

# **Interplay Between Local Tectonics and Deepwater Channel Process in the Mahanadi Deepwater Offshore Basin: Insight from High Resolution 3D Seismic\***

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## **Abstract**

Deepwater channels act as conduits for coarse-grained sediment, connecting the outer shelf to the basin floor bypassing the lower slope and often serve as important hydrocarbon reservoir targets in many deepwater offshore basins around the world. Although deepwater channels are widely observed in 3D seismic datasets routinely, the detailed mechanism for channel processes and their evolutionary behavior has received sparse attention in literature. This study shows how local tectonics can play a major role in influencing the subtle channel process itself and more precisely how it can trigger the meandering and incision of the main channel course by a contemporaneous interplay between tectonics and the channel building process. This study is based on an interpretation of a high resolution 3D Q-marine seismic data set in one of the deepwater hydrocarbon exploration blocks of the Mahanadi Basin in the East Coast of India.

Unlike 2D seismic data, 3D seismic reflection data is an ideal tool to study the complex process of channel building, channel course meandering, its overall morphological geometry, the channel fill type and also the possible link between local tectonics and evolution of the entire channel process. One of the Miocene channels in the study area displays characteristic meandering geometry and channel incision almost contemporaneous with strike-slip compressional structuring in the area. Sequential analysis of time structure maps along with detailed analysis of seismic facies in the channel complex through seismic attributes suggest the intricate relationship between how turbidity flow along a deepwater channel can incise and erode as a response to the structuring process caused by contemporaneous strike-slip compressional forces. The episodic nature of such structure building in the area can be seen to have resulted in some typical deepwater deposits anomalously distinct from the surrounding area.

## **Introduction**

Mahanadi Basin, located in the northeastern part of eastern passive continental margin of India, falls between the Bengal Basin to the northeast and the Krishna Godavari Basin to the southwest ([Figure 1](#)). The present study area falls in one of the deepwater blocks of the basin, situated approximately 200 km south of Chilka Lake. The bathymetry ranges from 2200 m to 2550 m. The general geology and hydrocarbon prospects of Mahanadi Basin is comprehensively dealt with by Fuloria (1993).

## **Objective**

The present study was primarily aimed at understanding from interpretation of 3D seismic data, one of the mechanisms of how a particular deepwater channel is affected by local tectonics and its impression on the sedimentary record almost contemporaneous with channel incision and sedimentary deposition under deepwater conditions. The delicate manner in which strike-slip compressional forces cause an anticlinal structure to form alongside which a deepwater channel can erode, incise and fill was sequentially studied as a tectono-sedimentary evolutionary process in this case.

## **Seismic Mapping and Analysis**

In the absence of any actual drilled well information in the study area, seismic horizons were tied through available regional 2D seismic data in the area with the drilled well information of one deepwater well of Mahanadi Basin which is about 180 kms further north and with few KG Basin wells in the southwest. Subsequently, detailed seismic mapping and analysis of one full 3D seismic volume (more than 300 sq km) of Q-marine PSTM data were carried out in IIWS. Part of the results of this interpretation work forms the main basis of the present study.

The high resolution Q-Marine 3D seismic data is quite amenable to interpretation of various deepwater depositional elements from TWT structure and thickness maps, time slices, horizon slices, various seismic attribute maps, etc. One representative seismic section ([Figure 2](#)) has been presented showing the main correlated sequences and subsequences in the study area. However, the exact biostratigraphic age of these units can be ascertained only when actual drilled well information is available. Although numerous channel features are seen in the 3D data set at several stratigraphic levels within the Tertiary, this study focuses on one particular deepwater channel in the Upper Miocene sequence by critically analyzing the seismic anatomy of its geometry and evolution.

## Discussion on TWT Structure Contour Maps at Various Tertiary Levels

To study the evolution of the structural disposition of the study area, particularly during the Tertiary period, all the major Tertiary sequences starting from top Paleocene all the way to Mid-Pliocene were mapped and studied in detail. A few such maps relevant to this paper are presented in [Figure 3](#). The TWT structure map close to Paleocene top ([Figure 3a](#)) shows the contour trend to be almost N-S, increasing gradually in contour values from west to east. There is a broad east-west trending low which is flanked by a NW-SE trending high in the east of this major low causing a swing to the south in the contours defining the broad low. The contour trend shows little variation in the western part of the study area with monoclinal dipping contours. The TWT map on top of Eocene ([Figure 3b](#)) shows a similar trend as that of top Paleocene event with comparatively less closely spaced monoclinal dipping contours in the western part of the study area gradually deepening to the east. There is a big low trend running almost east-west with a small high nosing making the contours swing north-south at the extreme eastern part of the study area in much the same way as that of the Paleocene level map. The TWT maps on top of Oligocene and Mio4 (not shown here) show almost identical behavior to the Eocene level map.

TWT structure map at Mio3 level ([Figure 3c](#)), the next younger level to Mio4, shows once again similar contour trends to Mio4 level with one small difference. The small high which was an independent structural closure just north of the major east-west trending low at the Paleocene level ([Figure 3a](#)) and also seen at Eocene level ([Figure 3b](#)) reappears distinctly as another independent closure at Mio3 level with a slight shift to the east indicating some sort of structural reactivation. The NW-SE trending high nosing at the Paleocene level to the east of the major low was also seen to exist, albeit with lesser relief, at all younger levels viz. Eocene, Oligocene, Mio4, but now almost disappears at Mio3 level.

There is then a distinctly different trend in the TWT structure maps at still younger levels, i.e., at Mio2 ([Figure 3d](#)) and Mio1 ([Figure 3e](#)) levels. A close study of the TWT structure maps ([Figures 3a to 3e](#)) of the above horizons, progressively from older to younger sequences, suggests how a very broad east-west trending low with wide spaced contours in the major part of the study area, except only at the western edge, is transformed into an anticlinal structure with plunging trend on either side to the north and south of the area where earlier the broad low existed ([Figures 3d and 3e](#)). The broad central east-west trending low now appears to be dissected by the north-south trending high ([Figures 3d and 3e](#)). The maximum structural deformation is clearly seen at Mio2 horizon ([Figure 3d](#)) with a distinctly north-south trending anticlinal high having two separate culminations and the earlier broad low now has its residual impression on either side to the east and west of this doubly-plunging anticlinal high. The northern culmination is the larger one in size and relief compared to the southern one.

The TWT structure maps at Plio5 and Plio4 levels (not shown here) are similar to that of Mio1 horizon. However, the independent structural culmination loses its trace by the time of Plio3 ([Figure 3f](#)) although the general high contour trend still exists. In summary, it can be said that the structural deformation was maximum at around Mio2-Mio1 time and the same structure continues to exist until Plio4 time and then slowly disappears from the time of Plio3.

### **How and When the Structure was Formed?**

The following discussion is aimed at explaining the possible geological history that led to the formation of this major structure in the study area. In fact this structure can be seen to have also affected even the Paleogene section. One representative seismic section is presented in [Figure 4](#) which shows the anticlinal feature affecting almost the whole Tertiary section from Paleocene up to Plio4 level.

If we analyse the same vertical seismic section as above, flattened at Mio2 top horizon ([Figure 5a](#)), we can see that the structure did not exist until the Mio2 period. At around Mio1 period (as seen from [Figure 5b](#) showing the same section flattened at Mio1 level), perhaps, the structure started forming. This is observed from the overall shape of the Mio1 horizon at a time when there was massive channel erosion triggered perhaps by the formation of the structure at around this period. The thinning of the section just above the Mio1 horizon seen right at the structural crest ([Figure 4](#)) is strong evidence for timing of structuring to be around the end of Mio1 or beginning of Plio5. On the contrary, the deeper Middle Miocene section between Mio2 and Mio3 clearly shows thickening at this position. The same seismic section has been flattened at Plio5 horizon and presented in [Figure 5c](#). There is a clear indication that by this time, during the deposition of Plio5 sub-sequence, the structure has already formed.

[Figure 6a and 6b](#) show the TWT thickness maps of Mio2 and Mio1 sequence. A close look at [Figure 6a and 6b](#) demonstrate unequivocally how the structural inversion has taken place in this area. The TWT thickness map ([Figure 6a](#)) shows a progressive increase of thickness to the east and southeast with considerable thickness of sediments along an east-west trending depositional low during Mio2 time of deposition. The seismic section in [Figure 4](#) also shows the increasing trend of thickness; the maximum thickness is observed at the central portion of the study area as is clear in [Figure 6a](#). The TWT thickness map presented in [Figure 6b](#) shows that the same area where there was the maximum thickness trend is now the minimum thickness area, suggesting that during Mio1 deposition the area had become positive and this is the strongest evidence of how structural inversion took place. This structural inversion has been caused by strike-slip compressional stresses, and the contour trend of both TWT structure maps at the Mio1 and Mio2 levels, as well as their thickness maps, suggest that strike-slip compression in the study area has been along the NE-SW trend and this major compressional event has had a definite impression on the structural history of the area. This is further explained from closer analysis of seismic sections, as shown below.

The sequence between Oligocene and Mio4 is relatively flat, characterized by high amplitude reflectors without much thickness variation (Figure 4) along with the sequence between Mio4 and Mio3 showing similar trend but characterized by much lesser amplitude reflectors. However, the section just above that, from top Mio3 to top Mio2, shows increasing thickness from north to south.

Although major extensional faults are not observed in the study area, small throw (10 ms) along a normal fault is clearly seen as shown along one representative Inline (Figure 7). These faults are more indicative of subtle structural forces coming into play during the sedimentation history of the area rather than defining basin-scale major structural features.

Figures 8a and 8b show the seismic Inlines only 125 m and 325 m away from the representative Inline of Figure 7. While Figure 8a shows a small anticlinal feature at the level where earlier there was a normal fault (at around 5300 ms to 5600 ms), Figure 8b shows a reverse fault at the same location. Thus Figures 6 to 8 demonstrate that there has been initial thickening of sedimentary pack (between Mio2 top and Mio3 top). Later tectonics have caused a normal sense of throw and reverse sense of throw at the same level only a few hundreds of meters away. The fault in the Inline of Figure 7 is a fault having a normal sense of throw down to the southeast and is expressed as a small anticlinal structure in another Inline just 125 meters away finally turning into a fault with clearly a reverse sense of throw as seen in the Inline 325 meters away from the first Inline. This confirms that there is clear-cut evidence of strike-slip compression which has affected the study area locally. The structural analysis, although shown in minute seismic scale here for clear understanding, has its link to the genesis of the major four-way structural closures found in several Tertiary levels as already discussed. Detailed analysis of the 3D data shows presence of another similar compressional structure around the southwestern part of the study area as described in the previous section on TWT structure contour maps (Figures 3d to 3f).

### **Morphology and Evolution of the Deepwater Channel in Upper Miocene Sequence**

Deepwater channels act as conduits for coarse-grained sediment, connecting the outer shelf to the basin floor and bypassing the lower slope. In plan view, the morphology of channels varies from straight to highly sinuous (Weimer and Slatt, 2007). The study area displays large numbers of channel/levee complexes in deepwater settings all through the Upper Tertiary, including the Miocene and Pliocene sequences. To delineate the channel morphology and to understand the evolution of one particular channel complex in the Upper Miocene sequence, amplitude attribute has been extracted at Mio2 horizon and corresponding coherency attribute has also been generated. Figure 9 shows the amplitude and coherency attribute maps for Mio2 surface taken within a window of (-40 ms to +10 ms). The amplitude attribute map (Figure 9a) shows two prominent channel complexes at this level, one trending in general along NNE-SSW direction towards the northern and western part of the study area, and the other one in NE-SW direction towards the central and southern part of the study area. The former one has a sharper image with an interesting kidney shaped body with very low amplitude

fill characteristics sitting at one of the sharp bends of the meandering channel. This channel traverses from the north of the study area with a sinuous geometry towards the south and ends at the western edge of the study area. The same channel outline can also be seen in the coherency attribute map (Figure 9b). Although the isolated body has low amplitude fill compared to the surrounding, it is surmised that the body has been deposited by a channel that has a clear-cut erosional base, perhaps cut by a canyon through the high amplitude parallel reflectors representing distal basin floor fine grained shales or hemi-pelagic mud.

The interesting fact about this isolated kidney shaped body is that it is located almost at the same place where the large four-way structural closure in Miocene and Pliocene levels is encountered. To illustrate this further, in one such figure, the amplitude attribute map (of Figure 9) has been superimposed with the TWT structure contour map at Mio1 level (shown in Figure 10a) and with that of Mio2 surface (Figure 10b). As was discussed earlier, perhaps this could be a relatively low area with a high turbidity current and at the meandering bend, caused by the evolving positive structure at this place in response to the strike-slip compressional forces acting contemporaneously; the peculiar kidney shaped body (fan?) got deposited. It is possible, as discussed earlier, during the time when the compressional forces were instrumental in creating a positive area, the turbidity current along the channel course caused incision and erosion of the channel beds (Figure 11) and also significantly, the channel course took a meandering turn almost around the western edge of the rising high (refer to Figures 3d and 3e).

### **Conclusions**

- The four-way structural closures at the Miocene and Pliocene levels mapped in the study area seem to be associated with exactly the same locations where channel sands are expected. The structural model for generation of these structures is considered to be due to a strike-slip compressional event affecting almost the entire Tertiary section and the timing of this event is possibly Upper Miocene-Lower Pliocene.
- The deepwater channel at the Mio2 level in the study area shows characteristic incision and erosion followed by deposition through infilling. The channel shows a meandering geometry around the western edge of an evolving structure as a response to the positive structure formation caused by strike-slip compressional forces and establishes how local tectonics can play a significant role in the channel morphology and its evolution.

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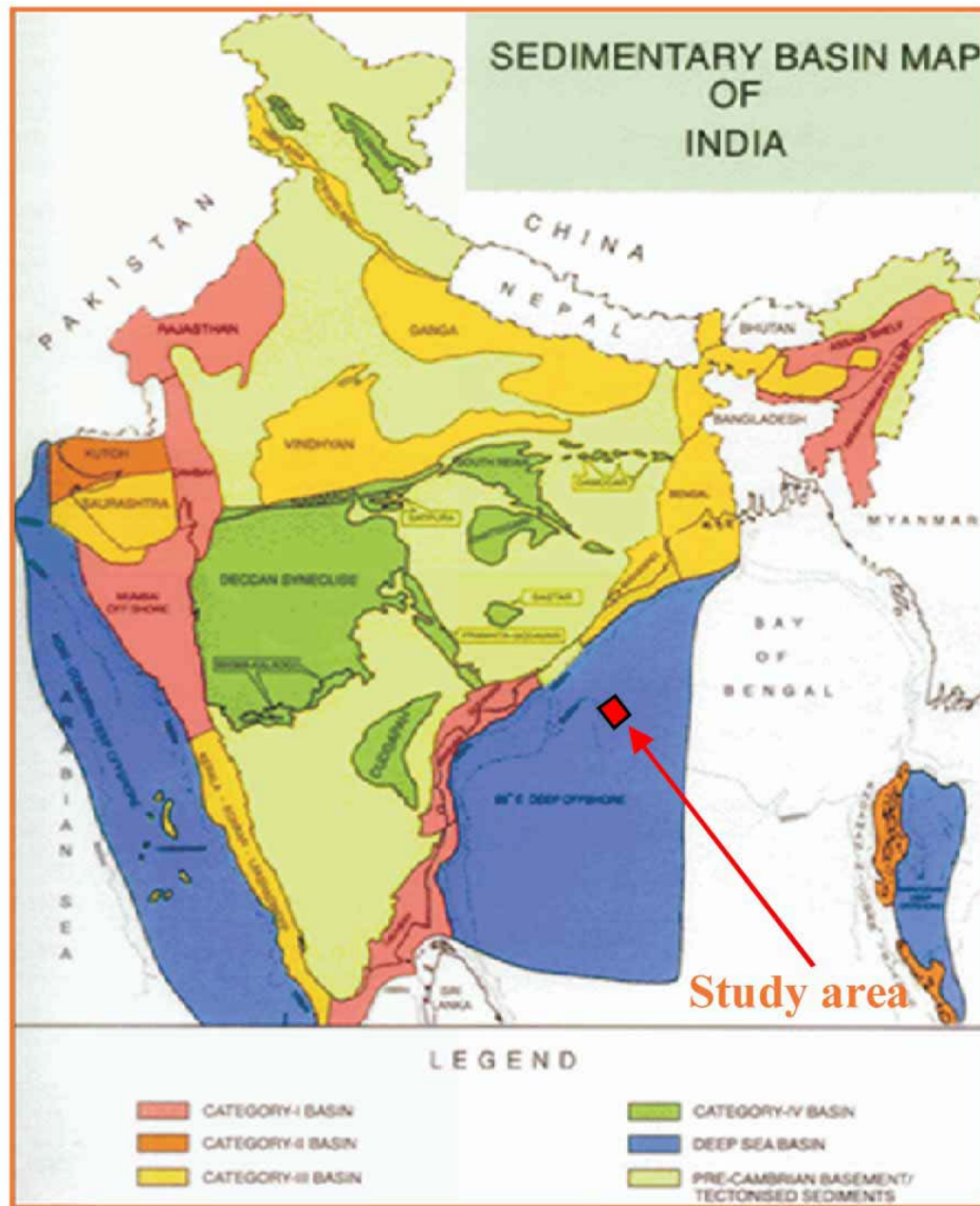
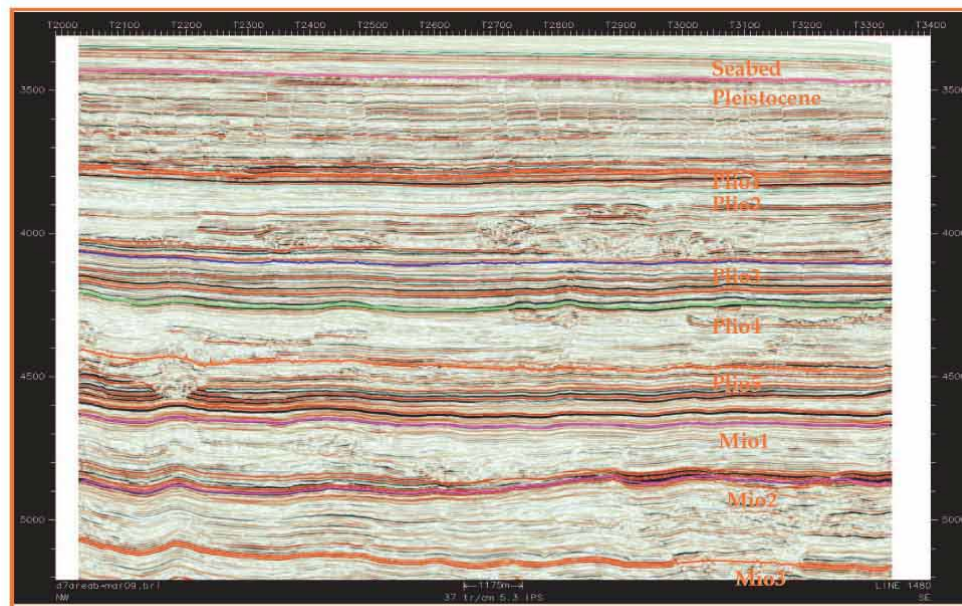
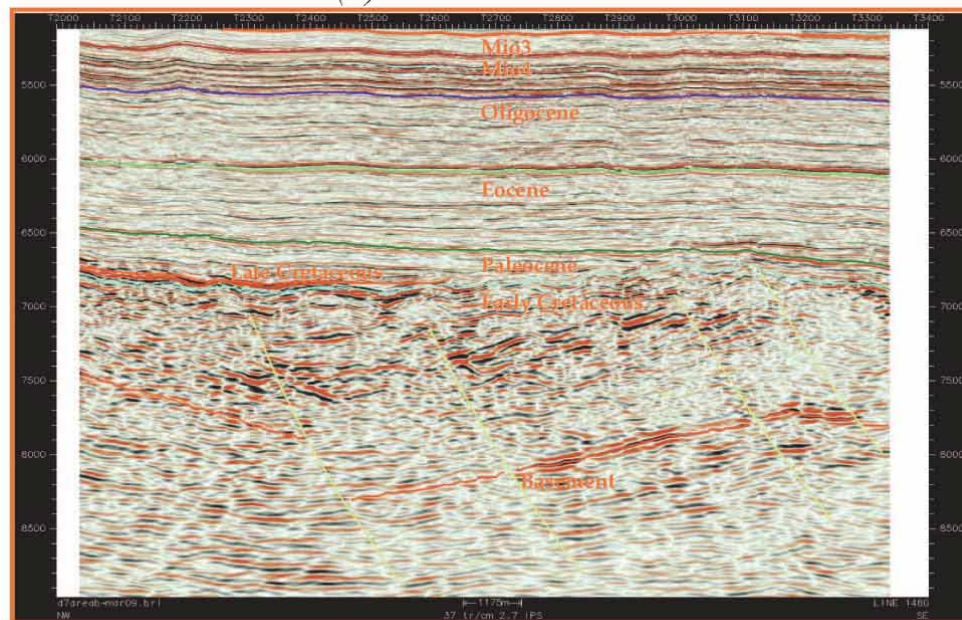


Figure 1. Location map of the study area.





(a)



(b)

Figure 2. Representative seismic section showing the correlated sequences in the study area. (a) Younger section, (b) older section.

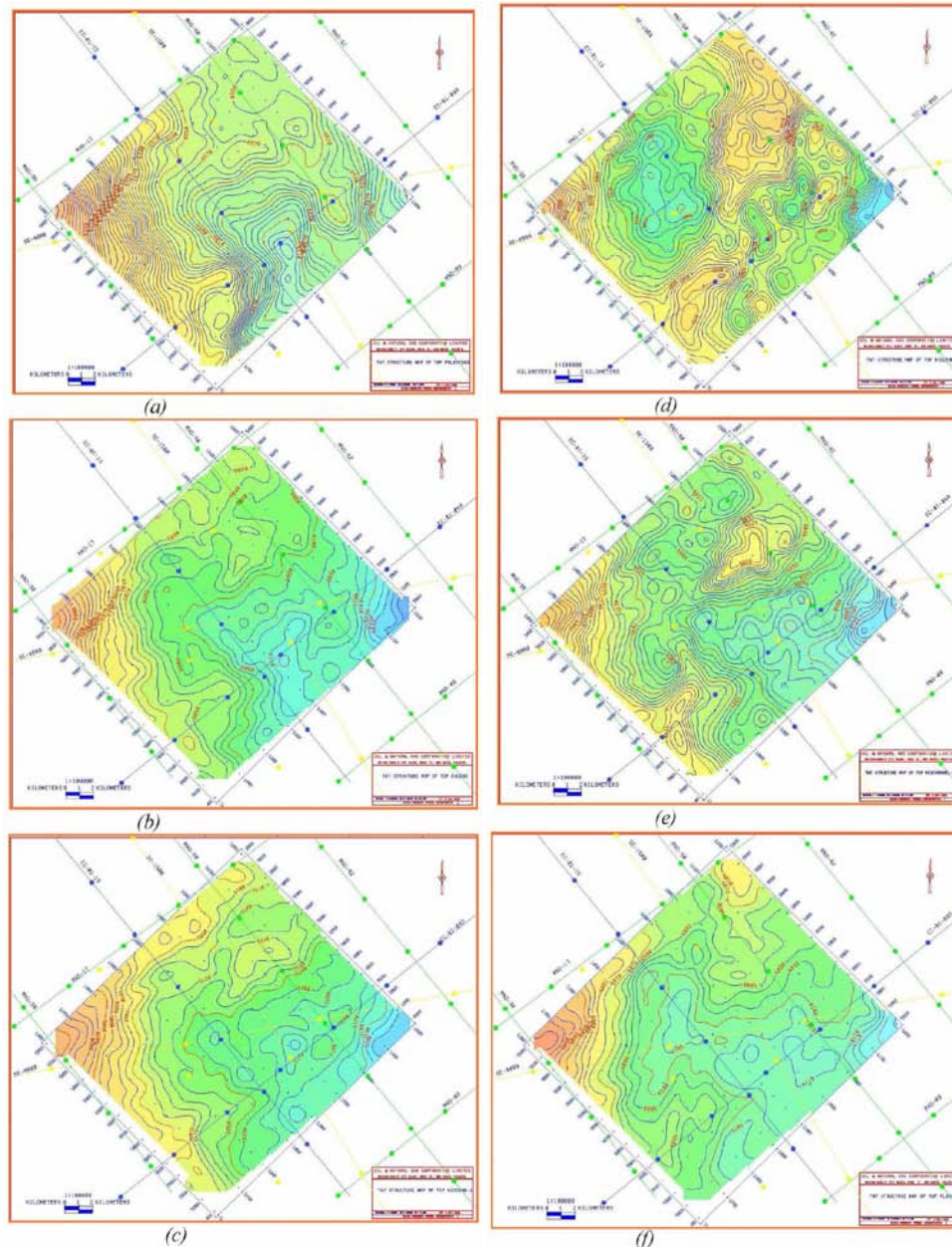
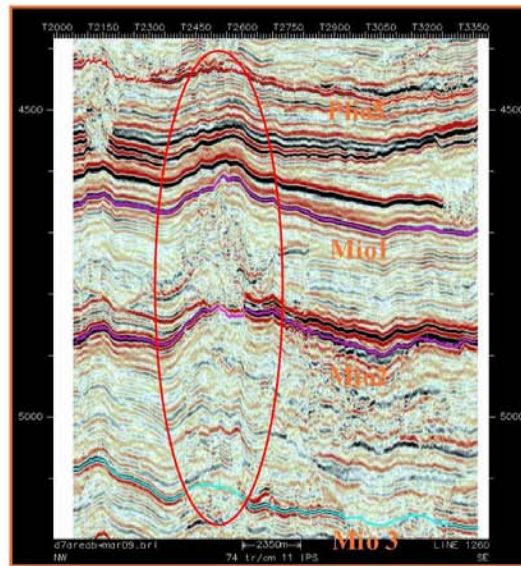
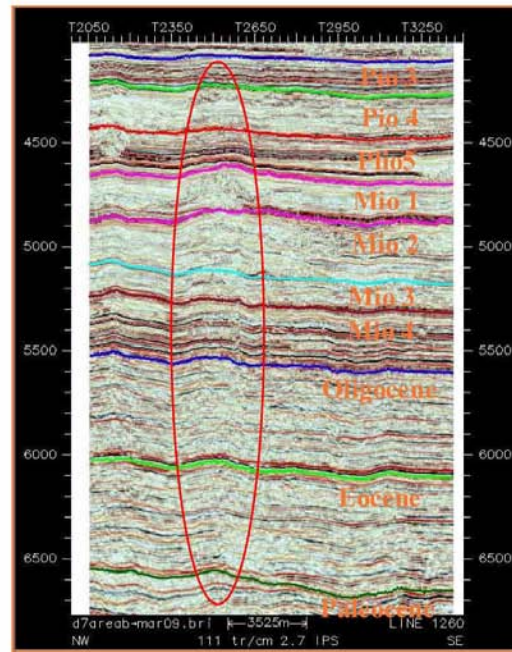


Figure 3. TWT structure maps on top of several major Tertiary sequences and sub-sequences. (a) On top of Paleocene, (b) on top of Eocene, (c) on top of Mio3, (d) on top of Mio2, (e) on top of Mio1, (f) on top of Plio3.





(b)

Figure 4. Representative seismic line showing the anticlinal structure affecting the entire Tertiary section. (a) Anticlinal structure seen at Paleocene-Plio4 levels, (b) zoomed view of part of Figure 4a.

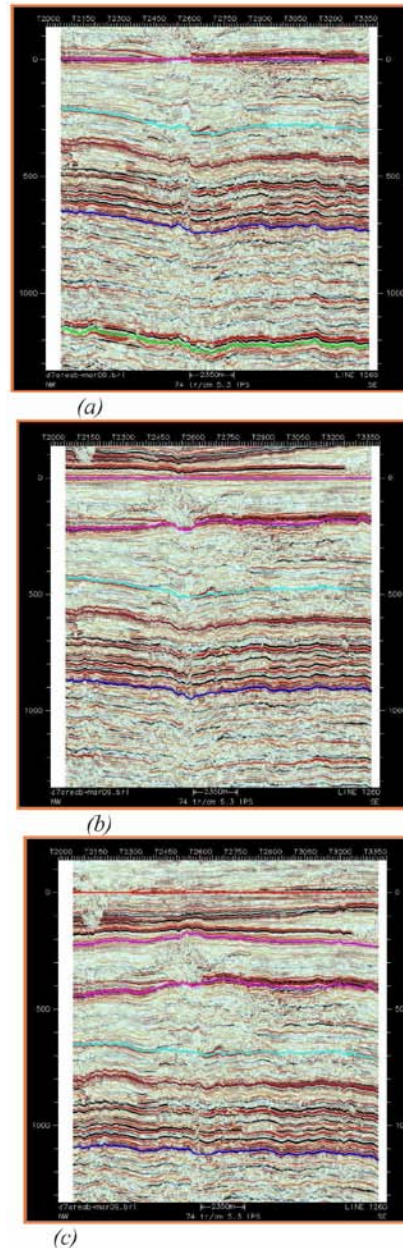
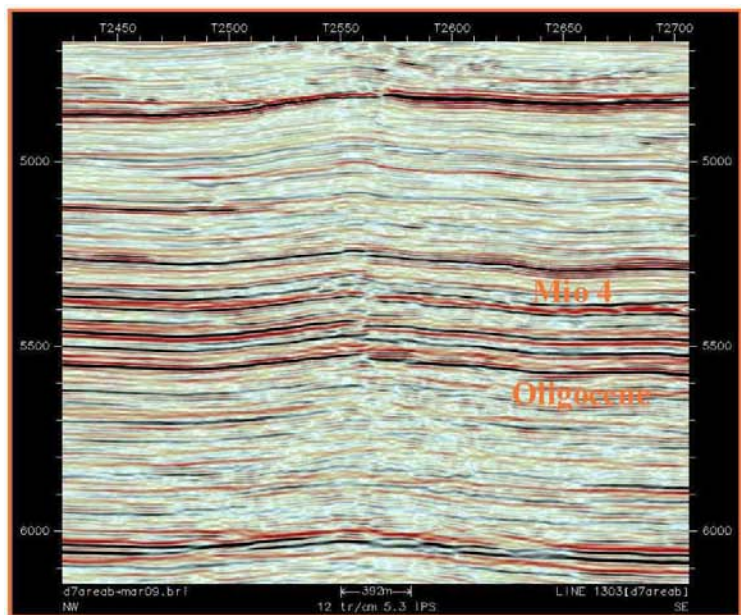


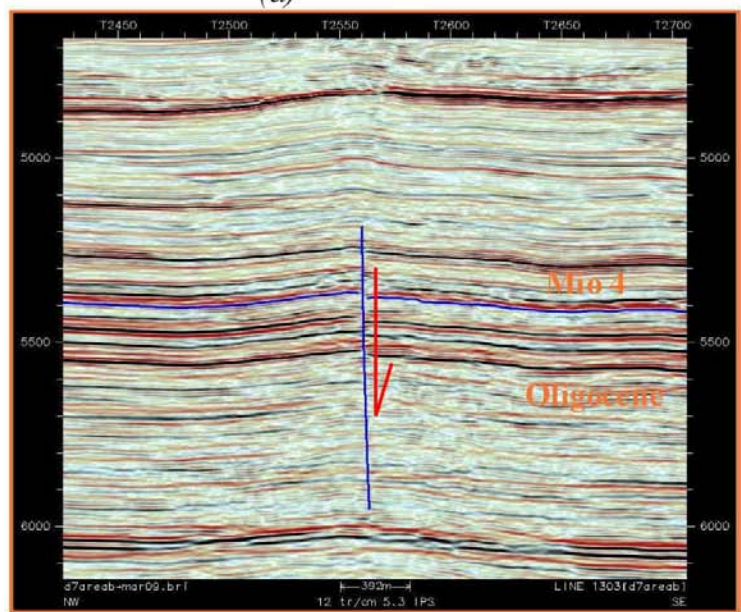
Figure 5. Seismic section (of Figure 4) flattened at different levels to explain the timing of structuring. At the time of deposition of Mio2 sequence there was no perceptible tectonics, but at around Mio1 level there is active tectonics forming the structure along with channel incision which is more prominent by Plio5 time as seen from the flattened section at Plio5 level. (a) Flattened at Mio2 horizon, (b) flattened at Mio1 horizon, (c) flattened at Plio5 horizon.





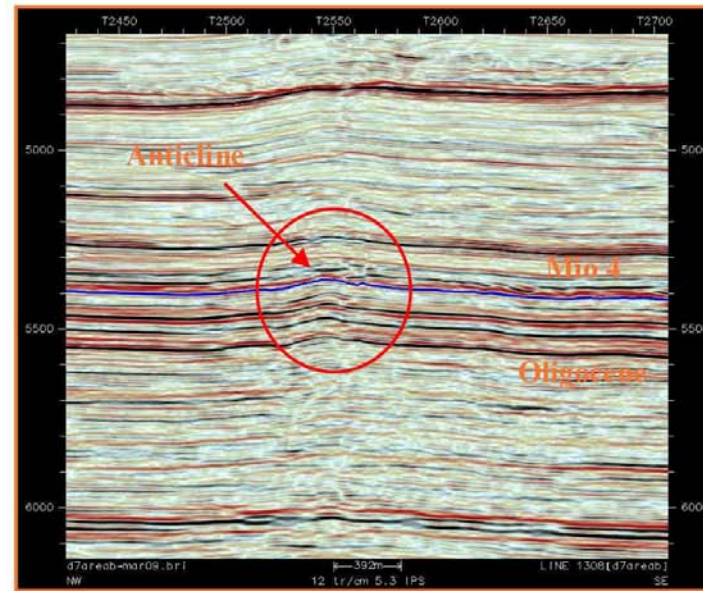


(a)

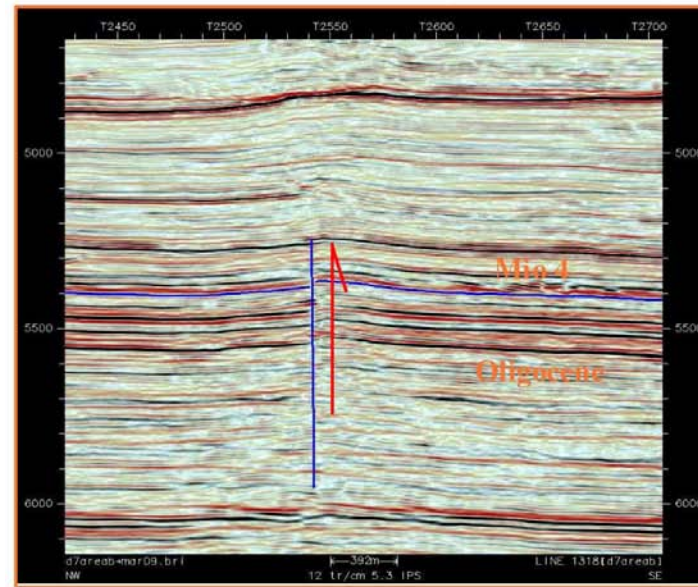


(b)

Figure 7. Representative Inline showing normal sense of throw to the right of the line (SE direction) along a small normal fault. (a) Uninterpreted, (b) interpreted.



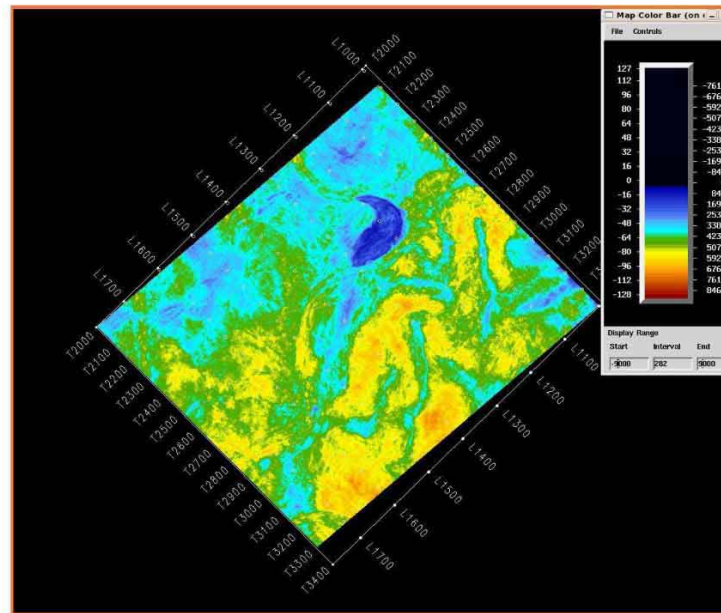
(a)



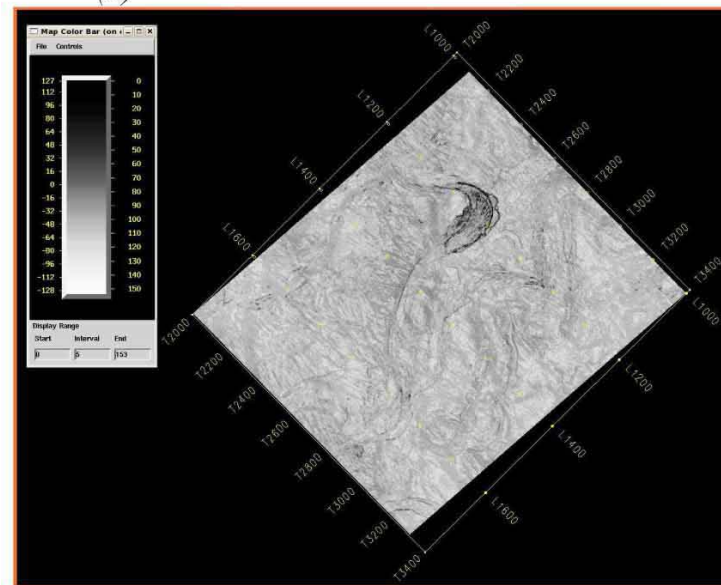
(b)

Fig. 8 (a) Inline showing a small anticlinal structure at the same level where there is a normal fault 125 m away. (b) Inline showing reverse sense of throw only another 13 lines (325 m) distance away from the Inline where earlier a normal sense of throw is seen.



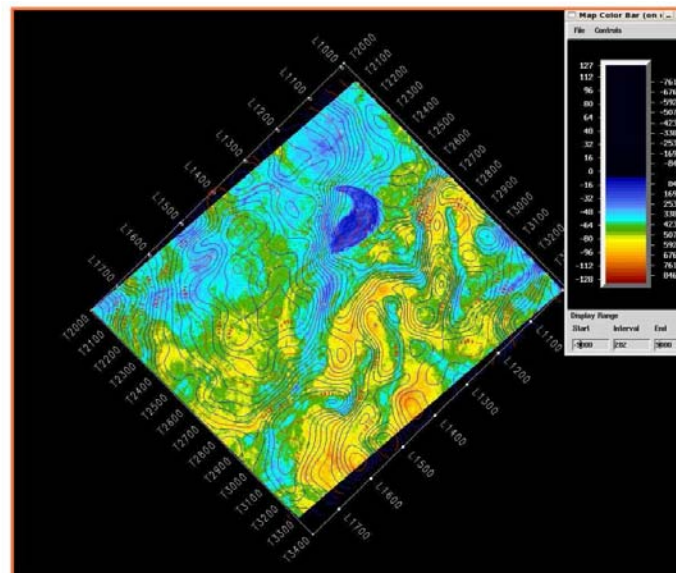
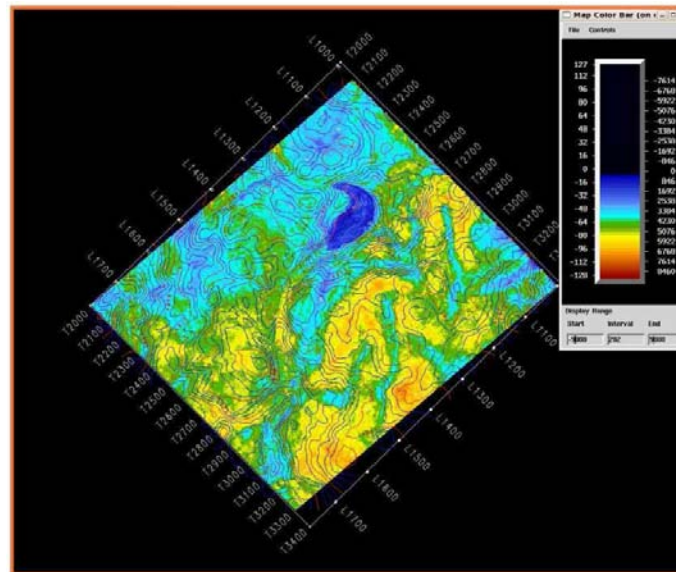


(a)



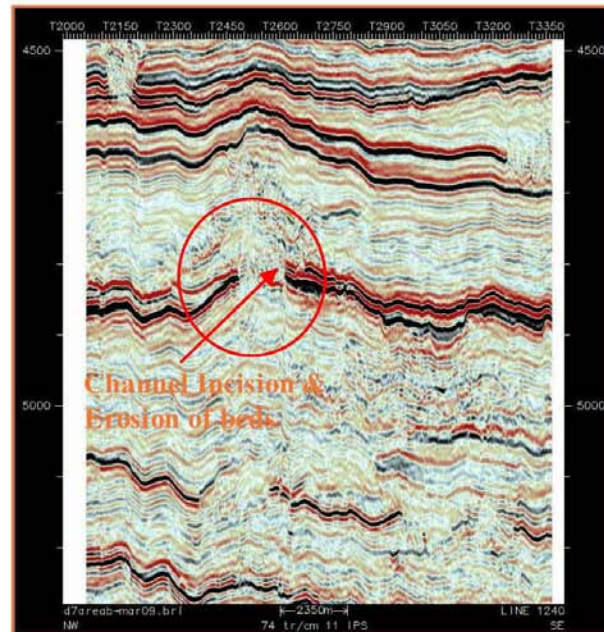
(b)

Figure 9. Seismic attribute maps for Mio2 surface (window: - 40 ms to +10 ms). (a) Average Absolute Amplitude attribute, (b) coherency attribute.

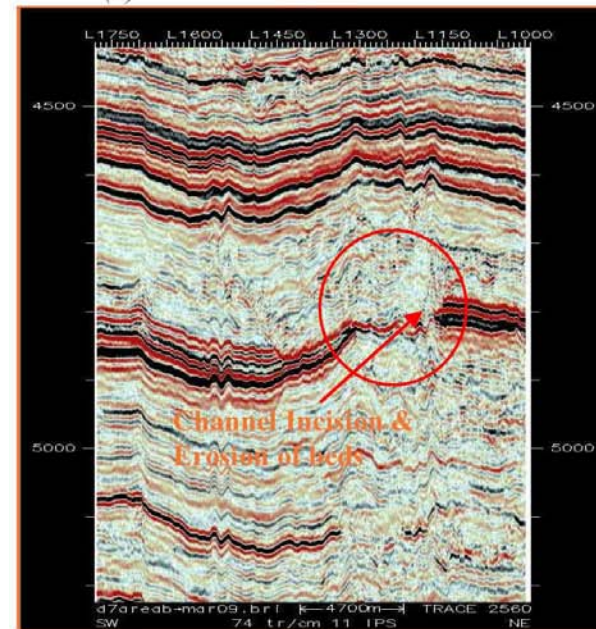


(b)

Figure 10. (a) Average Absolute Amplitude attribute map for Mio2 surface (window: -40 ms to +10 ms) superimposed with the TWT structure contour map on top of Mio1 Surface. (b) Average Absolute Amplitude attribute map for Mio2 surface superimposed with the TWT structure contour map on Mio2 surface.



(a)



(b)

Figure 11. Characteristic seismic signature of the deepwater channel. Note the channel incision and erosion of some units (missing reflectors). (a) Inline showing channel incision, (b) trace showing channel incision.