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Cenozoic siliciclastic & carbonate depositional systems and paleo-geographic reconstruction of Mahanadi Basin

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Abstract

Accelerated exploration activity in the Mahanadi Basin takes cues from recent hydrocarbon finds in offshore wells. In the shelf-slope margin area of Mahanadi offshore, deltaic bodies, crevasse-splay, reworked sediments, paleo-channels and channel cuts are common both in the Mesozoic and Cenozoic stratigraphy. The passive margin setup comprises late Cretaceous - Holocene stratigraphic sequence. Both the Paleogene shelf carbonate sequence and the Neogene deeper marine shelf-slope-bathyal clastic sequence are homoclinally dipping south-east with possible continuation into adjacent Krishna-Godavari basin. Extensive drilling in the onland and offshore areas of the basin has provided evidences of different paleoenvironmental setup prevailing during different geological times. Foraminiferal assemblages recorded in these sequences are the best indicators of paleoenvironmental and paleobathymetric conditions, so also to define marine / non-marine areas and paleogeographic realms. An entire array of the paleogeographic regimes ranging from fluvial-coastal to inner, middle and outer shelf and upper / lower bathyal or deeper have been demarcated. Paleogeographic maps from Paleocene to Pleistocene levels are prepared on the basis of prevalent foraminiferal biofacies as the bathymetric indicators. On the continental shelf, the Paleocene-Eocene is largely represented by the carbonates and associated thin sandstone. However, in deeper part, outer shelf facies are prevalent. Diversity and abundance of larger benthic coastal/ brackish water assemblages define marginal marine condition. Basinal features i.e. coastline, bathymetric zones, carbonate bank, foraminiferal biofacies, bathymetric and paleoenvironmental zones are interpreted. A large part of Oligocene has been a period of erosion/ non-deposition in most of the onland and shallow water areas; however, in the deeper/ basinal wells, the Oligocene sequence is well preserved. Post Oligocene, marine transgression and basin deepening resulted in the deposition of finer clastics with locally developed carbonates. Abundance of planktic foraminifera and deep water smaller benthics suggests outer shelf and upper bathyal environments. Radiolaria-rich assemblage with deep water agglutinated/ benthic forms suggest very deep (Bathyal) environment. The finer clastics of the shelf-slope margin areas have typically developed during the Pliocene-Pleistocene and may have been associated with increased deltaic activity in the basin.

Introduction

Mahanadi basin is passive margin, pericratonic basin situated in the east coast of India adjoining Bengal basin towards north-east and KG basin in the south-west (Fig.1). In onland part, Archean Crystallines and Athgarh Sandstone mark north-western basin margin. The generalized geology and stratigraphy of the basin was described by Fuloria (1993). Tectonically, the basement configuration shows NE-SW to ENE-WSW trending horst and graben morphology (Johnston et al, 2008). It was suggested that the 85° East Ridge was not a basement feature but dense sedimentary section hence a lot of exploration is targeted over this ridge. Basement relief in offshore ranges widely towards the fore-deep and the major structural elements are trending in NE-SW orientation as continental shelf, hinge zone / slope and fore-deep basin.

Siliciclastic & Carbonate Depositional Systems

Several paleodepositional schemes have been suggested by various authors over the time; however, commonly used scheme by Hedgpeth (1957) classified various fluvial-oceanic zones with bathymetric ranges. Sedimentation within the intertidal zone can occur under a variety of flow conditions where current strength may vary from still-water (at high tide) to faster runoffs. Inter-stratified carbonate and siliciclastic sediments represent an overall shallowing-upward succession of progradational shoreface to marginal marine setup that accumulates on a gently sloping continental margin (Zonneveld et.al.,1997). Depositional model for mixed siliciclastic-carbonate marine realm would be better described by the effects of fauna and flora (also tracefossils) besides the physical depositional processes. Hence prevailing facies will be recognized and defined on the basis of lithology, bounding surfaces, primary physical and biogenic sedimentary structures and the fossil assemblages. In siliciclastic environments, clean, translucent fine-grained quartz sands may get deposited at sites where hydrodynamic flow is sufficient to sweep the clay minerals from the system. Similarly, mixed siliciclastic-evaporite carbonate sedimentation will occur in areas of low clastic input which may be due to low relief or minimal fluvial activity and therefore, low sediment availability in the source area.

Siliciclastic and bioclastic grains often display inverse relationship. Shoreface sediments become increasingly carbonate-rich towards the shoreline and the foreshore is dominantly bioclastic in composition. Sedimentation is not only influenced by physical and chemical but also by biological factors. Reefs are significant sources of biogenic carbonate in shallow marine depositional systems. Intensive chemical precipitation of carbonates is a consequence of skeleton formation of organisms; therefore, significance of fossil biota in interpretation of geological processes is increasingly becoming important. Study of mechanical disturbance of sediments by burrowing, grazing, or resting of macro-organisms causes a variety of traces (trace fossils) in the sediments. It is unfortunate that such effects cannot be fully observed in the well cutting samples which are most commonly available study material for a petroleum geologist. Galloway (1998) defined seven basic facies as major components of most marine basin fills in the slope and deeper depositional systems. These include: turbidite channel cuts and fills; turbidite lobes; sheet turbidite; slide, slump and debris-flows; fine-grained turbidite fills; contourite drifts, and hemipelagic drapes and fills. Grain size of the supplied sediment is actually the primary control on channel and lobe morphologies so also on the scale of slump and debris-flow deposits. In deep water, siliciclastic slope systems may be either *constructional / allochthonous* which will include fans, aprons, and basin-floor channels; or *autochthonous* to include retrogressive aprons, canyon fills, and mega-slumps with slope reworking and re-sedimentation. Lithofacies architecture of allochthonous systems will be determined by sediment texture and sediment supply to the shelf margin. Thus proximal and distal slope fans and slope aprons (strike-elongate prisms of slope sediments) may be created and form significant exploratory targets. Features of similar characters are reported from deeper parts of Mahanadi basin. Shelf-margin deltas have also been interpreted as primary targets of exploration during Neogene, in the deeper basin in Mahanadi offshore.

Biostratigraphic Correlation and Sedimentary Facies

A number of recently drilled deep water wells in the area provided new biostratigraphic inputs to re-interpret biozonation and paleoenvironments so also to propose regional multi-microfossil biostratigraphic zonation scheme (Shukla et. al, 2013). Several correlation profiles along the generalized basinal dip and strike directions were prepared from the biostratigraphic data, covering a wide array of stratigraphic sequences and paleoenvironmental settings. The deep water wells close to the 85° East Ridge were correlated to the north-easterly situated deep wells and the very shallow shelf/ marginal marine part MND / NEC series wells. For the purpose of brevity, all the correlations and configurations are not possible to be discussed here, however, one important profile originating from the onland part and extending into the deeper basin (Wells MON-2; MON-3; MND-4, MND-6; MDW-2B; MDW-1; MDW-9) is discussed along with the important basinal observations through our study up to well MDW-22 (Fig.2). This corroborates different paleoenvironmental realms depicted in the paleogeographic maps at selected levels.

As per the sequence stratigraphy report (2008), the early Cretaceous Rift sequence is referred to the pre-Albian continental sediments encountered in the outcrop as Athgarh Sandstone so also in the wells MON-2 and MND-7. These were locally derived from both the lacustrine and continental environments. The Rajmahal Trap and associated sediments are present in wells MND 1, 5 and 7 and the lateral extent of this Trap is recorded up to the shelf near the Paleogene hinge zone. The well MDW-15 encountered basalt (4602-4924m) overlain by late Cretaceous sediments (4490-4602m) comprising dark grey and feebly calcareous laminated mudstone and associated reddish brown claystone also referred to the red beds. Late Cretaceous coastline appears to be close to the wells MND-4, MSW-2 and MND-1 roughly close to the 400ms value in time thickness contour. Biostratigraphically assigned Paleocene sediments encountered in wells MDW-14 (5160-5280m), MDW-15 (4460-4490m), MDW-18 (3105-3300m), MDW-19 (3520-3882m) and MDW-20 (4020-4082m) are represented by calcareous mudstone/ claystone, sandstone and limestone facies. Foraminiferal-algal wackestone/ packstone are present in wells MDW-18 & 19 and suggest inner–middle shelf conditions. Eocene claystone, limestone, minor sandstone with red clay sequence is observed in wells MDW-13 (4900-4950m), MDW-14 (4960-5160m), MDW-15 (4450-4460m), MDW-16 (6940-7022m+), MDW-18 (2905-3105m), MDW-19 (2900-3520m) and MDW-20 (3640-4020m). Limestone is encountered in wells MDW-16, 18 and 19. Oligocene in the onland part and shelf area is regressive as evident from part or complete absence of marine sediments in many wells (MND-1, MND-2, MND-7 and MND-5). Among the onland wells, MON-1 shows the presence of marine shallow shelf sediments during Oligocene. Oligocene limestone (foraminiferal packstone and bioclasts) is thinly interbedded with claystone in well MDW-19 representing mixed siliciclastic-carbonate marine facies. Quite often such sediments were deposited as shallow marine carbonates with minor transport and interspersed with claystone and mudstone. Towards the basinal side, late Oligocene finer sediments are characterized by inner shelf to outer shelf conditions in wells MDW-9, 12 and 17; outer shelf to upper bathyal in well MDW-16 and predominantly upper bathyal in well MDW-15.

Early to Middle Miocene transgressive sequence is thick and wide spread in offshore wells with relatively high rate of sedimentation. The predominant lithofacies such as claystone, sandstone and minor marlstone with fair reservoir characters is present in all the wells. Foraminiferal studies suggest that shallow marine conditions prevailed in the onland wells MON-1, 3 & 4 during Middle-Miocene, however, relatively deeper conditions (middle/outer shelf to upper bathyal condition) are observed towards the basinal side. Mixed siliciclastic sediments from the Mahanadi-Brahamani Rivers and Bengal fan system predominate the depositional lows parallel to the present day coast (wells MDW-18, 19, 20 and 21). During Late Miocene, the area of wells MDW-4A, 4B, MSW-1 and MDW-3 has upper bathyal conditions, whereas the well MDW-1 is even deeper i.e. lower bathyal suggesting perhaps a low. Relatively shallower conditions i.e. middle shelf to upper bathyal is recorded in wells MDW-9, 12, 17 during late Miocene and outer shelf to upper bathyal conditions are reported in nearby well MDW-15 and 16. Pliocene top is often unmarked in several wells and the sediments are mostly claystone/ mudstone with interbedded sandstone and minor calcareous layers. Sandy debris flow and turbidite with reworked sediments, paleo-channels and channel cuts are deposited under outer shelf to upper bathyal environment on slope-basin floor. Such deposits are widespread and foraminiferal data suggests that early Pliocene appear to be slightly regressive as compared to the Miocene intervals.

Summarizing, the extension and variations of various bio-chronounits from the siliciclastic / land part (MON wells) to the mixed siliciclastic-carbonate marine setup represented by shallow shelf wells (MND series) and further to the slope and deeper depositional systems (MDW series wells) depicts a complete picture much helpful in paleogeographic re-construction based on the microfossils. It is quite evident that a generalized thickening of Cenozoic bio-chronounits towards the basinal side would be observed, however, the data is constrained with the actual depths to which individual wells were drilled often bottoming into Oligocene or younger sequences. The onland areas have been characterized by the presence of only Early Cretaceous (Athgarh Sandstone) as in the case of well MON-2, however in well MON-4 marine Neogene sediments were also reported. Further towards the shelf area, bio-chronounits are better resolved more particularly during the Paleogene. The deeper wells have been characterized by relatively thin Paleogene bio-chronounits and huge thicknesses of Neogene sediments.

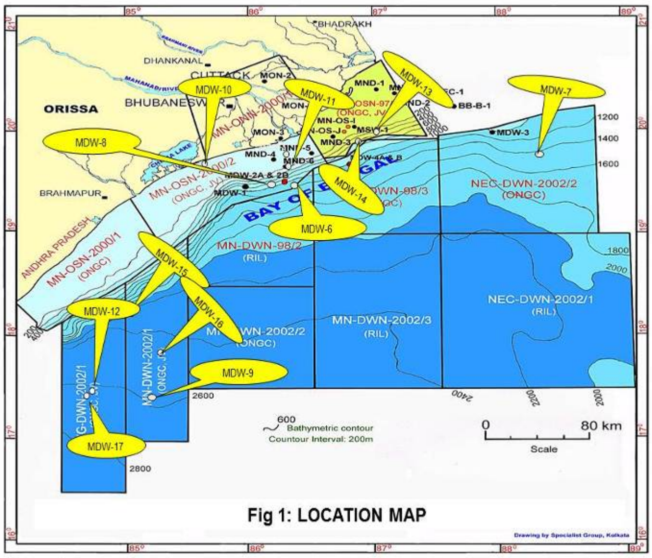

Fig 1: LOCATION MAP

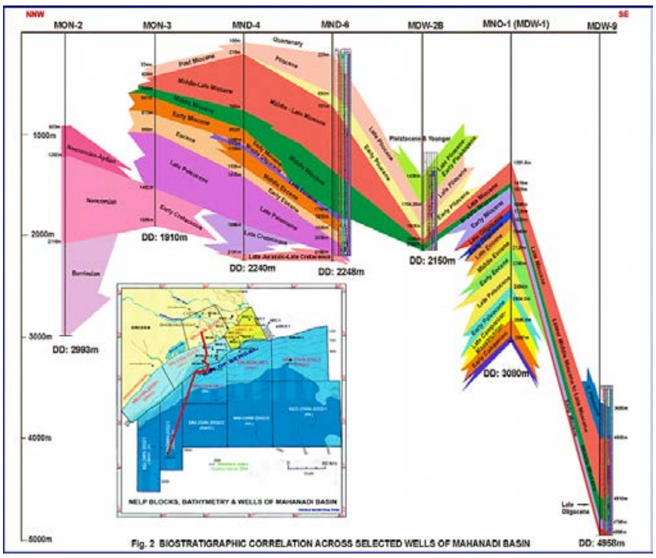

Fig. 2 BIOSTRATIGRAPHIC CORRELATION ACROSS SELECTED WELLS OF MAHANADI BASIN

Paleogeographic Reconstruction with Foraminiferal Biofacies

Paleogeographic maps were prepared utilizing foraminiferal data; interpreting paleobathymetry and relevant time thickness maps as the base maps. Foraminiferal assemblages are the best indicators of the paleoenvironmental and paleobathymetric conditions so also in demarcating marine / non-marine areas and different paleogeographic realms. The time thickness contours suggest paleo-depocentres and guide through the bathymetric trends. Thus various geomorphological features - the coastline, the bathymetric zones, carbonate shelf edge and deeper basin were interpreted. Foraminifera constitute the most important group of microfossils as paleobathymetric indicators. For the purpose of paleoenvironmental zonation, the radiolaria-rich assemblage with deep water agglutinated/ benthic forms including *Hoeglundina elegans*, *Cibicides wuellerstorfi*, *Bulimina* spp. and few planktics are suggestive of very deep marine (bathyal) environments. The abundance of planktic foraminifera along with the deep water smaller benthics such as *Uvigerina* spp., *Hyalinea balthica*, *Cibicides wuellerstorfi*, *Bulimina* spp., *Cassidulina* spp., *Neouvigerina* sp., *Loxostromum* sp., and several others is noted in outer shelf, bathyal environments. The diversity and abundance of larger benthic foraminifera is extremely helpful in defining smaller environmental zones within the inner to middle shelf conditions. The abundance of *Ammonia* sp., miliolids and rotaliids along with shell fragments and other coastal / brackish water assemblages define marginal marine to intertidal conditions. Following Hedgpeth (1957), the bathymetric divisions of the marine environments followed in the present study are plotted in respective paleogeographic maps and also record the prominent foraminiferal biofacies.

Cenozoic paleogeographic reconstruction takes cues from the intermittent transgressive sedimentation during Paleocene which restricted the siliciclastic influx over large part of the continental shelf and facilitated carbonate deposition in the area. Foraminiferal studies suggested that late Paleocene witnessed well established marine conditions in MON-3 and MON-4, whereas the areas of MON-1 and MND-1 appear to have remained positive over longer period of time. Presence of marine conditions in MON-4 and MON-3 is significant during **late Paleocene**. Marine sedimentation has transgressed into the present day onland part of the basin; however the areas of MON-1 and MND-2 appear to have remained positive areas with non-deposition of equivalent sediments (Fig.3). Shallow inner shelf conditions prevailed over large part of area including the wells MND-7, MND-2, MND-3 and MON-3. Relatively deeper conditions are envisaged in the area of MND-5, MDW-2A, 2B and MDW-1 and deeper basin. In the land part MON-3 is the only well suggesting shallow shelf bathymetry during the **late Eocene**. A wider shelf in the northern part in the areas of NEC-1 gradually narrowing towards southwest is also observed. Relatively deeper conditions are envisaged in the wells MND-6, MND-5 and further south in the MDW-1 and deeper basinal area. During Eocene, extensive carbonate sedimentation occurred in the northeastern shelf; however, the well MDW-1 shows local differential subsidence and deep water conditions (Fig.4).

During **late Oligocene** the onland wells MON-1 shows the presence of marine shallow shelf sediments whereas in several offshore wells such as MND-1, MND-2, MND-7, MND-5 and MND-6 the marine Late Oligocene sediments are absent suggesting an unconformity. Accordingly the shoreline has been depicted in fig.5. The inner shelf and outer shelf bathymetric zones are depicted with the southwestern part (MDW-1 being distinctly deeper (outer shelf to upper bathyal). Three onland wells MON-1, 3 & 4 have reported presence of shallow marine middle Miocene sediments. Relatively deeper conditions are observed towards the basinal side successively from middle/ outer shelf to upper bathyal conditions. MDW-1 area has distinctly been deepest as compared to other wells in the vicinity. The unconformity at Oligocene / Miocene level is correlatable to the base of Second Order Sequence CII 80 whereas the unconformity at the top of Eocene can also be correlated to base of CII 40. **Late Miocene** coastline is quite similar to the middle Miocene coastline and the inner shelf, middle shelf and outer shelf paleobathymetric zones are clearly divisible. The area of MDW-4A, 4B, MSW-1, and MDW-3 has shown deeper upper bathyal conditions whereas the area close to the MDW-1 may be placed in the deeper part close to lower bathyal conditions. On the time interval map, the late Miocene is consistently thickening into the center of the basin. The development of channel-levee-complexes may be possible through a combination of Mahanadi and Bengal siliciclastic input, prograding into the shelf and slope regions. Reworking of microfossils at different levels in few wells suggests reworked sediments over the shelf and down the slope into deeper basin. **Pliocene** coastline is defined with wells MON-3 and MON-4 showing evidences of shallow marine sedimentation. The area of MDW-4A, 4B and MSW-1 and MDW-3, so also MDW-2A and 2B is characterized by upper bathyal conditions. The shelf is becoming narrower with the shelf edge area maybe having steep dips and significant bathymetric changes. **Pleistocene** coastline is very close to the present day coastline and the inner shelf conditions prevail in the areas of MND-6, MND-4 to MND-7. Relatively deeper i.e., outer shelf and upper Bathyal conditions could be suggested in the south eastern parts of the basin on the basis of foraminiferal assemblages in wells MDW-3, MDW4A, 4B, MDW-2A and 2B and further south in basinal areas (Figs.6-8).

Conclusions

- Marine late Cretaceous sedimentation established with Campanian transgression and terminated at K/T boundary with an unconformity. Cenozoic sedimentation initiated with predominantly clastic input in relatively shallower paleoenvironment, gradually turning to mixed siliciclastic-biogenic carbonate sedimentation during Paleocene. Intermittent transgression established during late Paleocene and Eocene leading to inner-middle shelf conditions, restricting siliciclastic influx over the shelf and facilitating vast carbonate deposition.

- Eocene-early Oligocene shelf in Mahanadi basin represents gentle south-eastward dipping carbonate platform overlying the erstwhile late Cretaceous-Paleocene constructional siliciclastic (allochthonous) system. Further on, complex succession of mixed, interstratified carbonate and siliciclastic sediments on carbonate platform gradually changes to predominately finer clastics in the deep water areas.

- Oligocene has been a period of erosion / non-deposition in most of the onland and shallow water areas (MON wells, MND-1, 2, 3, 4, 5, 6, 7) and the most prominent hiatus being observed in MND-5, however, in the deeper / basinal wells (MDW-1, MND-8, MDW-6, 8 and 9) marine Oligocene is recorded. The hinge zone (Eocene shelf-slope) marks an increase in thickness of the overlying Oligo-Miocene and Pliocene sediments between the shelf margin and the basinal areas and provides steeper slopes with paleo-channels, channel cuts and reworked sections.

- During Miocene, inner shelf, middle shelf and outer shelf paleobathymetric zones are more clearly divisible on paleogeographic maps; however, deeper upper bathyal conditions prevailed near wells MDW-4A, 4B, MSW-1, and MDW-3 and towards basinal areas.

- Pliocene coastline is defined with wells MON-3 and MON-4 showing evidences of shallow marine sedimentation. However, the area of MDW-4 A&B; MSW-1; MDW-3, MDW-2 A&B and southern basinal lows is characterized by upper bathyal conditions. By this time the shelf is narrower with shelf-edge marked with steep dips and significant bathymetric variations.

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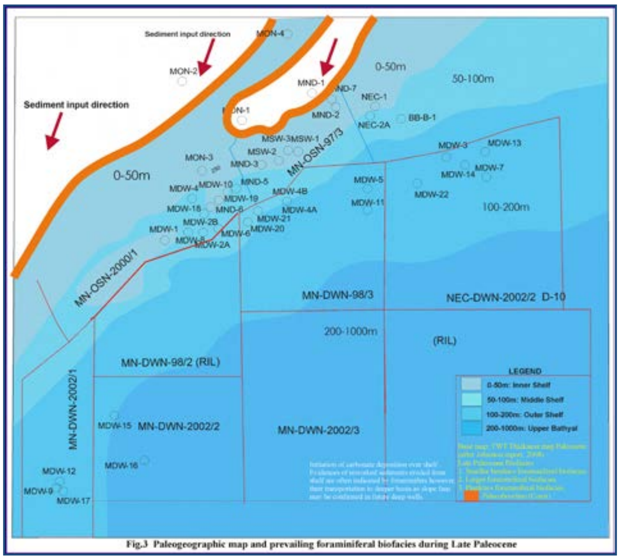

Fig.3 Paleogeographic map and prevailing foraminiferal biofacies during Late Paleocene

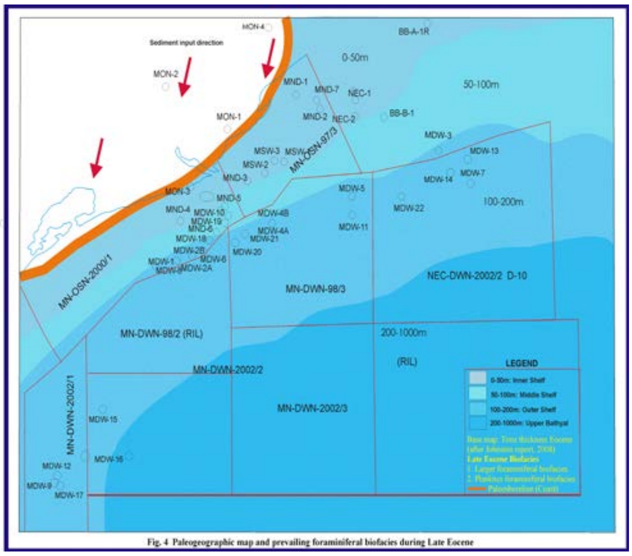

Fig. 4 Paleogeographic map and prevailing foraminiferal biofacies during Late Eocene

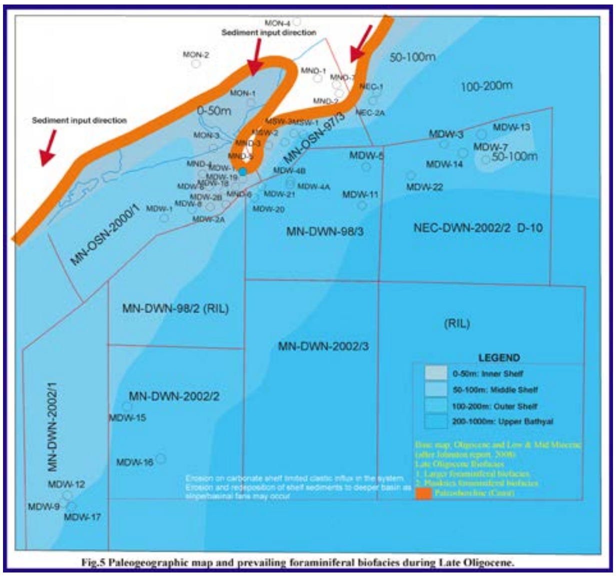

Fig.5 Paleogeographic map and prevailing foraminiferal biofacies during Late Oligocene.

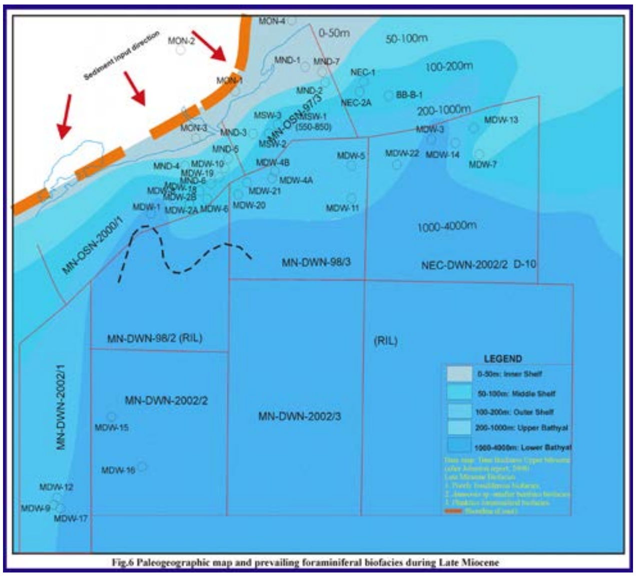

Fig.6 Paleogeographic map and prevailing foraminiferal biofacies during Late Miocene

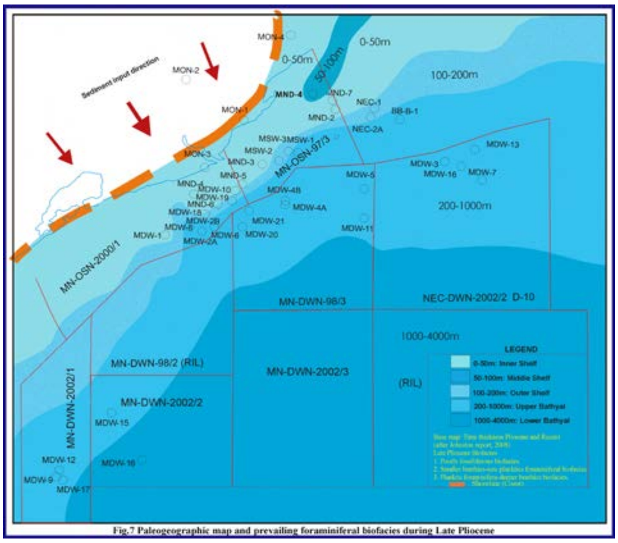

Fig.7 Paleogeographic map and prevailing foraminiferal biofacies during Late Pliocene

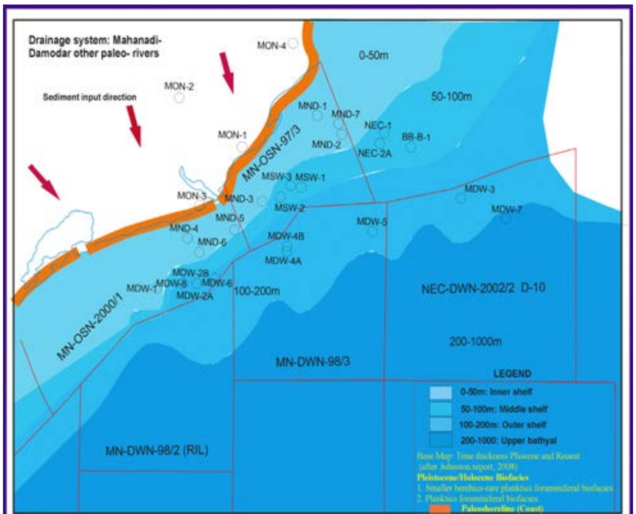

Fig.8 Paleogeographic map and prevailing foraminiferal biofacies during Pleistocene