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Depositional elements of Mahanadi deep water sediments

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Keywords

Depositional elements, Channel-levee complex, channel architecture, Crevasse splay, MTC

Abstract

A few gas discoveries have been established in the Mio-Pliocene and Paleogene sedimentary succession in deep-water set up of Mahanadi Basin in the East coast of India. These discoveries are mostly restricted to the channel-levee complexes barring a few deep-water fan system. A detail understanding of reservoir characteristics in time and space is essential to develop these fields and is considered as a great challenge for the geoscientific community. Considering this aspect, the present study has focused on understanding the intricacies of the Mahanadi deep-water depositional elements and its characteristics.

Different depositional units have been analysed on the basis of seismic reflectors and seismofacies characteristics which is integrated with electro-logs for better understanding of the depositional elements. Seismic data in 2D and 3D have been utilized to decipher the internal complexities of these units.

The depositional elements which have been studied include channel levee complexes, frontal splays, crevasse splays, fans/lobes, flood plain deposits and mass transport complexes. Out of these elements, Channel Levee Complexes have been focused by explorationists as the major play with fan system as a future play to be established.

The study in totality has brought the depositional intricacies in a holistic manner and recommended to put enough efforts to understand the reservoir behavior in future developments.

Introduction

Mahanadi Basin which is one of the passive margin basins in the East coast of India, is fed by Greater Mahanadi and Ganga-Brahmaputra drainage system. The geological set up of this basin has been brought out by various geo-scientific data including drilling of more than 40 wells distributed in onland, shelf-slope and deep water sedimentary regime. The well gridded 2D seismics, extensive 3D seismics and the drilled wells unraveled the complexities related to sedimentary depositional architecture and the hydrocarbon habitat. The recent success in establishing gas reserve in Mahanadi deep-water by ONGC, although sub-economic at present gas price, has encouraged the explorationists to understand the intricacies of the depositional dynamics to add more reserve to convert it as an asset in near future. The gas bearing sediments represent the part of various depositional systems, mainly, channel-levee complex, slope-fan complex, basin-floor fans, mass transport complex, various type of splays etc.

With the above background, the present study has been focused to identify and understand the internal depositional architecture of various depositional systems in a spatio-temporal framework. This study also documents the analysis of depositional elements associated with deep-water channel systems on Mahanadi continental slope within the study area. These systems can be traced from initiation point to the point beyond which those have been fanned out.

Study Area

Mahanadi Basin is situated in the northern part of the East Coast of India and is bounded by the Bengal Basin in the NE and Krishna-Godavari in the SW (Fig-1) and owes her origin to the extensional tectonics. The area under study includes 39000 sq.km area in the slope and deep basinal part covered by 2D and 3D seismics. The basement configuration of the basin has been brought out by gravity-magnetic, aeromagnetic, seismic and DSS surveys. The basin morphology near onshore to shallow offshore reveals ENE-WSW trending horst and Graben features in the western and central part of the basin that become NE-SW in the northern part. The interplay of NNW-SSE Gondwana trend, ENE-WSW and NE-SW Eastern Ghat trend and their reactivation resulted the present day tectonic set up of the basin.

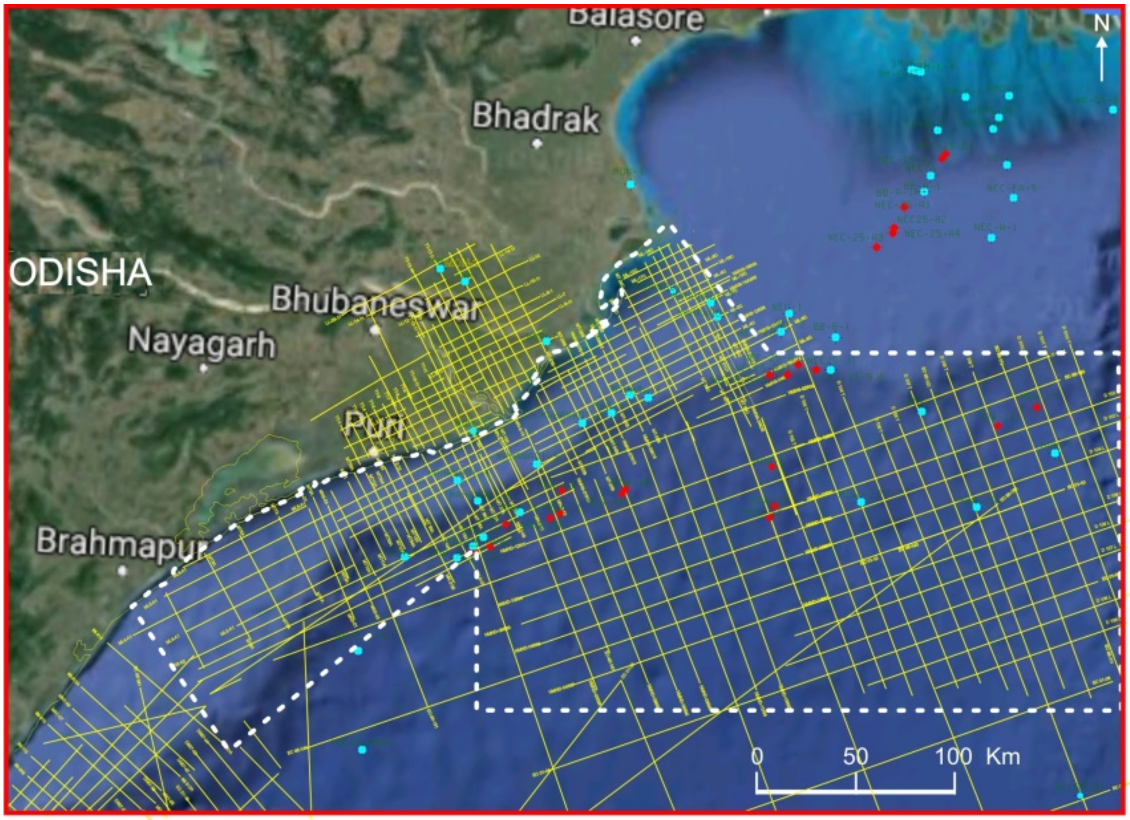


Fig-1: Satellite imagery with 2D coverage and wells. White dashed line showing study area in Mahanadi offshore. Red dots for gas wells and sky blue for dry wells.

Stratigraphy

Basement configuration in the deep-water Mahanadi is quite subjective because of the limitation of the seismic data. The last co-relatable and continuous reflector is the Early Cretaceous top. Late Cretaceous sediments overlie unconformably on the Early-Cretaceous top. Paleocene sequence shows mostly similar characteristics with that of Late-Cretaceous strata in the section. The thickness of the sediments is more towards the basin and near the slope-rise indicating the character of passive margin basin. This can also be explained by the phenomenon of slope-fan systems and deep water fans. Eocene displays thick sediment sequence in the basinal part and aggradations in the shelfal part. Near the shelf and upper slope areas the carbonate deposits and their derivative debris formed the prominent lithology while in the deep basin mixed clastic-carbonate and pelagic mud are present. The Oligocene sediments form a thin layer over the Eocene and they pinch out as onlaps on the underlying Eocene sediments in the slope area and is absent on the shelf. Neogene period marks the significant sediment input from the Ganga-Brahmaputra River System which forms a thick sediment stratum in the deep basin. Channel-levee complexes and other associated depositional elements are dominant in Neogene. The thickness of Pliocene and Recent sediments is more on the shelf and it decreases towards the slope and basinal part. Stratigraphy of Mahanadi basin in Table-I and stratigraphic correlation of different gas bearing wells on the basis of logs and lithology are presented in Fig 2.

TABLE-I

STRATIGRAPHY OF MAHANADI OFFSHORE BASIN

TIME	EVENTS	LITHOLOGY
Pliestocene to Recent	9. Progradation of clastic sediments with no subsidence.	Slope channels and canyons
Mio-Pliocene	8. Subsidence and progradation of clastic sediments	Slope channels,canyons and basin floor fans
Oligocene	7. Period of non-deposition or erosion	Absent on the shelf. Present in the deep basin.
Eocene	6. Developed shelf-slope break with further tilt towards east. 5. Collision of Indian plate with Asian plate.	Transgressive clastic starved sequence.
Paleocene	4. Drifting continued with basinal tilt and shelf-slope development.	Deltaic sedimentation through protoMahanadi
Late Cretaceous	3. Drifting continued with basinal tilt towards E with initiation of shelf-slope.	Sand in the upper and shale in lower part
Early Cretaceous-Late Jurassic	2. Rajmahal trap volcanism. 1. Rifting followed by drifting.	Rift fill sequence followed by volcanics
PreCambrian	Pre-rifting	Basement

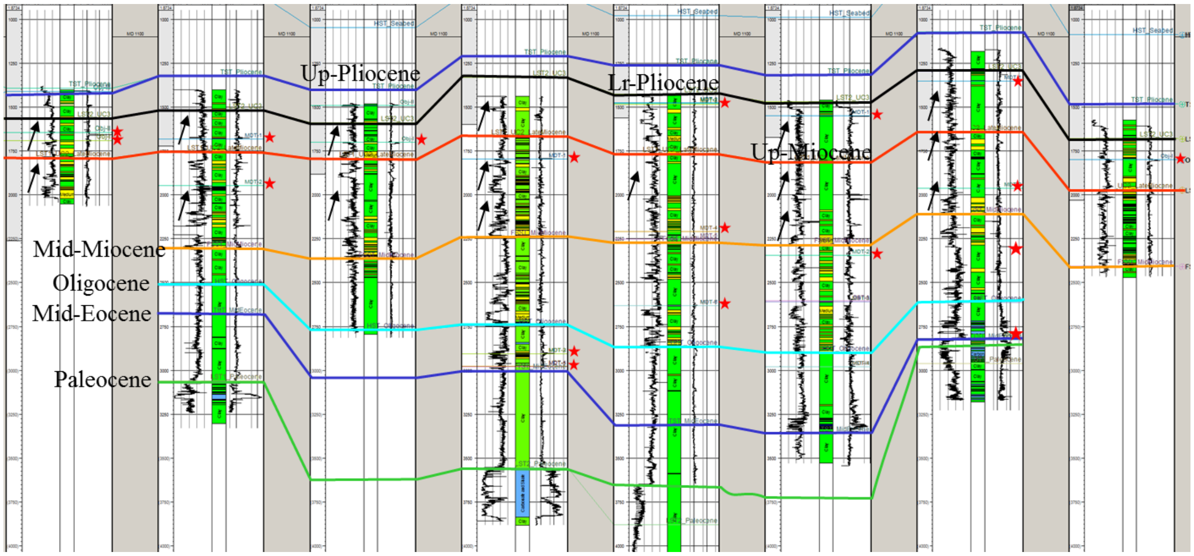


Fig- 2: Stratigraphic correlation of different wells on the basis of electrologs and lithology of different wells in the study area. Red stars are gas shows and arrows indicate the finning upward packages.

Methodology

The study area is mainly composed of a flood plain basin intercepted mainly by stacked channel levee complexes and occasionally splays and slope fan systems. The smallest unit of internal geometries and scales observed within channel fill deposits, levee, splays etc. are considered as depositional elements or architectural elements.

Different seismic attribute cubes are generated to extract seismic probes at different time intervals for identification of architectural elements. Out of all these, only RMS is presented here as window based attribute extraction. The entire volume comprising of 3000ms of sediments have been dissected by more than 150 windows with the help of proportional slicing and attributes are extracted within 20ms windows. Stratal stacking patterns, lithology and electro-log signatures are used for construction of depositional history of those architectural elements.

Correlation of specific time windows encompassing most of the pay zones have been carried out and extended in the study area. Most of the gas bearing intervals in Mio-Pliocene is present in different channel sands at different depths within Miocene. For correlation of the gas bearing intervals small windows of 10 to 20ms each are made along with proportional slices and corresponding attribute maps have been generated. Results of these attribute maps show extreme heterogenity and discontinuity in terms of hydrocarbon pools. Seismic facies along the total transect from shelf to deeper basin have been studied for identification of depositional elements and respective environment of deposition (Figs: 3 - 12).

Data

Studied interval in the 3D seismic is from seafloor to approx. 3000m, the zone of good seismic resolution. Analysis of seismic facies and seismic geomorphology are important tools for the study of depositional elements in subsurface. Ten types of seismic facies are identified to be present from shelf to slope and are detailed here. No structural grain is present in this interval. Lithologies are inferred from various data of wells and analysis is extended towards undrilled part.

Seismo-facies-1 (Fig-3) occurs after the shelf break and typified by discontinuous, high to moderate amplitude, parallel to sub-parallel, occasionally mounded reflections contained within cup or U shaped reflections indicating erosional channels.

Seismo-facies -2 (Fig-4) represents channel-levee architecture with levee denoted by birds-wing shaped reflections and channel by high amplitude, discontinuous, sub-parallel reflectors encased within levees.

Seismo-facies-3 (Fig-5) shows low amplitude semi-transparent prograding clinoforms indicating high rate of sediment influx compared to accommodation space generated by sea-level fluctuation and ideally present near the shelf break.

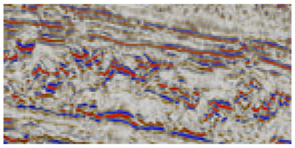


Fig-3 Seismic facies showing erosional channels on ILN.

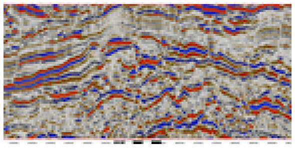


Fig-4 Constructional CLC on XLN

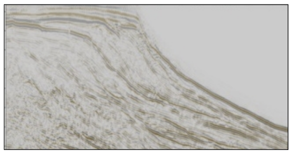


Fig-5: Seismic facies near shelf to slope break showing progradation

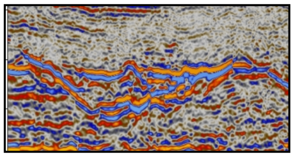


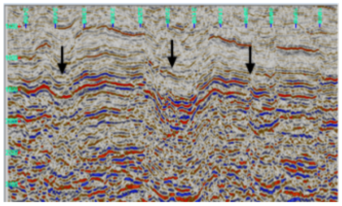
Fig-6: Seismic facies showing canyon-fill on Trace on the slope part of basin

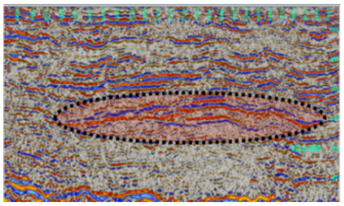
Seismo-facies-4 (Fig-6) contains V or U shaped erosional cuts filled with discontinuous, subparallel, chaotic and very high amplitude reflections indicating canyon fill sediments.

Seismo-facies-5 (Fig-7) is observed on shelf showing V or U shaped cuts filled with high amplitude, parallel to sub-parallel discontinuous reflections.

Seismo-facies -6 (Fig-8) is present in the deeper slope part of the area showing bi-directionally dipping, high amplitude and parallel to sub-parallel reflection pattern of slope fan.

Seismo-facies -7 (Fig-9) represents parallel reflectors. This is characterised by moderate to low amplitude, parallel to sub-parallel and mod to good continuity reflectors. This indicates aggradation of sediments.





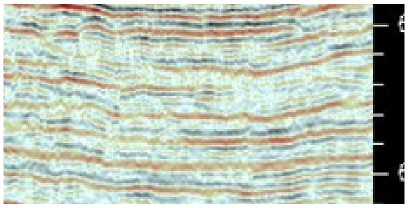


Fig-9: Parallel reflectors indicating aggradation of sediments

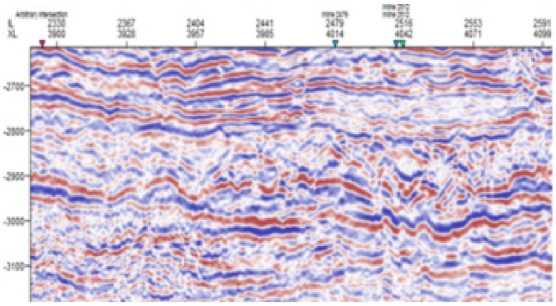


Fig-10: Chaotic reflectors in MTC

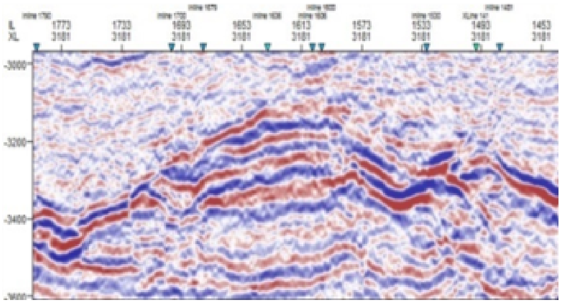


Fig-11: Seismic facies of remnant feature

Seismo-facies-9 (Fig.10) is characterized by chaotic reflectors of mass transport complex.

Seismo-facies-10 (Fig.11) represents the remnant feature. Reflectors are of high amplitude, discontinuous, sub-parallel, mounded and surrounded by transparent facies.

Depositional Elements

Deeply incised channel ways are the main transportation paths for sediments entering into the basin to form different depositional elements. Seven depositional elements viz channels, levees, crevasse splay, mass transport complex, slope fans, frontal splays and flood plain are identified from the seismic reflection pattern, electrolog signatures and also drilling data from shelf through slope to deep basin in the study area. Exploration of this basin has proved the presence of gas in channels and associated depositional elements. The gas bearing intervals mainly belong to channel levee complexes within Neogene and in a few cases slope fans within Paleogene.

Accommodation space on shelf edge and base level fluctuations together play the major role in determining the storage capacity and sediment delivery system. Consequently, reservoir stacking patterns in slope and basin floor environments are directly related to shelf edge accommodation (base level) and sediment supply (Beaubouef et al., 1999; Beaubouef et al., 2000a; Beaubouef and Friedmann, 2000). More continuous, river-fed sediment delivery (i.e., directly from incised valleys into the heads of canyons at lowstand) is more likely to generate turbidity currents. More episodic, catastrophic, delta-failure related sediment delivery is more likely to generate debris flows. These two fundamentally different flow types lead to very different reservoir properties like channels and fans (Sprague, A.R.G.1, Garfield, T.R.et.al, CIPM, 2005). Gradient of the sea floor and confinement by channel ways together control the patterns of sediment dispersal and hence reservoir architecture. The lateral and vertical distribution of the depositional facies is the basis for significant depositional elements analysed here.

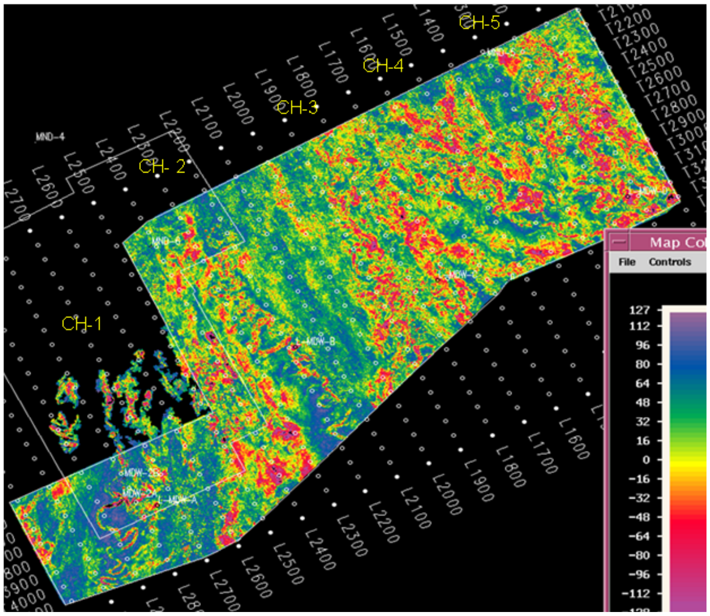


Fig-12 RMS map extracted within 40ms window within Upper Miocene showing five channel belts separated by flood plains.

i) Channel-Levee Complex (CLC)

Channel-Levee Complex is the major depositional element in Neogene period and most of the discovered gas bearing zones lies in this complex. This Channel-Levee Complex (CLC) is stratigraphically confined and the incised sediment conduit is flanked by outer levees (Fig.12). This is the primary conduit for transportation of sediment entering the basin. Five channel levee complexes have been identified from west to east within this sequence as observed in the RMS map (Fig-12). Amplitude variation along the course of the channel in the map may be attributed to different facies or variation of grain sizes of channel fill sediments.

Stacked CLCs suggest multiple episodes of cut-and-fill features. Discrete high-amplitude reflections at the base of the CLCs represent channel-fill elements. Levees and flood plains show lower-amplitude thereby demarcating a clear division between channel cuts surrounded by levees and flood plains. With decrease in energy, CLCs get fan out forming mound shaped

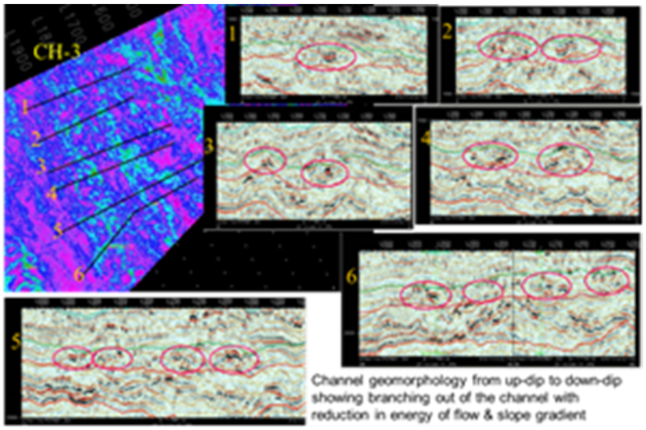


Fig-13: Channel geomorphology from updip to downdip showing branching out of the channels with reduction in energy of flow and slope gradient. Red circles indicate channel positions.

deposits. Spill-over is noticed towards the basin-ward side from where bifurcation or trifurcation starts before getting fanned out on the basin floor (Fig-13).

Channel morphology has been controlled by gradient of the sea floor, nature of bed rock, volumes of sediments and lithology. Seismic signatures of channels may vary from shingled to laterally migrated reflection pattern, lateral migration with stacking and entirely vertical stacking fill pattern. This variation in reflection pattern indicates extreme heterogenity of channel fills. Due to these complexities channel-fill lithofacies and grain size distribution are highly variable and reservoir-performance can vary laterally and vertically within a reservoir unit. In a primary channel different stories or compartments of secondary channels with variation in reflection pattern as mentioned earlier have probably added heterogenity in hydrodynamic condition as observed in the drilling results of these channels. Stories of secondary channels (Sprague. et al, 2002) are stacked together within the primary channel and migration of channels is reflected by the inclined and parallel channel traces (Fig-14). This channel complex is 1.6 km wide and 300m thick. Other channel complexes present in this area vary in width from 500m to 1500m and 50m to 150m in thickness.

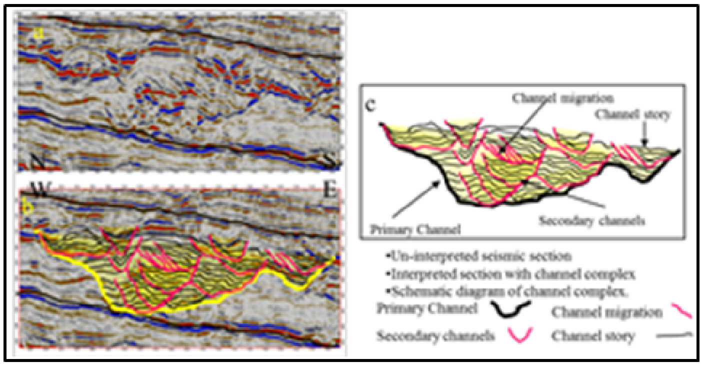


Fig-14 Channel architecture showing stories of channels housed within primary channel. Both lateral aggradation with migration and vertical aggradation observed in secondary channels (after Datta.et.al, 2013).

In SpecD map at 22 Hz the channels clearly show sinuous form with lateral migration, scrolling of point bars, cut-off etc (Fig-15) through the process of channel evolution. Thread like impressions is observed in the point bar migration which occurs with the change in course of the channel. In AAA map prepared within 40ms window (Fig-13), the blue areas (lower amplitude) are interpreted to be argillaceous sediments and the areas of hotter colours to be arenaceous (Fig-12 & 13). Electrologs with lithology of a drilled well are superimposed on a seismic (Fig-16) suggesting the vertical stacking of the channel-levee system.

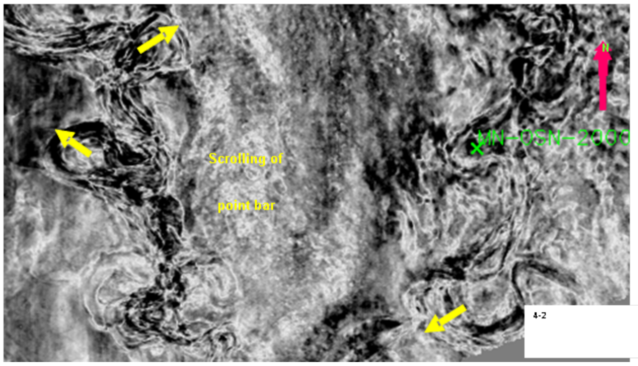


Fig-15: Scrolling of point bars within meandering channels shown by yellow arrows on Tuning map at 22Hz.

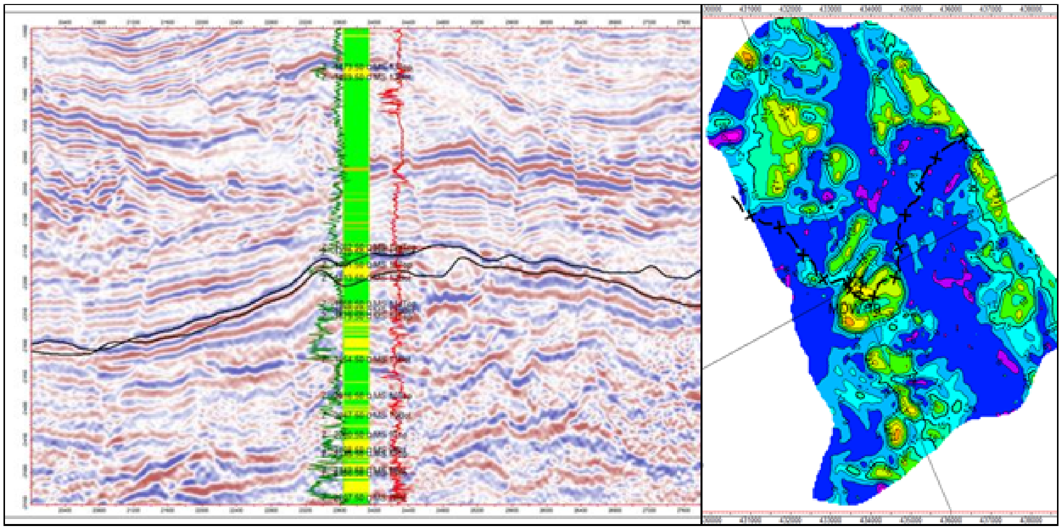


Fig-16: On the left Litho-logs and electro-logs superimposed on seismic with two tracked surfaces. On the right Time thickness map between those two surfaces showing meandering channel.

From the bell shaped feature of the log and sand-clay alternations, the top and bottom of a channel have been tracked in the volume and mapped accordingly. The time thickness map between these two surfaces revealed the meandering channel as seen in the Fig-16. TWT thickness maps of CLC-1 and CLC-2 in Fig-17 show their orientation in NE-SW direction suggesting the paleo-flow direction of sediment input from NE through Ganges-Bramhaputra river system which has influenced the depositional system of Mahanadi Basin. However, these are the elements found to be gas bearing and identification of such elements in a vertically stacked pattern in a single well may be commercial.

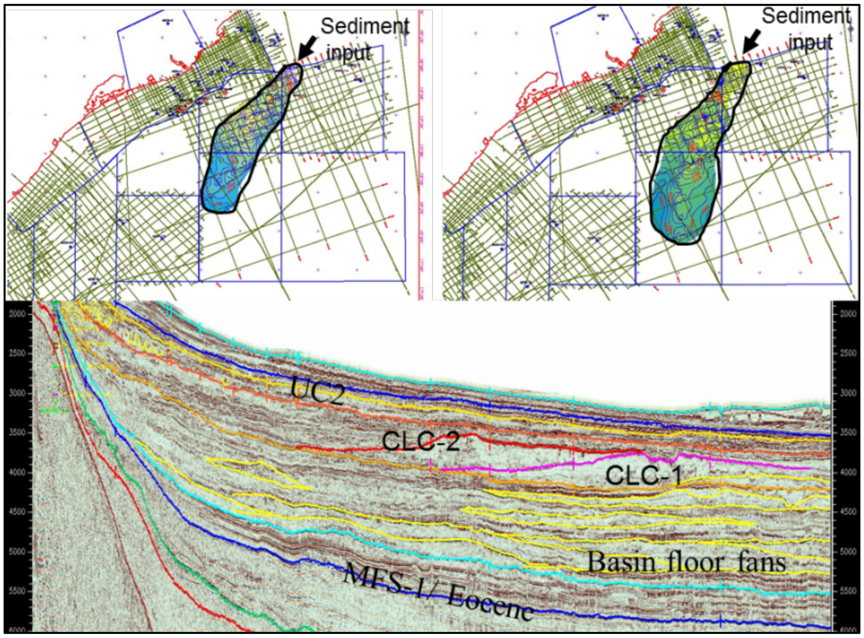


Fig-17: TWT maps of CLC-1 & CLC-2 (Right-CLC-1, left-CLC-2). The channel entry from NE through Ganges-Bramhaputra River shows the lateral shifting of the CLCs.

ii) Frontal splay

A process of spilling over from a confined to unconfined system causes mound shaped deposits. This avulsion may occur either due to progressive lowering of levee heights down the system or by occasional flooding. The decrease in levee heights may be attributed to the decrease in sand percentage down the system. The high density part of the flow eventually breaks through the levee splaying out in a braided pattern or dumped as mouth lobes leading to the formation of frontal splays (Fig-19).

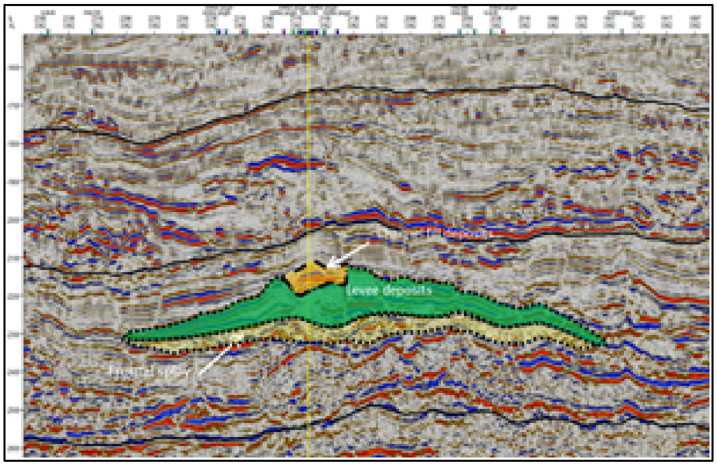


Fig-18: Channel-levee with frontal splay deposits. (After Datta et.al, 2012)

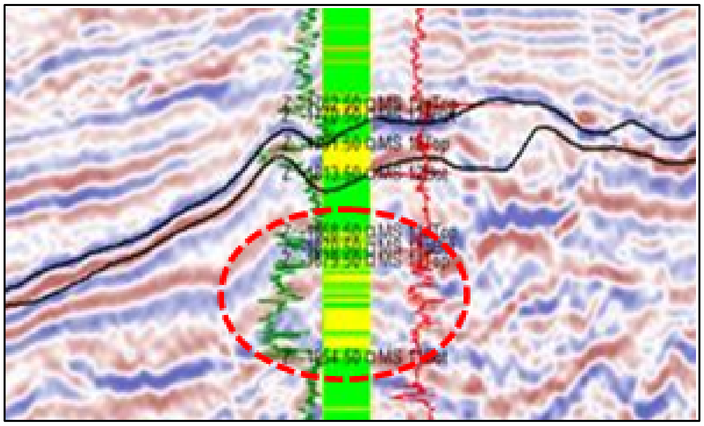


Fig-19 Zoomed Seismic signature of Frontal splay (marked by red circle) superimposed with logs and lithology showing finning upward sandy package in the well.

iii) Levee/Overbank

Levees are identified with the constructional channels in Neogene section. Levee-overbank deposits constitute large volumes of the sediments in mud-rich and mixed mud-sand rich systems and parallel to the trends of channels having extensive areal distribution laterally away from the channel. Levees drilled in the study area suggest thinly laminated sand and clay facies with more sand towards proximal part and more clay towards distal part. The seismic probe shows the meandering channel confined by levees on both sides (Fig-20). Wells drilled in channel and associated levee facies are presented here in Fig 20a. Well-A on the channel and Well-B on levee are both gas bearing. But this does not mean that channels and levees are always connected hydrodynamically.

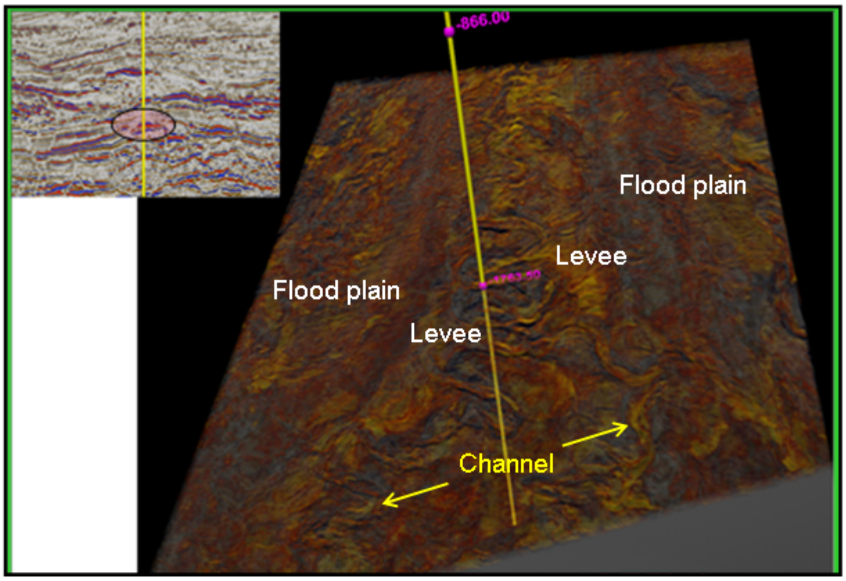


Fig-20 Seismic probe at Upper Miocene showing gas bearing meandering channel with levee. Yellow stick showing position of the well. Levee follows the course of the channel.

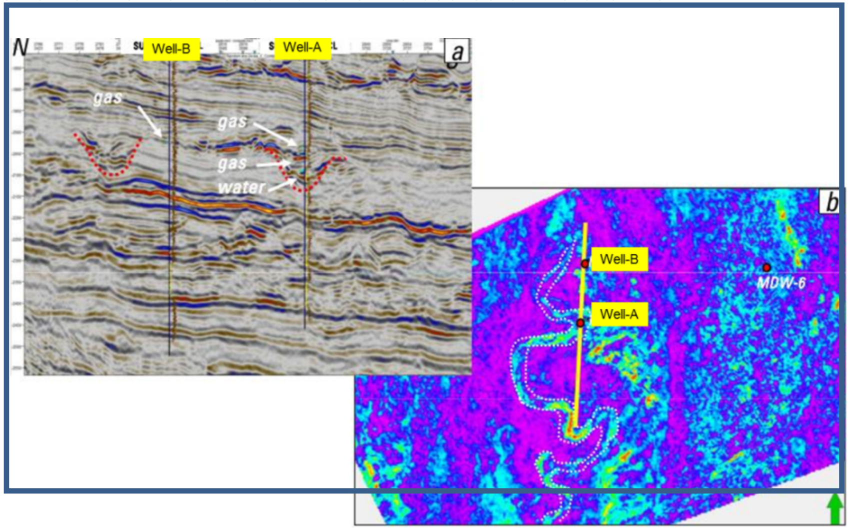


Fig-20a. **(a)** Seismic section with gas bearing Well-A drilled through a channel and Well-B through the levee. **(b)** Attribute map showing meandering channel with Well-A and B. Yellow line through the wells representing the position of seismic section.

iv) Crevasse-splay Complex

Crevasse splay complex is formed by the breaching of levee through spilling over of channels during flood or any other episodic high flows. A network of channels forms and produces sheet like sand rich deposits as crevasse splay. Both the seismic expression and corresponding attribute map of crevasse splay have been presented here in Fig-21a & 21b.

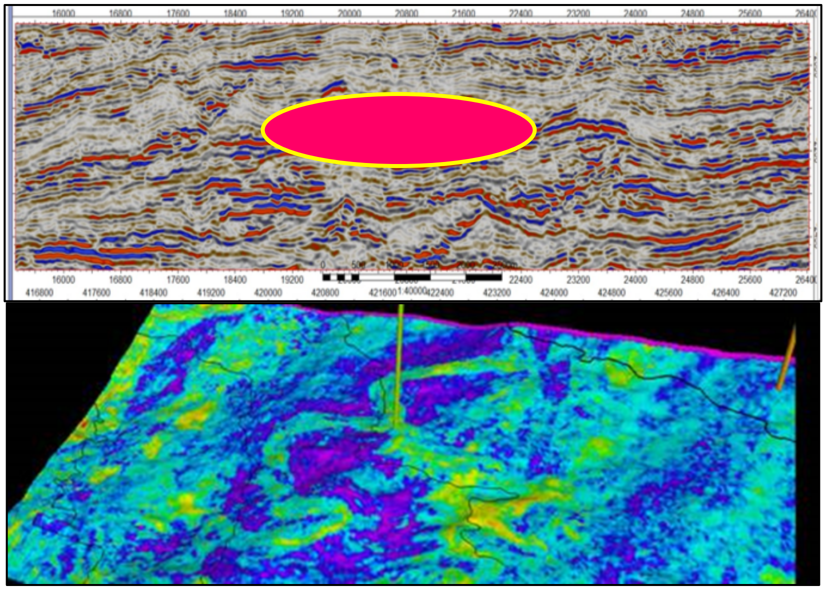


Fig21a Attribute map with seismic showing crevasse splay.

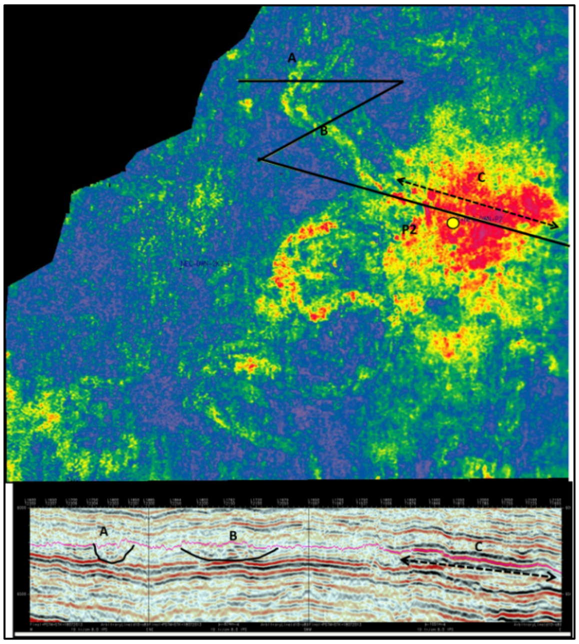


Fig-21b RMS amplitude map showing crevasse splay with seismic section as reconstructed line through it. In the seismic section C represents the splay by high amplitude standout.

v) Deepwater Fans and Lobes

Fluvial sediments that bypass the shelf through incised valleys and are transported to the deep down the basin through submarine canyons/ channels form the deep-water fan.

Seismic reflectors in a 3D volume have been tracked and attribute maps are extracted within those tracked horizons which suggest the geomorphic feature as a basin-floor fan. One representative RMS map has been presented to show the deep water fan (Fig-23). The distribution of sands as indicated by the hotter colour on the map suggests hydrocarbon reservoirs in a deep-water setting. This fan system indicates the input from NW to SE which may be attributed to the Ganga-Bramhaputra River system during Oigocene period. This deep-water fan system

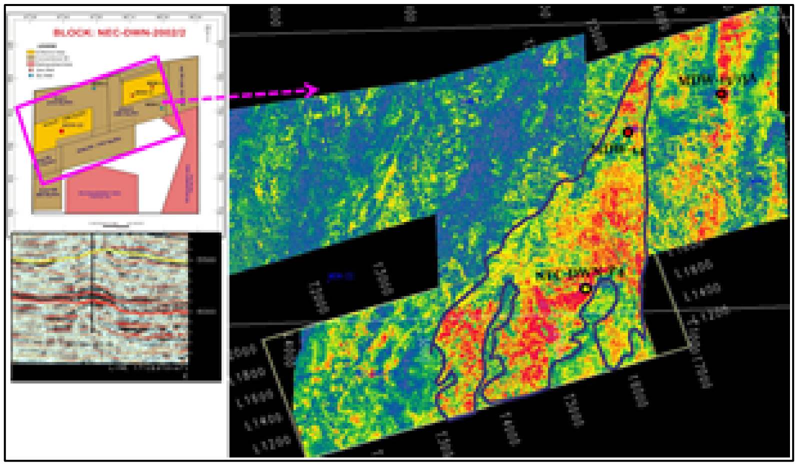


Fig-23 Basin floor fan in Mahanadi basin

may also have included turbidity flow leveed channels, overbank deposits, splays, distributary-channel complexes, lobes, channels etc. Basin floor fans are associated with Low-stand Systems Tract and are expected to be the most sand rich portion of the reservoir.

vi) Mass Transport Complex (MTC)

MTCs are observed at different intervals in the study area indicating occurrences of several catastrophic events in the geological past. Sudden catastrophic events like tsunami, cyclone, earthquake trigger the movement of unstable sediments on subaqueous slopes which move down as unconsolidated and extremely ill-sorted sediments to the deep basinal side. This unsorted sediment mass , known as Mass Transport Complexes vary in scale from cubic meters to cubic kilometers. In general, an earthquake triggers a massive slumping and stirring of sedimentary material. Mixed with seawater, a dense liquid mass forms, giving rise to a density current that flows down at speeds of several tens of kilometers per hour.

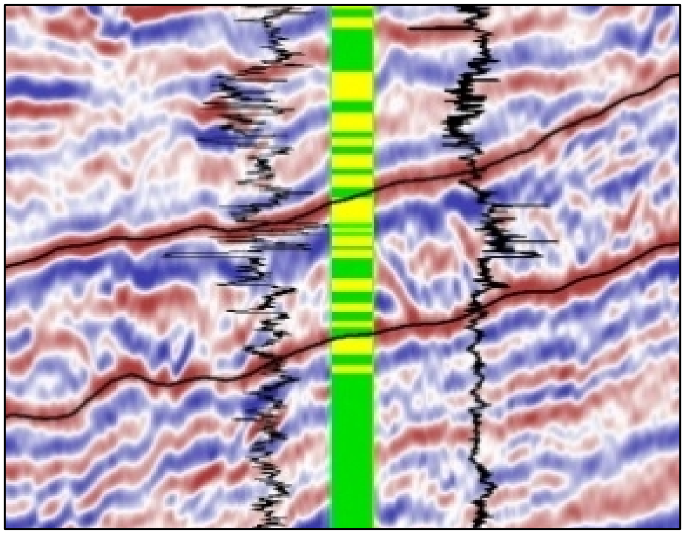


Fig-24: Seismic signature of MTC superimposed with lithology and electro-log. It is bounded by unconformity surfaces at top and bottom. Well drilled through MTC indicates presence of thick sandstone beds.

Fig-25: RMS attribute map with along with seismic section showing distribution of MTC.
MTC is very important depositional element in petroleum exploration in deep-water set up and requires detailed study as it puts a great hazard during drilling. Moreover, the understanding of hydrocarbon entrapment in MTC requires special attention and study for getting a success.

vii) Flood Plain Deposits

Areally extensive flood plains are well-recognised in the seismic attribute map at various stratigraphic intervals of Mahanadi Basin. The flood plain deposits primarily consist of structureless claystone with occasional channel belts of mixed lithology like sand, silt and clay. This flood plain which is dominated by finer clastics can act as both source and seal for hydrocarbon. All channels either confined or unconfined are separated by wider flood plain. In seismic either parallel high amplitude reflectors or transparent one indicate flood plain deposits. The RMS map indicates channel belts by hotter colour like red, yellow etc and flood plain by softer colour like blue with yellow patches (Fig-26).

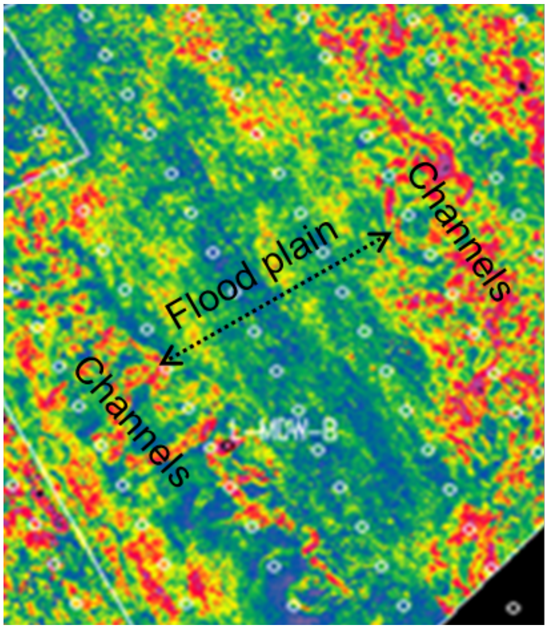


FIG-26: RMS map showing flood plain deposits between two channel belts

Conclusion

Mahanadi basin is composed of a laterally and vertically heterogeneous package of flood plain basin intercepted by discontinuous channels during the Mid Miocene to the early Pliocene time. Flood plain basin filled with claystone is the main depositional element in terms of volume and spread. Individual channels are seismically mappable units with a characteristic seismic response. The seismic facies and electro-log facies with lithology of wells suggest depositional environment. Attribute maps provide the information about sediment distribution pattern and prediction of facies away from the well bores. Both vertical sections and maps of depositional elements suggest laterally accreted channels as the reservoir with highest sand-mud ratio and vertically accreted channels with low to medium sand-mud ratio and hydrodynamically dis-connected to each other. Crevasse splay and deepwater fans suggest better reservoir size and quality. The depositional elements like MTCs and Levees are mainly of low net to gross and are less important from reservoir point of view, though proximal levees can also act as the reservoir. Information about deepwater depositional elements analysed and presented here provide the understanding of deepwater sedimentation and the fundamental controls on sediment distribution beyond the shelf edge to successfully predict reservoir properties. This study of depositional elements may lead to risk mitigation for the development of field in deepwater setup and is well applicable in Mahanadi deepwater.

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