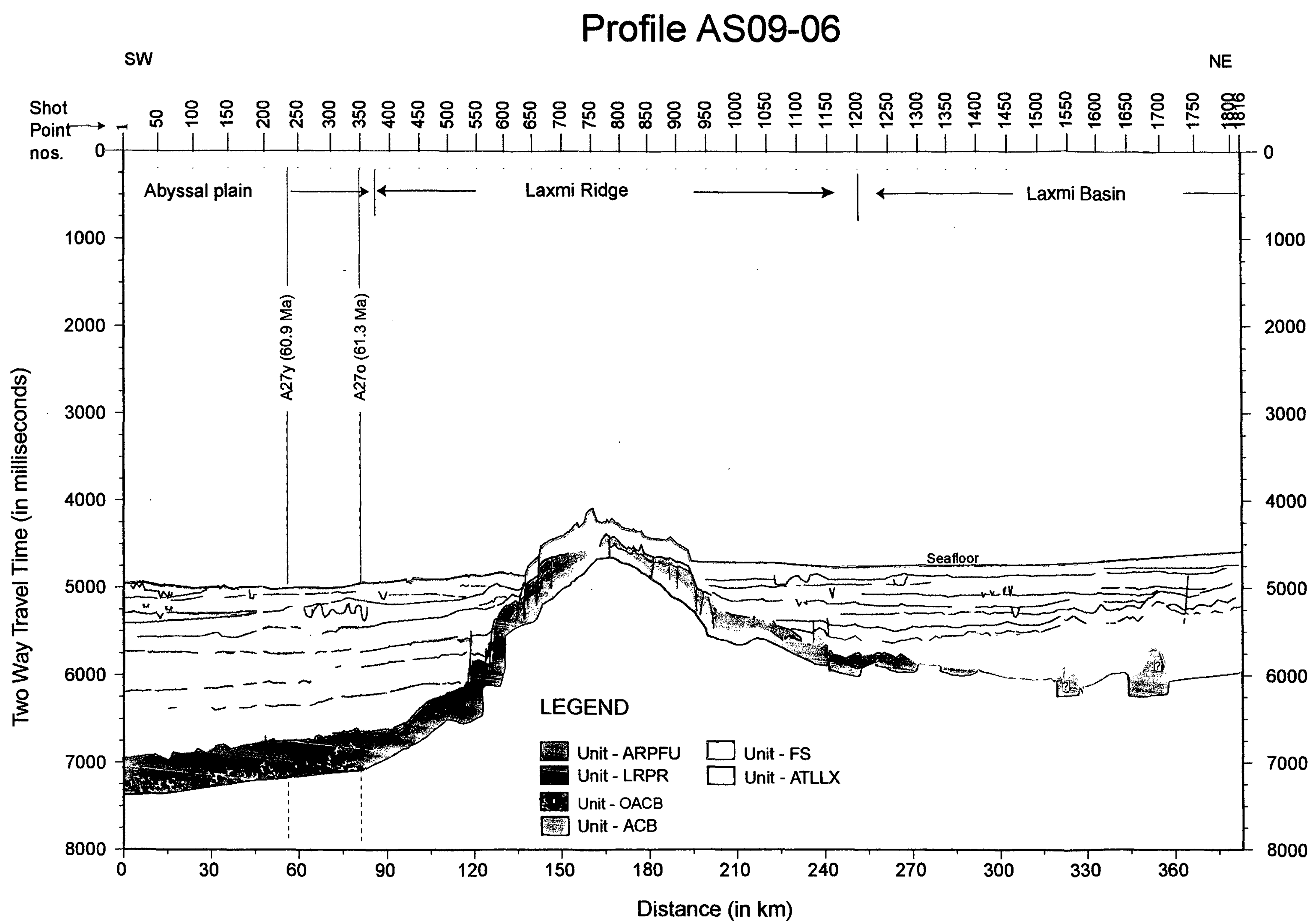


Fig. 5.13 Line drawing of interpreted seismic reflection profile AS09-08. Areas where the seismic section crosses the identified seafloor spreading magnetic lineations (Fig5.1) have been marked by vertical dashed lines labelled with correspnding magnetic anomaly number and age.

Basement could not be identified from the beginning of the profile at least up to SP1710. Between SP 1710 and SP 1400 the basement is observed as two isolated basement peaks. One of these two peaks attains a maximum relief of about 300 msec. Further westward of SP 1400 and at least up to SP 1200 the basement could be observed only as isolated patches. Between SP 1200 and SP 375, the basement is in the form of a broad high of about 190 km in width and about 2200 msec in relief. Location wise this high represents a part of the Laxmi Ridge. From apex of this ridge, towards east at least up to SP 1000 and towards west at least up to SP 550, the basement appears to be down faulted in steps. One of the faults (particularly centered around SP 580) appears to have caused large displacements in the basement levels by about 500 msec. Further west and eastward of these locations, the basement dips towards the adjacent basins. Over this faulted and dipping basement of the Laxmi Ridge, presence of the unit LRPR is observed and this unit LRPR also have been faulted along with the basement. Interestingly in the entire study area only along this profile wide spread occurrence of unit LRPR was observed and this was found to extend from the eastward flank of the Laxmi Ridge (near SP 1100) to its western flank near SP 350. Further westward between SP350 and SP1, the basement gently dips to west and appears to be similar to that of immediate southern line (profile AS09-04). Here also based on identified magnetic lineations the acoustic basement may represent the top of oceanic crust (Chaubey et al., 1998, 2002).

The interpretable sediment overburden in the summit area of the Laxmi ridge is about 500 msec whereas in the basinal parts on either side, it is much thicker. Further, the sedimentary disposition in the basinal parts on either side of the Laxmi Ridge appear to differ to some extent. From the eastern end of the profile, the unit ATLLX is observed to fill the basinal lows and cover the basement highs. This unit ATLLX onlaps the unit LRPR on the eastern flank of the Laxmi Ridge and also appear to drape over the Laxmi Ridge. The occurrence of the unit ATLLX could not be observed westward of about SP625. From eastern end of the profile, the thickness of the unit ATLLX is observed to reduce westward and wedge out over the eastern flank of the Laxmi Ridge. The upper most unit in the areas eastward of the Laxmi Ridge is the unit FS which onlaps over the upper surface of the unit ATLLX.

In the Arabian Basin part of the profile, westward of the Laxmi Ridge, the sedimentary overburden attains a maximum thickness of about 2250 msec. The unit ARPFU, which is the basal unit in this area has a maximum thickness of about 250 msec. The uppermost sedimentary package is the unit FS which attains a maximum thickness of about 2000 msec and overlies the unit ARPFU conformably in the western part of the profile, whereas this unit FS gradually onlaps the unit LRPR over the western flank of the Laxmi Ridge.

5.4 Depth to the acoustic basement

In the present study, the depths to the basement were measured from sea level in terms of two way travel time (TWT) and are presented as contours of depths below sea levels (in msec). The contours were hand drawn with the guidance of structural pattern depicted in the profiles and presented with an contour interval of 200 msec. The resulting contour map (Fig.5.14) provided an idea about basement configuration in the study area. Within the study area, the shallowest basement, lying at about 2800 msec below sea level (msec bsl) , is observed to be present in the southeastern part around 71° 15'E and 16° 20' N. The deepest part of the basement, lying deeper than 7200 msec below the sea level, is observed to be present in the northwestern part around 66°E, 16° 10'N. In general the contour pattern depict two dominant basement trends. In major and western part of the study area the contours depict a NW-SE basement trend, whereas in the eastern part of the map, the contours depict approximately N-S basement trend.

In the northwestern part of the study area, the Laxmi Ridge is expressed as a large NW-SE trending basement high zone. Towards southeast, this Laxmi Ridge basement high zone appears to extend approximately up to 68°30'E and 16°N. Towards north, the basement contours suggests continuation of this feature beyond the limits of the area covered by the seismic profiles. In general, the 5600 msec contour appears to define the base of this basement high in the east and south. Towards west, the depth to base of this basement high zone appears to lie at about 6200 msec. The shallowest region over the summit parts of the basement

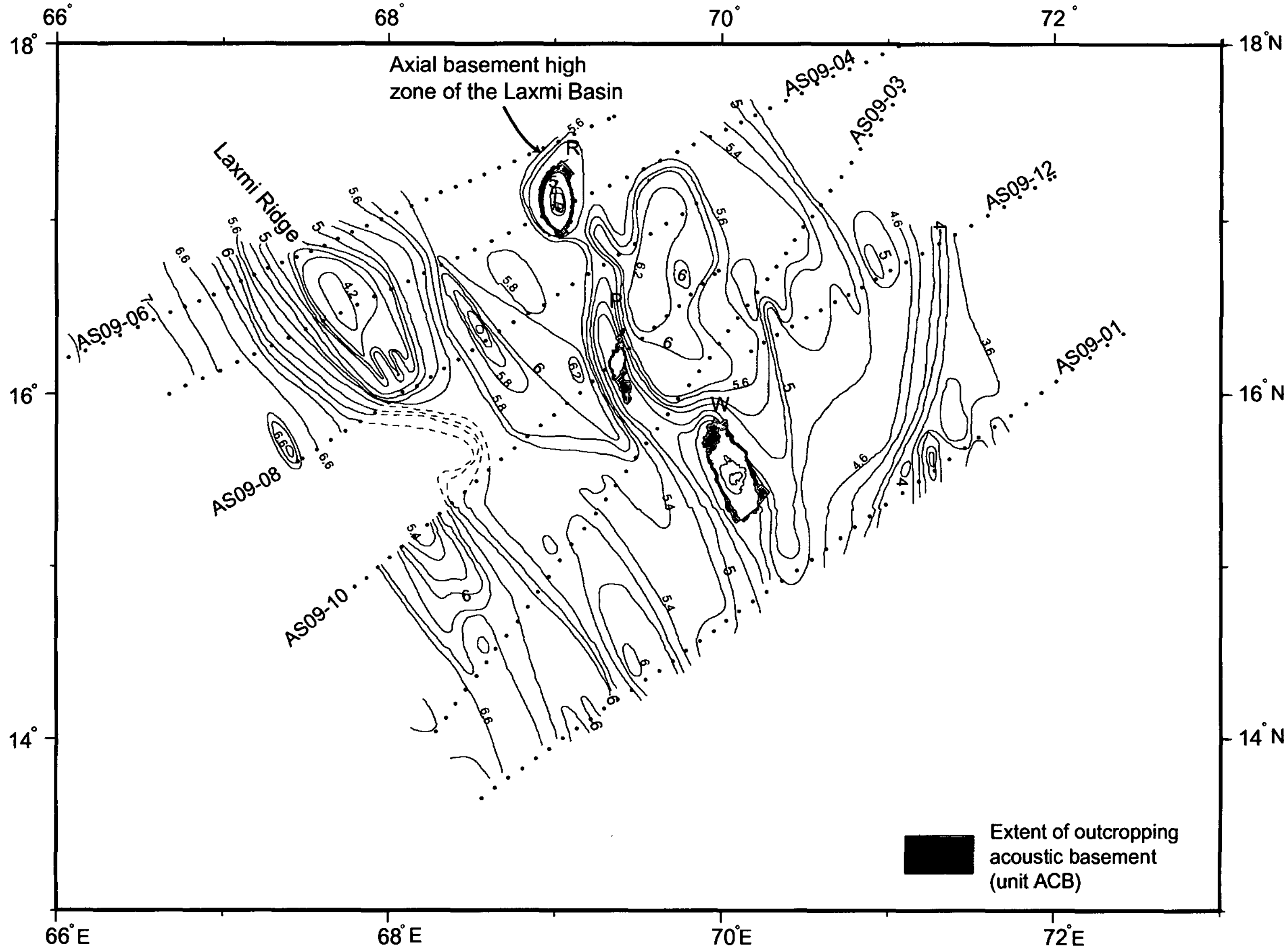


Fig.5.14 Contour map showing the depth to the basement from sea level (in msec of TWT) within the study area. Contour interval is 200 msec and the contours are labelled in thousands of msec. Location of seismic profiles are depicted by dots and are labelled with profile names. R: RAMAN Seamount, P:Panikkar Seamount, W:Wadia Guyot

high zone is defined by 4200 msec. It thus appears that there is noticeable difference in the depth to the surrounding basement on either side of the Laxmi Ridge. On the Laxmi Basin side, this surrounding basement is about 600 msec shallower than the same in the Arabian Basin side. .

Towards southeast of the Laxmi Ridge basement high zone, the contour pattern suggests presence of another NW-SE trending basement high. The summit of this high is approximately centered around 68°10'E, 15°10'N and is defined by 5400 msec contour. The contour pattern between this high and the Laxmi Ridge have been shown as dashed lines. This is because, gravity anomaly and magnetic lineation identification both suggested existence of a east-west trending deeper basement zone in this area, but, the area falling between two seismic lines (AS09-10 and AS09-08), did not allow constructing the contours properly.

Along the axial part of the Laxmi Basin the contours suggests the presence of a NW-SE trending basement high zone (Fig.5.14). For further discussion, this basement high zone will be referred as the "axial basement high zone (ABHZ) of the Laxmi Basin." The base of the basement high zone appears to be deepening towards north. From the bathymetric as well as seismic data it has been observed that, the location and extent of the three Laxmi Basin seamounts (the RAMAN Seamount, the Panikkar Seamount and the Wadia Guyot) fall within this basement high zone. The basement high zone appears to consist of several shorter segments, which depict left lateral offsets. Towards south, the basement high zone merges with the basement high of the Laccadive Plateau. On both sides of this basement high zone, two prominent basement troughs are present. The deepest (deeper than 6000 msec) portion of these basement troughs appears as a contour closure on both sides of the Panikkar Seamount.

In general the contour pattern depict two dominant trends. In major parts it is NW-SE, whereas in the eastern part of the map, the contours depict approximately N-S trend. This N-S trend represents the northward extension of the Laccadive Plateau.

5.5 Thickness of the sedimentary overburden

The thickness of the total sedimentary overburden (from seafloor to the basement) in the study area is measured in terms of two way travel time (TWT msec) and is presented as isopach map. The contours were hand drawn with the guidance of structural pattern depicted in the profiles and presented with a contour interval of 500 msec. Contours are not continued in the areas where the basement was not clearly identifiable. The resulting contour map (Fig.5.15) provided an idea about distribution of sedimentary overburden in the basins and their trends. In the areas where sediment thickness could not be estimated due to absence of seismic data, but the structural pattern warrants a particular contour trend, and the contours in those areas are shown as dashed lines. In general, the sediment thickness contour shows a pattern of NW-SE trending alternate bands of thin and thick zones. The widest of this thin zone is defined by the 500 msec thickness contour, which falls within the zone of Laxmi Ridge (marked as 'A' in Fig. 5.15), and the basement high zone southeast of it (marked as 'B' in Fig. 5.15). Westward

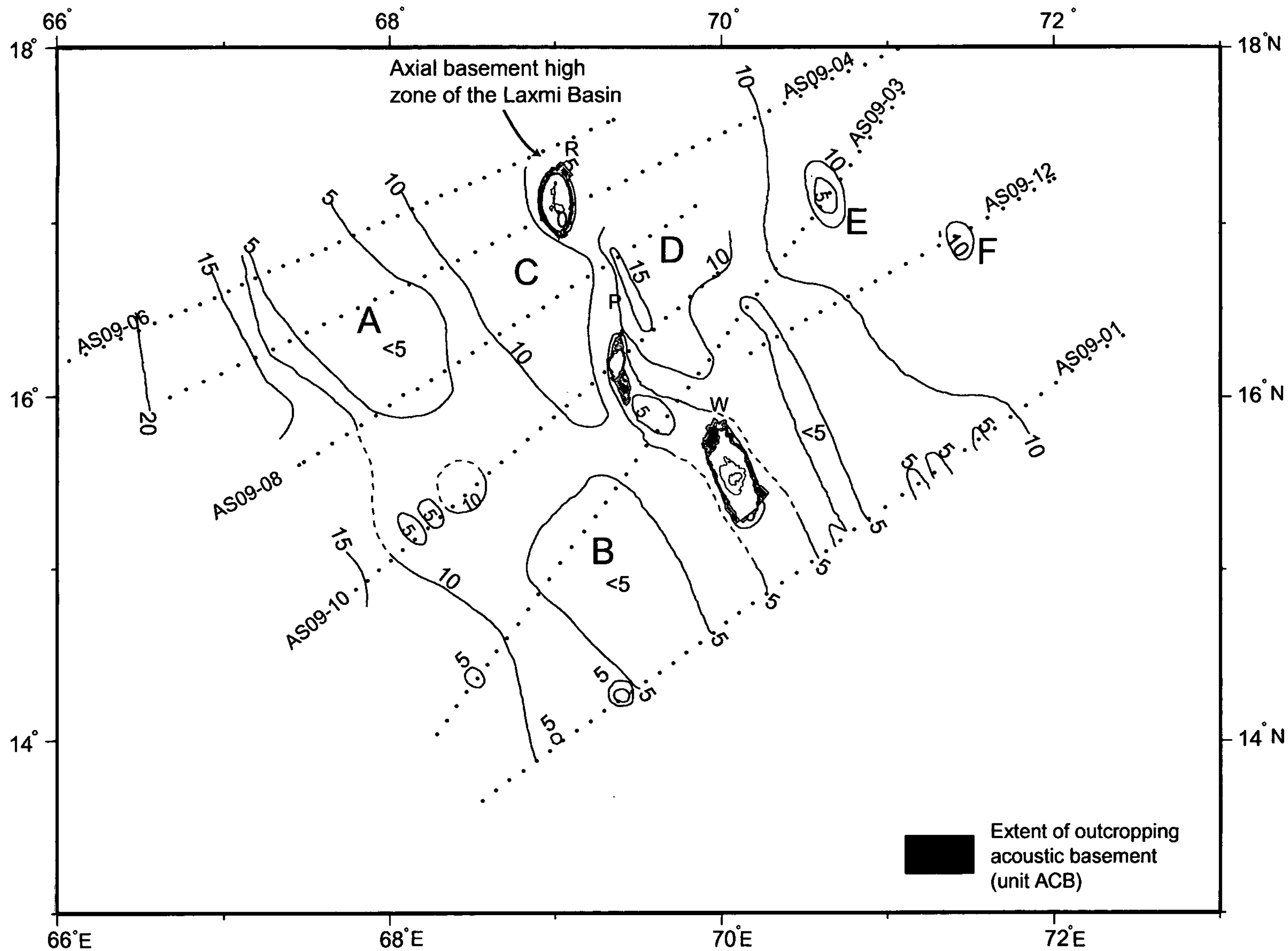


Fig.5.15 Contour map depicting the distribution of total sedimentary overburden (msec of TWT) within the study area. Contour interval is 500 msec and the contours are labelled in hundreds of msec. Location of seismic profiles are depicted by dots and are labelled with profile names. The zones are labellled as discussed in the text. R: RAMAN Seamount P: Panikkar Seamount, W:Wadia Guyot.

of zones A and B, the sediment thickness increases gradually towards the Arabian Basin and reaches about 2000 msec towards the end of the lines. Between the zones of A and B, there appears a complex zone with a number of contour closures associated with narrow and isolated, thin and thick sediment zones. Immediate eastwards of zones A and B is the Laxmi Basin area, along the axial part of which is the minimum sediment thickness zone coinciding with the axial basement high zone (ABHZ) of the Laxmi Basin. Between this ABHZ of the Laxmi Basin and the areas of A and B lies a larger sediment thickness zone. The sediment thickness in this zone appears to increase from south to north and reaches to more than 1000 msec in the areas west of the RAMAN and the Panikkar seamounts (marked as 'C' in Fig. 5.15). Over the eastern flank of this ABHZ of the Laxmi Basin, there appears to lie another band of large sediment thickness zone. This flanking large sediment thickness zone (marked as 'D' in Fig. 5.15) shows increase in its thickness from south to north. In the areas eastward of the RAMAN and the Panikkar seamounts the thickness reaches to more than 1500 msec. Eastward of this zone D, there appears to exists a narrow band of less sediment thickness zone where the sediment thickness varies around 500 msec. Eastward of this narrow band, except at two isolated locales (marked as 'E' and 'F' in Fig.5.15), the sediment thickness increases gradually and is at least more than 1000 msec. In these isolated locales E and F, due to presence of basement highs, the sediment thickness is depicted as less thickness closures.

CHAPTER 6

Chapter – 6

DISCUSSION

6.1 Introduction

Various physiographic features observed in the study area have been described in chapter-4. The basement features and disposition of various sedimentary units as observed along each seismic profile have been described in chapter-5. In the present chapter, the aerial extent and regional correlation of these various features have been presented and analyzed. In this chapter, emphasis is laid on discussing the features deciphered from integration of bathymetric and seismic data.

6.2 Inferred basement structures

Various basement high zones have been identified in the study area. In the intervening areas between these basement highs several shallow and deep basement troughs which have been filled with various units of sediments are present. For the ease of discussion, bounding limits or trends of these features have been shown as either colour shaded zones or by thick labelled dashed lines in Fig.6.1.

a) Axial basement high zone of the Laxmi Basin

Along the axial part of the Laxmi Basin existence of a narrow basement high zone was inferred (Fig.6.1) from the depth to basement contour map. From the bathymetric as well as seismic data, the location and extent of the

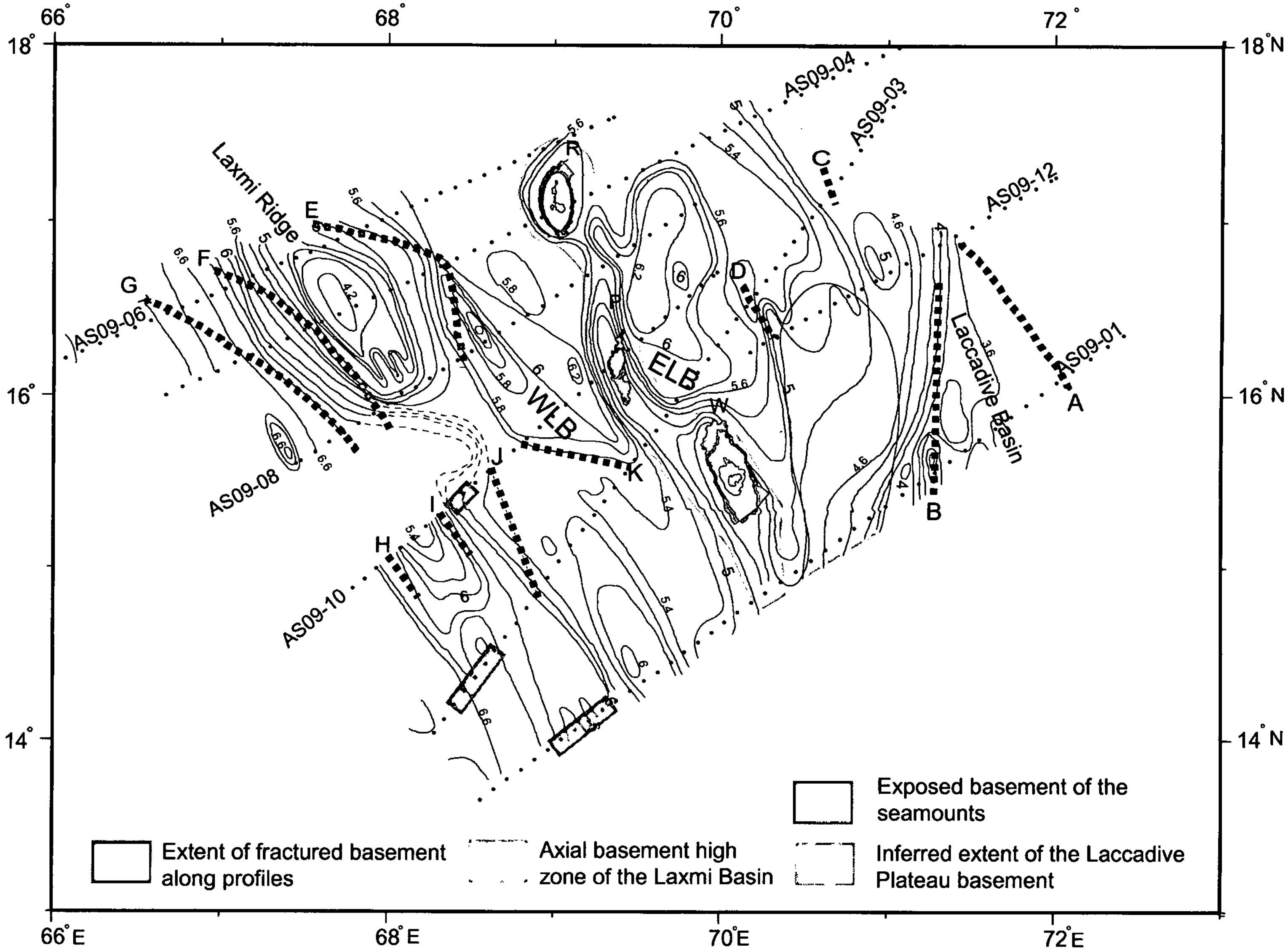


Fig. 6.1 Map showing the interpreted structural trends in the study area. Thick dashed lines are boudnaries of basement trends discussed in the text. The contours in the background are depth to the basement from sea level (in msec of TWT). Contour interval is 200 msec and the contours are labelled in thousands of msec. Location of seismic profiles are depicted by dots and are labelled with profile names. R: Raman Seamount, P: Panikkar Seamount, W: Wadia Guyot.

three Laxmi Basin seamount chain (consisting of the RAMAN Seamount, the Panikkar Seamount and the Wadia Guyot) fall within this basement high zone (Bhattacharya et al., 1994b). It is observed that the basement rocks outcrop along the flanks of these seamounts.

In the areas eastwards of the Laxmi Ridge Naini (1980) observed presence of several isolated basement peaks either as outcrop or as sub-crop. Together these features were considered by Naini (1980) as to represent a basement high zone. Based on analysis of additional seismic profiles in the neighbourhood, Gopala Rao et al. (1992) inferred that this basement high zone represents a 360 km long linear feature and named it as the Panikkar Ridge. This basement high zone approximately coincides with the reported axis of symmetry of two-limbed seafloor spreading magnetic anomalies, which Bhattacharya et al. (1994a) inferred to represent an extinct spreading center. The extent of this axial basement high zone of the Laxmi Basin as interpreted in the present study is shown in Fig.6.1 and the same is shown along with the extent of the basement high zones as inferred by Naini (1980) and Gopala Rao et al. (1992) in Fig.6.2. It can be seen that, present study clearly depicts the nature and southward extent of this basement high zone. This NW-SE trending basement high zone contains the seamounts and appears to be composed of several shorter segments which are offset left laterally. Further, as mentioned earlier, towards south, the Wadia Guyot, which is the southern major seamount edifice of this basement high zone appear to abut against the gently northwestward plunging Laccadive Plateau.

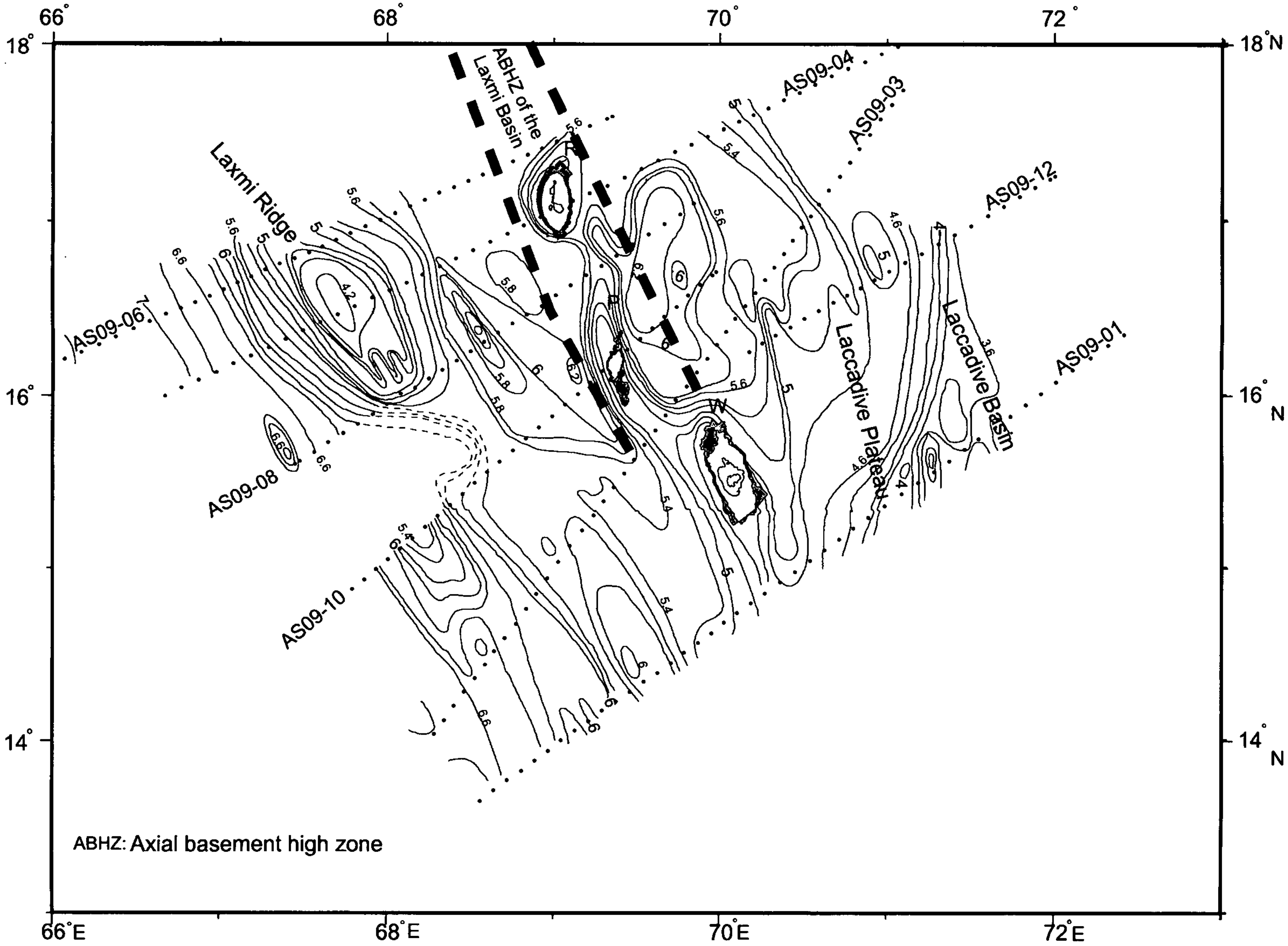


Fig. 6.2 Map showing the relation between axial basement high zone of the Laxmi Basin and similar features inferred earlier in the study area. The extent of basement high zone of Naini (1980) and Panikkar Ridge of Gopala Rao et. al. (1992) is shown as thick dashed lines. The contours in the background are depth to the basement from sea level (in msec of TWT). Contour interval is 200 msec and the contours are labelled in thousands of msec. Locations of profiles are depicted by dots and are labelled with profile names. Rest of the details as in Fig.6.1.

b) Laxmi Ridge and its southern limit

In the study area, the Laxmi Ridge is observed as a prominent NW-SE trending basement high zone whose relatively steeper bounding faces are shown by trend line 'E' and 'F' in Fig.6.1. The zone lying between trend line 'F' and 'G', is inferred to represent relatively gentle basinward dipping flank areas of the Laxmi Ridge. Towards north, the continuation of physiographic expression of the ridge has been established from the analysis of bathymetric data. The open nature of depth to the basement contours also suggests continuation of this feature northwards beyond the limits of the area covered by the seismic profiles.

The bathymetry data suggests that the southwestern limit of the Laxmi Ridge is in the form of a steep scarp face. The absence of seismic profile across this scarp face, do not permit inferring its attitude in sub-seafloor region. Towards southeast of the Laxmi Ridge, two other basement high zones were observed. One of these zones has been demarcated in Fig. 6.1 to lie between trend line 'H' and 'I', and the second zone between trend line 'J' and 'K'. The present data set is not enough to infer, whether these basement high blocks and the Laxmi Ridge together form a continuous feature or not. However, from the published literature (Chaubey et al., 1998, 2002) it appears that some oceanic crust of the age of anomaly 27 is present (Fig.5.1) in the region between the Laxmi Ridge and the southeastward lying basement high zones. Further the published gravity anomaly map (Sandwell and Smith, 1997) also suggests the existence of an east-west trending deeper basement zone in the intervening areas between the Laxmi Ridge and these basement high zones. In view of this, it is inferred, that the Laxmi Ridge perhaps gets terminated by a scarp face in the southeast approximately around 68°30'E and 16°N. It has been observed that, disposition and attitude of sedimentary overburden is very much similar over the summit regions of the Laxmi Ridge and these sub-cropping basement high zones. In view of that it is inferred that these basement high zones lying immediate southeastward of the Laxmi Ridge are not a continuation of the Laxmi Ridge main edifice, but they may represent slivers of the Laxmi Ridge.

c) Architecture and limits of the Laxmi Basin

On both sides of the basement high zone, which is present along the axial part of the Laxmi Basin, the depth to the basement contour map suggests the presence of two basement troughs. The basement trough towards west of this axial basement high zone lies between the Laxmi Ridge and its southeastward lying basement high zone. The basement trough towards east of this axial basement high zone is bounded in the east by the minor basement high features marked by trend lines 'C' and 'D' (Fig.6.1) and the inferred northward extension of the Laccadive Plateau. The deepest (deeper than 6000 msec) portions of these basement troughs are present on both sides of the Panikkar Seamount. In this basement trough region, particularly in the areas eastward of the RAMAN and the Panikkar seamounts, presence of large sediment thickness (more than 1500 msec) was also observed (Fig.5.15). Further as it will be described in a later section, an acoustically well laminated sedimentary unit, named as the intervening layered sediments of the Laccadive Plateau (unit LPIIL), is present as a basal unit in all the seismic profiles crossing this deepest basement trough region. This sedimentary unit LPIL wedges out on both sides apparently over the basement high regions. The eastward termination of this unit along the basement high regions marked by trend line 'D' is well observed along profile AS09-12 and AS09-03. Similarly the westward termination of this unit appears along the eastern flanks of the basement high zone of the Laxmi Ridge and other basement high zone located southeast of the Laxmi Ridge.

Based on presence of deep basement troughs, occurrence of thick sedimentary depocentres and extent of unit LPIL, it is inferred that on both sides of the axial basement high zone of the Laxmi Basin, there are two sub-basins. The bounding basement high regions of these sub-basins in the east and in the west may mark the boundaries of the Laxmi Basin. Tentatively for the purpose of discussion these two sub-basins are being referred (Fig.6.1) in the present study as the Eastern Laxmi Basin (ELB) and the Western Laxmi Basin (WLB). The sub-basins, ELB and WLB appear to widen northwards approximately from 16°N. In the areas south of 16°N, the sub-basins appear to become narrower and shallower. The northward widening, southward narrowing nature of these sub-basins together with the axial basement high zone appear to depict a "V" shaped configuration of the Laxmi Basin.

d) Northerly extension of the Laccadive Plateau

The broad, westward dipping basement feature which was observed over the Laccadive Plateau region along profile AS09-01 is not observable with all its characteristics further northward. What is relatively clearly observable northward of Laccadive Plateau is the axial basement high zone of the Laxmi

Basin and its flanking basin. However it appears that the basement block observed between SP 150 and SP450 along profile AS09-12 bears some resemblance with the eastern end of the Laccadive Plateau as seen along profile AS09-01 between SP 800 and SP 575. The similarities are that, in both these areas, the basement blocks have a eastern scarp face followed by a deep basin in the east and their western limit is defined by a basement high west of which marks the eastern depositional limit of the sedimentary unit LPIL. In both these areas, the basement blocks are depicted as composed of number of basement peaks and troughs. In view of above, it is inferred that towards north at least the eastern part of the Laccadive Plateau continues up to about 16°30'N as a N-S trending irregular subsurface basement feature Fig.6.1). From the depth to the basement contour it appears that this northward extension of the Laccadive Plateau is in the form of a relatively gentle northward plunging basement feature. Whether the western part of the Laccadive Plateau also continues further northward of profile AS09-01 could not be inferred in absence of any characteristics of the basement features.

e) Northerly extension of the Laccadive Basin

A part of the Laccadive Basin along with its decipherable sedimentary overburden and basement has been observed along the profile AS09-01 between SP 135 and SP550 (Fig.5.7). Northwards of profile AS09-01 existence of such a Laccadive Basin with similar sedimentary characteristics is not observed. However, along the profile AS09-12, a basin flanking the eastern limit of the inferred northward extension of the Laccadive Plateau between SP 450 and SP650 is observed. This basin along profile AS09-12 is inferred to represent the northward extension of the Laccadive Basin in the study area, which suggests that to the northward the Laccadive Basin extends approximately up to 16°30'N. The approximate boundaries of this basin have been shown by trend line 'A' and 'B' in Fig.6.1. It need to be mentioned here that, the eastern boundary of the Laccadive Basin is not clearly definable.

f) Zones of fractured basement

In the western part of the three southern profiles (AS09-01, AS09-03 and AS09-10) occurrence of narrow zones were observed where the basement is highly faulted. No where else in the study area such a fractured nature of the basement is observed. Extent of these fractured basement zones is shown in Fig.6.1. The zones do not depict any easily definable trends.

6.3 Inferred sedimentary features

Along the seismic profiles various sedimentary units have been identified in the study area. It has been observed that along the profiles a varying combination of / juxtaposition of these seismic units occur at different locations. The aerial extent and regional correlation of these various sedimentary units have been presented as colour shaded maps and discussed in the following paragraphs.

a) Faulted sediments of the Laxmi Ridge (unit LRPR)

As mentioned earlier, a conspicuous faulted sedimentary unit (unit LRPR) was observed to overly the basement of the summit regions and the limbs of the Laxmi Ridge and the basement high zone lying southwest of the Laxmi Ridge. Its presence was also observed over western sloping flank of the

Laccadive Plateau. This unit was observed as patchy occurrence along all the profiles and the extent of this unit is shown in Fig.6.3. The conspicuous characteristic of this unit is that it is highly faulted along with the faulted basement. This unit does not appear to be present westward of these basement high zones, where oceanic crust is inferred to exist. Similarly, eastward, this unit appears to be present to the extent where the basement high zones appear to have faulted down. Interestingly, the sedimentary units on either side of the basement high zones overlying this unit LRPR do not appear to have been faulted. As mentioned earlier, around 63 Ma (Late Paleocene), spreading in the Mascarene Basin gradually ceased and jumped north of Seychelles, carving the Laxmi Ridge out of the Seychelles to form a new spreading center – the paleo-Carlsberg Ridge. Thus, the Laxmi Ridge probably marks the boundary of rifted continental crust prior to this spreading event. As mentioned earlier, Naini (1980), Naini and Talwani (1982) and Talwani and Reif (1998) also suggested that the Laxmi Ridge is a continental fragment. Malod et al. (1997) also considered continental fragment nature of the Laxmi Ridge basement. Todal and Eldholm (1998) considered the Laxmi Ridge as a complex rifted marginal high comprised of both continental and oceanic crust where inner part of the ridge is underlain by faulted continental blocks. In view of above, it is inferred that the Laxmi Ridge may represent a block of rifted continental fragment and the faulted sediment overlying this ridge was deposited prior to the rifting of the ridge. Similarly, the other faulted basement highs southwest of the Laxmi Ridge, over which similar faulted sedimentary unit LRPR was observed also may represent similar continental slivers and the unit LRPR represents pre-rift stage sedimentation over these reported age of onset of seafloor spreading in the

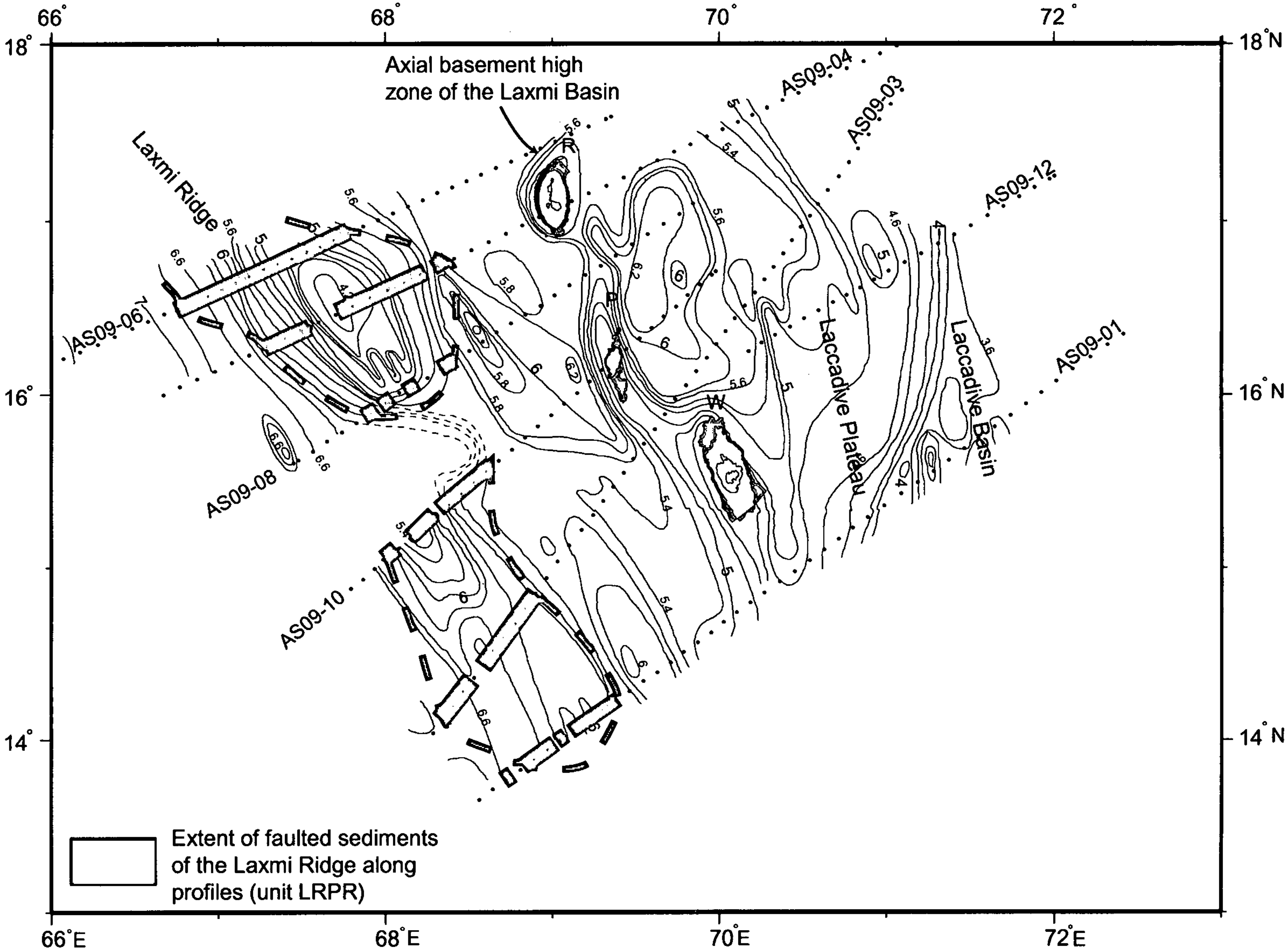


Fig. 6.3 Map showing the spatial distribution of faulted sediments of the Laxmi Ridge in the study area. The occurrence of this unit along the profiles are patchy, therefore, its inferred extent is shown by thick dashed line. The contours in the background are depth to the basement from sea level (in mssec of TWT). Contour interval is 200 msec and the contours are labelled in thousands of msec. Location of seismic profiles are depicted by dots and are labelled with profile names. Rest of the details as in Fig.6.1.

Arabian Basin as about 63 Ma (A27), then this unit LRPR appears to be older than the spreading event.

b) Acoustically transparent sediments of the study area

As mentioned earlier, occurrence of acoustically transparent sedimentary layers were observed in the study area. Two such units (unit ATLLP and unit ATLLX) have been identified. The lower unit ATLLP is observed over the Laccadive Plateau as basal unit, whereas the upper unit ATLLX is observed mainly in the Laxmi Basin and the adjacent slope regions. The summit regions of the Laxmi Ridge also appear to be draped by unit ATLLX. Similar acoustically transparent sedimentary layer is also observed over the Laxmi Basin seamounts. As such, the unit ATLLX is most wide spread across the study area (Fig. 6.4). In general, the thickness of this acoustically transparent unit increases shoreward. Interestingly, over the Laxmi Ridge this acoustically transparent unit was found to extend only up to the western edge of the summit part of the ridge.

In the study area, several direct indications suggest that this acoustically transparent unit could be pelagic or carbonate sediments. For example, analysis of a shallow (up to 480 cm in length) sediment core sample (sample courtesy S.W.A. Naqvi, NIO) over the Wadia Guyot yielded abundant (>90%) presence of foraminiferal assemblages (Abhijit Majumdar, NIO, personal communication) indicating pelagic sedimentation at the location of the core. Published results of drill well and seismic reflection data (Kothari et al., 2001) over the adjacent Padua Bank (drill well location 'D' as shown in Fig.2.5) area suggested the presence of thick carbonate sediments over the basement. The

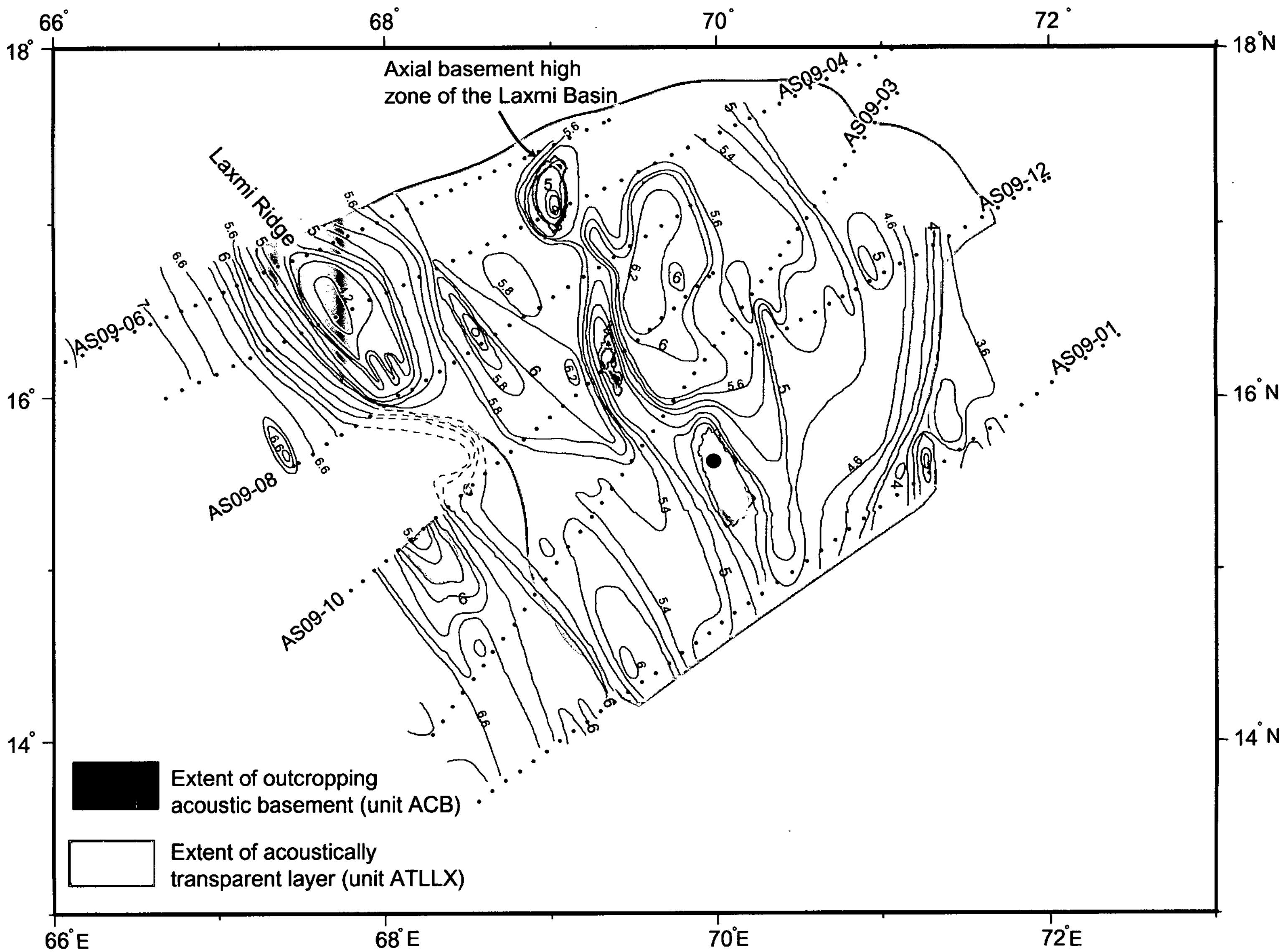


Fig. 6.4 Map showing the spatial distribution of acoustically transparent layer in the study area. The contours in the background are depth to the basement from sea level (in msec of TWT). Contour interval is 200 msec and the contours are labelled in thousands of msec. Locations of profiles are depicted by dots and are labelled with profile names. Solid circle : Location of core sample over Wadia Guyot

seismic section across DSDP drill Site 221 depicted presence of an acoustically transparent layer overlying the oceanic basement as well draping over the adjacent basement highs (Fig.6.5). Analysis of drilled samples suggested that this acoustically transparent unit represents pelagic sediments. Further, the seismic sections across the DSDP drill Site 237 (Shipboard Scientific Party, 1972) and ODP drill Site 707 (Backman and Duncan et al., 1988) in the saddle joining the Seychelles Bank to Saya de Malha depicted similar acoustically transparent unit above the basement. The analysis of drill hole samples at those locations also indicated that the acoustically transparent unit primarily represent pelagic carbonate sediments.

The analysis of seismic reflection records and drill well samples over the adjacent western continental shelf region revealed presence of prolific carbonate sedimentation during Middle Eocene to Early-Mid Miocene (Mohan, 1985; Pandey, 1986; Raiverman, 1986; Nair et al. 1992; Rao, 1994; Pandey and Dave, 1998). It was inferred that, during the northward movement of Indian landmass during this period, the shelf regions of western India experienced favourable conditions like stable platform conditions, warm climate and no terrigenous influx, which are conducive for the formation of prolific carbonate unit.

Based on the resemblance of the acoustically transparent units observed along the profiles in the present study and those observed at the locations of DSDP Sites 221 and 237 and results of direct sampling over the seamounts

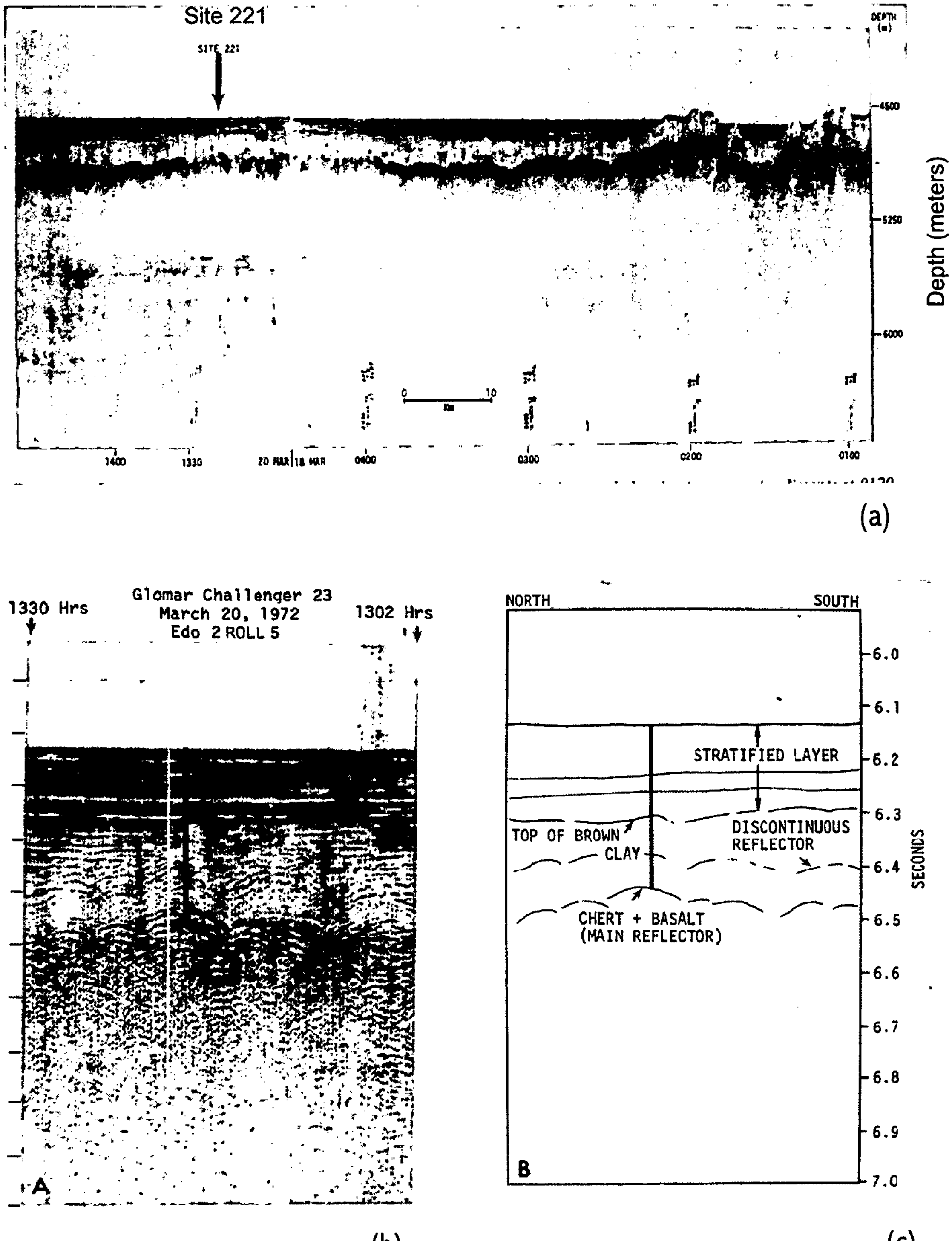


Fig. 6.5 Seismic reflection record across DSDP SIte 221 in the Arabian Basin depicting (a) transparent and stratified sediments; (b) enlarged view of seismic section at the location of Site 221 (thick continuous line) and (c) interpretative line drawing of seismic section presented in (b). Modified after Shipboard Scientific Party (1972).

and the Laccadive Plateau as mentioned above, it may not be unreasonable to tentatively infer that the acoustically transparent unit in the study area also represents carbonate sediments. However, it can not be deciphered whether this acoustically transparent layer represents sediments from the same source. Where the unit occurs as drape structure over the basement highs and seamounts may be of pelagic in origin. Since the thickness of the basal acoustically transparent unit of the Laxmi Basin increases towards shore suggesting that source of a major part of this acoustically transparent sediment is in the shelf region.

c) Intervening layered sediments of the Laccadive Plateau (unit LPIL)

As mentioned earlier a characteristic layered sedimentary unit was interpreted to be present as a basal or intervening unit in the Laxmi Basin and the higher reaches of the Laccadive Plateau region. The extent of this unit is shown in Fig.6.6. It can be seen that the unit is present on either side of the axial basement high zone of the Laxmi Basin. As depicted in the seismic profiles (AS09-01, AS09-03, AS09-10), the total thickness of this unit is more towards this axial basement high zone and wedges out away from the basement high zone. Further, at places individual layers of this unit show thickening towards the center of the basinal lows or the half-graben structures and also are affected by faulting, which might suggest that, the sediments of this unit were deposited on a subsiding basement. The reflection pattern of the unit suggests that the unit is stratified and consists of coarser material. The increase in thickness of this unit towards the vicinity of axial basement high zone, particularly the seamounts might suggest that the sediment source

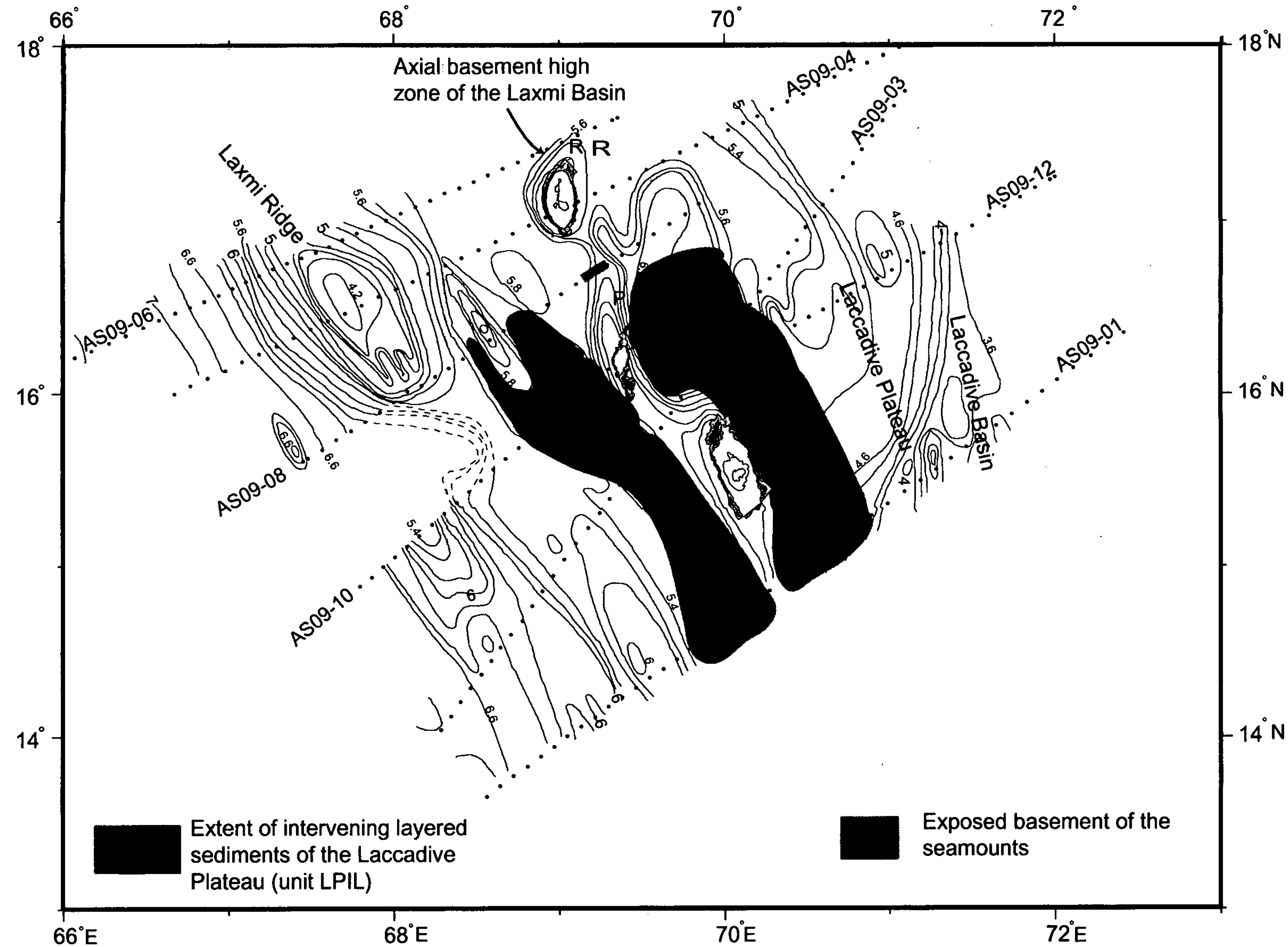


Fig. 6.6 Map showing the spatial distribution of intervening layered sediments of the Laccadive Plateau in the study area. The contours in the background are depth to the basement from sea level (in msec of TWT). Contour interval is 200 msec and the contours are labelled in thousands of msec. Location of seismic profiles are depicted by dots and are labelled with profile names.

for this unit were the rocks of the basement high zone or the adjacent positive features of the Laccadive Plateau. It may be worthwhile to mention here that from swath bathymetric data (Bhattacharya et al., 1994b) over the seamounts of the Laxmi Basin seamount chain indicated existence of extensive gully pattern which were inferred to have been caused by subaerial erosion of those seamounts. Therefore, it appears that these seamounts could have supplied large of amounts of erosional debris in the adjacent areas. In view of this it is inferred that this intervening layered sediments of the Laccadive Plateau (unit LPIL) perhaps was derived locally from the erosion of the axial basement high zone of the Laxmi Basin or the near by seamounts or basement highs of the Laccadive Plateau and deposited over a subsiding basement.

d) Seismic unit ARPFL/ARPFU

Near the western end of all the profiles (i.e. westward of the Laxmi Ridge and the basement high zone southwest of it) relatively thin layers of acoustically transparent sediments (seismic units ARPFL and ARPFU) were observed to be present between the basement and the overlying Indus river derived sediments (unit FS). The upper unit ARPFU was found to be more wide spread and its extent is shown in Fig.6.7. This acoustically transparent sedimentary unit ARPFU fills the irregularities in the basement and its upper surface is flat over which conformably lies the upper sedimentary unit. Further, it was also observed that the sedimentary unit occurs in the areas where the underlying basement of the Arabian abyssal plains is oceanic in nature. Perhaps, this sedimentary unit represents the pelagic sedimentation, which was prevalent in

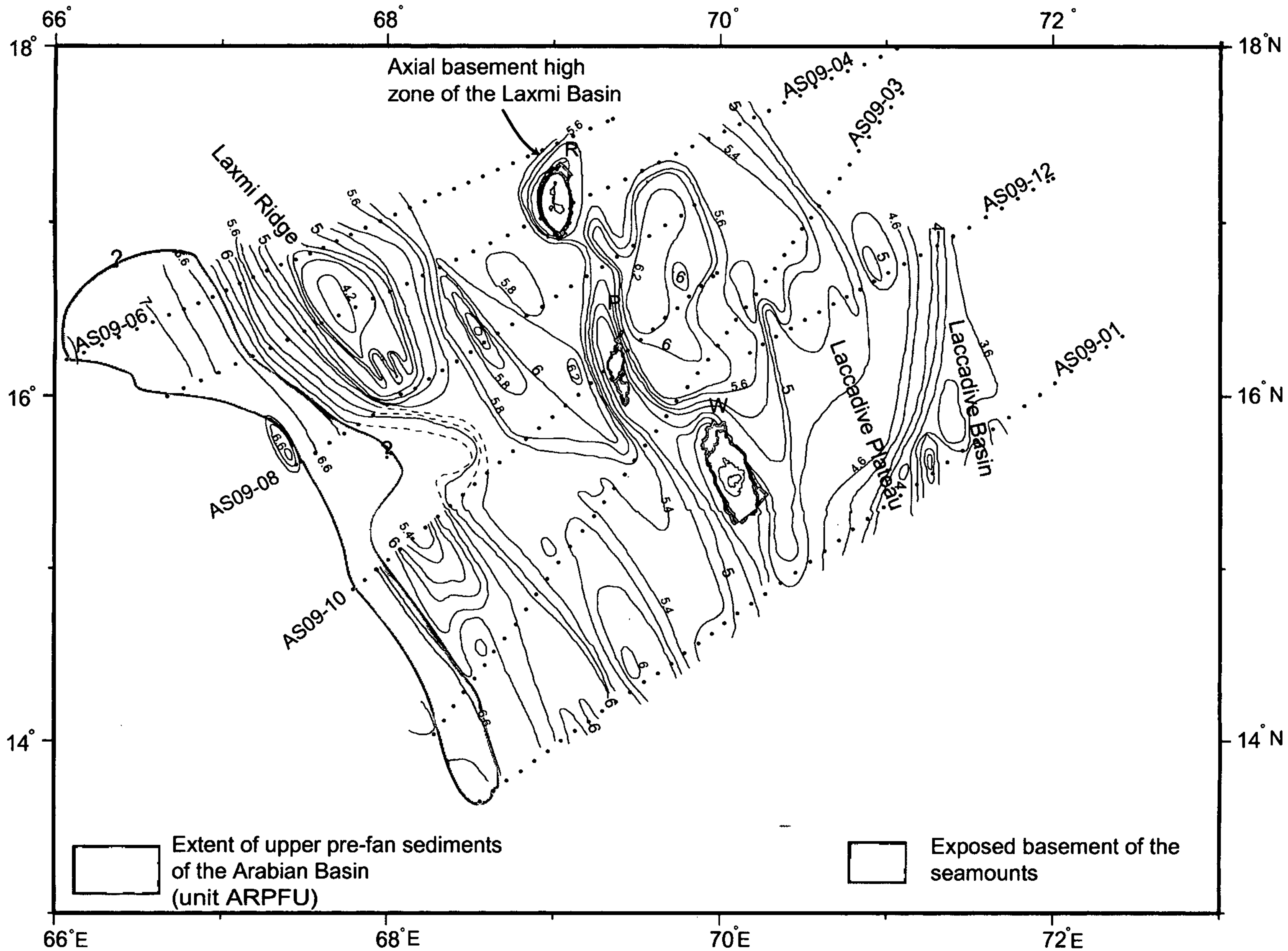


Fig. 6.7 Map showing the spatial distribution of upper pre-fan sediments of the Arabian Basin in the study area. The contours in the background are depth to the basement from sea level (in msec of TWT). Contour interval is 200 msec and the contours are labelled in thousands of msec. Location of seismic profiles are depicted by dots and are labelled with profile names.

the regions of Arabian abyssal plains prior to Indus river derived terrigenous dominant sedimentation. This inference is based on similarity of seismic records of the present study with that of record across DSDP Site 221 (Shipboard Scientific Party, 1972). Though this Site 221 lies much southward of the present study area, but it is located over similar oceanic crust regions and the seismic reflection record across this DSDP Site 221 (Shipboard Scientific Party, 1972) showed the presence of similar transparent basal unit (Fig.6.7a) over the basement. The analysis of drill hole information revealed that the unit consists of two sub-units (Fig.6.7b), the lower nanno-ooze and upper brown clay unit (Fig.6.7c). According to Shipboard Scientific Party (1972) these acoustically transparent units, which are homogenous represent uniform slow pelagic sedimentation approximately at the rate of about 3-5 m/My. Further, according to the results of DSDP Site 221, this pelagic sedimentation regime ended approximately around Middle-Late Oligocene (~30 Ma) when the Indus River derived terrigenous sediments became dominant at that site. In view of this, perhaps following age constraint can be put for this acoustically transparent pre-fan sediments inferred in the present study. The older age bound appears to be younger than 61.3 Ma, because the basement over which these sediments were deposited is dated to be at least 61.3 Ma old based on identification of magnetic anomaly A27. The younger age bound of this unit may represent Middle-Late Oligocene (~30 Ma) corresponding to onset of the Indus river derived sedimentation. If these age bounds are considered then this acoustically transparent pre-fan unit appears to have been deposited over a span of about 31.3 Ma.

e) The Indus fan sediments (unit FS)

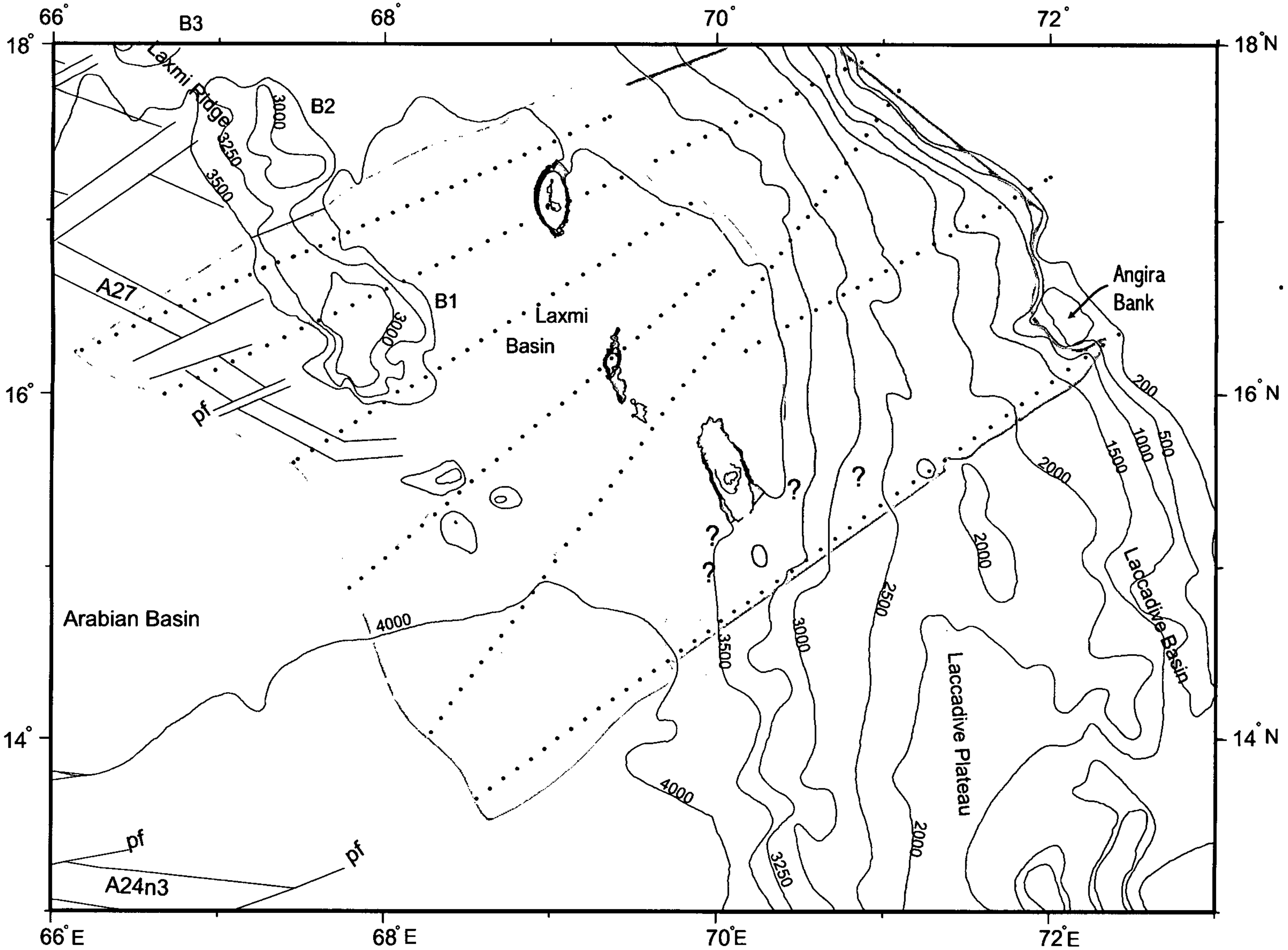
The Indus fan sedimentary unit (unit FS) is a prominent and widespread unit in the study area. In general, in Arabian Basin the unit overlies conformably the interpreted pre-fan sediments (unit ARPFU). In other areas, this unit either onlaps or lies conformably over the underlying sedimentary units or onlaps over the basement outcrop. In the abyssal plain area, this unit in general forms the seafloor. This sedimentary unit is absent over the positive bathymetric features. It was further observed that, the thickness of this unit is more towards western end of the profiles in the Arabian abyssal plains, and thins shoreward towards east. Similarly, the thickness of this unit appears to gradually increase from south to north in the Laxmi Basin area. These observations are considered to suggest that the sediments are brought by the turbidity channels of the Indus River. The absence of the sediments in the same depth levels in the Laxmi Basin area perhaps suggests that this Indus derived sedimentation commenced at much later time in the areas eastward of the Laxmi Ridge. It was also observed that, within this sedimentary unit the channel-levee features are present at different levels. However, they are more prominent only in the upper layers of this unit and occur more in the northern part of the study area. The observed increase in the thickness of the unit from south to north in the Laxmi Basin area, perhaps suggest that at the time of commencement of the deposition of this unit, the underlying depositional surface was also dipping from south to north.

f) Present day sedimentation regimes

Based on the interpretation of seismic reflection data it appears that the present day sedimentation within the study area can be broadly divided into three zones (Fig. 6.8). These broad zones are 1) zone of dominant pelagic sedimentation, 2) zone of dominant Indus river derived sedimentation and 3) zone of dominant terrigenous sedimentation of the shelf and slope regions.

The zone of dominant pelagic sedimentation is identified based on presence of the acoustically transparent sedimentary layer, which was identified in the present study as the unit ATLLX. The zone of dominant Indus river derived sedimentation was identified based on occurrence of unit FS. The zone of dominant terrigenous sedimentation of the shelf and slope regions was identified based on occurrence of unit SL.

It was observed that the pelagic sedimentation in the study area is present only over the positive bathymetric features formed over the basement highs and isolated seamounts. The zone of terrigenous sedimentation of the shelf and slope regions extends from the shelf regions westward up to about 3500 m isobath. The zone of dominant Indus river derived sedimentation is present in the abyssal plain area approximately west of 3500 m isobath. At places the shelf-slope sediments appear to creep into the unit FS and give rise to wavy seafloor topography, for example, near SP 725 along profile AS09-04 (Fig 5.12). Evidences of slumping as observed in the seismic reflection records of the slope region appear to continue even present day. However, the slumping appears to be more active in the shelf-slope region north of the Angria Bank.



Extent of outcropping acoustic basement (unit ACB)

Extent of acoustically transparent layer (unit ATLLX)

Extent of Indus fan sediments (unit FS)

Extent of sediments of the slope region (unit SL)

Fig. 6.8 Map showing the spatial distribution of different interpreted seismic units occurring in the present day seafloor. Selected bathymetric contours as prepared in the present study. Rest of the details as in Fig. 5.1

CHAPTER 7

Chapter – 7

SUMMARY AND CONCLUSIONS

7.1 Introduction

The present study deals with a sector of the continental margins and deep sea regions off the west coast of India and aims to decipher physiography, basement structure and disposition of sedimentary overburden in order to enhance the knowledge about the structure and tectonics of the region. Towards achieving these objectives, about 49000 lkm of bathymetry, published swath-bathymetric data and about 2800 lkm of single channel seismic reflection data were compiled and interpreted. The compiled data and interpretations are presented in the form of bathymetric profiles and contour map, interpretative line drawing sections of seismic reflection data, depth to the basement contour map, isopach map of total sediment thickness and maps showing deciphered basement and sedimentary features. This chapter presents a brief summary of the present work, salient inferences and scope for further work.

7.2 Summary

The most prominent bathymetric features of the deep sea regions adjacent to the west coast of India are the Laccadive-Chagos Ridge and the Laxmi Ridge. The intervening regions between these ridges and the continental shelf off India are identified as number of deep sea basins such as the Laccadive Basin, the Laxmi Basin and the Offshore Indus Basin. Westward of these ridges lie the Arabian

Basin. In context of this framework, the study area broadly spans over a part of the continental slope - rise regions off the central west coast of India and covers a major portion of the Laxmi Basin, the northern extremity of Laccadive-Chagos Ridge, southern part of the Laxmi Ridge and the eastern fringes of the Arabian Basin. The bathymetry data compiled in the present study enabled preparation of an updated bathymetry contour map, which depicts the physiographic expression of the major structural features within the study area more clearly. It was observed that the normal continental slope and rise configuration is relatively well pronounced in the areas north of 17°N, whereas in the areas south of 17°N the configuration is not clearly depicted due to presence of several isolated physiographic highs and the Laccadive Plateau. In general, beyond the slope, the seafloor is smooth till the eastern face of the physiographic highs (viz. Laccadive Plateau, seamounts, Laxmi Ridge). Within the study area the physiographically the Laccadive Plateau depicts a general N-S trend, a gently dipping western limb and a relatively steeper eastern limb. The Wadia Guyot (W) of the Laxmi Basin seamount chain is observed to abut against the gently northwestward plunging Laccadive Plateau (approximately near 15°N, 70°15'E) and appears as a spur like feature of the plateau. Physiographically the Laxmi Ridge is depicted as three blocks separated by shallow saddle like features. Three smaller isolated hill like features are found to exist in the seafloor areas south of the Laxmi Ridge.

Based on interpretation of seismic reflection data, fifteen gross seismic units are identified and the trends and configuration of the basement and overlying sedimentary units are mapped. It has been observed that along the profiles a varying combination / juxtaposition of these seismic units occur at different locations. Northward, the Laxmi Ridge appears to continue beyond the study area, however, in the southeast it appears to get terminated by a scarp face approximately around 68°30'E and 16°N. In the areas southeast of the Laxmi Ridge main edifice, a zone of isolated basement highs was found to be present. This high zone was inferred to represent slivers of the Laxmi Ridge. Within this zone of isolated basement highs, narrow zones of highly fractured basement were found to exist.

Towards north, the Laccadive Plateau is inferred to continue at least up to 16°30'N as a N-S trending, northward dipping, irregular subsurface basement feature. The Laccadive Basin is inferred to extend northward approximately up to 16°30'N. The western boundary of the Laccadive Basin appears to coincide with steep eastern scarp face of the Laccadive Plateau, whereas its eastern boundary is not clearly definable.

The Laxmi Ridge and the basement high regions southwest of it appear to be overlain by a basal sedimentary unit, which was affected by faulting due to faulting of the basement blocks. This faulted sedimentary unit is inferred to represent pre-rift sediments which overly the summit regions and the limbs of the Laxmi Ridge, the basement high zone lying southwest of the Laxmi Ridge and the western sloping flank of the Laccadive Plateau. Along the axial part of the Laxmi Basin existence of a NW-SE trending basement high zone, which contains the Laxmi Basin chain of seamounts is observed. This axial basement high zone appears to be composed of several shorter segments which are offset left laterally. Towards south, this basement high zone merges with the gently northwestward plunging broad basement high regions of the Laccadive Plateau. Two sub-basins are observed on both sides of this axial basement high zone of the Laxmi Basin. The bounding basement high regions of these sub-basins in the east and in the west may mark the boundaries of the Laxmi Basin. The northward widening, southward narrowing nature of these sub-basins together with the axial basement high zone appear to depict a "V" shaped configuration of the Laxmi Basin. A wide spread acoustically transparent sedimentary unit is present in the basinal lows of the Laxmi Basin. Similar acoustically transparent layer is also observed to drape over the structural highs of the Laxmi Ridge, the Laccadive Plateau and seamounts. This acoustically transparent unit is inferred to represent carbonate sediment, which probably has its source in the shelf region or of pelagic in origin.

A layer of stratified sediments is found to exist as intervening or basal layer on the flanks of the axial basement high zone of the Laxmi Basin. This sediments is inferred to be derived locally from the erosion of this axial basement high zone of the Laxmi Basin or the near by seamounts or basement high regions of the Laccadive Plateau and were deposited over a subsiding basement. This situation is inferred to suggest a sub-aerial conditions of these seamounts and basement high zones of the Laxmi Basin in the geological past.

In the Arabian abyssal plain area, west of the Laxmi Ridge, a relatively thin layer of acoustically transparent sediments are observed to occur between the basement and the overlying Indus river derived sediments. This sedimentary unit is inferred to represent the pelagic sedimentation regime, which was prevalent in the regions prior to the Indus River derived terrigenous dominant sedimentation. The upper sedimentary unit that forms the flat seafloor in the Arabian abyssal plain area is inferred to represent the Indus River derived sediments. Channel-levee like features are present within the upper layers of this sedimentary unit and these features are more prominent in the northern part of the study area. The present day sedimentation in the abyssal plains is predominantly the Indus derived sediments; in the slope regions it is continuation of the terrigenous sediments of the shelf and over physiographic highs in the Arabian abyssal plains it is mainly pelagic in origin. Evidence of slumping of sediments is observed in the slope region north of the Angria Bank. The sediments of the slope region appear to gradually creep into the Indus River derived sediments of the abyssal plain and the zone of transition between these two sedimentary units lies approximately along 3500 m depth contour.

7.3 Salient inferences

i. Along the axial part of the Laxmi Basin presence of a basement high zone is confirmed and its detail trend is established. This axial basement high zone is observed to abut against the gently northwestward plunging Laccadive Plateau.

ii. For the first time existence of three smaller hills are mapped in the seafloor southeast of the Laxmi Ridge.

iii. The southeast extent of the Laxmi Ridge is demarcated and the basement high zones lying immediate southeastward of the Laxmi Ridge is inferred to represent its slivers.

iv. Presence of two smaller basins is observed on the flanks of the axial basement high zone of the Laxmi Basin..

v. Existence of pre-rift sedimentary unit is inferred over the Laxmi Ridge and the basement highs to its southeast.

vi. Wide spread occurrence of acoustically transparent sediments in the

Laxmi Basin area is observed and its aerial extent established.

vii. Possible evidence of sub-aerial erosion of the Laxmi Basin seamounts and subsidence was inferred.

viii. Aerial extent of the present day pelagic, Indus Fan and shelf-slope sedimentary regimes in the study area has been mapped.

7.4 Scope for further work

The study enabled delineation of several prominent but hitherto unreported structural and sedimentary features in the area. However, more studies and selected ground truth data will be required to enhance the confidence in these inferences. Following are some studies, which may be pursued further.

a) Acquisition and study of seismic reflection data along selected transects to tie the present lines [line AS09-10 (SP 1000) to Line AS09-01 (SP 1350); Line AS09-04 (SP 825/SP1250) to Line AS09-01 (SP1050/SP1275)] and thereby establishing the correlation of features.

b) Seismic reflection investigations with more powerful acoustic source for mapping the lower boundary of the acoustically transparent unit and the top of the basement.

c) It may be worthwhile to collect sediment samples (surface and shallow cores) to delineate the zone of transition between fan and slope sediments.

d) Closely spaced, high resolution seismic reflection studies may be carried out to understand the distribution and evolution of the turbidity channels in the Indus Fan area.

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