Some geodynamic complexities related to the evolution of Bengal Fan and the neotectonic activity of the south Indian shield

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After three decades of the International Indian Ocean Expedition (IIOE) and in spite of extensive geophysical data collected during the last one decade, the geodynamics of the Bengal Fan and the Peninsular shield at the northern end of the Indian Plate remains complex and unresolved. Though recent analysis of few multichannel seismic sections from the Central Bengal Fan could resolve some of the ambiguities, views still differ on several aspects such as the nature and age of the oceanic crust, trends of fracture zones, origin and age of the hotspot traces in relation to the break up and drift of the Indian Plate. Recent inferences on the deformation from Peninsular shield have introduced further complications on the tectonics of the region and suggest a mosaic of east-west and north-south lithospheric upwarps beneath the south Indian shield.

THE earliest comprehensive study on the stratigraphy, structure and tectonics of the Bengal Fan by Curray *et al.*[1], from geophysical data collected during the IIOE and thereafter evoked considerable interest in the study of this region. These preliminary observations, based mostly on four widely spaced seismic sections (along 10°, 14°, 17° and 20°N) in the northern Bengal Fan provided significant information on the geodynamics of this strategic region, considered to have been evolved due to the break-up of Indian Plate from Antarctica during Late Cretaceous (120 Ma) and its subsequent collision with the Asian counterpart around Eocene time (54 Ma). Extensive geophysical coverage during the period from 1980 to 1995 led to several theories on the evolution of the Bengal Fan including the aseismics ridges in this region[2–18]. However, one serious problem encountered in these studies is the thick column of Fan turbidites (reaching at places to nearly 20 km)[8] that obscure the deeper information on the tectonics of the Fan. Most of the hitherto published results were based on potential field (gravity and magnetic) data and multichannel seismic (MCS) sections that could penetrate to the basement are relatively sparse. A recent study by Gopala Rao *et al.*[19] from three MCS sections (13° to 15°N, 81° to 90°E) resolved some of the ambiguities in the interpretation of potential field data. However, the geodynamic history of the region still remains complex, mainly due to lack of sufficient geophysical data in some critical areas of the Fan as well as the Peninsular shield. In particular, the dating of the break-up of Indian plate from Gondwanaland, and the traces of the hotspots and the stress-related neotectonic activity in the south Indian shield are some of the aspects over which divergent views were reported in recent times.

Break-up event

Earlier studies[1] proposed that the separation of the Indian plate from the Enderby Land of east Antarctica occurred around M-11 time (137 Ma), the break-up approximately perpendicular to the present NE–SW trend of the eastern continental margin of India (ECMI). This date was subsequently revised as M-4 (126 Ma)[8]. The Continent Ocean Boundary (COB) was assumed to be at the foot of the continental slope. However, since the eighties, different views were reported on the nature of the Bengal Fan crust, viz. continental[20], oceanic[1,8,15,16,19], transitional[3,4], partly continental and partly oceanic (separated by a graben)[2].

Analysis of extensive bathymetry and magnetic data of ECMI by Murthy *et al.*[9] delineated the COB at the foot of the continental slope and also a Cretaceous Quiet Zone (CQZ) of constant polarity seaward of the COB, only disturbed by the 85° ridge[18], thereby suggesting the break-up event around M-0. Ramana *et al.*[15] pushed back the break-up event to M-11 (137 Ma) based on the identification of seafloor spreading Mesozoic anomalies, M-11 to M-0 from few NW–SE sections taken across the Bengal Fan (10° to 15°N, 81° to 90°E). However, their interpretation suffers from the fact that this region (Block I, Figure 1) is structurally complex due to the influence of the 85°E ridge whose trend could not be delineated unambiguously from magnetic anomalies alone. Demarcation of the 85°E ridge trend by assigning a positive magnetic peak all along its strike[15] is not unique, as earlier studies[2,9,21] reported asymmetric magnetic anomalies of both positive and negative peaks, suggesting offsets along its strike.

MCS data[19] resolved some of these ambiguities and explained the probable uncertainties involved in the identification of Mesozoic anomalies in the Bengal Fan. These studies located the COB more precisely at the foot of the continental slope though it might be remembered that COB off passive margins is not a line boundary, but often associated with a transitional crust of considerable width (few tens of km) separating the continental and oceanic crusts[22]. Their studies also supported the break-up event around M-0 and a CQZ (120–85 Ma) associated with much of the Bengal Fan Crust. However, the drift-related NW–SE fracture zones identified by them in the southern Bengal Fan from the seismic sections (figures 2 and 5 of Gopala Rao *et al.*[19]) need more data to substantiate. Some offsets, either in the fracture zones or the 85°E ridge trend (Figure 1) should have been observed at the intersection of the older fracture zones and the younger 85°E ridge, which are not apparent from their interpretation (figure 5 of Gopala Rao *et al.*[19]). It appears that the structural disturbances in the oceanic basement on either side of the 85°E ridge observed in their seismic sections (figure 2 of Gopala Rao *et al.*[19]) are in fact the N–S fracture zones associated with the 85°E ridge activity (marked in dash and dots in Figure 1), and not related to the NW–SE break-up event. The only exception to this observation is, of course, the isolated steep basement high observed near the COB at the foot of the continental slope off Krishna–Godavari (KG) basin (MAN-01 section in figure 2 of Gopala Rao *et al.*[19]). This might represent an isolated volcanic source (a hotspot) as discussed in the subsequent section.

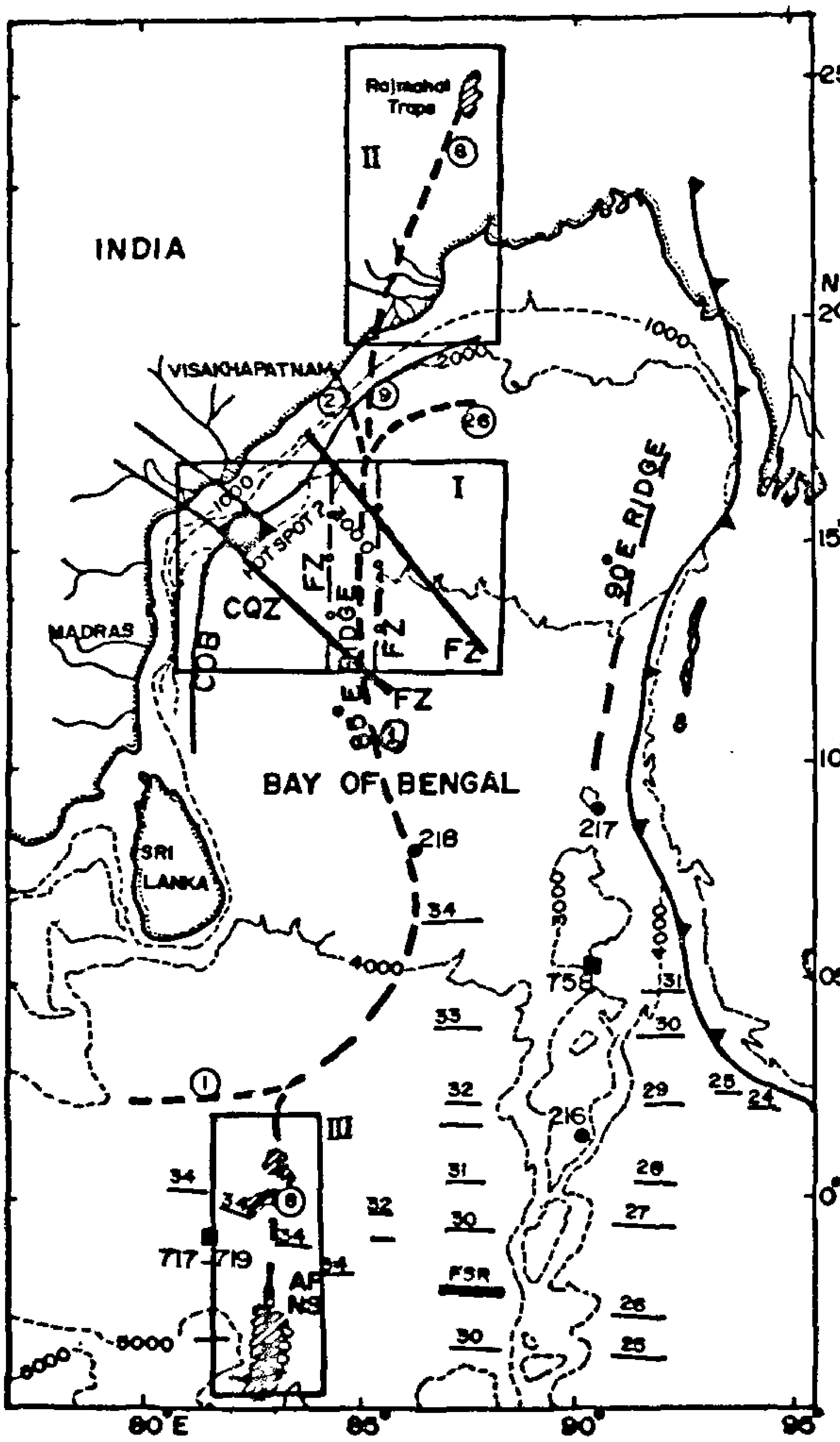

Figure 1. Northern Bengal Fan with critical areas (marked as Blocks I, II and III) where interpretations differ on seafloor spreading anomalies, fracture zones, Crozet (85°E ridge) and Marion hot spot trends[19]. Numbers in circles are references quoted in the text. COB: Continent Ocean Boundary; CQZ: Creataceous Quiet Zone; FZ: fracture zones identified by Gopala Rao *et al.*[19]; dash and dot lines are N–S fracture zones proposed from the present study. Af–NS: Afnasi-Nikitin seamounts.

Not many geological samples were available to date about the oceanic rocks, the only known outcrops from this region being the Afnasi–Nikitin seamounts (Figure 1) far south 4°S, 82°E. In a recent study[13], marine magnetic anomalies have been used to link the granulite facies rocks of ECMI with those of the Enderby Land of Antarctica, though these inferences could only be used to position the Indian Plate with reference to the east Antarctica in the pre-break-up scenario and do not help much in dating the oceanic crust. MCS data over the central Bengal Fan (Block I, Figure 1) at closely spaced (preferably half degree) interval are essential to differentiate the structural anomalies related to the 85°E ridge and the fracture zones and also to map the continental, transitional and oceanic segments of the Fan crust.

Hot spots and aseismic ridges

Traces of four mantle plumes document the different phases in the break-up and the northward trajectory of the Indian Plate since late Cretaceous; Kerguelen and Crozet (Antarctica–India separation at 120 Ma), Marion (Madagascar–India separation at 80 Ma) and Reunion (Seychelles–India separation at 60 Ma)[8,23]. Three of these traces represent prominent aseismic ridges, 85°E ridge (Crozet) and 90°E ridge (Kerguelen trace) in the Bengal Fan (Figure 1) and the Chagos–Laccadiv Ridge (Reunion) in the Arabian Sea. In contrast, the trace of the Marion hot spot inferred south of Madagascar in the western Indian Ocean is relatively less studied.

Murthy *et al.*[12] were of the opinion that the Marion plume was much older than Kerguelen and Crozet and might represent the initial break-up of India from Antarctica. They have located this hot spot (Figure 1) near the COB off Machilipatnam (in the Krishna–Godavari basin) from model studies on a suite of isolated magnetic anomalies. Its expression was also observed as isolated closure in the SEASAT derived Geoid and free air gravity anomaly maps of Bengal Fan[10,11]. It is also observed in the multichannel seismic section of the region[19]. The isolated steep basement high near COB at the foot of the continental slope (MAN-01 section, figure 2 of Gopala Rao *et al.*[19]) coincides with this feature inferred by Murthy *et al.*[12].

The trace of this hot spot in the offshore K–G basins needs a more detail study, though Murthy *et al.*[12] infer that two Precambrain cross trends (the Chintalapudi and Avanigedda trends) in the K–G basin might represent the trace of this hot spot. They further speculated its trace beneath the Peninsular shield[12] till about 80 Ma, when its trace was observed in the oceanic lithosphere, marking the separation of Madagascar from India[8,23]. Their views also get support from Reddy *et al.*[24,25] and Curray and Munasinghe[8]. Reddy *et al.*[24] from integrated study of deep seismic sounding (DSS) data of Peninsular shield were of the opinion that the southern segment of a major Trans-Asiatic lineament along 77°E from Indore to the southern tip of India (Figure 2) might represent the trace of Marion hot spot. Their studies[25] also suggest reactivation of this hot spot trace beneath the Peninsular shield on the basis of emission of smoke and gases observed immediately after the Lattur earthquake, from Adilabad, Nizammabad, Medak and Ranga Reddy districts of Andhra Pradesh. These regions fall on the NW–SE extension of the hot spot trace from the offhshore K–G basin[12], joining the 77°E lineament at Indore (Figure 2).

Curray and Munasinghe[8] positioned the Marion hot spot off K–G basin (in the Bengal Fan) in the palaeo-reconstruction of eastern Gondwanaland and speculated its trace beneath the Peninsular shield in a N–S direction from the initial break-up of the Indian Plate, till about 96 Ma when Madagascar got separated from India (figure 3 of Curray and Munasinghe[8]).

However, in the absence of more deep seismic sounding data, the trace of this hot spot beneath the Peninsular shield remains mostly speculative. The lack of surface expression of the Marion trace (if it had really passed beneath the Indian shield from 120–80 Ma), might be due to the thick continental lithosphere in contrast to the thin oceanic lithosphere in the western Indian ocean, where its trace was well established. DSS sections across the Peninsular shield might help to establish its trend. Nevertheless, it must be emphasized that studies on the origin and trace of this hot spot assume more significance, since this plume appears to be older than the Kerguelen and Crozet plumes and might represent the initial break-up of India from Antarctica.

While the origin and trace of the Ninety east ridge in the Bengal Fan were relatively well established, the 85°E ridge, considered to be the trace of the Crozet hot spot[8], remains a complex structure for the geophysicists. It is one tectonic lineament that was twisted at both ends to the left, right and straight (Figure 1), with

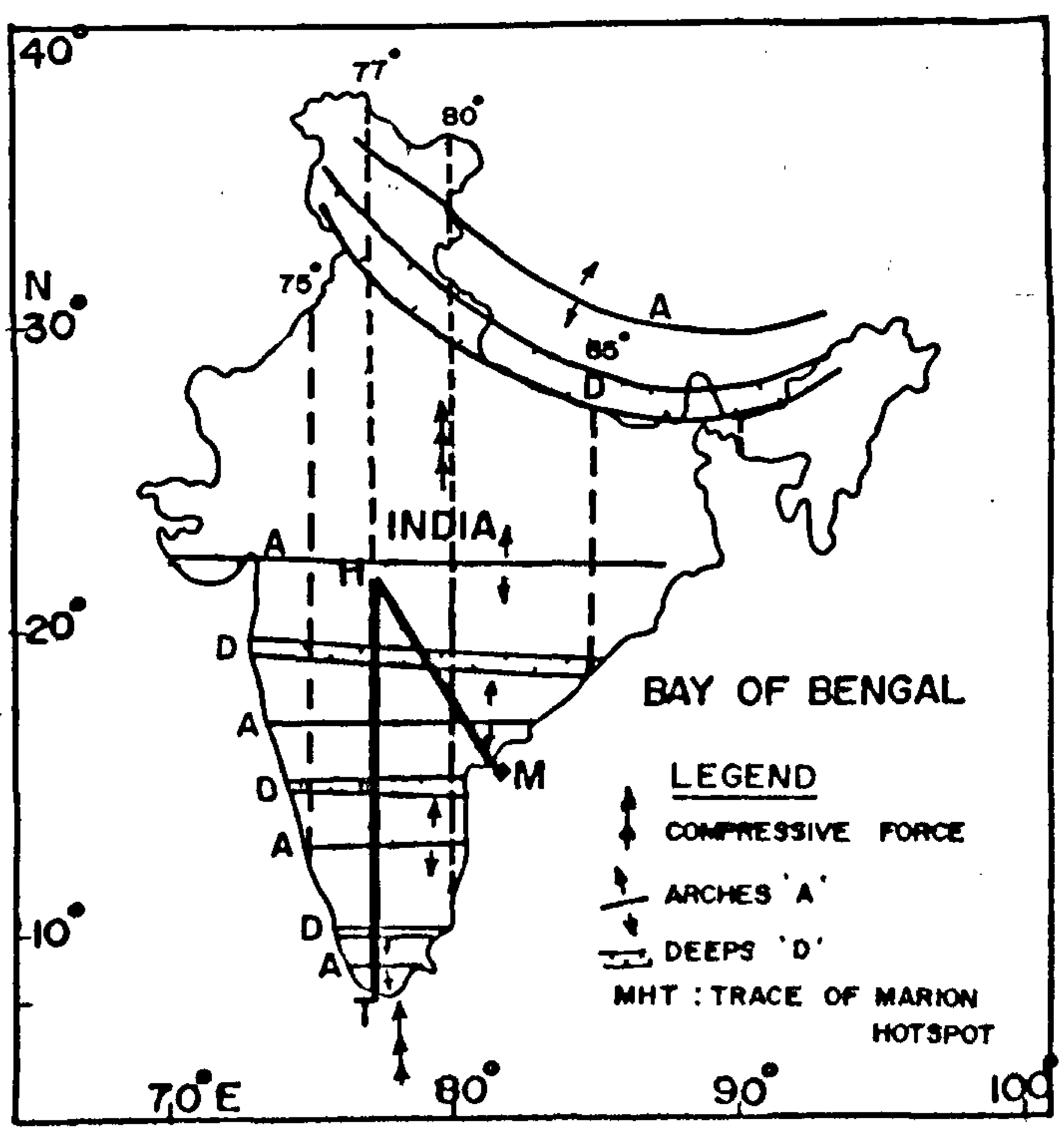

Figure 2. Tectonic fabric suggesting east–west (thick lines) and north-south (dashed lines) lithospheric upwarps in the south Indian shield[24,39,40,42].

various theories attributed to its origin. This ridge was identified, initially from two E–W seismic section along 10°N and 14°N in the Bengal Fan[1]. Its northern end could not be delineated beyond 17°N while the southern end was considered to follow a curved path towards west (Figure 1), passing south off Sri Lanka. Subsequently Curray and Munasinghe[8] reoriented its direction both at the southern and northern ends. Towards south they joined it to Afnasi–Nikitin seamount chain at 4°S, whereas at the northern end it was straightened to join the Raj Mahal traps at 25°N, 87°30'E (Figure 1), thereby linking them both as part of Crozet hot spot activity[8], in contrast to their earlier views considering Raj Mahal traps as part of Kerguelen plume.

Subsequently, different trends were proposed to this ridge (Figure 1), particularly at the northern end (beyond 17°N); a NW–SE trend abutting Visakhapatnam Shelf[2], a N–S trend abutting Chilka Lake (20°N)[9] and even a NE trend within the Bengal Fan[26]. Theories regarding its origin also vary considerably; an aseismic ridge[1,9], a hot spot trace[8], leaky volcanic zone[6], spreading centre[7], a fracture zone[27], with no reasonable age or origin attributed to it so far.

One of the main reasons for these complex views is the lack of deep seismic data across the strike of the ridge particularly beyond 17°N, where it is overlain by thick sequence of Bengal Fan sediments. Most of the inferences on the trend of this ridge were based on magnetic and gravity data, some attributing asymmetric magnetic anomalies of both positive and negative peaks[9,29], others only positive peaks[15] with symmetric anomaly pattern[7]. This is particularly critical in the Central Bengal Fan (10°–15°N) where it was found to be difficult to differentiate the 85°E ridge signature from fracture zones and the inferred Mesozoic spreading anomalies[15,19].

Analysis of rock samples from Raj Mahal traps over the continental region and the out-cropped Afnasi–Niktin seamounts (Figure 1) south of Sri Lanka might help to test the validity of their common origin[8] forming the trace of the Crozet hot spot.

Mid-plate tectonics

Intraplate deformation, a peculiar phenomenon within the Indian Plate, was observed for the first time in the equatorial region of the Central Indian Ocean basin (CIOB)[28,29]. Subsequently, this area was extensively studied by American, Russian and Indian scientists[30–38]. The stress acting on the Indian plate by spreading across the mid-ocean ridges in the CIOB and the resistance at the contact between Indian and Asian plates were considered to be the main reasons for the intense deformation in the Oceanic lithosphere manifested in the form of long wavelength (nearly 20 km) high amplitude (1 km) folds in CIOB.

In recent times, there are reports on the stress-related deformation from the Peninsular India, a region hitherto considered as a stable land mass. Significant among these observations is the major basement upwarp along 13°N from Mulki (near Mangalore on the west coast) to Pulicat (near Madras on the east coast)[39,40] inferred from land morphology, changes in the drainage pattern, and sea level records (submergence and emergence) from the coastal region (Figure 2). The offshore extension of this upwarp was also reported from bathymetry, magnetic and gravity data off Madras to Pulicat[41]. Another significant study[42] based on morphotectonics of the Tamil Nadu Shelf from remote sensing data, suggests that the south Indian Shield is being deformed into a series of E–W arches and depressions (Figure 2) due to the stress-related neotectonic activity since Quaternary (2 Ma). An altogether different orientation was given by Reddy *et al.*[24] from an integrated study of the DSS data of the Peninsular India, according to which the south Indian Shield and the Bengal Fan are underlain by longitudinal lithospheric upwarps (marked in dashed lines in Figure 2) at almost 5° interval (between 70° and 90°E), three of which, (Chagos–Laccadiv, 85°E and Ninety east Ridge) already well documented.

Most of these inferences were based either on coastal and land morphology or from deep-seated signatures inferred from seismic data with no surface expression. There are no data to time these events or to study their vertical extent in detail. But if these results were true, then the Peninsular India might be considered as a mosaic of east–west and north–south lithospheric upwarps (Figure 2), a situation that appears to be a little unrealistic at present. A few representative DSS sections both in latitudinal and longitudinal direction over the south Indian Shield might resolve this ambiguity.

In summary, it appears that a time has come to take stock of the situation and to integrate all the results published on the evolution of Bengal Fan and the neotectonic activity of the Peninsular Shield. There are some critical areas (Blocks I, II and III, Figure 1) in the Bengal Fan which need more detailed geophysical studies. Some of the priority tasks which might be taken up under major R&D projects of this region can be summarized as follows:

1. Multichannel seismic data in the southern Bengal Fan (10° to 15°N, 80° to 90°E) mainly to differentiate the continental, transitional and oceanic crust, to study the 85°E ridge signature in detail and also to establish the trend of the rift-related fracture zones (Block I, Figure 1). This might help in dating the break-up event more precisely.
2. MCS and DSS data over the shallow continental shelf off Chilka lake and on land regions between

Chilka lake and Raj Mahal traps (Block II, Figure 1) mainly to confirm the structural link between Raj Mahal traps and 85°E ridge.

3. Collection and analysis of rock samples (Blocks II & III, Figure 1) from Raj Mahal traps (25°N, 87°30′E) and Afnasi Nikitin seamounts (4°S, 82°E), to confirm their link to the Crozet hot spot activity[8]. These studies might help to trace the movement of the Indian Plate since the late Cretaceous break-up.
4. Few representative (N–S and E–W) DSS sections over the Peninsular Shield (Figure 2) to study the validity of the observations on the intraplate deformation events and also to test the inferences drawn on the trace of the Marion hot spot.
5. Correlation of onshore and offshore tectonic lineaments to understand their influence on the stability of south Indian Shield[43].

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