

Dating of the 85°E Ridge (northeastern Indian Ocean) using marine magnetic anomalies

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The 85°E Ridge is a typical aseismic ridge in the northeastern Indian Ocean in view of the fact that it associates with exceptional gravity and magnetic signatures. The ridge possesses two different gravity anomalies: the north part (up to 5°N latitude) is associated with negative gravity anomaly, whereas the south part coincides with positive gravity anomaly. In contrast to this, the ridge consists of alternate streaks of positive and negative magnetic signatures distributed for asymmetrical extents. With the consideration of ridge seismic structure and geomagnetic polarity reversals, we modelled both positive and negative magnetic anomalies of the ridge. This shows that the 85°E Ridge was formed during the period of rapid changes in the Earth's magnetic field, earlier to that, the underlying oceanic crust was created in the Cretaceous super-long normal polarity phase. The results further reveal that the positive and negative magnetic signatures of the ridge have been created, in general, by a relief of the ridge and polarity contrast between the ridge material and adjacent oceanic crust, respectively. On correlation of the ridge's magnetization pattern to the geomagnetic polarity timescale, we believe that the 85°E Ridge volcanism started at anomaly 33r time (~80 Ma) in the Mahanadi Basin by a short-lived hotspot, thereafter the process continued towards south and finally ended at ~55 Ma in the vicinity of the Afanasy Nikitin Seamount.

Keywords: Afanasy Nikitin Seamount, magnetic polarities, northeastern Indian Ocean, 85°E Ridge, short-lived hotspot volcanism.

It is widely accepted that the ocean floor below the Bay of Bengal and Enderby Basin, off East Antarctica has been simultaneously created during the early phase of drifting of Greater India from Australia–Antarctica. Integrated geophysical studies of the Bay of Bengal and Enderby Basin carried out by Krishna *et al.*¹ have clearly established that the present day Eastern Continental Margin of India (ECMI) had experienced multiple rifting processes/break-ups. During the early break-up of eastern Gondwanaland at around 130 Ma, normal rifting prevailed between combined north ECMI–Elan Bank and MacRobertson Land and between southwest Sri Lanka

and Gunnerus Ridge region of East Antarctica. Whereas between other conjugate margin segments, south ECMI and Enderby Land, transform motion was existed, this possibly had facilitated the normal rifting in the north as well as in the south until 120 Ma. Approximately during this period the Elan Bank, a small continental piece, detached from the north ECMI and led to reorganization of the entire rifting process along the ECMI. This model suggests that most part of the ocean floor in the Bay of Bengal evolved during the Cretaceous Magnetic Quiet Period (120–83 Ma). Subsequently within the Cretaceous Magnetic Quiet Period or probably later both aseismic ridges: 85°E and Ninetyeast ridges have initiated their volcanic emplacement in the Bay of Bengal. This implies that the 85°E Ridge is placed on an oceanic crust formed during the Cretaceous super-long normal polarity phase.

The 85°E Ridge is an enigmatic structural feature in the northeastern Indian Ocean (Figure 1) as it associates with complex gravity and magnetic signatures. The northern part of the ridge (north of 5°N) is completely buried under thick Bengal Fan sediments and show distinct negative gravity anomaly (Figures 2 and 3), whereas in the south the ridge structure occasionally rises above the seafloor and associates with positive gravity anomaly^{2–5}. But the magnetic signatures of the ridge are indeed very complex¹. In addition, a peculiarity exists in the ridge track off southeast of Sri Lanka, shifting westward by about 250 km (Figure 1). Thus the 85°E Ridge has become a mysterious geological feature in the Indian Ocean. Among the several hypotheses proposed for the evolution of the ridge, the hotspot hypothesis provides better convincing explanations for all anomalous geophysical characters.

Absence of reliable age details of the 85°E Ridge either by deep-sea drilling or by geophysical studies led several researchers to postulate quite a few theories for the origin of the ridge. Using plate reconstruction studies, Curry and Munasinghe² postulated that the Rajmahal Traps, 85°E Ridge and Afanasy Nikitin Seamount (ANS) forms the trace of Crozet hotspot from 117 to 70 Ma, but the geochemistry results of lava samples collected from the ANS do not support the Crozet hotspot volcanism⁶. Later Müller *et al.*⁷ have suggested that the 85°E Ridge segment between 10°N and ANS may have been formed by another hotspot now located underneath the eastern Conrad Rise on the Antarctic plate. Subsequent geophysical

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studies^{5,8} opined that short-lived volcanic activity had initiated the 85°E Ridge in Mahanadi Basin during the late Cretaceous and eventually terminated in the vicinity of already existing main plateau of the ANS at late Palaeocene. In recent studies, Bastia *et al.*⁹ and Radhakrishna *et al.*¹⁰ have also favoured the hotspot activity for the emplacement of the ridge, but the source of the volcanism remains speculative. Therefore, age determination of the ridge has become an important aspect in resolving the issues related to origin and evolution of the 85°E Ridge.

Keeping these aspects in view, we have made an attempt in the present work, particularly assigning ages to the 85°E Ridge using the marine magnetic anomalies. Also we have used seismic reflection and gravity data in order to obtain important inputs related to ridge structure required for magnetic model studies. The main objectives of this study are (i) to determine the magnetic response of the ridge all along, thereafter to demarcate the spatial extent of positive and negative magnetic signatures, (ii) to test the concept that the 85°E Ridge has been evolved during the period of post-magnetic anomaly 34 and emplaced on oceanic crust created during the Cretaceous Magnetic Quiet Period, and (iii) to ascribe approximate ages to the 85°E Ridge track following the correlation of ridge magnetization pattern to the geomagnetic polarity timescale¹¹. Thereupon, we discuss the geological processes involved in development of the ridge.

Geophysical dataset

Several research programmes of the Bay of Bengal have helped in creation of large database of gravity and magnetic data and few regional seismic reflection lines (Figure 1). In addition, we have also extracted gravity and magnetic profiles of the Bay of Bengal from National Geophysical Data Center (NGDC) database and used them for integrated studies. The seismic data include new (SK 107-06 and SK 107-07) and previously published (MAN-01 and MAN-03) profiles³ running from ECMI to Andaman Islands, along latitudes 13°N (MAN-03), 14°N (SK107-7), 14.64°N (MAN-01) and 15.5°N (SK 107-6). More details on compilation of gravity and magnetic anomaly data of the northeastern Indian Ocean were provided in our earlier publication¹. Gravity and magnetic anomaly profile data across the 85°E Ridge are shown in Figure 4.

The 85°E Ridge – geophysical signatures

An analysis of seismic stratigraphy was completed along two new (SK 107-06 and 07) and two previously published (MAN-01 and 03) E–W profiles running from ECMI to margin of Andaman Islands (Figure 2). Keeping the seismic characters and interpretations of Gopala Rao *et al.*³ in view, we have identified eight seismic sequences in the sediment section. The lower Eocene boundary lying immediately above basement topography divides the entire sediment section into two sediment packages deposited during pre- and post-continental collision between India and Asia. Earlier Curray *et al.*¹² and Gopala Rao *et al.*³ have interpreted that the lower package was deposited mainly from the rivers of the east coast of India, whereas the upper package was deposited from the Ganges and Brahmaputra rivers after the Indian subcontinent established contact with the Asian continent. Using high quality seismic reflection data, Bastia *et al.*¹³ have

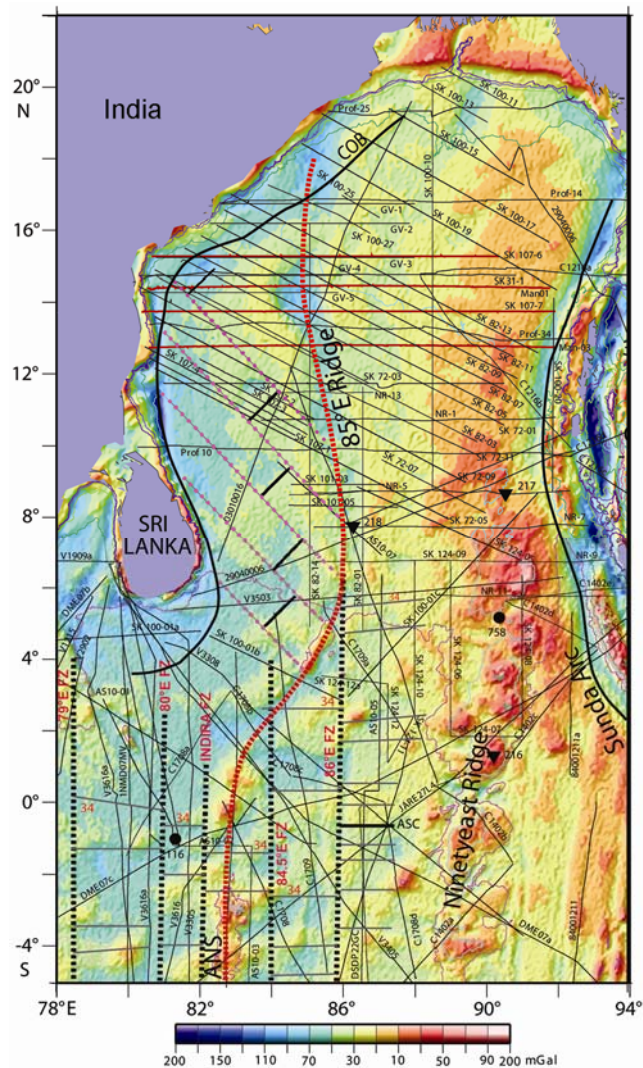


Figure 1. Satellite-derived free-air gravity anomaly map of the northeastern Indian Ocean²⁴. Curved strip line indicates continuity of the 85°E Ridge from the Mahanadi Basin to ANS. Few bathymetry contours derived from ETOPO5 data are shown in the map. N–S-oriented fracture zones, magnetic lineations up to 34 and abandoned spreading centre (ASC) shown in the distal Bengal Fan are adopted from Krishna and Gopala Rao²⁵. Whereas NW–SE trending fracture zones in the Bay of Bengal and continent-ocean bounding (COB) along the Eastern Continental Margin of India are implemented from Krishna *et al.*¹. Solid black triangles and circles indicate the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) drill sites respectively. Thin lines show the network of ship-borne geophysical profiles analysed in the present study. Seismic reflection data acquired along the solid-red lines are analysed in this study.

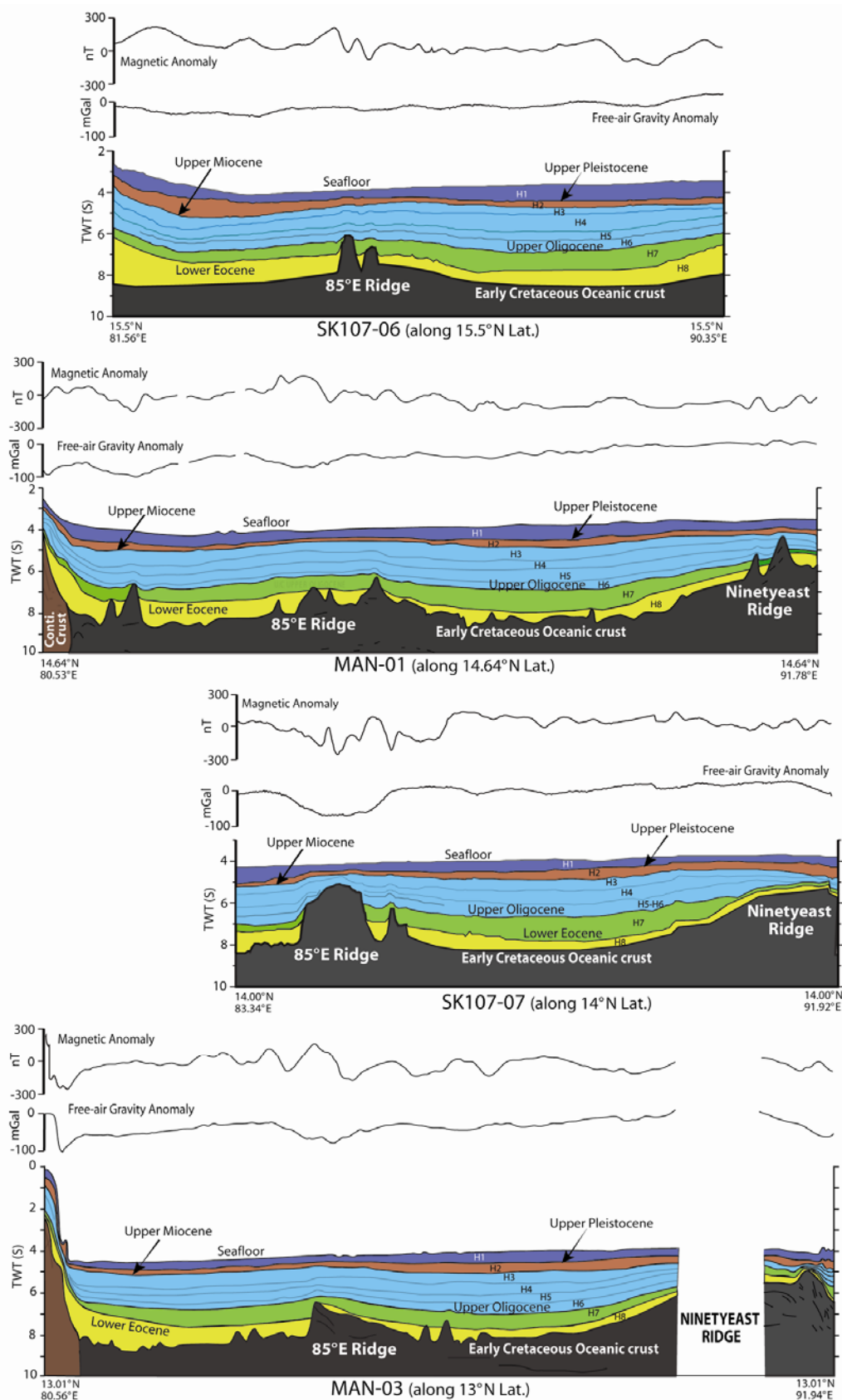


Figure 2. Line drawings of interpreted seismic reflection data together with free-air gravity and magnetic anomaly data along four regional profiles (SK 107-06, MAN-01, SK 107-07 and MAN-03) running from Eastern Margin of India to Andaman Islands. Profiles locations are shown in Figure 1.

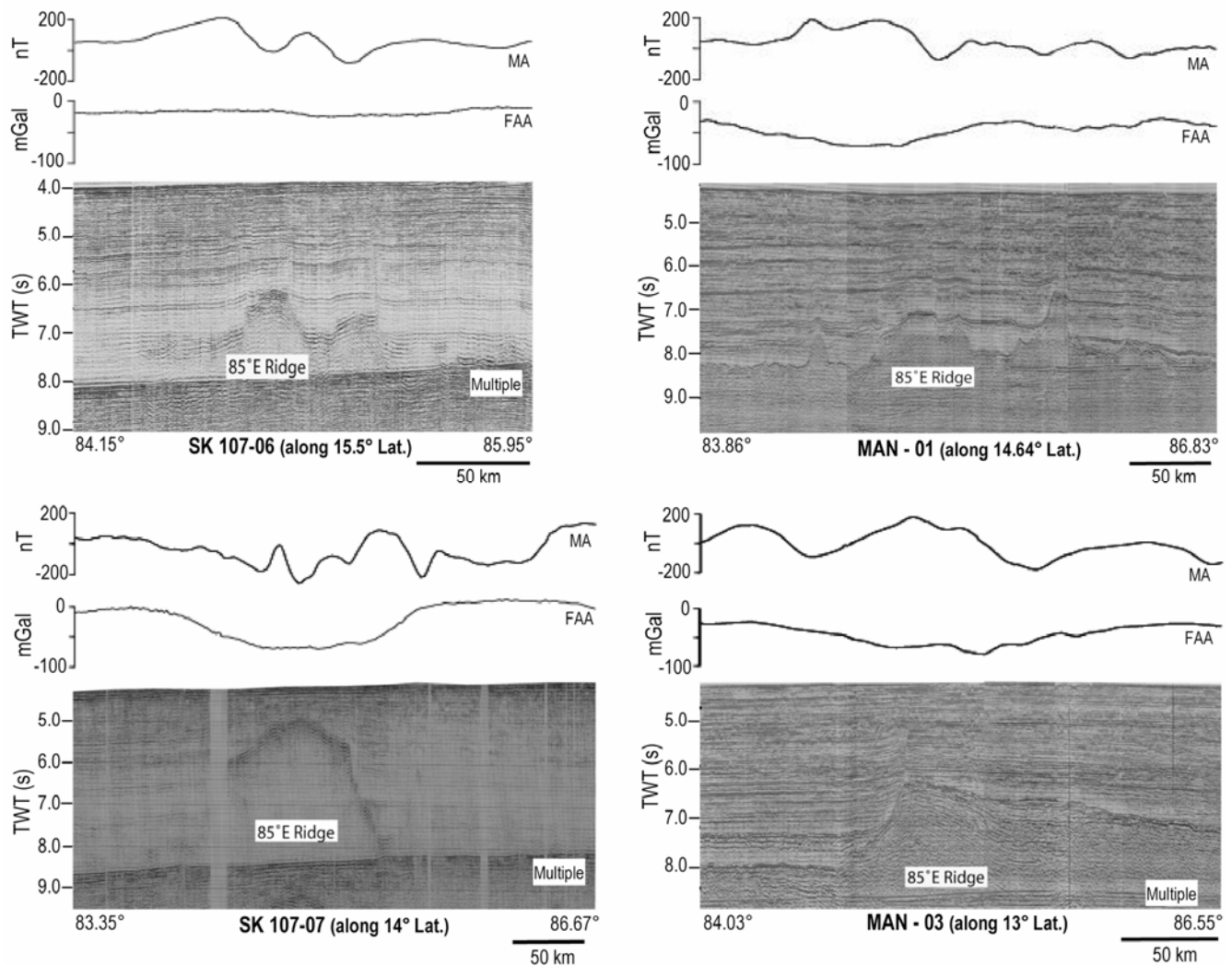


Figure 3. Seismic images and gravity and magnetic signatures of the 85°E Ridge along latitudes: 15.5°N, 14.64°N, 14°N and 13°N. Seismic data show variable ridge morphology and its depth of burial. The gravity anomaly of the ridge is consistently negative, but its magnetic signatures show variable anomalies.

also concluded that the major sediment source during the pre-collision time was from the Mahanadi and Godavari rivers and the emplacement of the 85°E Ridge was the major tectonic feature that controlled the sediment distribution in the Bay of Bengal. The pre-collision sediments consists of pelagic and terrigenous sediments, whereas the post-collision part mainly consists of Bengal Fan sediments⁷. In all four seismic interpreted sections (Figure 2), it is observed that basement topography is broadly consistent with manifestation of two aseismic ridges (85°E and Ninetyeast ridges) and two sizeable basins (central and western basins).

Four seismic reflection records crossing the 85°E Ridge at various latitudes (15.5°N, 14.64°N, 14°N and 13°N) (Figure 3) provide details on ridge structure and morphology. Although the ridge is completely buried below the Bengal Fan sediments, its structure and size are extremely variable from profile to profile (Figure 3). For

example along 15.5°N, 14.64°N and 13°N latitudes; the ridge is carpeted by about 2.4 s, 2.8 s and 1.7 s two-way travel time (TWT) fan sediments (Figure 3), respectively, whereas along 14°N, the ridge reaches to shallower depths and covered by relatively less thick (about 0.8 s TWT) sediment strata. It is surprising to notice that the ridge structure along 15.5°N is very small (about 75 km wide) in dimension and has almost no response in gravity anomaly data (Figure 3).

In gravity anomaly profile data (Figure 4a), we found presence of well-developed negative gravity anomaly on profiles between 17°N and 7°N. The amplitudes of the anomalies range from -90 to -40 mGal with a lowest anomaly located at 14°10'N lat. Earlier, Subrahmanyam *et al.*⁴ and Krishna⁵ have noted the continuity of the negative gravity anomaly towards south up to 5°N, thereupon the anomaly becomes positive. Seismic and gravity data of the 85°E Ridge (Figure 3) show that

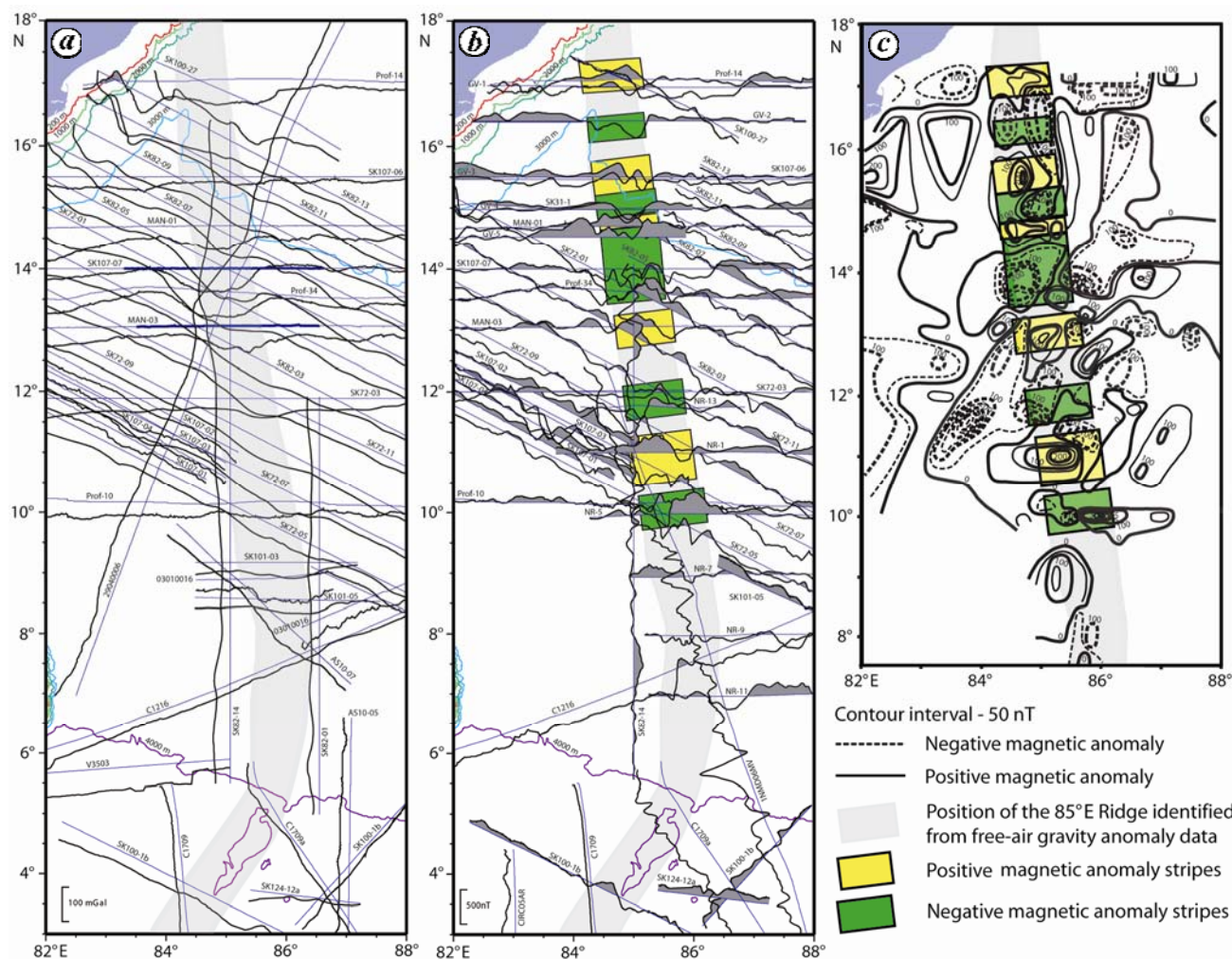


Figure 4. Ship-borne gravity and magnetic data of the 85°E Ridge. Grey-shaded portion between the latitudes 84°E and 86°E in panels A, B, and C indicates the location of the ridge. Magnetic anomaly contour data with 50 nT interval is shown in panel C. Yellow and green colour blocks shown in panels B and C indicate locations of positive and negative magnetizations, respectively.

negative gravity anomalies are associated with the ridge structure, therefore we used this specific anomaly character as a criterion for demarcation of the ridge crest and its spatial continuity in the Bay of Bengal. The ridge structure in the Bay of Bengal region is seen continuing into the Mahanadi Basin⁹ and is completely buried under variable thick Bengal Fan sediments^{3,12,14}. For example along 14°N latitude, the ridge is carpeted by about 0.8 s TWT fan sediments, whereas along 13°N about 1.7 s TWT thick sediments overlie the ridge crest (Figure 3). The seismic results together with published results^{3,5,12} reveal that the ridge morphology including its depth of occurrence is varying along the ridge track. Further, it is found that the ridge in the Bay of Bengal is in general buried under sediments deposited since the Oligocene.

Keeping the 85°E Ridge track observed from gravity and seismic data as a reference, we have examined magnetic profile and contour data in order to identify the ridge's magnetic response (Figures 3 and 4b and c). It is found that the ridge is associated with alternate stripes of

strong positive and negative magnetic signatures, whose amplitudes range from -400 to 350 nT. For the first time, suites of five each high amplitude positive and five negative magnetic anomalies covering asymmetrical extents are observed along the 85°E Ridge track (Figure 4b and c). As an example we have shown negative and positive magnetic anomalies associated with the ridge at 14°N and 13°N latitudes, respectively (Figure 3). Apart from these, magnetic anomalies of the Bay of Bengal are in general subdued and no correlations seem to be apparent between the profiles, suggesting that most part of the oceanic crust in the Bay of Bengal was created during the Cretaceous Long Normal Polarity period (120–83 Ma).

Magnetic modelling – a test for the hotspot hypothesis

In order to derive important constraints on ridge origin, we have modelled both positive and negative magnetic

anomalies of the ridge using GM-SYS software. The computations basically follow the procedures of Talwani and Heirtzler¹⁵. The magnetic anomaly profile data (MAN-03 and SK 107-07) running perpendicular to the ridge crest, have been chosen for modelling (Figures 3 and 4b). Initial models take into consideration seismic structure (Figure 3) and follow the broad concept that the ridge generates a positive magnetic anomaly solely by the ridge topography and its relief, whereas the negative anomaly is created on the whole due to the changes in Earth's magnetization fields.

In model computations, we have considered a magnetic layer of approximately 1 km thick oceanic crust with normal magnetic field and ridge structure with reverse magnetic field for negative magnetic anomaly and with normal field for positive anomaly (Figure 5). The remanent inclination was calculated for oceanic crust and ridge material with the consideration of paleo-latitudes 50°S and 43°S, respectively¹⁶, with the idea that the 85°E Ridge was emplaced approximately 35 m.y. after the formation of underlying oceanic crust^{5,17}. We achieved reasonably best fit models between the observed and cal-

culated anomalies by changing magnetic parameters within the limits and final models along with pre- and post-collision sediments are shown in Figure 5. The model for the magnetic profile SK107-07 corroborates that the 85°E Ridge was formed in the Earth's reverse magnetic field, whereas oceanic crust was formed earlier during the Cretaceous long normal magnetic field (120–83 Ma). The polarity contrast existing between the ridge rocks and adjacent oceanic crust, is in general producing negative magnetic anomaly of the ridge. Whereas second model derived for profile MAN-03 validates formation of both ridge material and oceanic crust during the normal magnetic field, but in different ages. Here, the positive magnetic anomaly is created by the ridge topography and its relief. Based on these results, we propose that the positive and negative magnetic anomaly belts associated with the 85°E Ridge for asymmetrical extents are generated by the ridge topography and polarity contrast, respectively. Therefore, we interpret that the ridge was emplaced over a period, wherein the Earth's magnetic field has changed from normal to reverse and vice-versa, and the underlying oceanic crust was formed in a lone normal magnetic field of the Cretaceous Quiet Period. Thus the derived geological model for the 85°E Ridge is consistent with the hypothesis of hotspot volcanism on approximately 35 m.y. old oceanic crust.

Magnetic pattern of the 85°E Ridge – correlation with the geomagnetic polarity timescale

In oceanic regions, where the crust remains unaltered by subsequent geological processes, marine magnetic anomalies are in general used as a tool to date ocean crust. Some oceanic regions record the composite magnetic signatures due to mixed sources of volcanic edifices and its underneath normal oceanic crust. In such geological settings using magnetic anomalies, it becomes rather complex to determine ages. For example, no systematic magnetic pattern is identified over the Ninetyeast Ridge as its emplacement was almost contemporaneous with the formation of the underlying oceanic crust¹⁸. In contrast, the 85°E Ridge has formed on approximately 35 m.y. old oceanic crust created during the Cretaceous Magnetic Quiet Period (120–83 Ma). Therefore the ridge magnetic signatures are expected to remain as strong as the observed one (Figures 3 and 4b and c). From magnetic data, we have identified five each alternate positive and negative magnetic anomaly stripes over the 85°E Ridge covering for asymmetrical extents. And from models, we interpreted that positive and negative magnetic anomalies were generated by the ridge material formed during the normal and reversed magnetic fields, respectively.

In order to assign approximate ages to the 85°E Ridge, we have compared identified magnetic stripes of the ridge to the geomagnetic polarity timescale of Cande and Kent¹¹.

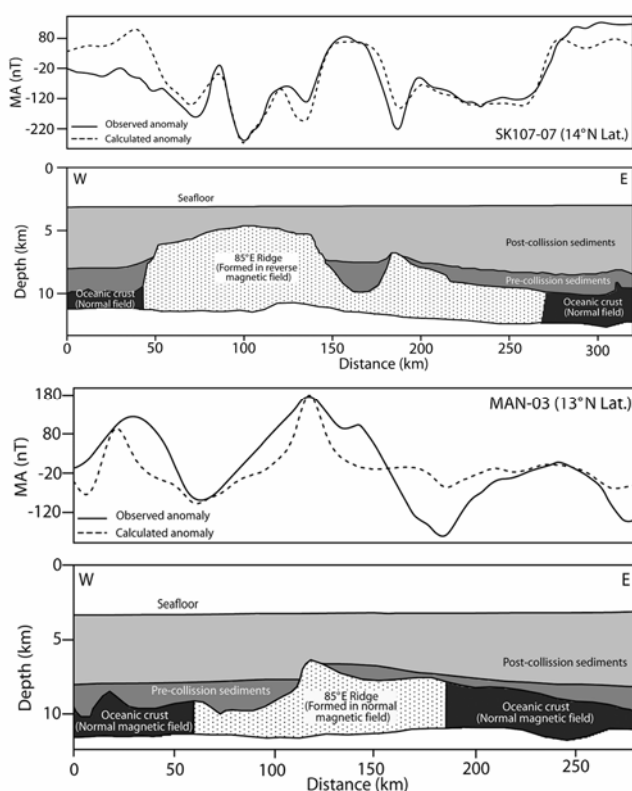


Figure 5. Two-dimensional magnetic models for profiles SK107-07 and MAN-03 are shown along with pre- and post-collision sedimentary layers. The anomalies are modelled with the consideration of normal magnetization for oceanic crust and both normal and reverse magnetizations for the ridge material. Parameters used in anomaly computations are total magnetic field 42000 nT, remanent magnetization 0.008–0.014 emu/cc, magnetic susceptibility 0.003–0.004 cgs units, inclination for oceanic crust 67° and for the ridge material 62°.

On careful examination, we found that the distribution of the observed normal and reversed magnetization patterns seem to be consistent with the intervals of Earth's geomagnetic polarities corresponding to the magnetic chrons 33r through 28r (Figure 6). The reversed magnetic block for the chron 33r is correlatable to the negative magnetic signature of the ridge identified in the Mahanadi Basin¹⁹. Rest of the polarity blocks correlated to the chrons 33n to 28r come from the present study. The correlation fairly suggest that the 85°E Ridge initiated in the Mahanadi Basin at magnetic chron 33r time (~80 Ma) and continued the ridge volcanism towards south through 9°N latitude at chron 28r time (~64 Ma). Earlier Maia *et al.*²⁰ have used similar methodology to date volcanic edifices of the Foundation Seamount chain, close to the Pacific–Antarctica Ridge and found that the deduced ages are in good agreement with radiometric dating. Therefore, we believe that ages deduced from the magnetic pattern of

the 85°E Ridge in the present work are reasonably fair and may be possibly considered as key tectonic constraints for better understanding the evolution of the northeastern Indian Ocean.

A sketch diagram is shown for illustrating the models discussed above for ages 83–73 Ma and 55 Ma (Figure 7). The ANS plateau and Marion Dufresene Seamount were emplaced nearly at the same time by a short-lived hotspot close to the ridge crest of the India–Antarctica Ridge at around 80 Ma (ref. 8). Concurrently another short-lived hotspot had started its activity in the northern Bay of Bengal and that led to the construction of the 85°E Ridge on already evolved and relatively older (35 m.y.) oceanic lithosphere (Figure 7). As the spreading process was in progress, the hotspot lying close to the India–Antarctica Ridge, had moved to the Antarctica plate. Another hotspot that started its activity close to the Mahanadi Basin interacted with the already existing seamount plateau (ANS) in Paleocene age (Figure 7) and brought it to the shallow water environment. Thus the hotspot activity has modified the ANS plateau with inclusion of seamount highs⁸. It can be noted that there is no southward continuity of the structure (85°E Ridge-buried hills – ANS) in the Central Indian Basin.

Summary and conclusions

Analysis of the marine magnetic data of the 85°E Ridge has clearly demonstrated that the ridge is associated with alternate positive and negative magnetic signatures distributed for asymmetrical extents. For the first time, distribution of normal and reversed magnetization patterns has been identified under the firm control of gravity and seismic results. Recent understanding on evolution of conjugate oceanic regions of Bay of Bengal and Enderby Basin^{1,21} enlighten that the most part of the oceanic crust in the Bay of Bengal was accreted during the Cretaceous super long normal polarity phase. Magnetic modelling of the ridge reveals that positive and negative magnetization belts are generated in general by the ridge topography and polarity contrast, respectively. Considering the magnetization pattern of the 85°E Ridge and age of the underlying oceanic crust, we interpret that the ridge was emplaced over a period, wherein the Earth's magnetic field has changed from normal to reverse and vice-versa, and the underlying oceanic crust was formed in a lone normal magnetic field of the Cretaceous Quiet Period. Thus derived geological model for the 85°E Ridge is consistent with the hypothesis of hotspot volcanism on approximately 35 m.y. old oceanic crust. Correlation of the ridge magnetic stripes to the geomagnetic polarity timescale of Cande and Kent¹¹ suggested that the distributed normal and reversed magnetization patterns resemble with intervals of Earth's geomagnetic polarities related to the magnetic chrons from 33r to 28r. Therefore,

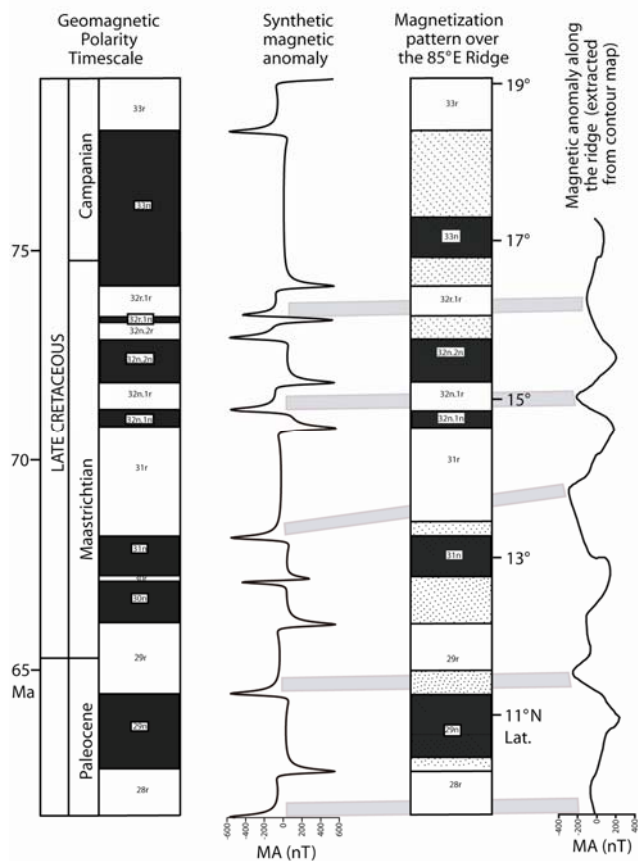


Figure 6. Magnetization pattern of the 85°E Ridge correlated to the geomagnetic polarity timescale of Cande and Kent⁹. Solid and open blocks show normal and reversed magnetic polarities. Dotted blocks show locations, where magnetic data are absent for identification of magnetizations. Synthetic magnetic anomaly profile prepared for magnetic chrons 33r–28r is shown to the right side of the polarity timescale. Profile data extracted from observed magnetic anomaly contour data is shown to the right side of the observed magnetic anomaly stripes. Shaded boxes indicate correlation of identified negative magnetic anomalies between synthetic and observed anomaly profiles.

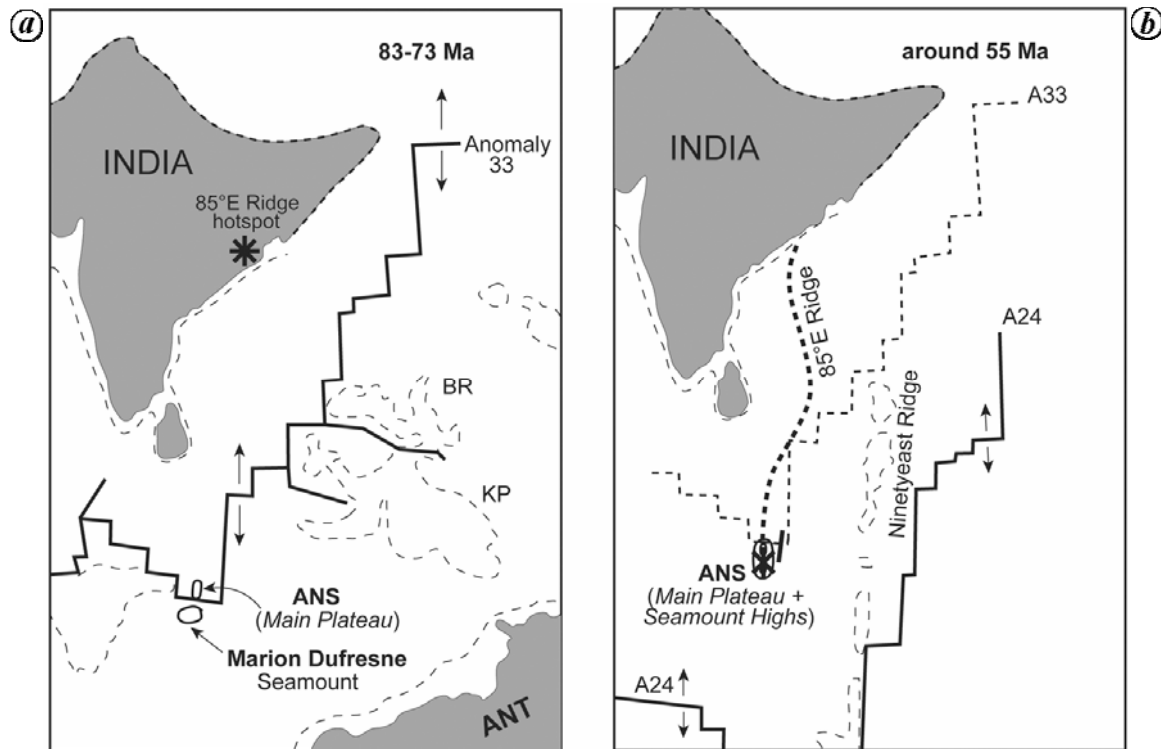


Figure 7. Sketch diagram of the formation of the 85°E Ridge through time. *a*, Initial emplacement of the 85°E Ridge in the vicinity of Mahanadi Basin, and emplacement of the Main Plateau of the ANS and Marion Dufresne Seamount near the India–Antarctica Ridge between 83 and 73 Ma. *b*, Interaction of the 85°E Ridge hotspot with the already existing main plateau at about 55 Ma. BR, Broken Ridge; KP, Kerguelen Plateau.

the present study strongly supports the origin of the 85°E Ridge by a hotspot volcanism on already evolved oceanic crust of approximately 35 m.y. old.

The present results obtained in this work are integrated with the earlier geophysical results of the 85°E Ridge^{5,8} and Conrad Rise²², and with the geochronology of the rocks recovered from the ANS²³ to understand the evolution of the ridge and ANS in a broader perspective. The 85°E Ridge volcanism started approximately 80 Ma ago in the Mahanadi Basin by a short-lived hotspot. Around this period, the Conrad Rise hotspot has emplaced the main plateau of the ANS and Marion Dufresne Seamount together close to the India–Antarctica Ridge, thereafter the hotspot has moved to the Antarctica plate leaving the plateau of the ANS as an isolated feature on the Indian plate. At the other end in the Bay of Bengal, the hotspot has continued to proceed towards south and finally ended at ~55 Ma in the vicinity of the ANS. Thus the ANS has been built by two short-lived hotspots in two phases, largely in late Cretaceous and a minor component in the Paleocene as an end product of the 85°E Ridge.

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