CHAPTER 4
Chapter 4
GEOPHYSICAL SIGNATURES AND INFERENCE ABOUT CRUST UNDERLYING THE OFFSHORE INDUS AND LAXMI BASINS

4.1 Introduction

The deep offshore regions in and around the study area are the Laxmi Basin, the Offshore Indus Basin, and the Arabian Basin (Fig. 4.1). The Arabian Basin is the conjugate of Eastern Somali Basin, which was formed by seafloor spreading across the Carlsberg Ridge. Earlier studies (Norton and Sclater, 1979; Besse and Courtillot, 1988; Royer et al., 1992) considered this seafloor spreading to have started at chron 28, and depicted the configuration of India and Seychelles in their paleogeographic reconstruction models of chron 28. Those reconstruction models of chron 28 suggest that there existed a wide deep offshore region between the Seychelles and the India/Pakistan continental slope at that time. It may be noted that the existence of the Laxmi Ridge was either not known or was not considered in those studies. However, the subsequent studies (Chaubey et al., 2002a; Royer et al., 2002; Miles and Roest, 1993) considered the existence of the Laxmi Ridge and shown that the oldest magnetic anomaly identified in the Arabian Basin is anomaly 28n, which is located immediately south of Laxmi Ridge (Fig. 4.1). This observation implies that

i) at chron 28n, Seychelles was juxtaposed with the Laxmi Ridge,

ii) if Seychelles was ever juxtaposed with India/ Pakistan mainland, then it was in the form of a Greater Seychelles, i.e., Seychelles together with the Laxmi Ridge,

iii) Greater Seychelles was juxtaposed with India/Pakistan mainland at a time prior to the time of anomaly 28n (i.e. earlier than ~62 Ma), and

iv) the wide deep offshore region between the present day Laxmi Ridge and the adjacent India/ Pakistan continental slope was created as a result of moving away of Greater Seychelles from India/Pakistan mainland.
Deccan Trap

An anomalous gravity high zone depicted from the satellite derived free-air gravity anomalies.

Axial basement high zones of the Offshore Indus and Laxmi basins.

The inferred boundary of the Laxmi Ridge.

The inferred fracture zones in the Offshore Indus Basin (Malod et al., 1997) and in the Laxmi Basin (Bhattacharya et al., 1994b).

Selected bathymetry contours of 200 m, 1000 m, 2000 m, 3000 m, and 4000 m.

Fig. 4.1 Generalized map of the deep offshore regions adjoining west coast of India/Pakistan, showing major tectonic elements. The solid black lines represent the mapped seafloor spreading type magnetic lineations inferred by Bhattacharya et al. (1994b), Malod et al. (1997) and Chaubey et al. (2002a). OIB: Offshore Indus Basin; LB: Laxmi Basin; LR: Laxmi Ridge; AGH: Anomalous Gravity High; BH: Bombay High; NR: Narmada Rift.
As described earlier in chapter 2, two views exist about the nature of the crust underlying the wide region between the Laxmi Ridge and the adjacent continental slope of India. Some researchers (Naini and Talwani, 1982; Kolla and Coumes, 1990; Miles et al., 1998; Todal and Eldholm, 1998; Lane et al., 2005; Krishna et al., 2006) believe that the crust underlying this region represents a thinned continental crust formed only by rifting, while the studies of others (Biswas and Singh, 1988; Bhattacharya et al., 1994b; Malod et al., 1997; Talwani and Reif, 1998; Bernard and Munschy, 2000; Bulychev et al., 2006) imply that at least the axial part of this region was formed by two-limbed seafloor spreading, which became extinct during chron 28n. It appears that most of these studies based their inference, about the nature of the crust underlying this region, on independent interpretation of one or other type of geophysical signatures rather than integrated analysis of all available data. In view of this, it is felt necessary to compile updated information about various geophysical signatures in the study area and to infer the nature of the crust underlying these regions based on integrated interpretation of those geophysical signatures. This chapter briefly describes those geophysical signatures and the inferences made from their integrated interpretation.

4.2 Geophysical signatures of the Offshore Indus and Laxmi basins

(a) Seafloor and basement features from seismic reflection profiles

The seismic investigations (Naini and Talwani, 1982; Kolla and Coumes, 1990; Malod et al., 1997; Collier et al., 2004a, b; Srinivas, 2004) carried out in the deep offshore regions adjoining to India/Pakistan mainland revealed the presence of various seafloor and basement features in the study area (Fig. 4.2). The major basement features among these are the Laxmi Ridge, the Palitana Ridge and the Panikkar Ridge. Sectional views of these features are available in some published seismic reflection sections from the Offshore Indus and Laxmi basins. The published seismic section from the Laxmi Basin is from Naini and Talwani (1982) and the two published seismic sections from the Offshore Indus Basin are from Malod et al. (1997) and Collier et al. (2004a, b). The locations of these three profiles have been shown in Fig. 4.2 and corresponding seismic sections in Fig. 4.3a-c. The sectional views of the basement highs representing
Axial basement high zones of the Offshore Indus and Laxmi basins.

Extent of the basement highs as depicted in the seismic reflection sections.

The inferred boundary of the Laxmi Ridge.

Fig. 4.2 Locations of the published seismic reflection profiles in the Offshore Indus and Laxmi basins. The seismic sections along the profiles AB, CD and EF are given in Fig. 4.3. PKR: Panikkar Ridge; PTR: Palitana Ridge. Other details are as in Fig. 4.1.
Fig. 4.3 Published seismic sections across the Offshore Indus Basin and the Laxmi Basin regions. Seismic reflection sections: (a) along profile AB (modified from Malod et al., 1997), (b) along profile CD (modified from Collier et al., 2004a, b) and (c) along profile EF (modified from Naini and Talwani, 1982). The basement high along the central part of the Laxmi Basin coincides with the axis of extinct spreading axis postulated by Bhattacharya et al. (1994a, b) and the location of Palitana Ridge coincides with the extinct spreading centre in the Offshore Indus Basin as postulated in the present study. Locations of the profiles are shown in Fig. 4.2.
the Laxmi Ridge as well as the axial basement high region of the Laxmi Basin are clearly observed from the seismic reflection section (Fig. 4.3c). In a similar way, the sectional view of the prominent basement high across the axial part of the Offshore Indus Basin is observed in both the seismic sections (Fig. 4.3a, b). The seismic results show (Fig. 4.2) that the basement expression of the southerly part of the Laxmi Ridge, which abuts the Laxmi Basin trends NW-SE and the northerly part of it, which abuts the Offshore Indus Basin region trends E-W. However, the seafloor topographic expression of the Laxmi Ridge is observed only over the NW-SE trending southerly segment. The axial basement high region of the Laxmi Basin is a NW-SE trending continuous basement feature, which at places outcrops as seamounts. The seismic and bathymetric results in the Offshore Indus Basin show that Palitana Ridge is an E-W trending continuous buried basement high feature. Interestingly, the Panikkar Ridge in the Laxmi Basin and the Palitana Ridge in the Offshore Indus Basin parallel the trend of the adjacent segments of the Laxmi Ridge. Further, the velocity-depth information derived from the seismic refraction results over the NW-SE trending (Naini and Talwani, 1982) and the E-W trending (Collier et al., 2004a, b) sectors of the Laxmi Ridge reveals the presence of deeper Moho than obtained for the Arabian Basin region.

(b) Gravity anomalies

The sea-surface gravity profiles (Naini and Talwani, 1982) in the Laxmi Basin revealed the presence of a short wave length gravity low superimposed on a broad wavelength gravity high. Axis of this short wave length gravity low coincides with the axial basement high feature seen in the seismic section. Subsequently, Bhattacharya et al. (1994b) observed that this prominent short wave length gravity low is a characteristic continuous feature within the Laxmi Basin and its trend is approximately NNW-SSE. The recent sea-surface gravity profile published by Collier et al. (2004b) interestingly depicted a similar feature in the Offshore Indus Basin, where also a basement high feature exist, which is associated with a short wave length gravity low atop a broad wave length gravity high.

In view of these similarities of gravity signatures, the available sea-surface gravity profiles have been compiled and studied to understand and compare the causative crustal structures of the Offshore Indus and Laxmi basins. For this
exercise, seventeen gravity profiles (Fig. 4.4) were selected. The gravity anomalies along these profiles were stacked after projecting them perpendicular to the trend of the Laxmi Ridge (Fig. 4.5). This stacking was done with respect to the inferred characteristic short wave length gravity low axis in both the basins. In the regions where gravity low axis could not be traced, the profiles were stacked based on the contiguity of the gravity signatures. Among the seventeen profiles, ten profiles are sea-surface gravity profiles archived in the NGDC and NIO databases. To fill the inter-profile wide gap areas, seven profiles have been extracted from the available (Sandwell and Smith, 1997; 2003) satellite derived free-air gravity anomalies. To test the reliability of the satellite gravity data to be used for the present study, the satellite derived free-air gravity anomalies have been extracted exactly along the location of sea-surface profile SK79-11. A comparison of gravity anomalies along these two profiles (Fig. 4.5) shows very good correlation between the satellite derived free-air gravity profile SK79-11(SG) and the sea-surface gravity profile SK79-11. In view of this, wherever additional gravity profiles were required for the correlation of characteristic gravity signatures, the satellite derived free-air gravity profiles have been extracted and used.

The stacked gravity profiles (Fig. 4.5) and the along track gravity anomalies (Fig. 4.6) show the presence of a major NW-SE trending broad free-air gravity low region existing between the Arabian Basin and the Laxmi Basin regions. This characteristic gravity signature shows that around 65°30'E this feature turns to WNW-ESE direction and extends westwards at least up to 63°40'E. A comparison of this gravity signature with the basement configuration of the regions showed that this signature correspond to the basement high region of the Laxmi Ridge. The broad wave length gravity high regions observed in the north and east of the Laxmi Ridge represent the gravity signatures of the Offshore Indus and Laxmi basins. In the Laxmi Basin region, the characteristic short wavelength gravity low atop the broad wavelength gravity high can be confidently correlated northwards at least till profile SK22-08. Similarly, in the Offshore Indus Basin region, similar gravity anomaly can be confidently correlated eastward till profile SG-05. In the region between profiles SK22-08 and SG-05, the continuation of this characteristic short wavelength gravity low axis
Fig. 4.4 Colour shaded-relief image of the satellite derived free-air gravity anomalies of the Laxmi Basin and Offshore Indus Basin regions. Black lines with white annotations are locations of selected gravity anomaly profiles used in this study to depict the characteristic gravity signatures of the region. Annotations along these profiles are profile identifiers. Profiles along which the free-air gravity anomalies have been extracted from satellite derived gravity anomalies are prefixed with SG. Other tracks are of sea-surface gravity anomalies along different ship tracks, the details of which are given in Table 3.1. Other details are as in Fig. 4.1.
The inferred landward boundary of the Laxmi Ridge.
The axis of the short wave length gravity low atop the broad gravity high region of the Laxmi and Offshore Indus basins.
The easternmost boundary of Laxmi Basin based on the oldest magnetic lineation identified by Bhattacharya et al. (1994b).

Fig. 4.5 Selected gravity profiles projected perpendicular to the trend of the Laxmi Ridge and stacked with respect to the axis of characteristic short wave length gravity low atop the broad gravity high region of the Laxmi and Offshore Indus basins. In the region where gravity low axis could not be traced, the profiles are stacked based on the contiguity of the other gravity signatures. Locations of these profiles are presented in Fig. 4.4. The excellent closeness may be noted between the sea-surface gravity anomaly along SK79-11 and the gravity anomaly profile SK79-11(SG) which is based on satellite derived gravity data grids.
Fig. 4.6 Map showing the gravity anomalies over the Laxmi Ridge, Laxmi Basin and Offshore Indus Basin regions, plotted perpendicular to the tracks. The gravity anomalies in both the Laxmi Basin and Offshore Indus Basin regions are characterized by a short wave length gravity low atop a broad wave length gravity high. Other details are as in Fig. 4.1.
could not be traced. Instead, it was observed that there exists an anomalous gravity high zone (AGH). The extent of this anomalous gravity high zone has been inferred in this study (Fig. 4.7a-d) based on the satellite derived free-air gravity anomalies. The free-air gravity anomaly contours (at 5-mgal interval) of this region clearly depict the presence of a gravity high region bounded by a steep gradient zone. This steep gradient zone around the anomalous gravity high has been considered to define its extent (Fig. 4.7a-d).

(c) Magnetic anomalies

The sea-surface magnetic profiles in the Laxmi Basin revealed the presence of fairly correlatable magnetic lineations (Bhattacharya et al., 1994b) between the Laxmi Ridge and the western continental slope of India. Bhattacharya et al. (1994b) observed that these magnetic lineations are symmetric about a central negative magnetic anomaly and the axis of symmetry coincides with a characteristic short wave length free-air gravity low atop a broad gravity high. Based on these observations, they inferred that the Laxmi Basin is underlain by oceanic crust created as a result of two-limbed seafloor spreading. Subsequently, Malod et al. (1997) mapped linear magnetic anomalies in the Offshore Indus Basin and inferred that these magnetic lineations represent oceanic crust formed as a result of two-limbed seafloor spreading process. However, the inferences of Bhattacharya et al. (1994b) and Malod et al. (1997) have been questioned in some of the subsequent studies (Todal and Eldholm, 1998; Miles et al., 1998) and were supported in several other studies (Bernard and Munschy, 2000; Talwani and Reif, 1998; Bulychev et al., 2006). The recent study carried out by Krishna et al. (2006) supported the postulation of Malod et al. (1997) that the Offshore Indus Basin is underlain by pre-Tertiary oceanic crust, however, they disagreed with the postulation of Bhattacharya et al. (1994b) that the Laxmi Basin is underlain by oceanic crust. In view of such different opinions, the available sea-surface magnetic profiles were compiled and studied to understand and compare the crustal structure causing the magnetic anomalies in the Offshore Indus and Laxmi basins.

For this exercise, seventeen sea-surface magnetic profiles (Fig. 4.8) archived in the NGDC database and NIO database have been selected. These magnetic profiles have been presented as plot along track map (Fig. 4.9a, b) and
Fig. 4.7 The extent of the anomalous gravity high (AGH) zone northward of the Laxmi Ridge as deciphered from the satellite-derived free-air gravity anomalies. (a) AGH as reflected in the colour shaded-relief image of free-air gravity anomalies; (b) AGH as depicted by the free-air gravity anomaly contours of 5 mgal interval; (c) the extent of AGH (thick black line) as considered in this study to be defined by the steep slope of gravity contours and (d) the extent of the AGH (shaded yellow), along with the other tectonic elements in the adjoining regions. Other details are as in Fig. 4.1.
Fig. 4.8 Map showing locations of selected sea surface magnetic anomaly profiles across the Laxmi Basin and Offshore Indus Basin regions, which are stacked and presented in Fig. 4.10. Annotations along the tracks are profile identifiers. Other details are as in Fig. 4.1.
Fig. 4.9 Map showing the magnetic signatures in the Offshore Indus and Laxmi basins plotted perpendicular to ship's tracks. (a) along with major tectonic elements and selected bathymetry contours (b) along with the axis of the characteristic short wave length gravity low atop the broad gravity high of the Laxmi and Offshore Indus basins. Other details are as in Fig. 4.1 and Fig. 4.4.
Fig. 4.10 Selected sea-surface magnetic profiles projected perpendicular to the strike of the inferred magnetic lineations and stacked with respect to the axis of the characteristic short wave length gravity low atop the broad wave length gravity high of the Offshore Indus and Laxmi basins. In the region where gravity low axis could not be traced, the profiles are stacked based on contiguity of prominent magnetic anomalies. Locations of these profiles are presented in Fig. 4.8.
as stacked profiles (Fig. 4.10). While stacking, the profiles were projected perpendicular to the strike of the inferred magnetic lineations and are aligned with respect to the axis of the characteristic short wave length gravity low atop the broad wavelength gravity high. As described earlier, the characteristic gravity low could not be traced between profiles SG-05 (the Offshore Indus Basin) and SK22-08 (the Laxmi Basin) due to the presence of an anomalous gravity high (AGH) zone. Therefore, the magnetic profiles located in this region have been aligned by considering the contiguity of the magnetic signatures along the profiles crossing with the characteristic gravity low axis.

It was observed that in the Laxmi Basin the sequence of positive and negative magnetic anomalies, flanking the axis of short wavelength gravity anomaly (along which the magnetic profiles are aligned), displays axial symmetry. As reported by Bhattacharya et al (1994b) this symmetry is particularly apparent (Fig. 4.10) from profile SK79-15 and SK79-15(reversed). In the Offshore Indus Basin area Malod et al. (1997) proposed such an axis of symmetry of magnetic anomalies; however, it was observed in the present study that the axis of symmetry proposed by them do not coincide with the axis of the characteristic short wave length gravity low or the location of Palitana Ridge.

d) Comparison of basement features and geophysical signatures

The gravity, magnetic and seismic information in the Offshore Indus and Laxmi basins and their association with the prominent basement features have been examined for their possible alikeness. Based on the seismic reflection and refraction information, it is clearly observed that both the basins show the presence of basement high features located approximately in the axial part of the basins. These axial basement high features parallel the trend of the adjacent segments of the Laxmi Ridge. These basement features in both the basins coincide with the axis of short wave length gravity low atop broad wavelength gravity high. These characteristic gravity lows merge with an intervening anomalous gravity high zone. The magnetic anomalies in both the basins reveal the presence of fairly correlatable linear and nearly parallel magnetic anomalies. In view of these observations, it appears that the crust underlying the Offshore Indus and Laxmi basins are similar in nature. Therefore, to infer the nature of the
crust underlying these regions, an integrated interpretation of these geophysical signatures was carried out.

4.3 Inference about the nature of crust underlying Offshore Indus and Laxmi basins

In this study, inference about the nature of the crust underlying the Offshore Indus and Laxmi basins have been made mainly based on crustal structure derived from forward modeling of gravity and magnetic anomalies. The gravity modeling was carried out following the procedure detailed in section 3.3.1. On obtaining a reasonable crustal configuration from gravity model, forward modeling of magnetic anomalies was carried out using the same crustal configuration. The magnetic anomalies are computed based on the procedure detailed in section 3.3.2.

a) Interpretation of gravity anomalies in the Offshore Indus Basin

To derive the crustal structure and density configuration in the Offshore Indus Basin and the adjoining regions, a ~500 km. long satellite derived free-air gravity profile (GCDH in Fig. 4.11a) that extend from the Arabian Basin to the continental rise off Pakistan has been used. This representative profile GCDH has been selected based on several consideration. First of all, this profile covers the well-correlatable magnetic lineations of the region. Secondly, over a part of this profile (segment CD) published latest seismic reflection results are available (Collier et al., 2004a, b) and refraction results are available (Collier et al., 2004b) over a nearby parallel profile RS (Fig. 4.11a).

As a first step for gravity modeling, an initial crustal model section (Fig. 4.11b) has been constructed by using the multichannel seismic reflection and seismic refraction results of Collier et al., (2004a, b). The seismic reflection results are more reliable for shallower regions (up to the basement), and seismic refraction results provide better information for deeper regions. Therefore while constructing this crustal section, shallower part was constrained from seismic reflection results and the deeper parts were constrained from seismic refraction results. To convert the depth to basement from the time to the depth units, an average velocity of 2.7 km/sec has been used for the sediments through out the profiles. This value was assumed following the empirical formula provided by
Malod et al. (1997) for the Offshore Indus Basin and following the sediment velocity provided by Naini (1980) for the Arabian Basin. Since the velocity information from Collier et al. (2004a, b) is available only as analog velocity model section, therefore wherever available, the refraction information (Fig. 4.12a, b) of Naini and Talwani (1982) from the stations falling close to the gravity profile have also been considered while assigning the average interval velocities. In the Arabian Basin region, the velocity structure for a typical oceanic crust as provided by Naini and Talwani (1982) has been considered. While assigning the interval velocities for Laxmi Ridge region, the velocity information (Fig. 4.12a, b) from station L02V34 only has been considered, rather than using the velocities provided by Naini and Talwani (1982) for a generalized crustal structure of the Laxmi Ridge, as this station is over the Laxmi Ridge, it lies very close to the profile GCDH and refraction of Moho was obtained at this station. In the Offshore Indus Basin region, as such no refraction stations of Naini and Talwani (1982) provided information about the deeper crustal layers of the region. Therefore, only the refraction results of Collier et al. (2004b) have been considered for assigning the interval velocities for the layers. In the region of continental rise of Pakistan, the velocity structure of a typical continental crust has been assumed.

All the above mentioned assumed velocity information have been summarized as average crustal columns (Fig. 4.13a) and an initial crustal model (Fig. 4.13b) has been constructed using these average crustal columns. While constructing the crustal model the layer densities have been estimated based on the velocity-density relationship of Ludwig et al. (1970). Since the bathymetry and basement information are available only for CD segment of the profile GCDH, therefore in the gap areas (segments GC and DH), the bathymetry data have been extrapolated using the satellite derived topography data (Smith and Sandwell, 1997). In the gap areas the basement has been assumed to lie at the level of top of the layer with $\geq 5$ km/sec velocity below the sedimentary layers. As seen from Fig. 4.11a, the gravity profile passes through four geological domains – the Arabian Basin, the Laxmi Ridge, the Offshore Indus Basin and the continental rise of Pakistan. In this initial crustal model, the probable lateral boundaries of each geological domain have been assumed mainly based on consideration of extent of different basement features and shapes of the gravity
Fig. 4.11 Available seismic reflection, refraction (Collier et al., 2004a, b) and magnetic profiles from the Offshore Indus Basin close to the representative profile GCDH, which was used for inferring the nature of the underlying crust. (a) Locations of seismic refraction profile (RS), reflection profile (CD) and the nearest available magnetic profile (CD2087-06). (b) Seafloor and basement information from seismic reflection section CD and velocity-depth information projected onto profile GCDH from the results of refraction studies along profile RS. Other details are as in Fig. 4.1.
Fig. 4.12 The seismic refraction information in Offshore Indus Basin and the adjoining regions after Naini and Talwani (1982). (a) Locations of seismic refraction stations (solid black and red circles annotated with station ID) in and around the study area along with profiles used for gravity and magnetic modeling. (b) Velocity-Depth information along gravity profile GCDH, based on the seismic refraction information from the nearby stations shown as solid red circles. Other details are as in Fig. 4.1.
Fig. 4.13 The velocity-depth information along the profile GCDH that has been used for modeling the gravity data. (a) The average crustal columns representing the Arabian Basin (AB), Laxmi Ridge (LR), Offshore Indus Basin (OIB) and the continental rise of Pakistan (CRP). (b) The crustal structure section that has been used as the initial model while performing the gravity modeling.
anomalies. The initial crustal model was refined successively so as to obtain a reasonable good fit between the observed and computed anomalies. While refining the model, the relatively reliable constraints, such as the calculated densities of the layers, depth to seafloor and depth to basement configurations obtained from seismic reflection, have been kept unchanged, while the boundaries of the deeper crustal layers have been adjusted.

The derived crustal model (Fig. 4.14) suggests the presence of ~6 km thick crust below the sediments in the Arabian Basin region. This region consists of a two-layered crustal structure, where a 2.63 g/cc density upper crustal layer and a 2.88 g/cc density lower crustal layer, underlie the sediment layer of density 2.17 g/cc. The crust underlying this region of the Arabian Basin has already been established by many earlier studies as oceanic, which contain clearly identifiable magnetic lineations of seafloor spreading origin. Therefore these layers with density 2.63 g/cc and 2.88 g/cc can be considered as the layer 2 and layer 3 of the oceanic crust respectively. In the continental rise region off Pakistan, the crustal model suggests presence of ~14 km thick crust which increases in thickness landward. The assumed layer densities in this region are consistent with the upper and lower continental crusts, however the thickness ~14 km of this region is much less as compared to the thickness of about 30 km for the adjacent continental crust region. It is inferred that this crust underlying the continental rise region off Pakistan is underlain by thinned continental crust.

The derived crustal model suggest that the Laxmi Ridge region along this profile consists of a two-layered crustal structure, where a 2.64 g/cc density upper layer and a 2.86 g/cc density lower layer, underlie approximately 2.5 km thick layer of sediments. These density configurations appear to be consistent with the upper and lower continental crustal layers, which is isostatically balanced by deepening of Moho to a depth of 17 km. The total thickness of the crust underlying the Laxmi Ridge is ~11 km. Based on these inferences about the thickness and density configuration the Laxmi Ridge appear to represent a region of thinned continental crust.

The derived crustal model (Fig. 4.14) in the Offshore Indus Basin region suggests that the region can be considered to consist of a ~6 km thick two-layered crustal structure, where a 2.66 g/cc density upper layer and a 2.89 g/cc
Fig. 4.14 Derived crustal structure across the Arabian Basin, Laxmi Ridge, Offshore Indus Basin and the continental rise of Pakistan based on forward modeling of gravity profile GCDH. The location of profile GCDH has been shown in Fig. 4.11. PTR: Palitana Ridge.
density lower layer, underlie approximately ~3.5 km thick layer of sediments. Interestingly, it is observed that except below the Palitana Ridge, the general depth to Moho in the Offshore Indus Basin region, almost is in the same level as that of the Arabian Basin. It appears that the density configurations, thickness of the crust as well as the similarity in Moho depth make the Offshore Indus Basin region comparable with the crustal configuration of the Arabian Basin, which is oceanic in nature. In that case the basement layer of the Offshore Indus Basin with density 2.66 g/cc and velocity 5.70 km/sec, can be equated to layer 2 of the oceanic crust. In the seismic refraction section of Collier et al. (2004b), a flat Moho has been depicted throughout the Offshore Indus Basin; however, the gravity modeling carried out in this study necessitated the Palitana Ridge region to be compensated by a deepening (~16 km) of Moho. This compensated structure was necessary to be introduced in order to explain the characteristic short wave length gravity low atop a broad wave length gravity high, which is associated with the Palitana Ridge region. Further, for better match with the observed gravity anomalies it became necessary also to introduce, just below the Palitana Ridge, a low-density body of density 2.6 g/cc beneath the layer of density 2.66 g/cc. As will be shown later, the Offshore Indus Basin region have been inferred to be underlain by an oceanic crust, where the Palitana Ridge is interpreted as an extinct spreading centre. In that case, existence of a low density body below the Palitana Ridge does not appear unreasonable as presence of similar solid low density body under an extinct spreading centre has been postulated by Jonas et al. (1991) to explain the observed gravity anomalies over extinct spreading centres. The gravity model suggests that under the Palitana Ridge the layer with density 2.66 g/cc rise upward. Considering this layer as layer 2 of the oceanic crust, such an upward rise do not appear to be uncommon as the recent seismic reflection studies carried out by Singh et al. (2006) over a segment of Mid-Atlantic Ridge clearly indicated upward rising of the base of Layer 2A towards the axis of the spreading centre. The derived crustal model further shows that a part of the basement layer (2.66 g/cc density layer) in the Offshore Indus Basin continues and falls over the inferred basinward edges of the continental crust over the Laxmi Ridge and the continental rise of Pakistan. As will be shown later, such an interpretation is necessary while carrying out the forward modeling of magnetic data and its integration with the gravity
interpretation. These regions may represent volcanics emplaced during the formation of ‘Initial oceanic crust’ as inferred in other continental margins by several researchers (Mutter et al., 1982; Talwani and Abreau, 2000). In view of all the above observations, it is tempted to believe that the Offshore Indus Basin region, in general can be considered to be underlain by an oceanic crust. However, to establish this inference, interpretation of magnetic data has been integrated with the gravity interpretation derived crustal structure.

(b) Interpretation of magnetic anomalies in the Offshore Indus Basin

If the Offshore Indus Basin region is underlain by an oceanic crust, then the magnetic anomalies along or close to this profile in the Offshore Indus Basin region should also be possible to be explained using the same crustal configuration derived from forward modeling of gravity data. As evidenced from the various seismic refraction studies, the ~6-7 km thick oceanic crust consists of two layers; viz. layer 2 and layer 3. The layer 2 consists of highly magnetic basalt flows whereas the underlying layer 3 consists of weakly magnetic gabbroic oceanic crust. As a result, in general, the layer 2 has been considered as the major source of the seafloor spreading magnetic anomalies (Cox and Hart, 1986; Banerjee, 1984). Therefore, attempt has been made to examine the possibility of an oceanic nature of the crust underlying Offshore Indus Basin, based on forward modeling of magnetic anomalies. While carrying out modeling of magnetic data, the magnetic anomalies are considered to have been caused by juxtaposed blocks of normally and reversely magnetized crust, which lie within the layer 2 of the oceanic crust inferred from gravity model.

The magnetic parameters, which influence the shape and amplitude of the magnetic anomalies are the thickness of the magnetized layer, its susceptibility, the depth to the top of the magnetized layer, present location and strike of the magnetic bodies, paleo-location at the time of formation and the width of each normally and reversely magnetized blocks. Among these parameters, the thickness and the depth to the top of the magnetized layer have been defined by limits of the inferred layer-2 derived from gravity modeling. The synthetic magnetic anomalies are computed for a set of E-W striking juxtaposed normally and reversely magnetized blocks, presently observed at 20°N, 65°E (Fig. 4.15a). As it will be shown later, the central block is considered to correspond to anomaly
27n (~61 Ma) of geomagnetic polarity reversal timescale. Therefore, to obtain the
crater location at the time of formation of this oceanic crust, a paleogeographic
reconstruction of the region (Fig. 4.15b) has been carried out for 61 Ma in fixed
hotspot reference frame using the finite rotation parameters of Müller et al.
(1993). This model suggested that the Offshore Indus Basin area was in the
southern hemisphere, near 11°S, 51°E, at the time of formation. The boundaries
of the adjacent normally and reversely magnetized blocks have been defined in
such a way that the computed synthetic magnetic anomalies give the best fit with
the observed magnetic anomalies. For comparison of synthetic magnetic
anomalies (Fig. 4.16) the projected profile CD2087-06 have been taken as the
observed profile even though Collier et al. (2004b) in their paper have provided
the plot of magnetic anomalies along profile CD. The reasons for not considering
that profile are the following. First of all, the digital data for this profile are not
available in public domain. Secondly, a comparison with two magnetic profiles
CD2087-06 and CD 2087-07, located very close to profile CD, strongly suggested
some inconsistency in the published magnetic profile of Collier et al. (2004b).
Lastly, the profile CD2087-06 is of much longer extent and digital data along this
profile is available from the NGDC database.

The magnetic modeling exercise (Fig. 4.16) shows that the observed
magnetic anomalies along the profile in the Offshore Indus Basin can be
considered to have been caused by juxtaposed normally and reversely
magnetized blocks, which lie within the basement layer. The sequence of these
magnetized blocks appear to be symmetrical about a central narrow normally
magnetized block, where the axis of symmetry of the magnetized blocks
coincides with the characteristic short wavelength gravity low atop a broad
wavelength gravity high and the basement high feature of the Palitana Ridge. As
discussed earlier, the basement layer (i.e. the layer with density 2.66 g/cc and
velocity 5.70 km/sec) of the offshore Indus Basin can be equated to layer 2 of the
oceanic crust. The parallel nature of the magnetic lineations and the symmetric
arrangement of the magnetized blocks within the basement layer (inferred as
layer 2 of the oceanic crust) support generation of the underlying crust by a two
limbed seafloor spreading. The continuation of magnetic anomalies (thereby
magnetic bodies) a short distance over the Laxmi Ridge and basement of
Fig. 4.15 Maps showing the locations and strike directions of the inferred paleo-
spreading in the Offshore Indus and Laxmi basins as used for computation of synthetic magnetic anomalies. (a) Present location and strike of the ridges. (b) Paleo-location of the ridges at anomaly 27n (61 Ma) time, as described by the finite rotation parameters of Müller et al. (1993) in fixed hotspot reference frame.
Fig. 4.16 Crustal structure along profile GCDH derived from integrated gravity and magnetic modeling. The forward modeling of the magnetic data shows that the magnetic anomalies in the Arabian Basin and Offshore Indus Basin can be explained in terms of juxtaposed normally and reversely magnetized blocks (susceptibility=0.01 cgs units) within the layer 2 derived by the gravity modeling. Synthetic magnetic profiles are computed for a ridge presently striking N90°E and observed at 20°N, 65°E which was formed at the location 11°S, 51°E. The computed magnetic anomalies are compared with the observed magnetic profile CD2087-06 (projected to an azimuth of 0°), which is located close to the gravity profile GCDH. The locations of the profiles have been shown in Fig. 4.11, other details are as in Fig. 4.14.
Pakistan continental rise perhaps represents the initial oceanic crust. In view of the above evidences from the gravity, magnetic and seismic information, it is interpreted that part of the Offshore Indus Basin, where the magnetic lineations have been mapped, is underlain by oceanic crust formed as a result of two-limbed seafloor spreading between Laxmi Ridge and continental rise of Pakistan and the axial basement high region (Palitana Ridge) represents the extinct spreading centre. It may be mentioned here that, earlier Malod et al. (1997) also reported existence of two-limbed seafloor spreading type magnetic anomalies in the Offshore Indus Basin region and thereby inferred an oceanic nature of the underlying crust. The interpretation of magnetic anomalies in the present study agrees with the inference of Malod et al. (1997) in one sense that the Offshore Indus Basin region is formed a two-limbed seafloor spreading, but differs on few important aspects. Firstly, the location of the axis of symmetry and thereby the location of the extinct spreading center is interpreted in this study at a location different than of Malod et al (1997). Secondly, the Palitana Ridge, which coincides with the axis of symmetry inferred in this study have been interpreted to represent the extinct spreading center, whereas Malod et al. (1997) considered the Palitana Ridge as an uplifted basement feature related to Miocene reactivation. Thirdly, as will be shown in a later section, the identification of the magnetic anomalies of the present study also differs from that of Malod et al. (1997).

(c) Interpretation of gravity anomalies in the Laxmi Basin

To derive the crustal structure and density configuration in the Laxmi Basin and the adjoining regions, an ~850 km long satellite derived free-air gravity profile RE-02(SG), that crosses the Arabian Basin, Laxmi Ridge, Laxmi Basin and the western continental shelf of India has been used (Fig. 4.17a). This profile has been selected since a recently published (Krishna et al., 2006) seismic reflection section RE-02 is available along this profile as a whole, and the location of the magnetic profile SK79-15 in the Laxmi Basin, which very clearly show the symmetric nature of the magnetic anomalies, is nearly coincident over large part of this profile.

As a first step, an crustal section (Fig. 4.17b) has been constructed by using the interpreted line drawings of the multichannel seismic reflection section
presented in Krishna et al. (2006) and seismic refraction results of Naini and Talwani (1982). As done in the case of Offshore Indus Basin region, shallower and deeper layers of this crustal section have been constrained from the seismic reflection and refraction results respectively. To convert the basement from the time section to the depth section, a velocity of 2.7 km/sec has been used for the sediments throughout the profile. The average interval velocities for all the layers in each geological domain have been estimated based on the interval velocity information of Naini and Talwani (1982). In the Arabian Basin region, the velocity structure for a typical oceanic crust as provided by Naini and Talwani (1982) has been considered. In the region of continental shelf of India, the velocity structure of a typical continental crust has been assigned. In the Laxmi Basin region, no sonobuoy refraction stations of Naini and Talwani (1982) provided information about the Moho depth. Their inference about the depth to the Moho under the Laxmi Ridge and Laxmi Basin regions were based on estimation of minimum depth to the Moho assuming a mantle velocity of 8.2 km/sec. Subsequent researchers, while performing gravity modeling, used that estimate of minimum depth to the Moho and a generalized regional average for the depth to other layers in the Laxmi Basin. Instead of such generalization, which appears to be less reasonable due to the structural complexity of the region, in the present study the seismic refraction information from only those stations have been used which are closer to profile RE-02(SG).

The most recent available seismic refraction results of Collier et al. (2004b) in the Offshore Indus Basin, which forms a part of the Eastern Basin of Naini and Talwani (1982), interestingly show that the depth to the Moho in the Arabian Basin and Offshore Indus Basin are almost in the same level. Therefore, in absence of well-constrained depth to the Moho information in the Laxmi Basin area, while constructing the initial crustal model the depth to the Moho has been assumed to lie in the same level as that in the adjacent Arabian Basin. This assumption was made considering the similarities of the Laxmi Basin and the Offshore Indus Basin in terms of basement features and geophysical signatures.

All the assumed velocity information has been summarized as average crustal columns (Fig. 4.18a) and initial crustal model (Fig. 4.18b) has been constructed using the above-mentioned average crustal columns. While
Fig. 4.17 The available seismic reflection and refraction information in the Laxmi Basin and the adjoining regions. (a) Locations of seismic refraction stations (after Naini and Talwani, 1982) shown as red and black solid circles annotated with station ID, seismic reflection profile (RE-02 of Krishna et al., 2006). (b) The Velocity-Depth information along profile RE-02, based on the seismic refraction results from nearby refraction stations. Gravity data along profile RE-02 and magnetic data along nearly coincident profile SK79-15 have been used for modeling. Other details are as in Fig. 4.1.
Fig. 4.18 The velocity-depth information along the profile RE-02, which has been used for modeling gravity data. a) The average crustal columns representing the Arabian Basin (AB), Laxmi Ridge (LR), Laxmi Basin (LXB) and the continental shelf of India (CSI). b) The crustal structure section that has been used as the initial model while performing the gravity modeling.
constructing the initial crustal model, the layer densities have been estimated using the velocity-density relationship of Ludwig et al. (1970). In this initial crustal model, the probable lateral boundaries of each geological domain have been assumed mainly based on consideration of extent of different basement features and shapes of the gravity anomalies. The initial crustal model was refined successively so as to obtain a reasonable good fit between the observed and computed anomalies. While refining the model, the relatively reliable constraints such as the calculated densities of the layers, depth to seafloor and depth to basement obtained from seismic reflection have been kept unchanged, while only the boundaries of the deeper crustal layers have been adjusted in order to obtain a fit between the observed and computed gravity anomalies. This approach has resulted in increasing the general depth to the Moho in the Laxmi Basin area. Further, while modeling, it was noticed that good fit between the observed and computed anomalies required consideration of few prominent short wave length observed anomalies too. Since short wavelength gravity anomalies have their origin in the shallower layers, therefore, at places slight refinement of the shallower layers became necessary. Examination of the interpreted line drawing of the basement and its comparison with the time section presented by Krishna et al. (2006), suggested scope to refine the depth to basement at places. In view of this, the inferred basement has been slightly refined at few places to obtain a better fit of the computed gravity anomalies with the observed gravity anomalies.

The derived crustal model (Fig. 4.19) suggests that the Arabian Basin region can be considered to consist of a ~5 km thick two-layered crustal structure, where a 2.63 g/cc density upper layer and a 2.88 g/cc density lower layer underlie the sediments. As mentioned earlier these layers with density 2.63 g/cc and 2.88 g/cc can be considered as the layer 2 and layer 3 of the oceanic crust respectively. The continental shelf/slope/rise region of India shows a two-layered crustal structure, where a layer of density 2.67 g/cc overlies a layer of density 2.85 g/cc. These layers with density configurations typical of upper and lower continental crust, are isostatically compensated at deeper levels with the landward increase in the Moho depth. In this region (between 630 – 670 km mark in Fig. 4.19), the interpreted line drawing of the basement shows two isolated peaks, which Krishna et al. (2006) have interpreted as volcanic intrusions.
Fig. 4.19 Derived crustal structure across the Arabian Basin, Laxmi Ridge, Laxmi Basin and the western continental shelf of India based on forward modeling of the gravity profile RE-02(SG). The location of profile RE-02 has been shown in Fig. 4.17. PKR: Panikkar Ridge.
Although both these peaks are of nearly equal dimension, still only one of them appears to be associated with a short wavelength gravity anomaly. If the presence of these two features is true, then the gravity modeling carried out in this study necessitates these two bodies to be explained as low-density features with a density of 2.3 g/cc. In such a situation, it appears that these features cannot be interpreted as the volcanic intrusives as inferred by Krishna et al. (2006), because the volcanic intrusive bodies are usually of higher density than the surrounding continental crust. Probably, these features of lower density represent carbonate growth features over thinned continental crust, which later got buried under the sediments. The gravity model shows that the Laxmi Ridge can be represented as a distinct structural high underlain by a three-layered crustal structure under thin (~0.5 km) veneer of sediments. The three-layered crust of the Laxmi Ridge consists of an upper 2.61 g/cc density layer, middle 2.77 g/cc density layer and lower 3.00 g/cc density layer. The layer with density 3.00 g/cc can be considered as the middle-lower crust and the layer with density 2.61 g/cc as the upper continental crust. The layer of 2.77 g/cc probably represents the upper continental crust in which the rift related magmatic materials were emplaced. This increase in average density of the layer may be due to the presence of higher density volcanic material emplaced in the layer of 2.61 g/cc density. It appears that the density configurations is consistent with the layers of continental crust, which is isostatically compensated by a ~22 km deep Moho and the total thickness of the crust underlying the Laxmi Ridge is only about 19 km. Based on these inferences about the thickness, density configuration and its characteristic negative free-air gravity signature, the Laxmi Ridge appears to be underlain by a thinned continental crust as was inferred in several earlier studies.

The gravity modeling derived crustal structure (Fig. 4.19) of the Laxmi Basin region suggest that except below the Panikkar Ridge, the general depth to the Moho in this region is ~13 km and the total thickness of the crust under the Laxmi Basin region is ~7 km. The gravity model suggests that the Laxmi Basin area consists of a three-layered crustal structure under ~3.0 km thick sediment layer. The three-layered crust of the Laxmi Ridge consists of an upper 2.61 g/cc density layer, middle 2.79 g/cc layer and lower 3.02 g/cc layer. The densities of these layers are close to the densities of the layers of Laxmi Ridge, but the layer
thicknesses vary considerably between the crusts of the Laxmi Ridge and the Laxmi Basin. In the Laxmi Basin region, the thickness of each layer is much less than that of Laxmi Ridge region. As seen from the crustal configuration, the total thickness of the crust in the Laxmi Ridge is ~19 km, whereas that in the Laxmi Basin is only ~7 km. These layers with densities 2.61 g/cc, 2.79 g/cc and 3.02 g/cc can be considered to represent the layers 2A, 2B and 3 of oceanic crust.

The gravity modeling carried out in this study also necessitated the axial basement high region in the Laxmi Basin to be isostatically compensated by a deepening (~18 km) of Moho. This compensated structure was necessary to be introduced in order to explain the characteristic short wave length gravity low atop a broad wave length gravity high, which is associated with the axial basement high region in the Laxmi Basin. Further, for better match with the observed gravity anomalies, it appears to be necessary to introduce, just below the Panikkar Ridge, a low density body of 2.6 g/cc beneath the layer of density 2.79 g/cc. The inferred layer 2 of the oceanic crust under the axial basement high appears to rise up towards the centre of the axial basement high as in the case of Palitana Ridge. The derived crustal model further shows that a part of the basement layer (2.61 g/cc density layer) in the Laxmi Basin continues and falls over the inferred basinward edges of the continental crust over the Laxmi Ridge and the continental rise of India. As will be shown later, such an interpretation is necessary while carrying out the forward modeling of magnetic data and its integration with the gravity interpretation. This situation is similar to the situation modeled in the Offshore Indus Basin and thus similarly inferred to represent volcanics emplaced during the formation of 'Initial oceanic crust'.

(d) Interpretation of magnetic anomalies in the Laxmi Basin

The interpretation of the gravity anomalies suggests that the Laxmi Basin region can be considered to be underlain by an oceanic crust. If this inference is correct, then the magnetic anomalies in the Laxmi Basin region also should be explained using the same crustal configuration derived based on modeling of gravity data. As is done in the case of Offshore Indus Basin, attempt has been made to examine the oceanic nature of the crust underlying the Laxmi Basin based on forward modeling of magnetic anomalies, where the magnetic
anomalies are considered to have been caused by juxtaposed blocks of normally and reversely magnetized crust, which lie within the gravity model derived inferred layer 2 of the oceanic crust.

The synthetic magnetic anomalies have been computed for a set of N30°W striking juxtaposed normally and reversely magnetized blocks, presently observed at 17°N, 69°E (Fig. 4.15a). As will be shown later, the central normally magnetized block correspond to anomaly 27n (~61.0 Ma) of geomagnetic polarity timescale. To obtain the paleo-location at the time of formation of this oceanic crust, a paleogeographic reconstruction of the region (Fig. 4.15b) has been carried out for 61 Ma in fixed hotspot reference frame using the finite rotation parameters of Müller et al. (1993). This model suggested that the Laxmi Basin area was in the southern hemisphere at ~15.0°S latitude at the time of formation. The bodies that caused the magnetic anomalies are considered to have a susceptibility of 0.01 cgs units, and the thickness and the depth to the top of the magnetized layer have been defined by limits of the inferred layer-2 derived from gravity modeling. The boundaries of the adjacent normally and reversely magnetized blocks have been obtained by a trial and error method in such a way that the synthetic magnetic anomalies computed using these symmetric magnetized blocks give the best fit with the observed magnetic anomalies.

The magnetic modeling exercise was carried out along profile SK79-15 as that displays very good axial symmetry and also is coincident over large part of the profile RE-02(SG) used for modeling the gravity data. The above exercise shows (Fig. 4.20) that the observed magnetic anomaly profile in the Laxmi Basin can be considered to have been caused by juxtaposed normally and reversely magnetized blocks, which lie within the basement layer. The sequence of these magnetized blocks appear to be symmetrical about a central narrow normally magnetized block, where the axis of symmetry coincides with the axis of the characteristic short wavelength gravity low atop the broad wavelength gravity high and the basement high feature (Panikkar Ridge). The parallel nature of the magnetic lineations and the symmetric arrangement of the magnetized blocks within the basement layer support generation of the underlying crust by two-limbed seafloor spreading. The continuation of magnetic anomalies (thereby magnetized bodies) a short distance over the Laxmi Ridge and basement of
Fig. 4.20 Modelled crustal structure along part of profile RE-02 to show the crustal structure across the Laxmi Basin area from integrated gravity and magnetic modeling. The forward modeling of magnetic data shows that the magnetic anomalies in the Laxmi Basin can be explained in terms of juxtaposed normally and reversely magnetized blocks (susceptibility = 0.01 cgs units) within the layer-2 derived by the gravity modeling. Synthetic magnetic profiles are computed for a ridge presently striking N30°W and observed at 17°N, 69°E which was formed at the location 15°S, 53°E. The computed magnetic anomalies are compared with the magnetic profile SK79-15, which is located close to the gravity profile RE-02. The locations of the profiles have been shown in Fig. 4.17. Other details are as in Fig. 4.19.
Indian continental rise perhaps represents the initial oceanic crust. In view of the above evidences from the gravity, magnetic and seismic information, it is interpreted that part of the Laxmi Basin is underlain by oceanic crust formed as a result of two-limbed seafloor spreading between Laxmi Ridge and western India and the axial basement high region (Panikkar Ridge) represents the extinct spreading centre. The interpretation of the Laxmi Basin magnetic anomalies in the present study is similar to the interpretation of Bhattacharya et al. (1994b) that the Laxmi Basin region is formed by a two-limbed seafloor spreading. However, as will be shown in a later section, the identification of the magnetic anomalies of the present study differs from that of Bhattacharya et al. (1994b).

It has been observed that the magnetic anomalies in the Laxmi Basin have relatively lower amplitude as compared to the Offshore Indus Basin and the Arabian Basin. If the magnetic anomalies in both these nearby regions are of similar seafloor spreading origin, then the difference in amplitude needs explanation. As will be shown later, the magnetic lineations (i.e. the magnetized blocks) of the Arabian and Offshore Indus basins strike nearly E-W, whereas the magnetic lineations of the Laxmi Basin strike NNW-SSE. The observed amplitude difference appears to be due to this difference in the strike directions of the magnetized blocks in these two areas. This explanation is based on an exercise carried out in this study by computing the magnetic anomalies over the same block model of juxtaposed normally and reversely magnetized blocks (Fig. 4.21) but at different strike angles. The model clearly demonstrates that the set of E-W striking bodies (as in the Offshore Indus Basin) generate relatively higher amplitude anomalies as compared to the set of NNW-SSE striking bodies (as in the Laxmi Basin).

The inferred extinct spreading centre in both Offshore Indus and Laxmi basins are associated with prominent basement highs (viz. Palitana Ridge in the Offshore Indus Basin and Panikkar Ridge in the Laxmi Basin) and as will be shown later these spreading centres became extinct around chron 27ny (~61 Ma). It is interesting to note that similar basement highs are also present in the well-established Mascarene Basin extinct spreading centre, which became extinct almost during the same period. This observation is based on published
Fig. 4.21 Magnetic anomalies computed for the same magnetic block model but with different strike angles. The amplitude of the magnetic anomalies are higher when the strike of the magnetized blocks is 90°, as in the case of the Offshore Indus Basin and lower when the strike of the magnetized blocks is 150° as in the case of Laxmi Basin. Magnetic anomalies were computed for a model of about 1.75 km thick juxtaposed alternate normally and reversely magnetized blocks (susceptibility = 0.01 cgs units) which formed at 15°S, 53°E and presently located at 17°N, 69°E.
Fig. 4.22 Bathymetric and magnetic profiles across the extinct spreading centre in the Mascarene Basin. The extinct spreading axis corresponds to the vertical dashed line. Modified after Schlich (1982).
(Schlich, 1982) two bathymetric and magnetic profiles (Fig. 4.22) across the extinct spreading centre in the Mascarene Basin.

4.4 Identification of the inferred seafloor spreading magnetic lineations of the Offshore Indus and Laxmi basins

The geophysical studies carried out so far suggest a two-episode spreading history of the Arabian Sea. Commencing at chron 27n, the older phase ended at chron 21n and spreading of the younger phase started shortly before the time of formation of anomaly 11n. In the intervening period (i.e., between chronos 21n and 11n) spreading in the Arabian Sea is considered to have either completely ceased or reduced to an imperceptible level (Naini and Talwani, 1982; McKenzie and Sclater, 1971; Chaubey et al., 1993). In the Arabian Basin region, a well-developed anomaly 27n was mapped in the areas west of the Laxmi Ridge, which indicates that the oceanic crust generated at the time (hitherto believed) of opening of the Arabian Sea lies seaward, west of the Laxmi Basin. Further, the strike of the post-chron 27n anomalies (i.e. anomalies 27n to 21n) is approximately E-W, whereas the lineations within the Laxmi Basin trend NNW-SSE. This noticeable change in the trends of the pre-chron 27 anomalies of the Laxmi Basin and post-chron 27 anomalies of the adjacent Arabian Basin perhaps suggests reorganization of the spreading centres during the intervening period. Therefore, in line with the opinion of Bhattacharya et al. (1994b) it appears necessary to invoke a third, pre-chron 27, episode of seafloor spreading to explain the inferred oceanic crusts of the Laxmi and Offshore Indus basins.

As discussed by Bhattacharya et al. (1994b) possibility of the existence of pre-chron 27 oceanic crust in the northeastern Arabian Sea was indicated in several earlier studies. Scotese et al. (1988), in their paleogeographic reconstruction model, have inferred a piece of Late Cretaceous (chrons 29–34) oceanic crust in this area. Norton and Sclater (1979) in their chron 28 time reconstruction model, place the spreading centre north of and immediate adjacent to Seychelles, thereby showing a large gap of crust in the northern Arabian Sea of unexplained origin. Masson (1984) noted the anomalous reduced width of the northwestern Mascarene Basin, as compared to the oceanic crust generated during the same spreading regime in the southeastern Mascarene and Madagascar basins and concluded that about 500 km of crust is ‘missing’ in the
northwestern Mascarene Basin. To explain this missing crust, Masson suggested a model according to which the missing oceanic crust in the northwestern Mascarene Basin is accommodated by a pre-chron 28 phase of seafloor spreading between India and the Seychelles Plateau. This spreading was linked to the spreading in the southeastern Mascarene Basin by a fracture zone passing east of the Seychelles Plateau. Based on updated magnetic anomaly identification in the northwestern and southeastern Mascarene basin region, and a paleogeographic reconstruction model for chron 27n, Bernard and Munschy (2000) opined that the geometry of the Laxmi Basin corresponds to the missing oceanic crust in the northwestern Mascarene Basin. These inferences provide further support to the proposition that the Offshore Indus and Laxmi basins represent a part of the pre-chron 27 oceanic crust in the northeastern Arabian Sea, and therefore this age limit has been assumed for the purpose of identification of the observed magnetic lineations. As described in the previous sections, the magnetic anomalies in the Offshore Indus and Laxmi basins are akin to the oceanic crust formed as a result of two-limbed seafloor spreading, where the Palitana Ridge and the Panikkar Ridge represent the extinct spreading centres. Therefore, an attempt has been made in this study to identify these magnetic anomalies in terms of geomagnetic polarity reversal time scale. Further, an updated magnetic isochron map of the study area have been prepared, which depicts the conjugate magnetic isochrons on both the sides of those extinct spreading centres.

(a) Identification of magnetic lineations in the Offshore Indus Basin

The magnetic anomaly sequence in the Offshore Indus Basin region is very short, and therefore could not be easily compared with the geomagnetic polarity reversal time scale. After several trials, a good correlation (Fig. 4.23) has been obtained between the computed and observed magnetic anomalies by equating the anomalies in the Offshore Indus Basin to the chron 27n–31n interval of the geomagnetic polarity reversal time scale, where the ridge axis is considered at 61 Ma, slightly younger than chron 27no (61.276 Ma). The half spreading rate (Table 4.1) that is calculated based on this identification of the linear magnetic anomalies shows that the Offshore Indus Basin spreading centre was a slow (< 1cm/yr) spreading centre. The inferred oldest magnetic anomaly in
Table 4.1 Half spreading rates for the Offshore Indus Basin, calculated from the derived model of juxtaposed normally and reversely magnetized blocks. Ages of the magnetic lineations are after Cande and Kent (1995).

<table>
<thead>
<tr>
<th>Chron</th>
<th>Young edge (Ma)</th>
<th>Old edge (Ma)</th>
<th>Duration (m.y.)</th>
<th>HSR (cm/yr)</th>
</tr>
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<tbody>
<tr>
<td>27n*</td>
<td>60.920</td>
<td>61.276</td>
<td>0.276</td>
<td>~0.05</td>
</tr>
<tr>
<td>27r</td>
<td>61.276</td>
<td>62.499</td>
<td>1.223</td>
<td>0.85</td>
</tr>
<tr>
<td>28n</td>
<td>62.499</td>
<td>63.634</td>
<td>1.135</td>
<td>0.30</td>
</tr>
<tr>
<td>28r</td>
<td>63.634</td>
<td>63.976</td>
<td>0.342</td>
<td>0.30</td>
</tr>
<tr>
<td>29n</td>
<td>63.976</td>
<td>64.745</td>
<td>0.769</td>
<td>0.30</td>
</tr>
<tr>
<td>29r</td>
<td>64.745</td>
<td>65.578</td>
<td>0.833</td>
<td>0.30</td>
</tr>
<tr>
<td>30n</td>
<td>65.578</td>
<td>67.610</td>
<td>2.032</td>
<td>0.60</td>
</tr>
<tr>
<td>30r</td>
<td>67.610</td>
<td>67.735</td>
<td>0.125</td>
<td>0.60</td>
</tr>
<tr>
<td>31n</td>
<td>67.735</td>
<td>68.737</td>
<td>1.002</td>
<td>0.60</td>
</tr>
</tbody>
</table>

*Seafloor spreading does not appear to have taken place during the total duration of chron 27n in this basin; it appears to have become extinct around 61 Ma.
this region is anomaly 31n, which suggest that spreading in this region was initiated at anomaly 31n time. The calculated half spreading rate of the region shows that during chronos 31n-30n, seafloor spreading took place with a half spreading rate of 0.6 cm/yr. Followed by this, the half spreading rate slowed down to 0.3 cm/yr from chron 29r onwards. This situation continued up to chron 28n. During chron 27r, the arrangement of magnetic anomalies necessitate considering a higher spreading rate. Subsequently, the spreading rate slowed down and the spreading in the region ceased, some time during chron 27n probably at 61 Ma.

Having inferred the magnetic lineations in the Offshore Indus Basin as anomalies sequence 27n-31n, attempt has been made to delineate the approximate boundaries of these normally and reversely magnetized blocks. Several authors (Roest et al., 1992; Chaubey et al., 2002a) have used the modulus of analytic signal technique (Nabighian, 1972, 1974) to pick the boundaries defining the blocks of juxtaposed normally and reversely magnetized crust. An attempt has been made to apply the same technique to the magnetic profiles in the Offshore Indus Basin region; however, it is observed that this method does not hold good both in the case of Offshore Indus Basin as well as in the Laxmi Basin. Probably, this may be due to the presence of narrow blocks of normally and reversely magnetized crust. This conclusion is based on exercises carried out to identify the boundaries of all magnetized blocks on the computed magnetic anomaly profile generated for the synthetic block models of both the regions. In view of this, a less disturbed representative profile in the Offshore Indus Basin has been selected and the approximate boundaries of the major blocks have been marked (Fig. 4.23) over this profile by comparing them with the corresponding computed anomaly profile, where locations of block boundaries have been marked with reference to model of magnetized blocks. Further, attempt has been made to pick these major block boundaries over other profiles (Fig. 4.24). These picks (block boundaries) have been transferred on a plot along track map (Fig. 4.25a) of the magnetic anomalies. Subsequently, the magnetic isochrons have been delineated (Fig. 4.25b) by connecting the corresponding picks on different profiles. Where an offset between two sets of magnetic
Fig. 4.23 Observed and computed magnetic anomalies along profile CD2087-06 across the Offshore Indus Basin to demonstrate delineation of boundaries of magnetized blocks on the profiles. The approximate boundaries of the magnetized blocks on the observed magnetic profiles have been marked by comparing them with the corresponding computed anomaly profile, where locations of block boundaries have been marked with reference to magnetized block model. The boundaries of magnetized blocks which could be reasonably approximated are labelled as e, f, and g. Other details are as in Fig. 4.16.
Fig. 4.24 Approximate boundaries of the normally and reversely magnetized blocks, picked over the magnetic profiles in the Offshore Indus Basin. The profiles were projected to an azimuth of 0° and stacked with respect to the axis of the characteristic short wave length gravity low atop the broad gravity high. Heavy dotted lines represent the axis of the characteristic gravity low. Other details are as in Fig. 4.23.
Fig. 4.25 Map showing inferred boundaries of magnetized blocks and magnetic isochrons along with magnetic anomalies in the Offshore Indus Basin plotted perpendicular to ship's tracks. (a) locations of the major boundaries of the normally and reversely magnetized blocks as shown in Fig. 4.25. (b) inferred magnetic isochrons. Other details are as in Fig. 4.24.
isochrons is apparent, fracture zones, orthogonal to these magnetic isochrons, have been invoked.

(b) Identification of magnetic lineations in the Laxmi Basin

Having interpreted the crust underlying the Laxmi Basin region as oceanic in nature, attempt has been made to identify the magnetic anomalies in this region. After several trials, a good correlation (Fig. 4.26) has been obtained between the computed and observed magnetic anomalies by equating the anomalies in the Laxmi Basin to chron 27n–33n interval of the geomagnetic polarity reversal time scale, where the ridge axis is considered at 61 Ma, slightly younger than chron 27no (61.276 Ma). The half spreading rate (Table 4.2) that is calculated based on this identification of these linear magnetic anomalies shows that the Laxmi Basin spreading centre was a slow spreading centre. The inferred oldest magnetic anomalies in this region are anomaly 33n, which suggest that the spreading in this region was initiated during chron 33n.

The calculated half spreading rate of the region shows that during chron 33n, seafloor spreading took place with a half spreading rate of 0.6 cm/yr. Followed by this, the half spreading rate increased to 0.8 cm/yr, which continued up to chron 32r1 time. The spreading rate slightly decreased to 0.7 cm/yr and slowed down to 0.2 cm/yr from chron 29r onwards. Interestingly, the period (~65.578 Ma) during which the spreading rate in the Offshore Indus and Laxmi basins slowed down was the time at which the Deccan Trap is considered to have erupted (Courtillot et al., 1986; Duncan, 1990). During chron 27r, the arrangement of the magnetic anomalies necessitate considering a higher spreading rate. Subsequently, the spreading rate slowed down and the spreading in the region ceased some time during chron 27n, probably around at 61 Ma. Based on this identification of the magnetic anomalies, it is observed that during times of anomalies 27n-28n, spreading was taking place simultaneously in the Offshore Indus, Laxmi and Arabian basins.

Having inferred the magnetic lineations in the Laxmi Basin as anomalies sequence 27n-33n, attempt has been made to delineate the approximate boundaries of these normally and reversely magnetized blocks. Since the analytic signal method was not found suitable in this region as in the case of Offshore
Table 4.2 Half spreading rates for the Laxmi Basin, calculated from the derived model of juxtaposed normally and reversely magnetized blocks. Ages of the magnetic lineations are after Cande and Kent (1995).

<table>
<thead>
<tr>
<th>Chron</th>
<th>Young edge (Ma)</th>
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<td>60.920</td>
<td>61.276</td>
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*Seafloor spreading does not appear to have taken place during the total duration of chron 27n in this basin; it appears to have become extinct around 61 Ma.
Fig. 4.26 Observed and computed magnetic anomalies along selected profiles across the Laxmi Basin to demonstrate the delineation of boundaries of magnetized blocks on the profiles. The approximate boundaries of the magnetized blocks on the observed magnetic profiles have been marked by comparing them with the corresponding computed anomaly profile, where locations of block boundaries have been marked with reference to magnetized block model. The boundaries of magnetized blocks which could be reasonably approximated are labelled as a, b, c, d, e, f and g. Other details are as in Fig. 4.20.
Fig. 4.27 Approximate boundaries of the normally and reversely magnetized blocks picked over the selected magnetic profiles in the Laxmi Basin region. The profiles were projected to an azimuth of 60° and stacked with respect to the axis of the characteristic short wave length gravity low atop the broad gravity high. Heavy dotted lines represent the axis of the characteristic gravity low. Other details are as in Fig. 4.26.
Fig. 4.28 Map showing inferred boundaries of magnetized blocks and magnetic isochrons along with magnetic anomalies in the Laxmi Basin plotted perpendicular to ship’s tracks. (a) locations of the major boundaries of the normally and reversely magnetized blocks as shown in Fig. 4.26, (b) inferred magnetic isochrons.
Indus Basin region, therefore a less disturbed profile in the Laxmi Basin has been selected and the approximate boundaries of the major blocks are marked (Fig. 4.26) over this profile by comparing them with corresponding computed anomaly profile, where locations of block boundaries have been marked with reference to magnetized block model. Further, attempt has been made to pick these major block boundaries over other profiles (Fig. 4.27). These picks (block boundaries) have been transferred on plot-along track map (Fig. 4.28a) of the magnetic anomalies. Subsequently, the magnetic isochrons have been delineated (Fig. 4.28b) by connecting the corresponding picks on different profiles. Where an offset between two sets of magnetic isochrons is apparent, fracture zones, orthogonal to these magnetic isochrons, have been invoked.

(c) Updated magnetic isochron map of the studied area

In summary the updated magnetic isochron map of the study area as prepared (Fig. 4.29a, b) in the present study suggest that in the Laxmi Basin region, the magnetic isochrons range from chron 33no (79.075 Ma) to chron 27no (61.276 Ma), while in the Offshore Indus Basin these isochrons ranges from chron 31no (68.737 Ma) to chron 27no (61.276 Ma). In both the basins, the spreading appears to have ceased around 61 Ma. It further appears for a period of about 1.8 my (from 62.8 Ma to 61 Ma), prior to becoming extinct, the spreading centers of the Offshore Indus and Laxmi basins were active simultaneously with the spreading centers of the Arabian Basin.
Fig. 4.29 Updated magnetic isochron map of the study area, (a) along with the selected bathymetry contours and the anomalous gravity high region, and (b) along with colour shaded-relief image of the satellite derived free-air gravity anomalies. White lines on colour shaded-relief image represent the mapped seafloor spreading magnetic lineations. Other details are as in Fig. 4.4.