16. Fuller, I. C., Wintle, A. G. and Duller, G. A. T., *Quat. Geochron. (Quat. Sci. Rev.)*, 1994, **13**, 539–543.
17. Lamothe, M., Balescu, S. and Auclair, M., *Radiat. Meas.*, 1994, **23**, 555–561.
18. Hutt, G., Jaek, I. and Tchonka, *Quat. Sci. Rev.*, 1988, **7**, 381–385.
19. Botter-Jensen, L., Ditlesen, C. and Mejdahl, V., *Nucl. Tracks Radiat. Meas.*, 1991, **18**, 257–263.
20. Aitken, M. J., *Thermoluminescence Dating*, Academic Press, New York, 1985, p.359.
21. Mejdahl, V., *Archaeometry*, 1979, **21**, 61–73.

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Record of the Cretaceous magnetic quiet zone: A precursor to the understanding of evolutionary history of the Bay of Bengal

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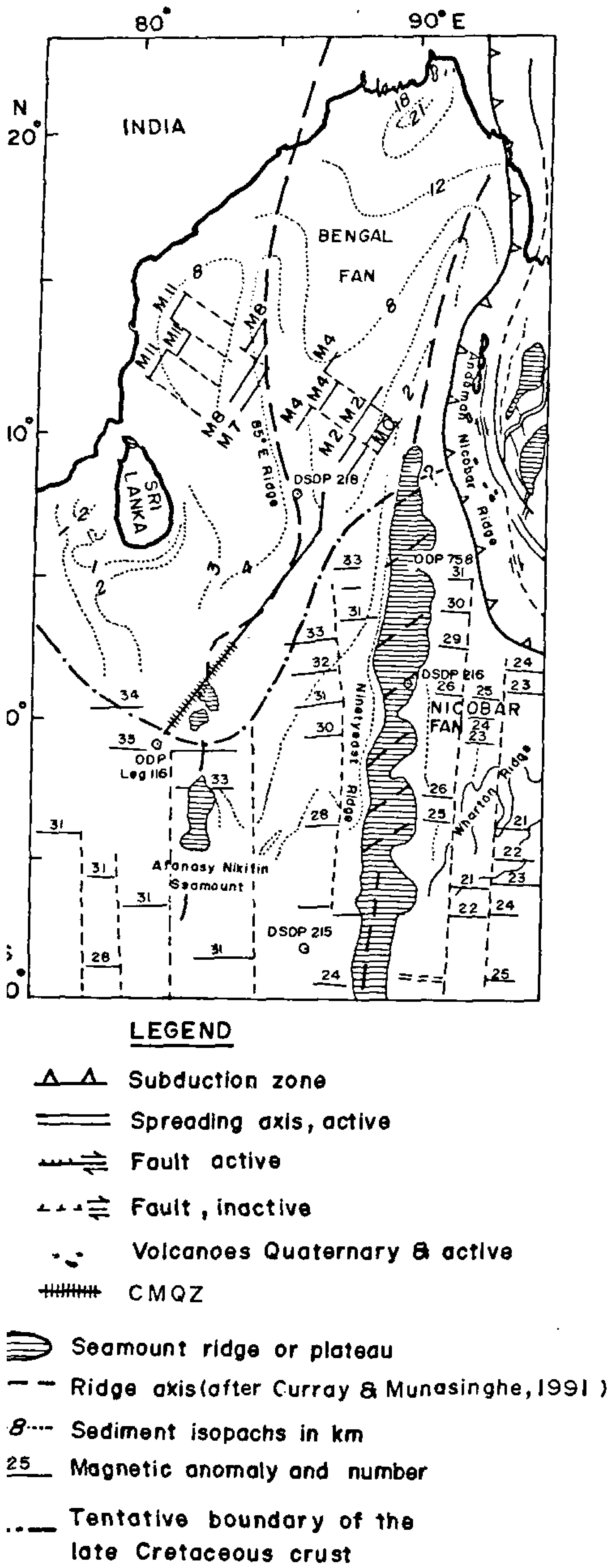
Magnetic study along a transect joining the sites of Ocean Drilling Programme (ODP) leg 116 (1°S, 81°24′E) and the vicinity of Deep Sea Drilling Project (DSDP) site 218 (7°N, 87°30′E) revealed the presence of a wide magnetic smooth zone sandwiched between the known Late Cretaceous anomaly A34 (≈ 84 Myr) and the younger magnetic anomaly sequence of Early Cretaceous crust, represented by M0 (≈ 118 Myr). The smooth magnetic zone seems to have evolved during the Cretaceous long normal polarity epoch (superchron K–T) 118–84 Ma and is usually referred to as the Cretaceous magnetic quiet zone. Identification of this zone in the distal Bengal Fan perhaps serves as a missing link between the Early Cretaceous and the Late Cretaceous evolution of the crust and establishes a continuous evolutionary record of the Bay of Bengal since India's breakup from the eastern Gondwanaland continents.

SEVERAL plate reconstruction models have been proposed for the breakup of Pangea and the eastern Gondwanaland, in which the east coast of India and the Enderby Landmass of Antarctica were juxtaposed and the western margin of Australia lies east of Greater India during the Late Jurassic[1–11]. The breakup of India from the Antarctica–Australian plate sets the stage for the evolution of the Bay of Bengal and the eastern Indian Ocean. The Bengal Fan is one of the thickest sedimentary basins of the world[12–15]. Powell *et al.*[7] were of the view that the magnetic anomalies will be hard to find off the east coast of India due to huge sediment accumulation. Though extensive underway geophysical data was collected during the International Indian Ocean Expedition Programme (1959–1965) and subsequent expeditions to unravel the evolutionary history of the Indian Ocean[16–19], not much was known about the age and nature of the ocean floor of the Bengal Fan[6,7,20,21]. Various plate reconstruction models[5,7,22] show the stage-by-stage evolution of the eastern Indian Ocean since the Late Cretaceous (84 Myr) to the Present. However, refined plate reconstruction models for the early opening prior to Late Cretaceous are poorly constrained[10] due to inadequate geophysical data, particularly in the Bay of Bengal, northeastern Indian Ocean.

Recent geophysical studies[23,24] in the northern Bay of Bengal revealed the presence of N30°E trending Mesozoic magnetic anomaly sequence M11 to M0 (corresponding 132.5 to 118 Myr age old crust) and N120°E (≈ NW–SE) trending fracture zones (Figure 1). The direction of these fracture zones indicates the initial motion of the Indian plate from Antarctica–Australia immediately after the Early Cretaceous breakup. In the present study, a smooth magnetic field has been observed on a transect joining the sites of ODP leg 116 and the vicinity of DSDP site 218 over a distance of about 415 km continuing from the known Late Cretaceous anomaly A34 (≈ 84 Myr) and culminating with the Early Cretaceous crust. This magnetic smooth zone is significant for establishing the continuous evolutionary history of the Bay of Bengal since India's separation from the eastern Gondwanaland during the Early Cretaceous.

About 1200 line km of bathymetry, magnetic, gravity and multichannel seismic reflection data along the transect joining the sites of ODP leg 116 and the vicinity of DSDP site 218 have been collected onboard *ORV Sagarkanya* during 1995 (April–May). The processed data (Figure 2) has been used to infer the nature and age of the crust in the distal Bengal Fan to better constrain the evolutionary history of Bengal Fan.

The identification of the Early Cretaceous crust[23,24] and the Late Cretaceous crust[5,22] in the northern and southern Bay of Bengal respectively suggests that the ocean floor of the Bay of Bengal should have a continuous evolution record since the Early Cretaceous. This can be established either by the sampling of the oceanic basement rocks or by the study of seafloor spreading type of magnetic anomalies. We have used the total intensity earth's magnetic field data to infer the nature of the basement. The observed magnetic



1. Tectonic summary chart of the northeastern Indian Ocean Bay of Bengal[20]. The Mesozoic magnetic anomaly lineations V–SE trending fracture zones dominate the northern Bay of [3]. The thick line joining the sites of ODP leg 116 and the of DSDP site 218 represents the multisensored geophysical (gravity, magnetic, bathymetry and multichannel seismic n data). The 415 km extent of the Cretaceous magnetic quiet CMQZ) sandwiched between the Early Cretaceous and Late ous crusts has been shown with hatching.

record (Figure 2) is characterized with magnetic anomaly 34 signature at the sites of ODP leg 116, about 415 km wide smooth magnetic field with subdued amplitudes (< 50 nT) and chain of magnetic anomalies with 200–600 nT amplitude towards northeastern end of the profile. The smooth magnetic field culminates with a positive magnetic anomaly, which, perhaps, represents the younger anomaly M0 ($\approx$ 118 Myr) of the Mesozoic sequence. The crust between the magnetic anomaly isochrons M0 and 34, evolved during the Cretaceous long normal polarity epoch (superchron K–T), corresponds to 118–84 Myr and has been commonly referred to as the Cretaceous magnetic quiet zone (CMQZ)[25]. Roots and Srivastava[26] quoted that the mechanism for occurrence of such magnetic smooth/quiet zones could be due to (i) period of non-reversal of the Earth's magnetic field[27] (ii) magnetization of the seafloor close to the magnetic equator[28] (iii) spreading being slow, the anomalies produced were too narrow to be individually resolved at the sea surface[29] and (iv) initial spreading between margins being markedly oblique to the spreading direction with the consequent fragmentation of the ridge into short spreading segments and the resultant production of magnetic source blocks too small to be resolved at the sea surface[30]. During this Cretaceous long normal polarity interval major plates reorganization has also been reported[4,7,21].

Analysis of the geophysical data revealed a distinct record (Figure 2) of about 415 km wide magnetic smooth zone prior to anomaly 34 ($\approx$ 84 Myr) in the distal Bengal Fan. Occurrence of this magnetic smooth zone prior to the Late Cretaceous magnetic anomaly isochron 34 suggests that this magnetic smooth zone is sandwiched between the Early Cretaceous and Late Cretaceous crusts. We attribute this magnetic smooth zone to CMQZ as mentioned earlier. The crude estimates reveal that the crust of the CMQZ seems to have evolved with a half-spreading rate of 1.2 cm/yr. Similar order of widths and spreading rates prevailed over the magnetic smooth zones elsewhere in the world oceans[25]. The estimated half spreading rate of 1.2 cm/yr for this magnetic profile may be apparent since the direction of spreading during the Middle Cretaceous was not known. At the same time, the orientation of this profile seems to be nearly parallel to the Early Cretaceous spreading ridge between India and contiguous Antarctica–Australian plates. Roots[30] offered an explanation that the initial spreading between the margins that were markedly oblique to the spreading direction results in the fragmentation of the ridge into short-spreading segments. The resultant production of magnetic source blocks became too small to be resolved at the sea surface by magnetic observations. Hence, low amplitude or smooth magnetic field would result due to oblique spreading. The observed magnetic profile (Figure 2) is distinctly characterized by such a smooth zone, the known magnetic signature of anomaly

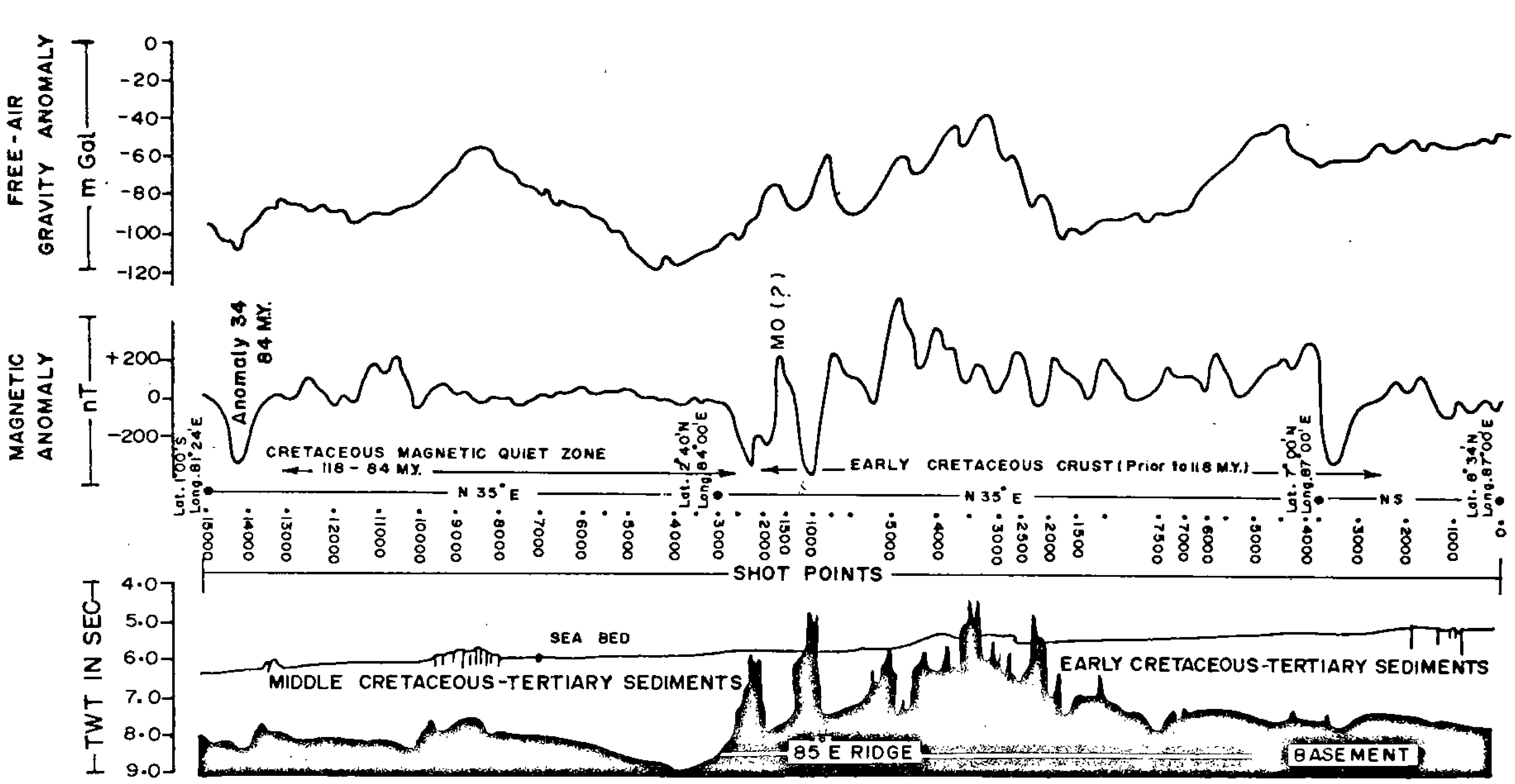


Figure 2. Composite geophysical anomaly map along the transect joining sites of ODP leg 116 and the vicinity of DSDP site 218. Part of the transect crosses the axis of the 85°E Ridge. The free-air gravity anomaly profile is characterized by long wavelength lows most probably corresponding to the 85°E Ridge[34]. The free-air gravity profile is superposed with high frequency anomalies corresponding to the irregular pinnacles of the exposed basement. The magnetic anomaly profile from southwest to northeast depicts the Late Cretaceous crust (magnetic isochron 34, ≈ 84 Ma), Cretaceous magnetic quiet zone (84–118 Myr) and the Early Cretaceous crust influenced partly by the 85°E Ridge. The line drawing of the unprocessed near trace record represents the seabed and the acoustic basement most probably the real basement. The basement of the CMQZ is relatively smooth and deeper.

34 (≈ 84 Myr) and the Early Cretaceous seafloor spreading type magnetic anomalies. The estimated average spreading rate for the Early Createaceous crust in the Bay of Bengal was 3.4 cm/yr (refs 23, 24). The two different spreading rates, i.e. 3.4 cm/yr for the Early Cretaceous crust represented by Mesozoic anomaly sequence M11–M0 (133–118 Ma) and the Cretaceous quiet zone (118–84 Ma) suggest that the seafloor spreading process slowed down during the K–T superchron with simultaneous major plates reorganization (India, Antarctica–Australia). Poehls *et al.*[25] reported similar slow-spreading rates (1.5 cm/yr) for the north Atlantic smooth zone.

The basement of the CMQZ, mapped from the seismic reflection profile in the distal Bengal Fan, occurs at about 8–9 km from the sea surface with an average sediment thickness of 3–4 km (Figure 2). This basement is relatively smooth. The CMQZ culminates with the crust of magnetic isochron 34 (≈ 84 Myr) at the sites of ODP leg 116, while towards north it merges with the Early Cretaceous crust of about 118 Myr (Figure 2). The boundaries of the CMQZ are marked by a sharp difference in the magnetic field. This may be an edge effect and is due to the amalgamation of CMQZ crust with the two different ages of the crust in the Bay of Bengal. The crust of the CMQZ between the magnetic anomaly isochrons M0 and 34 (118–84 Ma) near the northern exposure of the Ninetyeast Ridge (Figure 1) appears to be affected by the subduction processes, resulting in a narrower width of CMQZ. This part of the CMQZ crust in the Bay of Bengal may be an exception so far as the general width of the CMQZ in question is concerned.

The eastern Gondwanaland plate reconstruction models presented hitherto[5,7,9,10] seem to be incomplete due to lack of information about the age of the crust and trends of fracture zones in the Bengal Fan prior to the Late Cretaceous. This led to suggest India's breakup from the eastern Gondwanaland around magnetic isochron M0 (118 Myr) (ref. 10) and around M4 (126 Myr) (ref. 20). Further, a small segment of magnetic anomaly zone off the east coast of India has been interpreted as a magnetic smooth zone[31] prior to the Mesozoic anomalies. Banerjee *et al.*[32] have also interpreted the presence of Barremian or younger oceanic crust in the Bay of Bengal.

Mapping of considerably wide CMQZ (≈ 415 km) in the distal Bengal Fan from the present studies serves as a vital missing link between the Early Cretaceous and Late Cretaceous crusts evolved during the rifting and drifting of the Indian plate from the Antarctica–Australian plate during the Early Cretaceous period. Further, the present studies provided an observational

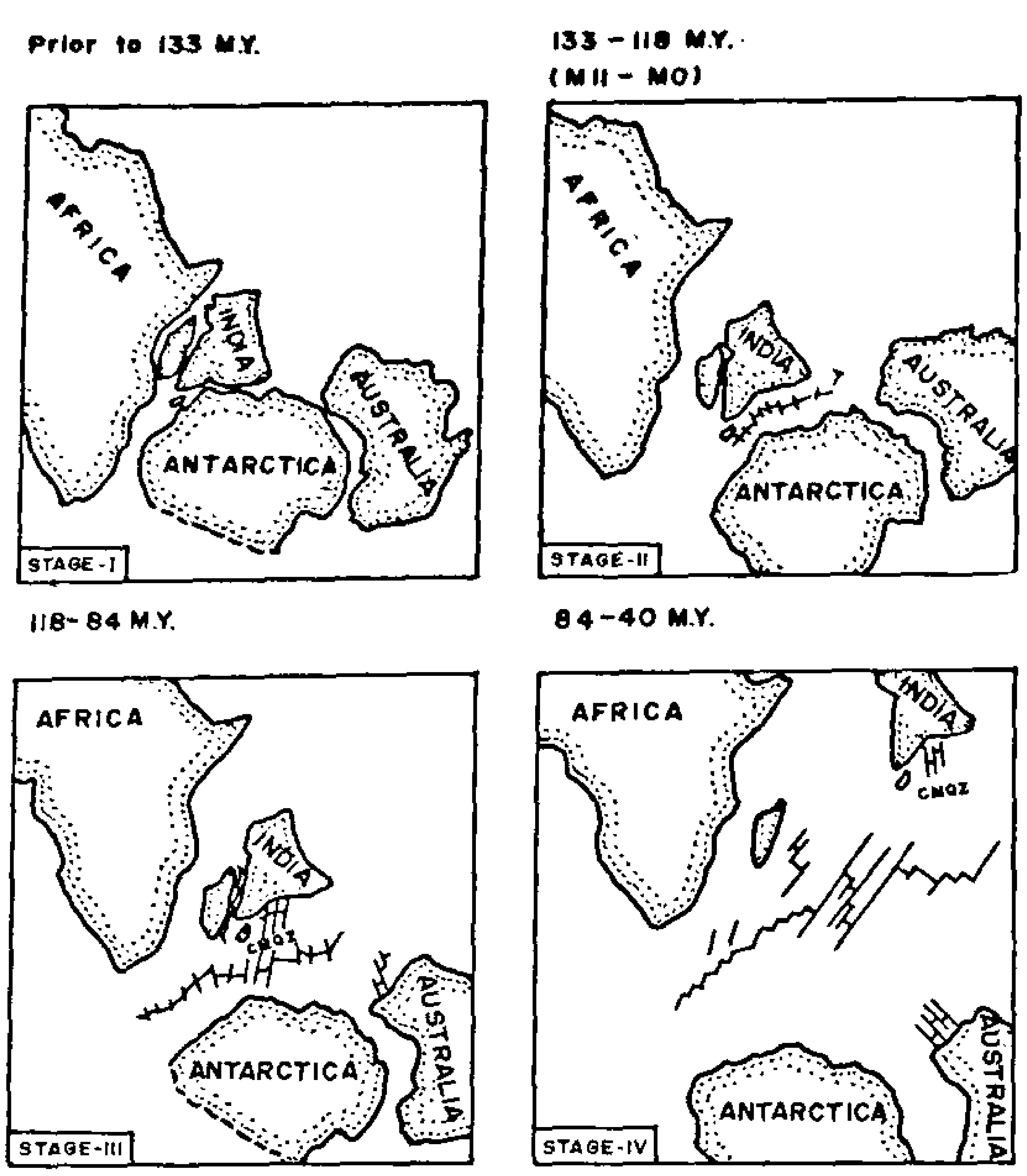


Figure 3. Schematic representation of the breakup of eastern Gondwanaland mass since the Early Cretaceous. *Stage I.* The configuration of the continents prior to 133 Myr; *Stage II.* India separated and moved in the NW–SE direction from the Enderby Landmass of Antarctica and about 1100 km wide Early Cretaceous crust, represented by the Mesozoic anomaly lineations M11 to M0, was evolved with an average spreading rate of 3.5 cm/yr. The spreading centre was between India and Antarctica; *Stage III.* The spreading rates decreased to 1.2 cm/yr and about 415 km wide Cretaceous magnetic quiet zone was evolved and India started moving from NW to NS direction; *Stage IV.* The northward movement of India was rapid and the late Cretaceous to Late Eocene crust with various tectonic elements like fracture zones, plateaus, seamounts and extinct spreading centres was evolved in the Indian Ocean. The evolutionary history of the northeastern Indian Ocean was well-documented since the Late Cretaceous to the Present.

evidence to develop a realistic plate reconstruction model of the eastern Gondwanaland after the Early Cretaceous breakup. We propose the evolutionary history of the Bay of Bengal in four stages (Figure 3) on the basis of the identification of the CMQZ, and the Mesozoic anomaly sequence M11–M0 and N120°E trending fracture zones[23,24]. During the first stage, the breakup of the Greater India from the contiguous Antarctica–Australian plate was initiated prior to 133 Myr. During the second stage (132.5–118 Myr) India separated from the Enderby Landmass of Antarctica and moved approximately in NW–SE direction, producing about 1100 km of Early Cretaceous crust characterized by M11–M0 anomalies in the Northern Bengal Fan. Around this time the continental extension between Antarctica and Australia took place and the eastern part of Greater India and Australia got separated, producing M10 and younger anomalies on the western margin of Australia[6]. In stage three (118–84 Myr), the direction of the Indian plate changed from NW–SE to N–S, with a slow spreading rate of about 1.2 cm/yr with spreading centre in between Indian and Antarctica–Australian plates and created about 415 km wide CMQZ. During this Cretaceous quiet period the trace of the Ninetyeast Ridge was also evolved[33] in the Bay of Bengal as the Indian plate moved over the Kerguelen hotspot, and the India's separation from Madagascar took place. During stage four (84–40 Myr), India's northward motion accelerated and Late Cretaceous to Late Eocene ocean floor was evolved with various tectonic elements like N–S trending fracture zones, plateaus, seamounts, extinct spreading ridges, etc. in the north eastern Indian ocean.

1. Du Toit, A. L., in *Our Wandering Continents*, Oliver and Boyd, London, 1937, pp. 366.
2. Smith, A. G. and Hallam, A., *Nature*, 1970, **225**, 139–144.
3. Dietz, R. and Holder, J. J., *J. Geophys. Res.*, 1970, **75**, 4939–4956.
4. Veevers, J. J., Powell, C. McA. and Johnson, B. D., *Earth Planet. Sci. Lett.*, 1975, **27**, 383–387.
5. Norton, I. O. and Sclater, J. G., *J. Geophys. Res.*, 1979, **84**, 6803–6830.
6. Veevers, J. J., Powell, C. McA. and Johnson, B. D., *Earth Planet. Sci. Lett.*, 1980, **51**, 435–444.
7. Powell, C. McA., Roots, S. R. and Veevers, J. J., *Tectonophysics*, 1988, **155**, 261–283.
8. Scotese, C. R., Gahagan, L. M. and Larson, R. L., *Tectonophysics*, 1988, **155**, 27–48.
9. Ziegler, A. M., Scotese, C. R. and Barrett, S. F., in *Tidal Friction and Earth's Rotation* (eds Brosche, P. and Sundermann, J.), Springer, New York, 1983, vol. 2, pp. 240–252.
10. Royer, J. Y., Sclater, J. G., Sandwell, D. T. *et al.*, in *Synthesis of Results from Scientific Drilling in the Indian Ocean* (eds Duncan, R. A. *et al.*), AGU Monograph, 1992, vol. 70, pp. 471–475.
11. Yoshida, M., Funaki, M. and Vitanagar, P. W., *Tectonics*, 1992, **11**, 381–391.
12. Curray, J. R. and Moore, D. G., *Geol. Soc. Am. Bull.*, 1971, **82**, 563–572.
13. Curray, J. R. and Moore, D. G., in *The Geology of Continental Margins* (eds Burke, C. A. and Drake, C. L.), Springer, New York, 1974, pp. 617–627.
14. Curray, J. R., Emmel, F. J., Moore, D. G. and Raitt, R. W., in *The Ocean Basins and Margins: The Indian Ocean* (eds Nairn, A. E. M. and Stehli, F. G.), Plenum, New York, 1982, vol. 6, pp. 399–450.
15. Curray, J. R., *Geology*, 1991, **19**, 1097–1100.
16. Udintsev, G. B. (ed.), *Geological–Geophysical Atlas of the Indian Ocean*, Pergamon, New York, 1975, pp. 1–151.
17. Mckenzie, D. P. and Sclater, S. G., *Geophys. J. R. Astron. Soc.*, 1971, **24**, 437–528.
18. Fisher, R. L., Sclater, J. G. and Mckenzie, D. P., *Geol. Soc. Am. Bull.*, 1971, **82**, 553–562.
19. Schlich, R., in *The Ocean Basins and Margins: The Indian Ocean* (eds Nairn, A. E. M. and Stehli, F. G.), Plenum, New York, 1982, vol. 6, pp. 51–147.
20. Curray, J. R. and Munasinghe, T., *Geology*, 1991, **19**, 1237–1240.
21. Muller, R. D., Royer, J. Y. and Lawver, L. A., *Geology*, 1993, **21**, 275–278.
22. Royer, J. Y., Sclater, J. G. and Sandwell, D. T., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1989, **98**, 7–24.
23. Ramana, M. V., Nair, R. R., Sarma, K. V. L. N. S. *et al.*, *Earth Planet. Sci. Lett.*, 1994, **28**, 469–475.

24. Ramana, M. V., Subrahmanyam, V., Sarma, K. V. L. N. S., Maria Desa, Ramprasad, T., Subrahmanyam, C. and Subba Raju, L. V., Ext. Abs. 32nd Annual Convention of Indian Geophysical Union, Hyderabad, 19–21 December 1995, p. 17.
25. Poehls, K. A., Luyendyk, B. P. and Heirtzler, J. R., *J. Geophys. Res.*, 1973, **78**, 6985–6997.
26. Roots, W. D. and Srivastava, S. P., *Mar. Geophys. Res.*, 1984, **6**, 395–408.
27. Heirtzler, J. R. and Hayes, D. E., *Science*, 1967, **157**, 185–187.
28. Vogt, P. R., Anderson, C. N., Bracey, D. R. and Schneider, E. D., *J. Geophys. Res.*, 1970, **75**, 3955–3968.
29. Le Pichon, X., Hyndman, R. D. and Pautot, G., *J. Geophys. Res.*, 1971, **76**, 4724–4743.
30. Roots, W. D., *Earth Planet. Sci. Lett.*, 1976, **31**, 113–118.
31. Murty, K. S. R., Rao, T. C. S., Subrahmanyam, A. S., Malleswara Rao, M. M. and Lakshminarayana, S., *Mar. Geol.*, 1993, **114**, 171–183.
32. Banerjee, B., Sengupta, B. J. and Banerjee, P. K., *Marine Geol.*, 1995, **128**, 17–23.
33. Duncan, R. A. and Storey, M., in *Synthesis of Results from Scientific Drilling in the Indian Ocean* (eds Duncan, R. A. *et al.*), AGU Monograph, 1992, vol. 70, pp. 91–104.
34. Liu, C. S., Sandwell, D. T. and Curray, J. R., *J. Geophys. Res.*, 1982, **87-B9**, 7673–7686.

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Precious metal association in the Jaduguda uranium ore deposit, Singhbhum Shear Zone, Bihar, and its significance

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Concentrations of Pt, Pd, Au and Ag in some ore samples and sulphide-rich flotation products from the Jaduguda uranium deposit in Singhbhum (Bihar) are reported. In all the samples analysed, Pd far predominates over Pt, and Ag over Au. The geochemical significance of these concentrations is discussed.

THAT the copper ores of Singhbhum Shear Zone, Bihar, contain significant trace quantities of valuable metals like Au, Ag, Te, Se, Bi, Co, Ni is well known[1]. Some of these metals, like Au, Ag, Te and Se are recovered from the anode slimes generated during electrolytic refining of copper in the smelter of Hindustan Copper Ltd at Ghatsila, Bihar. These metals are concentrated along with copper during flotation. The Mosabani ore is reported to contain an average of 0.25 ppm Au[1] and the Rakha copper ore 0.07 ppm (ref. 2). The occurrence of suspected osmiridium has been reported in the mineral separates from Mosabani[3]. However no data on the contents of PGE, Au and Ag in the different uranium ore deposits of the Singhbhum Shear Zone are available. Here we present some data on the Au, Ag, Pd and Pt contents in samples of uranium ore from Jaduguda and in the sulphide mineral-rich concentrates separated from the ore in the Jaduguda mill of Uranium Corporation of India Ltd.

The following six types of samples were analysed:

i) Two bulk samples drawn from two different levels of Jaduguda mine and one sample of run-of-mine ore from Narwapahar Mine;
ii) A Ni-rich grab sample from the 295 m level, and a Cu-rich grab sample from the 550 m level, both from the footwall lode in the Jaduguda mine;
iii) A number of samples drawn from the bulk sulphide float produced in the by-product recovery plant (JBRP) of Jaduguda mill;
iv) A sample of the heavy mineral fraction of the bulk sulphide float, obtained by tabling;
v) Two samples of copper concentrate produced in the JBRP; and
vi) Some test products of roasting and leaching of the bulk sulphide float.

Pt, Pd, Au and Ag contents of most of the samples have been analysed by ICP-MS, Model PR1, manufactured by Fisons Instruments Inc., UK, in the Geochemistry Laboratory of National Geophysical Research Institute, Hyderabad. The samples, ground to a state that passed through 230# BSS, were dissolved using aqua regia, bromine and hydrofluoric, perchloric and nitric acids. Rh at a concentration of 100 ng/ml was used as the internal standard, as the samples were found to contain negligible amounts of rhodium. The details of the analytical procedure are published elsewhere[4]. The precision of estimation is better than $\pm 10\%$. The Au contents of a few of the samples have been analysed by INAA in the Analytical Laboratory of AMD, while the Ag contents of some of the samples have been determined by AAS in the Ore Dressing Section of BARC. The precision of these analyses is not known, but as the values are in the same range as obtained in the ICP-MS, are believed to be good.

The results are given in Table 1. Where three or more samples of the same type have been analysed, the