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Delineation of the 85°E ridge and its structure in the Mahanadi Offshore Basin, Eastern Continental Margin of India (ECMI), from seismic reflection imaging

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ABSTRACT

The passive Eastern Continental Margin of India (ECMI) evolved during the break up of India and East Antarctica in the Early Cretaceous. The 85°E ridge is a prominent linear aseismic feature extending from the Afanasy Nikitin Seamounts northward to the Mahanadi basin along the ECMI. Earlier workers have interpreted the ridge to be a prominent hot spot trail. In the absence of conclusive data, the extension of the ridge towards its northern extremity below the thick Bengal Fan sediments was a matter of postulation. In the present study, interpretation of high resolution 2-D reflection data from the Mahanadi Offshore Basin, located in the northern part of the ridge, unequivocally indicates continuation of the ridge across the continent–ocean boundary into the slope and shelf tracts of the ECMI. Its morphology and internal architecture suggest a volcanic plume related origin that can be correlated with the activity of the Kerguelen hot spot in the nascent Indian Ocean. In the continental region, the plume related volcanic activity appears to have obliterated all seismic features typical of continental crust. The deeper oceanic crust, over which the hot spot plume erupted, shows the presence of linear NS aligned basement highs, corresponding with the ridge, underlain by a depressed Moho discontinuity. In the deep oceanic basin, the ridge influences the sediment dispersal pattern from the Early Cretaceous (?)/early part of Late Cretaceous times till the end of Oligocene, which is an important aspect for understanding the hydrocarbon potential of the basin.

1. Introduction

The northward migration of the Indian Plate over different mantle plumes resulted in the emplacement of volcanic provinces in the Indian shield with their trace in the oceanic crust (Curray and Munasinghe, 1991; Kent, 1991; Storey, 1995; Storey et al., 1995; Műller et al., 1997). The 85°E Ridge is interpreted to be one such trace in the Bay of Bengal, north-east Indian Ocean. However, the recognition of the ridge in the northernmost tracts, in offshore Mahanadi basin, was cryptic due to its burial under thick Bengal Fan sediments. South of 5°N, the ridge intermittently rises above the seafloor and finally joins with the Afanasy Nikitin Seamount (ANS), after a sharp bend off Sri Lanka (Fig. 1). The buried northern part of the ridge is associated with a prominent gravity low, while a prominent linear positive trend is seen to the south where the ridge rises above the seafloor. Liu et al. (1982) interpreted the negative gravity field to be caused by the emplacement of the ridge onto a young oceanic crust and subsequent burial under a massive sediment cover. Curray and Munasinghe (1991) postulated that Rajmahal traps in eastern India, the 85°E Ridge and the ANS represent the trace of the Crozet hot spot (Fig. 1). The subsurface structure of the ridge was earlier mapped from seismic reflection data up to 17°N in the Bay of Bengal (Curray and Moore, 1971, 1974; Curray et al., 1982). Based on the gravity signature and magnetic trends many workers (Ramana et al., 1997; Nayak and Rao, 2002; Subrahmanyam et al., 2008) interpreted the 85°E Ridge to be abutting against the Mahanadi coast. The characteristic gravity low attributed to the ridge is obscured by the shelf edge anomaly of the ECMI, and therefore it does not present a definitive interpretation of the ridge below the Mahanadi shelf. Anand et al. (2009) inferred termination of the ridge at 15°N and proposed that the structure seen along 17°N profile of Curray et al. (1982) could be a geomorphic expression of the basement. In order to address these issues, a detailed investigation of the 85°E Ridge across the continent–ocean boundary (COB) in the Mahanadi offshore is carried out based on several closely spaced high resolution 2-D seismic profiles (Fig. 2). The study is useful to understand the architecture and mode of emplacement of the 85°E ridge in the vicinity of the ECMI. In addition, the effect of the ridge on subsequent sediment dispersal pattern in the

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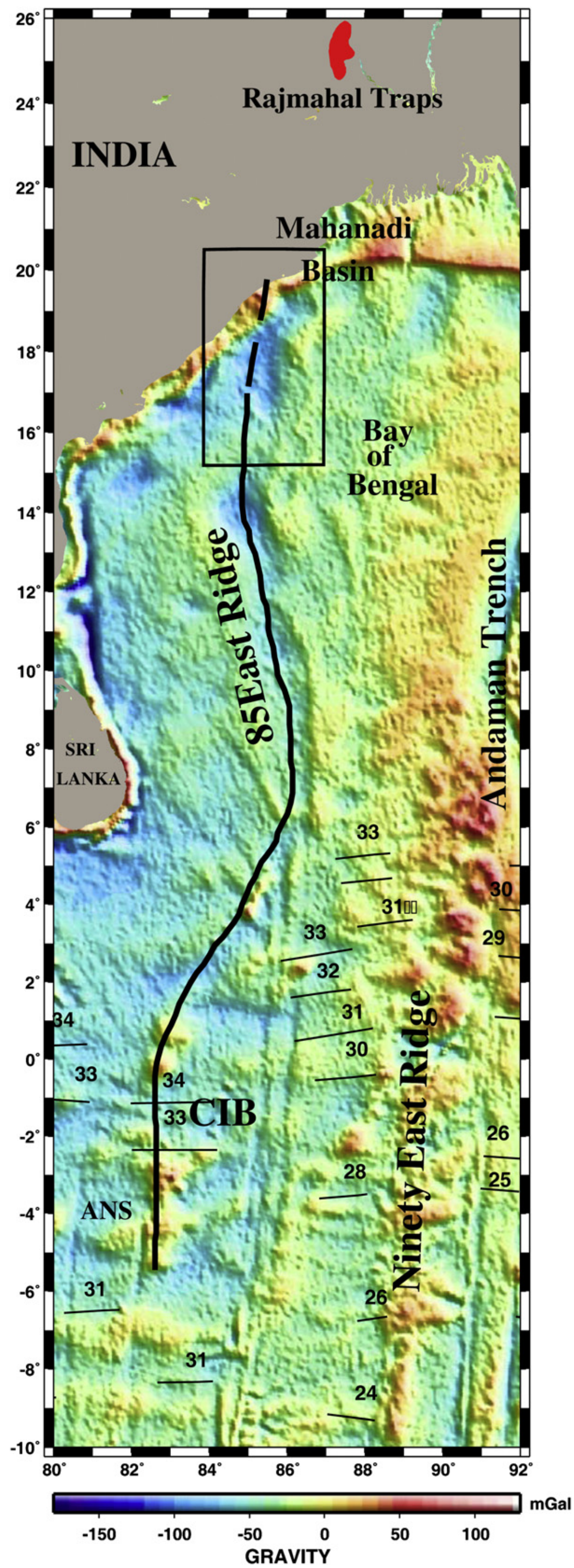


Fig. 1. Satellite derived gravity (Geosat) image of the 85°E Ridge and surrounding Bay of Bengal region. The thick line indicates the trace of the 85°E Ridge. The present study area is marked as a rectangular block. CIB – Central Indian Basin.

Mahanadi offshore basin is examined for its relevance to deep water petroleum prospectivity.

2. Data

Regional scale 2-D seismic lines, acquired as part of the exploration activity in the deep water Mahanadi offshore, have been studied to decipher the signature of the 85°E Ridge and to understand the causes for its emplacement. Seismic data are also used to prepare isochronopach maps between regionally significant sequence boundaries to aid the understanding of the interplay between the ridge morphology and the sediment depositional fairway. For the present purpose, selected 2-D lines are illustrated to bring out significant features and evidences regarding the morphology, structure and evolution of the ridge. The data are discussed in sections based on major structural sectors of the studied area.

3. Seismic character of the 85°E ridge off the Mahanadi margin

3.1. Shelf region

Seismic profiles a1, a2, b and c (Fig. 3a–c) traversing across the continental shelf show the presence of a prominent seismic event around 1.5 s two-way travel time (TWT), recognized as the Acoustic Basement Top (ABT), below which the seismic facies display a chaotic character without any discernible seismic reflections. Several wells drilled on the Mahanadi shelf have penetrated this event which corresponds to the top of a suite of effusive basic volcanic rocks. These rocks have been assigned an Early Cretaceous age based upon the age of the overlying paleontologically dated sediments, and have been correlated with the Rajmahal Traps that are exposed further to the north in the Indian continental shield (Fuloria et al., 1992; Fig. 1). In the neighbouring Bengal and Krishna–Godavari (K–G) basins, typical seismic signatures of rifted passive margins are recorded, and drilled wells have penetrated into non-volcanic crystalline continental crust (Bastia, 2006). This suggests that the massive outpouring of lavas may inhibit the recognition of such typical rift-related features in the Mahanadi shelf region.

3.2. Slope region

Thick wedges bounded by Seaward Dipping Reflectors (SDR's) are observed below the correlated top of volcanics (i.e., the ABT) in the slope region (Profiles a2, b and c in Fig. 3). These wedges become progressively younger and thicker in a basinward direction. The combined thickness of these wedges sharply varies between 2.5 and 4 s along the slope. The thicknesses as well as the dips are anomalous when compared to the normal thickness of SDR's associated with typical oceanic crust. Away from the main ridge axis, towards north-east and south-west, the SDR's are not seen in the slope region, while features showing typical linkage of normal continental curst to oceanic crust through rifted margin and proto-oceanic crust are observed (Fig. 3d and e). The presence of similar wedges bound by SDR's was reported from the Walvis ridge in SE Atlantic Ocean (Elliott et al., 2009). Near the base of the slope, several prominent upward doming events are observed, below which the SDR's are absent (Profiles a3 and b in Fig. 3). The region of prominent SDR's corresponds to the broad basinward plunging nose seen on the TWT map (Fig. 2) of the ABT. This region in the slope represents the northern limit of the morphological ridge in the Mahanadi offshore basin. However, as evidenced by a drilled well as well as by seismic data, it is suggested that the associated volcanism is present further northward in the shelf area.

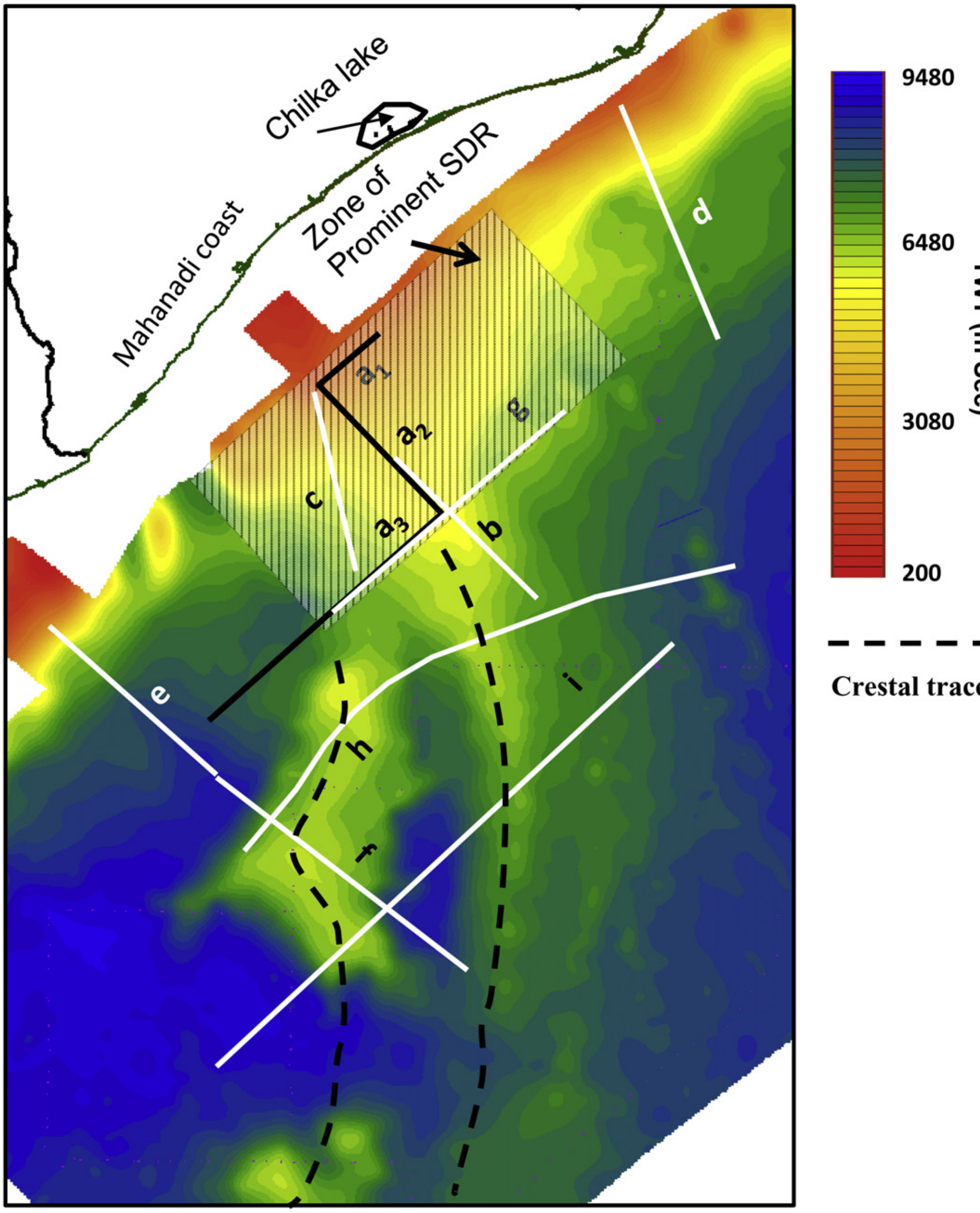


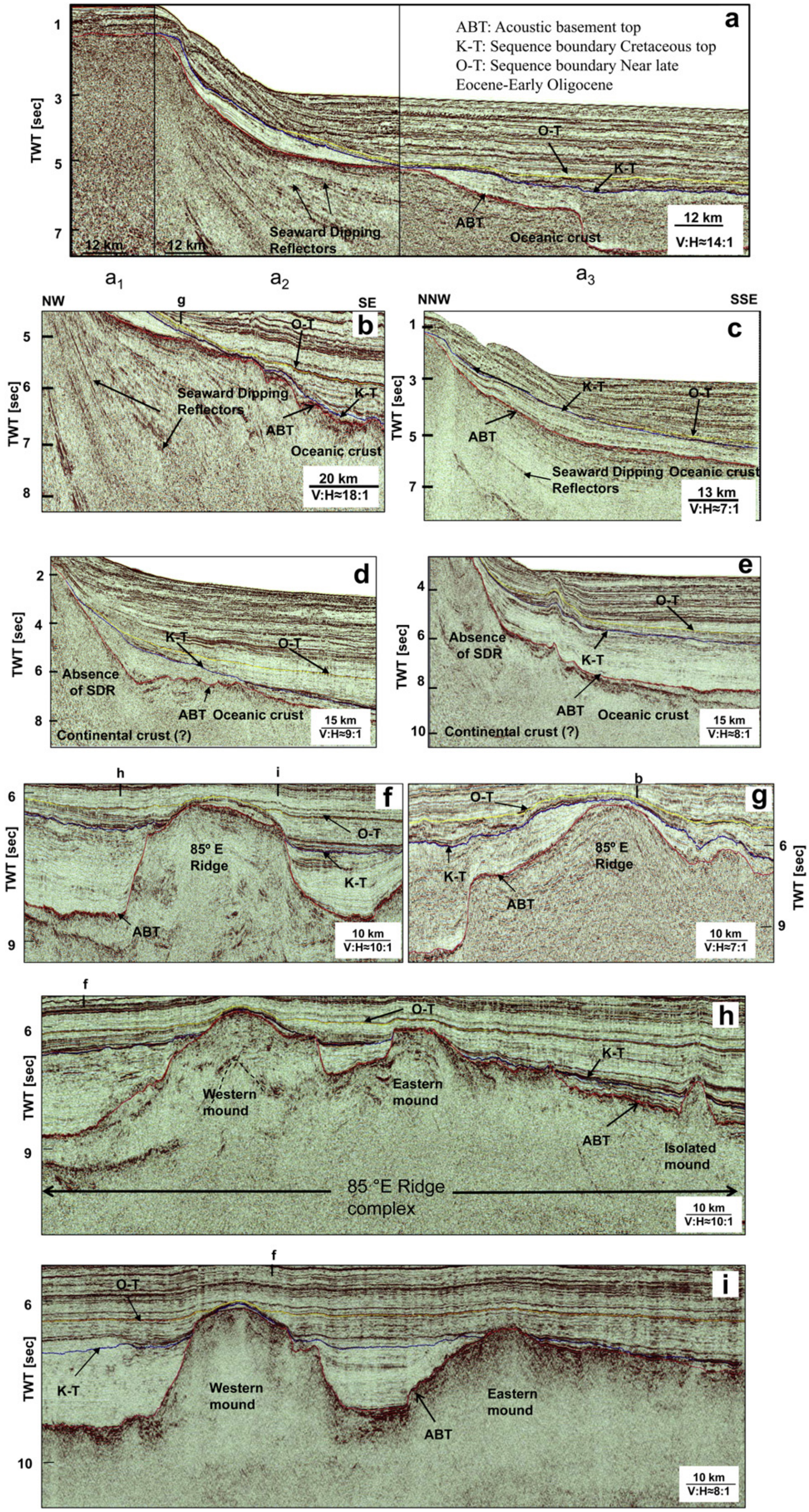
Fig. 2. Time structure map at the top of the acoustic basement (ABT) showing the crestal trace of the 85°E Ridge. The lines indicate the location of the seismic profiles used in Fig. 3. The shaded zone marks the area with prominent seaward dipping reflectors (SDR).

3.3. Oceanic crust

Two dip (Profiles b and f in Fig. 3) and three strike (Profiles g, h and i in Fig. 3) lines illustrate the morphology and internal structure of the ridge in this sector. In the proximal part of the abyssal plain, the internal reflection patterns of the ridge suggest the presence of several upward doming bodies, terminating the SDR's on their flanks. These are interpreted to be major eruptive centres. The dip profiles across such features illustrate the presence of prominent highs with a morphology typical of volcanic seamounts (Fig. 3g, h and i). Seismic images (e.g., Fig. 3h and i) show two prominent mounds which crop up parallel to each other. The western high is more prominent and of relatively greater relief compared to the eastern high, but the latter is observed to be more continuous throughout its trace. The western mound is symmetrical in shape, its western flank having slightly higher dip as compared to the eastern flank. These indicate the presence of multiple heads forming eruptive foci from the plume. The internal structure of the ridge appears to be complex with upward doming events (Fig. 3h). These indicate episodic eruptive activity over a period of time, as well as build up of prominent volcanoes. The downward concave bright reflector beneath the ridge (at approximately 9 s TWT; Fig. 3f) indicates lithospheric sagging due to the increased load of erupted volcanics. The TWT structure map at the ABT (top of volcanics) shows the presence of a possible chain of isolated volcanic mounds in the western part of the ridge, while the eastern part is more continuous and with a significant width (Fig. 2).

4. Effect of the ridge on sediment dispersal patterns

The 85°E Ridge seems to have erupted after the formation of oceanic crust. Distinctness of the different modes of volcanic


ABT: Acoustic basement top
K-T: Sequence boundary Cretaceous top
O-T: Sequence boundary Near late Eocene-Early Oligocene
a
TWT [sec]
O-T
K-T
ABT
Seaward Dipping Reflectors
Oceanic crust
12 km
V:H≈14:1
a1
a2
a3
NW
g
SE
b
Seaward Dipping Reflectors
Oceanic crust
20 km
V:H≈18:1
NNW
SSE
c
13 km
V:H≈7:1
d
Absence of SDR
Continental crust (?)
15 km
V:H≈9:1
e
15 km
V:H≈8:1
h
i
f
85º E Ridge
10 km
V:H≈10:1
b
g
10 km
V:H≈7:1
Western mound
Eastern mound
Isolated mound
85 °E Ridge complex
10 km
V:H≈8:1

activity (plume versus oceanic spreading related) is apparent from the discord between the directions of mapped magnetic anomalies (Ramana et al., 1997), and the trend of the 85°E Ridge. The earliest sediments overlying the 85°E Ridge show distinct downlap on top of volcanics in the slope and its toe region, whereas, in the abyssal sector, they terminate against the steeply rising walls of the ridge. Isochronopach maps are prepared for stratigraphic intervals bounded by two major unconformities associated with significant tectonic events that affected the Indian Plate namely the K–T boundary and the Late Eocene–Early Oligocene collision event (Curray and Munasinghe, 1991). The maps have been evaluated in order to understand the relation between sedimentation and the disposition of the ridge in the Mahanadi offshore region.

The basement structure map (Fig. 2) shows that the ridge is not continuous and occurs as two linear structural highs which merge towards the basin margin in the north before passing onto the continental shelf. Several subtle offshoots parallel to the main trend are seen on the eastern flank of the ridge. A maximum width of 130 km is observed for the ridge complex in this area, while the highest part of the ridge is located at a depth of 5100 ms TWT. An isolated sub-basin is observed between the western and the eastern highs of the ridge. The ridge remained as a sub-aqueous positive topographic high until the sequence boundary that correlates with the Late Eocene–Early Oligocene (OT) collision event (Figs. 3 and 4). The older sequences below this boundary show wedge-outs/terminations against the flanks of the ridge. Sediment accumulation rates above and below OT show marked variations especially in the areas east of the ridge. Sediment accumulation rates on either flank of the ridge are different both in the pre- and post-OT times.

The sequences below the K–T boundary (Fig. 4A) are significantly thicker in the western flank of the ridge, where they display a chaotic seismic facies, while on the eastern flank they are thinner, with subparallel seismic facies (Fig. 3h,i, 4B). In effect, the ridge acts as a subsea topographical divide between the Godavari basin to west and the Mahanadi–Bengal basin to the east. The Godavari dispersal system to the west is dominant during this time, with higher sediment supply than the relatively weaker Mahanadi and other (pre-Ganges–Brahmaputra) dispersal systems to the east. Due to the discontinuous nature of the western flank of the ridge, sediment was delivered to the intervening sub-basin, filling it up by the end of the Cretaceous.

Another important aspect is the presence of a relatively thin transparent pack on top of the ridge (at approximately 6–7 s TWT; Fig. 3f, h and i). Previous investigators inferred the presence of reefal carbonate growth (Gopala Rao et al., 1997) associated with a possible exposure of the ridge during Cretaceous–Paleocene times (Dangwal et al., 2008). A sediment wedge typical of continental slopes is observed in the initial post-volcanic sediments (Fig. 3a), shallower and updip from the transparent packet, without any reversal in the gradient of the volcanic top. This implies that the transparent packets developed on a sector of the ridge that was beyond the toe of the continental slope, and with a positive relief, relative to the basin floor. Considering the present day depth of these transparent packets at 5 s TWT (water depth of 3 s TWT), it is unlikely that they may have ever been near the photic zone (~200 m) to afford carbonate growth. Therefore, the observed transparent packet on top of the ridge can be interpreted as a thin veneer of condensed sediments that correlate with the sequences on the slope and flank of the ridge.

Sediments between sequence boundaries K–T and O–T are relatively thin over the ridge and show gradual thickening away from it (Figs. 3f–i and 4b). The slope is bypassed during this time (Fig. 3a–c and 4b) and the sediments accumulate only beyond the toe of the slope. The Godavari dispersal system delivers a lesser amount of sediment during this time than the Mahanadi – pre-Ganges/Brahmaputra systems (Fig. 4b). Seismic facies on either flank consist of parallel high amplitude continuous events with intervals of subparallel lower amplitude discontinuous events (Fig. 3h and i). The seismic facies and the thickness patterns suggest that the ridge area is starved of sediments, while the flanks have dominance of low energy passive fill sediments. The high amplitude, parallel continuous events are interpreted to represent major condensed intervals. This interpretation is further supported by the presence of extensive carbonate banks developed in the shelf (Fuloria et al., 1992), with little clastic input. Available accommodation on the flanks of the ridge is filled by the OT time; thereafter, it ceased to be a positive feature on the basin floor. Sedimentation is continuous across the ridge in post-OT times.

Between OT and the present day seafloor (WBT), the sediment thickness across the ridge is uniform (Fig. 4C); this indicates no later reactivation of the ridge in younger times, and attests its aseismic nature. The post-OT sequences show higher sediment accumulation rates due to increased sediment supply to the deep water of ECMI after the collision of the Indian Plate, its subsequent tilting, and the rise of the Himalayas. However, the differences in thickness and seismic facies characteristics still persist on either flank of the ridge due to the different dispersal systems that contributed with different rates of sediment influx on either side. Differential compaction of sediments over the ridge and the neighbouring basin floor is probably responsible for the lower thicknesses observed on the ridge (Fig. 4C and D).

5. Discussion

While earlier gravity and magnetic studies were inconclusive with regard to the continuation of the ridge near and beyond the continental margin, the seismic reflection images presented in this paper clearly bring out the subsurface morphology of the 85°E Ridge north of 17°N in the deep offshore Mahanadi basin. The ridge continues northward below the shelf region abutting the coast south-west of Chilka Lagoon. Further, the ridge is seen as a basement high in both continental as well as the oceanic crust. These observations unequivocally establish the northward continuation of the ridge and help us to further infer the nature of its emplacement.

Fig. 3. a) Zigzag seismic profile showing the morphology and internal seismic signature of the ridge below shelf (a_1), slope area (a_2) and abyssal plain (a_3). The significant sequence boundaries calibrated from the nearby wells are marked. Note, the SDR's are not observed below the shelf. b) Seismic profile showing the presence of prominent SDR's in the slope region. Younger sections show prominent onlaps against sequence boundary O–T. c) Seismic section across the slope showing the presence of a submerged ridge below the acoustic basement top (ABT) as evidenced by the presence of prominent SDR's. d) Seismic profile across the shelf slope boundary in northern part of study area. e) Seismic profile across shelf slope profile in southern part of study area. SDR's are absent in profiles d & e, indicating they are away from the trace of the ridge complex. f) Seismic line across the western volcanic mound rising above the abyssal plain, showing a complex internal geometry. Older sequences, within the low bounded by the two elements of the ridge, onlap against it on either side. Important to note is the presence of a transparent section on the top of the ridge (see text for details). g) Strike section across the ridge, close to the toe of the slope. Multiple volcanic mounds are present with the overall doming structure. h) Strike section along the proximal part of the abyssal plain showing the entire ridge complex that includes the western, eastern and other isolated mounds. A higher thickness below the K–T boundary is seen in the west as compared to the east, indicating that the ridge acted as a basinal divide during the Late Cretaceous. The onlap of the Early Tertiary sediments against the flanks of the ridge indicates that the ridge continued to act as a divide until the O–T boundary, after which it was buried and ceased to be a divide. i) Strike section, along the distal part of the abyssal plain, showing a more symmetric nature of the western mound with steeper flanks as compared to the eastern mound which is wider and continuous but with a more complex internal architecture.

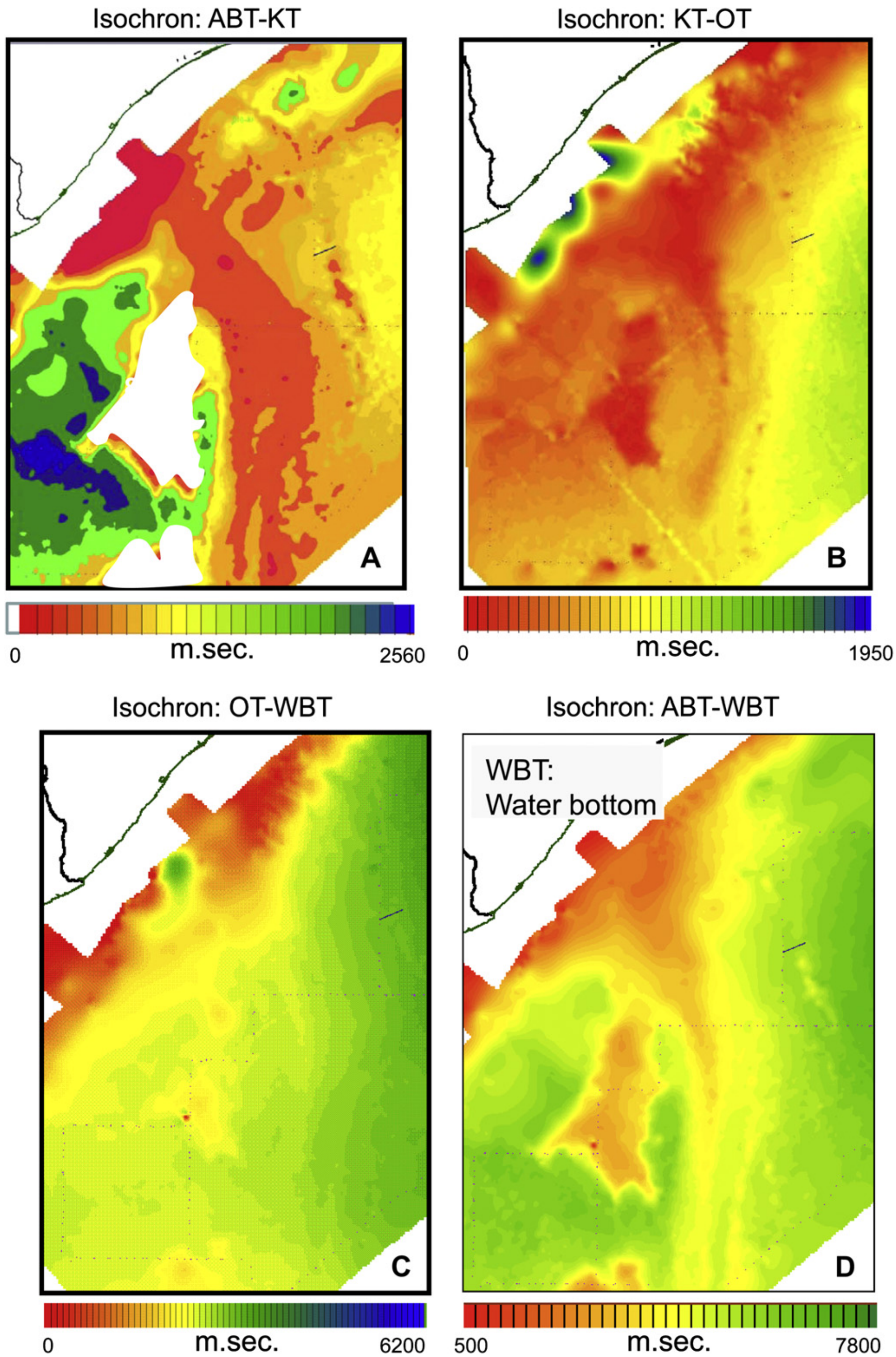


Fig. 4. Isochronopach maps of different stratigraphic sequences. A) Between the Acoustic Basement Top (ABT) and the KT sequence boundaries: the differential accumulation of sediments on either flank is significant. B) Between the KT and the OT sequence boundaries: similar sediment supply on both flanks and low sedimentation rates are evident in contrast to the earlier sequence. C) Between the OT and the water bottom (WBT); the ridge ceases to be a divide; the greater thickness of sediments on the eastern side is ascribed to the newly evolved Ganges–Brahmaputra system. D) Between ABT–WBT sequence boundaries: Total sediment thickness map of the Mahanadi offshore region.

The distinct presence of upward doming internal configuration within the mounds mapped on the ridge supports a volcanic origin. Further, such doming events seem to be building on top of each other (Fig. 3h) implying multiple volcanic episodes. These characteristics provide evidence to conclude that the ridge was emplaced due to the passage of the Indian Plate over a hot spot.

Considering its long trace up to the Afanasy Nikitin Seamount (ANS), many complexities are yet to be unravelled with regard to the time and mode of emplacement of the ridge during the evolution of the Indian Ocean. Some important theories on the probable mode of emplacement of the 85°E ridge are: trace of the Crozet hot spot connecting the Rajmahal traps and the ANS (Curray and Munasinghe, 1991); volcanism through a weak zone within a short span of time (Chaubey et al., 1991); northward continuation of the 86°E fracture zone (Kent et al., 1992); and shearing or sagging of crust by horizontal stretching/compressional forces (Ramana et al., 1997). Based on the interpretation of geophysical data, many later workers supported the hot spot theory as the most plausible mode of emplacement of the ridge (Gopala Rao et al., 1997; Subrahmanyam et al., 1999, 2008; Krishna, 2003; Krishna et al., 2009), though the source of the plume emplacing the ridge is still debated. The plume emplacement theory for the 85°E Ridge must take into account the timing and source for the Rajmahal volcanics, the volcanism at ANS, and the regional plate motion during the emplacement. The present interpretation for the eruption of 85°E Ridge over an oceanic crust supports the earlier views of post break up eruption. Recently, Krishna et al. (2009) synthesized the crustal evolution in the eastern Indian Ocean and concluded that the oceanic crust in the Bay of Bengal mostly evolved during the 120–83 Ma time interval, with three phases of seafloor spreading: the NW–SE spreading until mid-Cretaceous; N–S spreading until early Tertiary; and finally in an NE–SW spreading direction.

The connection between the Rajmahal Traps exposed in the eastern part of India and the Kerguelen Plume has been established in the past by several authors based on geochemical studies and the palaeo-position of the Indian Plate (Baksi et al., 1987; Frey et al., 1996; Kent et al., 2002). Most authors based upon data derived from the DSDP (Legs 22–28) and ODP (Legs 120, 121, 183) recognize the eruption of the Kerguelen Plume in the nascent Indian Ocean after the East Gondwana (India–Antarctica) break up in the Early Cretaceous (Valanginian–Hauterivian). The present day Kerguelen Large Igneous Magmatic Province (KLIMP) spreads over 22° of longitude and 15° of latitude, of which the older South Kerguelen Plateau encompasses nearly 12° longitude and 7° latitude (Bénard et al., 2010).

The tectonic reconstructions made by Royer et al. (1991) and Royer and Coffin (1992) indicate that the Ninety East Ridge, the Broken Ridge and the KLIMP have originated from a single hot spot in the Indian Ocean. Further, Royer et al. (1991) commented on the need to examine the 'volcanic spur' to the west of the present day Kerguelen Island and its relation to the Mc Donald Island Volcano in terms of its age and duration of volcanic activity. Their reconstruction of the hot spot migration with respect to the Atlantic and the Western Indian hot spots, on the plot of Fleitout's et al. (1989) model, requires the mirror image of the Kerguelen Island/'volcanic spur' to be present at a position west of the Ninety East Ridge, which would correspond with the 85°E Ridge. In all probability the two features present on the KLIMP, i.e. the Kerguelen Island and the associated 'volcanic spur' – Mc Donald Island Volcano, could represent two heads of the Kerguelen Plume. This would be consistent with the volcanic hot spot related origin for both the Ninety East Ridge and the 85°E Ridge.

6. Conclusions

The nature and origin of the 85°E Ridge, a prominent feature in the Indian Ocean, has been postulated by numerous workers in the past based on sparse and low resolution geophysical data particularly in the northern buried part. Newly acquired high resolution and close grid 2-D reflection seismic data have helped to detail the ridge morphology and develop an understanding on its origin. The presence of the ridge north of 15°N and its continuation below the Mahanadi shelf through the continental slope is now established. The ridge consists of N–S trending morphological highs with a broad continuous ridge in its eastern part and a linearly arranged chain of large isolated volcanic highs on its western side. The eastern high shows the presence of relatively more complex volcanic features of varying dimensions. The plume related volcanic origin is borne out by its internal doming morphology and the presence of a typical linear chain of subsea volcanic mounds. Obliteration of crustal features typical to continental margins due to the eruptive activity indicates relation to a mega plume. The present work documents the physical linkage for the geochemically correlated onland Rajmahal Traps and the coeval volcanics from the KLIMP. The timing for the emplacement of the 85°E Ridge post dates the formation of the oceanic crust in the Mahanadi Offshore Basin and has probably happened in the immediate post-Aptian/Albian times, during the early part of Late Cretaceous. Onlap of the overlying sediments on either flank of the ridge indicates that the sediments are younger to the volcanic emplacement in this region. Separation between the two major dispersal systems, i.e. the Godavari from the Mahanadi and associated ancient systems, by the ridge, is significant in the Late Cretaceous times, while in the overlying sequences until the boundary that approximates the Himalayan collision event the separation is of lesser significance. Post collision, the Ganges–Brahmaputra system becomes dominant with the rise of the Himalayas, and the Bengal Fan sediments cross the ridge which is by then buried and no longer acting as a divide.

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