

## Marine geophysical studies along a transect across the continental margin off Bombay coast, west of India

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**Abstract-** Study of underway geophysical data along a transect of 415 km across the continental margin off Bombay, between 80 and 3600 m water depths reveals seven seismic sequences consisting of parallel and continuous wavy reflections upto 1.0-1.2 s TWT in the shelf and slope regions. Abrupt truncation of reflectors within the upper sequences of the slope resulting in 'V' shaped troughs and continuous parallel reflections of increased areal extent in the abyssal plains are also noticed. Presence of continuous wavy reflections in the slope region suggest the absence of massive slumping. Recent active process is advocated to account for the truncated reflectors.

(A basement high in the abyssal plains as reported by NAINI and TALWANI (1982) is found to extend further north as a linear feature. Since several parallel basement ridge systems exist in the eastern Arabian Sea, we propose to name this linear basement high as *Panikkar Ridge* for ease of reference. Thin crust, 26-28 km below the shelf and 10-11 km in the abyssal plains is interpreted due to stretched lithosphere of the western margin of India.)

### INTRODUCTION

Detailed study of passive continental margin crust and overlying sediments especially close to oceanic crust is of great interest to unfold records of ongoing tectonic and geologic processes imprinted within sediments. Geology, stratigraphy and internal structure of Tertiary sediments and basement configuration on the shelf off Bombay were studied (RAMASWAMY and RAO, 1980; NAINI and KOLLA, 1982; BABENKO et al., 1981; BISWAS, 1982; GOPALA RAO, 1990a and 1990b). The studies revealed that 1) the shelf's upper crust consisting of sediments (> 2 km thick) resting on the Deccan flood basalts and/or granitic gneisses, correlatable to the adjacent onshore geology, and 2) the margin crust is shear-rifted resulting in horst and graben structures bounded almost by NW-SE and E-W trending faults. In this paper the results of an integrated interpretation of bathymetric, magnetic, gravity and seismic reflection data collected along a transect is presented and a possible crustal structure model is suggested.

#### *Offshore tectonics*

The western continental margin is characterised by the presence of horst and graben like features, NW-SE trending regional faults, Laxmi, Chagos-Laccadive and Prathap Ridge complexes and a basement high running approximately NW-SE off Bombay in the water depths beyond 3000 m. Further, NAINI (1980) demarcated the boundary of western and eastern basin in the Arabian Sea (Fig.1). The recent regional marine geophysical investigations in the offshore areas off Bombay revealed that :

1. NW to NNW-SE to SSE trending high anticlinal structures, and sediment filled depressions of the shelf are bounded by NNW- SSE and E-W trending regional faults (RAMASWAMY and RAO, 1980). A basement high occurring between 15°30'N and 17°30'N latitudes (Fig.1) around 3200 m water depth to east of the Laxmi Ridge is associated with 250-400 nT magnetic anomaly (NAINI and TALWANI, 1982).

2. Linear magnetic anomalies, corresponding to chrons 20 (45 My) and 28 (65 My) are reported in the western Basin between 10°N to 20°N latitudes and 60°E to 65°E longitudes (McKENZIE and SCLATER, 1971; NAINI and TALWANI, 1982).

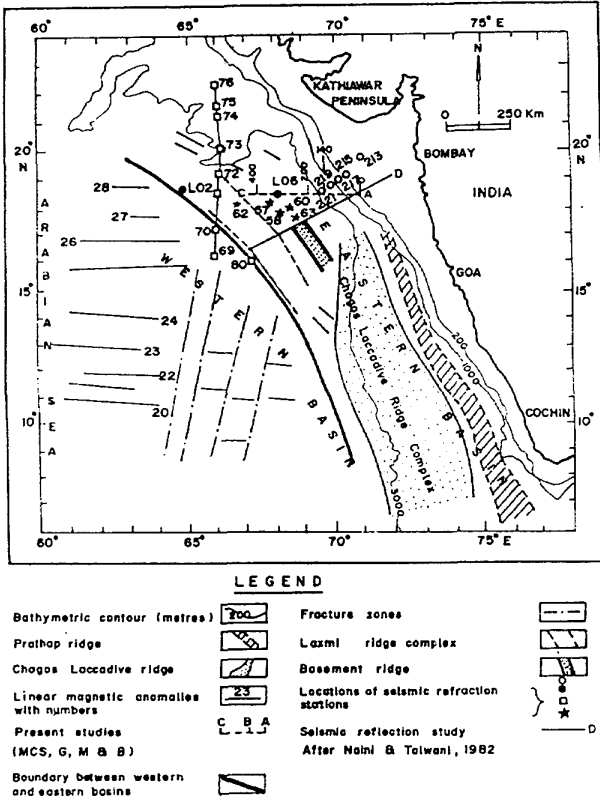


Fig.1. Map showing various structural elements, magnetic isochrons, boundaries of ridges (Laxmi, Chagos-Laccadive and Prathap), seismic refraction stations and location of reflection profiles in the western continental margin of India.

### Offshore data

During ORV *Sagar Kanya* cruise V in 1983, seismic reflection, gravity, magnetic and bathymetric data along a transect CA (Fig.1) of 415 km across the margin off Bombay in water depths 80 to 3600 m were collected. Ship's positions along the track were determined by an integrated navigation system interfaced to Magnavox dual channel satellite receiver (MX1107) for primary position control. Bathymetry was recorded by an ELAC narrow beam echosounder (12 and 3.5 KHz). Gravity data was collected using a shipborne non-astatized spring mass type gravity meter (Bodenseewerk KSS 30), with an accuracy of 0.1 mgal. Magnetic data was collected by deploying a proton precession magnetometer (Geometrics 801), with 1 nT resolution. Magnetic anomalies were obtained after subtracting International Geomagnetic Reference Field. Continuous seismic reflection profiling (12 fold CDP, 4 ms sampling rate) was carried out using a multichannel seismic equipment (DFS V), with an air-gun array (total volume 7.9 litres) as the seismic energy source. In the present study near trace monitor

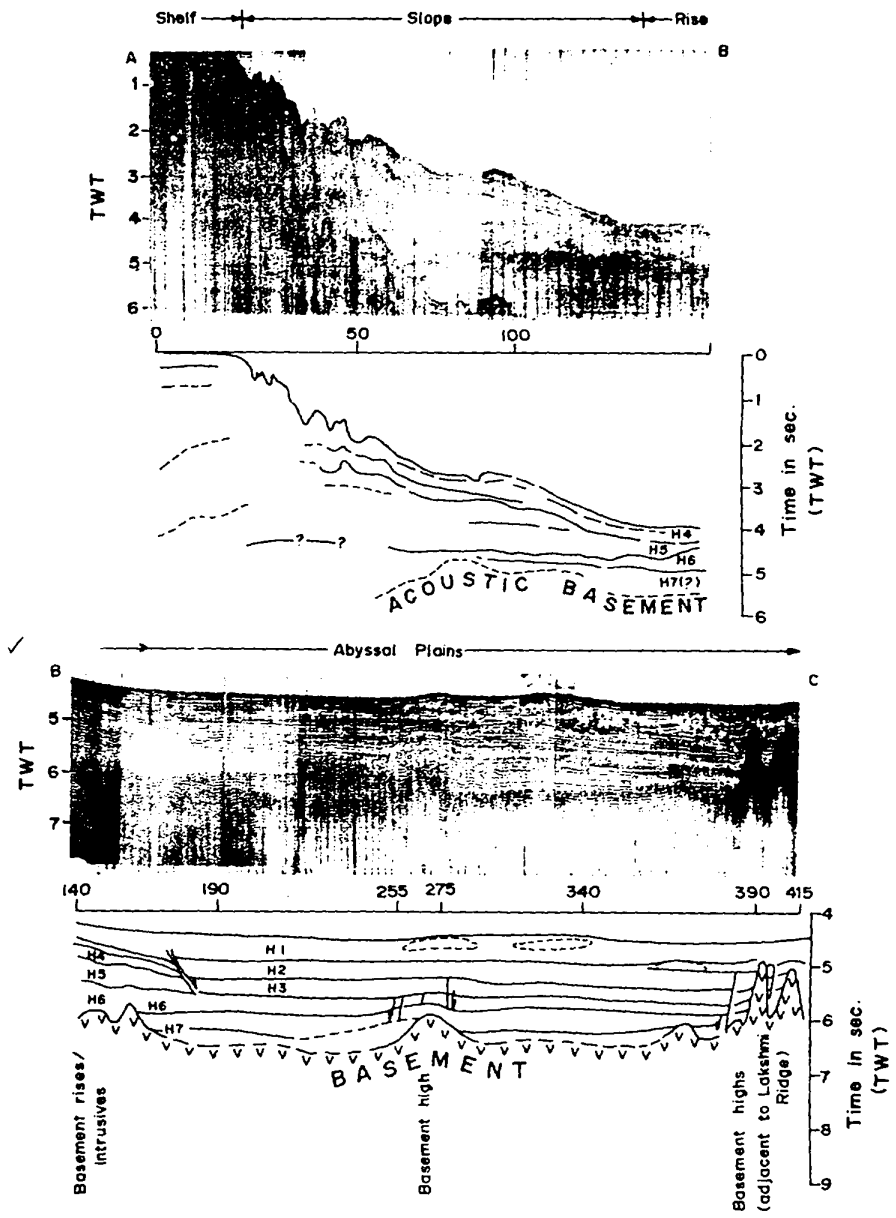


Fig.2. Single channel (near trace) analog record of the transect along with the interpreted line drawing with different seismic sequences (H1-H7) across the western continental margin, off Bombay.

record section (Fig.2) is used. Gravity and magnetic anomalies and line drawings of the interpreted seismic section are presented (Fig. 3). The seismic reflection record section is interpreted under constraints from the velocity structure of the crust estimated from four seismic refraction stations of (NAINI, 1980) (Fig.3). Two-dimensional crustal structure and density model (Fig.4) is generated to explain the estimated free-air gravity and magnetic anomalies along the transect.

### *Seismics*

The seismic record section and its interpreted line drawing of the transect (Fig.2) reveals seven (H1 to H7) seismic reflection sequences within the sediments across outer continental shelf, slope, continental rise, abyssal plains and the eastern flank of the Laxmi Ridge. The sequences H1, H2, H3, H6 and H7 in the abyssal plains and H4 to H7 on the continental rise overlain by thin sedimentary strata are seen. On the shelf (upto 20 km, Fig.2) parallel continuous reflections of the sediments upto 1.2 s TWT are underlain by landward dipping reflectors at 1.4-1.6 s, 2.0-2.8 s and 4.0-4.2 s. In the slope region (between 20 to 100 km, Fig.2) uneven seafloor, continuous wavy reflections upto about 1.2 s (maximum) and raised acoustic basement deepening landward are noticed. The abrupt truncation of the reflectors giving rise to 2-5 km wide 'V' shaped valleys (0.5 s deep, TWT) are observed within the upper seismic sequences of the slope. The acoustic basement occurs at about 3.4 s in the mid-slope and 1.6 s at the base of the slope. In the slope region typical chaotic reflections within the seismic sequences are not noticed (Fig.2). About 1.6 s thick sediments overlie on acoustic basement below the continental rise. Seismic sequence (H6) with discrete parallel to sub-parallel reflections occur continuously between seismic sequences H3/H5 and H7 within abyssal plains and the rise. The underlying basement consists of 0.05 s to 0.25 s relief/local rises. The overlying seismic sequences in the east excepting the top most, conform with the basement topography with decreasing magnitude of the reliefs towards the surface. The sequences H4 and H5 (Fig.2) could not be traced in the abyssal plains and appear to terminate against a fault. In the abyssal plains, sequence H6 is overlain by three distinct parallel seismic sequences H1, H2 and H3 about 0.3-0.5 s thick each. In the east, the sequences H1, H2 and H3 lap onto sequences H4 and H5 which are continuing seaward from slope region. About 2.2-2.4 s maximum thick sedimentary sequences overlie the basement here. The underlying basement deepen to the west towards a basement high in the middle of the abyssal plains of 20-25 km wide and 0.8-1.0 s relief. A sediment cover of about 1.4-1.5 s thick is observed over the basement high. Eastern flank of the high is relatively less steep (1:15) compared to western flank's with slope (1:4). The centrally depressed basement in the abyssal plains with a prominent central high (Fig.2) is covered with sedimentary sequences, H6 and H7 and these sequences appear to be similar to that on the slope to rise. The upper sequences H1, H2 and H3 with distinct seismic reflection character confine to the abyssal plains only. The sequence H6, about 0.4 s thick (maximum) is acoustically transparent. The sequence H7 laps on to the basement while the sequence H6 drapes over the basement high. In the abyssal plain area, two convex lens-shaped seismic sequences 15-18 km apart (10-12 km wide and 0.2 s TWT thickness) of acoustically transparent and contorted reflections are observed within the sequence H1. Similar lens-shaped sedimentary structure also occurs at about 0.5 s depth within sequence H2 in the west. A gentle swell of about 25 km wavelength in the seafloor is noticed right above these lenticular structures. On the western end of the transect a double peaked basement high of 7.5 to 10 km wide each (at its base) is a striking feature, having a relief of 1.8 s TWT. The peaks are covered by about 0.5 s thick sediments, while the trough between them is filled with 1.2 s thick sediments.

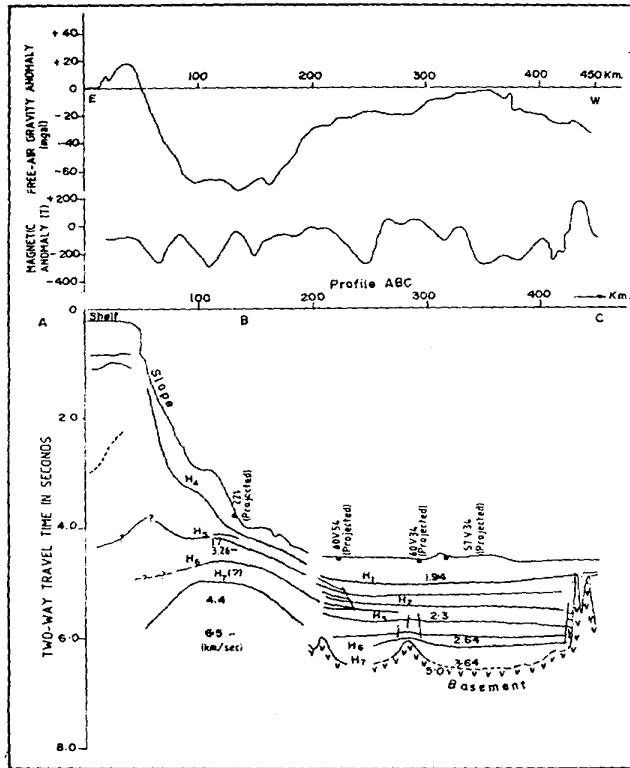


Fig. 3. Composite geophysical section of the transect showing magnetic, gravity anomalies and seismic (reflection study) and velocity (refraction study) structure.

### Gravity

Free-air gravity anomalies along the transect vary from +20 to -75 mgal. A broad, 160-200 km wide gravity low, about -75 mgal amplitude is associated with lower slope region (Fig.3). A broad low amplitude gravity swell is observed over the abyssal plains. Two-dimensional crustal structure model studies of the free-air gravity anomalies are carried out using TALWANI (1973) method. The crustal model (Fig.4) consists of four layers of water, sediment, lower crust and upper crust, mantle with densities of 1.03, 2.4, 2.6, 2.9 and 3.37  $\text{g/cm}^3$  respectively. The lower boundary of sedimentary strata of 2.4  $\text{g/cm}^3$  is constrained from the seismic section of the present study. The Moho's boundary is computed (NAINI and TALWANI, 1982) and shown as mantle boundary (Fig.4). The boundary between lower crust and upper crust is taken as the average of the depths to the bottom of the sedimentary strata and crust-mantle boundary. This boundary is adjusted while modelling the gravity anomaly. The model reveals that the sediment thickness varies between 2 to 7-8 km. Maximum thickness of the order of 7 km at the landward end of the transect and shelf margin basin and minimum of 3 to 4 km within the continental rise and abyssal plains are estimated. A basement high (70 km wide) at about 3 km depth below the seafloor in the mid-slope region separates the thick sedimentary basins of the shelf and slope regions. A maximum 28 km thick crust below the outer shelf and a minimum about 10-12 km in the abyssal

plains are further deduced from the model studies. 2D isostatic gravity anomalies (Fig.4) are computed based on Airy's isostasy model. The subdued isostatic anomaly over the shelf edge (Fig.4) perhaps indicates that the observed free-air gravity anomaly at the shelf edge is not only due to shelf edge but also due to subsurface density variations at deeper depths.

### Magnetics

Total magnetic intensity anomaly profile (Fig.3) shows a minimum of -300 and a maximum of +200 nT. Some of the basement highs (Fig.2) are seen associated with magnetic anomalies. The observed anomalies are interpreted in terms of two-dimensional prismatic block models (TALWANI and HEIRTZLER, 1964) under constraints from seismic and gravity results. The upper and lower surfaces of the magnetized blocks assumed to coincide with the crustal layer (density  $2.6 \text{ g/cm}^3$ ) deduced from the gravity model. Varied densities  $2.6$  to  $3.3 \text{ g/cm}^3$  for the basalts are reported (SAZHINA and GRUSHINSKY, 1971). Further, the magnetic anomalies are considered to have been generated by basaltic rocks similar to that of Deccan Traps which possess one of the two dominant magnetization directions (i.e.,  $I=52^\circ$  and  $D=151^\circ$ ; and  $I=5^\circ$  and  $D=80^\circ$ ). From the best fit model (Fig.4) it was concluded that the basement is composed of juxtaposed magnetized and nonmagnetized blocks of varying degree of magnetization.

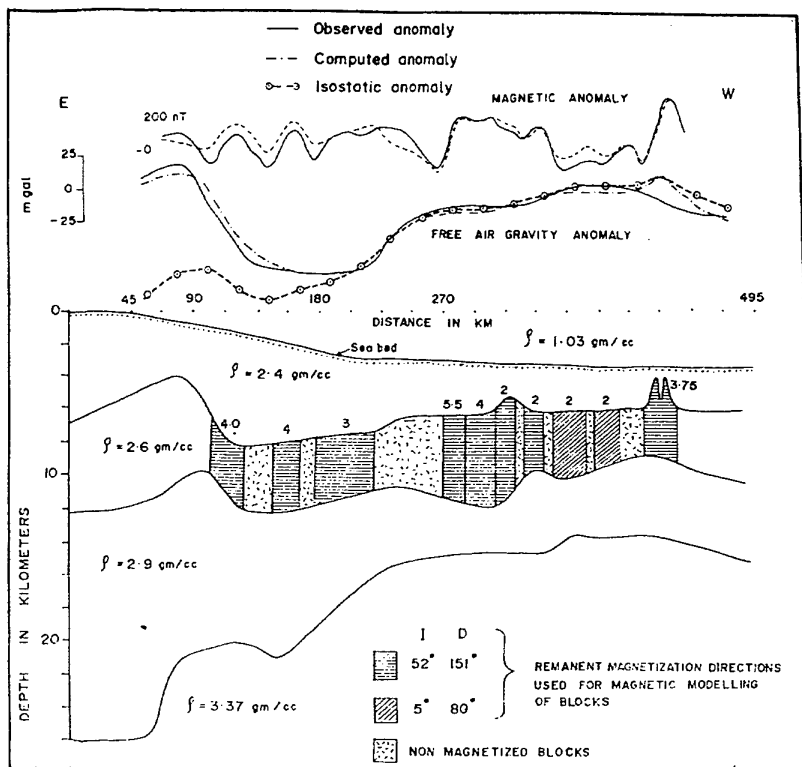


Fig. 4. Crustal model deduced from magnetic and gravity anomalies under constraints from seismic reflection results. Circled numbers denote intensity of remanent magnetization assigned to the block.

### Crustal structure and tectonics

The interpreted crustal structure model (Fig.4) revealed distinct structural configuration of the continental margin and abyssal plains separated by basement high in the slope region. The margin and plains are covered with 3-7 km thick sediments consisting of seven seismic sequences, H1 to H7 of definite seismic character and pattern. About 7-8 km thick sediments were interpreted by BABENKO *et al.* (1981) in the slope region off Bombay.

NAINI and KOLLA (1982) reported slumping of sediments off Kathiawar in the north where seafloor relief of the slope is about 5.0 s (TWT). The present study off Bombay which is situated far south of Kathiawar reveals relatively low order seafloor relief (3.0 s TWT) in the slope region. The abrupt truncated reflectors giving rise to the 'V' shaped troughs within the upper seismic sequence appears to be the resultant of recent tectonics and or high energy environment. The major order sliding/slumping processes are generally associated with the presence of asymmetric troughs contrary

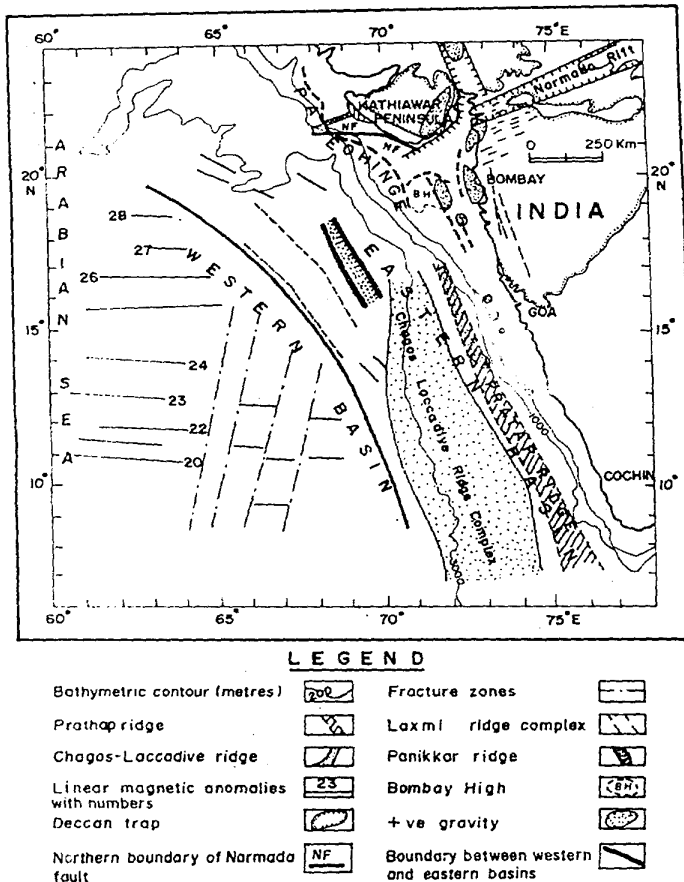


Fig. 5. Tectonic map of Western continental margin. The extent of Panikkar Ridge inferred from the present studies is shown.

to the presence of 'V' shaped troughs in this region (Fig.2). Hence, the observed continuous wavy reflections of the seismic sequence in the upper mid-slope region mark the absence of major sediment slumping. The comparatively less thick sediments on the continental rise, uneven seafloor and raised acoustic basement suggest the prevalence of active erosional processes. Further, the observed truncated reflectors and 'V' shaped troughs with deep cuts on the slope are the resultant of active erosional processes associated with contour currents (?).

In the abyssal plains, the centrally depressed basin like structure of basement and onlap of reflectors of sequences H6 and H7 and drape structure over the basement high in the middle clearly suggest that the folding in the basement occurred prior to sediment infill within the basin. This is followed by widespread sedimentation covering the entire area including the margin giving rise to seismic sequences, H4 to H6 (Fig.2). The absence of sequences H4 and H5 in the abyssal plains, occurrence of low order basement reliefs, deformed sediment sequences H6 to H4 of the continental rise and a fault limiting the westward continuity of seismic sequences H4 and H5, perhaps mark the stages of intrusion, faulting and erosion. Seismic sequences H1, H2 and H3 (about 1.2 s thick) lap onto the seismic sequences H4 and H5 on the continental rise in the east. This phenomenon of onlap indicates that the sediments are probably transported parallel to the margin off Bombay. Further, most of these sediments are riverine. Eastward migrated levee channels of the Indus river controlled by coriolis force in northern hemisphere and deposition of sediments along the western margin of India were reported by KOLLA and COUMES (1987). Thereby, the present study confirms that the Indus river sediments of relatively younger age are limited to the abyssal plains and unlikely extend to the slope region off Bombay. The estimated thickness of the sedimentary column (H1-H3) is around 1.45 km considering sediment velocity of 2.4 km/s. These sediments appear to be the Indus River input and the lens-shaped structures perhaps represent turbidites. Rates of sedimentation in deep waters are available only at DSDP sites 221 and 222 (WHITMARSH et al., 1974). The average sedimentation rate for Upper Miocene to Quaternary is around 300 m/My. Accepting this rate, the tentative age of 4-5 My is estimated to the lowermost reflector H3.

Being a rifted margin (BISWAS, 1982) and the occurrence of high amplitude broad wavelength magnetic anomalies (Fig. 4) in the abyssal plains suggest that the basement is generated by volcanic activity. The observed basement high, 20-25 km wide and rising to nearly 0.8-1.0 km and sheet drape structure of the overlying sediments help in understanding its development during the process of stretching and downwarping of the basement in the abyssal plains. This high is associated with 150-200 nT magnetic anomaly. A similar basement high associated with 250- 400 nT magnetic anomaly was identified further south by NAINI (1980) and NAINI and TALWANI (1982). We infer that these two features are genetically related. Thus, its northward extension is inferred for about 150 km (Fig.5) long in the abyssal plains parallel to the margin. The overall linear extension of this feature is around 360 km, with an average width of 20-45 km. For ease of reference, we propose to name this linear feature as Panikkar Ridge, after Dr.N.K.Panikkar, the former Director of the National Institute of Oceanography, Goa, India. The double peaked high (Fig.2) in the west appears to mark the eastern flank of the Laxmi Ridge. The interpreted crustal model (Fig.4) revealed 26-28 km thick crust below the shelf and 10-11 km in the abyssal plains. Such thinning is possible only in case of crustal stretching. Thinner Indian lithosphere (NEGI et al., 1986), shear-rifted (NAINI and TALWANI, 1982) and stretched crust (GOPALA RAO, 1990b; HOOPER, 1990) were suggested to account for the presence of varied crustal thickness on the western margin of India. The stretched crust as interpreted from the gravity, occurrence of intrusives (rift volcanism emplacement), the sediment loads and associated horizontal



compressions caused by spreading across Carlsberg Ridge are suggested for the development of basement highs/ridges, depression, horst and graben like features, faults and intrusives, and internal sedimentary structures

## CONCLUSIONS

The present integrated study reveals:

1. Absence of major slumping across the slope off Bombay.
2. The Indus river sediments confine only to the abyssal plains in the region.
3. The presence of various structural elements as a result of crustal thinning, rift emplacement volcanism, Carlsberg Ridge push, sediment loads and subsidence.
4. The linear feature extending in the NW-SE direction over a distance of 360 km termed "Panikkar Ridge" is the manifestation of above such processes.

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