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Identification and origin of a subsurface ridge on the continental margin of western India

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Abstract

Gravity and magnetic studies in the eastern Arabian Sea reveal the presence of subsurface and exposed ridges on and beyond the continental shelf of western India. Distinct patterns of geophysical anomalies are associated with the ridges and also reveal the presence of magnetic polarity reversals. The portions of negative and positive magnetic anomalies of the ridges indicate that the northern part was formed in normal polarity time and the southern part in reversed polarity time. The boundary line of magnetic polarity reversals is marked along 15°10'N. Further it is conjectured that these ridges probably originated because of the movement of the Indian Plate over the Reunion hotspot, during the Late Cretaceous and Early Tertiary.

1. Introduction

It is widely accepted that (1) the Indian Plate separated from the eastern Gondwanaland during the Cretaceous, and (2) the eastern Arabian Sea came into existence through a process of rifting between the Mascarene Plateau and the Indian subcontinent followed by seafloor spreading after magnetic anomaly 28, i.e., the early Paleocene (Naini and Talwani, 1982; Gopala Rao, 1991). Backman et al. (1987) suggested the Deccan Traps (67–68 Ma) of the western India, the Chagos–Laccadive Ridge system and the Mascarene Plateau (Fig. 1) as volcanic constructs laid by the Reunion hotspot on a rapidly northward moving Indian Plate.

The transitional crust (transitional between continental and oceanic crust) with a thickness of approximately 17 km along the western margin of India contains regional subsurface features often

with subtle surficial expressions paralleling the shelf edge and sediment filled basins. Numerous structural highs, a few square kilometers to as large as about 120 km², were reported on the shelf and majority of them occur in the midshelf (at water depths of 50–120 m). They are associated with appreciable geophysical signatures and are clearly seen in seismic results. The structural lineaments developed in the eastern Arabian Sea result from either or both the geological processes [(1) at the initial time of breakup of India from Gondwanaland, (2) volcanism due to passage of a Reunion hotspot on a rifted Indian margin].

Previous geophysical studies in the eastern Arabian Sea (Fig. 1) have evidenced the existence of exposed/submerged ridges, which are associated with complex geophysical signatures (Harbison and Bassinger, 1973; Ramaswamy and Rao, 1980; Naini and Talwani, 1982; Subrahmanyam et al., 1989; Kolla and Coumes, 1990; Subrahmanyam

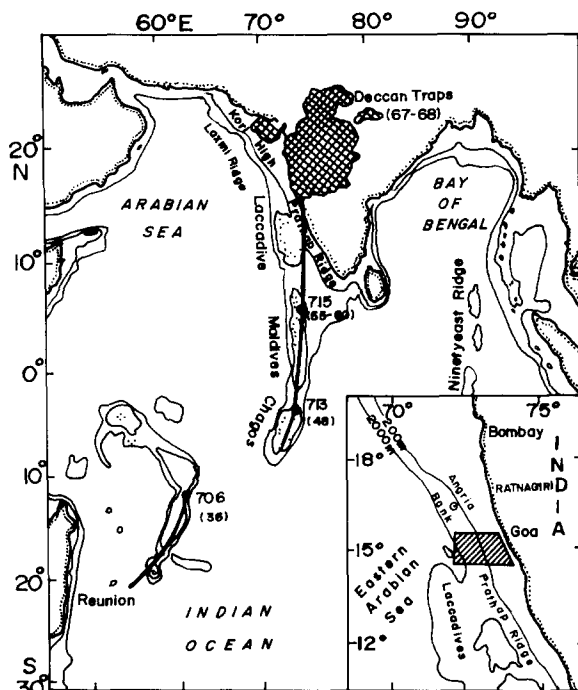


Fig. 1. Structural features of the Arabian sea (Naini and Talwani, 1982). Bathymetric contour (200 and 2000 m) and location of study area (single line hatch) are shown in inset map. The trail of volcanic ridges and islands left by the Reunion plume shown by a thick line. The ages (Ma) of volcanic activity along the Reunion hotspot track decreases to the south from Deccan Traps to ODP Sites 715, 713 and 706 (dots) (Courtillet et al., 1986; Backman et al., 1987). Major bathymetric features of the north Indian Ocean are shown by 2 and 4 km depth contours.

et al., 1991). The above authors have considered them as basement ridges of Precambrian (continental) origin because of rifting and/or upthrust tectonics. Nevertheless, we believe that a thorough investigation to single out their possible mode of origin is warranted.

The present study identifies the presence of a subsurface ridge on the margin. The associated magnetic and gravity signatures permit us to discuss its nature and possible origin.

2. Offshore geophysical data

The total magnetic intensity (1125 km) and gravity (630 km) data, together with bathymetry

(1125 km) were collected onboard ORV *Sagar Kanya* and RV *Gaveshani* along 7 E–W profiles with one N–S profile covering an area between 14°30' and 15°30'N, and 72° and 74°E. A satellite receiver (MX 1107) was used for positioning during the survey. Magnetic anomalies were computed by subtracting the diurnal variation as observed at Colaba Observatory, Bombay and the International Geomagnetic Reference Field (DGRF) (IAGA division, working group 1, 1986). The gravity data were acquired with reference to the observed and absolute values of the Marmagao Harbour base (Goa), which was established with reference base system IGSN-71. Then free-air gravity anomalies were calculated by applying the Eotvos correction and normal gravity (with reference ellipsoid GRS 67) at the observation positions.

Stacked anomaly maps and contour maps of bathymetry at 50 to 100 m interval, total magnetic intensity anomaly at 50 nT interval and free-air gravity anomaly at 5 mGal interval are presented in Figs. 2–5.

3. Results

The seafloor topography of the study area is lying between 40 and 2000 m water depth (Fig. 2). The topography exhibits two topographic highs, which are 400 and 1100 m from the surrounding water depth of 2000 m. These highs, with a trend in the NW–SE direction mark the northern extension of the Prathap Ridge complex.

The geophysical anomalies exhibit the same trend as the bathymetric highs (Fig. 3). Short wave-length (10–25 km) magnetic anomalies occur up to the shelf break (200 m water depth), and the long wave-length (around 45 km) anomalies extend beyond the shelf break (Figs. 3 and 4).

Two significant magnetic anomalies, a magnetic low (ML) of 350 nT on the shelf and a magnetic high (MH) of 350 nT beyond the shelf are distinctly seen. A positive free-air gravity high (GH) reaching more than 20 mGal on the shelf and a relative gravity high (RGH) of more than –15 mGal beyond the shelf are observed (Fig. 5). The magnetic high (MH) and a relative gravity high

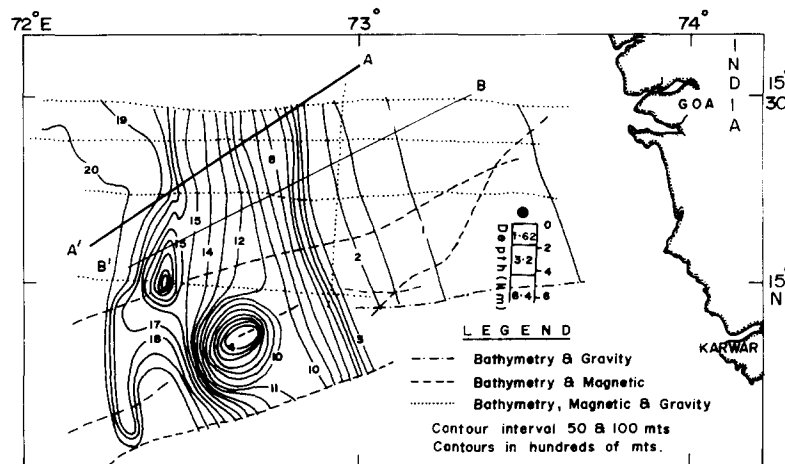


Fig. 2. Ship tracks and the bathymetric contours of the study area. Seismic reflection data along a solid line ($A-A'$) are shown in Fig. 6. A profile ($B-B'$) is used for model studies shown in Fig. 8. The dot indicates the location of seismic refraction station (85C17) with crustal column (Naini, 1980). Velocities are in kilometers per second.

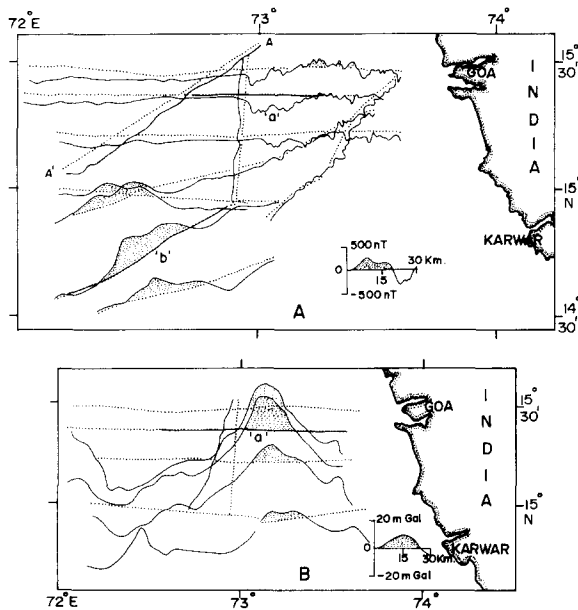


Fig. 3. Geophysical anomaly profiles plotted at right angles to the ship tracks. The positive anomalies have been marked with dots. (A) Magnetic map; (B) gravity map. The anomalies (a' and b') along continuous lines are modelled and shown in Fig. 7.

(RGH) are together associated with a topographic high beyond the shelf. On the shelf the magnetic low (ML) and the gravity high (GH) occur over smooth bathymetry.

4. Magnetic and gravity modeling

The magnetic and gravity anomalies along profiles 'a', 'b' and $B-B'$ (Figs. 2 and 3) are analysed by Werner Deconvolution, Marquardt's inversion and 2-D forward modeling methods suggested by Ku and Sharp (1983), Talwani et al. (1959) and Talwani and Heirtzler (1964). Seismic reflection results (Gopala Rao et al., 1987) in the study area indicated that the acoustic basement is in the shape of submerged ridges (Fig. 6). To the south, this submerged ridge (Prathap Ridge Complex) is exposed at the seafloor (Fig. 2). This linear feature contains variable magnetic characteristics (Fig. 4). The exposed portion of the ridge shows the positive magnetic signature, whereas the submerged portion shows the negative signature. This observation has prompted us to consider the normal magnetic polarity for magnetic low and reversed polarity for magnetic high.

Werner Deconvolution and Marquardt's inversion are applied for magnetic anomalies to obtain the initial estimation of the depth to basement and crustal magnetization. Werner solutions from the horizontal gradient of the anomaly ($\delta x = 1$ km and $\text{NOPR} = \text{varied from } 2 \text{ to } 5$) indicate thick interface bodies (Fig. 7), which are much wider than the depth to source bodies. We assumed the bottom edges of the basement at 12 km since the Werner

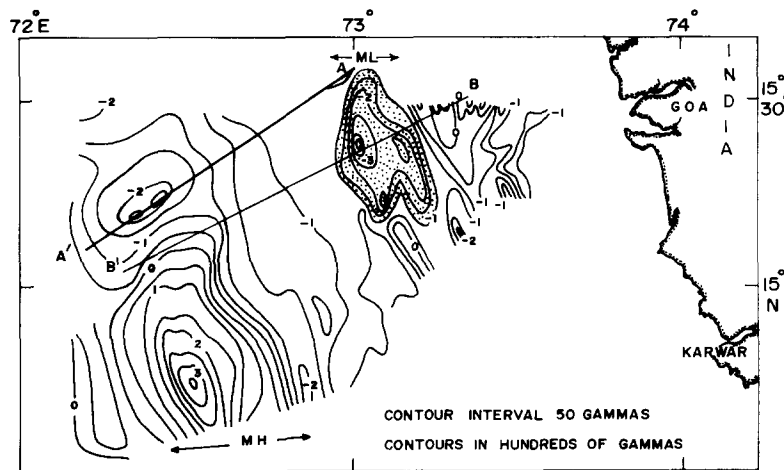


Fig. 4. Total field magnetic anomaly contour map. The thin line is the location of interpreted profile ($B-B'$) used in Fig. 8. $A-A'$ is the SCS line. ML =magnetic low (stippled area); MH =magnetic high.

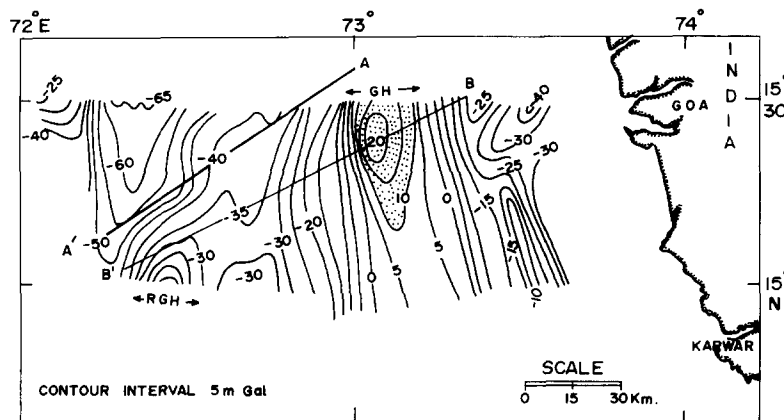


Fig. 5. Free-air gravity anomaly contour map. The thin line is the location of interpreted profile ($B-B'$) used in Fig. 8. $A-A'$ is the SCS line. GH =gravity high (stippled area); RGH =relative gravity high.

method could not provide this information. Werner horizontal gradient solution provides initial estimation of depth to basement (3.45 km for anomaly 'a', 2.0 km for anomaly 'b'), geometry of the source body and crustal magnetization (about 1.9 A/m for anomaly 'a', 1.7 A/m for anomaly 'b'). Marquardt's inversion was applied for the refinement of initial estimate parameters, which are used for 2-D magnetic forward model studies. Beside these initial estimates, we have considered mixed magnetic polarities and paleo-magnetic results of the Deccan Traps of western India

(Athavale, 1970) for 2-D magnetic studies. This method determines the depth to basement 3.5 km for anomaly 'a' and 1.7 km for anomaly 'b' (Fig. 7). The source body for anomaly 'b' is much shallower and its expression was seen on the seafloor as a rise.

We now present a model for gravity and magnetic anomalies along a selected NE–SW profile ($B-B'$). The main reason for selection of this NE–SW profile is that to cross (to the possible extent where gravity and magnetic data available) both the observed geophysical features. Seismic

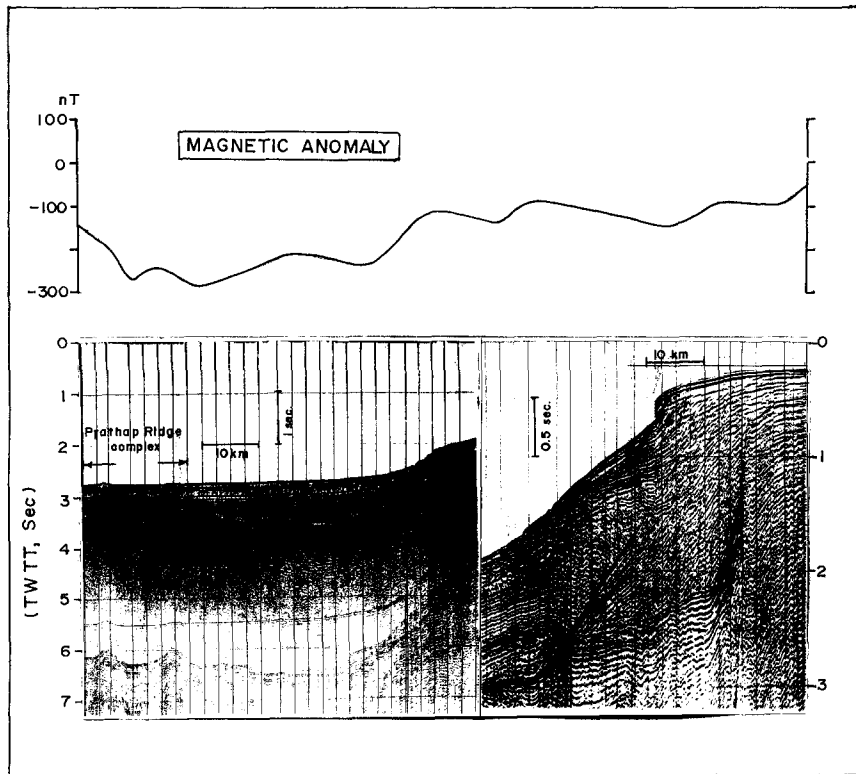


Fig. 6. Seismic reflection record along a line (A–A') parallel (about 15 km away) to model profile (B–B') shows the presence of submerged ridge beyond the shelf (after Gopala Rao et al., 1987).

reflection (Fig. 6) and refraction (Naini, 1980) results near the study area and Moho depth values calculated by the equation suggested by Naini and Talwani (1982) were considered for the determination of the depth to the interfaces and densities of the individual layers and structural highs. The computed geological structural model is shown in Fig. 8. The gravity and magnetic anomalies computed from the model match most of the observed anomalies and are compatible with the seismic results.

The two significant gravity and magnetic anomalies indicate the presence of structural highs or dense intrusions on and beyond the shelf, whose density and magnetization contrasts are relatively high. Two structural highs/intrusive bodies, interpreted through model studies, rise to about 3.75 and 3.0 km above the adjacent basement on and beyond the shelf, respectively. The width of the rises ranges from 30 to 35 km. The intrusive body,

under the shelf, is not seen in the seismic record (Fig. 6) because of its great depth. About 4 km thick sediments underlain by granite rocks of about 2.5 km thickness are interpreted between the two structural highs/intrusive bodies.

5. Comparison with other ridge systems of the western margin of India

Bathymetry and gravity and magnetic anomalies associated with exposed/submerged structural highs/ridges, in general, trend in a NW–SE direction and are parallel to the present day western margin of India. The Prathap Ridge complex (Fig. 1), a positive bathymetric feature, is associated with a relative positive free-air gravity anomaly and a positive magnetic anomaly in the study area. But the entire ridge is of variable magnetic nature and genetically comparable to the similarly

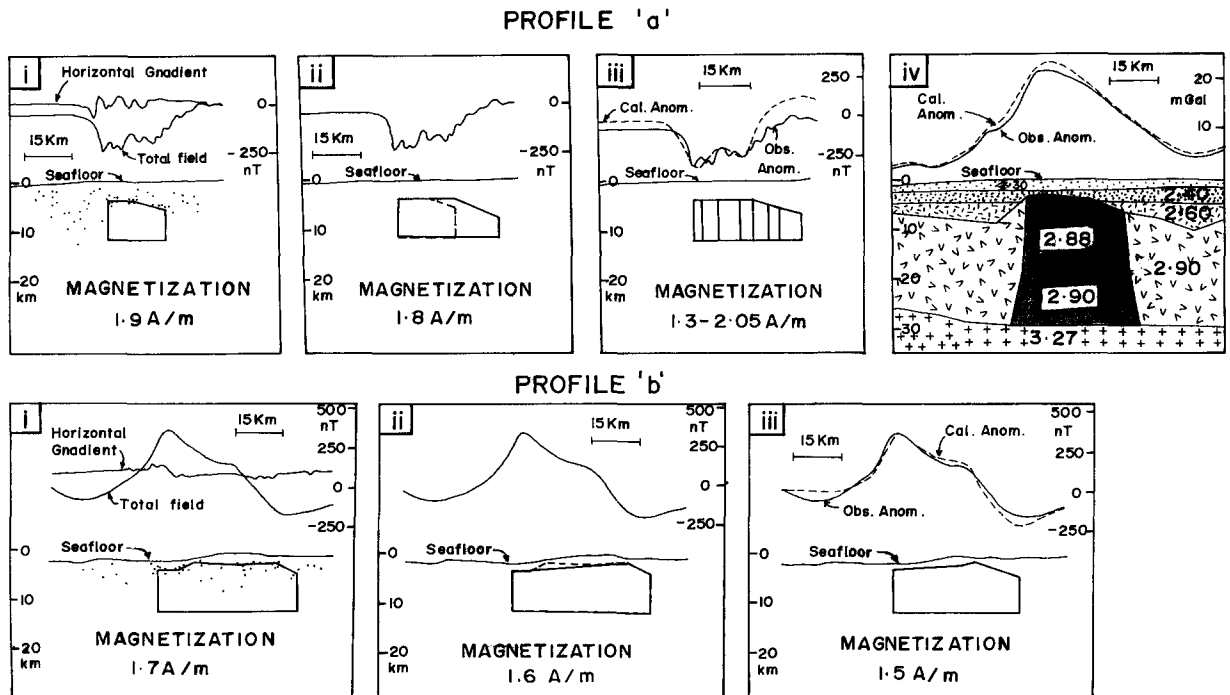


Fig. 7. (i) Werner Deconvolution, (ii) Marquardt's refinement and (iii) 2-D magnetic forward model of magnetic anomalies and (iv) 2-D gravity forward model of gravity anomaly. Symbols used in gravity model and parameters used in magnetic forward models are mentioned in Fig. 8.

variable magnetic nature of the Chagos–Laccadive Ridge system and the Ninetyeast Ridge. The ridge may be a part of the Chagos–Laccadive Ridge system and formed due to the Reunion hotspot activity (Krishna et al., 1992).

The positive gravity (GH) and negative magnetic (ML) anomalies (stippled areas in Figs. 4 and 5) on the shelf area are remarkable. We assume that these anomalies are due to a common structural source, although this is not exposed bathymetrically. Support for this belief comes from the refraction results of Naini (1980) on the shelf. Seismic refraction station (85C17) on the shelf of Goa (Fig. 2) indicates an uplift basement/structural high, of compressional wave velocity 6.4 km/s, at a depth of 4.5 km. This structural high appears to rise to about 3 km above the surrounding basement at 7 km. Based on these refraction results, we interpret the gravity high (GH) and magnetic low (ML) as a subsurface structural high, which is slightly shallower than the high located at the nearby refraction station.

To assess the regional extent of this structural high on the shelf, we have examined the results of the present study with earlier results [Subrahmanyam et al., 1989 (fig. 4); 1991 (figs. 4 and 5), NIO Technical Report, 1987 (fig. 3a)]. A belt of gravity highs and magnetic low/high closures extends from 13°30'N to 16°30'N. The gravity high which is interpreted as a structural high has a variable amplitude. Magnetic signatures over this feature are variable and similar to the Prathap Ridge complex. The occurrence of negative magnetic anomalies in the north of Goa and positive anomalies in the south of Goa is noticed. The change of reversals is distinctly seen on either side of a line parallel to 15°10'N. The gravity highs and magnetic lows/highs are together associated with a chain of structural highs and suggests a continuous subsurface ridge. This newly identified subsurface ridge appears to meet the Prathap Ridge at the place of Angria Bank, a submerged island near Ratnagiri coast and continues further north probably as a single feature. A small zone

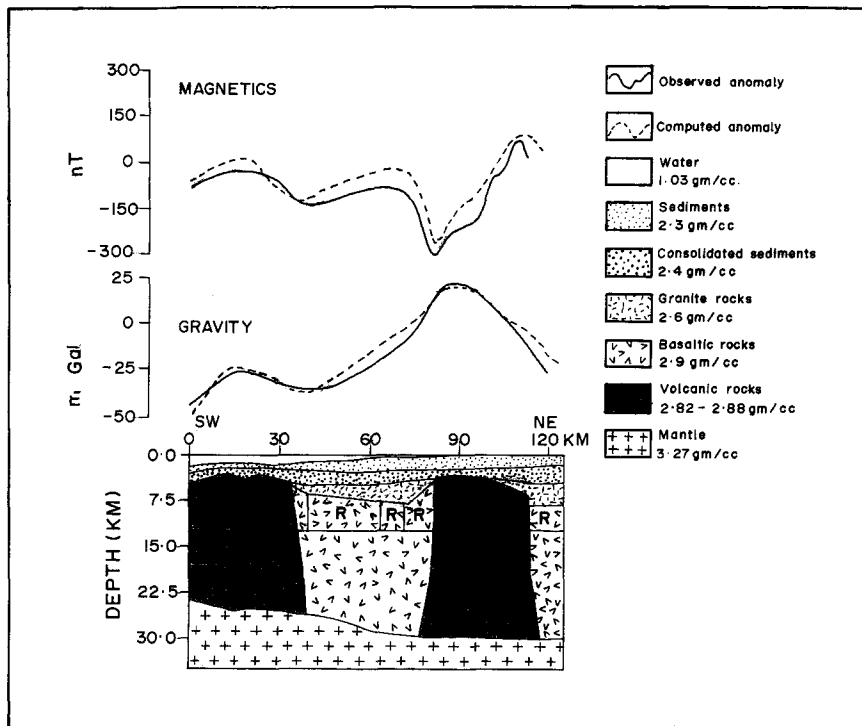


Fig. 8. Two-dimensional gravity and magnetic model of the crust along the profile (B–B') shown in Figs. 2, 4 and 5. Boundaries and types of magnetization (N-normal, R-reversal) for magnetic bodies are shown in the basaltic rocks layer and volcanic intrusions. Parameters used for anomaly computations are: densities = 1.03–3.27 g/cm³, total magnetic field 40250 nT, profile direction = 65° and remnant magnetization = 0.4–2.50 A/m. For reversal magnetic field, inclination = +50° and declination = +130°. For normal magnetic field, inclination = –50° and declination = +310°.

of gravity low between the Prathap Ridge complex and the new subsurface ridge indicates the presence of a thick sedimentary column.

The variable magnetic signatures of the subsurface ridge (alternative bands of positive and negative anomalies along the feature) suggest its construction during different magnetization periods. Also this magnetic study indicates that the ridge may have originated during a certain period of time, i.e. the time equivalent to at least two or more reversals. This observation rules out the possibility of formation of the ridge during the breakup of India from Gondwanaland and favors the possibility due to a hot plume volcanism on a rifted Indian margin. The exploratory well (R-2-1) drilled on the Angria Bank, which is at north of study area, indicated the presence of basic lava flows, corresponding to Deccan Traps (Ramaswamy and Rao, 1980). These results sup-

port the interpretation of volcanic origin for the identified ridge. As the location of the ridge closely follows the track of the Reunion hotspot, we link the formation of the ridge to Reunion hotspot volcanism. The radiometric studies of Deccan flood basalts (Courillot et al., 1986, 1988; Duncan and Pylee, 1988) and biostratigraphic ages of the oldest sediments at ODP Sites 715, 713 and 706 (Backman et al., 1987) indirectly assign that the ridge probably originated during the Late Cretaceous and Early Tertiary.

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