

Morphology and tectonics of Mahanadi Basin, northeastern continental margin of India - from geophysical studies

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Abstract

The bathymetry, total intensity magnetic and satellite free-air gravity data over the eastern continental margin of India between the latitudes 18° 30'N and 20°N within the water depths of 25-2300 m (between Paradip and Gopalpur) were analyzed and interpreted. Onshore aeromagnetic and Bouguer gravity data over the adjacent coastal region are also supplemented in the present analysis.

The basement configuration inferred from the bathymetry, magnetic and gravity data resembles a series of coast parallel structural highs and depressions and their shearing pattern in the Mahanadi offshore Basin. The Chilika offshore lineament and Dhamara offshore lineament constitute the southern and northern boundaries of the offshore basin respectively. In this sector, the inferred Continent Ocean Boundary (COB), around 170 km from the coast, approximately mimics the 2000 m isobath. The width of the inferred offshore basin between the Chilika Offshore Lineament and Dhamara Offshore Lineament is around 240 km and it extends approximately up to 170 km from coast to offshore (perhaps up to the COB). The inferred tectonics of the northeastern continental margin of India suggests pull-apart and sheared/transform mechanisms during the breakup of India from Antarctica. The model studies suggest that the northern part of the 85°E Ridge abuts the coast at Chilika Lake.

The shape of 2000 m isobath over the northeastern continental margin of India closely resembles to that of 2000 m isobath off the Lambert Graben of East Antarctica. This inference appears to further support the theory that the eastern continental margin of India and East Antarctica are closely aligned in the pre-breakup tectonic setting of the eastern Gondwanaland.

Keywords: Mahanadi Basin; bathymetry data; Chilika Lake; shearing; gravity data; pull-apart; channel; magnetic data; depression.

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1. Introduction

Mahanadi is a major sedimentary basin located along the east coast of India (Fig. 1). It extends over an area of 141,589 km², which is nearly 4.3% of total geographical area of the country. Mahanadi River rises from the district of Madhya Pradesh and flows about 851 km before it joins the Bay of Bengal. The coastal geomorphic province is drained by the Mahanadi River system (Mahanadi, Brahmani, Baitarani and Dhamara Rivers) with a sediment load to the basin of the order of 7.10×10^9 kg/yr (Subramanian, 1978) (Fig. 2). Due to more pronounced deltaic activity during the mid-late Miocene period, a wider continental shelf evolved in the Mahanadi Basin (Bharali et al., 1991). All the major rivers of India viz. Ganges, Mahanadi, Godavari, Krishna and Cauvery (Fig. 1) are attributed to the initial rifting of the Gondwanaland and the subsequent motions of the Indian plate, which presently subducts along the Andaman-Nicobar-Sumatra Arc and enjoys a convergent setup. The study of the deltas of these major rivers helps in understanding the Indian plate motions and the associated effects. The Mahanadi basin is typically suited for this purpose, as its onshore geology significantly differs from that of its offshore.

A major part of the onshore Mahanadi Basin is covered with alluvium with various rock exposures of upper Gondwanas, khondalites, granites, gneisses and laterites (Fig. 3a). Volcanic rocks equivalent in composition to the Rajmahal Traps are present throughout the basin. Sedimentary sequences resting on the metamorphic basement range in age from Cretaceous to Holocene. Both the onshore and offshore basins were believed to have come into existence during the Jurassic as a result of rifting and break up of Gondwanaland. During its evolution since the Cretaceous, the basin experienced a number of marine transgressions and regressions followed by development of several elongated depressions and intervening uplifts not only onshore, but also offshore (Fuloria, 1993). Several deep-seated faults in the basement were also reported (Dasgupta

et al. 2000) beneath the delta, which are responsible for a few moderate to large earthquakes in the state of Orissa (Fig. 2).

The present study aims to derive a detailed basement configuration and also to map morphological features on the seafloor by analyzing bathymetry, total intensity magnetic (new data) and satellite-derived offshore free-air gravity anomaly data (Sandwell and Smith, 1997) along with published onshore magnetic and Bouguer gravity data (Bharali et al., 1991; Hari Narain, 1975), with a view that such a detailed picture may enhance our understanding the tectonics of the basin and thereby the movement of the Indian plate during the breakup of India from Antarctica.

2. Data

The bathymetry and total Intensity magnetic data were collected along the seventeen-coast perpendicular traverses MB-1 to MB-17 (Fig. 2) between the latitudes $18^{\circ} 30'N$ and $20^{\circ}N$ within water depths of 25-2300 m (between Paradip and Gopalpur), onboard the Research Vessel Gaveshani by Regional Center, National Institute of Oceanography, Visakhapatnam.

Fig. 3a shows the stacked bathymetry profile map, while the bathymetry contour map prepared at an interval of 10 m in the near-shore, 20 m in the midshelf and 100 m towards the offshore end is presented in Fig. 4a. Nine coast parallel traverses (a-a', b-b', c-c', d-d', e-e', f-f', g-g', h-h' and i-i') have been selected on the bathymetry contour map (Fig. 4a) and they are presented in Fig. 3b for a better understanding of the coast-perpendicular topographic features over the eastern continental margin. The offshore total intensity magnetic anomalies were computed after correcting for the International Geomagnetic Reference Field (IAGA Division I, working group 1, 1986) and the magnetic anomaly profiles and contour maps are shown in Figs. 3c and 4b.

Satellite derived free-air anomaly map (Sandwell and Smith, 1997) of the region at a contour interval of 5mGals (Fig. 4c), and the absolute total intensity aeromagnetic and the Bouguer gravity maps (after Bharali et al., 1991; Hari Narain, 1975) over the land adjacent to the present study area (Figs. 4b and 4c) are used to supplement the offshore bathymetry and magnetic data.

3. Results and discussion

3.1 Bathymetry

The bathymetry profiles (Fig. 3a) reveal several channels in the slope region. A few “step-like” terraces followed by a “V-shaped” channel of 400 meters deep with a width of 9 km are observed along the profile MB-11. Further, several possible sediment slumps/ topographic highs are noticed varying in width between 4.5 and 9.0 km and have a relief of 140 to 400m from the adjacent seafloor along the profiles MB-12 and MB-13 (Fig. 3a). The seafloor of the Bengal Fan is marked by a series of channels (Fig. 1). The bathymetry also shows that the gradient of shelf break is steep (slope gradient ratio is 1:30 to 1:35) south of Chilika Lake, whereas it is gentle (slope gradient ratio is 1:50 to 1:43) in the north (Murthy et al., 1993), perhaps related to variation in sediment supply. The difference in slope gradients associated with the Chilika Lake may suggest the occurrence of southern limit of the Mahanadi offshore Basin. It also suggests that the basin extends further north up to Paradip. Several NW-SE, N-S and NE-SW trending channels observed in Fig. 4a may be part of the Bengal Fan dispersal system (Fig. 1). The coast parallel sections selected from the bathymetry contour map (Fig. 4a) are shown in Fig. 3b bringing out a typical “sickle shaped” geomorphic feature (channel) off the Chilika Lake below the sections a-a’, b-b’, c-c’ and d-d’. The lateral extension of this feature varies between 55 and 110m. It is narrow at the mouth of the Chilika Lake and wide towards the offshore. The depth of this feature from the adjacent seafloor varies from 50 to 1020m. The presence of this typical geomorphic feature off the Chilika Lake may suggest the imprints of Chilika Lake in the offshore region (Fig. 3b) (Subrahmanyam et al., 2006). Towards north and south of this feature the

seafloor is characterized by smooth topography except for a few “V-shaped” channels (Fig. 3b).

3.2 Magnetic data

The magnetic anomalies (Fig. 3c) are of low amplitude and broad-wavelength along the traverses MB-1 to MB-9 while they are of high amplitude and short-wavelength along MB-10 to MB-17. Based on the anomaly character, the area can be divided into two provinces, one north and the other south of the Chilika Lake. The very high amplitude and short-wavelength magnetic anomalies falling in the Southern Province may indicate that the basement is at a shallow depth, whereas the subdued magnetic anomalies in the Northern Province indicate deeper basement (Fig. 3c). A close examination of the profiles MB-1 to MB-11 reveals that the area between the 100-1500m isobaths is associated with a NE-SW trending magnetic low, probably caused by a structural feature running parallel to the coast, which might have been dislocated due to NW-SE shearing at several locations (Fig. 4b).

The magnetic data (Fig. 4b) also bring out a series of structural features trending in NE-SW, NW-SE, N-S, NNE-SSW and E-W directions, as indicated by the anomaly trends, ranging from 500 to -1600 nT over the offshore region. A band of elongated anomaly closures varying in amplitudes between -230 to -420 nT trending in NE-SW direction, parallel to the coast within the water depths of 100-1500 m are observed over a distance of approximately 180-190 km. This feature was dislocated at two locations by NW-SE trending lineaments named **A** and **C** (Fig. 4b).

The structural trend **C** lies in the offshore (Fig. 4b) and faces the Devi River, so as to suggest that the river is tectonically controlled and it extends towards the offshore. The NNE-SSW anomaly closures south of Chilika Lake appear to have changed their trend to the N-S, probably joining the land at Chilika Lake (Fig. 4b). This zone of anomalies correlates well with the northern

part of the 85°E Ridge as reported earlier by Ramana et al. (1997), Goutam Kumar Nayak and Rama Rao (2002). The offshore lineament **A** facing Chilika Lake, hereafter is referred as the Chilika offshore lineament (COL) (Fig. 4b) probably acts as the southern boundary of the Mahanadi offshore Basin and separates the study area into basinal (north) and non-basinal (south) provinces.

3.3 Gravity data

The offshore satellite gravity and the onshore Bouguer gravity anomaly map (Fig. 4c) bring out a few E-W, NE-SW, and NNW-SSE trending anomalies ranging from -70 to 65mGals and -65 to 40mGals. The closely spaced and elongated NE-SW to ENE-WSW trending contours of value -5 to -30mGals in the slope region can be attributed to the shelf break topography. These contours have taken a lateral shift towards the coast off the Chilika Lake and this shift occurs at the NW-SE trending Chilika offshore lineament **A**. Further north off the Chilika Lake, these contours are dislocated at several places from their normal trend, and these deviations are marked by WNW-ESE and NW-SE lineaments in Fig. 4c. Between this band of contours and the coast, a zone of NE-SW to ENE-WSW trending elongated positive closures (denoted as High in Fig. 4c) is observed north off the Chilika Lake, which may indicate a structural high in the shelf region. This gravity high is surrounded on both sides by gravity lows suggesting clearly that the basement is characterized by a combination of horst and graben like structures. The basement structure is sheared by the WNW-ESE and NW-SE lineaments. The lineaments, **C** and **B** correlate with the trend of the river Devi and the coastline near Dhamara River in the north respectively (Fig. 4c). The lineament **B** facing Dhamara River hereafter is referred as Dhamara offshore lineament (DOL). A zone of N-S to NW – SE trending strong positive anomaly ranging from 20 to 60 mGals lies south of Chilika Lake and its position correlates to the magnetic anomaly in Fig. 4b which is attributed to the northern part of the 85° E Ridge. If we assume that this positive anomaly really comes from the 85° E Ridge, then there is an observational contrast with the well established negative anomaly character of the ridge, which was studied

particularly south of 17°N latitude (Subrahmanyam et al., 2001; Ramana et al., 1997; Curray and Munasinghe, 1991; Krishna, 2003). The observational contrast from negative gravity to positive gravity over 85°E Ridge is shown in the map (Fig. 4d) (Subrahmanyam et al., 2001). The resultant effect of free-air gravity of the continental crust and the ridge material or the emplacement of the ridge at a shallow depth as is the case with it over south of Sri Lanka close to Afanasy Nikitin Seamount chain (Ramana et al., 1997; Krishna, 2003) may be the probable cause for this discrepancy. The emplacement of 85°E Ridge took place after the evolution of the early Cretaceous crust in the Bay of Bengal (Ramana et al., 1997).

The magnetic and gravity data (both on land and offshore) thus clearly reveal that the onshore and offshore basins of Mahanadi comprised a series of structural highs and depressions. The Chilika offshore lineament and Dhamara offshore lineament constitute the southern and northern boundaries of the offshore Basin.

3.4 Model studies

The magnetic data along five traverses **T1**, **T2**, **T3**, **T4** and **T5** perpendicular to the anomaly trend (Fig. 4b) are modeled by using GM-Sys 2D modeling software, considering all depth constraints due to local geology. Over the northeastern continental margin of India, the sediment thickness below the seabed was taken from the published sediment isopach map (Curray, 1991). Below the sediment layer, the magnetic basement was assumed at the level of upper crustal layer with a magnetization of 0.016 emu/cc and susceptibility: 0.002 cgs units. The total intensity magnetic field of the area was taken as 43000nT. The induced inclination and declination were considered as 24° and -1.35° respectively, whereas the remanant inclination and declination as -67° (normal) and 210° which are computed for the paleolatitude of ~47°S and responsible for the observed magnetic anomaly. Several attempts have been made to achieve a best fit with the observed total intensity magnetic anomalies. The final model is

presented in Fig. 5. The basement depths inferred from our analysis range from 2.9 to 10.0 km below T1, 4.0 to 10.0 km below T2, 4.0 to 9.8 km below T3 and 3.4 to 7.0 km below T4. These values correlate well with the actual borehole measurements. The basement depths encountered in the bore wells M5 and M3 are approximately 3810 and 2815 meters respectively, where as the wells M4 and M6 have not reached the basement (Fuloria et. al., 1992, and Fuloria 1993). The magnetic profile along the traverse T5 (Fig. 5) cutting across the 85°E Ridge is modeled by assuming the susceptibility and remanant magnetization as 0.016 cgs units and 0.017 emu/cc respectively for the 85°E Ridge material. The basement model reveal the occurrence of ridge material represented by dual peaks at shallow basement depths of 0.8 km with its central part at 3.5 km from the mean sea level in the shelf region south of Chilika Lake. Towards east of the 85°E Ridge the basement gradually deepens and the average depth is around 7.2 km.

Similarly, the satellite free-air gravity anomaly data along three traverses **P1**, **P2** and **P3** perpendicular to the anomaly trend (Fig. 4c) are modeled by using GM-Sys 2D modeling software.

The crustal model was generated by assuming sub-surface crustal layers beneath the seafloor at appropriate depth levels with varied densities. Based on the available seismic constraints, thick sediment layer of around 2.0-10.0 km was considered below the seabed (Curry, 1991). The density for seawater was considered as 1.03 gm/cc. The density of the thick sedimentary column was taken as 2.3 gm/cc. About 15 km thick crust was assumed below the sediments as upper crust and lower crust with densities 2.6 gm/cc and 2.8 gm/cc respectively. Below this a density of 3.3 gm/cc was considered for mantle. Several attempts have been made by keeping the local geology in mind to achieve a best fit with the observed anomaly. The final models were presented in Fig. 5. The interpretation puts the depth to the top of the upper crustal layer ranging from 3.0 to 10 km below P1, 3.0 to 9.5 km below P2 and 2.9 to 10.0 km

below P3. The depths observed to the upper crustal layer undulations in the gravity models are well correlateble with the basement depths derived from magnetic modeling. The rise in the free-air gravity anomaly towards offshore end of the profiles P1, P2 and P3 (Fig. 5) and the corresponding thinning of the upper crustal layer around 2000 m isobath probably indicate the Continent Ocean Boundary (COB). The interpreted COB is the most prominent boundary in deep water, and typically coincides with a prominent oceanwards step-up in the basement level (Fig. 5).

A tectonic map (Fig. 6) was prepared based on the results of the potential field data modeling and qualitative results of the bathymetry data. The map shows coast-parallel basement highs and depressions-like structural features and their shearing pattern in the Mahanadi offshore Basin, a double humped shallow basement feature in the shelf region, south of Chilika Lake and several features onshore. The basement configuration in the offshore region resembles a series of coast-parallel highs and depressions, namely the Konark high, northern basin depression, central basin high, southern basin depression and offshore high, at different depths from the mean sea level. The inferred COB approximately mimics the 2000 m isobath. The basement depth in the central basin high varies from 2.9 to 4.0 km whereas in the southern basin depression, it varies from 7.0 to 10.0 km (Fig. 6). The width of the inferred offshore basin between the Chilika offshore lineament and Dhamara offshore lineament is around 240 km and it extends approximately up to 170 km from coast to offshore (Fig. 6).

The shallow double peaked basement feature (Fig. 5) delineated from the model study of the magnetic data is associated with positive free-air gravity which can be attributed to the northern part of the 85°E Ridge. Similarly, the 85°E Ridge is characterized by positive free-air gravity anomaly south of Sri Lanka due to its shallow occurrence (Ramana et al., 1997; Krishna, 2003). Hence it may be

surmised that the northern part of the 85°E Ridge may be joining the landmass at Chilika Lake.

The major part of the eastern continental margin of India, which was associated with major tectonic movements, can be clearly observed up to 2000 m isobath. Based on the anomaly trends observed in the potential field data and also the inferred basement structure deduced from the gravity model studies over the eastern continental margin of India, the COB was interpreted approximately 170 km oceanwards of the east coast of India. The inferred COB closely follows offshore structural high (Fig. 6). In this sector, the COB approximately mimics the 2000 m isobath (Fig. 7). Our results correlates well with the recent geophysical study (Stagg et al., 2004) over continental margin of Enderby Land of east Antarctica, which revealed the occurrence of COB approximately around 170 km oceanwards between Enderby Land and Prydz Bay. The disposition of 2000 m isobath has helped in demarcating the COB for East Antarctica and the conjugate east coast of India and Sri Lanka. The 2000 m isobath of Enderby Land depicts a topographic depression followed by a rise adjacent to the Lambert Graben (Fig. 7). The 2000 m isobath over the northeastern continental margin of India (Fig. 3a) also depicts remarkably linear bathymetry similar to that of the topographic feature observed off Lambert Graben of East Antarctica. The present trend and location of the 2000 m isobath over the eastern continental margin of India with reference to the East coast of India has been transferred and shown in Fig. 7. This inference suggests that the eastern continental margin of India is a contiguous part of Antarctica. Earlier studies of Sheraton, (1983), Cooper et al. (1991), Subrahmanyam et al. (1999), Federov et al. (1982), Yoshida et al. (1992), Chetty, (1995) and Anand et al. (2002) clearly suggested the conjugate nature of eastern continental margin of India with respect to East Antarctica. The inferences of the present study appear to further support to the theory that the eastern continental margin of India and East Antarctica are closely aligned in the pre-breakup tectonic setting of the eastern Gondwanaland.

4. Conclusions

The basement configuration inferred from the bathymetry and the magnetic and gravity modeling resembles series of coast parallel structural highs and depressions and their shearing pattern in the Mahanadi offshore Basin. The Chilika offshore lineament and Dhamara offshore lineament constitute the southern and northern boundaries of the offshore basin. In this sector, the inferred Continent Ocean Boundary (COB) around 170 km from the east coast of India approximately mimics the 2000 m isobath. The width of the inferred offshore basin between the Chilika offshore lineament and the Dhamara offshore lineament is around 240 km and it extends approximately up to 170 km from coast to offshore (may be up to the COB). The inferred tectonics of the northeastern continental margin of India suggests pull-apart and sheared/transform mechanisms during the breakup of India from Antarctica. The model studies suggest that the northern part of the 85°E Ridge may be joining the landmass at Chilika Lake.

The shape of 2000 m isobath over the northeastern continental margin of India closely resembles to that of 2000 m isobath off Lambert Graben of East Antarctica. The COB from the northeast coast of India approximately mimics the 2000 m isobath. These inferences appear to further support the theory that the eastern continental margin of India and East Antarctica are closely aligned in the pre-breakup tectonic setting of the eastern Gondwanaland.

Acknowledgements

The authors are grateful to Dr.Satish Shetye, Director, National Institute of Oceanography, Goa for encouragement. Our sincere thanks to the cruise participants for data acquisition. We are thankful to the anonymous reviewers for valuable suggestions. This is National Institute of Oceanography contribution No: **4212**. Our thanks to Miss T. Madhavi for drafting the Figs.

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Figure captions

Fig. 1: Generalized map of Bay of Bengal. The shaded block represents study area. Major deltas along the east coast of India are shown.

Fig. 2: Map showing the survey traverses with annotations. Land and offshore Tectonics of the Mahanadi Basin (after Fuloria et al., 1992) are shown.

Fig. 3: (a) Map showing the bathymetry profiles along the survey traverses and the land geology.

(b) Map showing the bathymetry profiles along the coast parallel traverses a-a', b-b', c-c', d-d', e-e', f-f', g-g', h-h' and I-I' selected from the bathymetry contour map (Fig. 4a).

(c) Map showing the total intensity magnetic anomaly profiles plotted along the survey traverses.

Fig. 4: (a) Bathymetry contour map of the study area with varied contour interval in meters. Thin dashed lines a-a', b-b', c-c', d-d', e-e', f-f', g-g', h-h' and I-I' indicate the coast parallel traverses.

(b) Map showing the total intensity magnetic anomaly contours over the north-eastern continental shelf of India (present study data) and the aeromagnetic total intensity contours over the land (modified after Bharali et al., 1991) with varied contour interval. Inferred structural and tectonic trends are shown. T1, T2, T3, T4 and T5 are the traverses along which the profiles were selected for modeling.

(c) Map showing the satellite derived offshore free-air gravity (modified after Sandwell and Smith, 1997) and onshore Bouguer gravity (modified after Hari Narain, 1975) anomaly maps. Inferred structural and tectonic trends are shown. P1, P2 and P3 are the traverses along which the profiles were selected for modeling.

(d) Ship-board free-air gravity anomaly map over Bay of Bengal (after Subrahmanyam et al., 2001)

Fig. 5: Forward modeling of total intensity magnetic anomaly data along the traverses **T1**, **T2**, **T3**, **T4** and **T5**; forward modeling of satellite derived offshore free-air gravity anomaly data along the traverses **P1**, **P2** and **P3**.

Fig. 6: Map showing the inferred tectonic trends and coast parallel structural highs and depressions along with the range of depths to the structures from the Mean Sea Level (MSL) over the north Eastern Continental Margin of India and the adjoining land mass. Inferred Chilika offshore lineament (COL) and Dhamara offshore lineament (DOL) represent the southern and northern boundaries of the offshore Mahanadi Basin.

Fig. 7: Schematic diagram of India-East Antarctica plate reconstruction (modified after Cooper et al., 1991; Yoshida et al., 1992; Chetty, 1995)

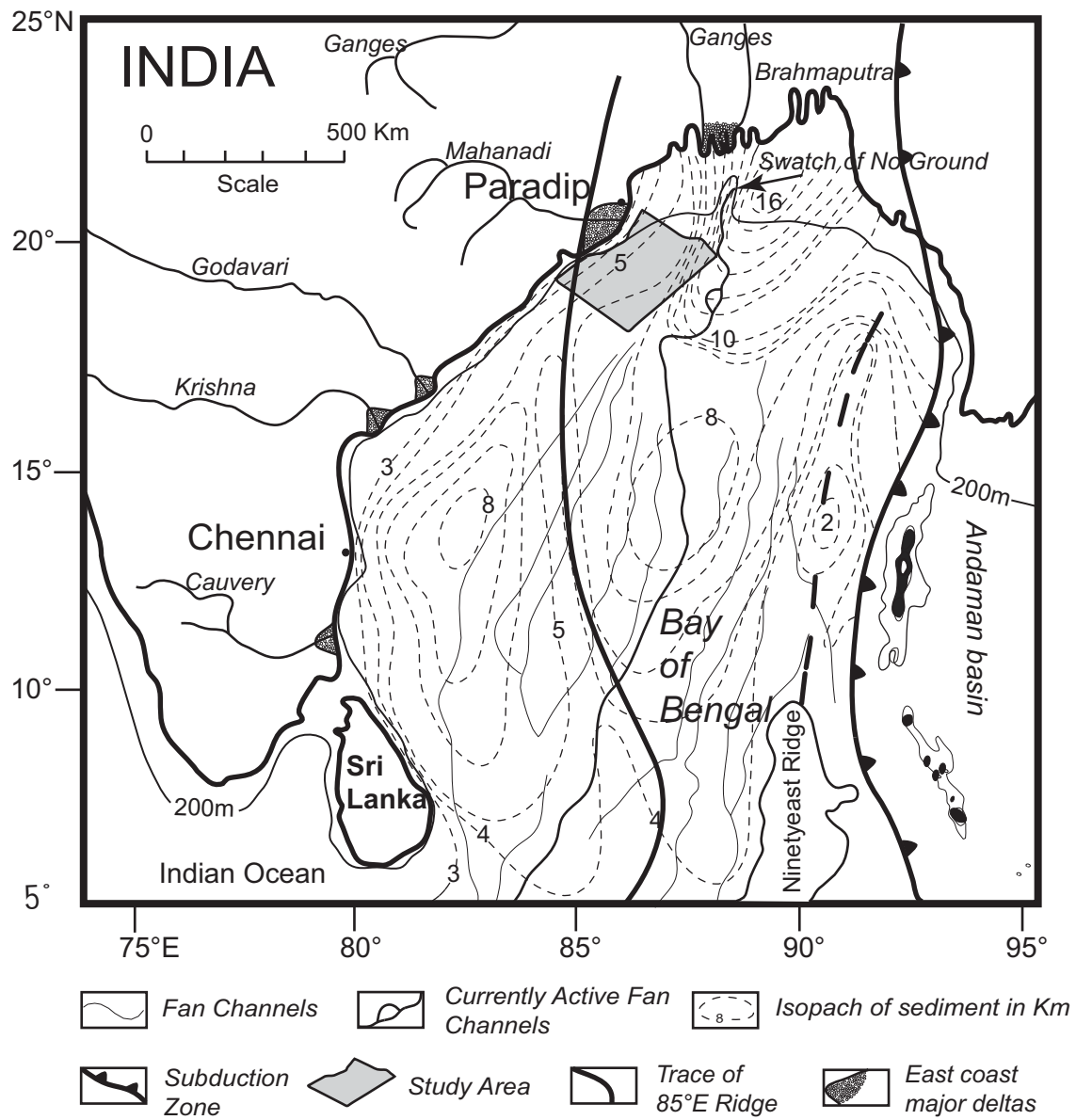


Figure 1

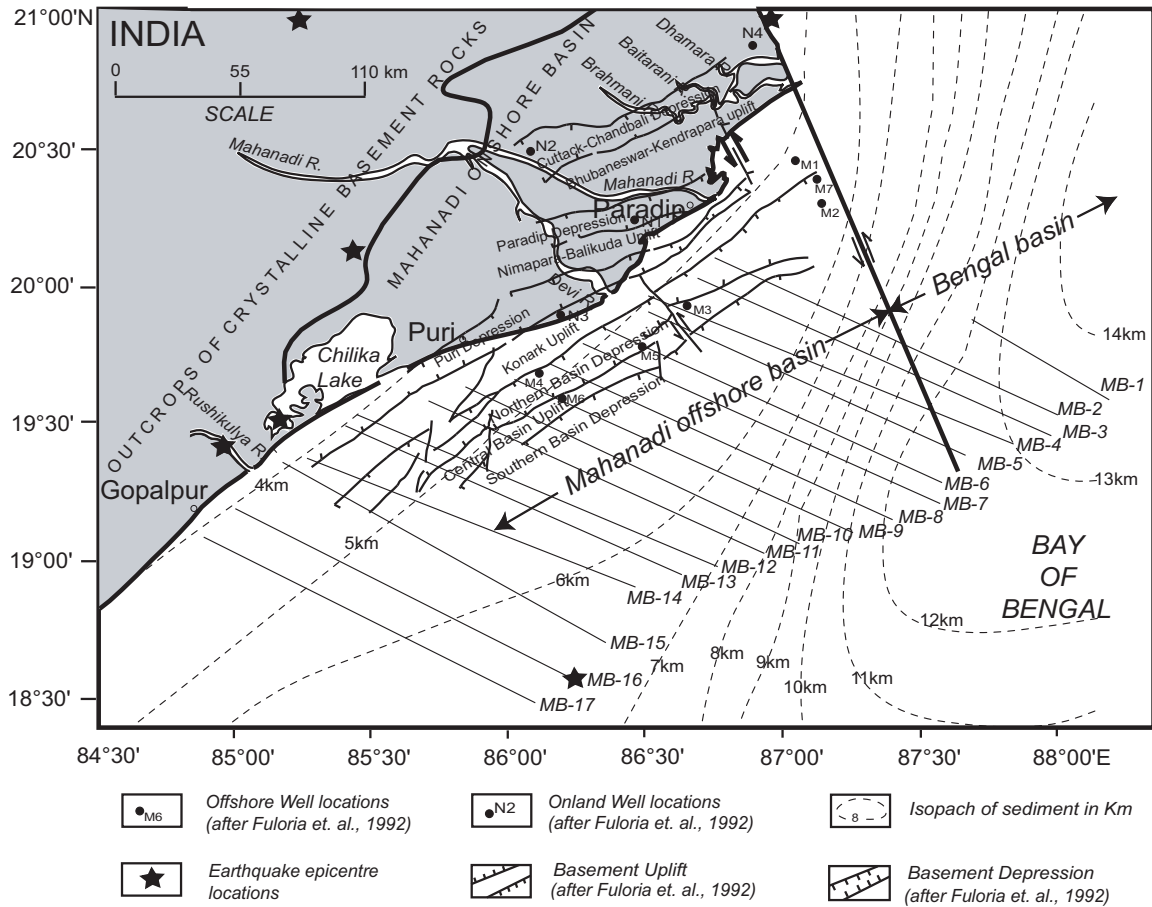


Figure 2

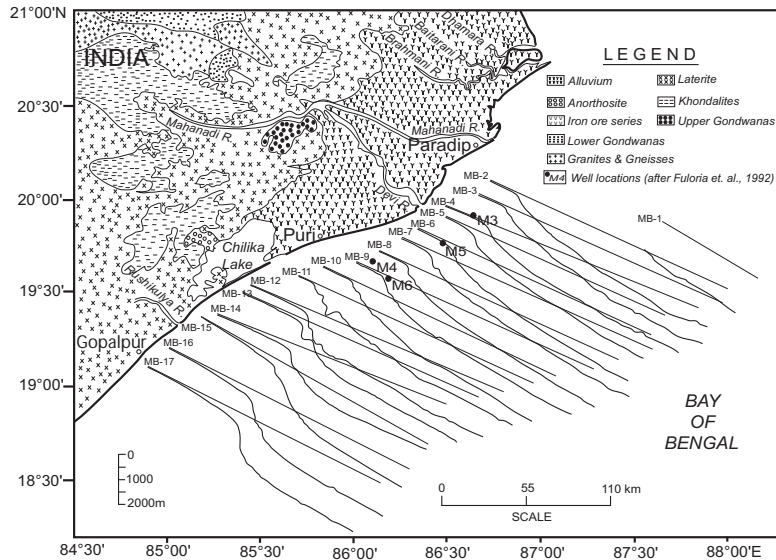


Figure 3a

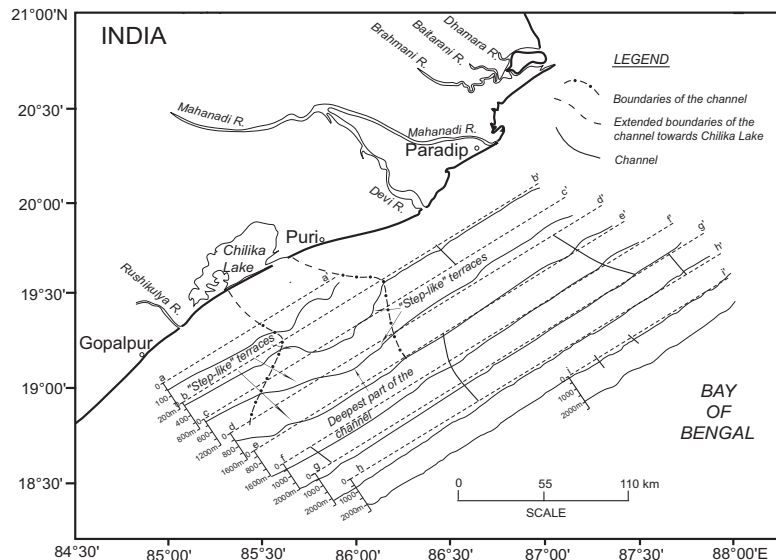


Figure 3b

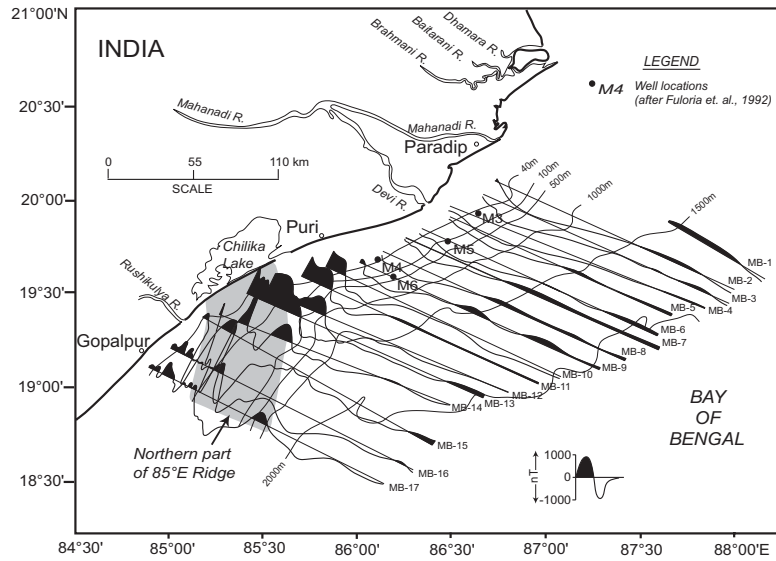


Figure 3c

Figure 3

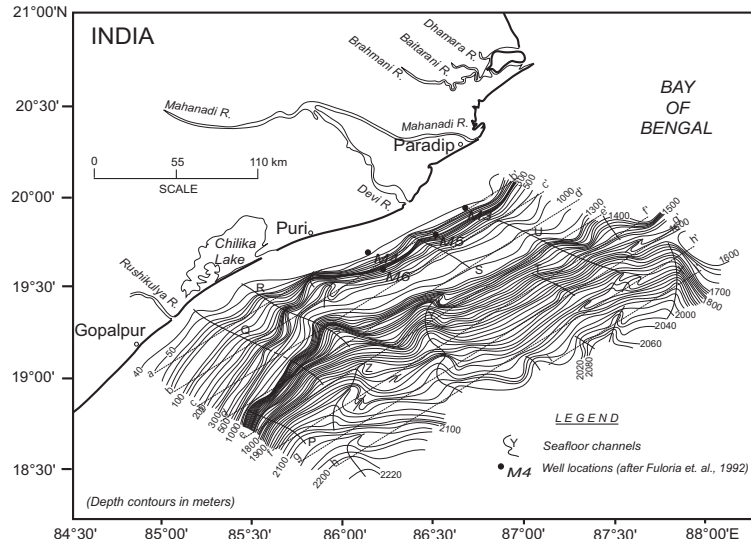


Figure 4a

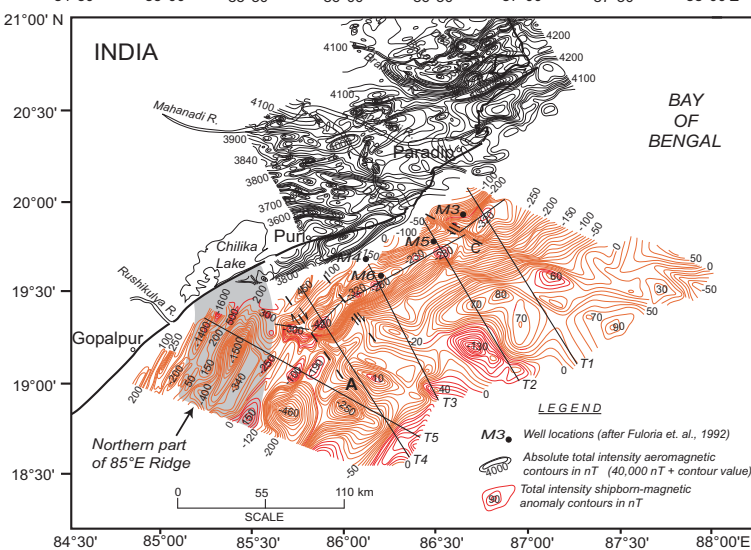


Figure 4b

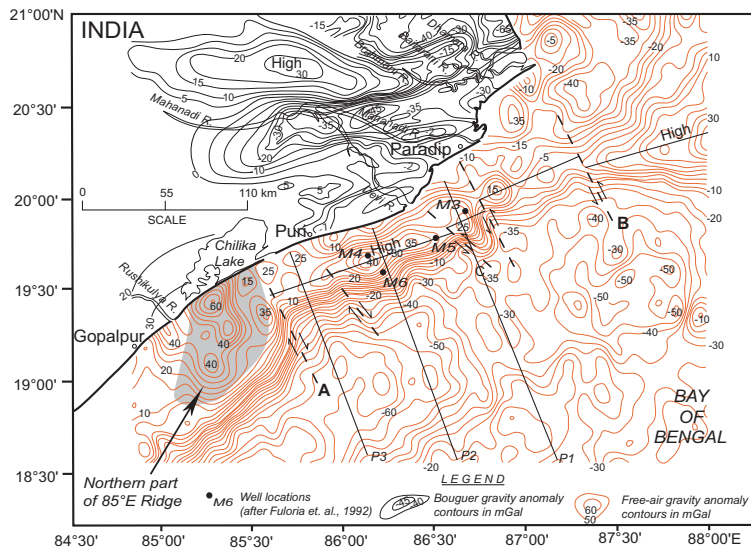


Figure 4c

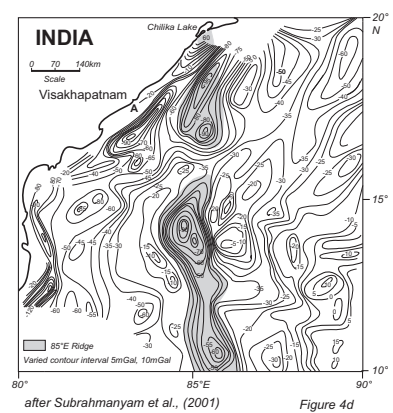


Figure 4d

Figure 4

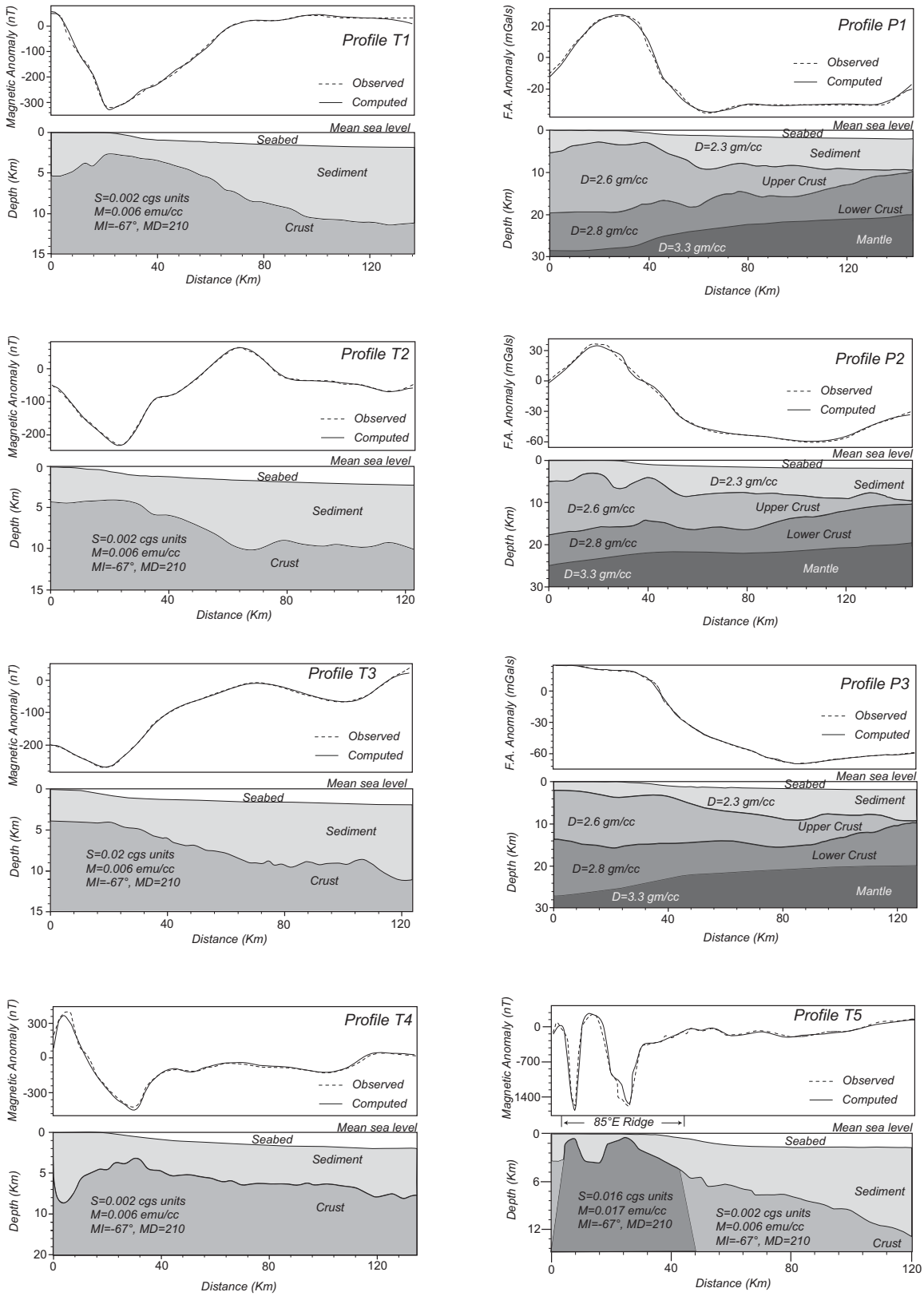


Figure 5

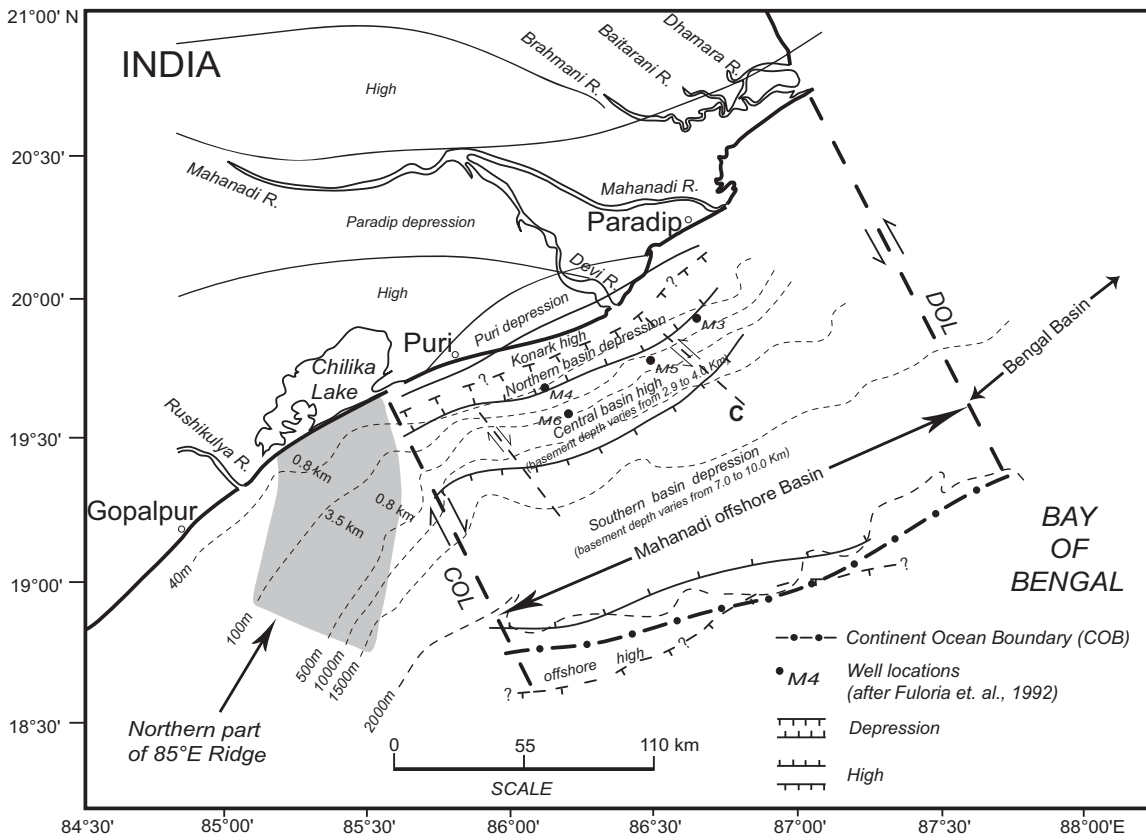


Figure 6

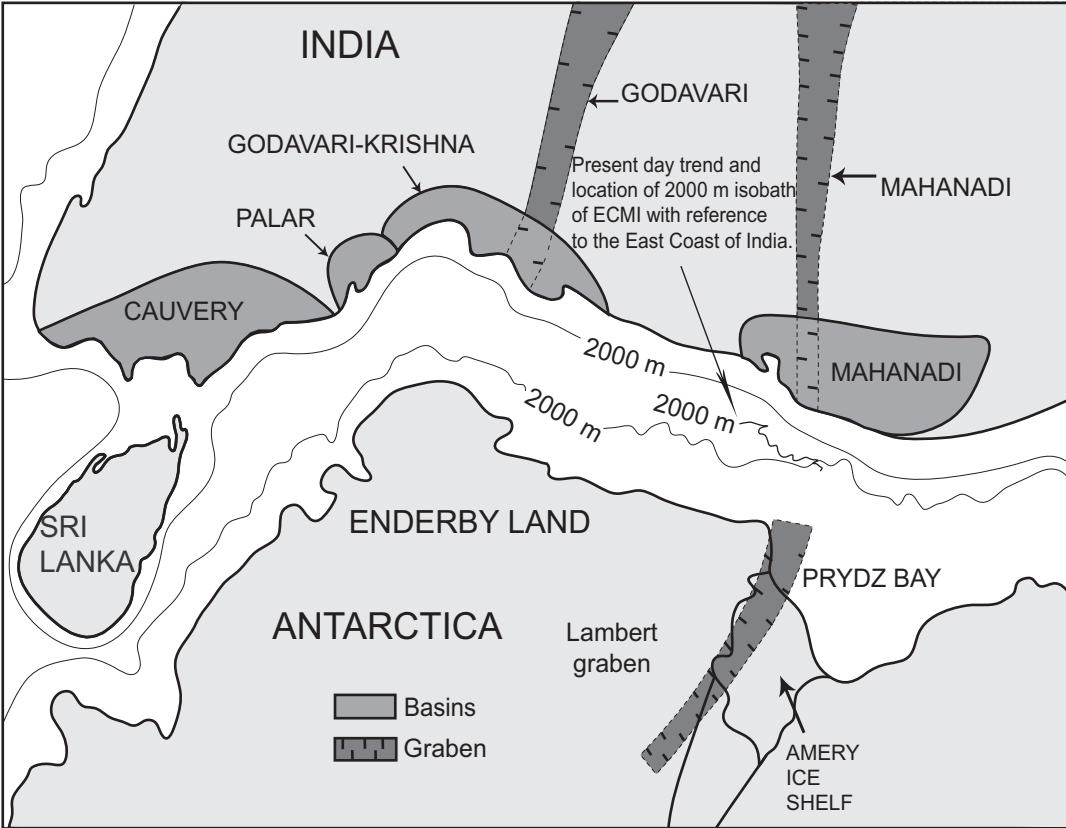


Figure 7