

Structural lineaments from the magnetic anomaly maps of the eastern continental margin of India (ECMI) and NW Bengal Fan

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ABSTRACT

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Three major structural lineaments are inferred from the magnetic and bathymetry data collected over the eastern continental margin of India (ECMI) and NW Bengal Fan, covering the area between 10°55'N to 20°15'N and 80°E to 88°E. Analysis of magnetic data associated with these trends suggests that (1) trend I, located at the foot of the continental slope (around 3000 m water depth) represents the ocean–continent boundary (OCB) of ECMI, (2) trend II represents the northern extension of 85°E ridge, abutting the continental shelf off Chilka Lake and (3) trend III, located over the continental shelf/slope between Visakhapatnam and Paradip represents a folded (ridges and depressions) nature of the continental basement.

The study also reveals the occurrence of dyke intrusions within the continental crust landward of OCB, which might be related to the rift-phase volcanism along the ECMI.

Introduction

Earlier geophysical studies over the eastern continental margin of India (ECMI) and Bengal Fan were based on magnetic, gravity and seismic reflection and refraction data collected during expeditions of Scripps Institution of Oceanography, SIO, (Curry and Moore, 1971; Moore et al., 1974; Curry et al., 1982, etc). Curry et al. (1982) presented a detailed study of the structure, tectonics and geological history of the northeastern Indian Ocean. During 1985–1987, the Regional Centre of the National Institute of Oceanography (NIO), Visakhapatnam, India has carried out geophysical studies related mainly to the nearshore structure and mineralization of the eastern continental shelf (Rao and Murthy 1980; Rao et al., 1980, 1985; Murthy et al., 1987a,b,c). Subsequently, Rao and Rao (1985, 1986) reported some major structural features of the Bay of Bengal

from the geophysical data along four widely spaced profiles collected during the SIO expeditions (Curry et al., 1982). Murthy et al. (1987b), Murthy (1989) and Murthy and Rao (1990) studied the subsurface stratigraphy of the upper continental shelf from Ongole to Paradip (14°30'N–20°15'N) and delineated two major depositional unconformities within the late Quaternary sediments. Since 1985, geophysical data comprising of bathymetric, magnetic and shallow seismic were collected over the ECMI and NW Bengal Fan along closely spaced profiles (Fig. 1). In this paper, some major structural lineaments from the bathymetry and magnetic anomaly maps are described and probable nature and origin of these lineaments are discussed.

Data collection

Geophysical data presented in this paper were collected on board the Indian research vessels

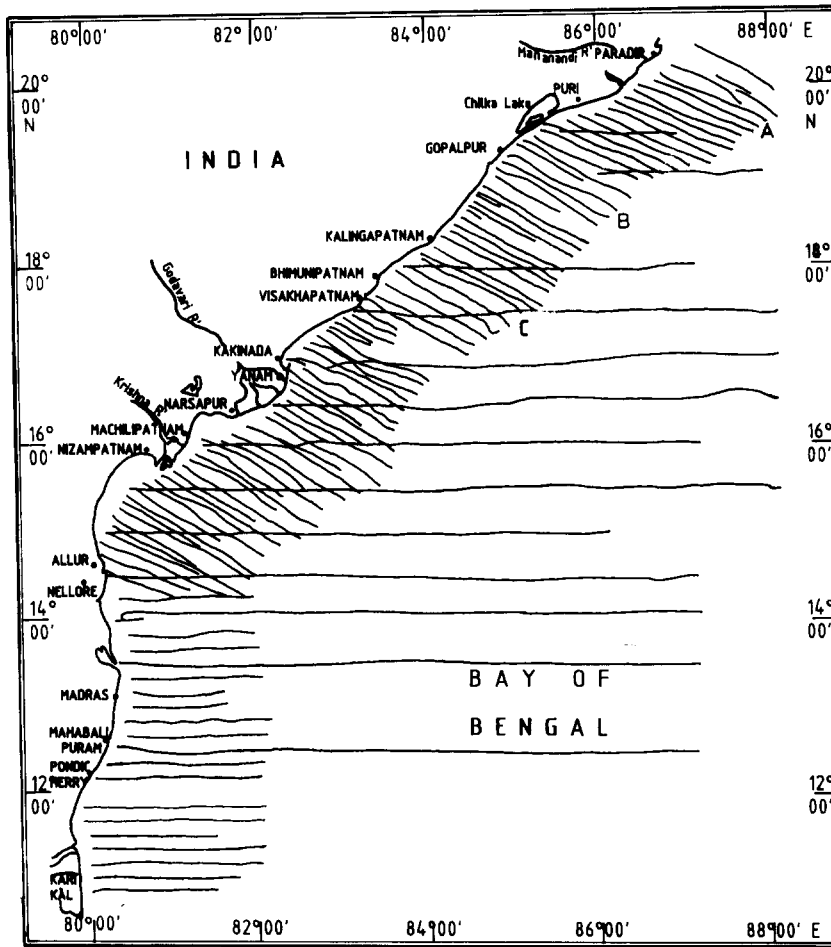


Fig. 1. Cruise track map of ECMI and NW Bengal Fan (A, B and C are locations of profiles in Fig 9).

Gaveshani, *Sagar Kanya* and *Nand Rachit* during the period 1983–1990. Over the ECMI, magnetic, bathymetry and shallow seismic (Sparker) data were collected at about 10 km profile spacing between $20^{\circ}15'N$ and $14^{\circ}30'N$, while bathymetric, magnetic and some gravity data were collected between $14^{\circ}30'N$ and $10^{\circ}55'N$, at about 20 km profile spacing (Fig. 1). In the deep-sea Bengal Fan (between $12^{\circ}30'N$ and $20^{\circ}N$, $80^{\circ}E$ to $88^{\circ}E$) magnetic and some gravity data were collected along profiles separated by 0.5° (54 km), with each profile extending from coast upto about $87^{\circ}E$ (Fig. 1)

Bathymetry and total field magnetic data thus collected over the ECMI and NW Bengal Fan were compiled and processed. The magnetic data were corrected for the variation in the regional

field (IGRF) and the residual anomalies were obtained. Bathymetry and magnetic anomaly contour maps are generated using the GMS software package of GECO, A.S., Norway.

Results

Bathymetry

The depth contours of the eastern continental margin (Fig. 2) nearly follow a N–S trend in the southern part between Karaikal ($10^{\circ}55'N$) and Nellore ($14^{\circ}30'N$) from where they take a NE–SW trend upto Paradip ($20^{\circ}15'N$) in the north, thus running subparallel to the coast line. The contours appear to be offset significantly at two places

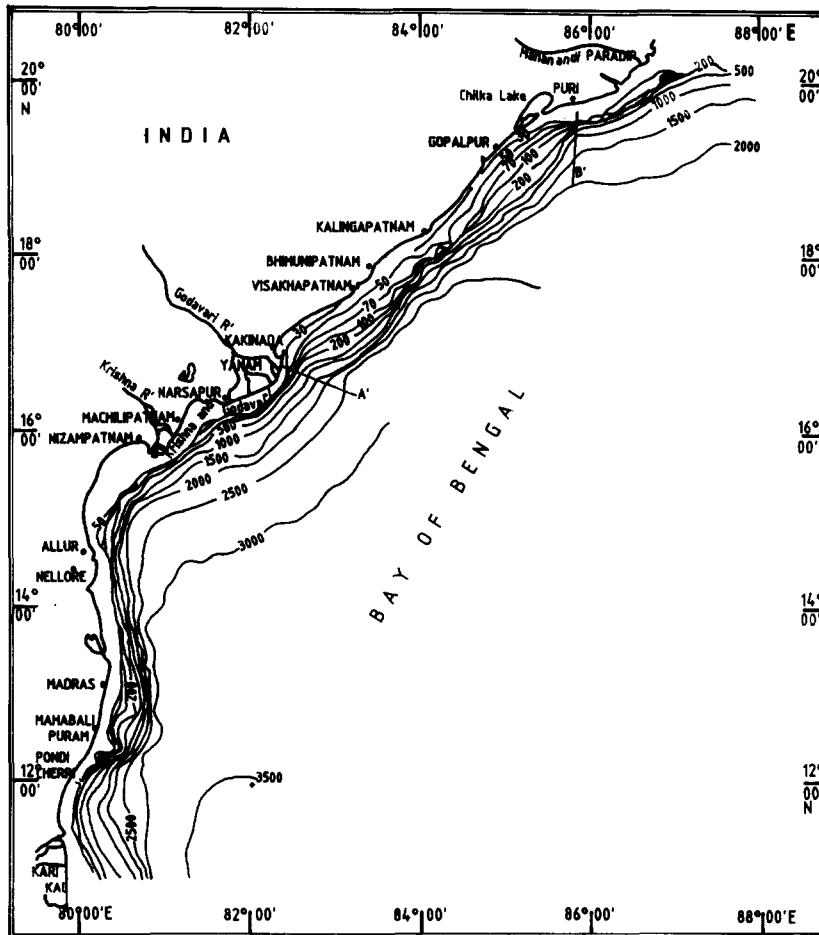


Fig. 2. Bathymetry map of ECMI (A' and B' are offsets in contours).

(marked as "A" and "B" in Fig. 2). Bathymetry sections (shown along selected profiles in Fig. 3) indicate in general a narrow shelf in the south from Karaikal ($10^{\circ}55'N$) to Nellore ($14^{\circ}30'N$), also off Krishna and Godavari river basins and a relatively wider shelf to the north from Kakinada to Paradip (Table 1). The minimum shelf width of 16 km is observed off Karaikal in the south whereas a maximum shelf width of 50 km is observed off Visakhapatnam and Paradip. The depth to the shelf break also varies considerably with a minimum value of 70 m off Karaikal, Nagapatnam ($10^{\circ}45'N$) and off Krishna and Godavari basins and a maximum value of 220 m from Gopalpur to Chilka lake. The shelf off the Krishna basin is rugged and is cut by several

V-shaped channels and rises (Rao et al., 1988; Murthy and Rao, 1990). The continental slope is relatively more steep (1:6 to 1:8) off Madras and Pondichery, whereas off Chilka lake, Paradip and off the Godavari and Krishna river basins it has a gentle gradient (1:25 to 1:50). Earlier studies by Rao et al. (1988) and Murthy and Rao (1990) indicate V-shaped valleys flanked by steep faults at some places over the continental slope off Krishna, Godavari and Mahanadi river basins. The foot of the continental slope occurs at a depth of 3000 m in the south but decreases to less than 2000 m depth in the north (Fig. 3). A topographic high (marked as T.H. in Fig. 3) is observed at the foot of the continental slope (at depths shown in Table 1) in some of the profiles. The topographic

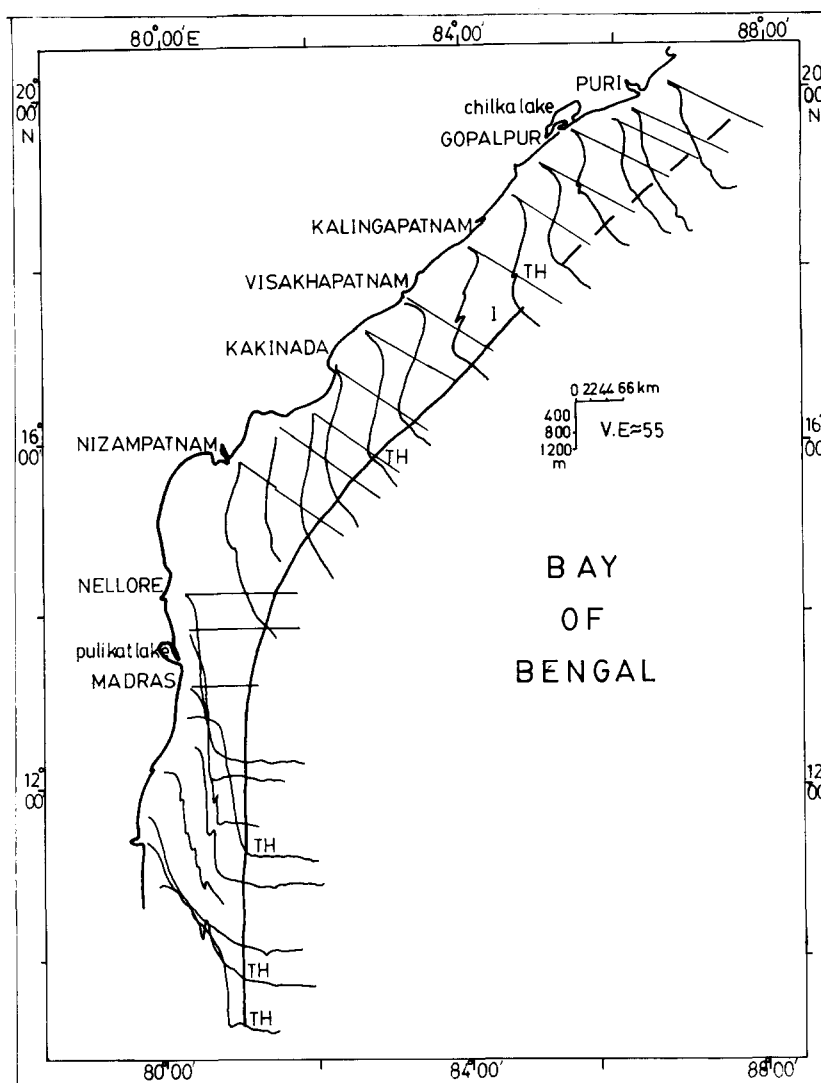


Fig. 3. Bathymetry sections of selected places of ECMI (Thick line represents trend I).

high is broader (about 20 Km) over the southern part compared to the northern part where it is recorded as a sharp peak (Fig. 3). The relief of this high varies from a few tens of metres to as much as 300 m. Echo characteristics of the surface sediments of the eastern continental shelf were discussed by Murthy (1989).

Magnetics

Total intensity magnetic anomaly map of the ECMI (Fig. 4) was contoured at an interval of 50 nT. However, a variable contour interval was used

in the northern part between Kalingapatnam and Chilka lake where very high amplitude magnetic anomalies of more than 2000nT were recorded. Magnetic data of long range profiles over the Bengal Fan are shown as sections in Fig. 5, since contouring for such widely spaced data resulted in several artefacts.

Magnetic anomaly map of ECMI (Fig. 4) shows an intense anomalous zone between Paradip ($20^{\circ}15'N$) and Visakhapatnam ($17^{\circ}40'N$) compared to the southern part between Visakhapatnam and Madras ($13^{\circ}N$). While the peak to peak amplitude of the anomalies observed over the northern

TABLE I

Shelf/slope characteristics off selected places over the eastern continental margin of India (ECMI)

Location (see Fig. 1)	Water depth at shelf break (m)	Shelf edge distance from coast (km) ^a	shelf gradient (ratio)	slope gradient (ratio)	Depth at which marginal high (M.H.) is recorded (metres)	Remarks (only relative terms)
1. Paradip	100	50	1:320	1:50	Not clear	Wide shelf, gentle slope
2. Puri	130	40	1:300	1:43	Not clear	Wide shelf, gentle slope
3. Chilka lake	220	40	1:200	1:28	800 ?	Wide shelf, gentle slope
4. South of Chilka lake	220	40	1:200	1:35	Not clear	Wide shelf, steep slope
5. South of Gopalpur	220	44	1:200	1:16	1500–2000	Wide shelf, steep slope
6. Kalingapatnam	120	35	1:280	1:16	1800–2000	Narrow shelf, steep slope
7. South of Kalingapatnam	130	45	1:345	1:15	2000–2100	Wide shelf, steep slope
8. Visakhapatnam	200	50	1:250	1:12	1900–2100	Wide shelf, steep slope
9. North of Kakinada	200	45	1:225	1:12	2400–2600	Wide shelf, steep slope
10. Krishna River	70	21	1:300	1:25	Uncertain due to slumping over the slope	Narrow shelf, gentle slope
11. Nizampatnam	70	22	1:300	1:25	"	Narrow shelf, gentle slope
12. Madras	200	43	1:200	1:8	2700	Wide shelf, very steep slope
13. North of Pondicherry	90	35	1:400	1:6	3000	Narrow shelf, very steep slope
14. Karaikal	70	16	1:200	1:19	3000	Narrow shelf, steep slope
15. Nagapatnam	70	24	1:340	1:17	3000	Narrow shelf, average slope

^a < 40 km: narrow shelf; > 40 km: wide shelf.

part exceeds 2000 nT, the southern part comprising mainly of Godavari and Krishna offshore basins shows subdued magnetic anomalies. The inner shelf between Visakhapatnam and Chilka lake is in particular associated with dense closures of short wavelength and high amplitude magnetic anomalies (Fig. 4). Magnetic anomalies of the Bengal Fan (Fig. 5) are mostly of low amplitude (100–200 nT) except along the 85°E (trend II) where the anomalies are relatively of higher amplitude.

Three major linear trends are identified from the magnetic anomaly maps and sections marked as I, II and III in Figs. 4 and 5. While the trends I and III run parallel to the coast, trend II extends nearly in a N–S direction. Trend I marks the boundary between low amplitude positive anomalies on the landward side to the seaward negative anomalies (Figs. 4 and 5). Trend II is associated with a prominent magnetic low following the 85°E. The NE–SW trend III follows the high amplitude magnetic low over the continental shelf between Visakhapatnam and Paradip (Figs. 4 and 8).

Discussion

The ocean–continent boundary (OCB)

The linear trend (I) inferred from the magnetic anomaly map of the ECMI and the sections over the northwestern Bengal Fan (Fig. 5) is more prominent in the southern part between Madras (13°N) and Kakinada (17°N) and it runs parallel to the coast for a distance of nearly 550 km. This trend essentially separates the low amplitude positive anomaly on the landward side from a negative field seaward of it (Fig. 5). This trend nearly follows the foot of the continental slope (around 3000 m water depth). A magnetic quiet zone is observed seaward of this trend in the southern Bengal Fan (12°30'N to 14°30'N, 82°E to 84°E, Fig. 5).

Magnetic data collected at closely spaced transects over a small part of the ECMI of Madras (12°30'N to 13°10'N, 80°E to 82°E, Fig. 6A) reveal that the magnetic signature associated with trend I is not as simple as observed from the widely

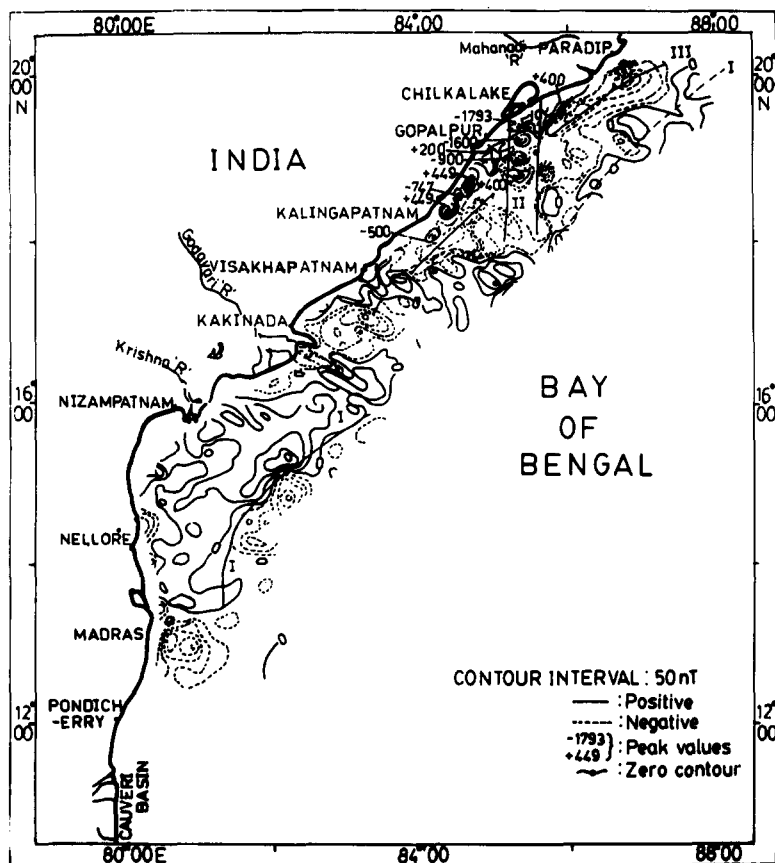


Fig. 4. Total field magnetic anomaly map of ECMI (with major trends *I*, *II* and *III* marked).

spaced long range profiles of Fig. 5. The sections show short wavelength, high amplitude magnetic anomalies landward of this trend and a broad low amplitude peak seaward of it. Free air gravity and bathymetry data along these sections (Fig. 6B and C) indicate that the shelf edge is associated with a free air high followed by a significant low of nearly 100 mGal over the slope. The topographic high (T.H.) beyond the foot of the continental slope is associated with a free air gravity high of as much as 20 mGal (Fig. 6B and C).

Magnetic anomalies along three profiles (at 12°40'N, 13°N and 13°10'N, Fig. 6A) associated with trend *I* are analysed using the forward modelling of Talwani and Heirtzler (1964) to determine the causative source. The derived model (Fig. 7) suggests that the linear trend (*I*) represents the ocean-continent boundary (OCB) off ECMI located at the foot of the continental slope (around

3000 m water depth), at a distance of nearly 40 km from the coast. Some of the salient features of this model are:

- (1) An oceanic crust seaward of OCB with a relatively high remanent magnetization (susceptibility 0.01 cgs units).
- (2) A continental crust landward of OCB with a weak magnetization (Susceptibility 0.003 cgs units).
- (3) A folded and faulted oceanic basement at OCB.
- (4) Two intrusives of high magnetization (susceptibilities varying from 0.006 to 0.01 cgs units) intruding into the continental crust. The seaward intrusive in all the three profiles is relatively of high magnetization compared to the landward one.

Both induced and remanent magnetizations were considered for oceanic crust and intrusives in the model study and the remanent magnetization

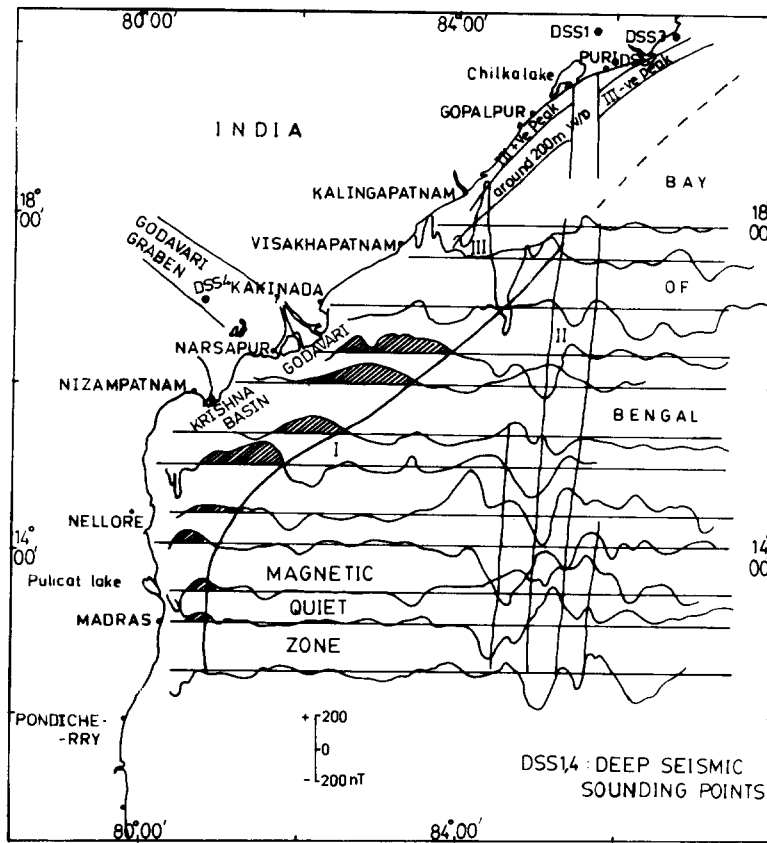


Fig. 5. Magnetic anomaly sections from long range profiles over the northwest Bengal Fan (trends I, II and III marked; shaded portion represents the positive peaks landward of trend I).

parameters obtained for the best fit indicate a palaeo-inclination of -60° for the oceanic crust, with an azimuth of polarization of $+30^\circ$ (clockwise) from north.

Curray et al. (1982) were also of the view that continental crust pinches out in favour of oceanic crust under the lower continental slope of ECMI, following the hinge line and further suggested that the initial break up of India from combined Antarctica and Australia occurred around anomaly M-11 time (126 Ma) across a NE-SW axis. A similar NE-SW trend of magnetic anomalies representing OCB was also reported by Veevers et al. (1985) along the lower continental slope off north-western Australia which was considered as contiguous to the greater part of India before the breakup of Gondwanaland. Considering that the oceanic crust adjacent to the OCB of ECMI is of the oldest period (126Ma), formed during the initial breakup,

the palaeo inclination of -60° obtained for the oceanic crust from the present model studies appears to be in good correlation with the plate reconstruction, as suggested by Curray et al. (1982).

Mukhopadhyay and Krishna (1991) from the gravity data of the ECMI suggested an upwarp or wedge in the oceanic basement at its contact with the continental crust which was also reflected in the bathymetry as the topographic high (T.H.) at the foot of the continental slope. The present model from the magnetic data also confirms a folded nature of the oceanic basement near OCB (Fig. 7).

Veevers et al. (1985) reported short wavelength magnetic anomalies landward of the OCB of west Australian margin and modelled them as rift related dykes of reverse polarity intruding into the continental crust. The present study also indicates such rift related dykes landward of OCB (Fig. 7).

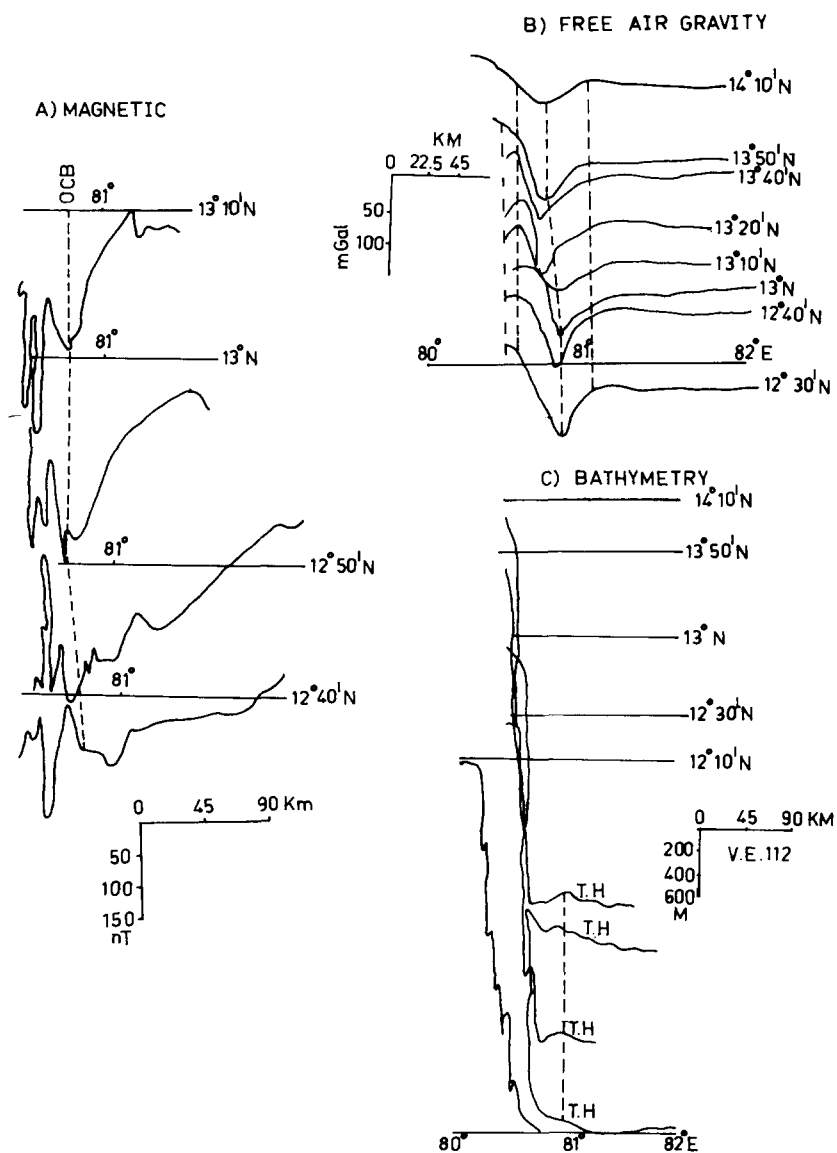


Fig. 6. Magnetic, bathymetry and free air gravity sections over ECMI off Madras (between 12°30'N to 13°20'N).

The preceding analysis on OCB is based mainly on magnetic data of the southern part of ECMI. It needs further study (1) to confirm the northern extension of the OCB (Trend I) beyond 17°N (2) to identify the Mesozoic magnetic lineations seaward of magnetic quiet zone in the southern part of the Bengal Fan.

Northward extension of 85°E ridge

The linear trend II (Fig. 5) represents N-S trending high amplitude magnetic anomalies (peak to

peak amplitudes of the order of 400 nT) between 12°N to 18°N, nearly following 85°E. It is mainly associated with a magnetic low of the order of -200 nT to -300 nT, with positive peaks of lesser amplitude flanking on either side. At some places, a positive peak of nearly 200 nT is aligned with this trend (Fig. 5). The width of this lineation is more (nearly 120 km) in the southern part between 12°N to 16°N and becomes narrow (nearly 50 km) towards north. The northern extension of this trend (from 18°N to 20°N) is inferred from the N-S trending magnetic anomalies of very high

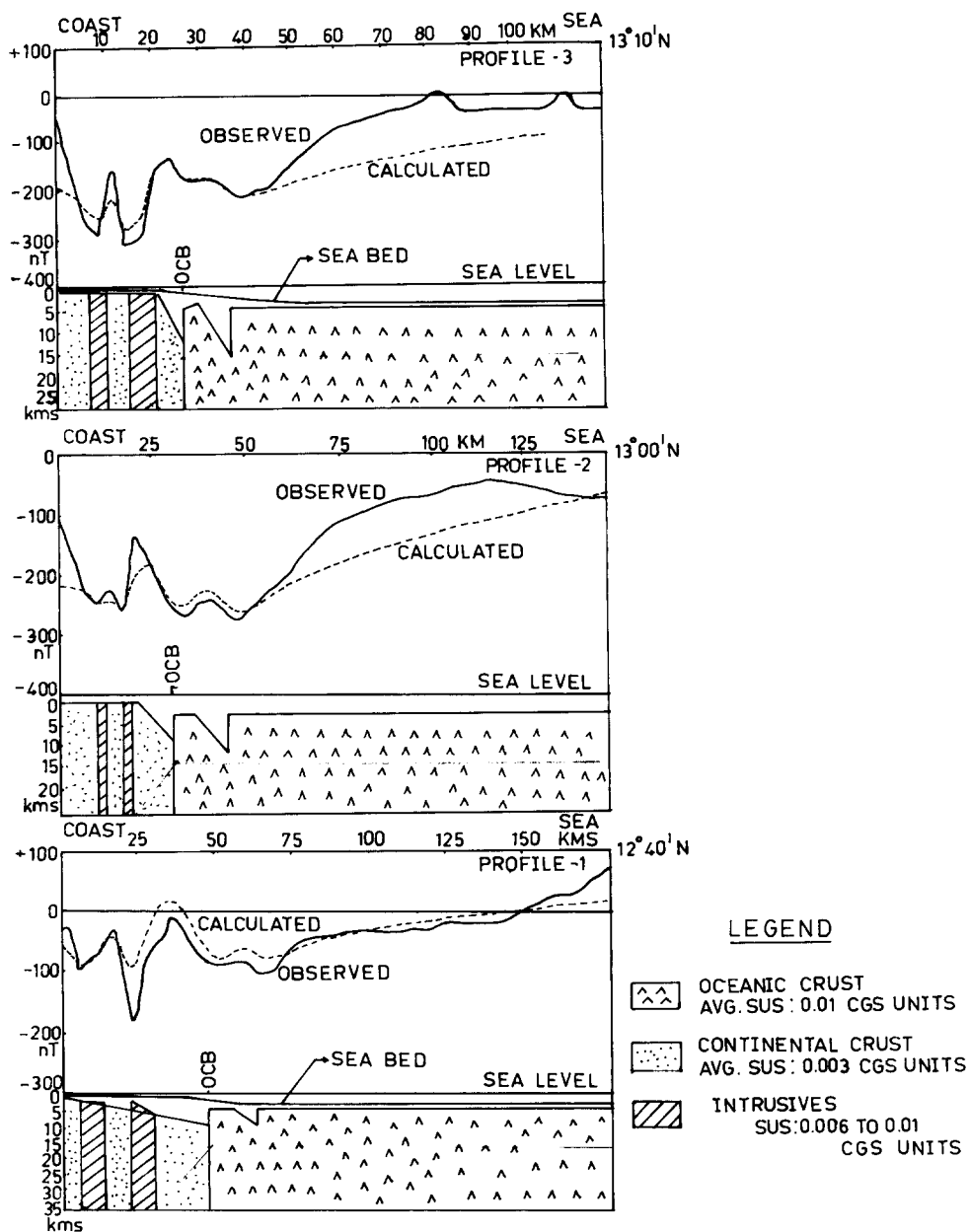


Fig. 7. Model for the ocean–continent boundary (OCB) derived from magnetic anomalies (along 12°40'N, 13°N, 13°10'N) shown in Fig. 6.

amplitude (> 1500 nT) of Chilka lake (Fig. 4 and profile 210-1 of Fig. 8). However, there appears to be a minor break in this trend around 18°N, 85°30'E where it crosses the NE–SW linear trend (I).

The N–S trending magnetic anomalies associated with linear trend (II) between 10°N and 20°N suggest the northern extension of the 85°E ridge

which was identified by Curray et al. (1982) from seismic reflection data as a subsurface ridge between 10°N and 17°N. It appears from the present data that the ridge abutts the continental slope off Chilka Lake, in contrast to the earlier views of Curray et al. (1982) that the ridge takes a NE–SW trend on approaching the continental slope. In a recent study, Curray (1991) and Curray

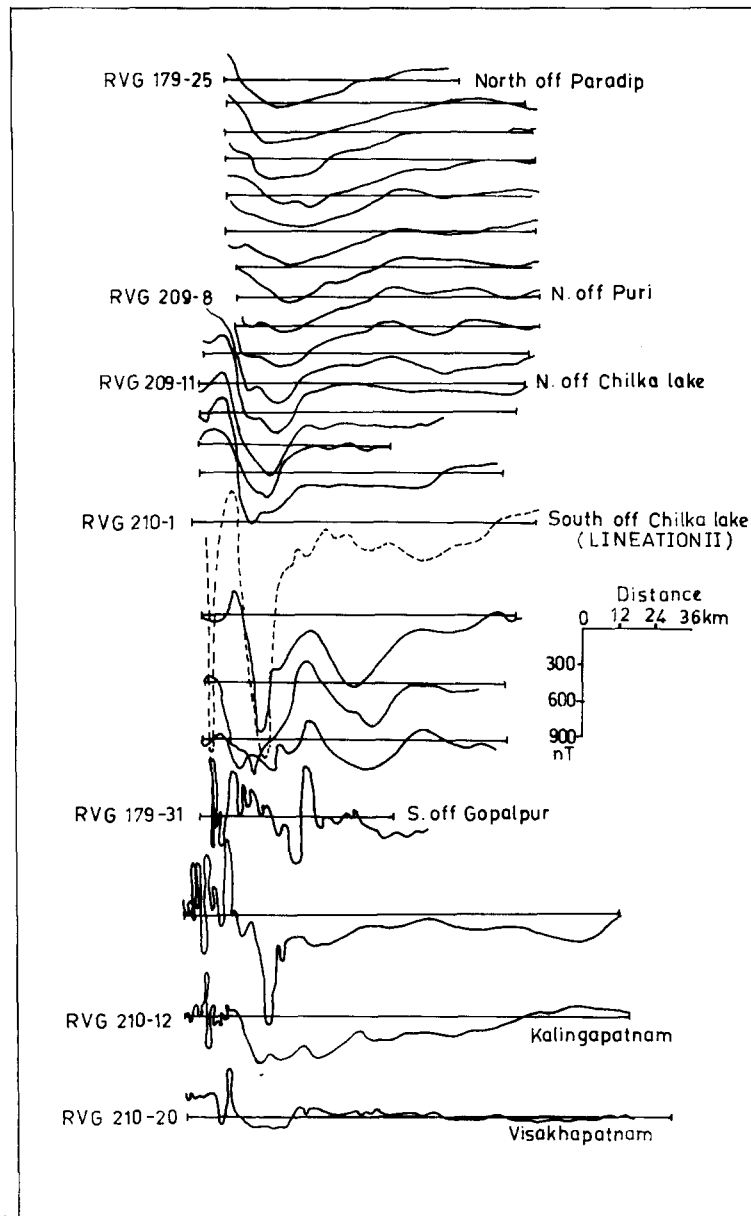


Fig. 8. Stacked magnetic anomaly sections over Visakhapatnam-Paradip shelf (trend III).

and Munasinghe (1991), however, linked the 85°E ridge and the Rajmahal traps located at 25°N (north of Chilka lake) as the trace of the Crozet hotspot, thereby suggesting a N-S trend for this ridge. Raval (1991) also reported northern extension of 85°E ridge activity below the Orissa and Bihar provinces. Baburao et al. (1982) reported a suite of very high amplitude magnetic anomalies from aeromagnetic survey of Mahanadi basin.

Outcrops of serpentized peridotites near Rambha, a small village near Chilka lake (V. Baburao and V. DivakarRao, NGRI, Hyderabad, pers. commun., 1991) might be related to the 85°E ridge, thereby suggesting ultramafic intrusions as the source rock for this anomaly.

The present study, only suggests the northern extension of the 85°E Ridge and it is not possible to conclude whether it represents aseismic ridges

(Liu et al., 1982; Curray and Munasinghe, 1991) or a spreading centre (Mishra, 1991). However, magnetic anomalies do not suggest any symmetric nature on either side of 85°E ridge (Fig. 5), as observed by Mishra (1991). They are more asymmetric in nature and do not follow a systematic pattern, as also reported earlier by Liu et al. (1982).

Basement undulations off Visakhapatnam–Paradip shelf

The linear trend (III) observed over the continental shelf/slope (between 200 and 800 m water depth) from Visakhapatnam to Paradip is in general associated with a broad magnetic low, running parallel to the coast with the anomaly amplitudes ranging from -300 to -500 nT. This magnetic low is flanked by short wavelength positive peaks of the order of 100 to 200 nT on the landward side (Fig. 8). The negative low is broader and of low amplitude off Paradip (20°N) than in the south, off Kalingapatnam. South of Chilka Lake, the anomalies are more complex, with multiple peaks of short wavelength observed landward of the prominent negative low similar to those observed landward of OCB off Madras (Figs. 6 and 7). There is a break in this linear trend (III) off Chilka Lake as it is cut across by the N–S linear trend II.

Two-dimensional modelling of the magnetic anomalies associated with this trend, both by forward modelling (Talwani and Heirtzler, 1964) and Werner Deconvolution (Murthy et al., 1987c) suggest an undulating basement (Fig. 9). The prominent NE–SW trending magnetic low is associated with a basement high at a depth of 1 to 1.5 km below the seabed with a landward depression of nearly 3 km off Paradip and 4.5 km off Kalingapatnam. Kaila et al. (1987) reported a series of NE–SW trending basement ridges and depressions in the Mahanadi Graben from deep seismic sounding (DSS) investigations carried out on land along three traverses covering the Konark–Bhubaneswar–Cuttack and Paradip area (locations shown as DSS1, 2 and 3 in Fig. 5). The model derived from the magnetic data suggests the offshore continuation of a NE–SW depression in basement between Puri and Paradip (DSS2 and 3) inferred by Kaila et al. (1987). The present study

further suggests the southward extension of this depression from Puri upto Kalingapatnam. Baburao et al. (1982), Dasgupta and Rath (1987) and Subrahmanayam (1987) also reported a series of linear NE–SW trending ridges and depressions (Horst and Graben) off Mahanadi Basin. Sastry et al. (1973) reported such NE–SW linear ridges and depressions off Cauvery, Palar, Godavari and Krishna river basins. Such a basement configuration (ridges and depressions) was also reported over other passive continental margins (Folger et al., 1979; Grow et al., 1979) whose origin was attributed to the vertical tectonics in the post-rift stages of the evolution of these margins (Scrutton, 1979; Bott, 1980).

Conclusions

Analysis of magnetic data over the ECMI and northwestern Bengal Fan suggests that the ocean–continent boundary is located at the foot of the continental slope and runs parallel to the coast in the southern part between Madras (13°N) and Kakinada (17°N). Its extension north of Kakinada, however, is only tentative and needs further study. The model derived for OCB also suggests a folded and faulted oceanic crust at its contact with the continental crust. The occurrence of dyke intrusions landward of OCB is significant as they might represent rift-phase volcanism during the evolution of ECMI. The present data reveals such intrusives off Madras and also off Visakhapatnam to Chilka Lake, and it needs a detailed study regarding the nature and extent of these intrusives and their relation to the land geology.

Magnetic data in the Bengal Fan indicate the northern extension of the 85°E ridge upto 20°N, though the present study could not make any attempt on the nature of the causative source. The horst and graben configuration within the continental basement observed off Mahanadi river basin might be related to the vertical tectonics in the post-rift stages of the evolution of ECMI.

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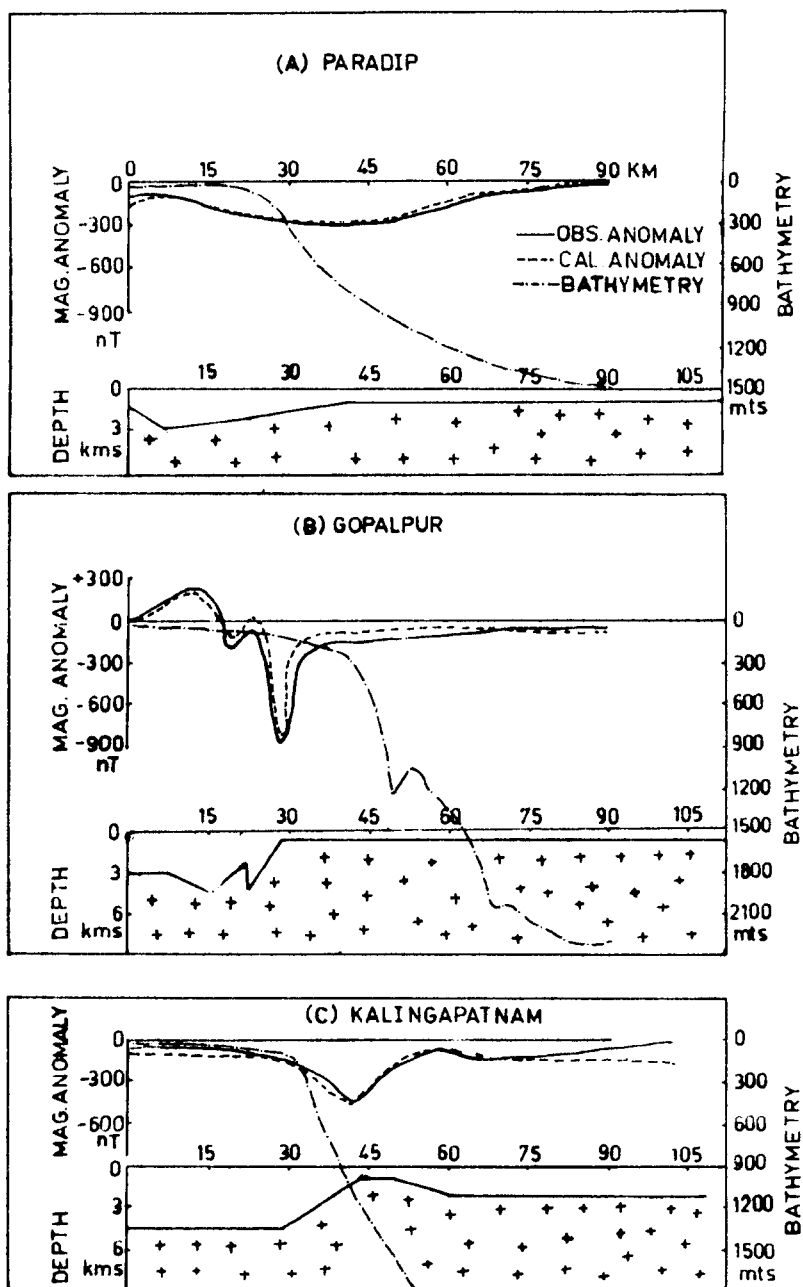


Fig. 9. Models derived from magnetic anomalies in Fig. 8. (A) Off Paradip; (B) Off Gopalpur; (C) Off Kalingapatnam (profile locations shown in Fig 1.).

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