Analysis of Multi-Channel Seismic Reflection and Magnetic Data Along 13° N Latitude Across the Bay of Bengal

D. GOPALA RAO, G. C. BHATTACHARYA, M. V. RAMANA, V. SUBRAHMANYAM, T. RAMPRASAD,
K. S. KRISHNA, A. K. CHAUBEY, G. P. S. MURTY, K. SRINIVAS, and MARIA DESA
National Institute of Oceanography, Dona Paula, Goa 403004, India

S. I. REDDY, B. ASHALATA, C. SUBRAHMANYAM, G. S. MITAL, R. K. DROLIA, S. N. RAI, S. K. GHOSH, and R.N. SINGH
National Geophysical Research Institute, Uppal Road, Hyderabad, 500 007, India

R. MAJUMDAR
Jadavpur University, Calcutta, 700 032, India

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Abstract. Analysis of the multi-channel seismic reflection, magnetic and bathymetric data collected along a transect, 1110 km long parallel to 13° N latitude across the Bay of Bengal was made. The transect is from the continental shelf off Madras to the continental slope off Andaman Island in water depths of 525 m to 3350 m and across the Western Basin (bounded by foot of the continental slope of Madras and 85° E Ridge), the 85° E Ridge, the Central Basin (between the 85° E Ridge and the Ninetyeast Ridge), the Ninetyeast Ridge and the Sunda Arc. The study revealed eight seismic sequences, H1 to H8 of parallel continuous to discontinuous reflectors. Considering especially depth to the horizons, nature of reflection and on comparison with the published seismic reflection results of Curray *et al.* (1982), the early Eocene (P) and Miocene (M) unconformities and the base of the Quaternary sediments (Q) are identified on the seismic section. Marked changes in velocities also occur at their boundaries.

In the Western Basin the acoustic basement deepening landward is inferred as a crystalline basement overlain by about 6.7 km of sediment. In the Central Basin possibly thicker sediments than in the Western Basin are estimated. The sediments in the Sunda Arc area are relatively thick and appears to have no distinct horizons. But the entire sedimentary section appears to be consisting of folded and possibly faulted layers.

The comparatively broader wavelength magnetic anomalies of the Central Basin also indicate deeper depth of their origin. Very prominent double humped feature of the 85° E Ridge and broad basement swell of the Ninetyeast Ridge are buried under about 2.8 km thick sediments except over the prominent basement high near 92° E longitude. The positive structural relief of the buried 85° E Ridge in the area is reflected in magnetic signature of about 450 nT amplitude. Flexural bulge of the 85° E Ridge and subsidence of the Ninetyeast Ridge about 24 cm my^{-1} rate since early Eocene period have been inferred from the seismic sequence analysis.

1. Introduction

The Bay of Bengal sedimentary basin, one of the world's largest ocean basins, extends from 22° N to 7° S latitudes between 80° E and 93° E longitudes in the northeast Indian Ocean. The eastern boundary of Bay of Bengal is the Andaman Island Arc system which is also the eastern boundary of the Indian Plate. In the north and west it is surrounded by the passive margin of the eastern part of the Indian subcontinent. The most important tectonic elements of the Bay of Bengal and contiguous regions are: the passive eastern margin of India, the 85° E Ridge and the Ninetyeast Ridge, the intervening deep ocean basins with thick pile of sediments and the Sunda Arc systems with the associated back-arc Andaman Basin (Figure 1). Holeman (1968) estimated the annual discharge of sediments from Himalayas through the river systems clearing into the Bay of Bengal as 15×10^8 tons. Sediment accumulation in the Bay of Bengal extend the Bengal Fan to a distance of about 4000 km up to 7° S latitude.

The DSDP (Leg 22) and ODP (Leg 116) drill well sites investigations identified organic rich mud turbidities and pelagic clays since early Miocene, 78–82 Ma old basal sediments at site 217 and

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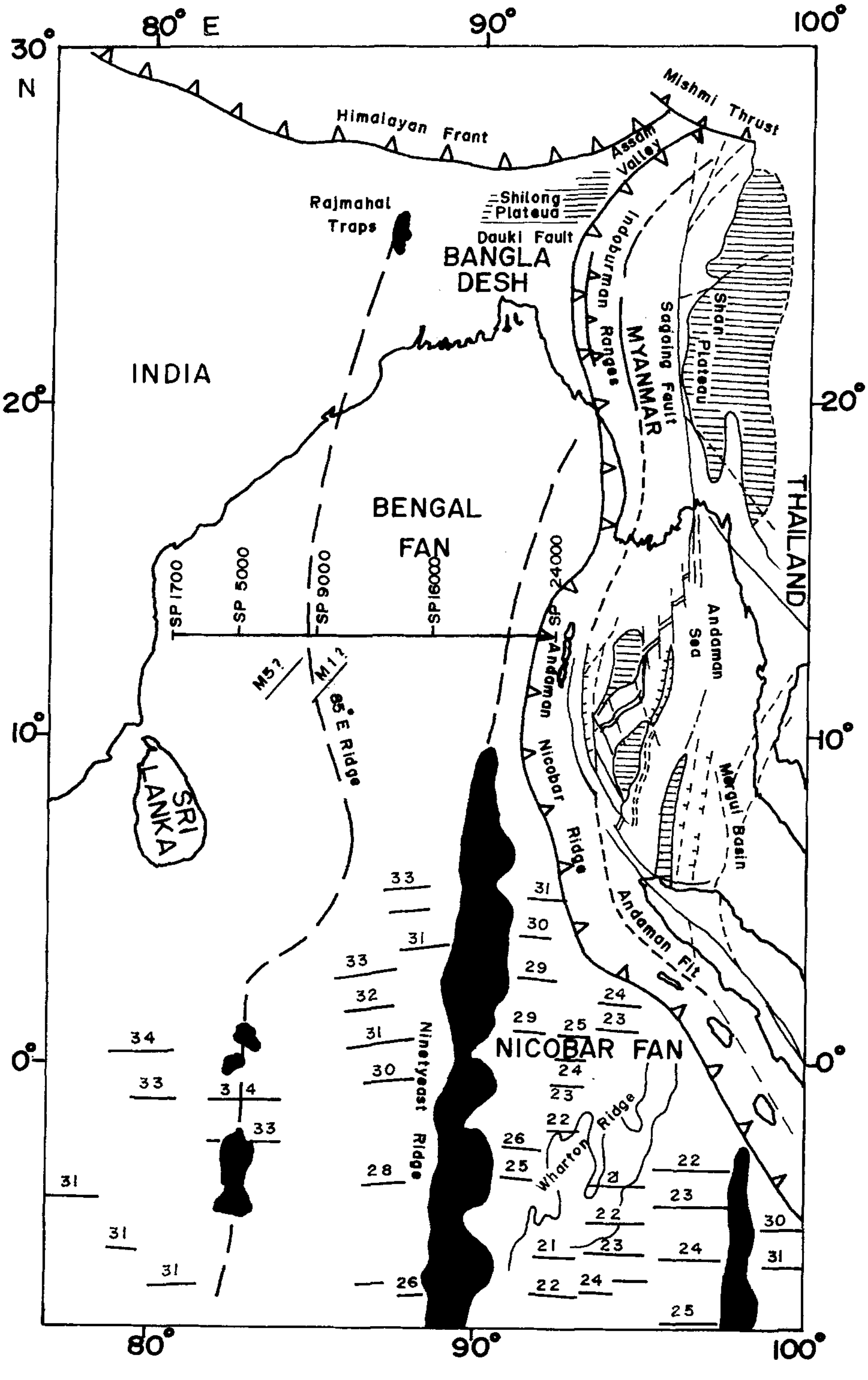


Fig. 1. Tectonic map of the northeastern Indian Ocean (after Curray, 1991) and the present study traverse shown with solid thick line with shot point numbers.

hotspot origin of the Ninetyeast Ridge (Pimm, 1972; Cochran, Stow *et al.*, 1987).

Curray and Moore (1971) have studied the growth of Bengal Fan sediments as early as in the early seventies and identified the prominent unconformities. Sediment influx rate was extrapolated into past suggesting the unconformity to be late Miocene corresponding to periods of orogeny in Himalayas.

Curray *et al.*, (1982) reviewed the existing geophysical data of the Bay of Bengal and proposed a tentative tectonic model of the evolution of the Bay of Bengal. Sediment thickness estimates have been made based on seismic reflection and refraction studies which revealed maximum thickness of 16 km in the offshore areas of Bangladesh. However, these estimates have been revised (e.g. Curray, 1991) suggesting an increased thickness of 22 km of this, 6 km pre-collision and 16 km post-collision sediments have been identified. Rao and Bhaskara Rao (1986) interpreted from model studies of the gravity and magnetic data a 'Marginal Basin' a 'Graben', a 'Central Basin', and the 'Ninetyeast Ridge'. Brune and Singh (1986) suggested 20 km thick crust for the basin area and 30 km beneath Ninetyeast Ridge from surface wave dispersion studies. The studies of Singh (1988) show a thick crust across Ninetyeast Ridge on its western side. The best fit models show an average of 23 km crust for the entire region which is characterized by a 7 km lower crustal layer with P wave velocity 7.7 km $\sec^{-1}$ under the sediment cover. He explained the anomalous crustal thickness as due to chemical differentiation and graded transformation of top mantle material into material having crustal-like velocity. In another effort, a comparative study of anomalous crustal structure of Bay of Bengal and other passive oceanic basins was given by Brune and Priestly (1989) stating that normal oceanic crust could alter into continent-like crust by mechanism related to stretching and rifting, thermal perturbation induced by emplacement of aseismic ridges and thick sediment cover.

The oldest identifiable magnetic lineations in the northeast Indian Ocean are anomaly numbers 32, 33 and 33b, indicating 78–82 Ma age crust, at 6° N latitude southeast of Sri Lanka. Seafloor spreading type magnetic anomalies are not reported till date for Bay of Bengal region. But various plate reconstruction models obtained for the Gondwanaland mass of Jurassic period, place the east coast of India against west coast of Australia, or adjacent to Enderby Land of Antarctica. In the widely accepted eastern Gondwanaland reconstruction model, east Antarctica is along the eastern margin of India. The breakup between the two was initiated at about 126 Ma corresponding to M4 anomaly (e.g. Curray and Munasinghe, 1991).

Present Data

Multichannel seismic reflection, magnetic and bathymetry data have been collected in Bay of Bengal in cruise 31 of ORV Sagar Kanya during March–April, 1987 along a transect shown in Figure 1. It is along 13° N latitude and between 80°30′ E and 92°20′ E longitudes.

For seismic data acquisition a DFS V unit with a 24 channel streamer (group interval 25 m) and a D-type airgun array as energy source (7.98 l) were used. The data were recorded at 4 ms sampling interval and 12 s record length. Shot interval is 50 m yielding a 6-fold subsurface coverage during the survey.

The total intensity of earth's magnetic field was measured by towing the Geometrics magnetometer sensor about 300 m behind the ship. Data were acquired at intervals of 50 m. Bathymetric data were acquired using the Honeywell Elac narrow-beam echosounder System used with a beam width of 3.4° at 12 kHz and operated in the single stylus mode. Integrated Navigation System (INS) was used for position location with an accuracy of ± 50 to 150 m. The seismic data were processed using the standard processing techniques to obtain a Stack section. The seismic section and its interpreted line drawing together with magnetics are shown in Figure 2.

Bathymetry

Along the transect the water depths range from 525 to 3350 m. The depth at the base of the continental slope off Madras coast is about 3350 m which gradually rises to 2900 m near 90° E longitude (Figure 2). Two shallow topographic depressions, approx. 100 km wide and about 100–110 m deep, are noticed on the profile. The first one is about 60 km east from the base of the continental slope off Madras Coast and the second one is at the base of the continental slope off Andaman Coast. The seabed topography reveals channels at several places with varied dimensions. They are the main turbidity current channels, 750–7500 m wide and

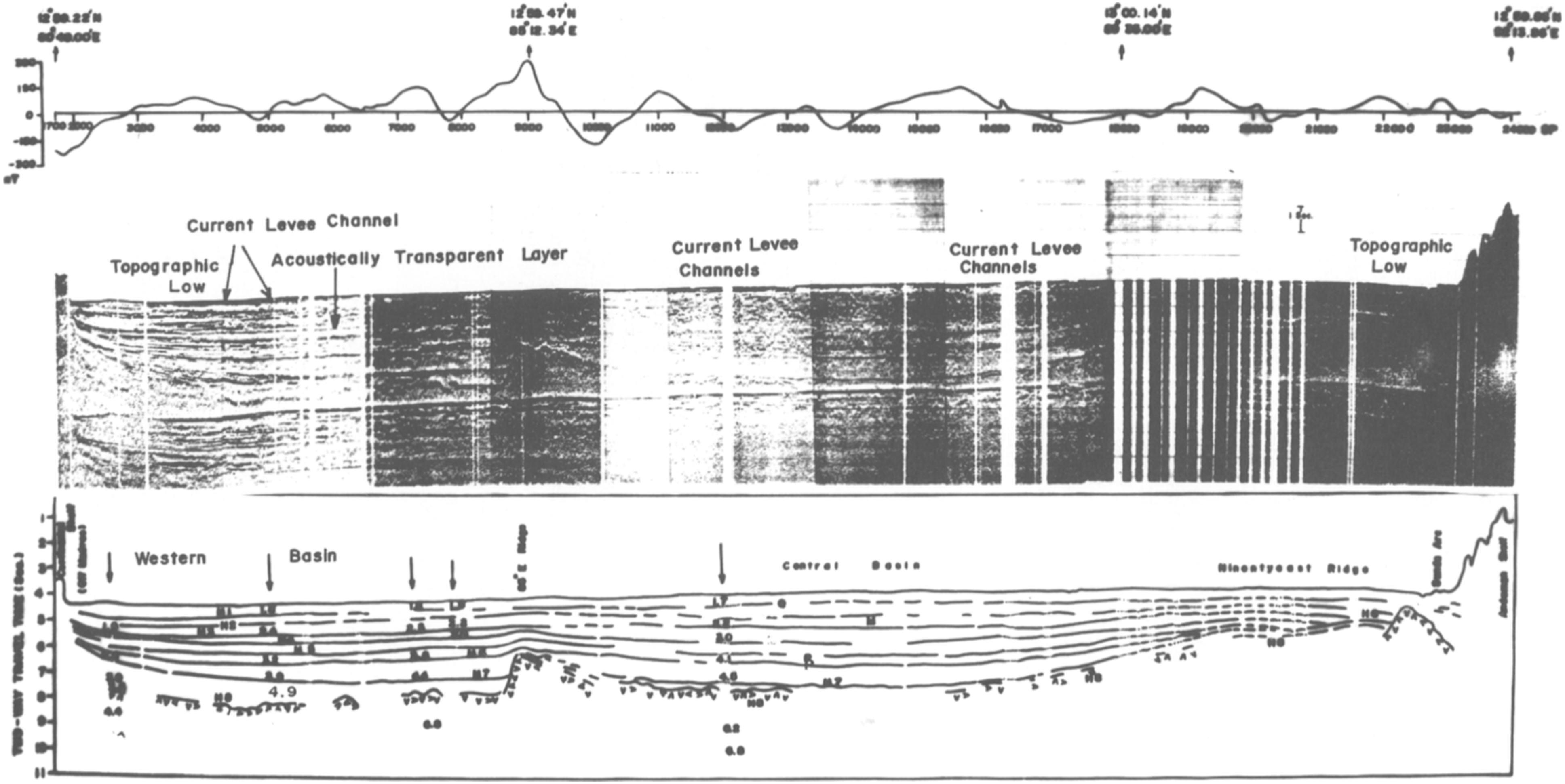


Fig. 2. Processed multichannel seismic reflection record along 13° N latitude across Bay of Bengal and its line diagram showing 8 seismic sequences, 85° E Ridge, Ninetyeast Ridge and discontinuous basement at places together with magnetic anomaly data. Arrows indicate seismic refraction stations (Curray *et al.*, 1982)

40–70 m deep, of the seafloor and occur between shotpoints (sps) 3500 to 6500, 10300 to 13000 and 14500 to 23200.

Seismic Sequence Analysis

On the seismic section we recognize the five structural elements namely Western Basin (between the continental shelf of Madras Coast and the 85° E Ridge), the 85° E Ridge, the Central Basin (between the 85° E Ridge and the Ninetyeast Ridge), the Ninetyeast Ridge and the Sunda Arc (between the Ninetyeast Ridge and the shelf off Andaman Island Arc) (Figure 2). Based on the continuous seismic reflections (Table II) eight seismic sequences, i.e. H1 to H8 with high impedance contrast at their bases are identified. In the Western and Central Basins the reflectors of the sequences H1 to H8 with high impedance contrast at their bases are identified. In the Western and Central Basins the reflectors of the sequences H1 to H4 are semi-continuous and parallel (Figures 2, 3a and b), unlike the relatively intense continuous reflective nature of the underlying sequences. The reflectors of the H5 to H8 sequences in the Western Basin are comparatively nearly parallel with intense reflectivity and H8 reflectors deepen to the west. While in the Central Basin they are weakly reflective units especially in the lower section. Sequence H1 is acoustically transparent, about 0.2 to 0.5 km thick and occurs throughout. In three zones, upper half of sequence H1 consist of parallel prominent opaque reflectors. They occur in the Western Basin and Central Basin. In the Western Basin this zone of the reflectors is about 150 km wide (sps 3500 to 6500). In the Central Basin the zone is about 130 to 140 km wide (sps 10300 to 13000) near to the 85° E Ridge and about 400 km wide (sps 14500 to 23200) towards the east of the basin. In these zones, besides continuity in the reflectors, abruptly truncated reflectors of limited extent occur at the seafloor and subsurface. Adjoining to them, subparallel reflectors with topographic relief (small in size) that are wedge-shaped in cross section which become thinner away from them occur. The truncations in the east are more wide, 0.8 to 8.0 km and deep, about 0.1 km. Intense reflections occur at base of the truncations. In general the composition of sediments of the Western Basin appear to be different from the Central Basin considering the stratal pattern and acoustic character. Much of the sediments (upper section of sequences H6 to H1) of the basins, about 3.6 km thick consist of alternate bands of acoustically transparent to opaque sediments. The opaque reflectors are most likely the Levee channel turbidities and marked by abrupt termination of the continued basal reflectors at places and instead they occur at greater depths. While the acoustically transparent reflectors represent the homogenous sediment distribution, the weakly reflective sediments of the sequence H7, about 2.0 km thick in the Central Basin are in contrast to the overlying sediments. In the Central Basin the basement (Figure 3b) below the sediments could not be mapped due to masking by strong multiples. In the Western Basin the H8 basal reflector at about 8.5 s (TWT) is the acoustic basement deepening to the west has maximum slope 1:12 (eastern margin between sps: 6100 to 6400). Its reflection pattern is subparallel to parallel continuous to uneven hyperbolic high intense reflection. Within the sequence H6 (Figure 3a) a lens-shaped reflection, 8 to 10 km wide and 350 m thick (considering 3.5 km s^{-1} velocity of the layer) with a large amplitude occur (between sps: 3500–3700) at about 7.2 s (TWT).

High amplitude reflections occur from the uneven acoustic basement at the base of the sequence H8. In both basins it deepens along the flanks of the almost north-south trending 85° E Ridge. The ridge is seen as a very prominent double-humped buried feature (Figure 3c) with its western limb being relatively steeper than the eastern limb. Some faint eastward dipping reflectors occur in the trough between the two humps of the 85° E Ridge. Thickness of sediments on the ridge is about 2.8 km. Variations in thicknesses of the sequences in the basins and on ridges are listed in Table I. Maximum thickness of the sediments of 6.7 km in the Western Basin and 6.2 km in the Central Basin is noticed. The sediments immediately overlying 85° E Ridge bears evidence of gentle bulging marking drape structure of sediments over it. The older sediment section, i.e. sequences H5 to H7 lying over crest of the ridge also show faint indication of faulting. The Ninetyeast Ridge is expressed as a totally buried broad basement swell (Figure 3d). At the eastern edge of the basement swell near 92° E longitude a very prominent basement high is noticed. The high also has a relatively steeper western limb and a gently sloping eastern limb. Thickness of sediments on the high is about 0.6 to 0.8 km. The reflectors of the seismic sequences H4/H3 to H1 show significant flexural down warp atop the ridge (sps: 21700 to 23300).

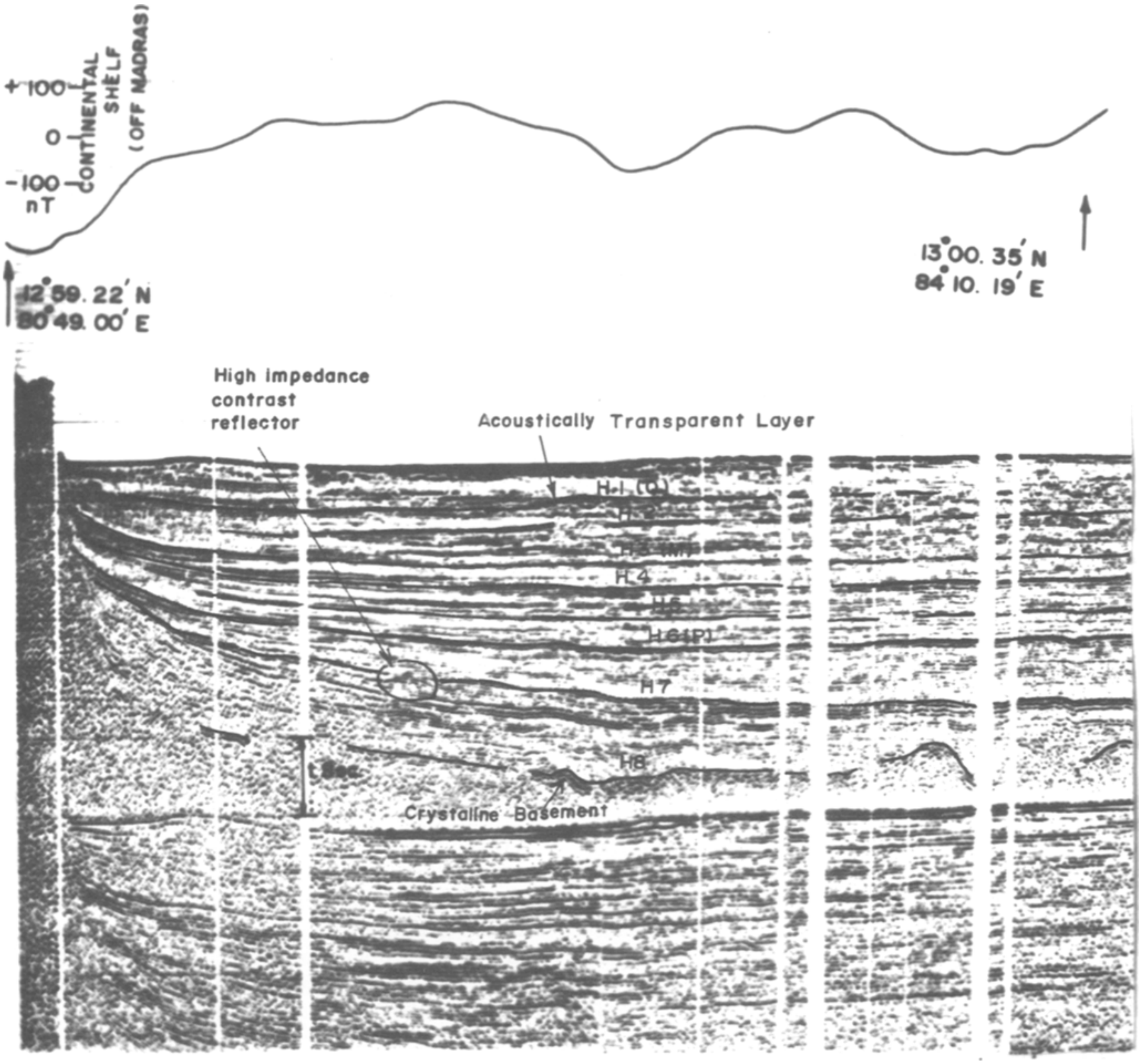
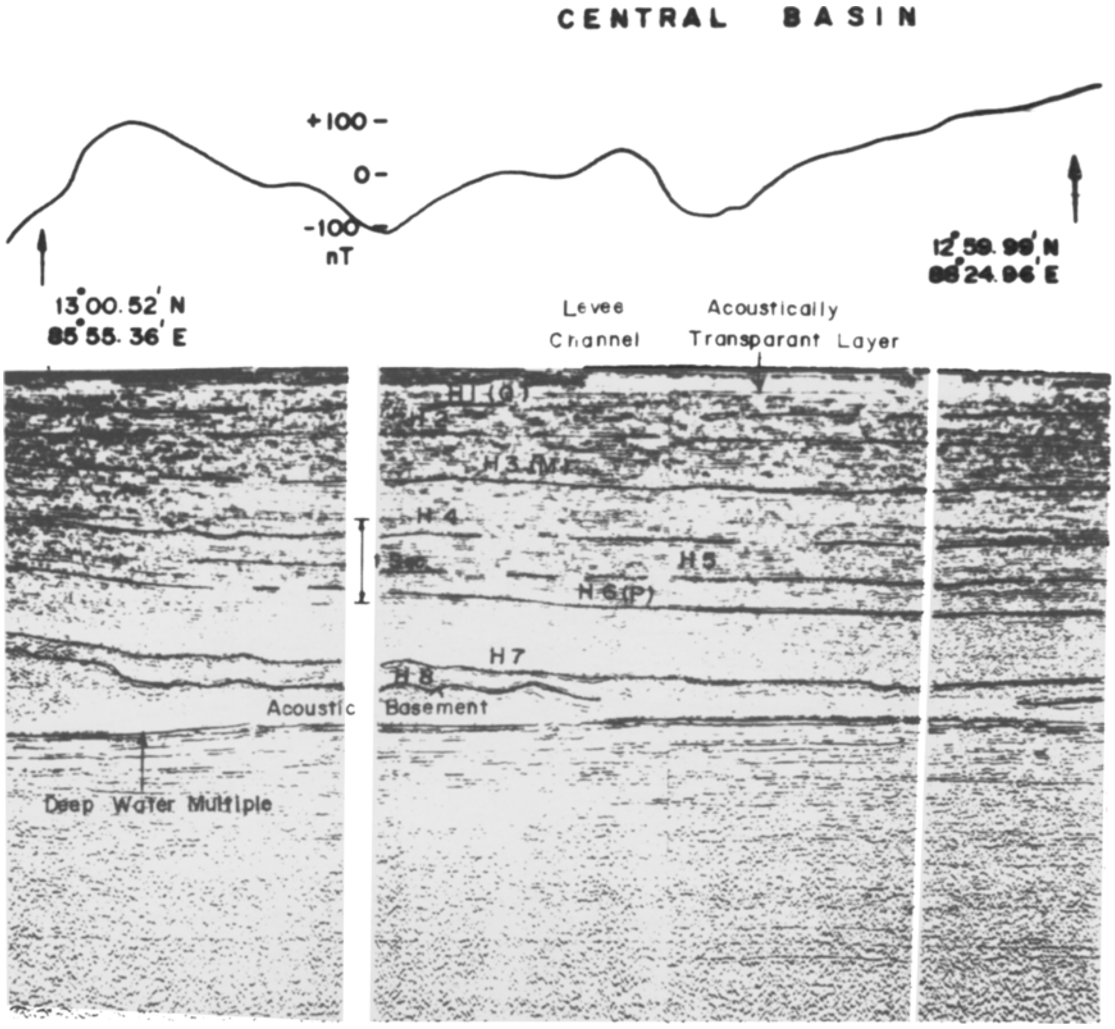


Fig. 3. Segments of seismic reflection records. (a) Western Basin, (b) Central Basin, (c) 85° E Ridge, (d) Ninetyeast Ridge.

The magnetic anomaly pictures (Figures 2 and 3c) indicate presence of a very prominent well-developed anomaly of about 450 nT amplitude over the 85° E Ridge. By contrast, over the Ninetyeast Ridge, the anomalies are high amplitude and short wavelength in nature superposed on broad wavelength subdued anomaly. In the Western Basin the anomalies occur over the acoustic basement reliefs. In the Central Basin they are broad in wavelength and high in amplitude.

Crustal Structure and Tectonics

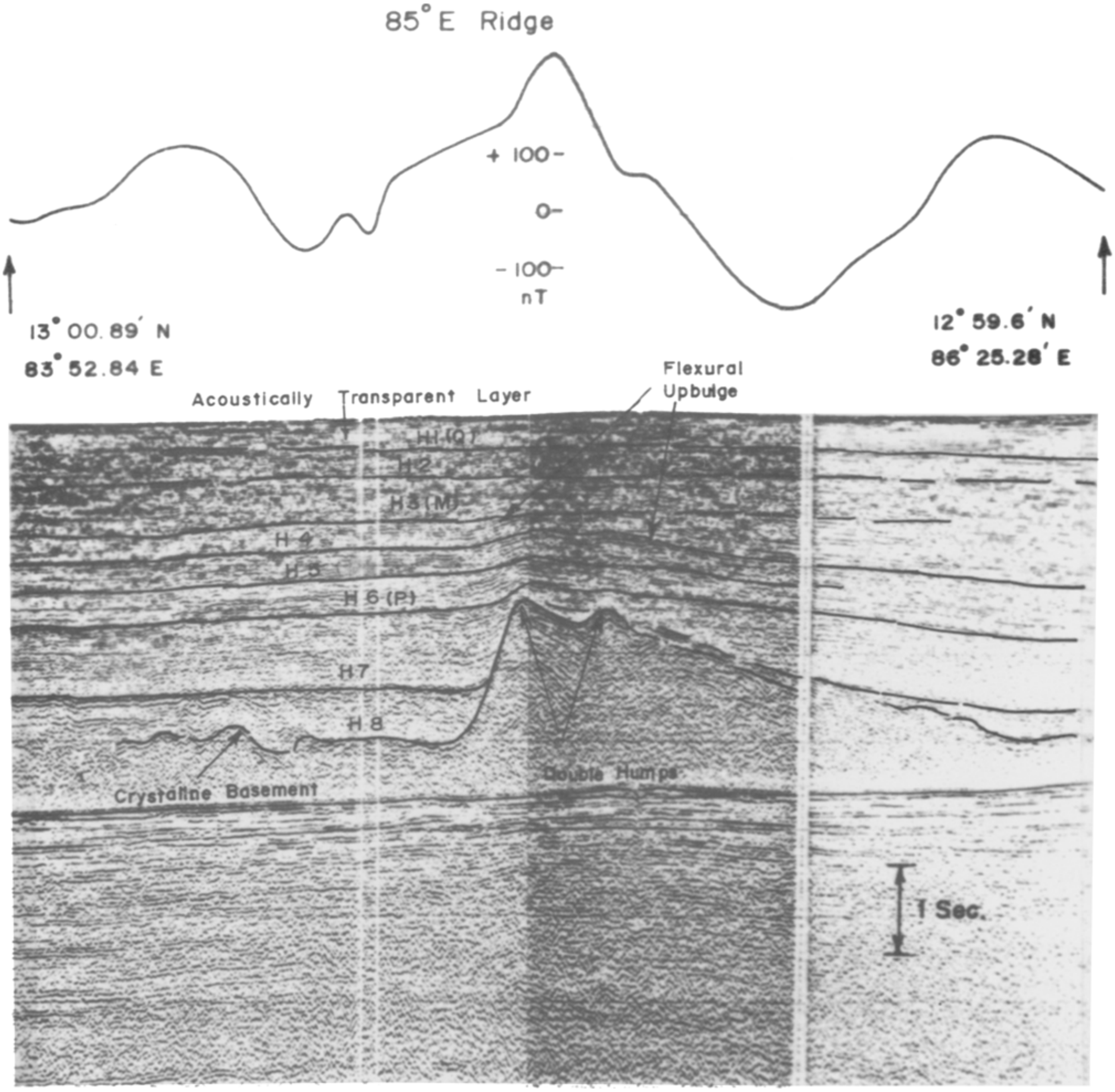
The subtle variations in reflectivity confined to the parallel reflectors of upper sequence (H1) and the underlying turbidities indicate variations in cut and fill type of turbidities of Levee channels. The DSDP and ODP site investigations identified silts and muds and dark grey organic rich mud turbidities at the distal parts (near to equator) of the sedimentary fan (Von der Borch, Sclater *et al.*,



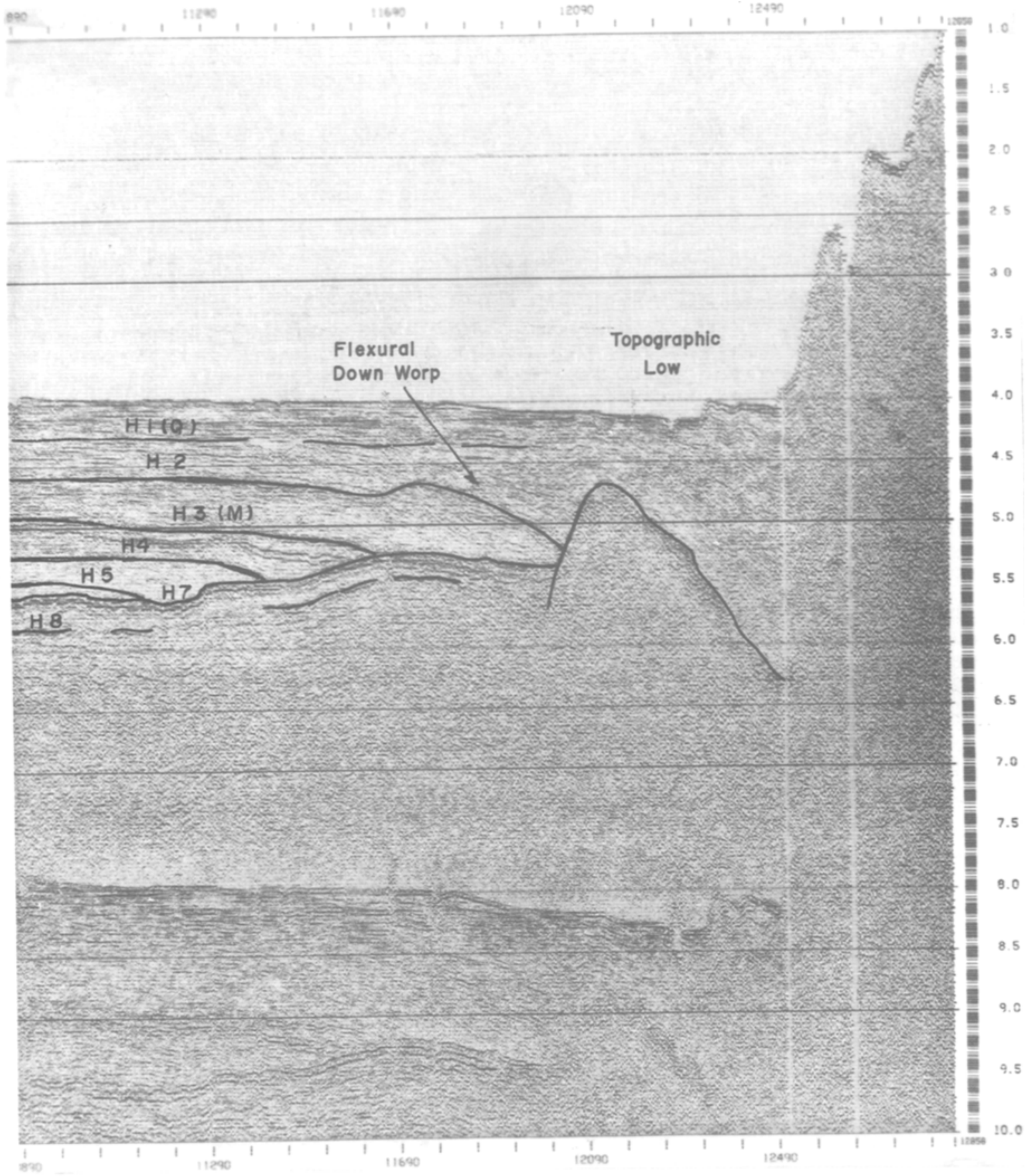
(b)

1972; Cochran, Stow *et al.*, 1987). Channel migration and lobe switching appear to cause these features. The relative variations in reflectivity and continuity of the sequences mark the coarse compact fraction sediments with intense parallel reflections. The DSDP Site 217 investigations identified coarse compact sediments, e.g. dolomite sandstones and chert at the base to clay rich nanno fossil ooze below seafloor (Von der Borch, Sclater *et al.*, 1972). The sequence H8 consisting of relatively intense nearly parallel reflectors in Western Basin, might represent the basal type sediments.

Stratigraphy of some of the sequences which are noted in Figure 2 are inferred by comparing their depth of occurrence and reflection pattern with seismic results of Curray *et al.* (1982) and DSDP site 217 investigations. The sequences H3 and H6 basal reflectors discussed above correspond to the unconformities in upper Miocene (M) and early Eocene (P) period, respectively. About 2.2 and 3.2 km s^{-1} velocities are also reported at boundaries of the sequences (Curray *et al.*, 1982). The upper section of the acoustically transparent sediments of sequence H1 with parallel reflectors might represent Pleistocene to Recent mud turbidite sediments. The acoustically transparent sediments, of 0.2 to 0.5 km thick, occur all along with a distinct boundary of high amplitude parallel reflections at its base. Considering the age of the basal reflector of H1 sequence as the early Pliocene, a sedimentation rate of 20–25 cm 1000 yr^{-1}, in general, during the Quaternary period is suggested. Between the Miocene and early Eocene unconformities, two or more sequences with nearly parallel, continuous intense



reflections also occur. Their stratigraphic determination needs drill well investigations. Limited extent subparallel discontinuous reflections and associated diffractions pattern (weak) commonly occur with Miocene and Quaternary sequences H1 to H4. They might represent relatively less compact sediments of the rivers from north. The underlying older sediments of sequences H5 to H6 are more compact marked by the high amplitude, nearly parallel continuous reflections. Curray and Munasinghe (1989) suggested a hiatus in sedimentation following collision of India with Asia during Eocene period; post-Miocene period turbidities related to Himalayas orogeny subsequent to collision of Indian Plate with Eurasian Plate and pre-Eocene period sediments derived from the eastern margin. The present study identifies about 3.4 km thick turbidity section of sediments of post-Miocene period and more than 2.0 km thick pre-Miocene sediments derived from the rivers of eastern margin of



(d) **SP 20110** **SP 23985**

India and Burma. The pre-Miocene sediments are possibly about 3.8 km thick in the Western Basin and are characterized by intense reflectivity. Such a marked change in reflectivity of the sediments of the Western Basin can be attributed to the fine compact fraction of the sediments. The sediments were possibly transported over long distances from north. The north-south trending 85° E Ridge might have acted as a barrier to the sediments from the adjoining eastern margin of India. As such, much of the sediments appear to have deposited over the pre-existing structural features of the crust seems to

TABLE I

Sediment thickness (in km) of Q (Quaternary), M (Miocene) and P (early Eocene) and depth (in km) to acoustic basement

	Q		M		P	
	Max	Min	Max	Min	Max	Min
1. Western Basin	0.5	0.3	1.5	0.8	1.2	0.5
2. Central Basin	0.4	0.3	2.2	1.5	1.1	0.4
3. 85° E Ridge	0.3	-	1.1	-	1.0	-
4. Ninetyeast Ridge	0.3	-	1.1	-	0.5	-
Acoustic basement (max. depth)						
Western Basin		6.7 km				
Central Basin		6.2 km				
85° E Ridge		2.8 km				
Ninetyeast Ridge		2.8 km				

have controlled earlier sedimentation processes in the Bay of Bengal.

The Ninetyeast Ridge in the area is shown as broad basement high (Curray *et al.*, 1982) which is seen to the west of the basement high on our seismic section (Figures 2 and 3d). The high at 92° E is not clearly understood. It could represent the crest of the Ninetyeast Ridge or a flexural bulge due to its proximity to the Sunda Arc. Along the western flank of the high at 92° E, most of the reflectors of sequences H1 to H5/H6 show flexural down warp, i.e. to the east. A typical depression of the seabed topography, about 100 km wide and 100–110 m deep also occur over the ridge. They may well reflect the subsidence due to the sediments load and tectonism of the ridge (active subduction along Sunda Arc in the south and north-south compression due to northward Indian Plate motion). The sequences are of early Eocene to Recent period. So a subsidence rate of 20 cm my^{-1} of the ridge since Eocene period onwards is suggested. As a whole the broad basement swell, being close to the subduction zone along the Sunda Arc, experienced subsidence perhaps throughout the above geological period of the sedimentation.

As mentioned earlier, the sedimentary sequence is thicker in the basins formed on either side of the 85° E Ridge. In the Western Basin the acoustic basement occurs at about 8.5 s (TWT) i.e. about 6.7 km. The acoustic basement deepen to the west. It is mostly characterized by strong reflections, large diffraction pattern, discontinuity in the reflectors and opacity and unevenness which are most likely indicative of a crystalline basement covered by about 6.7 km thick sediments. Depressions of the reflectors at the base of the sequences H2 (sps: 2900–4800), H4 (sps: 3600–5200) and H6 (sps: 4000–5800) at varied levels also occur in the basin. They clearly reveal successive westward displacement of the depression (Figures 2 and 3a) with respect to younger age of the sequences. It is likely that the depressions in the seabed topography and also of the deep reflectors with westward shift in relation to the younger ages and the gentle bulging of the sediments overlying the 85° E Ridge mark the continued upthrust related tectonics and differential compaction of sediments.

In the Central Basin the acoustic basement deepens towards its centre from both sides. Its extent of deepening beyond 8.3 s (TWT) could not be identified due to its masking by the strong signals of the seabed multiple occurring at the depths. Broad wavelength magnetic anomalies occur in the basin. So, greater depths to the basement are suggested. Here the sediments are possibly thicker than those in the Western Basin. Towards east, the sedimentary sequences lap over and at places pinches out over the broad swell of the Ninetyeast Ridge.

The sedimentary sequences in the Sunda Arc area (Figure 3d) are relatively thick and folded. Here the sequences' boundaries could not be identified in spite of intense reflections from folded sediments. The entire sequence appears to be consisting of folded and possibly faulted sediments.

The high amplitude magnetic signature associated with the 85° E Ridge is consistent with the positive structural relief of the ridge. It is not very clear whether the anomalies on the profile are linear seafloor spreading type anomalies or not. Its confirmation needs more data. But magnetic isochrons up to 31/33 have been identified at 5° N latitude (Royer and Chang, 1991). Considering the unified eastern Gondwanaland, the older sequences of linear magnetic anomalies are possibly present (e.g. Norton and Sclater, 1979; Royer and Chang, 1991). Further, an altered continental crust may be present (Brune and Priestly, 1989) in the offshore regions of the east coast of India. To resolve this further, shipborne geophysical data on closely spaced grid are needed.

Conclusions

The present analysis of seismic and magnetic data reveals:

1. Several turbidity channels of varied dimensions occur at the present seafloor and subsurface. Eight seismic sequences of nearly parallel reflec-

TABLE II

Simplified seismic sequence stratigraphy of the study area

Seismic sequence	Inferred age	Average interval velocity (km s^{-1})	Likely lithology	Reflection pattern	
				Western Basin	Central Basin
H1	Pliocene to recent	1.8	Mud turbidities	Acoustically transparent to opaque continuous — discontinuous parallel reflections with upper half consisting of occasional opaque reflections	Acoustically transparent and parallel reflectors with upper half consisting of opaque reflections in three zones. Occasionally truncated reflections occur at seafloor
H2	—	1.9	Less compact fraction turbidities	Nearly parallel and continuous to discontinuous with occasionally weak diffraction pattern	Alternate bands of acoustically transparent to opaque reflections
H3	Late Miocene	2.2–2.5	"	"	"
H4	Late Oligocene–early Miocene	3.0	"	"	"
H5	Late Eocene–early Oligocene		Hiatus	Intense, nearly parallel with alternate bands of acoustically transparent to opaque reflections	Relatively less intense, nearly parallel reflections
H6	Early Eocene	3.2–4.1	Fine, more compact fraction turbidities	"	"
H7	—	4.1–4.9	Sediments transported by rivers	"	"
H8	Cretaceous	>4.9	Base is probably cystalline basement	Subparallel continuous to uneven hyperbolic high intense reflections, deepening to the west at the base	Discrete continuous (sagging to the middle) reflections

tions of varied thicknesses are identified. Tentative stratigraphic ages for H1, H3 and H6 as Quaternary (Q), Miocene (M) and Paleocene–Eocene boundary (P), respectively are suggested. The current active channels of the seafloor and subsurface of the recent geologic past are confined to the three localities of the basins. Sedimentation rate of 20–25 cm 1000 yr^{-1}, in general, is suggested during the Quaternary period.

2. Sediment thickness of these sequences in the Western Basin is most likely to be around 6.7 km. And in the Central Basin thickness of sediments is likely to be more than 6.2 km.
3. Subsidence rate of 20 cm my^{-1} since Eocene period for the Ninetyeast Ridge (broad basement swell) and the basement high at 92° E longitude and a slow uplift of the 85° E Ridge are suggested.

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