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Pre- and post-collisional depositional history in the upper and middle Bengal fan and evaluation of deepwater reservoir potential along the northeast Continental Margin of India

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ABSTRACT

The Bengal fan is the largest submarine fan in the world that has formed as a result of high sediment transport from the Himalaya by the Ganga–Brahmaputra river system. The Himalaya was formed as a result of the collision between the Eurasian and Indian plates. The initiation of this collision known as "soft" collision occurred around 59 Ma, whereas, the major collision, known as "hard" collision took place around 15 Ma ago. Prior to the collision, sediments into the Bay of Bengal were derived from the northwest by relatively smaller river system like Mahanadi–Godavari. The switching of river systems with time was not distinct but gradational. In the post- collision period, the sediment input from the NW was masked in most instances because of rapid sediment supply from the Himalaya to the north. Pre-collisional sediment dispersal pattern from the NW was largely affected by pre-existing basement high known as 85°E Ridge; this ridge was submerged during the post-collisional period. Post-collisional sediments are commonly referred to as the Bengal fan sediments and show huge accumulation along the shelf and beyond. High resolution 2D seismic data acquired along a corridor covering the upper, middle and distal parts of the present day active Bengal fan system indicates that the fan has prograded southward with time because of continuously increasing sediment supply and has, therefore, masked the effect of eustacy. The present day geometry of the fan shows a single active canyon and an associated single active fan. The active channel shows typical meandering pattern that shifts laterally with time. The seismic facies analysis indicates that both the pre- and post-collision basin has significant hydrocarbon potential. The thermogenic model is best suited for modeling source rock maturity in the pre-collision basin whereas both biogenic and thermogenic models best explain source rock maturity in the post-collision, younger Bengal fan. The wedge out against the 85°E Ridge is considered to be one of the important play types for hydrocarbon exploration in the deeper part of the basin. On the other hand, the channel levee complexes and frontal splay/basin floor fan are the possible target areas for petroleum exploration in relatively younger Bengal fan deposits.

1. Introduction

Submarine fan systems form the largest deep-water sediment bodies near continental margins and the depositional history of these sediments contains useful record of past land and marine climate, sea level changes, local and regional tectonic activity. Because of their huge sediment repository, very often, submarine fans are known to be potential areas of hydrocarbon exploration (Lopez, 2001). On the basis of tectonic setting, Shanmugam and Moiola (1988) classified submarine fans into four types: (i) immature passive-margin fans (North Sea type); (ii) mature passive-margin fans (Atlantic type); (iii) active-margin fans (Pacific type); and (iv) mixed-setting fans (Bay of Bengal). Based on the sediment supply, they can also be broadly divided into four types such as the mud rich (Amazon fan, Flood et al., 1991), sand rich (Sierra Nevada, California, Busby-Spera, 1985), mud-sand rich (California deep sea basin fan, Normark, 1970) and gravel rich fans (Upper Jurassic system in North Sea, Hurst et al., 2005)

The Bengal Fan is bordered by the Indian continental shelf in the west, continental shelf of Bangladesh in the north and Sunda trench in the east (Fig. 1). It is one of the largest submarine fans in the world covering the entire Bay of Bengal from 20°N in 1400 m water

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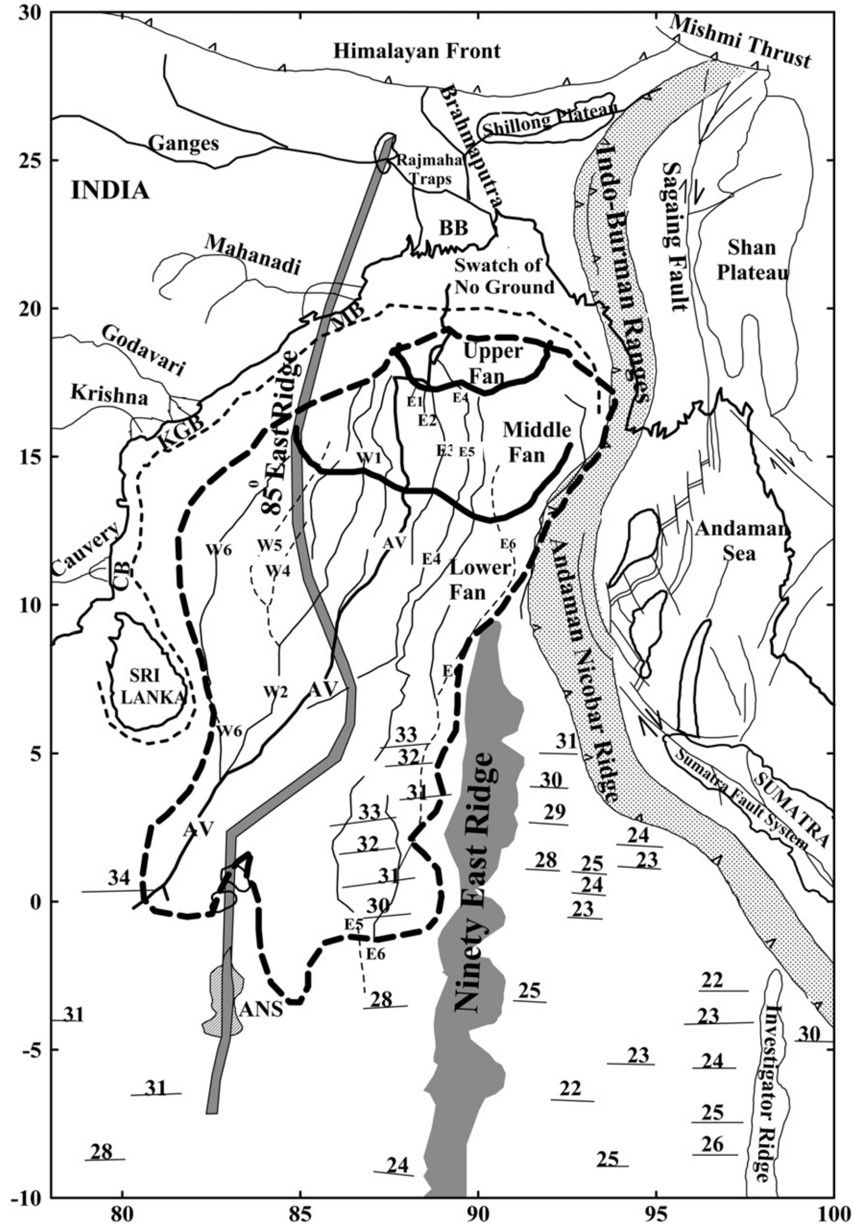

Fig. 1. Tectonic map of Bay of Bengal and the adjoining regions (modified after Curray, 1991). Thick dashed line indicates the outline of Bengal Fan, E1–E6 and W1–W6 are channels on either side of the active channel AV after Curray et al. (2003). The sub-division of Bengal Fan into upper, middle and lower fans from north to south is indicated with thick east-west lines.

depth to 7°S at 5000 m water depth over a N–S length of 3000 km (Curray and Moore, 1971). Though some of the major rivers from eastern India feed into the Bay of Bengal from the west, sediments of the fan are largely contributed by the erosion of the Himalayas and transported by the Ganga–Brahmaputra River system (Curray and Moore, 1971; Curray et al., 2003). Although soft collision (Curray et al., 2003) between India and Asia can be considered as the time of the initiation of the fan, the major sediment supply started after the hard collision during Mid-Miocene which caused continuous progradation of the Bengal fan southward. Detailed seismic reflection and refraction studies as well as echo sounding investigations in the Bengal Fan by several previous workers gave rise to valuable information on the stratigraphic development, sedimentation history of the fan as a whole (Curray and Moore, 1974; Curray et al., 1982, 2003) and evolution of channel–levee system (Curray et al., 2003; Schwenk et al., 2003, 2005). The time of initiation of the fan in the northern part is considered to be Early Eocene (Curray, 1994) and the regional unconformity at Early Eocene (55 Ma) is considered to differentiate between pre- and post-collisional deposition. The timing of initiation of fan becomes younger towards south pointing to progressive progradation of the Bengal fan. However, an Early Miocene age for initiation of the fan has been observed in southern part of the fan (Cochran, 1990). This indicates that the possibility of deposition of fan sediments in Pre-Miocene period in the northern proximal part of the fan cannot be ruled out.

This paper presents results obtained from the analysis of high resolution seismic data acquired along a corridor covering the upper, middle and distal parts of the present day active Bengal fan system (Fig. 1) to understand the development of the depositional fairway in pre- to post-Bengal fan deposition. In addition, we characterize different types of sediment flows for constructing the paleogeography during Mio-Pliocene time. High-resolution multibeam bathymetry data has been used to reinterpret parts of the present-day active channel system. Finally, the results of this study have been integrated to explore the development of possible petroleum system during pre- and post-collision history of the Bengal fan.

2. Regional geologic setting

The Bengal fan covers the entire Bay of Bengal from 20°N to 7°S over a length of 3000 km. The width of the fan varies between 1430 km at 15°N and 830 km at 6°N with an area of approximately 3×10^6 km^2 excluding the area of Nicobar fan (Curray et al., 2003). Towards north, the deepest sedimentary section of over 22 km is observed below the Bangladesh shelf and the sediment thickness progressively decreases towards south (Curray, 1994).

2.1. Morphology

The Bengal fan is fed by two major river systems Ganga and Brahmaputra. The transfer of the sediments from the delta to the fan is guided through a canyon deeply incised into the shelf; this canyon has been referred to as the 'Swatch of No Ground' (Emmel and Curray, 1985; Kudrass et al., 1998; Michels et al., 1998). The head of the 'Swatch of No Ground' lies in about 38 m water depth, and the canyon continues south for 160 km as a long, straight trough to a depth of 1400 m, with an average gradient of 8.2 m/km. High rates of deposition takes place at the inner end of the canyon floor as sediments are trapped and mobilized by storms and tidal currents (Kudrass et al., 1998). However, the supply of sediments to the canyon has greatly reduced since the Holocene (Curray et al., 2003). The sediments supplied through the active fan are deposited in the deeper part in the abyssal plain through active channels. However it is believed that at any point of time only a single channel (consequently a single fan) was active. Considerable amount of shifting of active canyon has also been observed (Curray et al., 2003). Therefore, the present day geometry of the Bengal fan is a collage of several subfans that were active during different geological times. A regional scale map of the present day active channel was presented by Curray et al. (2003). High resolution multibeam bathymetry images along a segment of this active channel system (Fig. 2) show highly meandering nature of the channel along with a sharp bend of the active channel near 18°N. Based on the present-day stratigraphic architecture and bathymetric (fan surface) gradient, the Bengal fan has been divided into three sub-environments, the upper, middle and lower fan (Emmel and Curray, 1985) (Fig. 2). The boundary between upper-middle fans occurs approximately at 2250 m water depth while the middle-lower fan boundary occurs at 2900 m. Considerable variation in grain size, structure and morphology of channel levee complex is also observed in each of these three sub-divisions (Curray and Moore, 1974).

2.2. Tectonic history

The tectono-stratigraphic succession as well as detailed marine geophysical investigations in the Bengal Fan and the adjoining margins gave considerable insight on the early rift-drift history, India-Asia collision scenario, sedimentation and the growth of the Bengal Fan as well as the formation of the 85°E and the Ninetyeast ridges (Curray et al., 1982; Curray and Munasinghe, 1989, 1991; Curray, 1994; Gopala Rao et al., 1997; Krishna, 2003; among many

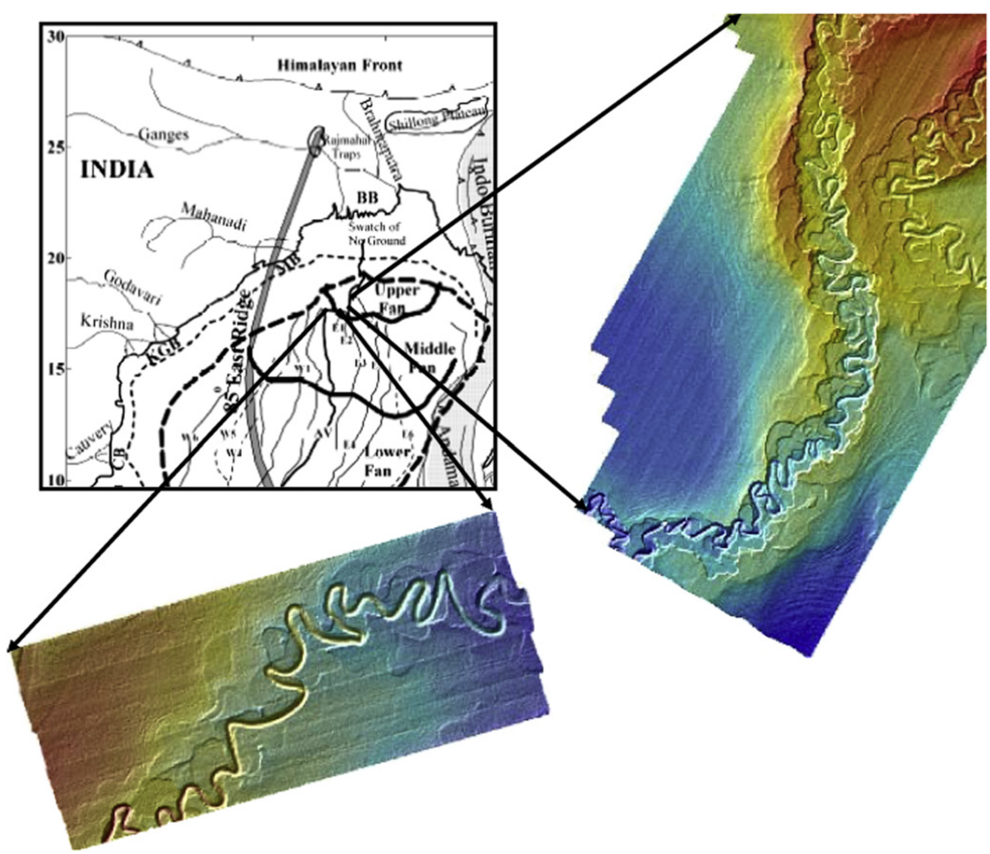

Fig. 2. Multibeam bathymetry images along parts of active channel showing the meandering pattern of the active channel as well as major shift of the channel near 18° latitude.

others). There were three main episodes in the disintegration of Gondwana mainland (Storey, 1995), the initial rifting started in early Jurassic time (180 Ma), the second stage occurred in early Cretaceous (120 Ma) and the third stage occurred in late Cretaceous time (92–100 Ma). The formation of crust beneath the Bengal fan initiated during early Cretaceous with the separation of Antarctica from India in a NW–SE direction. This orientation changed to NS with major plate reorganization around 90–80 Ma (Klootwijk et al., 1992). The basin is dissected by two almost N–S trending ridges namely the 85°E and the Ninety east ridges that are believed to be related to the Crozet and Kerguelen hotspots respectively (Curray et al., 1982; Curray and Munasinghe, 1991). Of these, the 85°E ridge, passing through the study area is now a completely buried structure characterized by gravity low and complex magnetic signature. The origin of this ridge is still enigmatic. Formation of this ridge has been explained as the trace of a hotspot during the time interval of 117–84 Ma (Curray and Munasinghe, 1991), as the result of volcanism along a fissure/crack (Ramana et al., 1997), and as an intraplate ridge that was part of and formed on an older oceanic crust (Krishna, 2003).

During India's northward drift, the initial "soft" collision between India and Asia might have occurred around 59 Ma (Fig. 3) and initiated the Himalayan uplift (Curray and Munasinghe, 1989). The subsequent "hard" continent-continent collision of the Indian plate with the Asian landmass resulted in the closing of the marginal sea behind the Tethyan island arc at around 15 Ma (Middle-Miocene) and initiated the main Himalayan orogeny. The resultant topographic high associated with the Himalaya caused significant increase in sediment supply (Alam et al., 2003). The initiation of Bengal fan has been marked by a strong unconformity that can be traced throughout the fan. This unconformity is recognized as the Paleocene–Eocene hiatus by Curray et al. (2003) and indicates a period of non-deposition that separates pre-Bengal fan sediments from the Bengal fan sediments. Late Miocene (~8 Ma) records the intraplate deformation of the oceanic lithosphere which is evident from the concentration of compressional stresses related to the continuing collision of India and Asia (Cloetingh and Wortel, 1985). Tertiary deposition in the Bengal Fan was significantly influenced by the early Eocene Himalayan orogeny, and continued through India/Asia plate collision to the present day. As a result of this massive Tertiary sedimentary influx, the Bengal Fan is recognized as the largest fan system in the world (Curray et al., 2003).

3. Data

Hydrocarbon exploration during the last decade along the eastern continental margin of India in both shallow and deep water areas has resulted in the generation of a large volume of high-quality 2D and 3D seismic data. In the present study, some of the processed seismic sections covering the active channel–levee system in the upper-to-lower fan sub-divisions of the Bengal fan have been utilized. Available high-density seismic data is further used to prepare isochronopach maps in order to understand the main depositional fairway and its implication on the hydrocarbon potential of the basin. In the absence of deep-water wells in Bay of Bengal, correlation from shallow water wells has been extended to the deeper part. The seismic stratigraphy approach has been applied to examine the continuity of stratigraphic surfaces from shallow to deep water. As studied by earlier workers (Catuneanu,

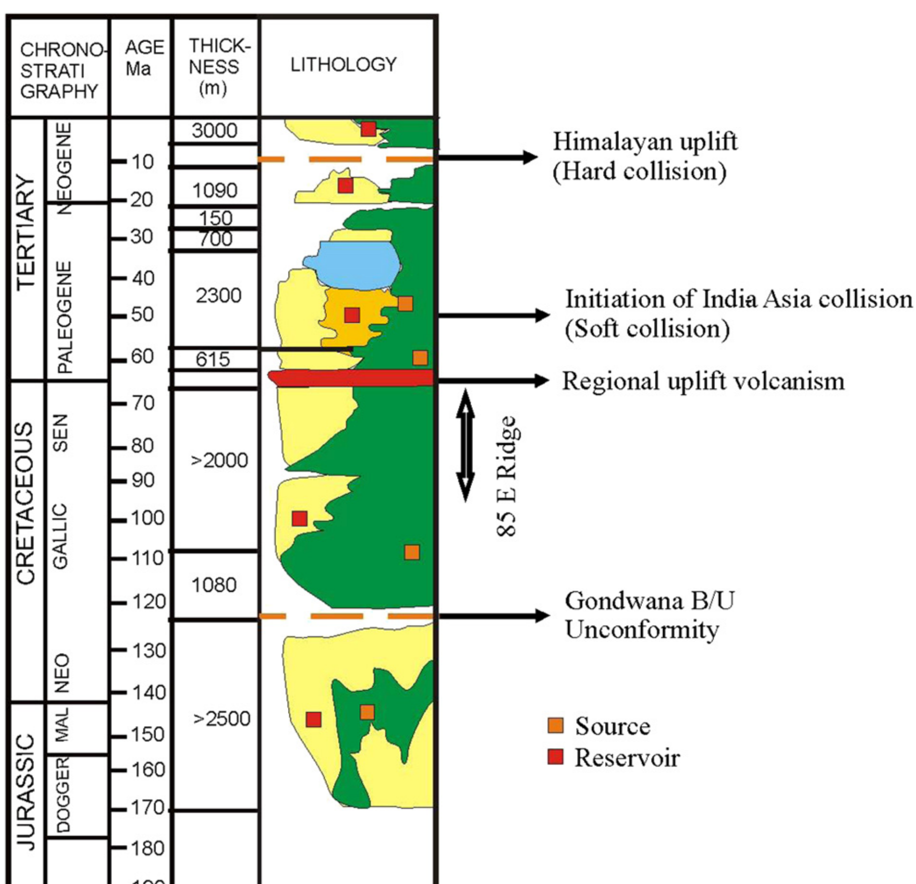

Fig. 3. Shows simplified lithostratigraphic column along with major tectonic events and the possible source and reservoir facies representing the study area.

2008), all sequence boundaries present in deep water may or may not be linked towards the shelf, but, deep-water processes cannot be independent of the processes operated in the shelf. Therefore, with proper understanding, such an attempt can be considered as a good approximation to obtain information regarding deep-water stratigraphy and processes.

4. Results and discussion

The interpretation presented in this section is made mainly based on available 2-D and 3-D seismic data integrated with regional tectono-stratigraphic information.

4.1. Depositional pattern

The isochronopach maps for the total sediment thickness in the region (Fig. 4) show development of larger sediment accumulation in the north and west part of the Bengal fan. However, this map alone is not sufficient to discuss the depositional pattern in different times, as multiple systems were active in the region during the development of the basin. The river system from the west (Mahanadi, Godavari as for example) was mostly active during pre-collisional period, whereas the rivers from north (Ganga, Brahmaputra river system) was active from post Paleocene onwards following the onset of "soft" collision. The regional seismic section presented in Fig. 5 shows the onlapping of Bengal fan derived sediments against the Mahanadi slope. However, from zoomed part of the section, it seems that the onlap does not follow one single surface (sharp separation between the two systems) as there are times (in the post Eocene) during which the Mahanadi

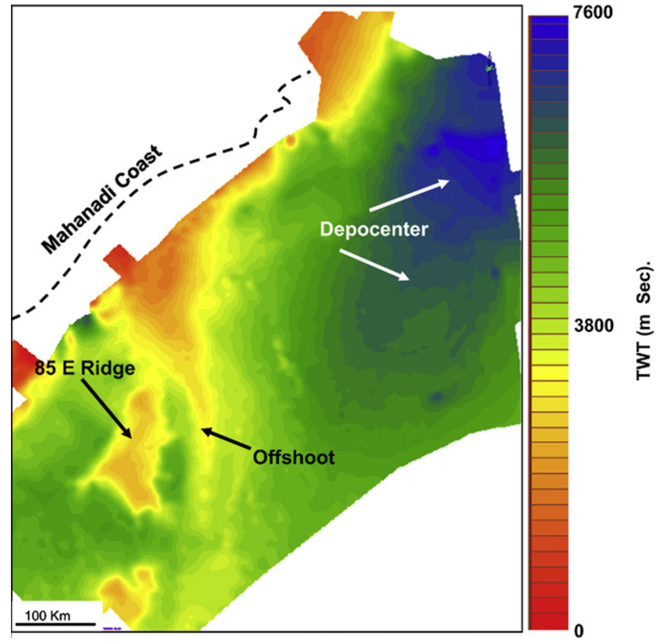

Fig. 4. Sediment isopach (in time) map of the study area showing the total sediment thickness. Note the thickness increment towards the north (marked as depoceneter) and thickness reduction over the 85°E ridge and its offshoot as well as towards Mahanadi shelf.

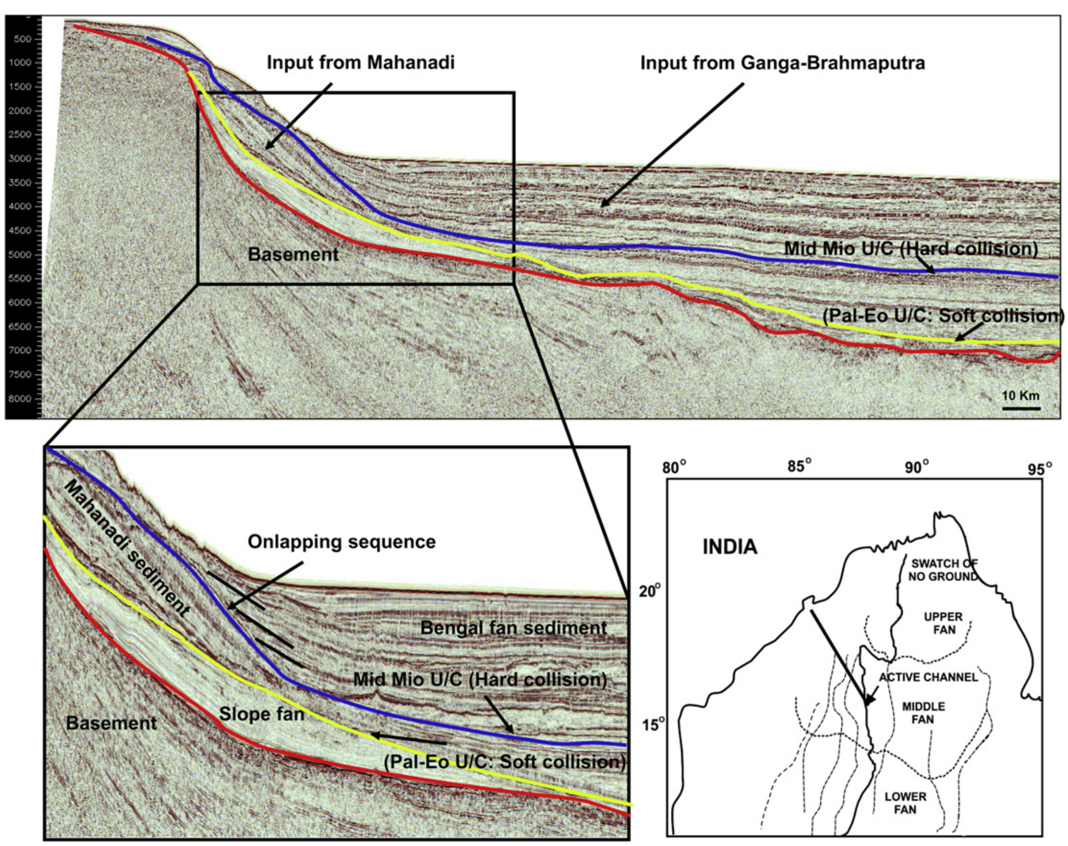

Fig. 5. Seismic section showing two systems that were active in different geological times. While river systems from west (Mahanadi and Godavari) were active during Pre-Eocene time, the Ganga–Brahmaputra dominated the Bengal fan system became active following the India-Asia collision. Major sequence boundaries related to tectonics are marked (see text for details).

slope also contributes sediments in the deeper basin. Despite the contribution from west (Mahanadi), it can be stated with certainty that sediment input after the "hard collision" is much higher from N–S river system in comparison to Mahanadi. In addition, the sediment dispersal pattern was also controlled by two major tectonic events (i) the emplacement of 85°E Ridge, and (ii) collision between Asian and Eurasian plates and uplift of Himalayas in the north. In view of this, we discuss the sediment dispersal pattern under the three broad divisions.

4.1.1. Pre-collision (>59 My)

Prior to soft collision (>59 My), no active depositional system has been reported from north and the major sediment supply in this part was mostly from west. The prevailing rivers Mahanadi, and Godavari can be considered as major sediment source in pre-collisional pre-Bengal fan time. The major tectonic event that affected the sediment distribution during this period was the emplacement of 85°E ridge (Fig. 6). Although the origin of this ridge is a matter of debate, its presence as pre-existing basement high significantly controls the depositional fairway for the Paleogene sediments. However, as the 85°E ridge was not present as a continuous structural high, minor sediment accumulation has been observed towards the east of the ridge within the sub-basin.

4.1.2. Between soft and hard collision (59 My–15 My)

During this time, the Bengal fan system was initiated and the sediment accumulation was mostly confined towards the northern part. A very week depositional fairway can be observed from the isochronopach map (Fig. 7a). The time slices in semblance volume presented in Fig. 7b and c shows the development of channel system from north which supplied the sediment further into the deeper part of the basin.

4.1.3. Post-hard collision (<15 My)

The "hard" collision marks the rapid rise of Himalaya and sediment supply increases manifold from this period onwards; the depocenter was also shifted southward (Fig. 8a). Many channel–levee systems have been developed which transport the sediment further into the abyssal plain forming splay deposits beyond the toe of the slope. Typical sequence in the proximal part of the fan shows vertical building of mud flow-splay-channel levee deposits (Fig. 8b and c). The active channel levee system is formed by erosion of inter channel lows with formation of HARP (High Amplitude Reflection Pattern) deposits (Weber et al., 1997; Schwenk et al., 2005). The levee is formed by overspilling of mud. HARP is also observed at the base of the channel and referred as splay/ frontal lobes in the study area.

4.2. Progradation of the Bengal fan with time

The scrutiny of available 2-D seismic lines from the present day proximal, middle and distal fan reveals continuous progradation of the Bengal fan with time. Fig. 9 shows three seismic lines that provide the strike-view of available western deep-water Bengal Fan sediments and is part of the present day upper fan. The Neogene section is interpreted in the context of a prograding submarine fan system, with a vertical change from unconfined distal lobe and fan fringe deposits progressively overlain by channelized units, and capped by a succession of very large channel–levee type systems.

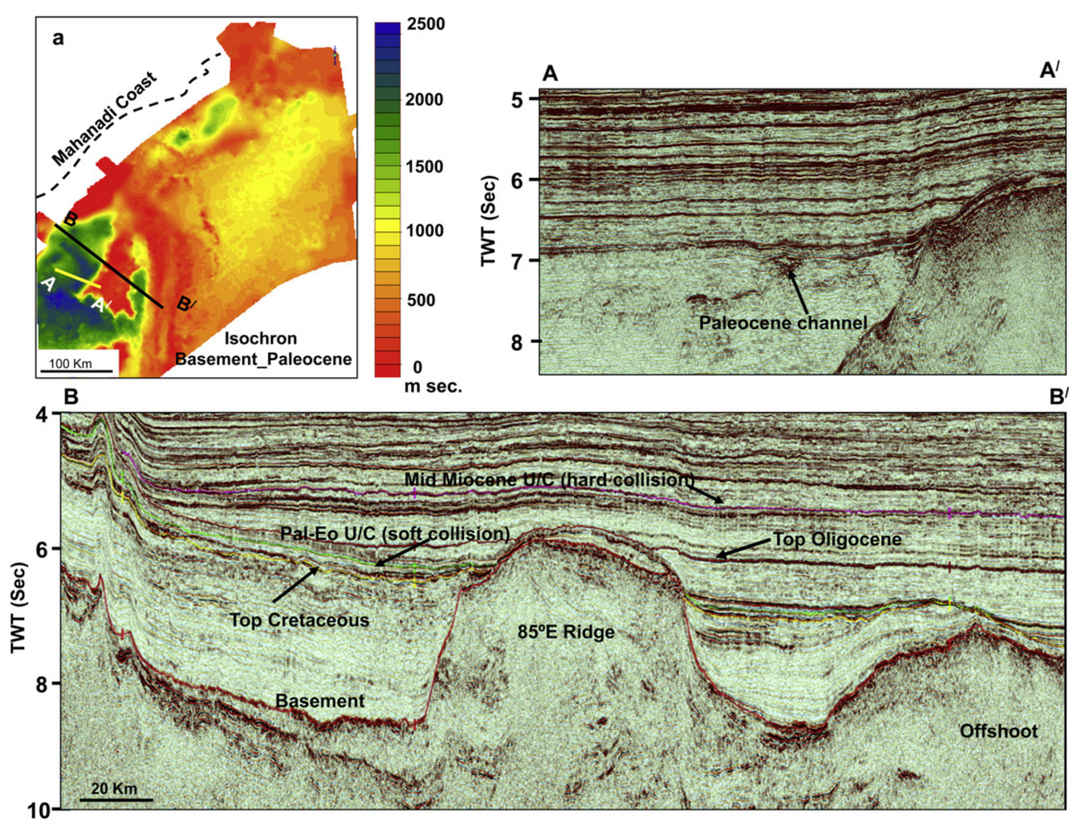

Fig. 6. Sediment isopach (in time) map of the study area showing the pre- "soft collision" (Pre-Eocene) sediment thickness. Important to note the Cretaceous depocenter towards west of the 85°E ridge, indicating that during this period ridge was acting as barrier for sediment supply towards east. The profiles (A–A′ and B–B′) shows prominent high amplitude channel towards western basin of 85°E ridge which wedges out against the ridge. Also important to note the presence of restricted mini basin on either side of the ridge which can be considered to have better source rock potential.

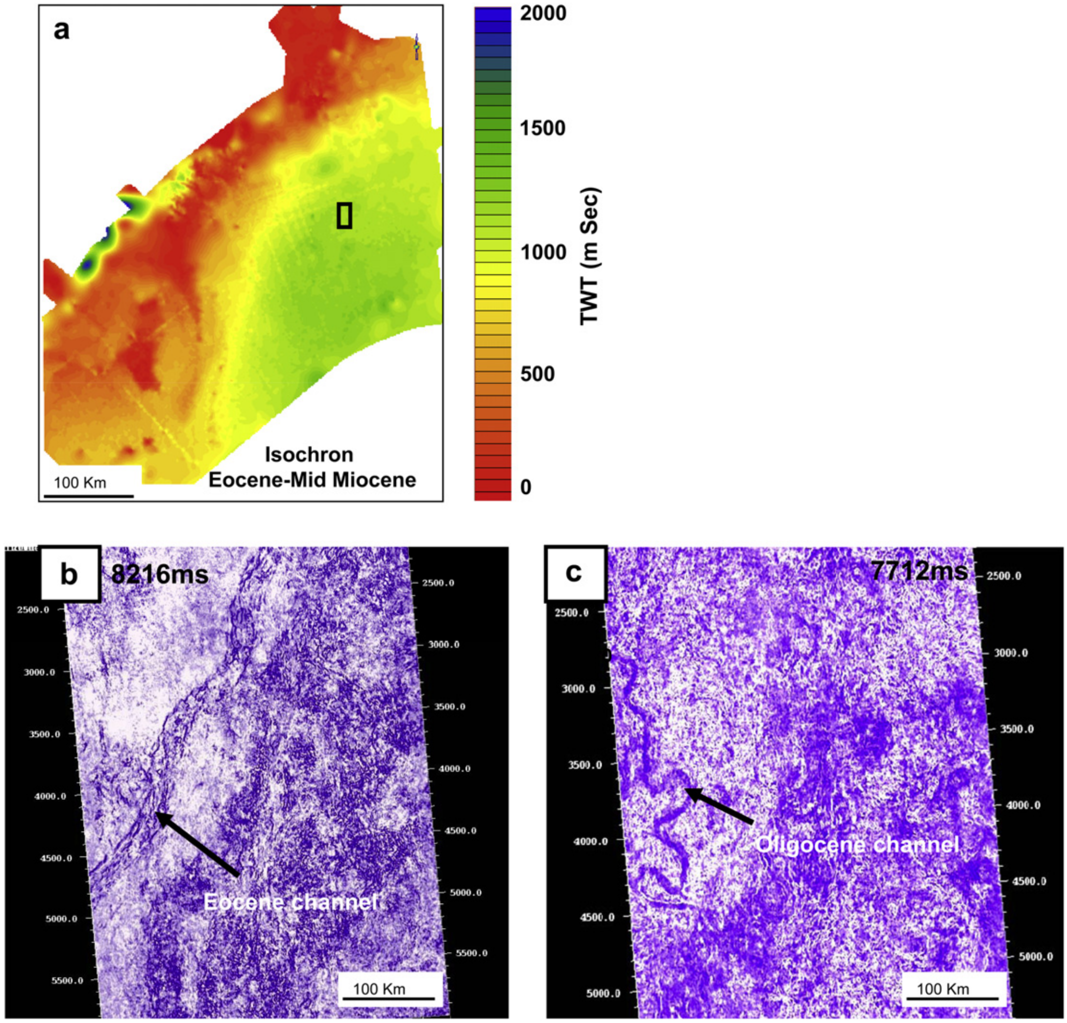

Fig. 7. (a) Sediment isopach (in time) map of the study area showing the "soft to hard collision" (Post-Paleocene to Mid-Miocene) sediment thickness. The map shows shifting of depocenter from west (before soft collision) towards east indicating initiation of Bengal fan during this time. Time slice equivalent to (b) Eocene and (c) Oligocene level showing presence of N–S trending meandering channel obtained from high resolution 3D seismic coherency volume which indicates that Bengal fan system was active as early as Eocene however channel activity was less compared to post hard collision growth of the fan.

The seismic lines in Fig. 10 provide a strike-section of western part of the deep-water Bengal Fan Sediments in the present day middle fan environment. The seismic sections record the progradation of the Bengal fan from lower to middle fan environments during the Neogene. The majority of the section in this area corresponds to the lower fan environment, with channel–levee height reduced considerably relative to the more proximal sections described above. The majority of Paleogene section consists of variable amplitude, continuous seismic facies with increasing truncation of reflectors into the Pliocene. The seismic lines in present day distal fan on the other hand records only lower fan lobes (Fig. 11). The parallel high amplitude reflection can be interpreted as occurrences of sheet sands in the frontal lobe.

Conceptual paleogeographic diagrams were constructed as part of this study and are presented for both the Miocene and Pliocene (Fig. 12). The major mud flow (Fig. 12a) deposits probably marks the major base level fall in the basin. Mud flows are observed within the upper fan region. The splay deposits are expected further down into basinal part. Comparison of Fig. 12a and b clearly shows southward progradation of overall facies with time. Sediment input from Mahanadi and Godavari is also schematically depicted, which indicates that even during Mio-Pliocene time there were times when sediment from Mahanadi were transported beyond the continental slope and formed unconfined sheet turbidites/ splay deposits.

4.3. Reservoir potential of the deepwater depositional system

With the advent of new technologies in the recent times exploration targets have been extended more into the deep water abyssal plains. The major element with respect to reservoir aspect of the system are channel levee complexes. In different fans, the sinuous channel levee system has been the focus of hydrocarbon exploration (Kolla et al., 2001). The possible depositional model for the Bengal fan is shown in Fig. 12. The major influx of sediments was from west in the pre-collision (Pre Eocene) time. Presence of 85° E ridge system gave rise to restricted mini basins that increased preservation potential for source rock because of restricted circulation. Thermogenic model best explains the hydrocarbon generation during this time. As discussed earlier, the input from the west also continues in the post-collision period. Wedges against 85°E ridge could also act as good entrapment locations for pre-Eocene petroleum system.

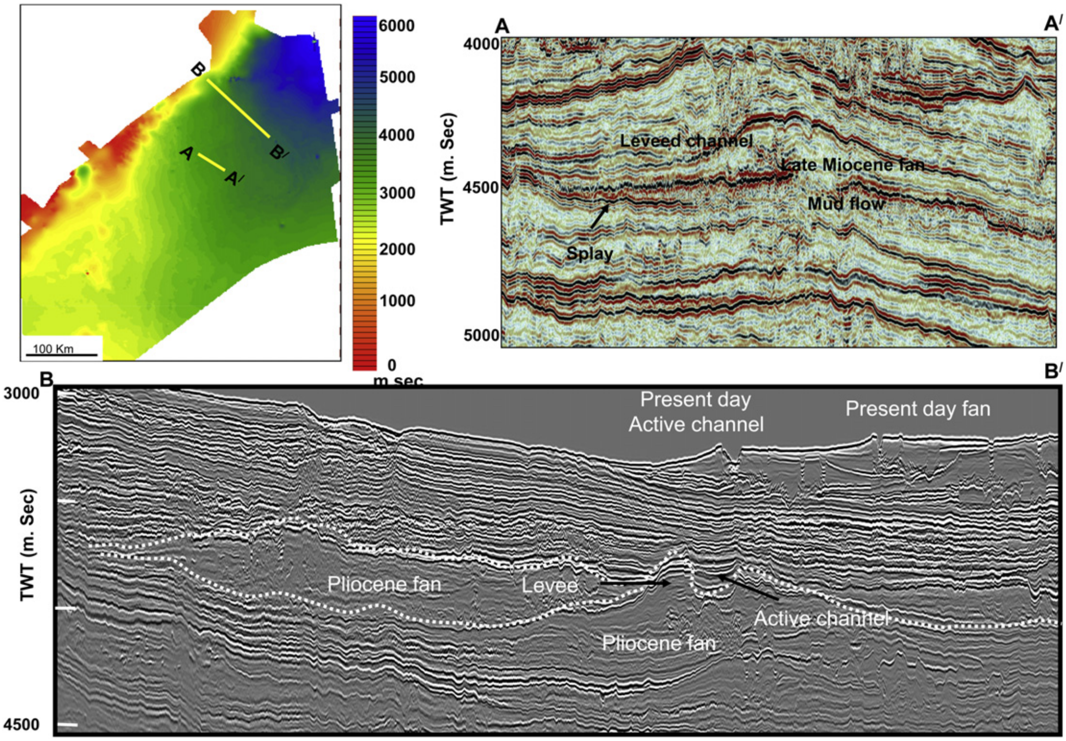

Fig. 8. Sediment isopach (in time) map of the study area showing the "post-hard collision" (Post-Mid Miocene) sediment thickness that indicates major depocenter towards north. The huge sediment loading is related to rapid rise of Himalaya and therefore much faster growth of Bengal fan which transport the sediment in deeper basinal part. Characteristic seismic facies during Miocene (A–A') and Pliocene (B–B') showing deep water sequence buildup involving mud flow followed by splay and followed by channel–levee facies. The location of present day active channel is shows in profile B–B′.

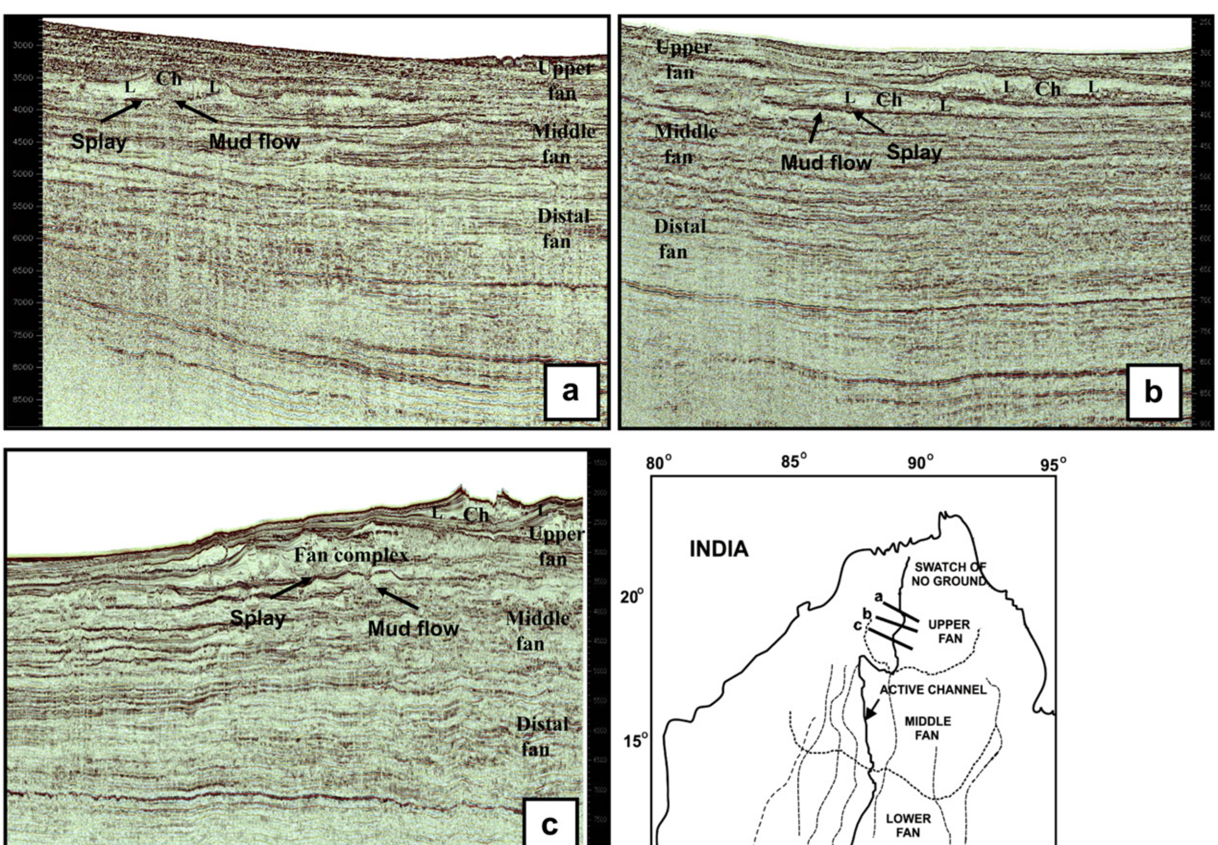

Fig. 9. Profiles (a–c) across the present day upper fan showing shifting of distal fan system to younger proximal fan therefore indicating continuous progradation of Bengal fan with time. The proximal part in shallower section is characterized by mud flow-splay and leveed channel.

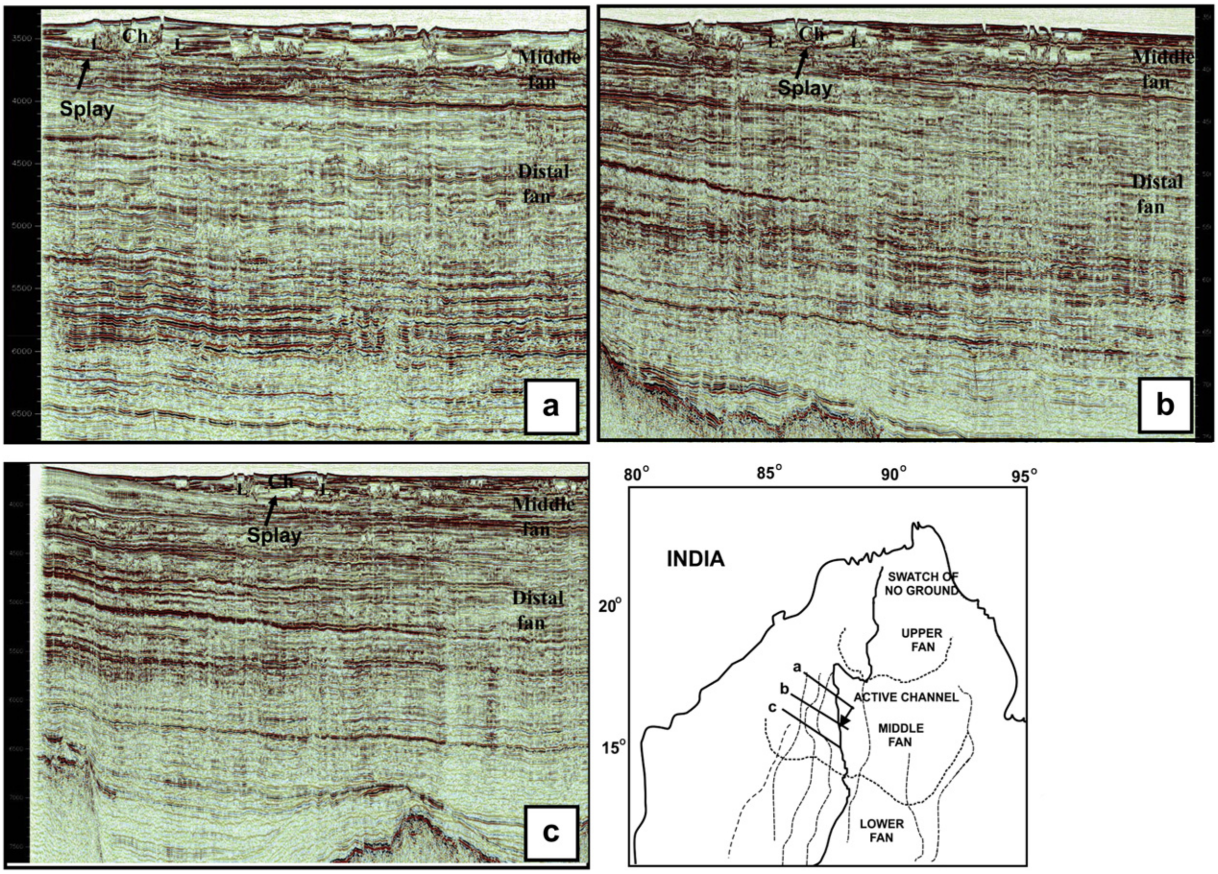

Fig. 10. Profiles (a–c) across the present day middle fan characterized by channel levee and splays. However, deeper section is mostly comprises of Channel–levee facies. Important to note the absence of mud flow in middle fan.

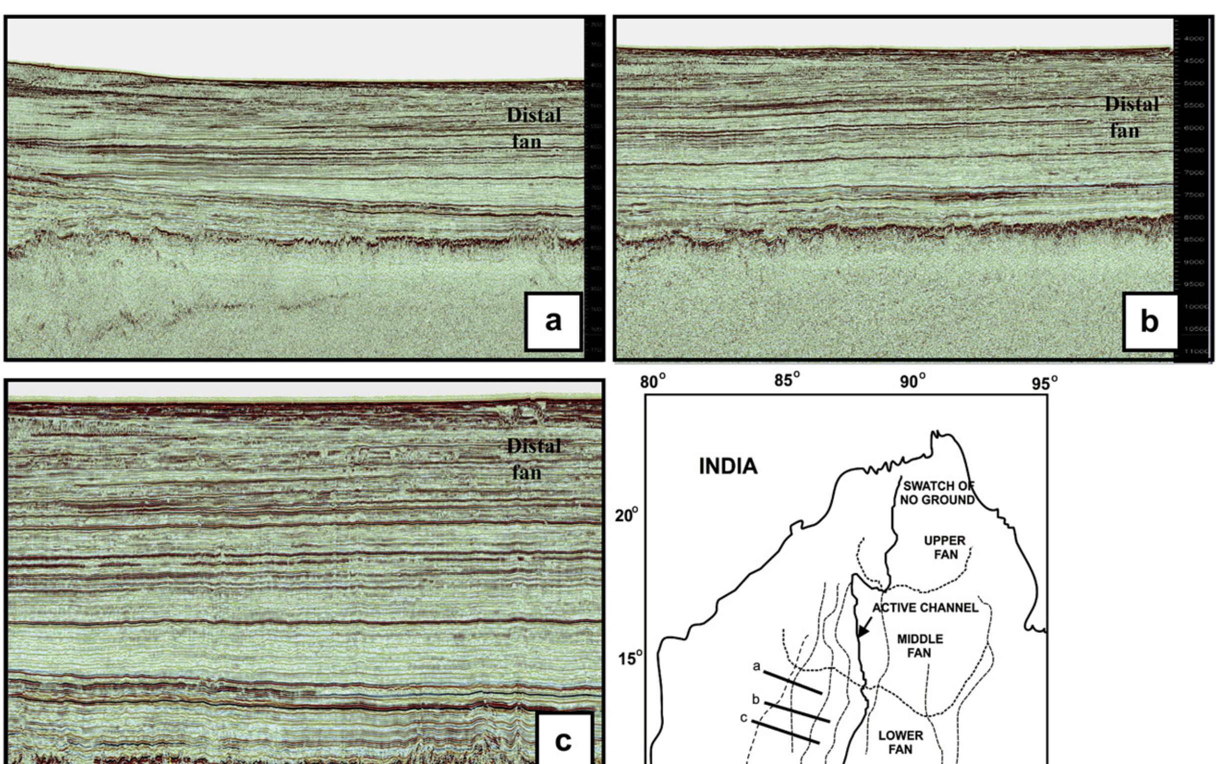

Fig. 11. Profiles across the present day distal fan which is characterized by channel system and absence of mud flow and splays. Also important to know the levee height reduces considerably in this region to almost absent.

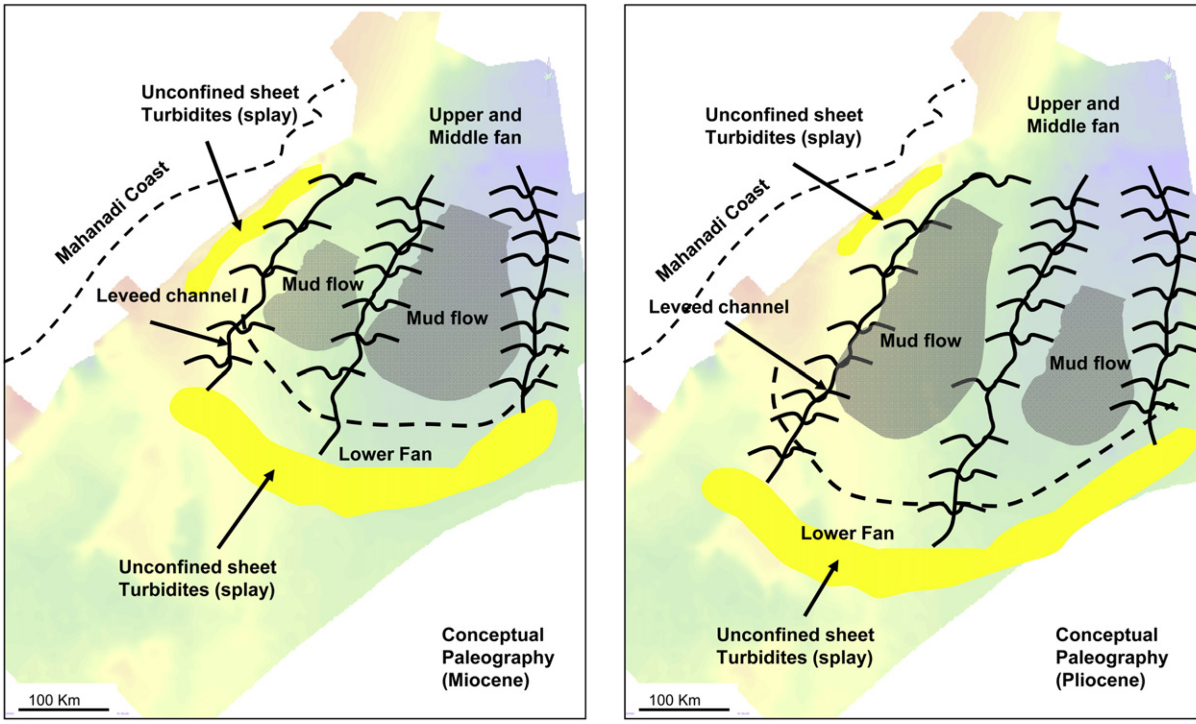

Fig. 12. Conceptual paleogeography in Miocene and Pliocene indicating seaward shifting of facies during progradation. The extent of mud flows and expected splay deposits are shown.

On the other hand, post-collision Bengal fan is believed to contain good reservoir because of its huge sediment supply. The possible location should be channel–levee complexes. The high amplitude reflection packets representing basin floor fan/frontal splay are also expected to have good reservoir potential provided connectivity and amalgamation of sand deposit are maintained (Kolla et al., 2001; Schwenk et al., 2005). It can be stated that the exploration target also depends on the location of sand deposit with respect to fan system. In the distal part, the frontal splay/basin floor is of more importance, whereas channel levee deposits play an important role in present day upper and middle fan. Unlike the deeper Cretaceous–Paleocene section the shallower Mio-pliocene petroleum system is more likely to have mixed thermogenic and biogenic source. Pure stratigraphic entrapment condition is expected for the younger section. For the mud rich system like the Bengal fan, vertical seal is not a problem, however, for updip seal, the truncation of reservoir facies by younger mud flows is favorable.

5. Conclusions

From the above analysis, the following conclusions can be drawn.

- Pre-collisional depositional pattern was controlled by emplacement of 85°E ridge that divided the basin into mini sub-basins. The restricted environment between basement highs provides good opportunity to develop hydrocarbon source rock facies.
- Post-collisional depositional pattern in the study area is interplay of different system from N–S and NW–SE. While, the N–S trending Bengal fan trend became more prominent after post-Mid Miocene ("hard" collision) period, there were times when the deeper part received sediments from Mahanadi also.
- Although channel levee deposits are of prime interest for reservoir facies, the frontal splay/lobes are expected to have better reservoir quality because of higher sand–mud ratio. Very high sediment input in the post-mid Miocene onwards resulted in supply of sediments to much deeper parts and sand bearing frontal splay could also be focus of interest from a hydrocarbon reservoir point of view.

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