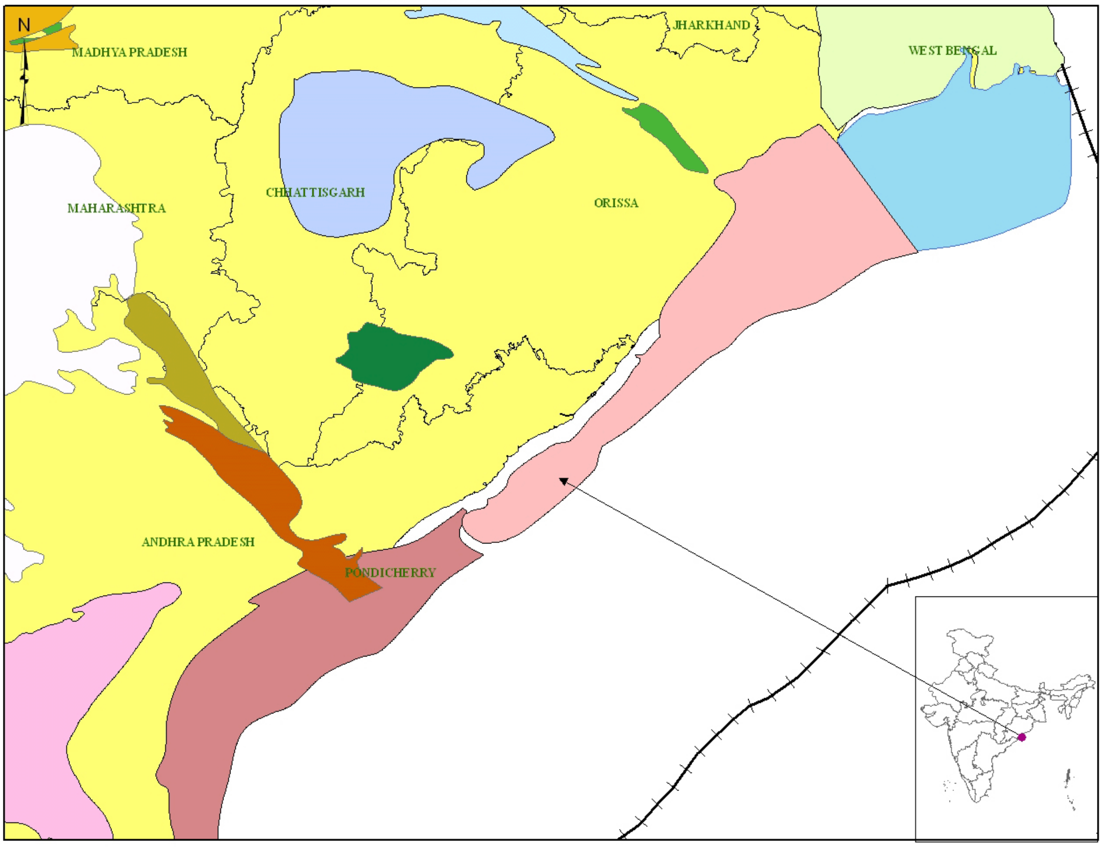
Basin Introduction:.

Mahandi-NEC Basin



The Mahanadi Basin, a product of rifting and break up of Gondwana Land, situated on the East Coast of India (Figs.1 & 2) is a basin with significant unexplored hydrocarbon potential. Like its immediate neighboring, Krishna-Godavari Basin, Mahanadi Basin also has a geological extension into offshore. The basin covers a total area of 55,000 Sq. Km. out of which about 14,000 Sq. Km. lies in the shallow offshore area. The shelf break occurs approximately along 150 m isobath. The deep-water part of the basin covers a much larger area. The prognosticated resource of the onland part of the basin is in the order of 45 MMt and that of the shallow offshore basin is about 100 MMt. Deep water part of the basin holds huge significant additional hydrocarbon potential.

The onland part of the basin is limited to north west and west by Pre-Cambrian outcrops belonging to the Indian crystalline Shield (Fig. 3). Towards northeast, it merges into North East Coast region (NEC) with Bengal Basin lying further northeast. Onshore Mahanadi Basin is located in the State of Orissa. Geographically, the shallow offshore part of the basin lies off the coast of Andhra Pradesh and Orissa. The 850 E Ridge occurring to the south of Lake Chilka forms the approximate southwestern limit of the basin. Subsequent to Late Oligocene / Miocene period, Mahanadi-NEC area is so greatly influenced by Bengal deltaic sedimentation system that its northeastern boundary with Bengal Basin becomes obscure.

To date, four wells in onshore part (MNO-1 to 4) and seven wells in Mahanadi shallow offshore (MND-1 to 7) have been drilled, some of which indicated significant hydrocarbon shows during drilling. In NEC area, two wells viz. BB-A-1R and BB-B-1 were drilled by Carlsberg, four wells viz. NEC 1,2,3,and 4 were drilled by OIL and in more recent times another Company drilled 6 wells. Some of the wells gave very encouraging results. Geochemical Sniffer Surveys conducted by

M/s Interocean of USA revealed a number of geochemical sniffer anomalies in the shallow offshore area. An independent comprehensive basin modeling study for the area also gave encouraging results. These positive observations indicate the hydrocarbon potential of the basin. The recent promising finds in Mahanadi-NEC shallow offshore gave further fillip to the envisaged potential of the basin.

General Geology:.

A. TECTONIC EVOLUTION OF EASTERN CONTINENTAL MARGIN

The Gondwana paleo-geographic reconstruction shows juxtaposition of Antarctica to the east coast of Peninsular India with Australia lying further to the east. The eastern continental margin of India is a rifted passive margin evolved in response to continental rifting. Indian Craton is circumscribed by rifted grabens and marginal sag basins. The east-west trending Narmada-Son Tectonic Lineament, an important line of discontinuity across the Indian shield is a mid-continental rift system, which divides the shield into two halves; a northern 'Foreland block' that now forms the Himalayan Foreland Region and a southern' Peninsular Block'. The process was initiated along the Satpura weak zone during Late Carboniferous / Triassic time due to crustal stretching that also caused co-genetic rifting of Mahanadi and Godavari grabens along NW-SE tectonic trend. During the Early Rift Stage (Permo-Triassic), down warping of the Eastern Margin formed a series of northeast southwest trending faults following an older set of Achaean fault lineaments 'The Eastern Ghat Trend'. Initial break-up of the Indian Craton was caused by rift initiation possibly by the formation of a series of triple junctions forming two sets of cross trending grabens.
Northwesterly paleo-current directions during Permo-Carboniferous and Triassic times, marine intercalations and deltaic facies of Godavari and Mahanadi grabens suggest the presence of a sea to the north of these grabens. This and the formation of depocenters at the meeting point of these grabens with the Narmada-Son rift (Satpura and Son) prompted to reasonably infer the presence of a seaway along this major rift. This rift episode seems to have ended by Late Triassic when the seaway was probably filled up and uplifted as the Indian Plate had started drifting away. The failed arms of these rifts forming aulacogens have been exploited by the Mahanadi, Krishna, Godavari and Cauvery river systems.

During Late Jurassic to Early Cretaceous period, India – Australia plates rotated from Antarctica with continental extension between Australia and Antarctica and a right lateral transform movement along the southern part of the Coromandal coast (east coast) margin of India (to the south of Krishna-Godavari Basin) and Indian plate got separated from Antarctica. Thus the initial break up of the Indian Plate from Australia-Antarctica possibly occurred prior to Early Neocomian, creating the proto Bay of Bengal Ocean with the onset of sea-floor spreading. Since Cretaceous, the Indian Plate rotated northwestward. Development of a new spreading center (?) initiated spreading in north-south direction. It was during Late Albian that the paleoslope was reversed in these graben basins with the southeasterly tilt of the peninsular block. This event coincided with first basin wide marine transgression during Cenomanian and continued up to Maastrichtian. The post-rift thermal subsidence continued throughout remainder of the Cretaceous and Tertiary. An extensive uplift of that major rift and erosion followed the end of Cretaceous prior to the volcanic episode of Deccan trap. The northward drift continued till it had initial (soft) collision with Eurasia in Paleocene. Sea level fall in Upper Oligocene followed this. The southeasterly/ easterly tilt of the Peninsula had resulted in the increase of fluvial energies of various fluvial systems leading to pouring of substantial sediment loads into the adjoining sea. In Early Miocene, crustal shortening continued as the Indian Plate continued its northward drift with the resultant further increase of fluvial activity. Himalayan upliftment and deposition of sediments by the Ganges and Brahamaputra commenced in Miocene. Thus Miocene and younger times witnessed very significant increase in the sediment outpouring into the offshore extending the basins into the deeper waters.

The evolution of East Coast of India as a passive margin set up resulted in the formation of a number of peri-cratonic basins- Bengal, Mahanadi, Krishna-Godavari, Pennar and Palar, while Cauvery basin developed as an intra-cratonic basin.

B. BASIN EVOLUTION/ GEOLOGICAL HISTORY AND STRATIGRAPHY

The Eastern Continental margin of India represents a rifted passive margin evolved in response to continental rifting. Regional Tectonic Element of the East Coast of India. India separated from southern super-continent Gondwana Land during Late Jurassic- Early Cretaceous, although rift initiation was during the Permo-Triassic prior to continental splitting. Rift initiation was in the form of linked rift triple junctions. One of the failed arms of these rifts forming aulacogen north of the Mahanadi Basin has been exploited by Mahanadi river systems (Mahanadi Graben). These aulacogens, representing favorable locations for the development of fluvial systems, provided great drainage basins for the progressive erosion of the cratonic hinterland. Predominantly continental sediments of Upper Paleozoic and Mesozoic age were deposited and preserved in this aulacogen – Mahanadi Graben. Rifting and synrift infill of the Mahanadi Graben was continuing in Jurassic and Early Cretaceous.

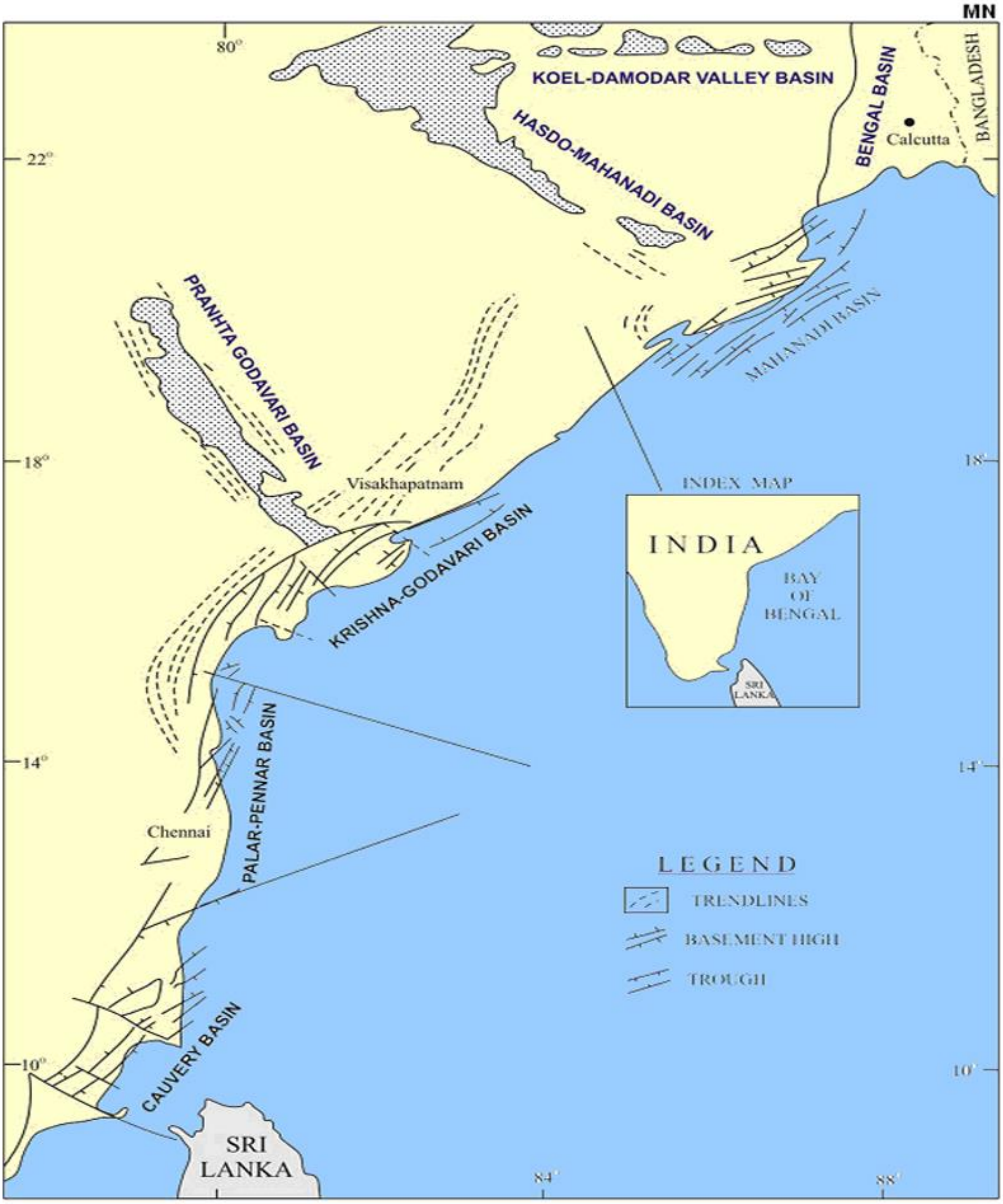


FIG. 7. REGIONAL TECTONIC ELEMENT OF THE EAST COAST OF INDIA

- **Rift Stage**

Mahanadi Basin, a peri-cratonic basin was initiated probably during Late Jurassic by rifting and subsidence of the Pre- Cambrian Basement by a number of major faults with a dominant ENE-WSW trend and subordinate NNE-SSW and NNW-SSE trends. These faults, which are parallel/sub-parallel to the present day coast line divided the basin into a number of linear depressions and uplifts Bhadrak Shallow Basement Block, Cuttack- Chandbali Depression, Bhubaneswar- Kendrapara Uplift, Paradip Depression, Nimapara-Balikuda Uplift, Puri Depression and Konark Uplift from north to south in the onland part. Tectonic Map of Mahanadi Onshore Basin. The Konark Uplift extends into shallow offshore part of the basin. Further southeastward, the shallow offshore part up to the Eocene Hinge Zone has also been differentiated into a number of ENE-WSW trending uplifted blocks and depressions. Tectonic features of the Mahanadi offshore Basin. Further to northeast, a NNW-SSE trending fault is present probably, due to which the Eocene Hinge Zone takes a sudden NE-SW swing and further northeastward, it assumes almost a N-S trend. North of this part of Hinge Zone is designated as NEC area.

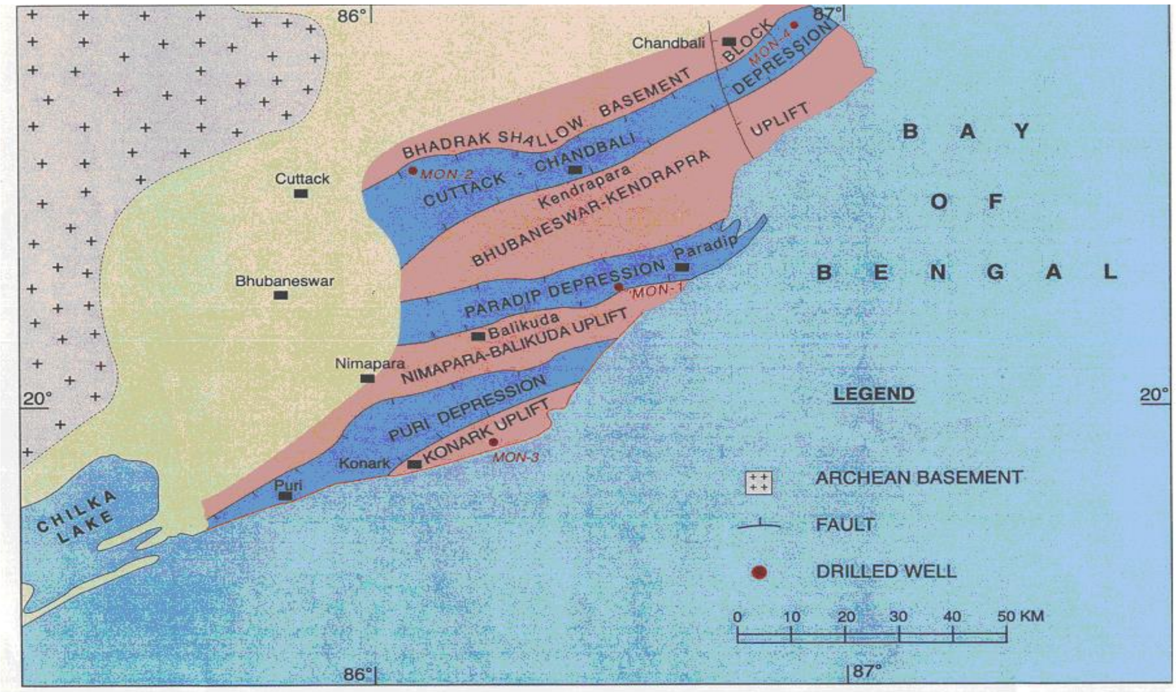


FIG. 8. TECTONIC MAP OF MAHANADI ONSHORE BASIN

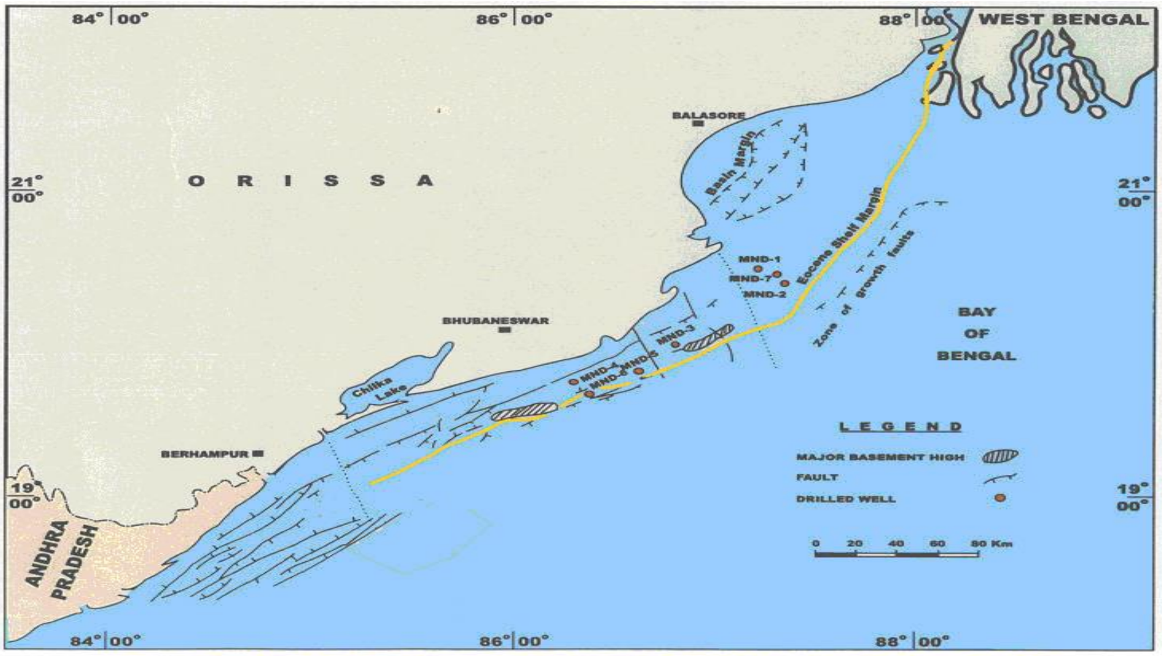


FIG. 10. TECTONIC FEATURES OF THE MAHANADI OFFSHORE BASIN

A Generalized Lithostratigraphic column of Mahanadi shallow offshore basin. Available regional geoscientific information suggests that the Basement in the Mahanadi onland and shallow offshore area is of continental type to the north of the Eocene Hinge Zone . It may be mainly of oceanic type further to the south of it. A transition zone from continental to oceanic crust of varying width may be present in different parts of the basin. Continental Basement is made up of Eastern Ghat granulites and gneisses of Pre-Cambrian age. The oceanic basement has not been drilled so far in any of the Mahanadi wells, but it is likely to have an affinity with the Early Cretaceous volcanic rocks encountered in some of the drilled wells. The upper age limit of the oceanic basement may be Early Cretaceous. The Bouguer Anomaly Map indicates that the lineament from which ocean spreading initiated was coast parallel implying that rifting and spreading was controlled at least in part by the NE-SW trending Achaean Eastern Ghat trend. NNW–SSE trending faults divide the basin into transverse blocks. Significant lateral movement has taken place along these strike slip faults during the course of basin development. As mentioned earlier, both the basin strike and the alignment of the Eocene hinge takes a sharp turn to NE along one of these faults suggesting a post-Eocene movement.

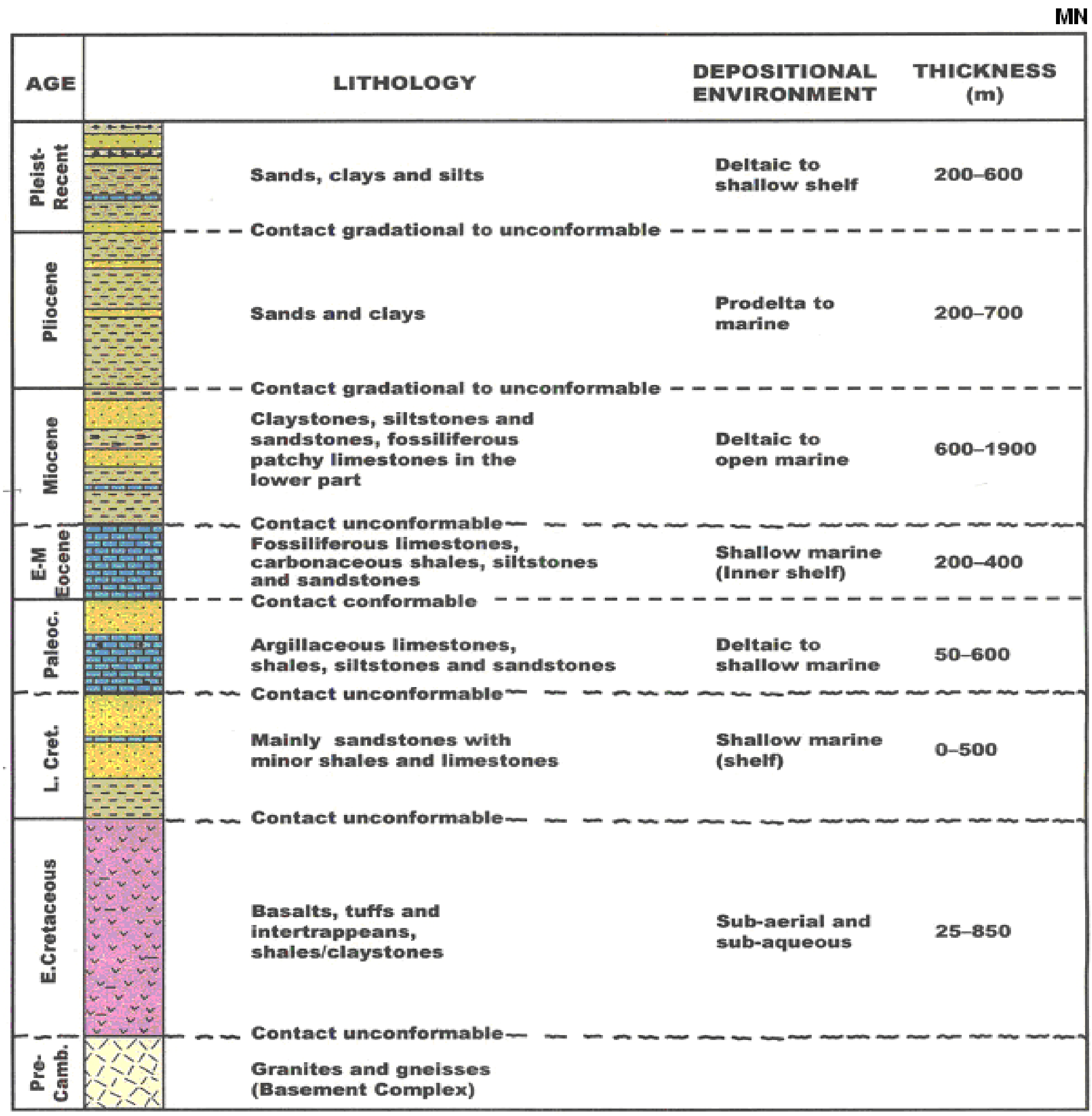


FIG. 12. GENERALIZED LITHO-STRATIGRAPHIC COLUMN OF MAHANADI SHALLOW OFFSHORE BASIN

Oldest exposed sediments in onshore part of Mahanadi Basin belong to Athgarh Sandstone Formation of Late Jurassic to Early cretaceous age. These sediments directly overlie Pre-Cambrian Basement rocks along the western basin margin near Cuttack and are concealed under a widespread cover of laterite and alluvium of Pleistocene to Recent age at places.

Predominantly coarse grained sandstone with subordinate shales and thin coal streaks of Late Jurassic to Early Cretaceous age have been encountered in the onland wells drilled in Depressions. These sediments have been inferred to be deposited under fluvial conditions with occasional marine incursions. Several flows of basic volcanic rocks of different thickness are met within this sequence. However, the shallow offshore part of the basin witnessed more intense volcanic activity albeit with a few interruptions. This predominantly volcanic sequence made up of basalts, tuffs and inter-trappeans is resting unconformably over Pre-Cambrian Basement. These volcanic rocks have both sub-aerial and sub-aqueous characteristics. The thickness of volcanics varies from around 25 m in MND -3 to 850m in MND -7 indicating the variation in volcanic activity over the basin. Based on palynological evidence, these volcanics are correlated with Rajmahal Trap and have been assigned Neocomian-Aptian age (133 to 144 Ma). The inter-trappeans are mainly argillaceous and their thickness vary from 150 m in MND-1 to almost nil in MND-7.

Accumulation of Early Cretaceous syn-rift sediments in complexly dissected relief caused by rift development explains their composite and heterogeneous lithology as well as vertical and lateral variations within the basin.

- **Early Thermal Subsidence**

The initiation of early thermal subsidence during Late Albian is marked by a southerly / southeasterly tilt of the continental margin leading to marine transgression. The structural configuration continued to be of horst- graben type but less differentiated than earlier.

Unconformably overlying the volcano-clastic rocks of Early Cretaceous is an appreciably thick sequence of sandstones and shales with minor limestone at places deposited under shallow inner shelf conditions in the present day shallow offshore part of the basin. The thickness of this stratigraphic sequence varies widely from almost nil to 500m. However, the equivalent sediments in the onland part were deposited under fresh water conditions suggesting restricted marine transgression.

- **Late Thermal Subsidence**

The first soft collision took place in Early Paleocene as continental India collided with the Eurasia Continental margin. Rifting had ceased and northward drifting was initiated. Eastward flowing rivers along the East Coast of India deposited Paleocene sediments that filled Cretaceous ography. Marine transgression continued through Paleocene. However occurrence of Paleocene sediments in only two wells drilled on shore viz. MON-3 drilled on Konark Uplift located relatively basinward and in MON-4 in Chandbali Depression, seaward part of the Cuttack-Chandbali Depression, suggests that the marine transgression during Paleocene was restricted to the basinward periphery of the present day onland part of the basin. While the sequence is represented by shales, sandstones and thin limestones deposited in the shallow marine environment, in the offshore part it is represented by a dominant argillaceous limestone, shales, siltstone and sandstone deposited under deltaic to shallow marine conditions. Based on the well data, it can be surmised that there was a paucity of clastic supply into the area during Early Paleocene resulting in the deposition of limestone in the present day shallow offshore area (i.e. where the wells are located). However the clastic supply got resumed (possibly from a provenance located in NE part of the onland basin with a southeasterly drainage direction) during Late Paleocene resulting in the deposition of sands and silts with minor limestones possibly under deltaic conditions in the southwestern part of the offshore basin. However, northeastern part of the offshore part of the basin (MND-2&7) continued to be deprived of clastic supply leading to uninterrupted deposition of limestone.

Dominant presence of fossiliferous limestone with minor clastics in the Eocene sequence in the shallow offshore wells and presence of seismic mounded facies corresponding to this sequence possibly represent carbonate build-ups along the hinge. Occurrence of medium to fine grained sandstone and shales deposited under inner shelf conditions in a lone well proximal to present day shoreline and total absence of this sequence in other wells strongly suggest that major part of the onland part possibly remained uplifted inhibiting marine transgression into the northern part of the onland basin.

As mentioned earlier, Eocene Hinge can be clearly identified through seismic data. Clear evidence of deep erosion into the upper part of the Eocene sequence is reflected in the form of uneven ographic surface and erosional channels and total absence of Oligocene section in both onland and shallow offshore part of the basin indicates a major Late Eocene-Oligocene marine regression from the basinal area. In contrast, there was widespread sedimentation during this period in the adjacent Bengal Basin. In the NEC area, the well NEC-1 located 40 km away from Mahanadi offshore well MND-2, encountered 567m of Oligocene. However, in deep offshore, Oligocene sediments seem to wedge out against Eocene shelf edge.

Crustal shortening initiated in Late Eocene – Oligocene continued into Early Miocene during the northward drift of the Indian plate and the consequent upliftment of Himalayas that initiated Gangetic sedimentation. Further upliftment of the Himalayas during Mid-Miocene caused Gangetic delta to dominate the sediment deposition in a significant part of eastern offshore viz.- Bengal, NEC, Mahanadi and northeastern part of Krishna-Godavari Basin. It also altered the course of the Brahamaputra River to join Ganges with a resultant spectacular increase in the rate of sedimentation into Bay of Bengal. The most prominent feature in Bay of Bengal i.e. Bengal Fan can be considered as the largest deep sea fan complex in the world with a length of 3000 Km. extending from the mouth of Ganges to Latitude 7 0 S in the Central Indian Ocean.

The significant increase in the sedimentation rate during Miocene and younger times had its own positive impact in terms of hydrocarbon exploration in the area. It initiated 'sediment induced tectonics' in these sequences.

Eocene Hinge Zone paralleling the coastline represents a prominent tectonic element in the area, providing slope with 10 – 2 0 dip at shelf-edge and 60 – 12 0 dip on the slope. Beyond the slope, it flattens out to 10-20 in the deep basinal area. This provided an excellent geological setting to carry the huge sediment loads into the deep offshore area. During sea level lowstands, sediments were delivered to the shelf edge initiating the formation of shelf edge deltas, levee-channel and basin floor fan complexes.

Initiated in Late Oligocene, a broad regressive cycle comprising successive periods of delta building followed through Miocene and Younger times. Frequent sea level fluctuations alternated the periods of transgression and progradation.

Seismic expression of both Upper Miocene and Pliocene sequences exhibits deltaic facies in the lower part while the upper part of the sequences exhibit deep canyon cut and fill features. The canyon cuts are steep sided, narrow to wide and at times 1-2 Km deep. These canyons have created locally deep-water conditions over the shelf. Channels within these canyons acted as conduits for transporting coarser clastic sediments into deep-water areas. As the canyons got filled up, they gradually came under shallow water environment. It is observed that those canyons fills, in general, are of fine clastics with some sands representing the channel facies within them. The cyclic nature of occurrence of shelfal canyon complexes clearly suggest periodic spurt in the fluvial energy coupled with sea level fluctuations.

Data from a few wells drilled in the above discussed sediment induced tectonic setting have indicated some very exciting hydrocarbon opportunities in the shelf and deep-water areas.

Petroleum System:.

The Geochemical Sniffer Surveys carried out by M/s INTEROCEAN of USA in part of the Mahanadi shallow water area in 1988 have revealed the presence of a number of Geochemical Sniffer anomalies. Basin modeling studies carried out by M/s BEICIP of France indicated presence of mature source rocks in some of the onshore depressions, suggesting similar possibilities in deeper parts of various depressions in the basin . Presence of organic mater has been reported in different sequences in some of the onshore and offshore wells. Temperature gradient in onshore and offshore wells is found to be >2.5 0 C/100 m . Presence of structural and stratigraphic traps and the above observations clearly indicate the hydrocarbon potential of the basin.

Significant hydrocarbon shows have been encountered in most of the exploratory wells drilled in the Mahanadi Offshore basin. Gas recovered during Formation Interval Testing (FIT) of Miocene sandstones and Eocene limestones in the well MND-2 contained significant proportions of higher hydrocarbons including iC4. In addition, specks of tarry matter were noticed in few sidewall cores from the Paleocene carbonate sequence of MND-2. Recently, six exploratory wells drilled in Block NEC-OSN-97/2 by RIL have proved to be gas bearing within Upper Miocene to Pliocene sequence.

A. SOURCE ROCK:

The onland well MON-2 drilled in the Cuttack Graben has a high content of TOC (upto 9.5%) in the Early Cretaceous sequence and the well MON-1 drilled in Paradip Depression has adequate TOC of more than 2% in the Miocene sequence. A total thickness of 960 m of source rocks have been encountered in the well MON-2 with an average potential of 7 Kg HC/ton rock (coal beds included). Most of the organic matter is of type II and III. Maturation in the Cuttack Graben was obtained around 2300 m depth. This indicates similar possibilities in the deeper parts of other depressions in the basin.

Source rock studies on drill cuttings and sidewall cores from the wells drilled in shallow offshore indicate presence of adequate organic matter (TOC 1.5-2.5%). TOC values of more than 3% also have been recorded in some samples. The organic matter within Paleogene sequence of well MND-2 has reached adequate maturity (Vro of 0.55 at about 2800 m and 0.65 at about 3300 m. In the well MND-7, organic matter within Paleocene and older sediments appear to be mature. This observation suggests that better source sediments can be present in the deeper parts of the basin. The organic matter in the Paleogene and older sequences in MND-5 and MND-6 shows marginal maturity. Additionally, Rock-Eval studies show that migratory hydrocarbons are present in the Miocene and older sediments of Mahanadi offshore wells.

B. RESERVOIR ROCKS:

Sandstone reservoir facies have been encountered in the wells drilled in Cuttack Depression in the onshore part of the basin. Average porosity in these sands is in the range of 15 to 25%. The inter-trappean sequences with associated fractured and weathered volcanic flows are also potential reservoir rocks.

The subsurface data in the shelf part of the basin suggest availability of good reservoir rocks within Early Miocene and older sediments. Porous and permeable sandstones and carbonates within Late Cretaceous, Paleogene and Early Miocene are the potential reservoir levels.

Reservoir sands within Channel/ Levee complexes of Pliocene and Pleistocene and Late Oligocene Wedge-outs against the Eocene Hinge in deep offshore part of the basin are also the potential reservoir targets.

C. CAP ROCKS

Presence of claystones and shales at different stratigraphic levels reported from the drilled wells are likely to provide cap rock in the basin and in particular a relatively thick sequence of Miocene comprised of claystones provides a good regional cap rock for hydrocarbon accumulation.

D. ENTRAPMENT/ TRAP TYPES

Structural And Fault Related Traps In Syn-Rift Cretaceous Sediments:

Presence of coarse-grained sandstones in the synrift Cretaceous sequence coupled with availability of source facies within this sequence can be a very potential situation for hosting hydrocarbons. The potential traps may be sealed vertically by Paleocene / Eocene shales. Complex development of this sequence has brought out diverse potential situations- local faulted anticlines, fault related structures and positive erosional features over the Cretaceous surface .

Paleocene-Eocene Carbonate Buildups And Sand Bodies:

Carbonate buildups can be envisaged along/over the Eocene hinge. It is observed that the carbonate bodies show distinctly less internal reflections in comparison to the surrounding sequences. Faults within the underlying Cretaceous and Paleocene sequences can act as effective migration pathways.

Paleocene To Miocene Wedgeouts And Pinchouts:
The 85 deg East Ridge to the southwest acts as a barrier onto which Paleocene, Eocene, Oligocene and Miocene sediments onlap and can have entrapment potential. These units may consist of thin sands, carbonates and shales terminating against the Ridge. The eastward basinal tilt in post Late Cretaceous could have facilitated hydrocarbon migration northwest from the basinal depocenters. Oligocene Wedgeouts against the Eocene hinge can also have entrapment potential.

Submarine Canyon And Turbidite Fan Systems:
Submarine canyon and turbidite fan Systems are more characteristic of Pliocene-Pleistocene sequences with slope failures caused by significant increase of sediment input into the basin. Canyon fills can be interpreted as the Ganges delta builds into the basin or as sediment forced during a highstand as the sediment supply outpaces the accommodation space. Channel sands within the Canyons also can have potential entrapment conditions.

Thus, Mahanadi Basin- onshore and most significantly the offshore part is endowed with a good combination of source and reservoir facies with potential entrapment situations. The deep offshore part of the basin with the characteristic sediment induced tectonics coupled with the envisaged good reservoir and source facies holds high promise for challenge loving explorationists. Similar geological situations in the neighboring Krishna- Godavari Basin already started paying rich dividends to the explorationists.