Nature of the crust in the Laxmi Basin (14°-20°N), western continental margin of India

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Abstract

The nature of the crust in the Laxmi Basin, western margin of India is an uncertain issue; more importantly this has implications on paleo-geographic reconstructions of the western Indian Ocean. We have analysed three geophysical datasets and modelled gravity and magnetic anomalies for determining nature of the crust. Basement of the Laxmi Basin includes numerous highs, which make the basement uneven and shallower compared to the Western Basin. The Laxmi Basin is characterised by a broad gravity high and a narrower prominent gravity low within it, while within the basin the broad anomaly gradually increases towards north. The Panikkar Ridge is associated with the gravity low, which is comparable, at least in sign, to known negative gravity anomaly of Laxmi Ridge. Intrusive structures mapped in the Laxmi Basin coincide with significant magnetic anomalies, which were earlier interpreted as seafloor-spreading anomalies. Model studies reveal that the Laxmi Basin consists of ~14 km thick stretched continental crust, in which magmatic bodies have been emplaced, whereas Panikkar Ridge remains less altered stretched continental crust. The crust of the Laxmi Basin is mostly thinner than crust under Laxmi Ridge and continental margin. In addition to the rift-drift related stretching of the continental margin the Laxmi Basin possibly has undergone extra stretching in E-W direction during the pre-Tertiary period. At ~68 Ma Deccan volcanism on western India may have disrupted the initial conditions that were leading to onset of spreading in the basin. Subsequently the Ré;union hotspot had emplaced the volcanic material within the stretched thinned continental crust. We interpret the Laxmi Basin as a failed rift, undergone stretching following intraplate kinematics prior to Deccan volcanism.

Key words: Laxmi Basin, Laxmi Ridge, Panikkar Ridge, stretched continental crust, Deccan volcanism, northwest continental margin of India

1. Introduction

The western continental margin of India had evolved after break-up of the Madagascar in mid-Cretaceous and Seychelles micro-continent at the end of the Cretaceous from India (Norton and Sclater, 1979; Courtillot et al., 1988; White and McKenzie, 1989). The Deccan basalts erupted by the Ré;union hotspot (68.5-62 Ma) are found as continental flood basalts on western Indian shield as well as on the Praslin Island in the Seychelles micro-continent (Devey and Stephens, 1991). Subsequently the hotspot had emplaced magmatic intrusions within the crust of the western continental margin of India (Pandey et al., 1996; Singh, 2002). The present continental margin consists of numerous NW-SE trending structural features namely Laccadive Ridge, Laxmi Ridge, Prathap Ridge Complex, Panikkar Ridge, etc. (Figure 1), which are approximately parallel to the west coast of India and mostly buried under the Indus Fan sediments (Naini and Talwani, 1983; Biswas, 1987; Kolla and Coumes, 1990; Gopala Rao et al., 1992; Krishna et al., 1992 & 1994; Subrahmanyam et al., 1995).

The Laccadive and Laxmi ridges divide the continental margin of western India and the adjoining Arabian Sea into two basins (Naini and Talwani, 1983). The Eastern Basin is lying between western margin of India and the ridges, whereas the Western Basin is lying between the ridges and the Carlsberg Ridge. The broad Eastern Basin consists of several sub-basins and NW-SE trending structural features/ ridges. The Laxmi Basin is one such runs parallel to the western margin of India and occupies an area of about $2.4x10^5$ km^2 between the Laxmi Ridge and margin; between latitudes 15°N and 20° 30’N (Figure 1). Although several investigations were carried out in the Laxmi Basin, the nature of the crust under the basin is still uncertain. This is a key issue for paleo-geographic reconstructions of the western Indian Ocean. If the crust in the Laxmi Basin is continental, it has to find a place in the re-assembled Gondwana; alternately if it is oceanic, it has to be included in the complex spreading history, which separated Africa, Madagascar, Seychelles micro-continent, Laxmi Ridge and India.

The present study analyses bathymetry, magnetic, gravity (ship-borne and satellite) and seismic reflection and refraction data of the northwest continental margin of India with a view to 1) understand structural configuration and associated gravity and magnetic signatures, 2) discuss origin of the structures in light of evolution of western continental margin of India and in particular from the point of Réunion hotspot volcanism and 3) interpret the nature of the crust below the Laxmi Basin. In addition, we also demarcate the ocean-continent boundary along the western continental margin of India.

2. Geophysical Data

A collaborative project between NIO and ONGC on 'crustal architecture and evolution of the western continental margin of India' had provided an opportunity to put together three individual datasets of seismic reflection, gravity and magnetics. In the present work we use the data of the northwestern continental margin of India to investigate mainly the nature of the crust below the Laxmi Basin. For this purpose we have analysed multi-channel seismic reflection (4130 line km), gravity (2595 line km) and magnetic (3445 line km) data acquired along RE profiles (RE-01, 02, 03, 04 and 11) and SK Profiles (05-06 and 05-09) onboard MV Anweshak and ORV Sagar Kanya, respectively, across the northwest continental margin of India (Figure 1). Line drawings of interpreted seismic reflection profiles are stacked with free-air gravity and magnetic anomaly profiles, thereby an integrated analyses has been carried out for mapping various structural features and for understanding the nature of the crust below the Laxmi Basin. Gravity and magnetic anomalies along profile RE-11 were modelled under the constraints of seismic reflection and refraction results for determining the crust below the shelf, Laxmi Basin and Western Basin.

3. **Crustal structure – associated gravity and magnetic anomalies**

In the present study we have integrated the new datasets with published geophysical data: Conrad 1707 profiles (Naini, 1980), SK- 12, 22, 50, 64 and 79 profiles (Bhattacharya et al., 1994a; Chaubey et al., 2002) and twelve long-range sonobuoy refraction stations (Naini and Talwani, 1983) (Figure 1) for carrying out integrated interpretation of the data.

3.1 Previous Results

On the basis of magnetic anomaly pattern Naini and Talwani (1983), Miles and Roest (1993), Miles et al. (1998), Chaubey et al. (1998) and Dyment (1998) have identified seafloor-spreading magnetic anomalies and propagating ridges in the Western Basin and inferred that the basin is underlain by oceanic crust. From sonobuoy refraction results Naini and Talwani (1983) have suggested that the Eastern Basin is underlain by about 14 km thick crust that is thicker than normal oceanic crust, but thinner than normal continental crust. They favoured continental origin for the Eastern Basin, as it was hard to identify seafloor-spreading type anomalies in the Eastern Basin. Subsequent investigations of the Laxmi Basin, a subbasin within the Eastern Basin, gave rise to two divergent views about the nature of the crust. One considers presence of stretched/ extended continental crust beneath the basin (Kolla and Coumes, 1990; Miles et al., 1998; Todal and Eldholm, 1998; Mishra et al., 2004). The other, on the basis of magnetic anomaly picks, considers the presence of pre-Tertiary oceanic crust along with extinct spreading centre in Laxmi Basin (Bhattacharya et al., 1994a; Talwani and Reif, 1998) and in Gop Rift (Malod et al., 1997). The extinct spreading centre of the Laxmi Basin was earlier identified as a subsurface basement structure between 16°N and 18°30'N and named as the "Panikkar Ridge" (Gopala Rao et al., 1992). From crustal models and tectonic implications Pandey et al. (1995 & 1996), Miles et al. (1998), Todal and Eldholm (1998), Singh (1999 & 2002) and Radha Krishna et al. (2002) have suggested the possible magmatic impact of the Ré;union hotspot along the western margin of India, but no concrete evidences were offered with observational data for demonstrating the presence of hotspot related magmatic intrusions within the pre-existing continental crust.

3.2 New Results

Seafloor topography along the northwestern continental margin of India clearly shows shelf and shelf break, whereas other features like slope, foot of the slope and rise are less explicit (Figure 2). Along profile RE-11, the slope is modified with exposure of basement structures. The seafloor topography in the Laxmi Basin is generally smooth except in the central part, where the seafloor is elevated and manifested as isolated seamounts: Wadia, Panikkar and Raman. Another prominent feature in the study area is the Laxmi Ridge (Figures 1 and 2). The ridge along RE-02 rises above the adjacent seafloor by about 700 m, whereas on profiles RE-11 (south) and RE-01 (north), the ridge is almost buried without any bathymetric expression (Figures 2 and 3).

Seismic reflection data show images of the structures of Laxmi and Panikkar ridges, structure of continental margin and basement topography of the Laxmi and Western basins (Figures 2, 3 and 4a-c). The interpreted seismic sections were integrated with free-air gravity (ship-borne and satellite) and magnetic anomalies for the purpose of identifying the characteristic gravity and magnetic signatures of various structural features. The characteristic signatures were considered for mapping the regional extent of structural features on profiles (22-06, 22-08, 64-18, 50-03, 79-11, 12, 14, 15 and C17-C, D), where only gravity and magnetic data were acquired (Figures 1, 5 and 6).

The sediments in the study region are reaching up to 4 km thick, while they are thin over the Laxmi Ridge and some of the structural rises of the Laxmi Basin. These sediments were derived mostly from the Indus Cone (Kolla and Coumes, 1990). The sediments are in general thicker in the Western Basin than in the Laxmi Basin. The sediment column is divided into two units (Figure 2), which are separated by a seismic boundary. The boundary is well expressed in the shelf region and was interpreted by Chaubey et al. (2002) as Miocene unconformity. The unconformity was also identified on our seismic profiles that extend in deep offshore regions (Figure 2). In the Western Basin thin pre-Miocene sediments (up to 0.2 s, TWT) and thick post-Miocene (more than 2 s TWT) sediments are observed, on the other hand in the Laxmi Basin thick pre-Miocene (up to 1.5 s TWT) and thin post-Miocene (as low as 0.4 s TWT) sediments are noticed.

The basement topography of the study region consists of two distinct patterns (Figures 2, 7 and 8). In the Western Basin the basement topography is relatively smooth and lies at a depth of ~7.5 s (TWT), whereas in the Laxmi Basin the basement is shallow (at ~6.0 s TWT) with highly irregular topography. Earlier Kolla and Coumes (1990) and Todal and Eldholm (1998) have observed such irregular basement features in east and north of the Laxmi Ridge. The two basement patterns are separated by nearly NW-SE trending partly buried Laxmi Ridge. The basement in the Laxmi Basin is broadly at elevated level by approximately 1.5 s TWT, nearly equal to 2.0 km, with respect to that of the Western Basin. Another prominent feature, having width and length of about 30 km and 600 km respectively, lies in the middle of the Laxmi Basin and trends in NW-SE direction. The feature was earlier identified as Panikkar Ridge (Gopala Rao et al., 1992). Its elevation along strike is variable (Figure 2), for example on profile RE-11 the buried Panikkar Ridge is manifest as an isolated seamount with a relief of about 2 km from the adjacent seafloor (Figures 4a and 7). Earlier Bhattacharya et al. (1994b) had identified the seamount as Wadia Guyot. The ridge is principally a buried continuous feature, but at three places the feature is elevated above the seafloor in the form of seamounts (Wadia, Panikkar and Raman seamounts). Further, we have also observed several of the structural rises in the Laxmi Basin crust and adjacent continental shelf and slope regions (Figures 2, 3, 4b, 7 and 8). The structural rises consist of contorted basement topography with faults and uniform thick basal sediments (Figures 4b, 7 and 8) as we approach the structure, indicating that they are volcanic intrusive structures. Similar criteria were followed for identification of such intrusive structures on western continental margin of India (Prasada Rao and Srivastava, 1984). The rises particularly in slope regions (RE-11 and

02 in Figure 2) appear to have similar morphological character and extend for shorter distances. Some of the rises in the southern part below the shelf and slope regions were earlier identified as part of the Prathap Ridge Complex (Naini and Talwani, 1983; Krishna et al., 1992 & 1994; Todal and Eldholm, 1998). These rises and sediments derived from the Indus Cone have indeed modified the continental slope and rise of western continental margin of India.

Free-air gravity anomalies of the study area in general, does not show trends of the seafloor topography except at shelf break and on continental slope (Figure 2). The most notable observation is that the Laxmi Basin as a whole is characterised by a regional gravity high with a prominent gravity low (~20 mGal amplitude and 100 km wide) within it. The gravity low is clearly seen extending in NNW direction as a linear anomaly paralleling the shelf in profile data (Figure 5) and in satellite-derived gravity anomaly map (Figure 9) as well. The gravity low is associated all along with the crest of the Panikkar Ridge except in areas where the ridge is elevated and manifested as isolated seamounts, Wadia on profile RE-11 and Raman on profiles 50-03, 64-18 and C-17A (Figure 5). The Laxmi Ridge is also associated with broad low gravity anomaly (Figure 2). Landward side positive gravity anomalies are, as expected, associated with Prathap Ridge isolated peaks and continental shelf (Figures 2 and 5). The gravity anomalies of the Panikkar Ridge are similar with those of the Laxmi Ridge in character (negative anomaly), although the former is narrow in width. To the west of the Laxmi Ridge free-air gravity anomaly swiftly rises and continues seaward without prominent anomalies (Figures 2 and 5). Both the ridge structures continue southward up to profile RE-11 (Figure 5). On profile C17-C and 12-07 the gravity anomalies are correlated to Laccadive Ridge and Prathap Ridge complex.

The satellite-derived free-air gravity anomaly map (Figure 9) shows the trends of various geomorphic features identified on profile data. The distance between the Miocene shelf edge and present shelf edge increases toward north, reaching about 100 km off Mumbai. The Laxmi Ridge trends approximately in NW-SE direction and veers nearly E-W direction at about 19°N latitude. The Panikkar Ridge also trends in NW-SE direction, but terminates at 19°N latitude. There the ridge merges with another E-W trending ridge, termed as Palitana Ridge (Malod et al., 1997). Interestingly the Panikkar and Palitana ridges show gravity signatures of opposite sign. The Panikkar Ridge is associated with negative anomaly, whereas the Palitana Ridge, buried under the Indus Fan sediments, is associated with positive anomalies. Free-air gravity anomaly over the Western Basin is about 40 mGal more than that over the Laxmi Ridge (Figure 2). While the free-air anomaly over the Laxmi Basin is also more than the Laxmi Ridge (Figures 2 and 5), its amplitude increases from south (30 mGal along profile RE-11) to north (70 mGal along profile SK 22-08). Earlier Talwani and Reif (1998) have reported 60 mGal more positive free-air anomaly over the Laxmi Basin than the anomaly of the Laxmi Ridge along profile C17-A.

Magnetic anomaly profiles (Figure 6) were analysed with a view to determine the contribution of various geomorphic features and to outline patterns. West of the Laxmi Ridge the magnetic profiles RE-01 and 11 (Figures 2 and 6) show long-wavelength subtle anomalies due to oblique orientation of the profiles to the magnetic reversal blocks. Keeping the locations of structural features identified in the seismic reflection and gravity data in view (Figures 2, 3, 5 and 7), we have demarcated the boundaries of the Laxmi, Panikkar, Laccadive and Prathap ridges on magnetic anomaly data (Figure 6). Demarcation of these features otherwise might not have been easy solely on the basis of magnetic anomaly profiles alone. As the seismic reflection data along profiles RE-11 (Figures 2 and 7), SK-12-07 (Chaubey et al., 2002) and other published profiles (Prasada Rao and Srivastava, 1984) show the existence of numerous intrusive structures within the sediments, we believe that these structures have contributed to the magnetic field either in positive or negative sense. The anomalies in the southeastern part are associated with the Prathap Ridge Complex, which extends up to 17º45'N and then diminish further north. The anomalies over the Laccadive Ridge are also significant but have relatively lesser amplitudes to that of the Prathap Ridge Complex. A narrow magnetic low within a broader high is observed as characteristic anomaly of the Panikkar Ridge along all its length. No systematic anomalies are seen over the Laxmi Ridge, but localised high-amplitude anomalies are observed. The magnetic anomalies on either side of the Panikkar Ridge are seen to be associated with the intrusive structures (Figures 2, 7 and 8) in most cases, but in contrast, the anomalies observed west of the Laxmi Ridge (Figures 2 and 6) are not associated with basement structures.

The velocity-depth results obtained from seismic refraction experiments of Laxmi Ridge, Laxmi Basin, Western Basin, Seychelles Bank and Indian continental shield (Naini and Talwani, 1983; Davies and Francis, 1964; Mathews and Davis, 1966; Kaila and Sain, 1997; Reddy et al., 1999) are shown in Figure 10 and Table 1 for the purpose of discussing the velocity distributions in different geological regions. In eastern Arabian Sea we have used only long-range sonobuoy refraction stations (10, 06, 57, 11, 09, 04, 05, 07, 02, 70, 64 and

55) (Figure 1) as they reached into the crust at greater depths up to 12.4 km. Average crustal columns of all the regions were combined (Figure 10) with a view to compare the Laxmi Basin velocity structure with that of known oceanic (Western Basin) and continental (Seychelles Bank, Laxmi Ridge and Indian subcontinent) crust. No refraction signals have been received from Moho boundary both under the Laxmi Ridge and Laxmi Basin areas, while the boundary was identified below the Seychelles Bank, Western Basin and Indian subcontinent. An anomalous velocity layer, 7.0 to 7.4 km/s is observed in the lower crust of the Laxmi Basin and Laxmi Ridge (Figure 10). In the Western Basin, mantle arrivals with velocities of about 8.0 km/s, are observed at 10-12 km depth from sea surface (Figure 10), which includes ~3.5 km water column and more than 3 km thick sediments. Below the sediments there are two crustal layers with an average velocity of 5.5 and 6.7 km/s, which represent the seismic layers 2 and 3 respectively and together form a crust of about 5 km thick. The velocity structures below the Seychelles Bank, Laxmi Ridge and Indian subcontinent (Figure 10) indicate that the average depth to Moho boundary is over 20 km. We emphasize that the velocity 6.2 to 6.3 km/s is observed in all the regions except in the Western Basin (Figure 10).

4. Origin of the Panikkar Ridge

Isolated seamounts (Wadia, Panikkar and Raman) and intervening basement highs in the Laxmi Basin form a continuous structure, named the Panikkar Ridge (Figures 1 and 2). Earlier Naini and Talwani (1983), Gopala Rao et al. (1992) and Bhattacharya et al. (1994a & b) had mapped the Panikkar Ridge on different transects as basement highs, ridge and seamounts, respectively. In the present study it is established that all these structures together form a continuous feature in the form of a ridge. The ridge runs for about 600 km in NNW direction in the middle of the basin and parallels the Laxmi Ridge in the west (Figures 2 and 9). The Panikkar Ridge is associated with ~10 mGal low gravity anomaly and highs within it at seamount locations (Figures 2, 5, 8 and 9). Towards north the gravity anomalies of the ridge become subdued as its structure deepens to sub-crustal depths (Figures 2 and 9), where it meets the E-W trending significant positive gravity anomalies of the Palitana Ridge. It may be noted that both the gravity and magnetic signatures of the Panikkar and Palitana ridges are markedly different. Considering the positive relief of the Panikkar Ridge the low gravity anomaly is enigmatic and need explanation.

Free-air gravity and magnetic anomalies of profile RE-11 were modelled with constraints from seismic reflection (Figures 2 and 7) and refraction data (Figure 10). Igneous intrusives, dykes, sills and seaward dipping reflectors imaged in seismic reflection data (profile RE-11) have been considered as sources in magnetic model studies. The model studies show that the Panikkar Ridge consists of about 14 km thick and 60 km wide, low density (0.05 g/cc density contrast) and non-magnetic rocks relative to the crustal rocks of the adjacent basin (Figure 11). The Laxmi Ridge associated with low gravity anomaly is also explained by ~14 km thick and 0.05-0.1 g/cc low-density rocks in contrast to adjoining crust. Sonobuoy refraction investigations (Naini and Talwani, 1983) have revealed more than 16 km thick crust beneath the Laxmi Basin and the Panikkar Ridge. Thus the NW-SE orientation, low gravity anomaly and crustal structure of both the Laxmi and Panikkar ridges are all similar and therefore, may presumably consist of similar rocks.

Earlier investigations have decisively interpreted the Laxmi Ridge as a continental sliver, whereas in the case of Panikkar Ridge, varied views regarding its origin were suggested. Gombos et al. (1995), Miles et al. (1998) and Todal and Eldholm (1998) have interpreted extended continental crust below the Laxmi Basin. On the other hand Bhattacharya et al. (1994a) and Talwani and Reif (1998) have interpreted the Panikkar Ridge as an extinct spreading center. Both the Panikkar (Bhattacharya et al., 1994a; Talwani and Reif, 1998) and Palitana (Malod et al., 1997) ridges were interpreted as extinct spreading centers, but their gravity anomalies and spreading histories are distinctly different. In case of the Palitana Ridge, Malod et al. (1997) have shown significant positive gravity anomaly and symmetry in magnetic anomalies with respect to the ridge. They have explained the magnetic anomalies with pre-Tertiary magnetic reversals (29-29R) with full-spreading rates of 5.5 cm/y. In comparison to those well-developed anomalies, the magnetic anomalies of the Laxmi Basin lack symmetry except along the profile SK 79-15 (Figures 6 and 8). This is the profile that had prompted Talwani and Reif (1998) to infer the formation of pre-Tertiary oceanic crust by the Panikkar Ridge in the Laxmi Basin. Exceptionally slow and variable spreading rates (0.26 to 7.0 cm/y) calculated for the magnetic anomalies of the Laxmi Basin neither match with the spreading history of the Palitana Ridge nor with other contemporaneous spreading centers that presently lie on the eastern margin of Madagascar, western Indian Ocean (Schlich, 1982). The magnetic and gravity anomalies of the profile SK 79-15 were integrated with the almost coincident seismic profile RE-02 (Figure 8) for the purpose of finding correlations between anomalies and seismic structures. Three of the four positive magnetic anomalies are obviously correlatable to the volcanic intrusive structures.

Spreading-related rift valley is not observed in the Panikkar Ridge as usually expected for slow spreading centres, in such a case it is difficult to explain low gravity anomaly in terms of extinct spreading centre. There are some extinct spreading centers, for anomaly in terms of extinct spreading center. There are some extinct spreading centers, for example Palitana Ridge in the Arabian Sea (Malod et al., 1997) and some other segments in the northeastern Indian Ocean (Krishna and Gopala Rao, 2000), do not posses rift valley, however they display positive gravity anomalies. Bhattacharya et al. (1994b) believe that the seamounts of the Laxmi Basin (Wadia, Panikkar and Raman) were formed by volcanism due to the spatial and temporal proximity of the Ré;union hotspot when the Laxmi Basin spreading center was still hot. In such a geological setting the seamounts are expected to compensate isostatically at deeper depths. But the gravity anomalies of the seamounts are appreciably high (reaching up to 75 mGals) commensurate with their elevation, implying that the seamounts are not isostatically compensated at depths (Figures 2 and 11). Even the low amplitude (20 nT) magnetic anomaly over the Panikkar Ridge (RE-11 in Figures 2 and 7) is difficult to explain considering spreading related basaltic rocks, as the near source rocks of the ridge should contribute considerable large amplitude magnetic anomalies. And also most of the magnetic anomalies correlate well to the intrusive (volcanic) structures in the Laxmi Basin (Figures 2, 7 and 8). No hyperbolic reflections with vertices at varied depths, indicating oceanic or volcanic rocks, are observed in seismic data beneath the Panikkar Ridge; instead flat-lying basal seismic reflections are observed (Figure 4a). Hence we interpret ~14 km thick and 60 km wide, low density, non-magnetic crust of Panikkar Ridge as a continental sliver, similar to the rocks of the Laxmi Ridge. We therefore interpret the Laxmi and Panikkar Ridges are fragments of stretched continental crust formed under extension and rift-related regimes.

5. Nature of the Crust below the Laxmi Basin – Continental or Oceanic?

Symmetrical magnetic anomalies in the Laxmi Basin (particularly along the profile SK 79-15), broad free-air gravity high of the Laxmi Basin, low gravity anomaly of the Panikkar Ridge, accreted magmatic material within the crust of the Laxmi Basin and velocity structure and intermediate crustal thickness (about 14 km) below the Laxmi Basin have been used in the past for interpretation of the nature of the crust in two diametrically opposite ways, continental or oceanic.

Laxmi and Western basins show two distinct patterns of basement topography. In the Western Basin the basement is relatively smooth and lies at ~7.5 s, while in the Laxmi Basin the basement is shallower (~6.0 s) with highly irregular topography. If the crust in the Laxmi Basin was formed by the seafloor spreading process in pre-Tertiary period, the crust should have subsided to deeper depth than the depth of subsidence of the crust in the Western Basin. On the contrary the seismic reflection results reveal that the basement in the Laxmi Basin is elevated by approximately 2.0 km. Seismic results of the central Indian Ocean indicate that pre-Tertiary basement lies at a depth of ~7.7 s (Krishna et al., 1998 & 2001a). The shallow basement in the Laxmi Basin is also not consistent with the predictions of lithospheric-plate cooling models of pre-Tertiary age oceanic crust (Parsons and Sclater, 1977).

Seismic reflection data of the Laxmi Basin clearly show the presence of NW-SE trending regional features (Laxmi and Panikkar ridges) and igneous intrusive structures (Figures 2, 4a-c, 7 and 8). Analysis of integrated geophysical data reveals that the intrusive structures are associated with magnetic and gravity anomalies (Figures 2, 7 and 8). Other evidence for the presence of denser rocks within the crust of the Laxmi Basin comes from the gravity data. Gradual rise of free-air gravity anomalies from south, 30 mGal to north, 70 mGal in the Laxmi Basin relative to the anomalies of Laxmi Ridge and Western Basin (Figures 2 and 5) may be interpreted in terms of accretion of additional magmatic material toward north within the crust. Intrusive structures in the form of dykes and accretion of magmatic material in the form of sills may possibly be generated by the Ré;union hotspot at the time of Deccan volcanism (~68 Ma) and at later stage by its trail. Dykes very similar to the distinctive Bushe magma-type identified from the Deccan traps have also been reported on the Seychelles micro-continent (Devey and Stephens, 1991). Geological and geophysical studies in the western part of the Indian shield and adjoining continental margins of India showed the presence of abundant Deccan-related volcanic intrusions (Krishnan, 1968; Hinz, 1981; White and McKenzie, 1989; Kaila and Sain, 1997; Singh, 2002). Near offshore Goa (15°30’N latitude) Widdowson et al. (2000) have mapped early Paleocene (about 61 Ma) age Deccan-type feeder dykes.

High heat flow values range from 70-100 mW/m^2 in the Laxmi Basin (Ravi Shankar, 1988) and a large number of hot-springs (Saxena and Gupta, 1986) along the Konkan coast (between 14° and 18°N) reveal anomalous thermal conditions on the western continental margin of India. The heat flow is higher in the Laxmi Basin than the values expected either for the pre-Tertiary aged oceanic crust or for the Precambrian continental crust. The crust below the basin, whatever its nature (continental or oceanic), was modified by the magmatic intrusions generated by the Ré;union hotspot that eventually contributed to the excessive thermal conditions within the crust. This is third evidence supporting the supposition that the crust below the Laxmi Basin has been modified with the accretion of magmatic material. The crustal thinning across the western continental margin of India due to the stretching process may also have caused the thermal anomaly in the region.

Based on seismic reflection results and the above discussion, we have segregated the magnetic anomalies that are associated with the intrusive structures (Figures 6, 7 and 8). The origins of the rest of the magnetic anomalies are unclear, therefore the sources of the anomalies can equally be argued in both ways either due to spreading-related magnetic reversals or due to volcanic intrusive structures. However the present study shows that the magnetic anomalies in the Laxmi Basin, excluding the ones associated with the intrusive structures, lack symmetry with respect to the Panikkar Ridge (Figures 6 and 8). The argument for the Laxmi Basin to be underlain by oceanic crust comes principally from the identification of symmetrical magnetic anomaly picks on profile SK 79-15 (Bhattacharya et al., 1994a; Talwani and Reif, 1998). These anomalies, at least three of the four, can now best be explained by the volcanic intrusive structures imaged in the seismic reflection data (Figure 8).

The velocity structure of the western continental margin of India shows the presence of an anomalous velocity (7.0 to 7.4 km/s) layer in the lower crust of the Laxmi Basin and Laxmi Ridge. These velocities are not usually seen in either normal continental or oceanic crusts. Similar velocity layer is also reported below nearby geological features, Laccadive Ridge (Naini and Talwani, 1983) and Cambay and Koyana regions, western part of the Indian continental shield (Kaila et al., 1981 & 1990; Kaila and Sain, 1997; Singh and Mall, 1998; Reddy et al., 1999). Various processes have been proposed for the formation of this high velocity crustal layer near the base of the crust. Pandey et al. (1995), Miles et al. (1998), Singh (1998 & 2002) and Radha Krishna et al. (2002) have suggested the presence of underplated volcanic rocks within the lower crust of both the Laxmi Ridge and Laxmi Basin. On the other hand Talwani and Reif (1998) believe that the high velocity layer beneath the

Laxmi Basin represents "initial oceanic crust". Surprisingly, similar high velocity layer is absent beneath the Seychelles Bank (Francis and Shor, 1966; Francis et al., 1966) and most part of the Deccan volcanic region of northwest India. It is generally accepted that besides Laxmi Ridge, Laxmi Basin and Koyana and Cambay regions, Seychelles Bank and Deccan volcanic region were also under the influence of the Ré;union hotspot volcanism at the time of K-T boundary. In such geological setting it is difficult to consider the accretion of underplated crust under some selective features. We propose that the high crustal velocity layer was formed during rift-drift related stretching process along western margin of India. Similar velocities beneath the Hatton margin and Baltimore canyon trough, east coast of North America were interpreted as pre-existing stretched continental crust (White et al., 1987; Watts and Marr, 1995). Beneath the Ninetyeast Ridge the higher crustal velocities were interpreted as underplated material due to the accretion of magmatic material within the lithosphere (Krishna et al., 2001b).

On close observation of velocity profiles beneath the Seychelles Bank, Laxmi Ridge, Laxmi Basin and western part of the Indian continental shield (Figure 10) we found that 6.2 - 6.3 km/s layer is conspicuously present in their upper crust, but not in the Western Basin. Instead, the Western Basin crust has about 6.7 km/s velocity layer, which is considered as a normal velocity for layer 3 of the oceanic crust. The velocities in the range 5.8 – 6.4 km/s have been considered generally to be characteristic of the granitic layer in continental crust (Tucholke et al., 1981). The velocities ranging from 6.0 to 6.4 km/s are widely accepted to be characteristic of the upper crustal rocks of the continental crust. These velocities usually don't form a significantly thick layer in oceanic crust. Therefore the velocity layer 6.2-6.3 km/s observed below the Laxmi Basin may be attributed to upper crustal rocks (granitic gneisses) of the continental crust, not oceanic crust.

The crust is ~22 km thick beneath the Indian continental shelf and thins seaward up to 8 km in the Western Basin (Figure 11). The crustal thickness below the Laxmi Basin averages 14 km thick (range from 12 to 16 km). Crustal structures below the Laxmi Ridge and Laxmi Basin obtained from sonobuoy results (Figure 10) and gravity model studies (Figure 11), in general show that the crust is comparatively thin beneath the Laxmi Basin. We believe that the Laxmi Basin might have undergone extra stretching in addition to the rift-drift related stretching of the continental margin. Subtle changes in rheology of rocks of the basin owing to proximity of Ré;union hotspot might have aborted the existing E-W extensional tectonics; otherwise the tectonic process could have lead to the initiation of seafloor spreading in the Laxmi Basin. As an alternative for keeping the spreading activity away from the Deccan volcanism, rifting process had migrated westward leading to initiation of break-up between the Laxmi Ridge and Seychelles micro-continent. Even in subsequent ages (in early Tertiary) the Ré;union hotspot had shown its influence on spreading segments of Carlsberg Ridge and propagated in westward and eastward up to 46 Ma (Chaubey et al., 1998; Dyment, 1998). The gravity anomalies and crustal structure of the western continental margin of India (Figure 11) are comparable to that of western Galicia margin, off Spanish coast (Carbo et al., 2004). The Galicia margin consists of Iberian Abyssal Plain, Galicia Bank and Interior Galicia Basin similar to Western Basin, Laxmi Ridge and Laxmi Basin respectively, of the western continental margin of India. Carbo et al. (2004) have attributed a relative gravity high of the Interior Galicia Basin to the extremely stretched continental crust, where Moho is observed at a minimum depth of 14 km below sea level. The Laxmi basin is also underlain by extremely stretched continental crust with a thickness of about 14 km excluding water slab (Figure 11).

In view of possible seafloor spreading scenario of the Laxmi Basin offered by Bhattacharya et al. (1994a), we have carefully examined the magnetic anomalies of the basin for identifying the causative sources. Our results show that volcanic intrusives on both sides of the Panikkar Ridge imaged in several seismic profiles have contributed to the magnetic anomalies of the basin (Figures 2 and 11), which are demonstrated in Figures 7 and 8. In Gop rift region, northwest of the Laxmi Basin, Malod et al. (1997) have identified E-W trending well-correlated magnetic anomalies 29 and 29R, whereas in the Laxmi Basin such distinctly correlatable anomalies are apparently not found on regional scale. If the Laxmi Basin evolved through spreading process prior to Deccan volcanism (~68 Ma), the Seychelles micro-continent, much believed breakaway part from India, would not have received the volcanic rocks equivalent to Deccan traps. Talwani and Reif (1998) have observed misfit (space problems) in plate reconstruction model of the anomaly 34 in case of early opening of the Laxmi Basin. The interpreted crust and velocity models of the Laxmi Basin are in contrast to the Western Basin and in agreement with the Laxmi Ridge, Indian shield and Seychelles Bank. These contentious issues do not favour the origin of the Laxmi Basin due to seafloor spreading. We therefore interpret that the Laxmi Basin consists of stretched continental crust mixed with volcanic rocks contributing to magnetic anomalies and may thus be described as a failed rift.

Western part of the Greater India (India-Madagascar-Seychelles) had experienced continental rifts several times in the geological past; thereby new basins have formed on continent as well as in the western Indian Ocean. Not all the continental rifts led to continental break-ups viz, Cambay and Kutch rifts; they got aborted due to some changes in geological settings. Extensional tectonics at the trailing edge of the northward moving Greater India have resulted in detachment of few continental fragments such as Madagascar and Seychelles, and failed rifts. The seafloor spreading may had initiated for short duration in the Gop Rift, soon ceased its activity due to some changes in tectonic settings. The Laxmi Basin had also stretched due to the tectonics, but did not reach the spreading stage and eventually remained as failed rift. Failed rifts such as Cambay, Kutch and western part of Narmada-Tapi are reported on northwest Indian shield (Raval and Veeraswamy, 2003). Thus it is clear that the Laxmi Basin had undergone extensional tectonics like other rifts of western part of the Indian shield, but the thermal plume may have altered the extensional tectonics in the Laxmi Basin. The results have far-reaching implications for the future perspective plans in the area. The spatial extent of the continental crust up to the Laxmi Ridge on the western margin of India has to be considered in plate reconstruction analysis of re-assembling of eastern Gondwana landmasses.

6. Continent-Ocean Boundary on Western Continental Margin of India.

Seismic reflectors observed on profile RE-11 below the basement on west of the Laxmi Ridge are dipping seawards (Figures 2 and 4c) and adjoin the early Tertiary oceanic crust. The reflectors are identified as seaward dipping reflectors (SDRs). We consider that the dips of the reflectors arose from basaltic lava flows emplaced during initial continental split-up and subsequent subsidence. According to Hinz (1981) and Mutter et al. (1982) the regions of SDRs generally mark areas of rifted continent and their dips arose from the subsidence of enormous volumes of basaltic lava flows. The feather edges of these SDRs lie on their landward side. Feather edges of the SDR have been used to demarcate seaward extent of the continental crust of V↵ring plateau of Norwegian margin, Argentina margin and east coast of US (Baltimore Canyon Trough and Carolina Trough) (White et al., 1987; Watts and Marr, 1995). By analogy we interpret the identified SDRs on western flank of the Laxmi Ridge are indicative of rifted continents and volcanism prior to onset of seafloor spreading. Besides, the lateral shift of ~30 mGal in regional gravity field (Figures 2 and 11) lead to interpret the presence of high-density oceanic rocks west of the Laxmi Ridge. Using similar criteria

Chaubey et al. (2002) have marked ocean-continent boundary on the west of the Laccadive Ridge on southwest continental margin of India. Seismic reflection studies across the Seychelles-Laxmi Ridge margins (Collier et al., 2004) have clearly imaged the SDRs on the southern edge of the Laxmi Ridge and close to the foot of the Seychelles Bank. The presence of SDRs and their feather edge along the west of the Laxmi Ridge, lateral shift in the regional free-air gravity and relatively broad wavelength magnetic fields of the oceanic crust lead us to identify the edge of the rifted continent, and thereby to demarcate the ocean-continent boundary along the western margin of the Laxmi Ridge.

7. Conclusions

Integrated geophysical studies of the Laxmi Basin, northwest continental margin of India have provided important results on seismic structure and nature of the crust below the Laxmi Basin. Important observations are the following.

1. The basement topography in the Western Basin is relatively smooth and lies at deeper depth, whereas in the Laxmi Basin the basement is at shallow depth (about 2 km) with highly irregular topography. The Panikkar Ridge having width and length of about 30 and 600 km, respectively, lies in the middle of the Laxmi Basin and parallels the trend of the Laxmi Ridge. The ridge is a buried continuous feature, but at places it is elevated above the seafloor in the form of seamounts. In addition to these, several structural rises are observed below the Laxmi Basin and adjacent continental shelf and slope regions.

2. The Laxmi Basin as a whole is characterised by a broad gravity high and a prominent gravity low within it. The gravity low is associated with the crest of the Panikkar Ridge. However, the low is perturbed by gravity-highs at places where the buried ridge is manifested as isolated seamounts. The gravity anomalies of the Panikkar Ridge are generally comparable with those of the Laxmi Ridge in character (low anomaly) although the former structure is narrow in width. Amplitude of the free-air gravity anomaly over the Laxmi Basin increases from south, 30 mGal, to north, 70 mGal, possibly indicating the accretion of additional magmatic material toward north within the basin. Numerous intrusive structures mapped within the crust of the Laxmi Basin have contributed to magnetic anomalies.

3. Seismically, the structure of the Laxmi Basin is comparable with that of the Laxmi Ridge, Seychelles Bank and western part of the Indian continental shield. As the velocity layer, 6.2 - 6.3 km/s is often considered to indicate granitic rocks of the continental crust, we

believe that the layer below the Laxmi Basin could be the upper crustal rocks of the continental crust.

4. Geophysical anomalies and crustal structure indicate that the Laxmi and Panikkar ridges are fragments of stretched continental crust developed under extension and rift related regimes. The crust beneath the Laxmi Basin has undergone extra stretching in E-W direction. Ré;union hotspot had emplaced numerous volcanic structures within the stretched continental crust of the Laxmi Basin. Magnetic anomalies of the Laxmi Basin, earlier interpreted as seafloor-spreading anomalies can best be explained by volcanic intrusives of the stretched continental crust.

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Figure captions:

Figure 1. General bathymetry of the Laxmi Basin and adjoining regions, depths are in meters. Lines with labelling show the geophysical profiles. Magnetic isochrons 28Ny-24N1 are shown on west of the Laxmi Ridge (Chaubey et al., 1998). Locations of seismic sonobuoy stations are marked by solid circles. L1-L4 represents magnetic lineations identified by Bhattacharya et al. (1994a). Solid dashed line along L1, WG, PS and RS represent Panikkar Ridge, Wadia Guyot, Panikkar seamount and Raman seamount, respectively. Arrows encircled by dashed line show axis and boundaries of the Laxmi Ridge. Seismic sections of solid tracks along the profiles RE-01, RE-02 and RE-11 are shown in Figure 3. Seismic, gravity and magnetic data along the solid track and dashed-dot track on profile RE-11 are shown in Figures 7a and 7b, respectively.

Figure 2. Stacked regional geophysical profiles of interpreted multichannel seismic reflection, free-air gravity and magnetic anomalies. Locations of profiles are shown in top left corner. Profiles RE - 01, 02, 03, 04 and 11 were acquired using DFS IV instrument onboard MV Anweshak with 48-channel seismic streamer, using Bolt-type air-gun array with a total capacity of 10 L. A DFS V instrument system, 24-channel seismic streamer and D-type array of seven air-guns with a total capacity of 7.98 L were used aboard ORV Sagar Kanya for acquisition of data on profiles SK - 05-06 and 05-09. P1, P2, P3 and P4 are panels of seismic sections shown in Figure 4 a, b & c and 8 respectively. PR and LR represent Panikkar and Laxmi ridges respectively. Vertical dotted lines show correlations between volcanic intrusive structures and magnetic anomalies.

Figure 3. Seismic reflection images of the Laxmi and Panikkar ridges along RE-01, RE-02 and RE-11 profiles. Locations of the sections are shown with a solid line along the profiles in Figure 1.

Figure 4a. Seismic reflection profile (RE-11) shows basement topography and stratified sediments of the Wadia Guyot.

Figure 4b. Seismic reflection profile (RE-11) shows basement structures, dykes and sills overlain by the stratified sediments.

Figure 4c. Seismic reflection profile (RE-11) shows series of intra-basement seaward dipping reflectors, SDRs are covered by about 2.4 km thick stratified sediments on west of the Laxmi Ridge. The SDRs deepen to the west and their feather edges occur at shallow depth in the east.

Figure 5. Gravity profiles collected on various cruises of research vessels: ORV Sagar Kanya (SK 05, 12, 22, 50, 64 and 79), MV Anweshak (RE lines) and RV Conrad (C17A-D) are stacked with reference to the Panikkar Ridge. KSS-30 Bodenseewerk and Lacoste-Romberg Gravimeters with reference base system IGSN-71 were used onboard the research vessels, Sagar Kanya and Anweshak, respectively to record the gravity data. Free-air gravity anomalies were calculated by applying the Eötvos correction and normal gravity (with reference to ellipsoid GRS 67) at the observation positions. Dashed lines show correlated anomalies of the Prathap, Laccadive, Panikkar and Laxmi ridges. The anomalies that are seen associated with volcanic structures on the seismic sections are shaded.

Figure 6. Magnetic profiles collected onboard various research vessels: ORV Sagar Kanya (SK 05, 12, 22, 50, 64 and 79), MV Anweshak (RE lines) and RV Conrad (C1707)

are stacked with reference to the Panikkar Ridge. Geometric proton Precession magnetometer was used onboard the research vessels (Sagar Kanya and Anweshak) to record the total field magnetic data, which subsequently reduced to anomaly by subtracting the IGRF values. Dashed lines show correlated anomalies of the Prathap, Laccadive, Panikkar and Laxmi ridges. The anomalies that are seen associated with volcanic structures on the seismic sections are shaded.

Figure 7a: Seismic reflection profile (eastern part of RE-11) across the continental margin, Prathap Ridge Complex and part of the Laxmi Basin is integrated with gravity and magnetic anomaly data. Miocene sedimentary boundary is shown with a solid undulated line in the sediment column. Volcanic intrusive structures coincide with the magnetic anomalies (shown by solid track).

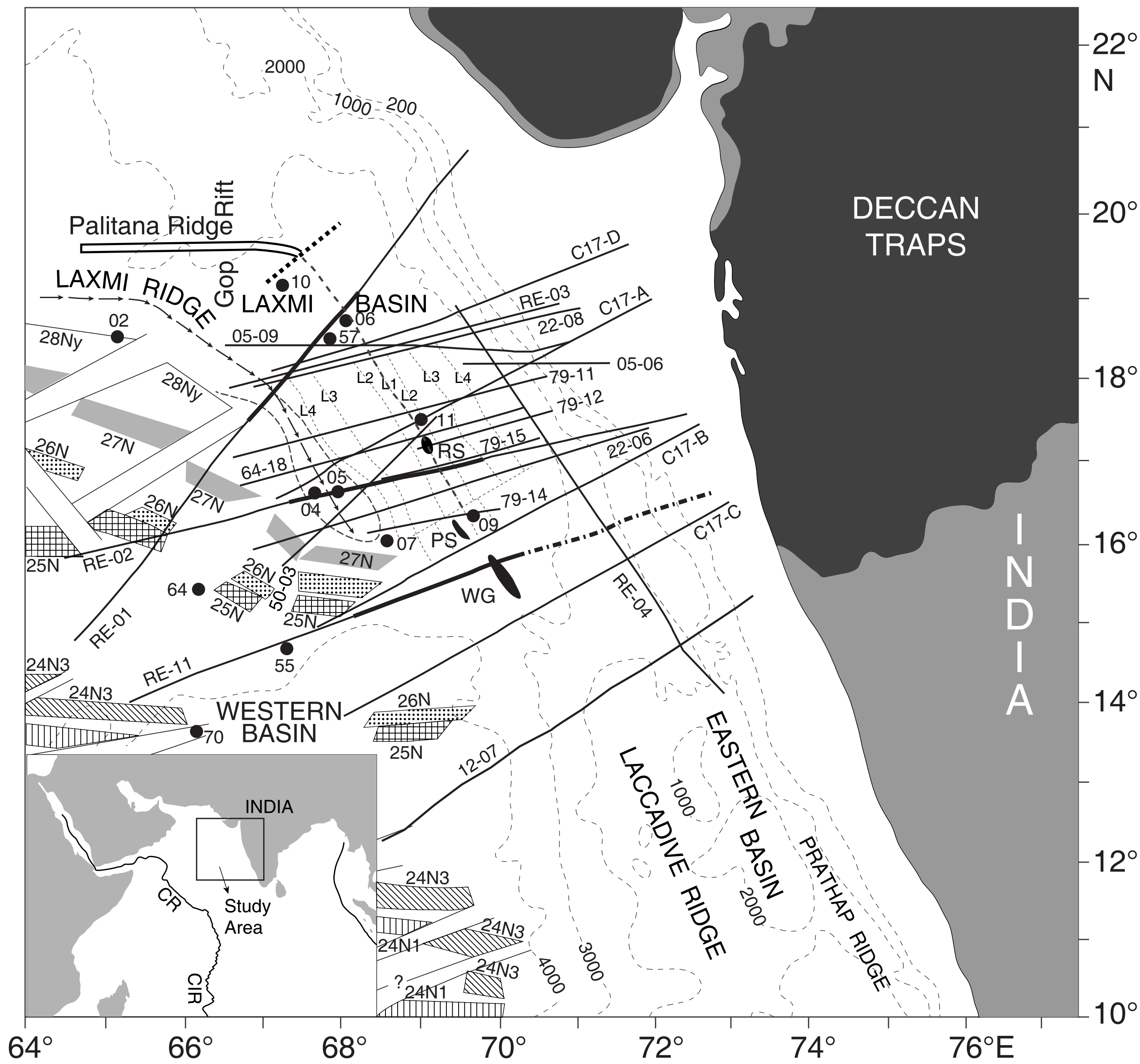
Figure 7b: Seismic reflection profile (central part of RE-11) across the Wadia Guyot, part of the Laxmi Basin and Laxmi Ridge is integrated with gravity and magnetic anomaly data. Miocene sedimentary boundary is shown with a solid undulated line in the sediment column. Volcanic intrusive structures coincide with the magnetic anomalies (shown by dashed-dot track).

Figure 8. Seismic reflection record and its interpreted crustal section of profile RE-02 and free-air gravity and magnetic anomalies of nearly coincident profile SK 79-15 are stacked. Both the profiles were acquired very closely in the Laxmi Basin. Dotted lines show axis of Panikkar Ridge and volcanic structures.

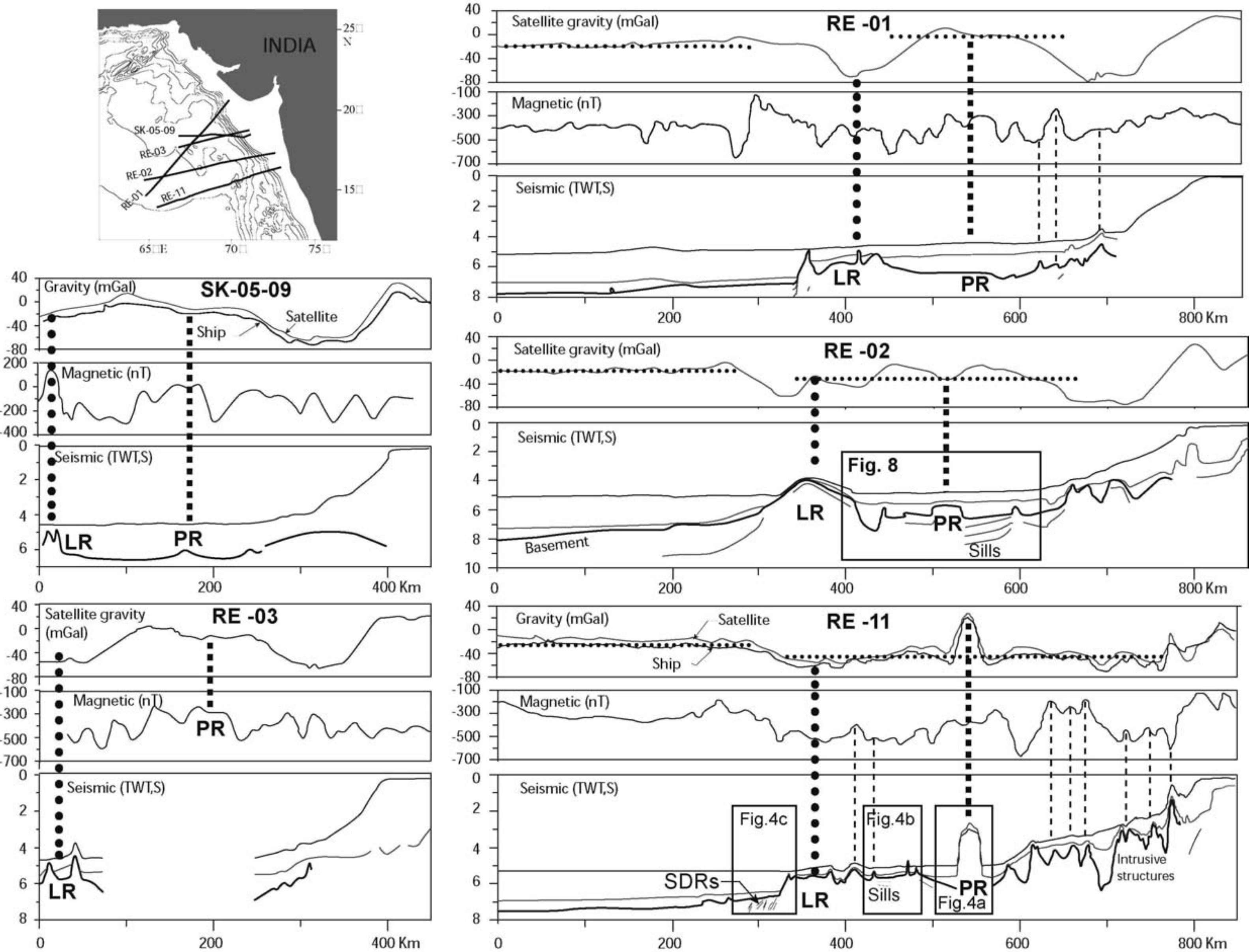
Figure 9. Map shows satellite free-air gravity anomalies (Sandwell and Smith, 1997) and interpreted geomorphic features. Features are outlined by square-dotted lines and labelled. WG = Wadia Guyot, RS and PS are Raman and Panikkar seamounts respectively, PTR = Palitana Ridge, PR = Panikkar Ridge and BH = Bombay High structure.

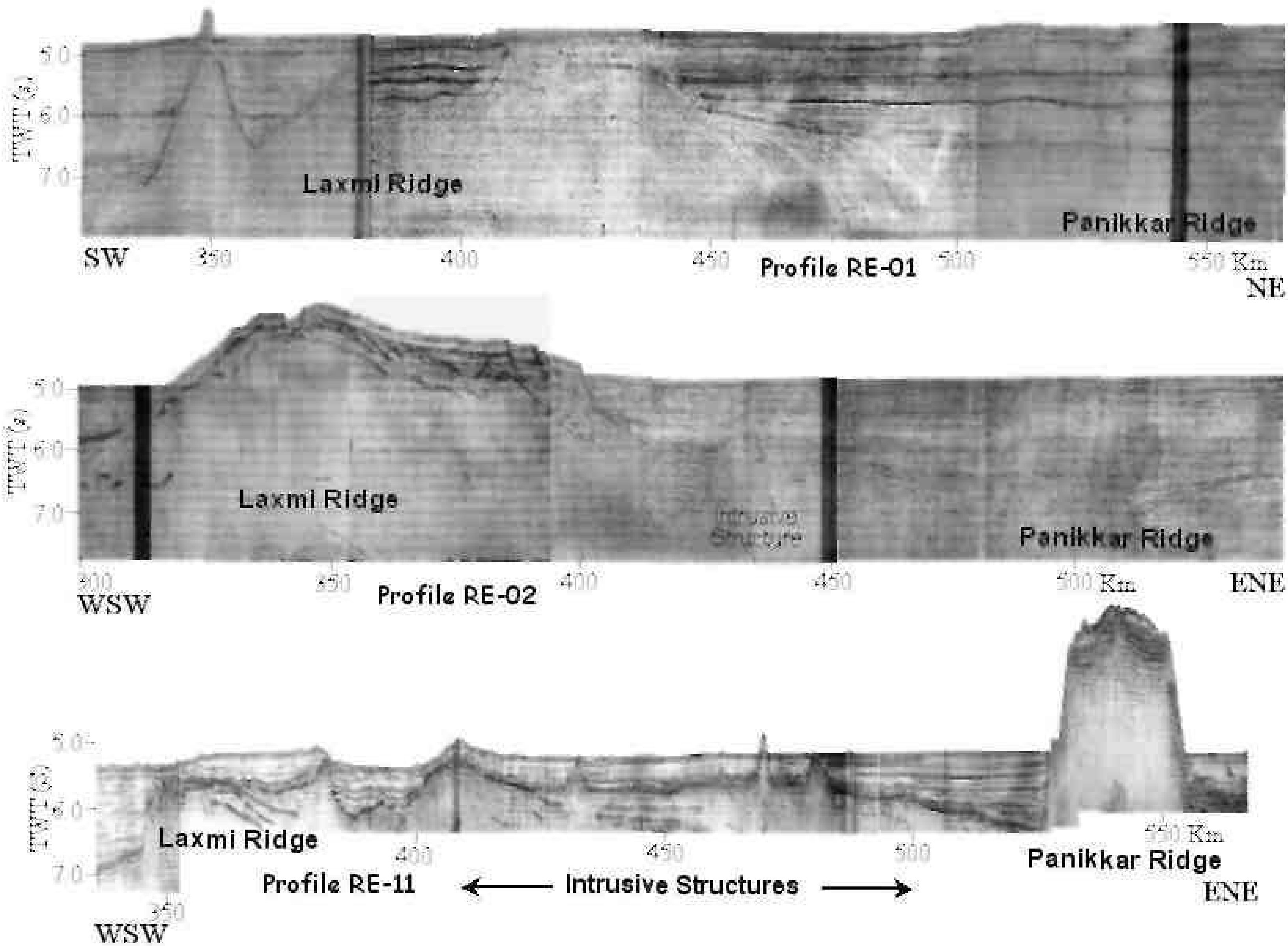
Figure 10. Velocity-depth plots from sonobuoy stations of the Western Basin, Laxmi Ridge, Laxmi Basin, Seychelles Bank and western Indian shield (Naini and Talwani, 1983; Davies and Francis, 1964; Mathews and Davis, 1966; Reddy et al., 1999). Non-continuous lines in graphs of Western Basin, Laxmi Ridge, Laxmi Basin and Indian shield represent the average crustal velocities and thicknesses. In right-side bottom graph crustal columns and velocities of all the regions are stacked with respect to the basement. The 6.7 km/s velocity layer (oceanic layer 3) of the Western Basin is absent beneath the Laxmi Ridge and Laxmi Basin. The anomalous velocity layer 7.0 to 7.4 km/s is noticed in the lower crust of the Laxmi Ridge and Laxmi Basin.

Figure 11. Modelled crust structure across the continental shelf, Laxmi Basin, Panikkar Ridge, Laxmi Ridge and eastern Arabian Sea from free-air gravity and magnetic anomalies. The Laxmi Basin basically consists of stretched continental crust, while the crust adjacent to the Panikkar Ridge in the basin is intermixed with the Deccan volcanic rocks. Magnetic anomalies are modelled with intrusive structures caused by the Deccan Volcanism. Seaward dipping reflectors are considered for modelling the magnetic anomaly on west of the Laxmi Ridge. Parameters used in anomaly computations are: densities = 1.03 – 3.3 g/cm^3, total magnetic field 40400 nT and remanent magnetization = 1.0 – 4.0 A/m. For reversal magnetic bodies (shown with plus sign): inclination = +50° and declination = +130°. For normal magnetic bodies (shown with open star): inclination = -50° and declination = -40°. Long-range sonobuoy (stations 55, 07 and 09, close to profile RE-11) velocity results are projected onto the crustal model. The values below the stations represent the velocities in km/s.

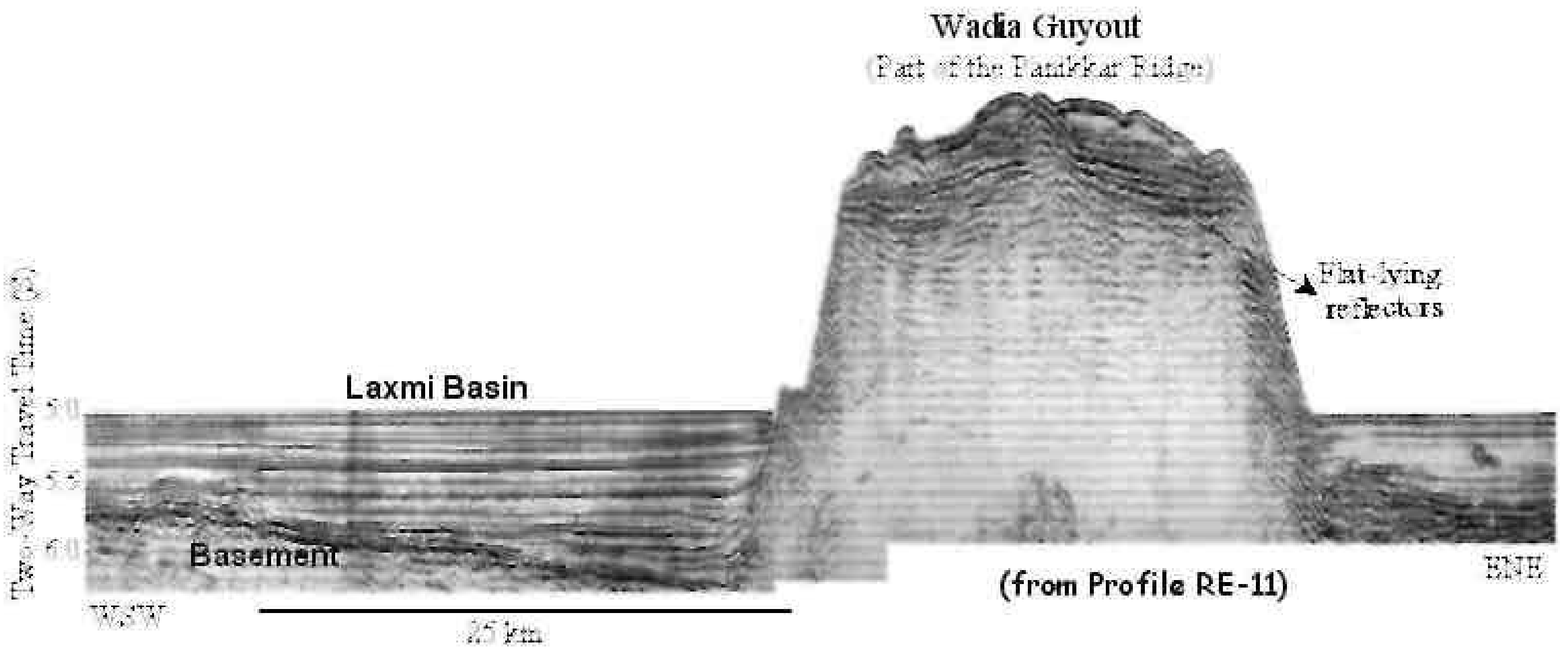


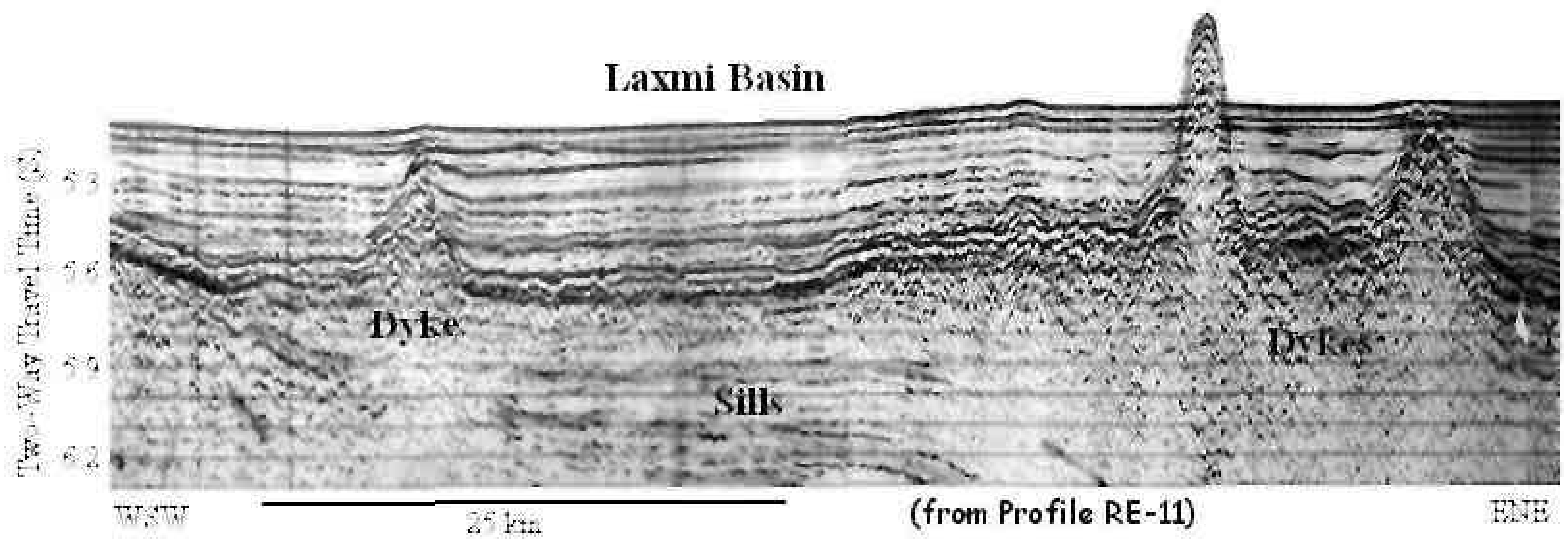
DECCAN
TRAPS
INDIA
Palitana Ridge
Gop
Rift
LAXMI RIDGE
LAXMI BASIN
WESTERN BASIN
EASTERN BASIN
LACCADIVE RIDGE
PRATHAP RIDGE
RE-01
RE-02
RE-03
RE-04
RE-11
C17-A
C17-B
C17-C
C17-D
05-09
05-06
22-08
22-06
79-11
79-12
79-14
79-15
64-18
50-03
12-07
L1
L2
L3
L4
RS
PS
WG
28Ny
27N
26N
25N
24N3
24N1
2000
1000
200
3000
4000
INDIA
Study Area
CR
CIR
22°
N
20°
18°
16°
14°
12°
10°
64°
66°
68°
70°
72°
74°
76°E

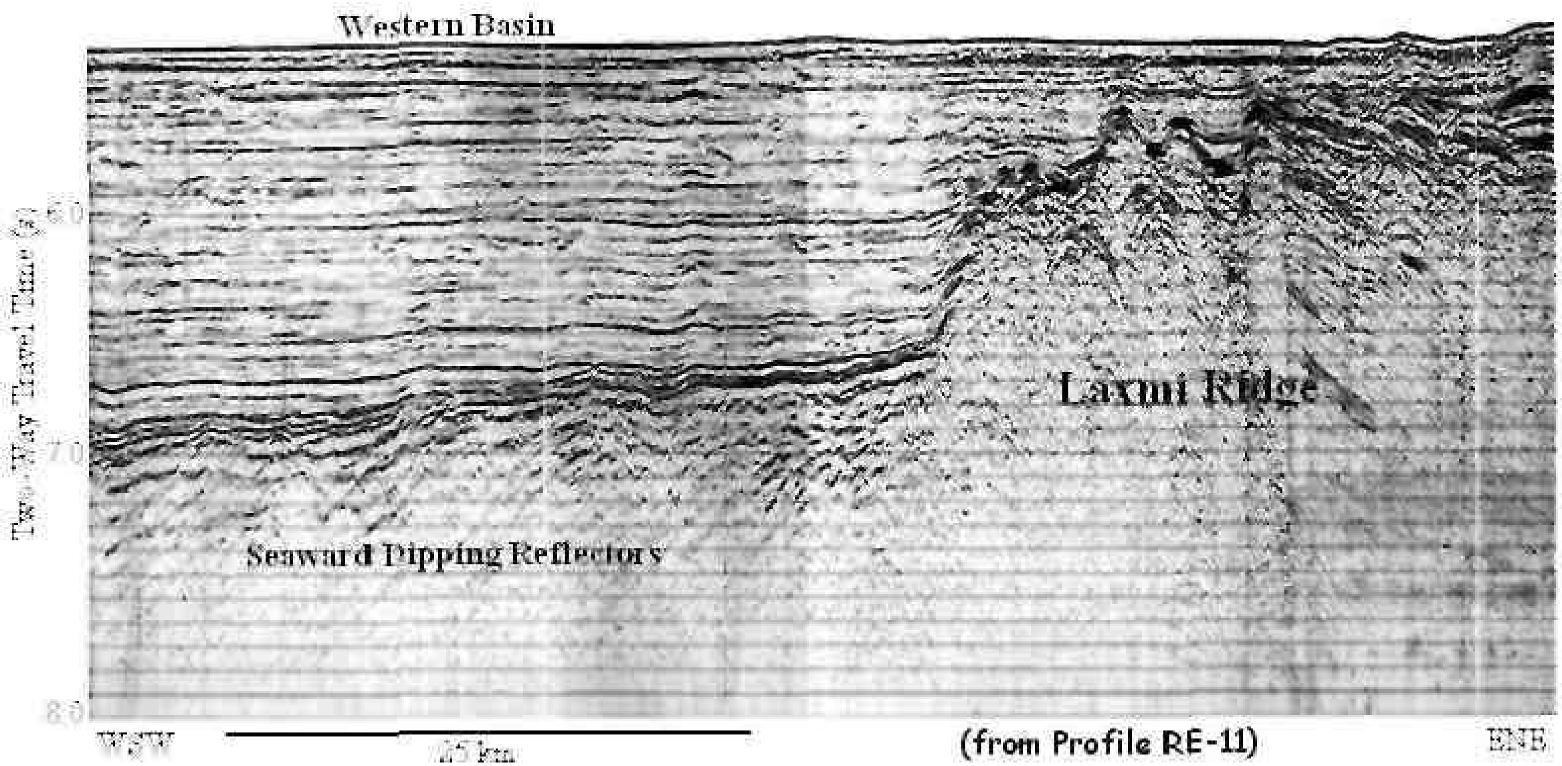

INDIA
SK-05-09
RE-03
RE-02
RE-01
RE-11
Gravity (mGal)
SK-05-09
Satellite
Ship
Magnetic (nT)
Seismic (TWT,S)
LR
PR
Satellite gravity (mGal)
RE -03
Satellite gravity (mGal)
RE -01
Satellite gravity (mGal)
RE -02
Fig. 8
Sills
Basement
Gravity (mGal)
RE -11
Fig.4c
Fig.4b
Fig.4a
SDRs
Intrusive structures
400 Km
800 Km

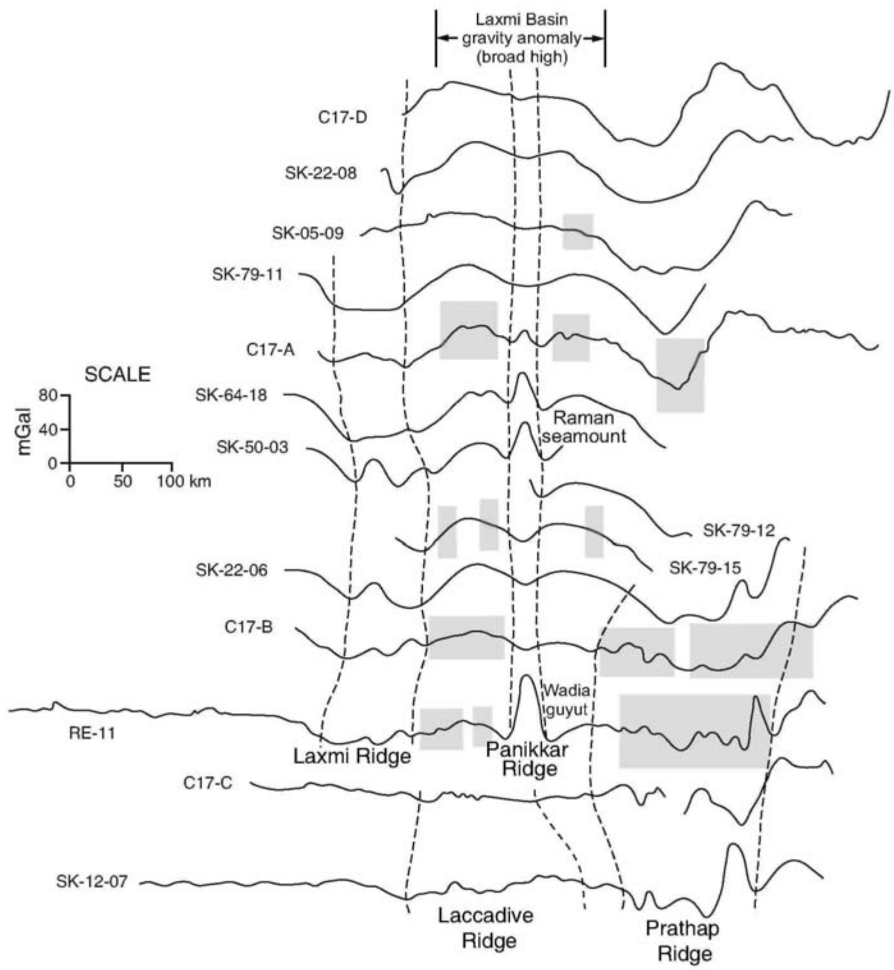


TWT (s)
5.0
6.0
7.0
Laxmi Ridge
Panikkar Ridge
SW
350
400
450
Profile RE-01
500
550 Km
NE
Laxmi Ridge
Intrusive Structure
Panikkar Ridge
300
WSW
350
Profile RE-02
400
450
500 Km
ENE
Laxmi Ridge
400
450
500
550 Km
Panikkar Ridge
Profile RE-11
Intrusive Structures
ENE
350
WSW

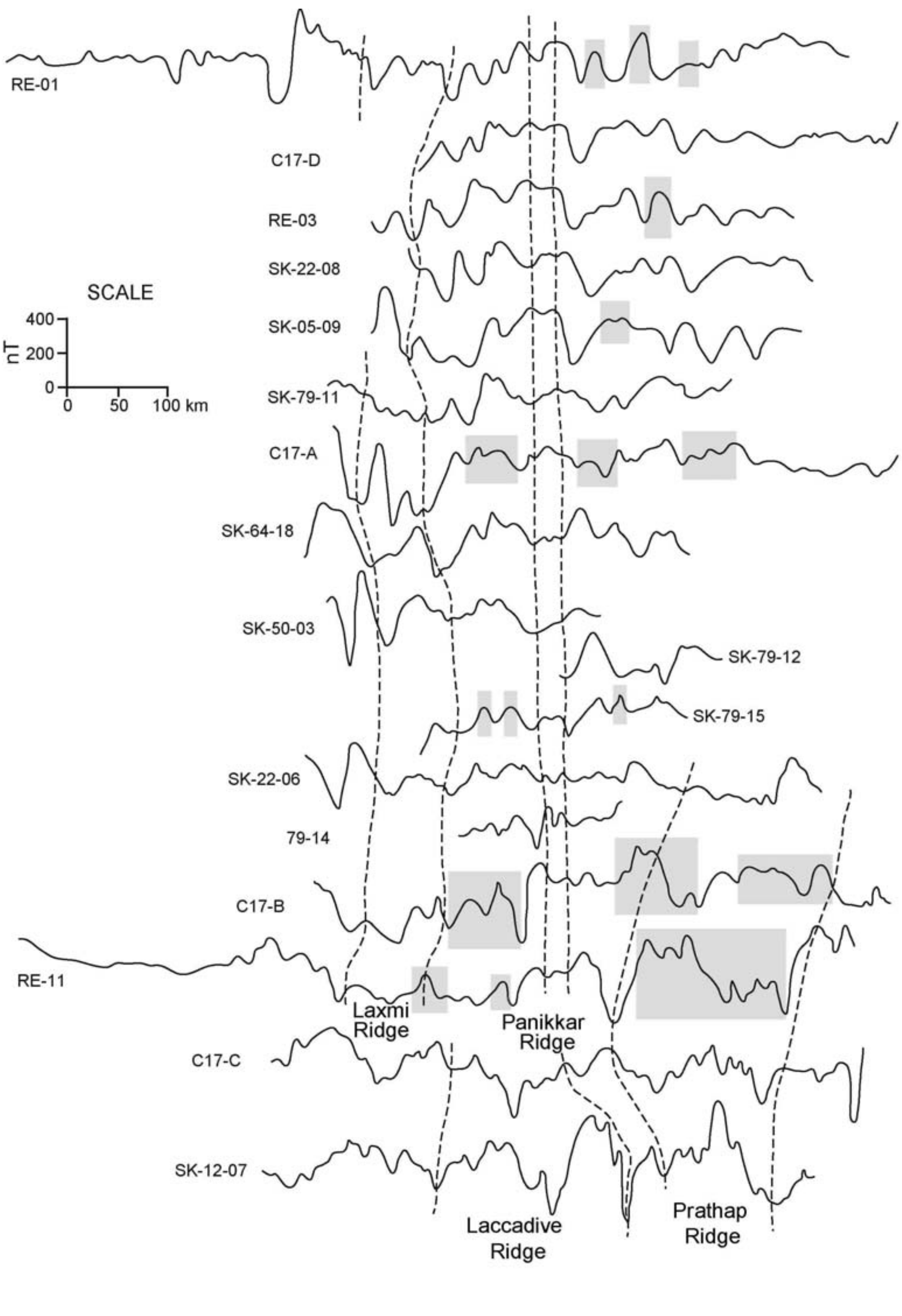

Wadia Guyout
(Part of the Panikkar Ridge)
Flat-lying
reflectors
Laxmi Basin
Basement
Two-Way Travel Time (s)
5.0
5.5
6.0
WSW
ENE
25 km
(from Profile RE-11)


Laxmi Basin
Two-Way Travel Time (s)
5.3
5.6
5.9
6.2
Dyke
Sills
Dykes
WSW
25 km
(from Profile RE-11)
ENE

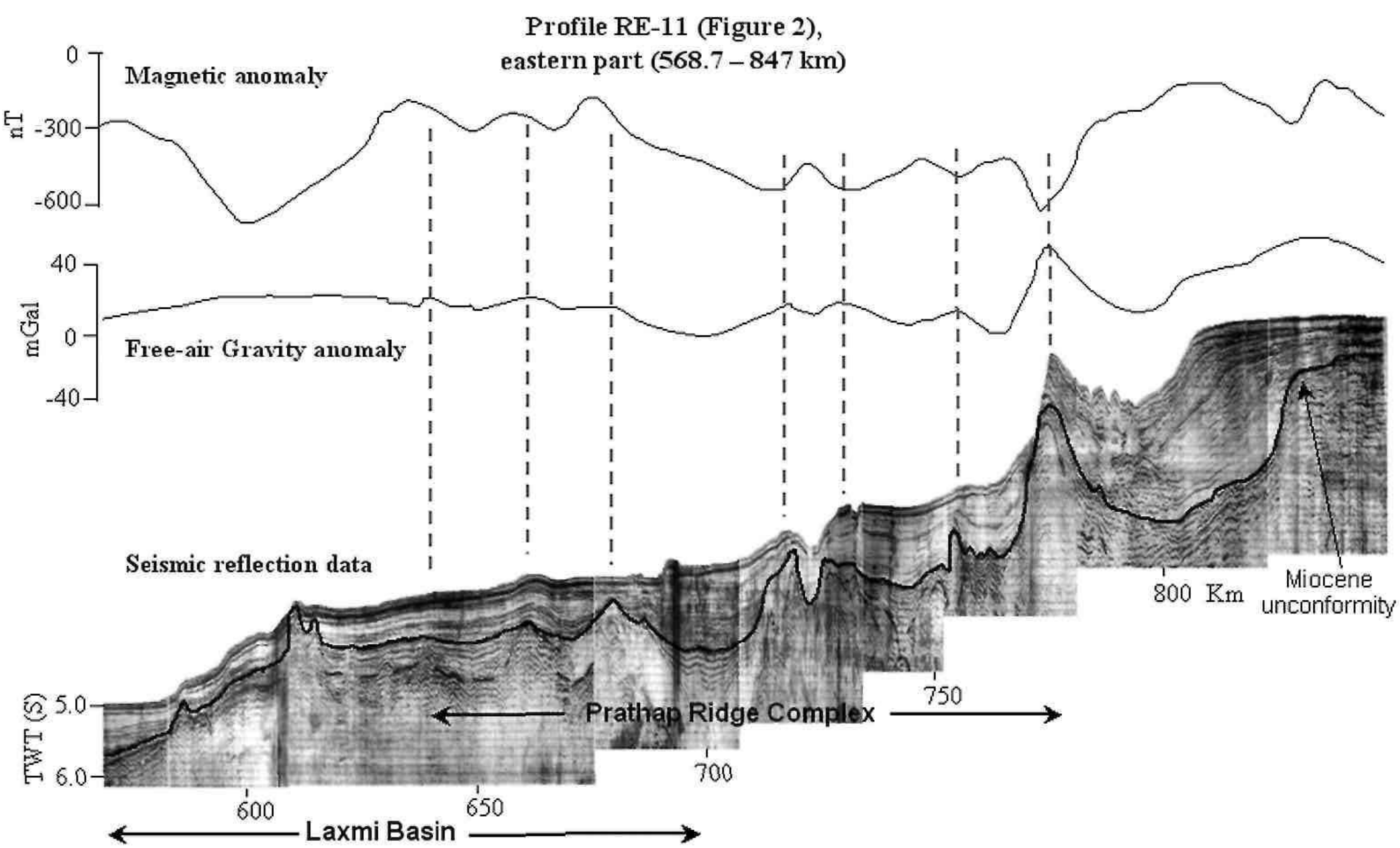

Western Basin
Laxmi Ridge
Seaward Dipping Reflectors
Two-Way Travel Time (s)
6.0
7.0
8.0
WSW
ENE
(from Profile RE-11)

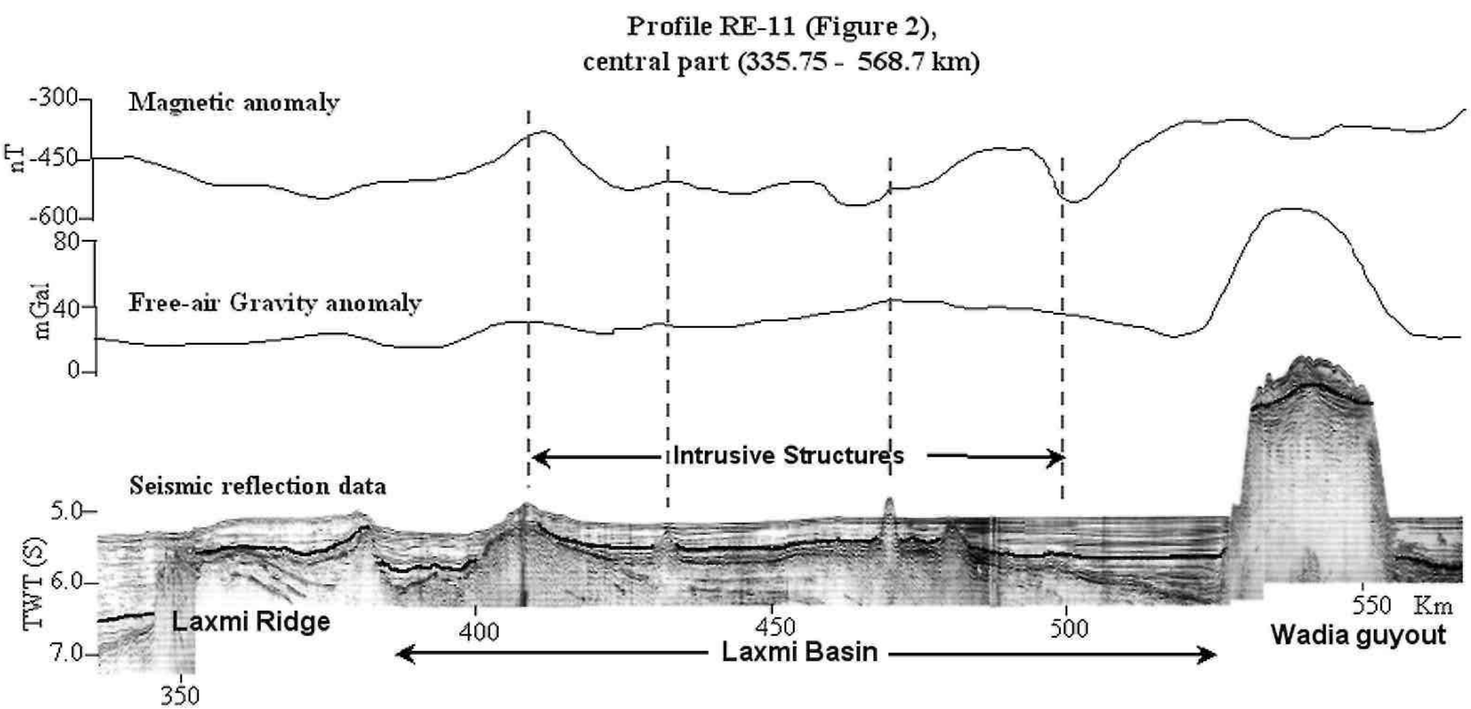


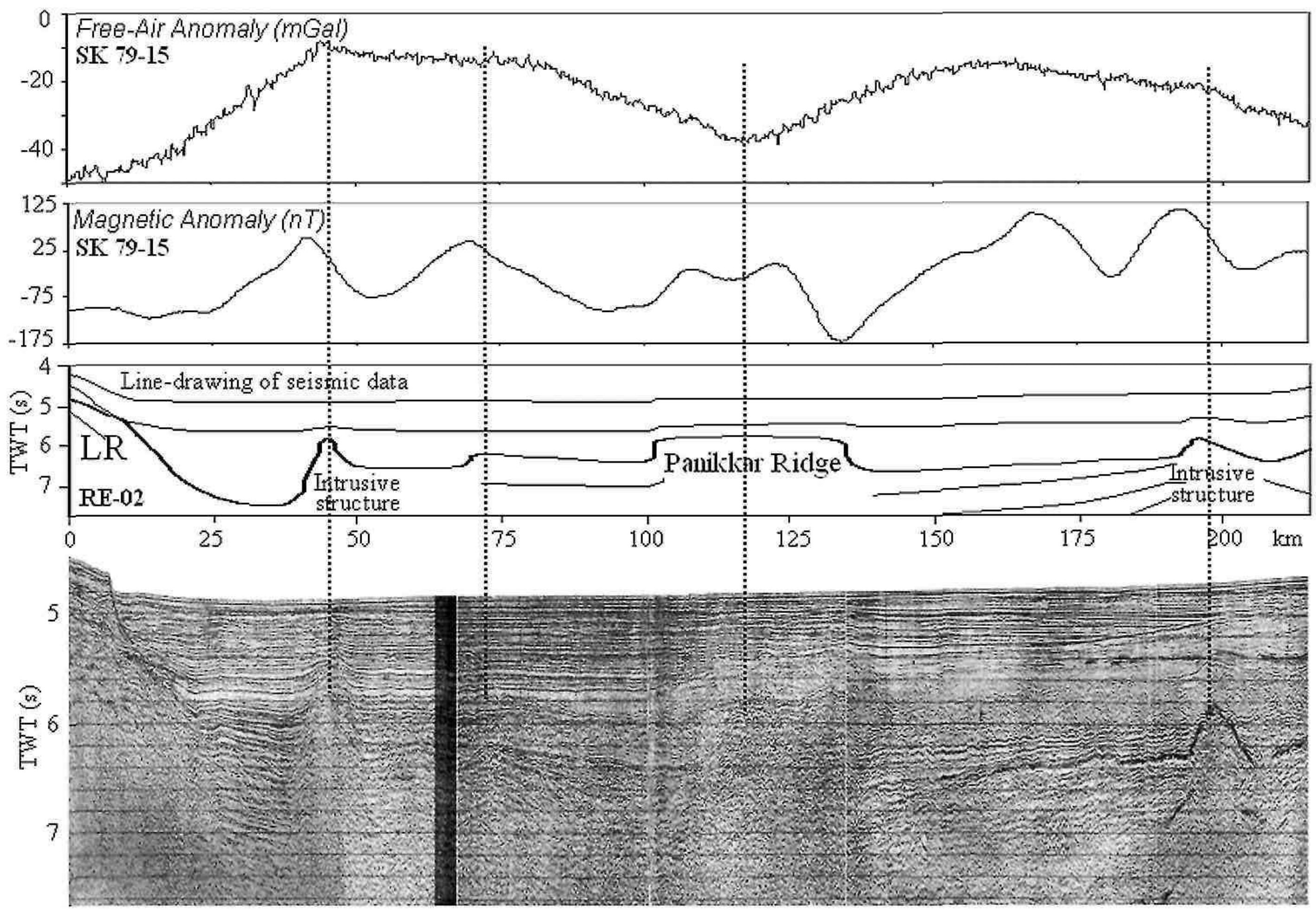
Laxmi Basin
gravity anomaly
(broad high)
C17-D
SK-22-08
SK-05-09
SK-79-11
C17-A
SCALE
80
mGal
40
0
0
50
100 km
SK-64-18
SK-50-03
Raman
seamount
SK-79-12
SK-79-15
SK-22-06
C17-B
Wadia
guyut
RE-11
Laxmi Ridge
Panikkar
Ridge
C17-C
SK-12-07
Laccadive
Ridge
Prathap
Ridge



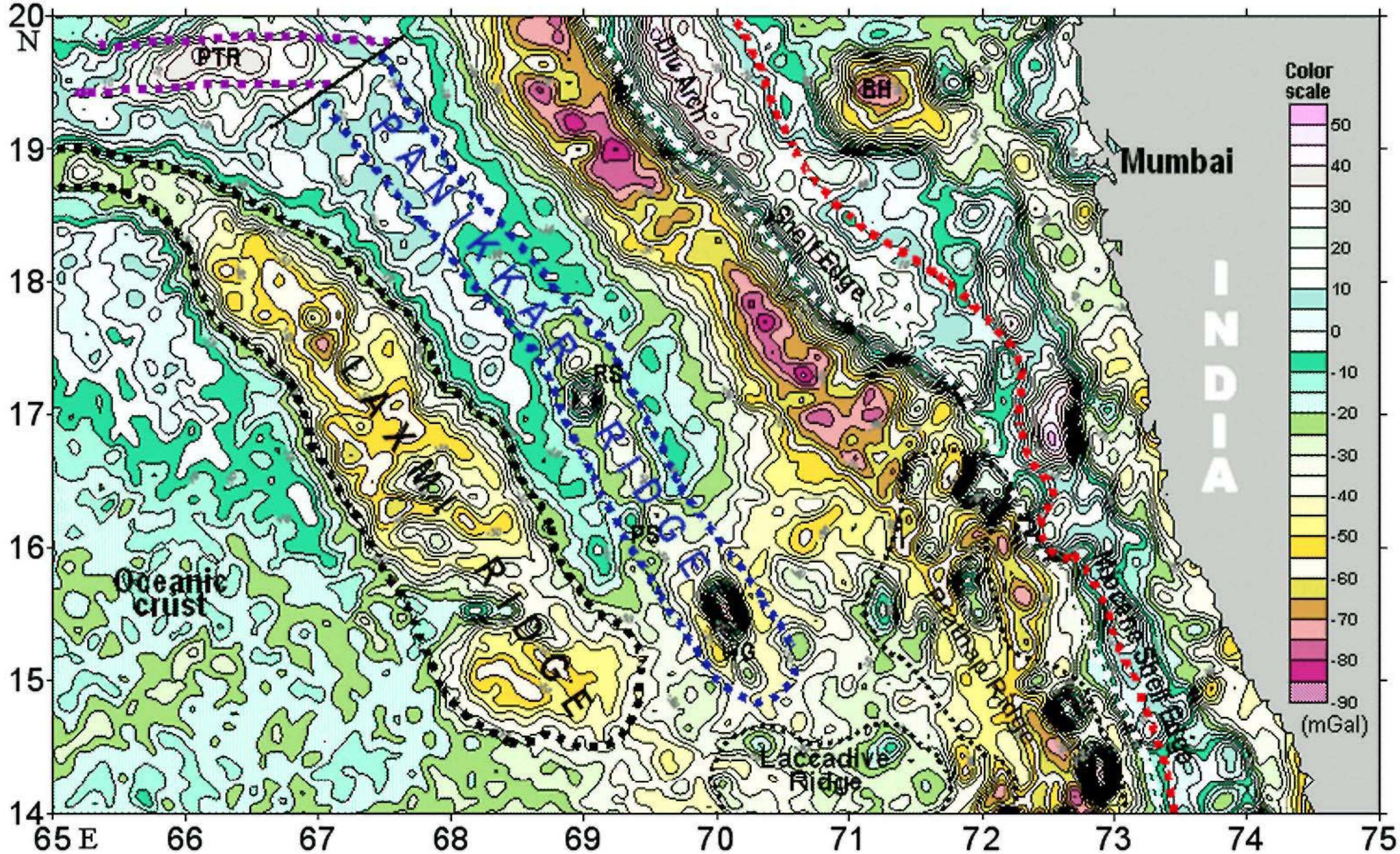
RE-01
C17-D
RE-03
SK-22-08
SCALE
400
200
0
nT
0
50
100 km
SK-05-09
SK-79-11
C17-A
SK-64-18
SK-50-03
SK-79-12
SK-79-15
SK-22-06
79-14
C17-B
RE-11
Laxmi Ridge
Panikkar Ridge
C17-C
SK-12-07
Laccadive Ridge
Prathap Ridge

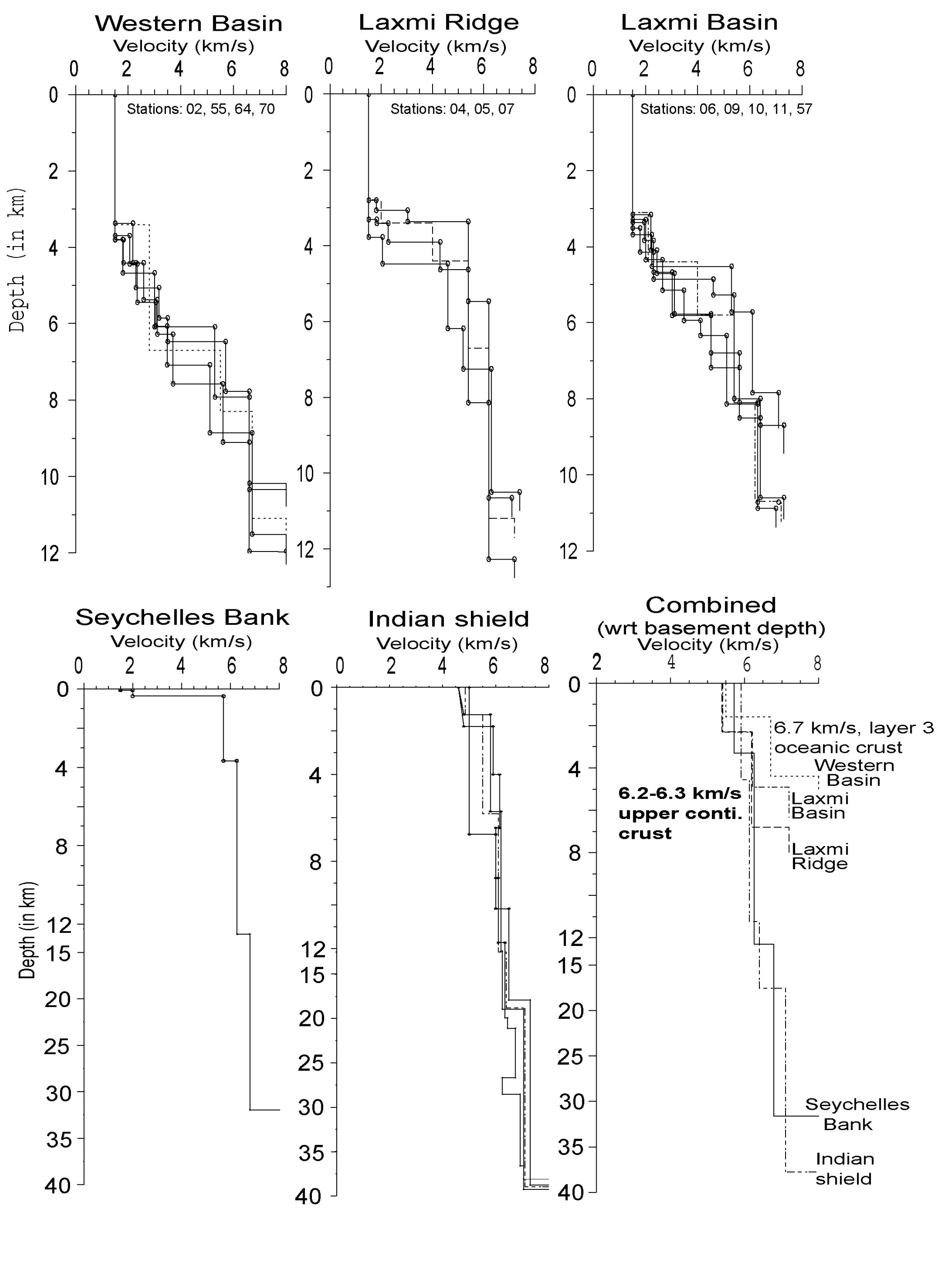

Profile RE-11 (Figure 2),
eastern part (568.7 – 847 km)
Magnetic anomaly
nT
0
-300
-600
40
0
-40
mGal
Free-air Gravity anomaly
Seismic reflection data
TWT (S)
5.0
6.0
600
650
700
750
800 Km
Miocene
unconformity
Prathap Ridge Complex
Laxmi Basin


Profile RE-11 (Figure 2),
central part (335.75 - 568.7 km)
Magnetic anomaly
nT
-300
-450
-600
Free-air Gravity anomaly
mGal
80
40
0
Seismic reflection data
TWT (S)
5.0
6.0
7.0
Intrusive Structures
Laxmi Ridge
Laxmi Basin
Wadia guyout
350
400
450
500
550 Km

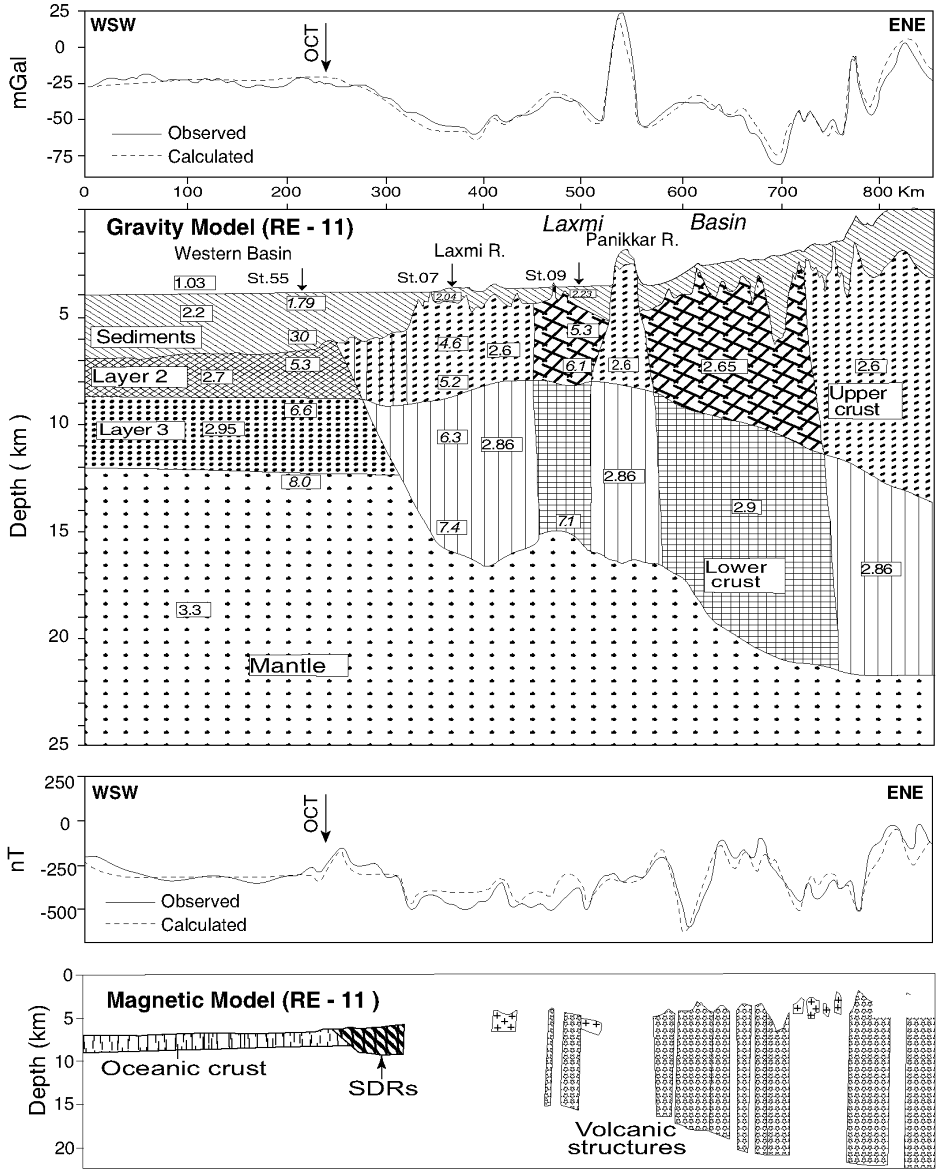


Free-Air Anomaly (mGal)
SK 79-15
Magnetic Anomaly (nT)
SK 79-15
Line-drawing of seismic data
LR
RE-02
Intrusive structure
Panikkar Ridge
Intrusive structure
TWT (s)
km


20
N
19
18
17
16
15
14
65 E
66
67
68
69
70
71
72
73
74
75
PTR
PANIKKAR RIDGE
LAXMI RIDGE
RS
PS
G
BH
Diu Arch
Shelf Edge
Oceanic crust
Laccadive Ridge
Prathap Ridge
Mumbai
INDIA
Color scale
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
(mGal)



Western Basin
Velocity (km/s)
Stations: 02, 55, 64, 70
Depth (in km)
Laxmi Ridge
Velocity (km/s)
Stations: 04, 05, 07
Laxmi Basin
Velocity (km/s)
Stations: 06, 09, 10, 11, 57
Seychelles Bank
Velocity (km/s)
Depth (in km)
Indian shield
Velocity (km/s)
Combined
(wrt basement depth)
Velocity (km/s)
6.7 km/s, layer 3
oceanic crust
Western
Basin
6.2-6.3 km/s
upper conti.
crust
Laxmi
Basin
Laxmi
Ridge
Seychelles
Bank
Indian
shield



WSW
ENE
OCT
mGal
25
0
-25
-50
-75
Observed
Calculated
0
100
200
300
400
500
600
700
800 Km
Gravity Model (RE - 11)
Laxmi
Basin
Western Basin
Laxmi R.
Panikkar R.
St.55
St.07
St.09
Sediments
Layer 2
Layer 3
Upper crust
Lower crust
Mantle
Depth (km)
1.03
2.2
1.79
30
5.3
2.7
6.6
2.95
8.0
4.6
2.6
5.2
6.3
2.86
7.4
7.1
6.1
2.6
2.65
2.9
3.3
nT
250
0
-250
-500
Magnetic Model (RE - 11)
Depth (km)
Oceanic crust
SDRs
Volcanic structures

Geologic Domain	Station ID	Lat (N)	Long (E)	Water Depth (km)	Sediments		Sediments +Volcanics		Crustal layers		Anomalous layer		Mantle	
					Vel. (km/s)	Thick (km)	Vel. (km/s)	Thick (km)	Vel. (km/s)	Thick (km)	Vel. (km/s)	Thick (km)	Vel. (km/s)	Depth to Moho (km)
Western Basin	02	18°38.2’	67°14.2’	3.376	2.18-3.7	4.2	-	-	5.6-6.6	4.38	-	-	8.0	11.96
	64	15°14.2’	66°12.4’	3.703	2.05-3.48	3.38	-	-	5.1-6.7	4.43	-	-	8.2	11.51
	55	14°54.4’	67°21’	3.769	1.79-3.0	2.29	-	-	5.3-6.6	4.26	-	-	8.1	10.32
	70	13°41.2’	66°08.9’	3.814	1.82-3.5	2.66	-	-	5.7-6.6	3.71	-	-	8.3	10.18
Laxmi Ridge	04	16°25.5’	67°42’	2.811	1.8-3.03	0.56	-	-	5.4-6.2	7.28	7.1	7.3	-	-
	05	16°27.4’	67°59.3’	3.136	1.82-2.27	0.77	4.3	0.73	5.4-6.2	7.64	7.2	10.7	-	-
	07	15°51’	68°37.5’	3.779	2.04	0.7	4.6	1.71	5.2-6.3	4.31	7.4	5.79	-	-
Laxmi Basin	10	19°01.1’	67°18’	3.161	2.2-3.1	2.61	4.5	1.03	5.6-6.3	4.08	7.0	9.0	-	-
	06	18°34.5’	68°07.1’	3.369	1.94-3.01	2.44	4.5	1.38	5.6-6.4	3.41	7.3	6.65	-	-
	57	18°20.2’	67°55.1’	3.294	2.0-3.47	2.65	4.1	0.4	5.1-6.3	4.38	7.1	-	-	-
	11	17°22.1’	69°03.4’	3.519	1.78-2.3	1.34	4.6	0.41	5.4-6.4	3.43	7.3	6.47	-	-
	09	16°10.1’	69°43.5’	3.685	2.23	0.84	-	-	5.3-6.1	3.32	7.1	7.26	-	-
Seychelles Bank		-	-	-	-	-	-	-	2.37-6.78	31.5	-	-	8.1	31.5
Indian Shield	KR	-	-	-	-	-	-	-	4.6-6.45	20	6.75-7.05	18	8.25	38
	N-S L	-	-	-	-	-	-	-	5.0-6.5	18	7.3	20	8.2	38
	CB	-	-	-	-	-	-	-	4.6-6.65	17	7.05	22	8.05	39

Table 1: Details of Sonobuoy stations from Western Basin, Laxmi Ridge, Laxmi Basin and Seychelles Bank (Naini and Talwani, 1983; Davies and Francis, 1964; Mathews and Davis, 1966), and DSS profiles from Indian Shield (Kaila and Sain, 1997; Reddy et al., 1999). KR, N-S L and CB represent Koyana region, Narmada-Son Lineament (Mehmadabad-Billimora) and Cambay Basin (Navibandar-Amreli), respectively.