

Evidence for seafloor spreading in the Laxmi Basin, northeastern Arabian Sea

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Abstract

Marine magnetic anomaly data from the Laxmi Basin for the first time reveal the presence of fairly correlatable NNW-trending magnetic lineations. These magnetic lineations are symmetric about a central negative magnetic anomaly and the axis of symmetry coincides with a characteristic short-wavelength free-air gravity low. The anomalies are interpreted as representing a two-limbed seafloor spreading sequence which can be equated to the A28–A33 interval of the geomagnetic polarity reversal timescale. These results suggest that the Laxmi Basin is underlain by an oceanic crust. Evidence of seafloor spreading in this basin possibly implies a pre-A27 spreading episode in the evolutionary history of the Arabian Sea.

1. Introduction

The northeastern Arabian Sea (Fig. 1a) is considered as being broadly divided into two crustal provinces [1,2]. The area between the western end of the Laxmi–Laccadive Ridges and the adjacent continental shelf of India is referred as the Eastern Arabian Basin (EAB), and the area westward of this region up to the Carlsberg Ridge as the Western Arabian Basin (WAB). The WAB is considered as being underlain by an oceanic crust, because it has a crustal structure similar to a normal oceanic crust and contains well recognizable magnetic lineations [1,2], whereas the geophysical studies carried out so far have not per-

mitted an unequivocal conclusion regarding the nature of the crust underlying the EAB. For example, some authors [1,2,3] believe that the crust under the EAB is a transitional type formed by the taphrogeny, while others [4] considered the crust here to be oceanic in nature. We believe that part of the EAB region is indeed underlain by oceanic crust, and to substantiate our contention some new geophysical data are presented in this paper.

2. Tectonic framework and previous studies

We identify the Laxmi Basin (Fig. 1b) as that part of the EAB that is bound in the west, south and east by the Laxmi Ridge, the northern extremity of the Chagos–Laccadive Ridge and the continental shelf of India respectively. We con-

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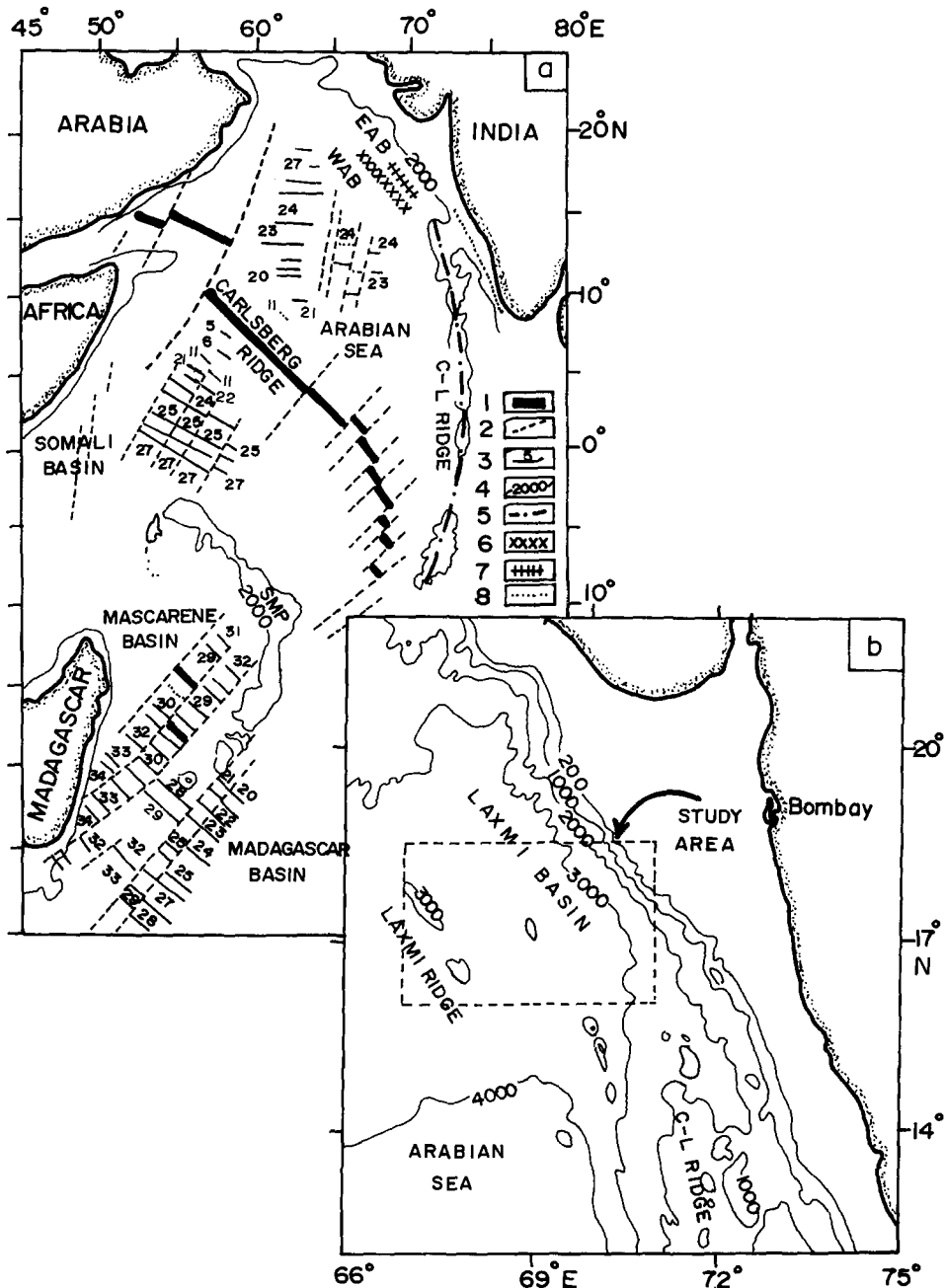


Fig. 1. (a) Generalised map of the Arabian Sea, showing magnetic lineations and main structural features (compiled from Naini and Talwani [2], Schlich [15] and Chaubey et al. [10]). 1 = Mid-ocean ridge crest; 2 = fracture zones; 3 = magnetic lineations; 4 = bathymetric contours (m); 5 = Chagos-Laccadive Ridge; 6 = Laxmi Ridge; 7 = basement high; 8 = Prathap Ridge; SMP = Seychelles-Mascarene Plateau; WAB = Western Arabian Basin; EAB = Eastern Arabian Basin. (b) Location of the study area and simplified bathymetry of the adjacent areas.

sidered that the northern boundary of this basin lies approximately along 21°N where the bathymetric contours abruptly change to a westerly trend. Our study area (Fig. 1b) covers a major part of this basin. The Laxmi and the Chagos–Laccadive Ridges, which are contiguous with our study area, are the most distinct bathymetric fea-

tures seawards farthest from the shelf edge of the western continental margin of India. These ridges are attributed to various processes, such as transform faulting, microcontinent tectonics and a hotspot trace ([1,2], and references therein). However, based on the inferred crustal structure, Naini and Talwani [2] favoured a continental

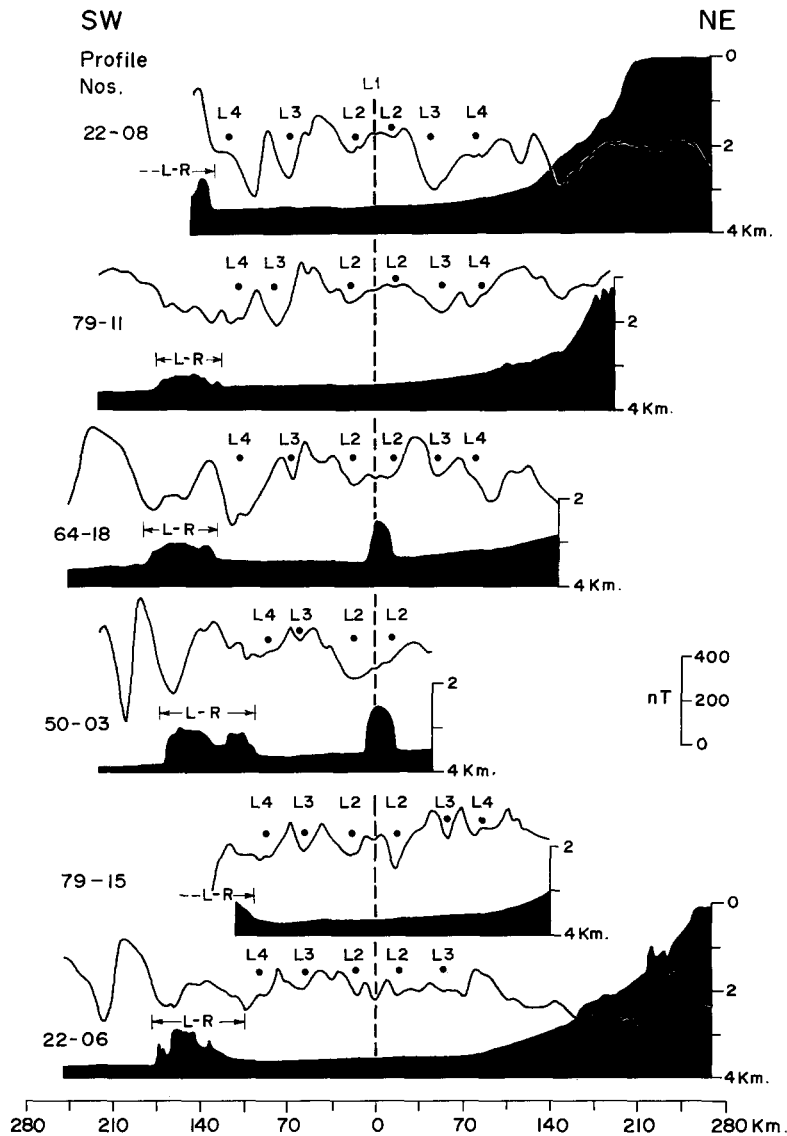


Fig. 2. Selected bathymetric and magnetic profiles projected at an azimuth of 060° and stacked with respect to the axis of the short-wavelength gravity low (heavy dashed line) discussed in the text. L1–L4 are the magnetic anomaly lineations inferred in the present study. L–R = Laxmi Ridge. Location of the profiles is shown in Fig. 5.

fragment origin for the Laxmi Ridge and the northern Chagos–Laccadive Ridge. The adjacent continental shelf is the widest part (about 350 km off Bombay) of the entire western continental shelf of India, where the bathymetric contours from the shelf edge to about 2000 m are relatively straight and trend approximately NW–SE. Approximately in the axial part of the Laxmi Basin there are several prominent isolated basement peaks, which were suspected to be part of a continuous basement feature [1]. Apart from these topographic highs, the seafloor within this basin in general shows a southwestward dip, and the depth gradually increases from about 3000 to 3750 m.

The gross crustal structure of the EAB as revealed by seismic refraction [1,2] indicates that ca. 2.4 km of sediment overlies a ca. 11 km thick crust. According to Naini [1], even though this crust is thicker than the average oceanic crust, the observed crustal layers are nevertheless comparable to the different oceanic crustal layers of recent models. In view of this, he opined that the velocity structure and thickness of the crustal layers of the EAB on their own do not rule out the possibility of an oceanic nature of this crust.

In the Laxmi Basin, Naini [1] further observed a low-amplitude (~ 20 mgal) short-wavelength

(~ 60 km) free-air gravity low superimposed on a long-wavelength (~ 350 km) gravity high. This gravity anomaly was found to be similar both in magnitude and in wavelength to that observed by Weissel and Watts [5] over an extinct spreading centre in the Coral Sea Basin. Naini therefore suspected that the basement structures associated with this gravity low might be representing an extinct spreading centre and the crust underlying the Laxmi Basin might be oceanic. However, he ruled out this inference because, in this area, he observed no seafloor spreading magnetic anomalies. He therefore concluded that the Laxmi Basin is underlain by a transitional crust formed during the initial phase of rifting.

3. Data

For the present study we have used part of the bathymetric, gravity and magnetic data collected during four cruises aboard the R.V. *Sagar Kanya* in 1986–1992. The positions along five of the profiles were provided with the GPS, and for the remaining three profiles (22-06, 22-07 and 50-03) an integrated navigation system (with a dual channel satellite receiver as the primary navigational aid) was used. The measured depth values

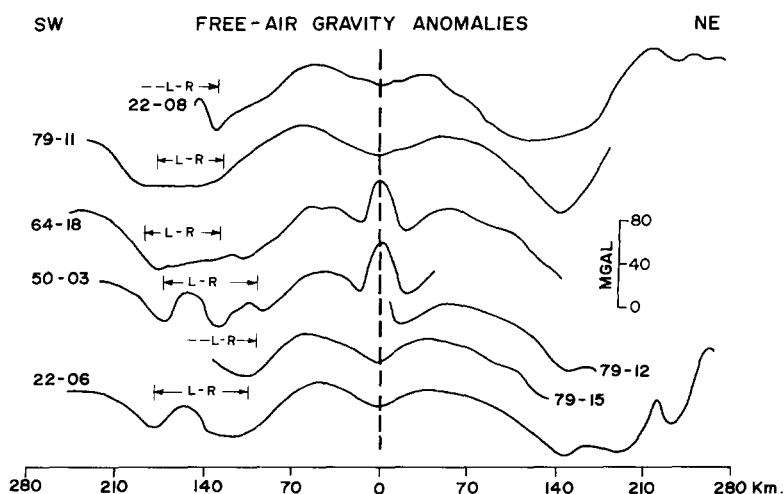


Fig. 3. Stacked free-air gravity anomaly profiles. Heavy dashed line represents axis of the gravity low. Location of the profiles is given in Fig. 5 and other details are as in Fig. 2.

were corrected for the variation of the sound velocity in seawater using Matthew's tables [6]. The residual magnetic anomalies were calculated by removing the International Geomagnetic Reference Field (IGRF) of the appropriate epochs. The gravity anomalies were obtained using the IGA 1967 international gravity formula. The bathymetric, gravity and magnetic data are presented as projected profiles (Figs. 2, 3 and 4) and the magnetic anomalies are also shown as profiles along the ship's tracks (Fig. 5).

4. Results and discussion

4.1. Bathymetry

Eastwards of the study area the bathymetric profiles depict a typical continental shelf and

slope configuration (Fig. 2). The prominent positive bathymetric feature observed on all the profiles towards their western end is the seafloor manifestation of the Laxmi Ridge. Bounded by relatively steep scarp faces, the outcrop of the Laxmi Ridge appears to be a continuous linear feature within the study area. The area between the Laxmi Ridge and the continental slope is relatively smooth. The only feature which is conspicuous within this apron is a seamount which was crossed by two profiles.

4.2. Gravity anomalies

All the profiles depict (Fig. 3) a prominent long-wavelength (~ 350 km) gravity high which spans the study area. However, the gravity anomaly on which we focus our attention is a short-wavelength (~ 70 km) free-air gravity low

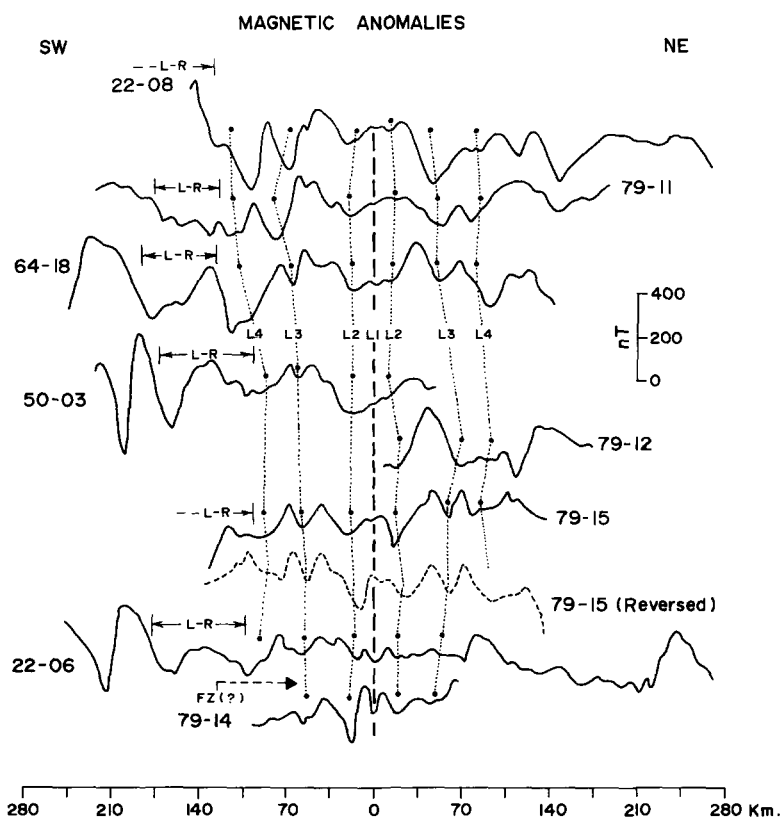


Fig. 4. Stacked magnetic anomaly profiles. Heavy dashed line represents axis of the gravity low and location of the axial magnetic anomaly lineation (L1). Light dotted lines represent other correlated magnetic lineations (L2–L4). Location of the profiles are given in Fig. 5 and other details are as in Fig. 2.

(amplitude of about 20 mGal) superimposed on this long-wavelength gravity high. The gravity low can be easily seen on all the profiles except 50-03 and 64-18. On these two profiles, the low appears to be partially masked by a short-wavelength gravity high that was obviously caused by the topographic effect of a seamount at this location (Fig. 2). It is therefore evident that this prominent short-wavelength gravity low is a continuous feature within the Laxmi Basin, and its trend is approximately NNW. We have used the axis of this short-wavelength gravity low to align our bathymetric and magnetic profiles.

4.3. Magnetic anomalies

We could discern a very interesting magnetic anomaly pattern in the Laxmi Basin. The sequence of positive and negative anomalies flanking either side of a negative axial anomaly displays symmetry about the axis. This symmetry is particularly apparent (Fig. 4) from profiles 79-15

and 79-15 (reversed). The anomaly pattern can be fairly well correlated between 79-15 and the profiles northwards, whereas southwards of profile 79-15 this correlation is tenuous. We believe this correlation (Fig. 5) indicates the presence of NNW (N30°W) trending magnetic lineations in the Laxmi Basin and tentatively number these lineations as L1 to L4, using the letter L for the Laxmi Basin. We further observe that the lineations are confined in the area between the Laxmi Ridge and the adjacent continental slope of India (Fig. 2).

We have attempted to determine the structure responsible for this anomaly pattern by constructing a magnetic block model based on the Vine–Matthews hypothesis [7]. We have assumed that the magnetic anomalies have their source in the upper 2 km of the crust below the sediment and have constrained the depth to the sediment–basement interface within the limits imposed by the published seismic results [1,2]. We computed simulated magnetic anomalies for different strikes

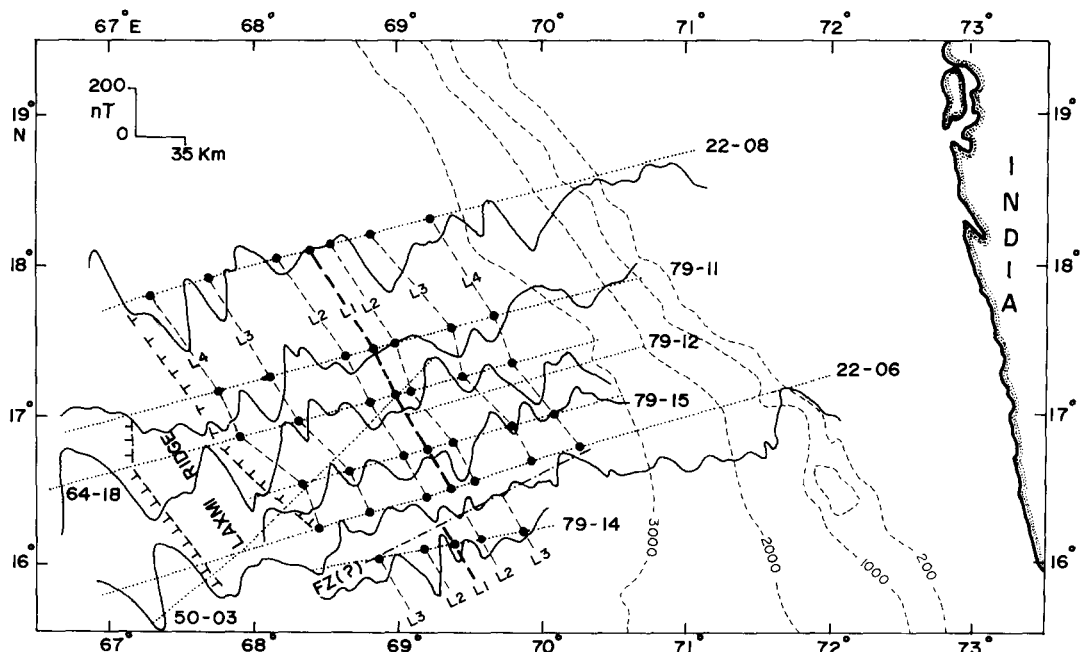


Fig. 5. Magnetic anomalies in the Laxmi Basin plotted perpendicular to ship's tracks. Dots joined by dashed lines represent correlated magnetic lineations (L2–L4). For clarity the anomalies along tracks 79-12 and 50-03 are not shown. Survey tracks and bathymetric contours (m) are shown with dotted and light dashed lines respectively. Heavy dashed line represents axis of the gravity low and location of the axial magnetic anomaly lineation (L1).

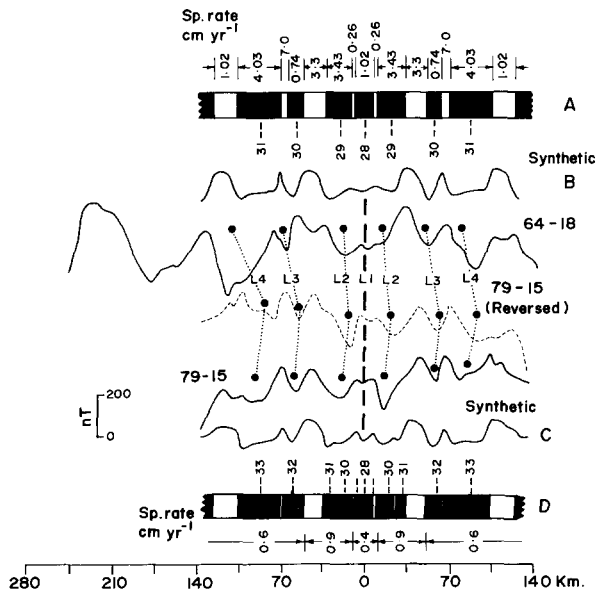


Fig. 6. Observed and simulated magnetic anomalies along selected profiles across the Laxmi Basin. The observed profiles are projected at an azimuth of 060° . The simulated profiles B and C were generated for seafloor spreading models A and D respectively. Synthetic magnetic profiles are computed for a ridge striking $N20^\circ W$ at a latitude of $19^\circ S$ and now observed at $17^\circ N$, $69^\circ E$. Magnetic anomaly identifications are according to the reversal timescale of Berggren et al. [13]. Normally magnetized blocks are indicated with black. Magnetized layer (susceptibility 0.005 cgs units) is flat, 2.0 km thick, and its top lies at 4.5 km below sea surface. Axis of gravity low and axis of symmetry of the magnetic anomalies is marked with a heavy dashed line. In simulated profile B each successive magnetic lineation is considered as representing the successive normal event of the reversal timescale, whereas in simulated profile C (made for a slow-spreading model) some of the magnetic lineations were considered as corresponding to the combined effect of several polarity reversals. Model D is our preferred model.

of the body and at different latitudes. After several trials, we achieved a good correlation (Fig. 6) between the simulated and observed anomalies when we assigned a 340° strike to the body and assumed the anomalies to have been generated in the southern hemisphere ($19^\circ S$). It may therefore be seen (Fig. 6) that the observed symmetric magnetic anomaly profile can be modelled by a magnetic source layer divided into juxtaposed normally and reversely magnetized blocks, where

the sequence of blocks is symmetrical about a central normally magnetized block. In our opinion, this symmetry and parallel nature of the magnetic lineations and the symmetric arrangement of the magnetized blocks of the crustal model suggest generation of the underlying crust by seafloor spreading. It may be mentioned here that the inferred crustal structure [1] discussed earlier did not altogether negate the possibility of an oceanic nature of the crust underlying the Laxmi Basin. We therefore consider that the magnetic lineations identified in this study thus provide additional evidence to suggest that the Laxmi Basin is underlain by oceanic crust. As we will show later, we have identified the central normally magnetized block as corresponding to anomaly 28 (65 Ma, early Paleocene) of the geomagnetic polarity reversal timescale and according to the reconstruction model [8] for this period our study area was in the southern hemisphere. Therefore we feel our inference regarding the emplacement of this oceanic crust (Laxmi Basin) in the southern hemisphere is quite reasonable.

The geophysical studies carried out so far suggest a two-episode spreading history of the Arabian Sea. Commencing at A27, the older phase ended at A21 and spreading of the younger phase started shortly before the formation of A11. In the intervening period (i.e., between A21 and A11) spreading in the Arabian Sea is considered to have either completely ceased or reduced to an imperceptible level [2,9,10]. In the northeastern Arabian Sea, a well-developed A27 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. In view of this, we believe that spreading in the Laxmi Basin pre-dates A27. Further, the strike of the post-A27 (i.e., A27–A21) anomalies is approximately E–W (Fig. 1a), whereas the lineations within the Laxmi Basin trend NNW–SSE (Fig. 5). This noticeable change in the trends of the pre-A27 anomalies of the Laxmi Basin and post-A27 anomalies of the adjacent WAB perhaps suggests reorganization of the spreading centres during the intervening period. We therefore feel it necessary to invoke a third episode

(pre-A27) of spreading of the Arabian Sea to explain the spreading in the Laxmi Basin.

Possibility of the existence of pre-A27 oceanic crust in the northeastern Arabian Sea was also indicated by several earlier studies. Scotese et al. [11], in their continental reconstruction model, have inferred a piece of late Cretaceous (A29–A34) oceanic crust in this area. Norton and Sclater [8], in their anomaly 28 time reconstruction model, place the spreading centre north of and immediate adjacent to the Seychelles, thereby showing a large gap of crust in the northern Arabian Sea of unexplained origin. Masson [12] 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-A28 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. These inferences, we believe, lend further support to our proposition that the Laxmi Basin represents a part of the pre-A27 oceanic crust in the northeastern Arabian Sea, and therefore we assume this age limit for the purpose of identification of the observed magnetic lineations.

The magnetic anomaly sequence in the Laxmi Basin is short, and therefore could not be easily compared with the magnetic reversal timescale. Therefore, on their own the magnetic anomalies do not provide any indication about their age. As a starting point we therefore considered block model A (Fig. 6) assuming that the central normal block represents A28 and that the subsequent normal blocks of the model represent the subsequent normal polarity events of the geomagnetic polarity reversal timescale of Berggren et al. [13]. We observed that under these assumptions the lineations L1, L2, L3 and L4 correspond to A28, A29, A30 and A31 respectively. Further,

this model requires assignment of different spreading rates (varying from 0.26 to 7.0 cm yr⁻¹) to almost each individual block. In the second model (model D of Fig. 6) we have assumed slower spreading rates. Further, following the argument of Cande and Mutter [14] we considered that at slower rates each observed anomaly may correspond to the combined effect of several polarity reversals. This second model suggests the lineations L1, L2, L3 and L4 correspond to A28, A30–A31, A32 and A33 respectively. We favour the second model, for the following reasons: Firstly, in this model the spreading rates (< 1.0 cm yr⁻¹) do not vary widely. Secondly, the ages bounding the interval of spreading in the Laxmi Basin agree with the time of the other established pre-A27 spreading events in the Mascarene and Madagascar Basins [15].

4.4. Gravity low and extinct spreading centre

Linear gravity lows are associated with several confidently identified extinct spreading centres in other oceanic areas, such as the Labrador Sea [16,17], Norway Basin [18], Coral Sea Basin [5] and Baffin Bay [19]. As mentioned earlier, the possibility of association of the Laxmi Basin gravity low with an extinct spreading centre was ruled out by Naini [1], because he did not observe any definite magnetic anomaly pattern.

We have now shown that magnetic lineations resembling a two-limbed seafloor spreading are present in the Laxmi Basin. We have also shown that the gravity low has the same trend as that of the magnetic lineations, and the axis of symmetry of the magnetic anomalies coincides with the axis of the gravity low. This coincidence definitely suggests that these features are genetically inter-related. As mentioned earlier, several isolated basement peaks are also associated with the gravity low. All these characteristics appear to be similar to those seen over the extinct spreading centres delineated in other oceanic areas. We therefore believe that the gravity low marks the site of the extinct spreading centre in the Laxmi Basin.

Discussion about the origin of this gravity low is beyond the scope of this paper. However, we

would just like to mention two recent studies which dealt with this subject: Jonas et al. [20] are of the opinion that the presence of a solid low-density body at shallow mantle depths beneath the axis best explains the observed gravity anomaly field over extinct mid-ocean ridges. Osler and Loudon [21] reported the results of OBS refraction studies at and near the extinct axis in the Labrador Sea and observed lower than normal P-wave velocities for the crust as well as the upper mantle layers. However, according to Osler and Loudon no evidence exists for a deep root zone underlying the accretionary axis. The Laxmi Basin extinct axis may provide another candidate site for a detailed seismic refraction experiment to understand the crustal structure underlying an extinct accretionary axis.

5. Summary and conclusions

We have presented evidence that fairly well correlated NNW-trending magnetic anomalies resembling a two-limbed seafloor spreading sequence are present in the Laxmi Basin. These magnetic lineations are contiguous and parallel to the adjacent segment of the Laxmi Ridge in the west and the continental shelf edge in the east (Figs. 2 and 5). Based on these observations we conclude that the Laxmi Basin (a part of the EAB) is underlain by oceanic crust.

We tentatively identify these lineations as an A28 to A33 sequence of the geomagnetic polarity reversal timescale [13]. Based on these identifications we propose that (1) the opening of the Laxmi Basin commenced shortly before A33 (around 84 Ma, Late Cretaceous) along a spreading centre parallel to the present-day shelf edge, (2) the spreading continued at a very low rate and finally ceased around 65 Ma (early Paleocene) when the spreading centre jumped west of the Laxmi Ridge, and (3) the evidence of seafloor spreading in the Laxmi Basin implies the existence of a third episode of spreading (pre-A27) in the history of the evolution of the Arabian Sea.

Our inferred extinct spreading centre in the Laxmi Basin is associated with a characteristic free-air short-wavelength gravity low. The bathy-

metric profiles show a seamount (Fig. 2) to be associated with the axis of this gravity low. On the other profiles the seafloor exhibits a smooth topography along the same axis. We therefore could not locate the extinct spreading centre on the basis of basement morphology. This seamount is possibly a seafloor manifestation of the remains of the extinct spreading axis; in other places it is buried under sediment.

We have mentioned earlier that south of profile 79-15 the correlation of the magnetic lineations is difficult. However, we feel that the correlation can be extended also to profile 79-14 if we consider the presence of a fracture zone between profiles 79-14 and 22-06 (Figs. 4 and 5). Similarly, the magnetic lineations appear to continue northwards beyond the edge of our study area. We therefore believe that the oceanic crust identified in this study may extend both north and south of our study area, although confirmation must await additional surveying.

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