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Seafloor Geomagnetic Sounding near the 85°E Ridge in the Bay of Bengal

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Seafloor geomagnetic field variations in three components were recorded in the Bay of Bengal near the 85°E ridge, to investigate whether the negative gravity anomaly over the ridge is due to thick sedimentary deposit or due to a thick crust. Comparison of the X-, Y- and Z-variations in the vicinity of the 85°E ridge and near the continental margin suggests that a resistive thick crust underlies the 85°E ridge. The validity of conclusions arrived at from a simple inspection of magnetograms is supported by numerical calculations using a thin sheet approximation.

1. Introduction

The Bay of Bengal in the northeast Indian Ocean is a geologically complex region with deepsea fans, submarine canyons, subduction zones and two aseismic ridges: namely the Ninety East and 85°E ridges. Among these, the 85°E ridge is one of the least studied structures. The seismo-geological map derived from marine geophysical and other geological data (Sastri *et al.*, 1973) indicates the presence of a crustal upwarp around 85°E, which was not active during the period of sediment deposition. Seismic data (Curray *et al.*, 1982; Liu *et al.*, 1982) have partially defined the ridge crest and its flanks, and a significant anomaly in the gravity field has been noted in the vicinity of the ridge: the area shows a negative free-air gravity anomaly of -60 mgal (Liu *et al.*, 1982).

Generally seafloor aseismic ridges show positive gravity anomalies; for example the Ninety East ridge has a strong positive gravity anomaly. However the 85°E ridge differs from other aseismic ridges in being completely buried by sediments. This paper addresses the question why the gravity anomaly over the 85°E is negative. There are two ways in which this unusual feature could be explained:

(i) Liu *et al.* (1982) attribute the gravity low to a thickening of oceanic crustal material forming the ridge, with an underlying root in the lithosphere, as given in Fig. 1.

(ii) According to Rao and Rao(1986), the basement near the 85°E meridian in the Bay of Bengal had been pushed down, forming a graben-like structure with loading by a thick sedimentary column. This structure causes a large negative gravity anomaly as shown in Fig. 2.

Generally oceanic crustal material is considered to be less electrically conductive than sedimentary material. So if the hypothesis of Liu *et al.* is correct, the sub-surface structure beneath the ridge will be a poor conductor; in the hypothesis of Rao and Rao, the same will be a good conductor. Electric current induced in the Bay of Bengal ocean crust by transient geomagnetic variations will avoid flowing through the 85°E ridge in the first case, and may concentrate there in the second case. The two possible structures may produce different signatures in geomagnetic variation recorded on the seafloor near the ridge. Thus simultaneous records of magnetic variations from a linear array of magnetometers across the ridge could show whether induced electric current is being concentrated under the ridge or is being deflected away from the ridge.

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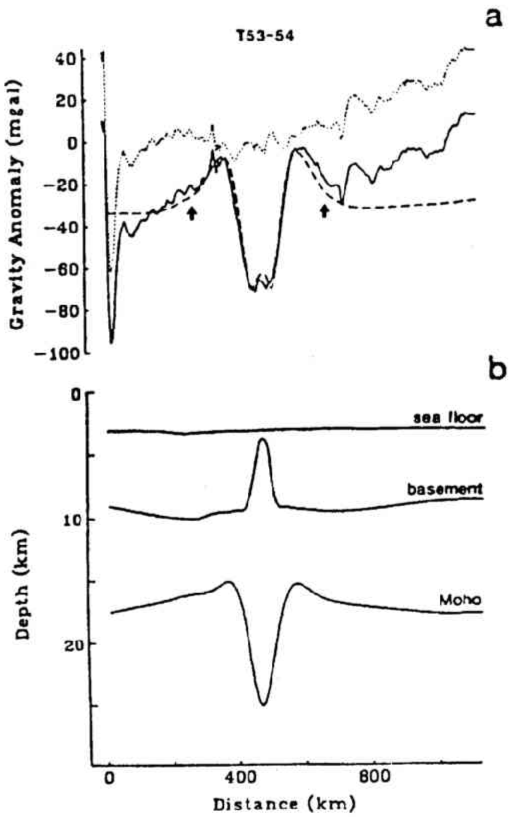


Fig. 1. (a) A comparison between the observed free air gravity anomaly (solid line), the predicted anomaly for the best model (dashed line) and residual gravity (dotted lines). (b) The "best model" (after Liu et al., 1982).

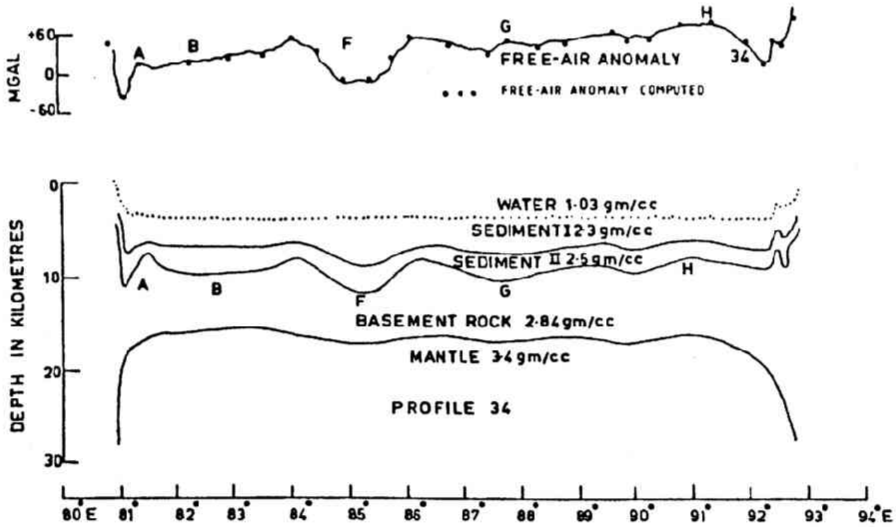


Fig. 2. Crustal structure and free air gravity anomaly observed and predicted (after Rao and Rao, 1986).

The 85°E ridge is a north-south oriented structure while the ionosphere-magnetosphere current systems near the magnetic dip equator usually produce an inducing field which has no east-west component. Such inducing fields will thus be expected to be aligned with the 85°E ridge, and the usual method of looking for reversals in the sense of Z-variations across a conducting region may not be straightforward here. However to the extent that induced electric currents in the Bay of Bengal are deflected from an east-west path by the resistive Indian landmass, then a conductor associated with the 85°E ridge structure may also disturb the flow of the induced electric currents and show its signature in transient geomagnetic variations recorded on the seafloor. Given that the induction process may be 3-dimensional in the Bay of Bengal, the present experiment has been the exploratory one of installing seafloor magnetometers across the 85°E ridge to seek evidence of anomalous conductivity structure there.

2. Data collectionn and processing

The deployment of the ocean bottom magnetometers (OBMs) was done in two phases, and the station locations are shown in Fig. 3. These sites were selected with respect to a seismo-geological map of the Bay of Bengal prepared by the Oil and Natural Gas Commission (personnel communication). Phase I consisted of five seafloor stations with a land reference station at Salem (SLM), Tamil Nadu. Sites were selected such that BYB 5 and BYB 8 were on the western and eastern flanks of the 85°E ridge, while BYB 6 and BYB 7 were over the ridge. BYB 9 was selected to be remote from both the 85°E ridge and the Ninety East ridge. For phase I, simultaneous data were collected for a period of 12 days in March 1991.

Phase II also had five seafloor stations. Here station BYB 10 was near the eastern continental margin of India, BYB 12 and BYB 14 were over the western and eastern flanks of the ridge, and BYB 13 right over the ridge. BYB 11 was between the eastern continental margin of India and the 85°E ridge and remote from both the places. For phase II, simultaneous data were collected for a period of 16 days in February-March 1992, and data from the permanent magnetic observatory Annamalainagar (ANR) was used as the land reference station. Details of station locations and recorded data are given in Table 1.

The OBM used is basically a fluxgate type magnetometer having ring core sensors with low temperature drift and sensitivity of 0.1 nT (Segawa *et al.*, 1986). Lowering of the OBMs were car-

Table 1. Details of the station locations and the data sets.

Stations	Phase	Position		Depth	Sampling	Period
		North	East	(m)	(min)	(Days)
SLM	I	11°55′	78°10′	LAND	1	20
BYB 5	I	14°00′	84°50′	3138	1	12
BYB 6	I	14°00′	85°10′	3125	1	12
BYB 7	I	14°00′	85°30′	3070	1	12
BYB 8	I	14°00′	86°00′	3072	1	12
BYB 9	I	14°00′	88°00′	2980	1	12
ANR	II	11°22′	79°41′	LAND	1	*PMO
BYB 10	II	12°00′	81°00′	3310	1	16
BYB 11	II	12°00′	83°00′	3430	1	16
BYB 12	II	12°00′	85°00′	3325	1	16
BYB 13	II	12°00′	85°30′	3317	1	16
BYB 14	II	12°00′	86°00′	3285	1	16

*Permanent Magnetic Obsevatory.

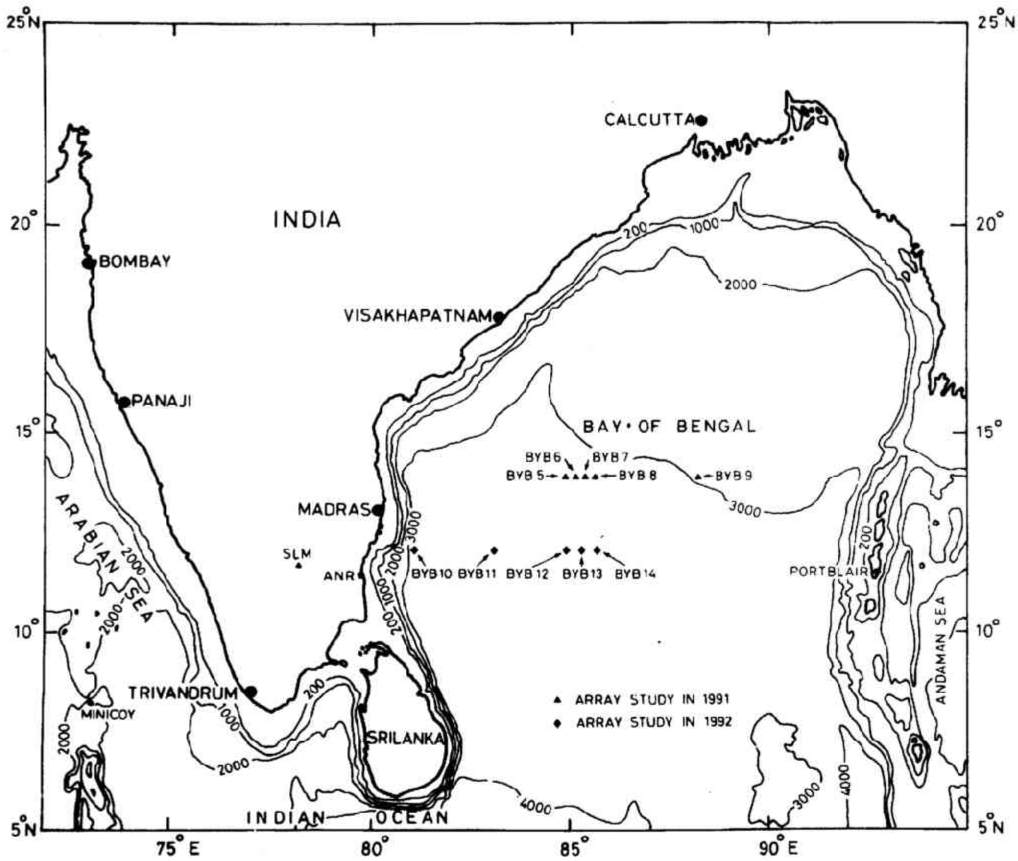


Fig. 3. Station locations with detailed bathymetery of Bay of Bengal.

ried out by free falling from the sea surface, after the sites of deployment were accurately located using the Global Positioning System (GPS). The data were collected at a one minute sampling interval using a Z-80 microprocessor-based system, and stored in Erasable Programmable Read Only Memory (EPROM). Each EPROM card has a capacity of 128 K bytes, and can store up to one month of three-component data. Recovery of the instruments from the seafloor was conducted by an onboard acoustic release system.

The OBM assembly settles at the seafloor in a random orientation, but upright because of the weight attached with it. The sensor assembly is mounted on a gimbal so the horizontal sensors are oriented in a horizontal plane while the vertical sensor is oriented in a vertical plane. The vertical sensor thus measures the field directly, while the two horizontal sensors are in a direction orthogonal to each other but at a random orientation with respect to geographic north and east. Since the system measures the values of ambient field components, the values recorded during the quiet periods in night-time can be used in conjunction with model values from International Geomagnetic Reference Field (IGRF) to estimate the orientation of the two horizontal sensors through the relations:

$$\sin\theta = \frac{X_2Y_1 - X_1Y_2}{X_1^2 + Y_1^2}, \tag{1}$$

$$\cos\theta = \frac{X_1X_2 + Y_1Y_2}{X_1^2 + Y_1^2}, \tag{2}$$

where X_1 and Y_1 are the northerly and easterly components of the field values given by IGRF, X_2 and Y_2 are the field values recorded by the OBM sensors and θ is the angle of orientation of the horizontal sensors with respect to the geographical north.

Once the orientation angle θ is known, the geomagnetic field components in the geographical north (X) and east (Y) can be computed using measured X_2 and Y_2 through the relations:

$$X = X_2.\cos\theta - Y_2.\sin\theta, \tag{3}$$

$$Y = X_2.\sin\theta + Y_2.\cos\theta. \tag{4}$$

3. Analysis, Results and Discussion

Selected data were first plotted for visual comparison. Since the area under consideration is an equatorial region, we restricted ourselves to the local night-time data only for analysis, because the inducing field then should be uniform and have no Z-component of external origin. Figure 4 shows the stack plots of one of the local night-time geomagnetic variations recorded simultaneously for phase I stations, corresponding to 1231-0030 Hrs (UT) of 19–20 March 1991. Figure 5 shows a similar set of data collected from phase II stations corresponding to 1231-0030 Hrs (UT) of 2–3 March 1992. Data from stations BYB 8 and BYB 12 were found noisy and could not be used for analysis.

Careful examination of such time series reveals important features of the data. The magnetic field components shown in the diagram are X-(geographical north), Y-(geographical east) and Z-(vertical downward). We notice that the Z-component fluctuations at seafloor stations in the close vicinity of 85°-86°E longitude are nearly zero. Normally near a conducting zone, for the appropriate polarization of the inducing field, one would expect non-zero Z-variations, with a phase reversal at the two edges. The nearly zero Z-variations recorded near the 85°E ridge thus give no evidence of lateral conductivity contrast underneath.

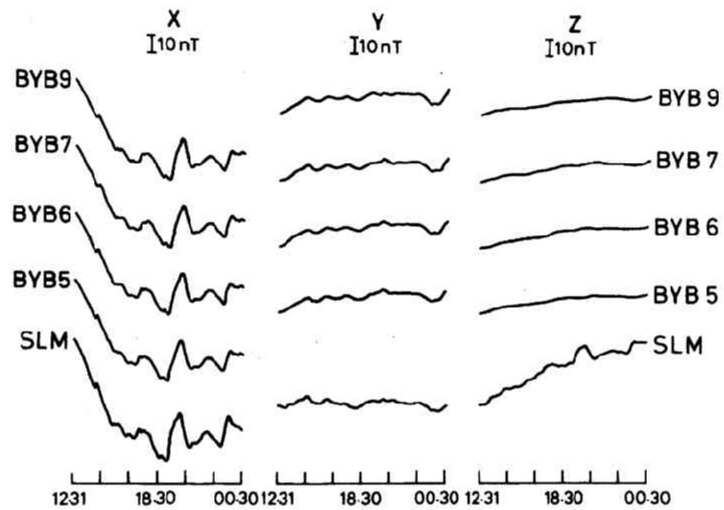


Fig. 4. Geomagnetic field variations recorded simultaneously for phase I stations corresponding to 1231-0030 Hrs (UT) of 19–20 March 1991.

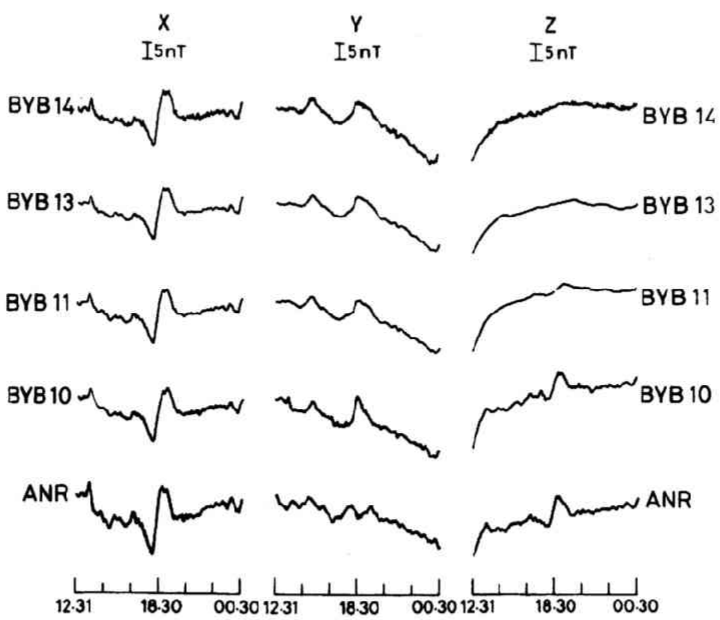


Fig. 5. Geomagnetic field variations recorded simultaneously for phase II stations corresponding to 1231-0030 Hrs (UT) of 2–3 March 1992.

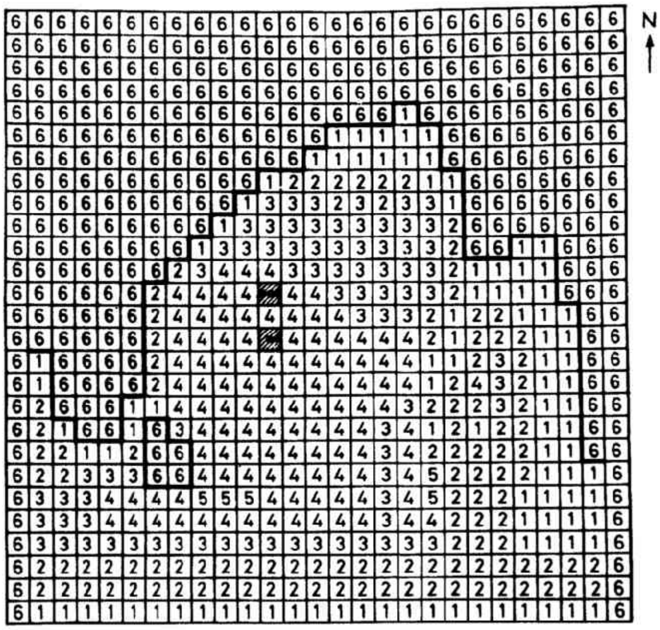
At seafloor station BYB 10 (near the continental margin) and the land stations SLM (phase I) and ANR (phase II), Z-variations are prominent. Further the Z- and X-components are in-phase at all these stations. The explanation for this behaviour is that, corresponding to a positive X-variation, the external current in the equatorial region is eastward and the related induced electric current in the water and the sub-surface region would be westward. At the continental margin, the westward current gets deflected in the north-south direction due to the land-sea boundary.

Returning to the sites near the 85°E ridge, and away from the coast line, an external current during night hours which was uniform, and oriented in an east-west direction, would produce only north-south (X) field and no east-west (Y) field. However, eventhough Z-variations are nearly zero at the sites near the 85°E ridge, Y-variations are not zero at these sites. To further investigate the situation envisaged where the Y-signals observed on the seafloor are of internal origin only, while X has both external and internal contributions, we now take a 3-D model of the Bay of Bengal and solve it numerically.

4. Numerical Modelling

If conductivity anomalies are confined to a surficial layer, the computational procedure for the numerical solution of 3-D structure can be greatly simplified by representing the non-uniform layer as a thin sheet of variable conductance (Price, 1949). The charges collected at conductivity discontinuities affect the local electric field (Price, 1973). Examples of the formulations approximating 3-dimensional structures by thin sheets are those by Vasseur and Weidelt (1977), and Dawson and Weaver (1979). Such algorithms have been applied to a variety of real and synthetic problems. We used the thin sheet algorithm of Vasseur and Weidelt (1977) for estimating the electric field components (E_x and E_y) and the magnetic field components (B_x and B_y) in a model of Bay of Bengal (Fig. 6).

In this model the Bay of Bengal between the east coast of India and the west coast of



THIN SHEET CONDUCTANCE DISTRIBUTION

No.	Conductance (S)
1	660
2	3300
3	6600
4	9900
5	13200
6	10

Fig. 6. Conductance map of Bay of Bengal. Solid circles in the hatched area are the sites of seafloor stations BYB 5, BYB 6, BYB 7 of phase I and BYB 13, BYB 14 of phase II.

Burma(Myanmar) is divided into a 27×27 mesh, with a grid spacing of 100 km. The whole region is that between 5°–25°N latitude and 75°–100°E longitude. In Vasseur and Weidelt algorithm, the anomalous domain must be surrounded by a region of normal structure. The thin sheet approximation is ideally suited for a sea water layer, which can be considered to have negligible thickness for periods greater than a few hundred seconds. Here we have taken the average sea water conductivity (σ) as 3.3 S/m (e.g. Filloux, 1987). The conductance of each cell is calculated by considering the bathymetry of the region. The edge effect has been minimised by extending grids to sufficently large distance away from the observational domain, and by gradually tapering conductance values. Five grid cells were added to the bottom (southern side) of the conductance map. Their conductances are 9,900 S (1 grid), 6,600 S (1 grid), 3,300 S (2 grids) and 660 S (1 grid) as shown in Fig. 6. Two grid cells of conductance 10 S are added to the top (northern side) of the conductance map. Similarly one grid cell of conductance 10 S is added to either (eastern and western) sides of the conductance map. This way the anomalous structure was kept sufficently away from the edges of the model. Since the sub-surface electrical conductivity pattern of Bay of Bengal is not known, the thin sheet of variable conductance was considered to overlie a half space of 0.001 S/m conductivity (Weaver, 1982; Jozwick and Beamish, 1986). Thus the thin sheet conditions are satisfied every where. Computations were made with an inducing magnetic field of 1 nT having a north-south component only. Iterations were continued till the difference between successive values reduces to 10^{-7}. Once the convergence has been obtained, the electric field in the northerly and easterly directions (E_x, E_y) are printed. Significant non-zero E_x was seen in certain area of the Bay of Bengal, which immediately suggest that the sub-surface geoelectric structure has introduced perturbation in the east-west flow of current. We stress again that the inducing field has no E_x component. Once E_x, E_y are known and we assume that the conductivity of sea water is uniform all through, we can estimate current strength through the sea water column as:

$$J_x = \sigma.E_x.d, \tag{5}$$

$$J_y = \sigma.E_y.d, \tag{6}$$

where d is the thickness of sea water column. Knowing the current strength, change in field strength in the two sides of the thin sheet are given by:

$$B_x = \mu_o.J_y = \mu_o.\sigma.E_y.d, \tag{7}$$

$$B_y = \mu_o.J_x = \mu_o.\sigma.E_x.d. \tag{8}$$

So far as B_y is concerned the field observed at the sea bottom is totally of internal origin. With respect to B_x, the current in water column is in a direction opposite to the external field. Hence the current in the sea water attenuates the external field observed at sea surface, and a computation of the attenuation has been carried out for a period of 60 min. The computed values give an attenuation of 21.74% for phase I, corresponding to a water depth of 3000 m; and an attenuation of 35.25% for phase II, corresponding to a water depth of 3300 m.

To compare the model values with the observed attenuation, one requires sea surface and seafloor measurements. Due to the difficulty of making vector magnetic measurements at the sea surface, we followed the suggestion of Weaver(1963) and used land-based data to represent the sea surface measurements. We have used X- and Y-field variations recorded at SLM for phase I and ANR for phase II as the sea surface magnetic field components. Similar approximations have also been taken by Poehls and von Herzen (1976); Law and Greenhouse (1981); Lilley *et al.* (1987); Ferguson *et al.* (1990) and Heinson *et al.* (1993). Knowing the surface values, attenuation factors at BYB 5, BYB 6, and BYB 7 of phase I, and BYB 13 and BYB 14 of phase II were then calculated, and are given for different period ranges in Tables 2 and 3. The values corresponding to 45–60 min. range are in good agreement with the model calculations.

The thin sheet model was also used to investigate the occurrance of non-zero Y-signals on the seafloor, for an inducing field in a purely east-west direction. We found non-zero Y-signals at the seafloor stations of both phase I and phase II, with Y-amplitudes larger for phase II stations. The thin sheet model thus indicates that Y-variations measured at the sites on the seafloor may be entirely due to the current induced in the sea water.

Table 2. Observed percentage of attenuation of X-Component on seafloor.

Periods (min.)	BYB 5	BYB 6	BYB 7
100–120	25.50	22.20	22.60
45–60	27.50	25.30	25.80
30–40	34.10	31.50	31.50
20–30	37.50	36.60	36.90
15–20	44.30	43.50	43.60

Table 3. Oberved percentage of attenuation of X-Component on seafloor.

Periods (min)	BYB 13	BYB 14
100–120	21.50	21.30
45–60	34.50	34.25
30–40	40.55	41.10
20–30	48.15	47.75

5. Conclusions

Seafloor magnetic data collected from the Bay of Bengal show some distinctive features. The vertical (Z) component of the field in the close vicinity of the 85°E ridge is nearly zero. Had the sub-surface comprised a significant electrical conductivity anomaly, there may have been a concentration of internal electric currents in a north-south direction, leading to non-zero Z-variations with a characteristic reversal pattern across the anomaly. As no such pattern is seen, the ridge appears as a resistive structure.

In model calculation for the Bay of Bengal, B_x attenuation estimated is in good agreement with observed values. Similarly the strengths of B_y, for both phase I and phase II sites, are also matching. In our calculations we do not include a conductor underneath the 85°E ridge and hence our results favour the proposition of Liu *et al.* (1982), that the gravity low over the 85°E ridge is due to the thickening of oceanic crustal material forming the ridge with its underlying root in the lithosphere. A more exact thin sheet model would need inclusion of sedimentary column.

The pattern of X- and Y-variations at the sea bottom in the Bay of Bengal confirms the suggestion of earlier workers on the deflection of electric current by land-sea contrast. The anomalous Z-variation observed near the continental margin is due to this perturbation in the flow of currents. Thus the seafloor magnetic field measurements recorded contribute to an understanding of the electric current pattern in the Bay of Bengal.

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REFERENCES

Curray, J. R., F. J. Emmel, D. G. Moore and R. W. Raitt, Structure, tectonics and geological history of the northeastern Indian Ocean, in *The Ocean Basins and Margins.*, Vol. **6**, The Indian Ocean, edited by A. M. E. Nairn and F. G. Stehli, pp. 399–450, Plenum, New York, 1982.

Dawson, T. W. and J. T. Weaver, Three dimensional induction in a non-uniform thin sheet at the surface of a uniformally conducting earth, *Geophys. J. R. Astron. Soc.*, **59**, 445–462, 1979.

Ferguson, I. J., F. E. M. Lilley and J. H. Filloux, Geomagnetic induction in the Tasman Sea and electrical conductivity structure beneath the Tasman Seafloor, *Geophys. J. Int.*, **102**, 299–312, 1990.

Filloux, J. H., Instrumentation and experimental methods for oceanic studies, in *Geomagnetism*, edited by J. A. Jacobs, Vol. I, part 3, pp. 143–247, Academic Press, 1987.

Heinson, G. S., A. White, L. K. Law, Y. Hamano, H. Utada, T. Yukutake, J. Segawa and H. Toh, EMRIDGE: The Electromagnetic Investigation of Juan de Fuca Ridge, *Marine Geophys. Res.*, **15**, 77–100, 1993.

Jozwick, W. and D. Beamish, A thin sheet model of electromagnetic induction in northern England and southern Scotland, *Geophys. J. R. Astron. Soc.*, **85**, 629–643, 1986.

Law, L. K. and J. P. Greenhouse, Geomagnetic variation sounding of the asthenosphere beneath the Juan de Fuca Ridge, *J. Geophys. Res.*, **86**, 967–978, 1981.

Lilley, F. E. M., J. H. Filloux, I. J. Ferguson, N. L. Bindoff and P. J. Mulhearn, The Tasman Project of Seafloor Magnetotelluric Exploration: experiment and observations, *Phys. Earth Planet. Inter.*, **53**, 405–421, 1989.

Liu, C.-S., D. T. Sandwell and J. R. Curray, The Negative Gravity Field Over the 85°E Ridge, *J. Geophys. Res.*, **87**, 7673–7686, 1982.

Poehls, K. A. and R. P. von Herzen, Elecrical resistivity structure beneath the north-west Atlantic Ocean, *Geophys. J. R. Astron. Soc.*, **47**, 331–346, 1976.

Price, A. T., The induction of electric current in non-uniform thin sheet and shells, *Q. J. Mech. Appl. Math.*, **2**, 283–310, 1949.

Price, A. T., The theroy of Geomagnetic induction, *Phys. Earth Planet. Inter.*, **7**, 227–273, 1973.

Rao, T. C. S. and V. B. Rao, Some structural features of the Bay of Bengal, *Tectonophysics*, **124**, 141–153, 1986.

Sastri, V. V., R. N. Sinha, G. Singh and K. V. Murthy, Stratigraphy and tectonics of the sedimentary basins on the east coast of Peninsular India, *Amer. Assoc. Petrol. Geol. Bull.*, **57**, 655–678, 1973.

Segawa, J., Y. Hamano, H. Utada and H. Toh, A Sea floor magnetometer model OBM-S4, *J. Geodetic Soc. Japan.*, **32**, 248–273, 1986.

Vasseur, G. and P. Weidelt, Bimodal electromagnetic induction in non-uniform thin sheet with an application to the northern Pyrenean induction anomaly, *Geophy. J. R. Astron. Soc.*, **51**, 445–462, 1977.

Weaver, J. T., The electromagnetic field within a discontinuous conductor with reference to geomagnetic micropulsations near coastline, *Can. J. Phys.*, **41**, 484–495, 1963.

Weaver, J. T., Regional induction in Scotland; An Example of Three-Dimensional Numerical Modelling Using the Thin Sheet Approximation, *Phys. Earth Planet. Inter.*, **28**, 161–180, 1982.