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Magnetic lineations in the Central Indian Basin for the period A24–A21: a study in relation to the Indian Ocean Triple Junction trace

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A Detailed study of magnetics and bathymetry was carried out in the Central Indian Basin between latitudes 9°S and $16^{\circ}30'\text{S}$ and longitudes 73°E and $79^{\circ}30'\text{E}$. The observed east–west trending magnetic anomalies are identified as anomalies 21 to 25. The magnetic lineation pattern revealed the presence of a new fracture zone at $75^{\circ}45'\text{E}$ trending $\text{N}12^{\circ}\text{E}$. This fracture zone runs parallel to the 86°E fracture zone and appears to change its direction south of 20°S latitude. The differential offsets observed in the identified magnetic anomalies across the new fracture zone are explained in terms of the evolution of the triple junction. The study also confirms the strike of the 79°E fracture zone and its southern extension through the study area.

1. Introduction

The morphology of the Indian Ocean is dominated by three major active ridge systems and several fracture zones offsetting these ridge axes. The Central Indian Ridge (CIR), South-East Indian Ridge (SEIR) and South-West Indian Ridge (SWIR) meet at the Indian Ocean Triple Junction. The spreading along CIR and SEIR and the Indian Ocean Triple Junction play an important role in the tectonic history of the Central Indian Basin.

McKenzie and Sclater [1] identified pronounced magnetic anomalies out to anomaly 5 on the SEIR between Amsterdam and St. Paul Islands and the triple junction to the west. They showed that the ridge axis trends northwest–southeast and has a direction of spreading approximately $\text{N}45^{\circ}\text{E}$. North of this ridge axis in the Central Indian Basin they identified magnetic lineations for anomalies older than 21, trending east–west. Furthermore, they identified two fracture zones in the northern portion of the Central Indian Basin which they named Indira (83°E) and Indrani (79°E) fracture zones. Sclater and Fisher [2] postulated that these anomalies have originated from an ancient east–west trending SEIR. Sclater et al. [3] identified a fracture zone south of 27°S trending $\text{N}45^{\circ}\text{E}$ between 82°E and 85°E which appears to change its direction to $\text{N}10^{\circ}\text{E}$. He

explained this change in the magnetic lineation pattern by the reorientation of the SEIR from east–west to northwest–southeast between the times of anomalies 18 and 15 (~ 43 to 39 Ma). The Indian Ocean Triple Junction, located at about $25^{\circ}30'\text{S}$ and 70°E representing the convergence point of the Indian, African and Antarctic plates, has played a major role in controlling the structural evolution of the Indian Ocean [4]. Close to the triple junction, the CIR and the SEIR have bathymetric characteristics of typical mid-ocean ridge spreading centers, exhibiting well-defined median valleys [5]. Sclater et al. [6] observed generally small and very few deep transform faults on the CIR and SEIR and in particular noticed small transform faults on the SEIR at 26°S , $27^{\circ}30'\text{S}$ and $28^{\circ}30'\text{S}$ as revealed by topography and the offsets in magnetic lineations. According to Tapscott et al. [7] the CIR near the triple junction has been spreading symmetrically at a nearly constant half-rate of 2.7 cm/yr over the last 4 Ma. The SEIR prolongs the CIR as a medium rate spreading center (~ 3.0 cm/yr half-rate) and, by contrast, the SWIR is a slow spreading ridge (0.8 cm/yr), which approaches the CIR as an elongate triangular deep with its apex at the triple junction [7]. The Central Indian Basin between CIR and Nintyeast Ridge, bounded in the south by the SEIR and the Indian Ocean Triple Junction, has a

complex evolutionary pattern as it might have been affected by the evolution of the triple junction, the slower spreading CIR and the medium rate spreading SEIR. The complexity of the pattern comes from a quick increase in the two spreading rates. Detailed surveys of magnetics and bathymetry are carried out to decipher the evolutionary history of the Central Indian Basin between 9°S and $16^{\circ}30'\text{S}$ latitudes and 73°E and $79^{\circ}30'\text{E}$ longitudes.

2. Methods

The study was carried out using the shipboard data collected as part of the project "Surveys for Polymetallic Nodules". About 7850 line km of total magnetic intensity and bathymetry data are collected along 14 profiles at approximately 0.5° spacing (Fig. 1). The positions were obtained by Satellite Navigation System. The total magnetic intensity data were collected using the Geometrics

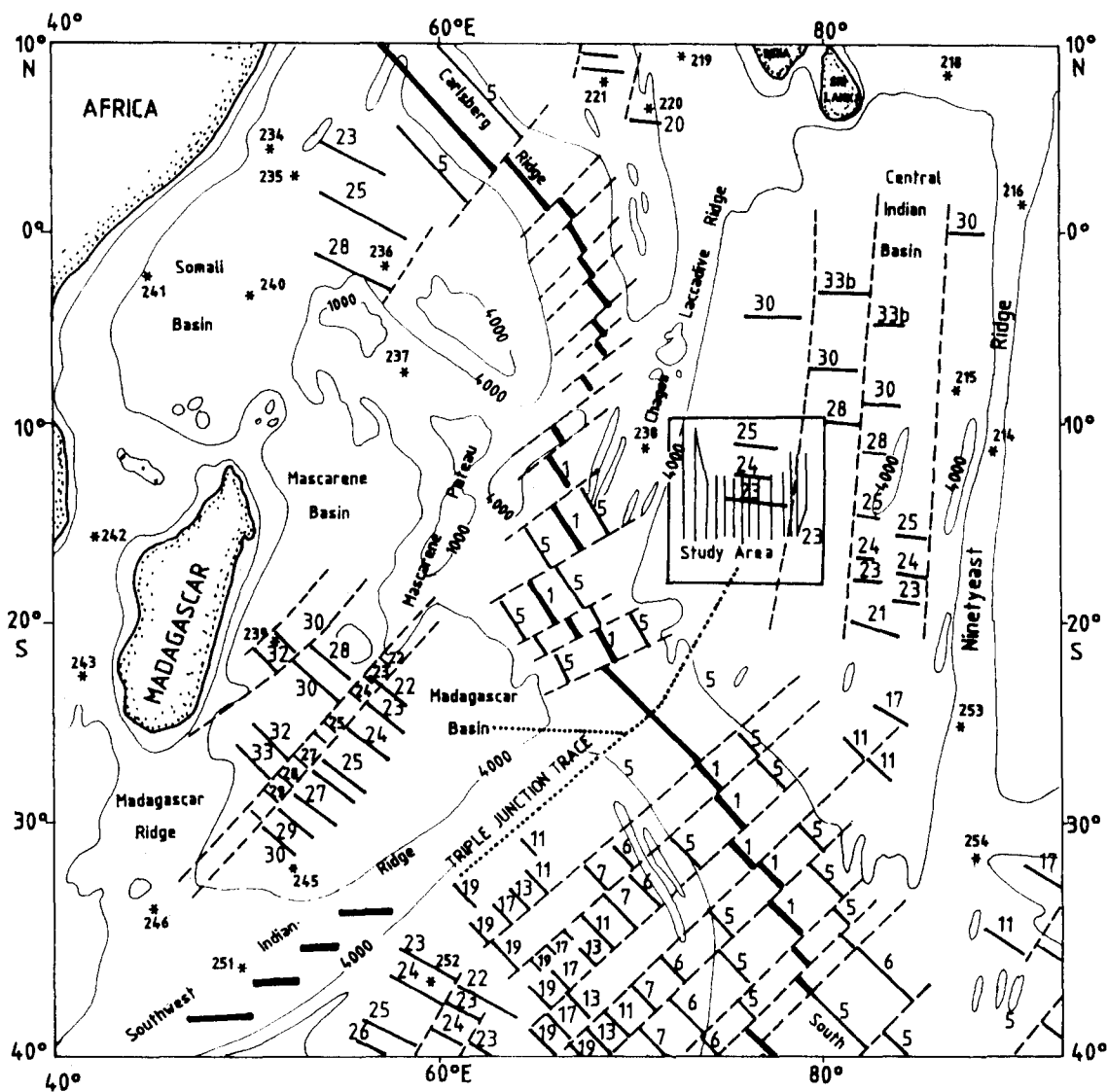


Fig. 1. Map showing the study area with identified magnetic anomalies (numbered solid lines), fracture zones and bathymetric contours (after Schlich [4]). Star symbol with number denotes DSDP site location. The triple junction trace, as delineated by Slater et al. [6], is marked as a dotted line.

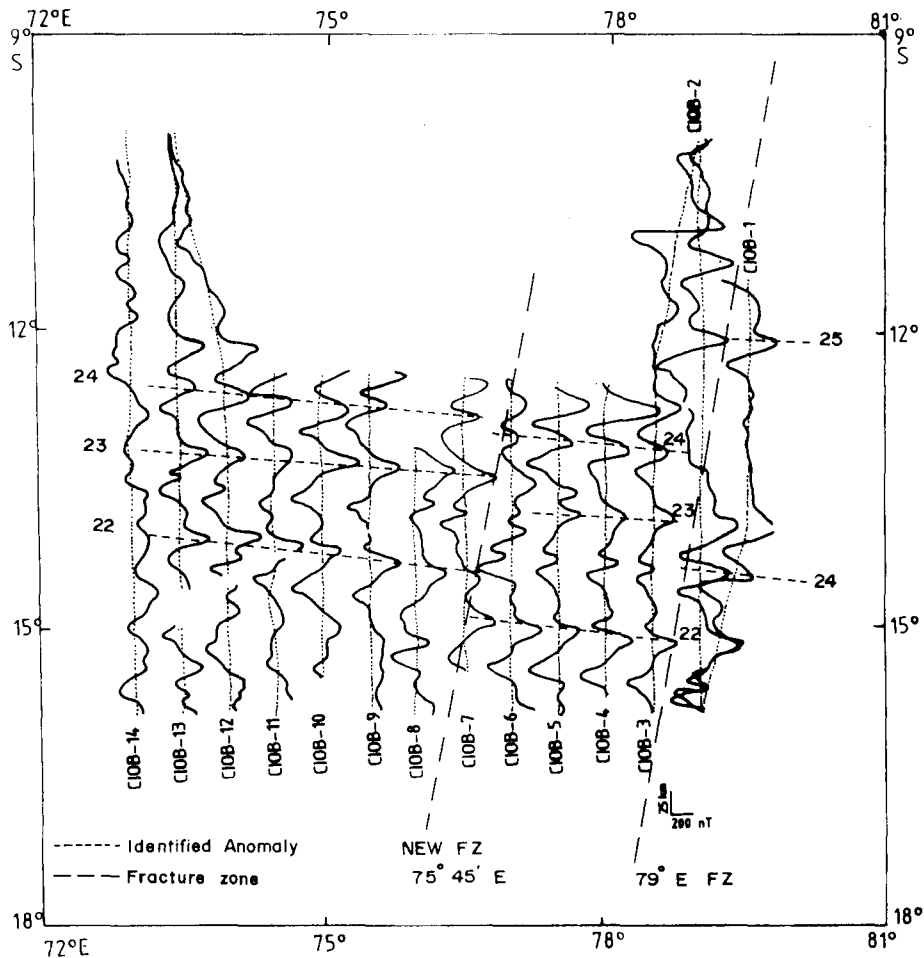


Fig. 2. Stacked magnetic anomaly map, showing the reduced magnetic anomalies plotted perpendicular to the ship's track. The identified magnetic anomalies and the fracture zones are indicated.

marine magnetometer and the bathymetric data were collected with a 12 kHz deep-sea Raytheon echosounder. The magnetic data were reduced by subtracting the value of the International Geomagnetic Reference Field [8] computed at each observation point. Bathymetric data were reduced for transducer and Matthew's corrections [9]. The reduced magnetic anomalies were plotted (Fig. 2) perpendicular to the ship's track. The reduced magnetic and bathymetric profiles together with model are plotted in Fig. 3 while their contour maps are presented in Figs. 4 and 5.

3. Results and discussion

Compared to the western part in the study area the bathymetry in the eastern part is less rugged.

There appears to be poor correlation between bathymetry and magnetics along the profiles; however, in lines CIOB-13 and CIOB-14 the magnetic anomaly signature appears to have been affected by prominent variations in the bottom topography of the order of 800–1000 m. However, there is no clear indication in the magnetics suggesting the presence of a fracture zone. From the bathymetric contour map (Fig. 5) it is seen that the southern part of the study area is more rugged than the northern part with a series of subparallel lows and highs. A conspicuous bathymetric feature is observed in the northeastern corner of the study area depicting a bathymetric low of 5400 m; this feature extends to about 125 km with topographic elevations on either side. This bathymetric feature is associated with the 79°E fracture zone

offsetting the magnetic anomalies across lines CIOB-2 and CIOB-3. A remarkable correlation is noticed on the stacked magnetic anomaly map (Fig. 2). Magnetic anomalies numbered 21, 22, 23, 24 and 25 are identified from the magnetic polarity scale of LaBrecque et al. [10]. The magnetic anomaly contour map (Fig. 4) depicts alternate bands of positive and negative anomalies trending in an east-west direction. Seafloor-spreading model studies have been carried out assuming a uniformly magnetized block with a thickness of

500 m and a susceptibility of 0.01 c.g.s. units (Fig. 3). McKenzie and Sclater [1] have suggested that the seafloor beneath this part of the Indian Ocean was not formed where it now is, but closer to the South pole and has since drifted. The best fit of the model is obtained by assuming the ridge axis location at 35°S with nearly N10°E spreading. When compared to the synthetic profile, the amplitude of the observed anomalies is less. The shape of the anomaly, however, is in close agreement. The shape of the anomaly is considered to

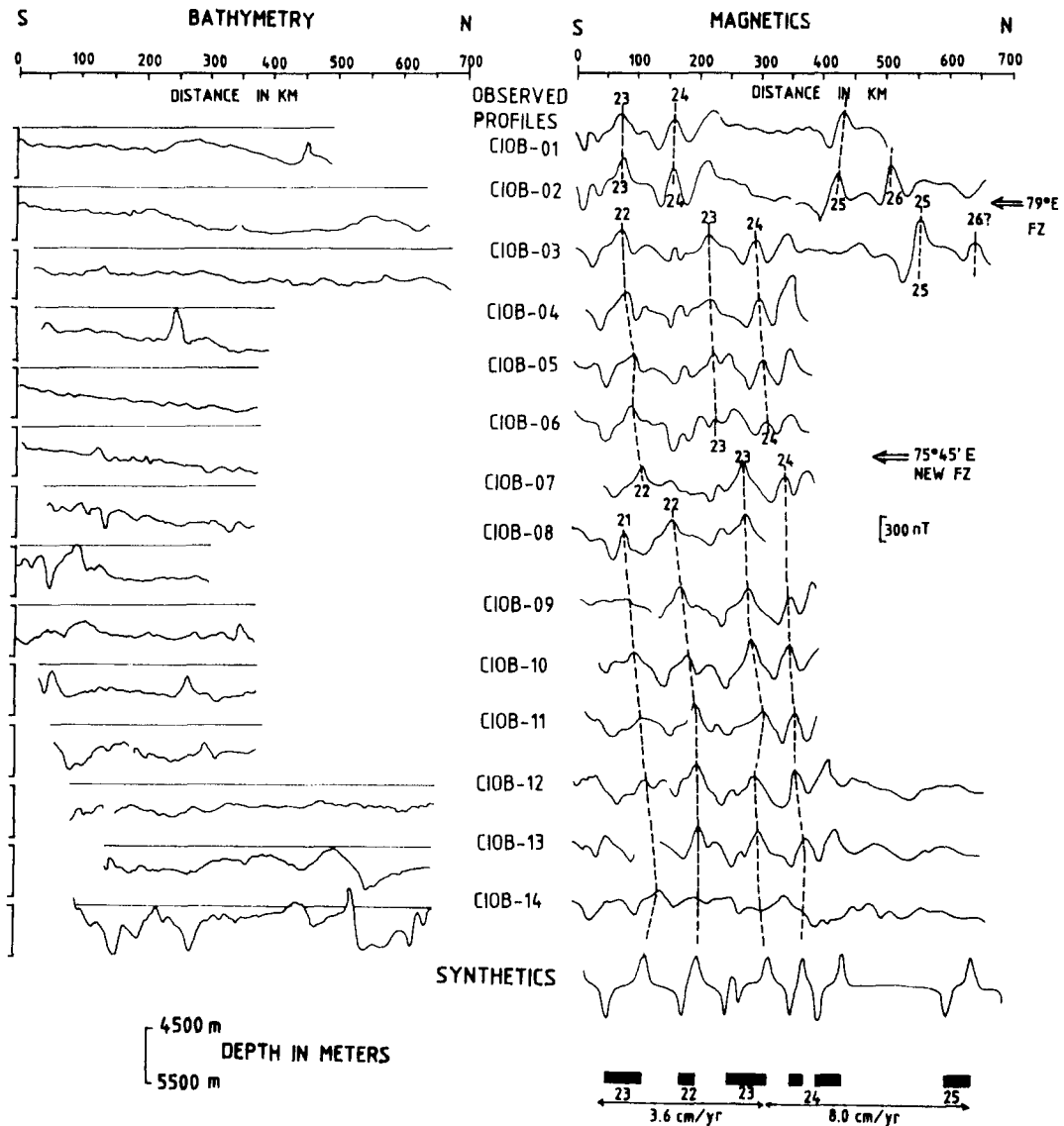


Fig. 3. Bathymetric and magnetic profiles (see Fig. 2 for profile locations). Also shown are the synthetic magnetics. The magnetic anomalies 21, 22, 23, 24, 25 and 26 are identified and the fracture zones marked.

be more important than the amplitude, because the amplitude depends on the value of susceptibility which is poorly known and probably variable. The shape of the anomalies, however, is a function of the Vine-Matthews model. Possible contamination effects of the magnetic signal are not considered as these are significantly high only at slower spreading rates resulting in a narrower width of the single-polarity blocks [7]. The seafloor-spreading model studies indicate a variable spreading rate of 3.6 cm/yr between anomalies 21 and 23 and 8.0 cm/yr between anomalies 23 and 25, these rates are approximately the same as reported earlier for the SEIR [1-3]. The correlation of the anomalies is not continuous across the study area. Furthermore, a variable difference in the offset between the identified anomalies is noticed. The large offset in magnetic anomaly 24 across lines CIOB-3 and CIOB-2 and the associated bathymetric features indicate the southern extension of the 79°E fracture zone which was earlier identified by

McKenzie and Sclater [1]. The magnetic anomalies are uncorrelatable across lines CIOB-7 and CIOB-6 indicating a clear offset between anomalies 22, 23 and 24 around 75°E. The flexures in the magnetic anomaly contours (Fig. 4) also indicate a nearly north-south trending fracture zone which offsets magnetic lineations right-laterally towards the south. We therefore suggest that there may be a discontinuity or fracture zone in this region at 75°45'E, trending N12°E which is parallel to 83°E and 79°E fracture zones.

The postulated fracture zone at 75°45'E in the study area has strong implications on the evolution of the triple junction. It can be seen from Figs. 1 and 6 that the trace of the triple junction, as delineated by Sclater et al. [6], extends into the study area. The dotted line in Fig. 6 represents the trace of the Indian Ocean Triple Junction on the Indian, Antarctic and the African plates during the evolution of the triple junction. Shortly before 80 Ma, the ridge axis that had existed north of

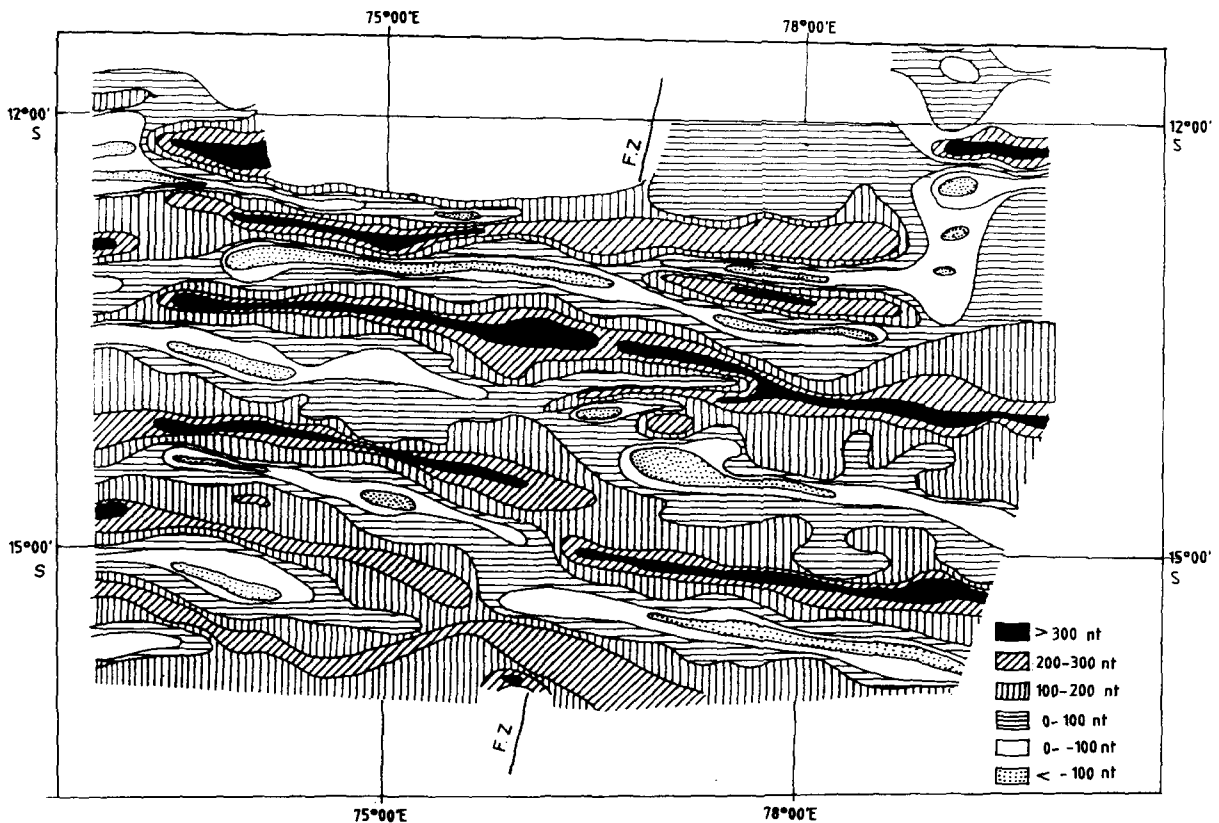


Fig. 4. Magnetic anomaly contour map, the postulated fracture zone is marked.

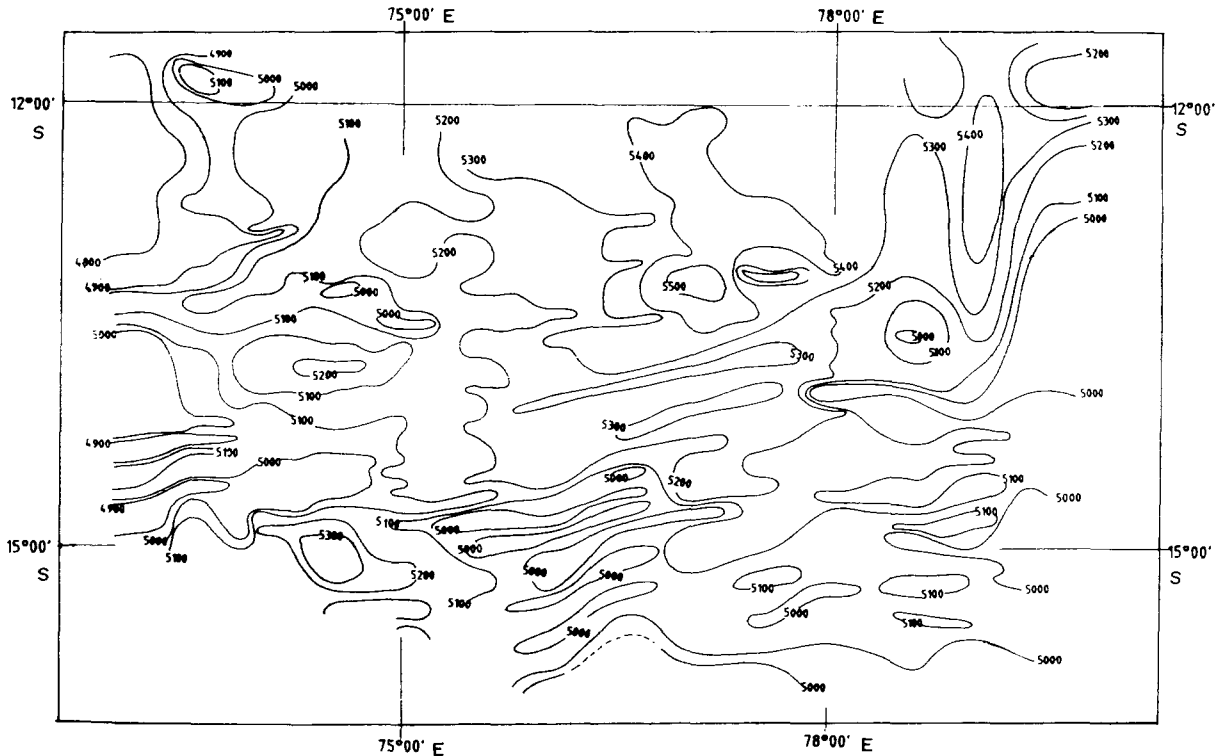


Fig. 5. Bathymetric contour map; contour interval 100 m.

Madagascar [11] jumped south, changed direction and commenced to separate Madagascar from India. A RRR (ridge–ridge–ridge) triple junction was created at the southeastern extremity of Madagascar Ridge, joining the newly formed CIR spreading center to the already active SWIR and SEIR that had been separating India and Antarctica. The above observations by Fisher and Sclater [12], based on their reconstruction studies, indicate that the triple junction has been created before 80 Ma (anomaly 34). Between 80 and 64 Ma, India and Madagascar continued to separate as did India and Antarctica and the triple junction moved both east and south. By 53 Ma (anomaly 22), India had separated farther from Madagascar and Antarctica, and the triple junction moved further east and to the north. Rapid eastward migration of the triple junction with respect to the African plate was reported by Tapscott et al. [7] and Sclater et al. [6] during post-44 Ma (anomaly 19) times. Considering the reconstructions of [6,7,12,13], it appears that the crust in the study area has been affected by the fast spreading SEIR

and the slower CIR and has been subjected to modifications as a consequence of the evolution of the triple junction. This indication leads us to suggest that the evolution of the triple junction has influenced the crust in the study area. This may be one of the possible causes for the decreasing offsets observed in the identified magnetic anomalies as the crust ages; the offset near anomaly 24 is very much less when compared to the offsets across anomalies 21, 22 and 23.

The more recent studies by Royer and Schlich [14] on the SEIR between triple junction and the Amsterdam and St. Paul Islands indicate several fracture zones on this segment of the ridge. Fig. 6 summarizes the findings from the present study along with those of earlier studies [3,4,14]. The detailed kinematic studies on the SEIR showed that the fracture zones tracked in the Crozet Basin can be carried north into the Central Indian Basin [14]. The postulated new fracture zone had been predicted from the observed offsets in magnetic anomalies 22–20 in the Madagascar Basin and from the reconstruction of the same isochrons

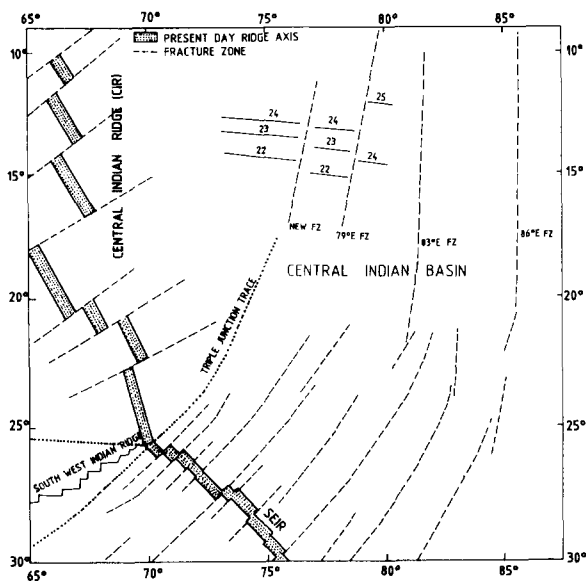


Fig. 6. Tectonic summary of the Central Indian Basin in relation to the Indian Ocean Triple Junction, Central Indian Ridge (CIR) and South-East Indian Ridge (SEIR). The new fracture zone at $75^{\circ}45'E$ and the identified magnetic anomalies (numbered solid lines) in the study area are shown along with the other fracture zones on the CIR and SEIR. Fracture zones on the CIR are from Schlich [4], $83^{\circ}E$ and $86^{\circ}E$ fracture zones in the Central Indian Basin are from Sclater et al. [3]. The Triple Junction trace as delineated by Sclater et al. [6] is indicated with a dotted line. Fracture zones on the SEIR segment are from Royer and Schlich [14].

within the Indian plate, indicating a conjugate fracture zone [15]. The reconstructions proposed by Patriat and Segoufin [15] indicated that this fracture zone originated as a result of the ridge jump along the CIR during the times of anomalies 22 to 20. However, the predicted isochrons [15] are not compared with the observed magnetic lineations west of the suggested triple junction trace. When the observed magnetic lineations (anomalies 21 to 25) in this region are modelled assuming that these anomalies have originated from the SEIR (Fig. 3), the fit is also reasonable. These observations and the trends of $79^{\circ}E$ and $86^{\circ}E$ fracture zones in the vicinity of the study area lead to two possible origins for the postulated new fracture zone: it could have originated from either SEIR or CIR. This can be resolved with additional data south of the present study area.

Several changes in the spreading rate accompanied by minor spreading direction changes at about 10, 19, 24 and 45 Ma are observed in the vicinity

of the SEIR [16,17]. One more phenomenon that has effected this part of the ocean floor is the global plate reorganization in the Indian Ocean resulting in the reorientation of the SEIR from east–west to northwest–southeast, causing a major spreading direction change in the Central Indian Basin during the Eocene [3,14,18]. This is believed to have taken place immediately before anomaly 20 near 45 Ma and was completed before anomaly 19 near 44 Ma [18]. Sclater et al. [3] showed that the $86^{\circ}E$ fracture zone changes direction from $N10^{\circ}E$ to $N45^{\circ}E$ at $27^{\circ}S$ as a consequence of the reorientation of the SEIR from east–west to northwest–southeast during Eocene. The postulated fracture zone might also have undergone a change in the direction from $N12^{\circ}E$ to $N45^{\circ}E$ during anomaly times 18 to 20, the period which marked the spreading direction changes on the SEIR and CIR [15]. The change in the direction of the postulated ($75^{\circ}45'E$) fracture zone may be located south of $20^{\circ}S$ latitude.

4. Conclusions

The strike of the anomalies 21, 22, 23, 24 and 25 are clearly identified indicating the presence of a fracture zone at $75^{\circ}45'E$ and the southern extension of the $79^{\circ}E$ fracture zone. The strike of this new fracture zone trends $N12^{\circ}E$ and it is parallel to the fracture zones reported earlier. It appears to have changed its direction from $N12^{\circ}E$ to northeast–southwest during the Eocene, south of $20^{\circ}S$. From the present studies it can be concluded that the evolution of the Indian Ocean Triple Junction might have caused the observed differential offsets in the magnetic anomalies across the $75^{\circ}45'E$ fracture zone. The above observations suggest that the evolution of the triple junction and the reorientation of the SEIR and CIR resulting in the major spreading direction changes in the Central Indian Basin during the Eocene are the major processes that have influenced the evolution of the ocean floor in the study area.

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