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Research Paper

Paleogene and Neogene Cyclic Carbonate Deposition in Western Continental Shelf of India and its implications for the hydrocarbon migration and accumulation in Mumbai Offshore Basin

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Abstract
Mumbai Offshore Basin is the most prolific hydrocarbon producer with Mumbai High, the supergiant oil field as its central structure harboring huge volumes of hydrocarbons in the multi layered Miocene carbonates. Large number of satellite structures have also developed multi layered Eocene and Oligocene carbonates with prolific hydrocarbon production. Cyclic carbonate sedimentation under two mega cycles during Paleogene and Neogene period has resulted into these world class oil and gas reservoirs. The paper analyses various facets of the cyclic carbonate sedimentation in the basin and attempts to define the geometry and depositional pattern, spatio-temporal variability, correlation with their surface analogues along with its genetic relationship with the evolving structural fabric of the basin. Implications for the hydrocarbon migration and accumulation is also genetically correlated.

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I. Introduction

Western Indian continental shelf constitutes a typical Passive Margin set upwith well-defined structural configuration having a wide shelf area and three basins developing its strike namely, Kautch-Saurastra in the north, Mumbai Offshore Basin in the central and Kerala-Konkan in the south (**Figure 1**). It evolved through a long and stable geological history under tropical latitudes throughout Paleogene and Neogene periods, exhibits multicyclic sedimentation processes with alternating Carbonate and Clastic deposition. Carbonate factory developing in Early Eocene has brought huge volumes of Carbonate sediments distributed over the entire shelf in cyclic impulses which is imprinted in form of resultant lithostratigraphic units across the basin. The magnitude and time span of the carbonate production cycles have primarily controlled the individual units. Concurrent activity of the terrestrial drainage system and clastic supply flow into the Arabian Sea (**Figure-2**) has influenced the distribution of clastic - carbonate interface in time and space and has also governed the mixing of two lithologies. The Eustatic and relative sea level changes driven by the tectonic activity in the basin have defined the accommodation space and sedimentation rates and thus carved out a unique Chronostratigraphic framework in the basin. Different structural blocks in the Mumbai Offshore Basin have varying combination of the magnitude of tectonic impulses vis-à-vis depositional energy changes and proximity to the provenance, which has resulted in to a complex Lithostratigraphic variation in the basin from one block to the other. Depending upon the water depth changes and Carbonate-Clastic sediment supply balance, and rate of changes in the accommodation space 3D geometries of the respective carbonate units have been defined. The associated petrophysical and lithofacies varying from Mudstone-Wackestone-Packstone-Grainstone and bioclastic assemblages have evolved with typical facies transition trends.

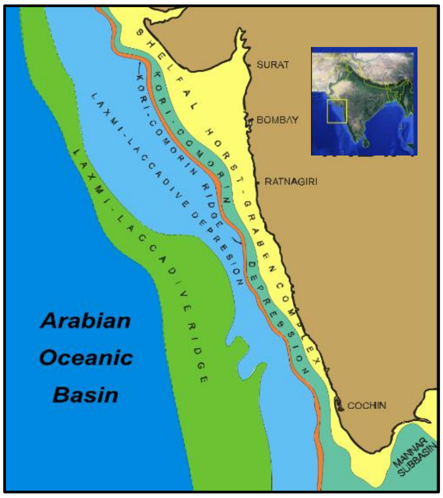


Figure-1 Tectonic Map of western continental Shelf showing major structural blocks (After Biswas et.al 1988)

Figure-2 Bathymetry Map of Cambay Gulf area, western continental Shelf showing schematic sediment dispersal pattern in tidal deltaic set up (Background Image: Google earth; Imagery@2020 CNES/ Airbus, Maxar Technologies

Genetically, two first order Mega Sequences representing the Rift Phase and Passive Margin Extension Phase are developed in the Basin over the Deccan Trap Basalts acting as the Basin Floor (**Figure 3**). At some Paleo highs like Mumbai High, Heera and some isolated highs, Granitic / Metamorphic Basement is present as the depositional floor as Basalt flooding did not cover these Paleo highs. Embedded in these two Mega sequences, two major Carbonate Cycles are developed. One representing the start of the Carbonate factory in the Early Eocene and spanning to Early Oligocene period and define the Devgarh-Bassein-MuktaLithostratigraphic assemblage, informally named as Paleogene Carbonate Cycle. It harbors the largest hydrocarbon volume in the basin, outside Mumbai High. The second major cycle spans from Early Miocene to Middle Miocene comprising the Bombay and Bandra Formations, informally named as Neogene Carbonate Cycle (**Figure 4**) and it constitutes the major hydrocarbonreservoirs over Mumbai High, the sole super giant oil field in the Basin. The period during major part of the Oligocene is marked by the transgressive phase with oscillatory cyclic changes in the relative sea level in the basin and resultant alternations of the thinner carbonate layers embedded in the dominant shale , silt and marls of Heera, Daman, Alibag and Panvel Formations. Schematic section across the Panna-Bassein-Heera Block (figure 4) depict the lateral and vertical expanse of the Eocene and Miocene Carbonate cycles covering several oil and gas fields within Eocene Carbonates. There is marked transition to the Clastic facies towards north in Miocene Carbonate Cycle which clearly indicate the increasing clastic influence in Miocene time. Post Middle Miocene period is marked by the sharp rise in the relative sea level as well as increased supply of the clastics in the basin, which drowned the Carbonate Factory and resulted in the dominant finer clastics of Tapti and Chinchini Formations. However, in the northern part of the basin in Tapti-Daman block, this period is marked by arenaceous facies due to the proximity of the provenance and inherent increased clastic supply under higher energy depositional conditions.

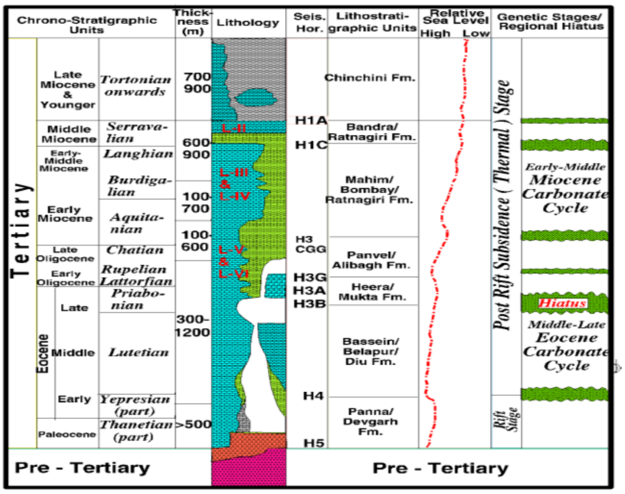


Figure-3 Tertiary Lithostratigraphic Chart of Mumbai High Are, Mumbai Offshore Basin showing the depositional cyclicity and seismic horizons (Verma NK et al, 2002)

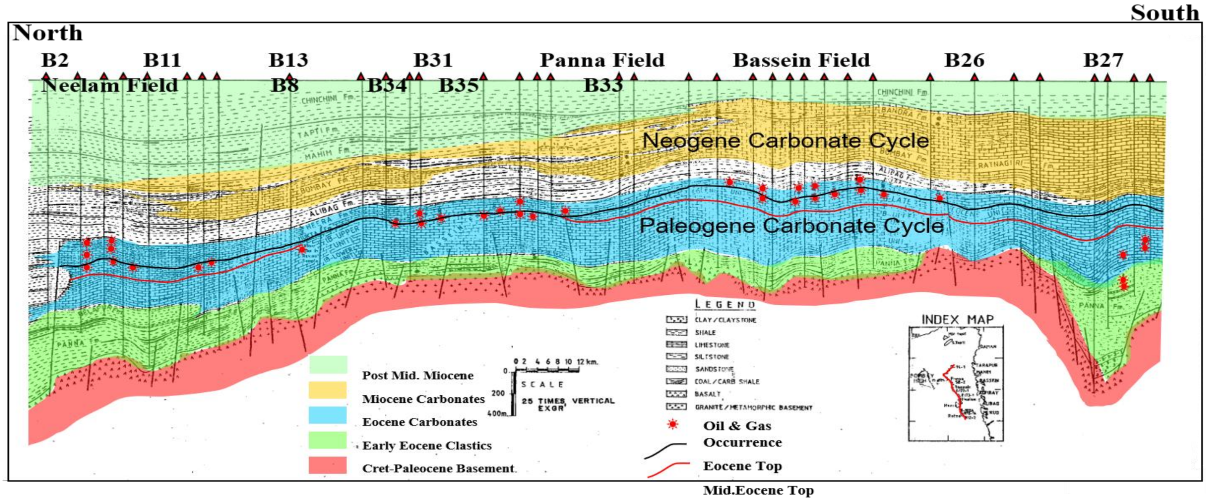


Figure-4Schematic North- Soth Geological section across Mumbai Offshore Basin showing the Paleogene and Neogene Carbonate Cycles

Paleogene and Neogene Carbonate cycles described above are in fact composite cycles with second and third order cycles developed within them mimicking the sea level changes happening during the period (Figure 5). For example, the Paleogene Cycle has three second order cycles namely Devgarh, Bassein and Mukta, with cumulative thickness varying from 300-1200 m in various parts of the basin. Chronologically it starts with the first marine transgression during Early Eocene at around 55 ma in the deeper parts of the basin like Murud Depression and outer shelf areas. It culminates at the close of Mukta sedimentation in Early Oligocene with H3B/H3A unconformity at around 33.9 ma, which also marks a major tectonic event in the basin. With the brief hiatus, its followed by oscillatory sea level transgression impulses resulting into Heera, Alternations. and Alibag, Panvel formations. The second major Carbonate cycle started in Early Miocene at around 23.03 ma with a high stand phase initiating a major carbonate depositional system in the basin. It is best developed over the Mumbai High and surrounding areas because of favorable bathymetry conditions. In areas away from Mumbai High it deteriorates in thickness and spread, and the quality of carbonates also get dirtier with the clastic mixing. Seismically it coincides with H3CGG horizon with a marked reflection interface and this cycle encompasses multiple Carbonate reservoirs of Mumbai High like LIII, LIV, LV and LVI. Transitioning into a brief phase of partial drowning it again culminated into another carbonate cycle developing into LII and LI reservoirs of Mumbai High. Neogene carbonates are generally not charged in the areas away from Mumbai High but because of their changing thickness, textural fabric, and lithological impurity, causes severe seismic aberrations in the structural geometries of underlying reservoirs. This is one of the major problems in the exploration and production from Bassein and Panna Reservoirs. Workers have used different approaches to resolve the issue by mapping these carbonate layers as well as by seismic driven methodologies to minimize or eliminate the impact (Vandana S et.al, 2018).

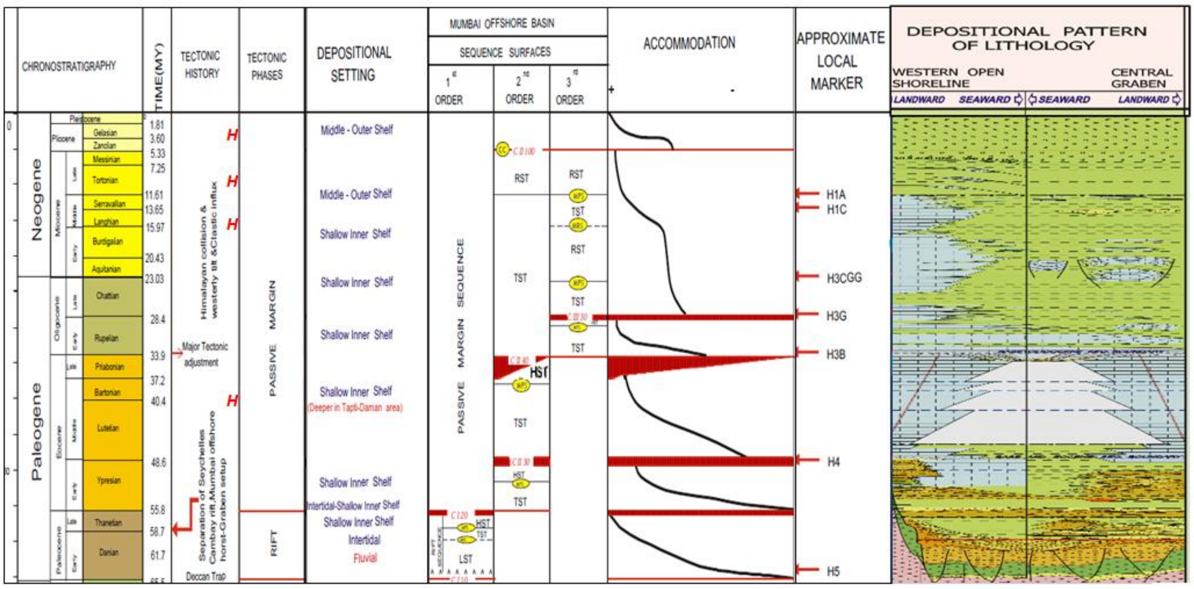


Figure-5 Depositional facies pattern, environmental set up and relative sea level cycles observed in Paleogene-Neogene period in Mumbai Offshore Basin depicting second and third order cyclicity(Verma NK et al, 2002)

Paleogene carbonate cycle

Paleogene Carbonate Cycle is initiated with the onset of the Carbonate factory in Early Eocene time at around 55 ma when the first Carbonate sedimentation regime was established in outer shelf areas under Devgarh formation. The separation of Seychelles from Indian plate triggered the marine transgression and resulted in to flooding of low-lying areas in the Central Graben and open sea around the Mumbai High platform with shallow marine sea in late Paleocene at around 58.7 ma . Paleogeography was marked by large, exposed areas of Deccan Basalt with isolated exposures of granitic and Metamorphic basement rocks over Mumbai High, Heera , Bassein and few other isolated paleo highs. This triggered a new fluvio-marine drainage and sedimentation system girdling around the exposed Basalt and Granitic basement highs which quickly filled up the erstwhile existing and newly formed grabens. With high sediment discharge from the adjoining highs and supporting precipitous terrestrial drainage from western ghats, large tracks of fluvial-brackish-marine sedimentation under Panna Formation were established covering a major part of the basin. The basin floor was uneven and conspicuously marked by the horst and graben geometries which guided the flow of sediments through the newly formed drainage system.

Early Eocene transgression cycle from 55 to 49 ma significantly increased the marine influence over the sedimentation and covered part of the areas around the girdle with newly emergent tidal and marginal marine conditions. The exposed areas were narrowed down and segmented due to rise in the relative sea level and provided additional accommodation space for sedimentation. An array of alluvial and marginal marine fan assemblages and distributary mouth bars were deposited around the higher exposed areas feeding the high sediment volumes which were often poorly sorted and texturally immature. However, at places, the arenaceous sediments arriving in the depositional system through terrestrial drainage from the provenance were recycled into shore face and intertidal sedimentary assemblages along the open marine paleo shorelines at several places.
Transgressive marine cycle with reduced supply of arenaceous clastics in the system eventually culminated into relatively low energy conditions in Later part of the Early Eocene ie ~ around 46-48 ma with carbonaceous shales and coal deposition within Panna formation. Rhythmically alternating siliciclastic sediments/coal/carbonaceous shales of Panna formation have been classified under lowermost 2nd O PM Sequence with preserved HST, TST and HST system tracks which is topped by Chrono-Boundary H4 at 48.6 ma (Dave et al,2004).

Devgargh Carbonate Cycle

Right from Thanetian time (58.7 ma) all around the southwestern, western and northwestern girdle around Mumbai High platform open sea conditions were established and beyond the influence area of clastic sedimentation, relatively Tranquille conditions developed which enabled the initiation of the Carbonate Factory and carbonate sedimentation under Devgarh Formation started and laid the foundation of Paleogene Carbonate Cycle in the basin. This is the time analogue of Panna Formation and genetically part of the Synrift sequence. However, in the northern part of the basin in Tapti-Daman block as well as in Central Graben areas this facies transition is not developed because of predominance of the Clastic supply and faster sedimentation rates.

Lithologically, it comprises of off white to grey compact and tight limestone with subordinate shales embedded at places. From hydrocarbon accumulation point of view this Early Eocene Carbonate play is yet to be proven commercial and is only interesting in D11, D14, R7 and Murud low area.

Bassein Carbonate Cycle

Chrono Marker H4 marks a major sea level fall and resultant unconformity in the entire basin except in the deeper parts of outer shelf areas. It also coincides with the major change in the depositional environment from predominantly clastic to carbonate in the basin. The new transgressive cycle starting at around 49.5 ma, establishes an active Carbonate factory with widespread carbonate sedimentation in large parts of the basin. The Carbonate sequence with subordinate shales deposited from 49.5 to 36.0 ma and ranging from 200-400m in thickness is classified under Bassein formation. It is one of the most prolific hydrocarbon reservoirs in large part of the basin away from Mumbai High. In deeper outer shelf areas and Murud depression, its lower boundary represents a Carbonate-carbonate change over as Devgarh Carbonates transition in to Bassein Carbonates. Similarly, in the Tapti Daman, Diu and some parts of Shelf Margin block, carbonate facies in not developed and instead finer clastics represent the geological time which are classified under Diu-Belapur and Panvel Formation. Mumbai High was still exposed during this phase as sea level rise was not enough to submerge it and it contributed to the clastic sediment supply to the bordering Wedge Out areas making the carbonates dirtier or marly clastic assemblages. The lower boundary of the sequence is identified as the chrono-boundary CII 30 – Base Mid Eocene Sequence Boundary and the top is marked by the sequence boundary CII 40- Base Oligocene Sequence Boundary (Alok Dave et al. ONGC report). SB CII 40 is a major hiatus interface in wester offshore basin spanning ~3 ma to ~ 6 ma and coincides with a major drop in sea level. Bassein Carbonate Cycle starts with a transgressive systems tract culminating in to second order maximum flooding surface marking the top of Lower Bassein formation (46.8 ma). These Mid Eocene carbonates comprising Transgressive System Tract (TST) are generally widespread in lateral extent but lithologically tight with poor porosity and not very interesting reservoirs from petroleum point of view. However, in the areas of relatively higher structural positions, minor unconformities are developed with associated leaching and porosity development and have led to selective hydrocarbon charging.

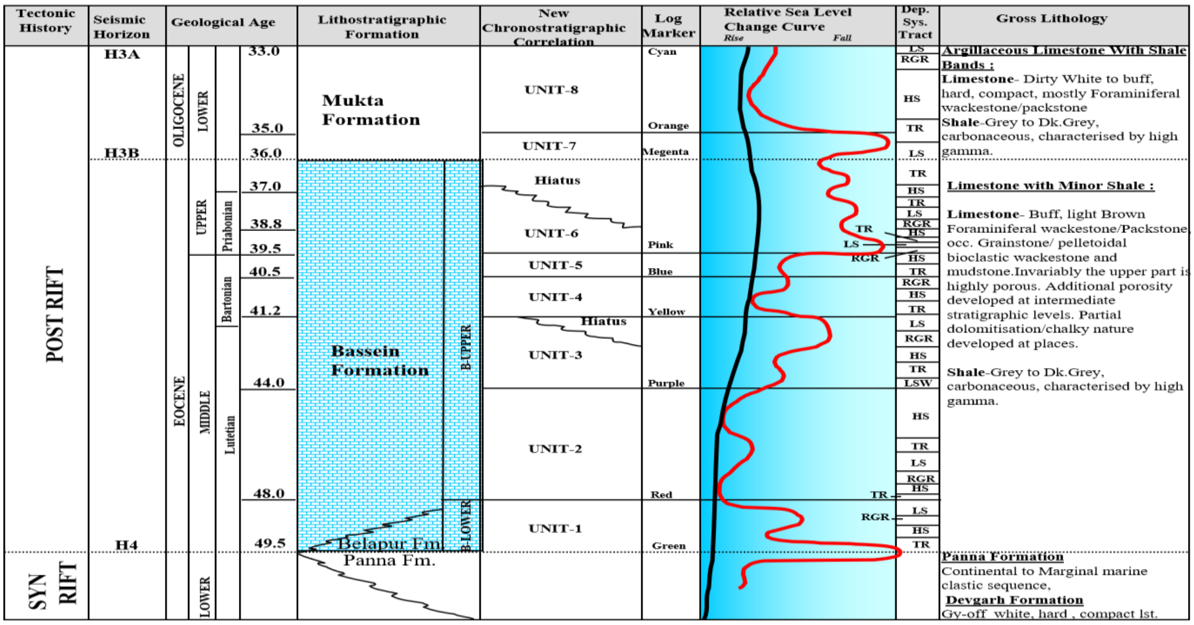


Figure-6 *Depositional cyclicity pattern, lithofacies variation and relative sea level cycles observed in Paleogene-Neogene period in Panna-Bassein-Heera Platform area Mumbai Offshore Basin depicting second and third order cyclicity ((Verma NK et al, 2002)*

The thick and massive carbonates of Bassein formation deposited predominantly under High Stand Systems Tract, in fact comprise of multiple cycles of carbonate sedimentation resulted from successive transgression-regression sea level changes.

In a major study of Bassein Formation in the Heera-Panna-Bassein Block, eight well defined carbonate cycles of smaller order were mapped in the area with minor sea level changes as depicted in the **Figure-6**(Verma NK., et al 2002). They mapped the associated geometries, genetic framework of the changes and reservoir properties in 3D space to get insights for further exploration and development work.

Depositional cyclicity with age boundaries of the mapped units were derived from the sea level correlation and relative sedimentation rates were computed to get an idea of the depositional accommodation space changes during the Bassein Carbonate cycle . The carbonate sedimentation started with slow vertical accommodation, picking the speed in the middle part, and then again slowing down. Yet another cycle of increased vertical accommodation was achieved in the terminal phase where it attained the maximum rates. These changes led to the corresponding changes in the vertical aggradation vis-à-vis lateral growth of the carbonate platform to keep the equilibrium with the overall carbonate sediment volume generated by the carbonate factory which also controlled the lithification and porosity development process in cyclic manner with associated minor local unconformities and correlative conformities.

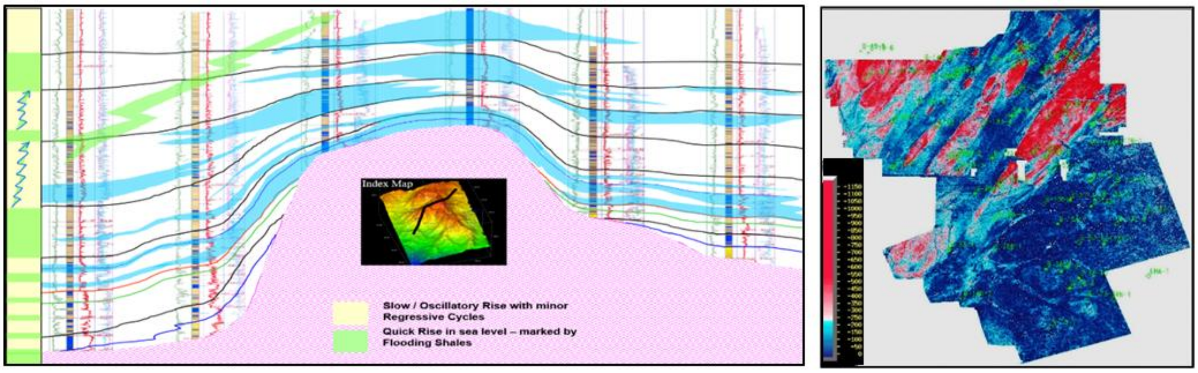


Figure-7 Left Panel : Seismo-geological section across B-119-121 basement High in wedge out area south of Mumbi High showing carbonate cycycity pattern in the Paleogene and Neogene sequences. Carbonates are identified on the logs and well corroborated with core data. Right Panel : Structure controlled preferential Carbonate sedimentation over inverted linear structure (Red Color).

Duringthe Middle Eocene-Lower Bassein formation widespread carbonate sedimentation was established except the Mumbai High inlier. Within the Panna-Bassein-Heera platform areas, around submerged paleohighs shallower bathymetry existed with a possibilities of shoaling and exposures during the smaller cycles of sea level fluctuations (**Figure 7**). In these areas packestone-wackestone carbonate assemblage is dominant with occasional grainstone and bioclastic carbonates deposited. Towards outer shelf to the west and southwest, bathymetry increases with lower energy regime with carbonate mudstone and wackestone being predominant. Towards northern part in Tapti-Daman area the clastic supply interferes with the carbonate sedimentation and across Diu fault sharp facies transition takes place, which demarcates the Carbonate-Clastic boundary towards north. In Cntral Graben and Vijaydurg Graben areas, the bathymetry is slightly higher and thus moderate to lower energy carbonate sedimentation dominates with seldom shallowing of the depositional surface due to minor sea level cycles.

Lower Bassein Carbonate cycle passes upwards in to Upper Bassein Carbonate Cycle which is the most prolific hydrocarbon bearing reservoirs in the basin. The upper most part is a conspicuous unconformity which resulted into thick leached section at the top with excellent intergranular and vuggy porosity making it a good reservoir. Due to continued carbonate deposition, the basin floor irregularities are evened out as compared to Lower Bassein cycle and over all shallowing of the basin has taken place. Large tracts on the eastern homocline, and peripheral l girdle around western slopes of Mumbai high shallow bathymetry was developed and these areas have been subjected to frequent shoaling due to sea level oscillations and have created multicyclic porosity development. Areas between the Heera-Panna-Bassein high trend and Mumbai high including southern slopes of Mumbai high structure have moderate bathymetry with less frequently exposed depositional floor. Outer shelf areas including Murud Low has deeper bathymetry with lower energy mudstones and interbedded layers of wackestone. Northern part in Tapti-Daman areas have clastic sedimentation continued like Lower Bassein time.
The upper most Unit of the Upper Bassein formation represented by Late Eocene time span (39.5 ma to 36 ma) forms a well-defined carbonate sub cycle which has impacted the hydrocarbon accumulation selectively in some areas due to differential sedimentation in some parts whereas exposure and erosion in other parts. This has led to the development of diachronous porosity pods at the unconformity interface at the top of Bassein formation. Based on the foraminiferal assemblage and dinoflagellate data, the hiatus span is inferred to range from 3-6 ma (Alok Dave et al 2004) depending upon the structural position and is directly related to the thickness and intensity of the leaching driven porosity zone.

Narendra K Verma et al (2002) have identified multiple unconformities / correlative conformities and associated hydrocarbon plays while mapping the six discrete carbonate Units and these are akin to the 3rd order cycles with in Bassein Carbonate Sequence. Detailed log correlation with chronostratigraphic approach in conjunction with relative sea level template and seismic data depicts several flooding surfaces and regressive cycle boundaries forming the basis of division of whole Bassein Carbonate cycle into discrete genetic depositional Units analogues to the 3rd order cycle (Figure 6). Pseudo log property models in form of vertical sections depicting the porosity changes across the platform indicate finer layering and genetic controls on the porosity development (**Figure 8**). Structurally higher areas and areas in close proximity to the major faults exhibit higher porosity development and cyclic exposure and near exposure surfaces have given additional impetus to the selective and layered porosity development.Aerial spread and thickness distribution of these Units indicate active changes in the accommodation space and sedimentation rate changes in different Units as well as spatially over different parts of the Heera-Panna-Bassein platform(**Figure-9**). Lithologically, the Late Eocene carbonates comprise of buff and off white, grey colour Foraminiferal wackestone-packestone assemblage with occasional mudstone and pelloidalgrainstone as well as bioclastic carbonate derivatives. These are interspersed with grey to dark grey marine and carbonaceous shales marking the oscillatory changes in the depositional system.

Field analogues of the Middle Eocene Carbonates are exposed in the Kutch onland, which exhibit thinly bedded light yellow to buff color mudstone – Wackestone and Packestone assemblage with profuse micro and mega fossil contents and bioclastic remains (**Figure 10**). Different facies types are bedded into gradational cycles of massive carbonate beds – beds with pinch and swell kind of pillow structures, thinly bedded and laminated carbonates mimicking the fining up cycles of clastic regime. These cyclic changes reflect the ongoing oscillations in the sea level changing the energy level. In some of the layers, high concentration of larger fossils and bioclastic material is embedded in the finer mudstone matrix which are possibly basal lags in the high energy impulses. Later on,the finer carbonate mud assimilated the bioclastic material. Large mega foraminiferal fossils and echinoids and sponges are seen in abundance in the carbonate exposures.

Mukta Carbonate Cycle

At the close of the Bassein Carbonate cycle a major sea level fall is recorded at around 36 ma which resulted into a major unconformity in large part of the basin covering almost entire Panna-Bassein-Heera platform as well as peripheral areas of Mumbai High. After a lowstand phase of around 1 ma, another major transgression cycle with sharp rise in the sea level developed which onset the new sedimentation of tight carbonates and marls with thin bands of subordinate shales. This Early Oligocene Carbonate Cycle (Mukta Formation) comprises white- dirty white and buff colour, hard, compact wackestone - packestone and mudstone. Shales are grey to dark grey, carbonaceous, and invariably characterized by high gamma readings.

Paleogeographic map (Figure 9) depicts the rising sea level with large tracts brought under moderately deeper bathymetry ranging from 150-200 m shown in dark blue and in these areas, carbonates are mudstone dominated with localized enrichment of bioclastic fragments and wackestone - packstone assemblage. In the central part of the Panna-Bassein-Heera platform bathymetry ranged from 50-150m with marine cyclic oscillations prevelant and in these areas dominant carbonate facies werewackestone andpackestone. However, as compared to Bassein Carbonates, Mukta carbonates are dirtier with increased carbonate and clastic mud matrix thus negatively affecting their reservoir quality. Mumbai High structure was still exposed as sea level could not submerge it. Another major change evident during this cycle is the south ward extended reach of the clastic influx from northeastern Tapti-Daman area imprinted over the carbonate sedimentation in internment impulses which created compartmentalization of carbonate reservoirs in Mukta formation. Mukta Carbonate cycle ceases to sustain the carbonate sediment for long and eventually passes into more argillaceous unit of Heera Formation which is marked by the alternation of Carbonate and shales with decreasing carbonate contents upward. In Tapti-Daman Block this geological span is occupied by Mahuva Formation with predominant argillaceous sequence along with subordinate and discrete sands deposited under tidal, intertidal and prodeltaicenvionment.

This practically demarcates the end of the Paleogene Carbonate Cycle with the top of Mukta formation. In late Oligocene west ward tilt is witnessed in the basin which further increases therelative sea level in major part of the Heera-Panna-Bassein Block as for the first time Mumbai High structure is submerged under shallow marine conditions. This triggered a new readjustment in the entire basin in terms of the bathymetry changes and associate depositional ecosystem. A new equilibrium is established with new locales of carbonate sedimentation over the Mumbai High structure and surrounding areas. Concurrent increase in the clastic supply and its influence radius reaching to the Panna-Bassein Block, the carbonate sedimentation was practically ceased in a major part of the platform.

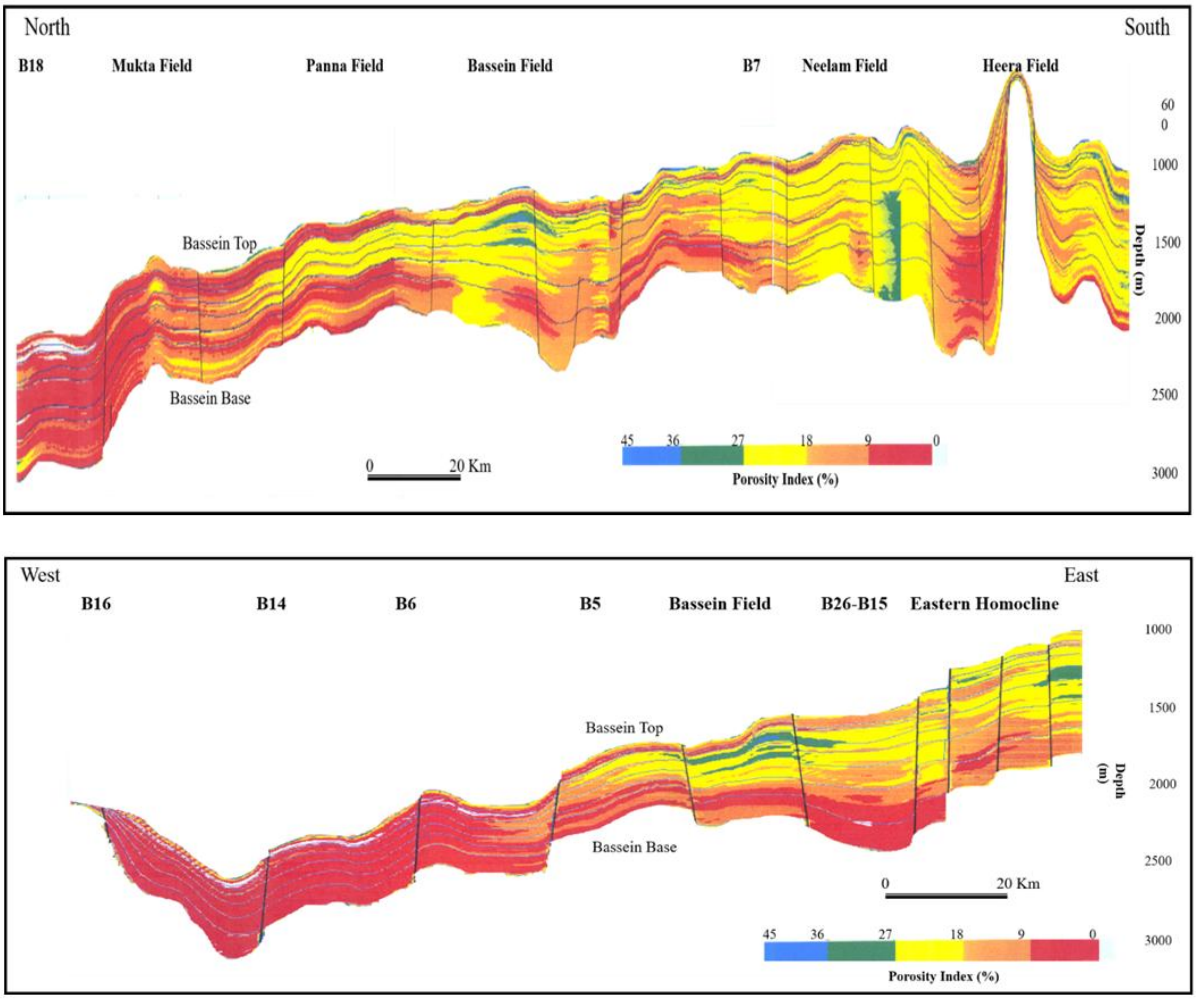


Figure-8 N-S and E-W Pseudo log property sections across Heera-Panna-Bassein platform area showing the cyclic variation in the porosity due to exposure and leaching driven by the relative sea level changes and resultant submergence / exposure of areas (Narendra K Verma et. al 2002)

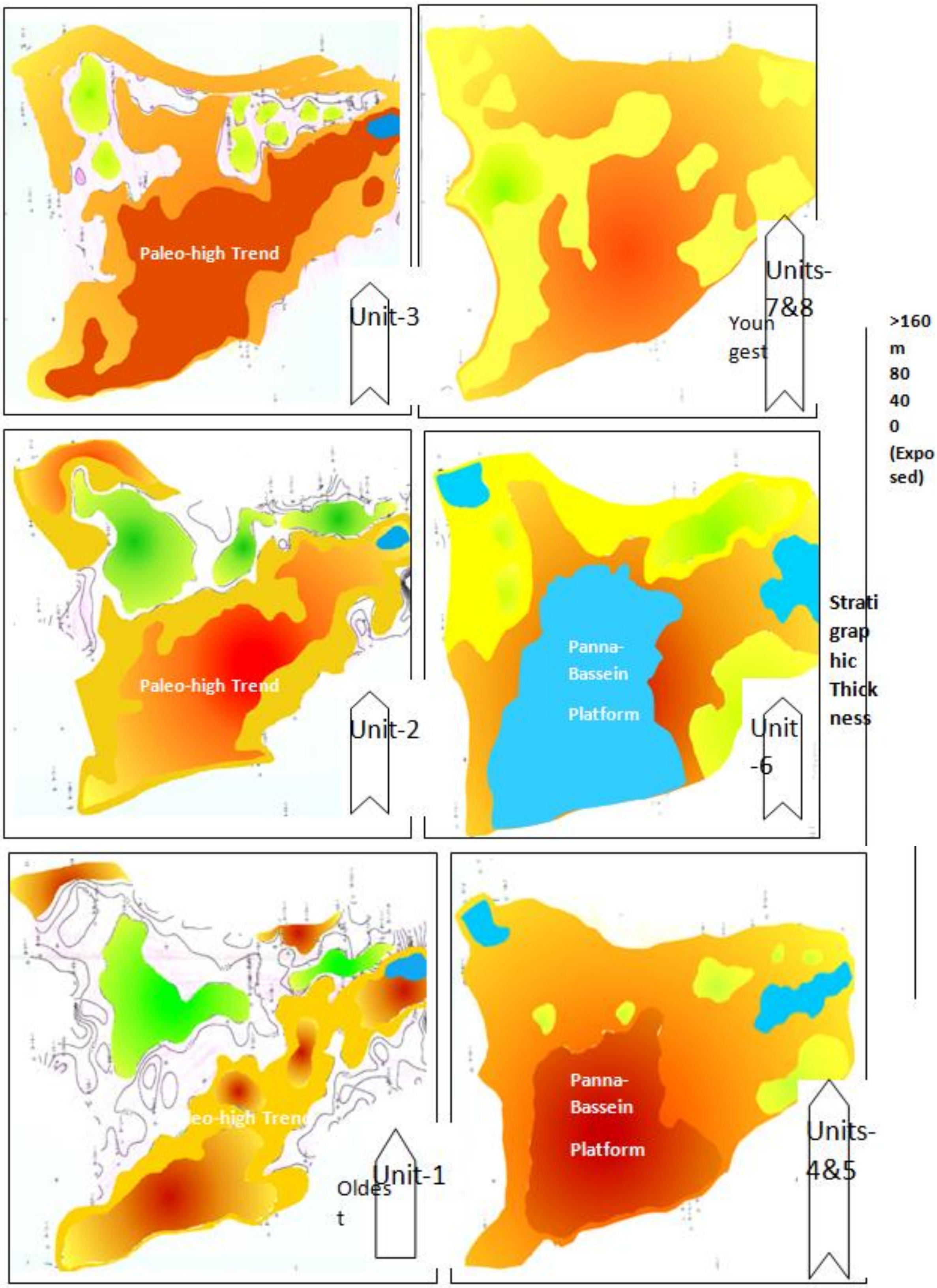


Figure-9 Spatial cyclic variation in the Bassein-Mukta Carbonate Sequence with discrete third order carbonate cycles mapped over Heera-Panna-Bassein Platform (Narendra K Vermaet.al 2002)

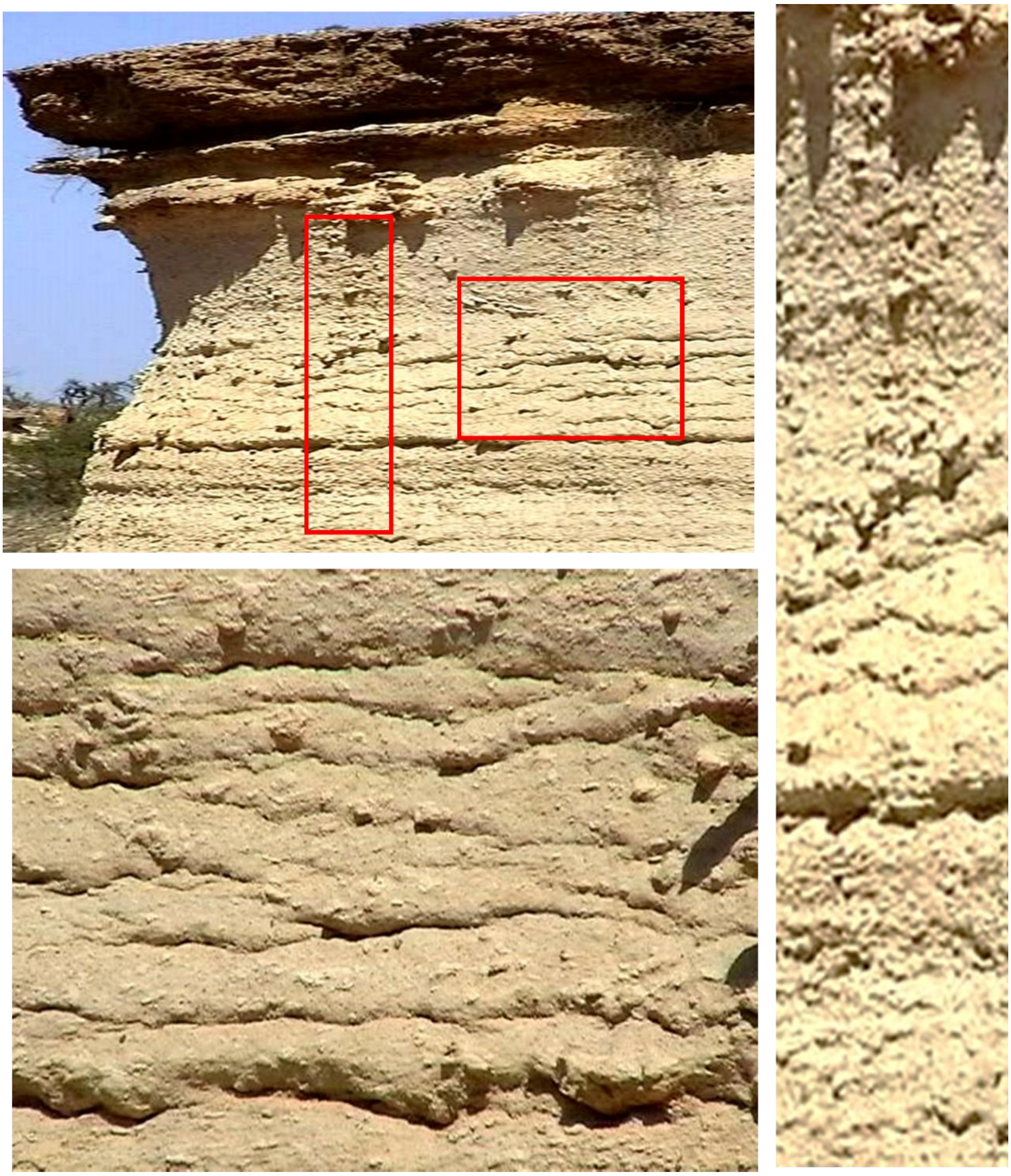


Figure-10 Field Photograph mosaic of Eocene carbonates exposed in Kutch on land showing the depositional cyclicity similar to that observed in the subsurface analogues of Eocene carbonates (Bassein Formation) in seismic and log data. Rectangles marked on the upper panel are zoomed in the lower and right panels depicting the details of the cyclic variations.

Neogene Carbonate Cycle

Although the Neogene Carbonate cycle onsets in Early Miocene with the deposition of Bombay Formation carbonates, however late Oligocene being the link between Paleogene and Neogene Cycles, we need to consider its critical events and stratigraphic details.

Towards the end of the Early Oligocene transgressive cycle, (~29 ma) maximum flooding surface (MFS) is recorded in Heera Formation depositing the shale and carbonate alternations. This passes into a regression cycle leading to a marked unconformity in most of the tectonic blocks in the basin (CIII 30 seq. boundary, Dave et.al.2004) except the Shelf Margin block, where in the Early Oligocene to Late Oligocene sedimentation continues without interruption (**Figure 11**). Seismically this boundary is mapped as H3G horizon and in Shelf Margin Block its mapped as correlative conformity. After a brief hiatus, the basin experiences another transgressive cycle which continues till the end of the Oligocene. During the Late Oligocene, clastic supply from the northern Tapti-Daman deltaic system increased significantly and it was spreading over a major part of Heera-Panna-Bassein Platform. Concurrent tectonic tilting of the basin westward with consequent rise in the relative sea level in western parts, led the carbonate sedimentation retreated westward. Entire Heera-Panna-Bassein Platform was brought under the low energy finer clastic sedimentation as depicted in the paleogeographic map for the period.Carbonate factory was subdued in its magnitude and spread and mostly confined to the stable platform over Mumbai high and its western slopes up to shelf margin. In fact, multicyclic and thick Carbonates (> 600m) of Panvel formation deposited during this period have been established as important hydrocarbon reservoir in D1, B192, B46/B48 areas in Bombay high DCS Block. LV and LVI carbonate reservoirs of Mumbai High also fall with the Late Oligocene time span. On the other handa thick sequence comprising shale, silt and marl with occasional thin streaks of limestone was deposited over entire Heera-Panna-Bassein platform and Diu block which is classified under Alibagh formation. in the shelf edge area towards Murud low, clastic sediment bypassing has resulted in to localized clastic depositional system. In Tapti-Daman Block to the north, this chrono span is represented by Daman formation with plenty of arenaceous clastics along with shales, which are gas bearing in several entrapments.

The Late Oligocene sedimentation culminated into terminal flooding surface at around ~26 ma (FS80; Dave et.al 2004) which marks the youngest shale unit within the Late Oligocene cycle. This changed the depositional equilibrium in the basin with newly established carbonate depositional system in and around Mumbai High with high quality carbonates being deposited under high stand system tract. Mumbai High platform was active and accommodating large thickness of cyclic carbonates deposited under regression phase. Periodic changes in the relative sea level due to tectonic and eustatic factors, resulted in to repeated cycles of high quality packestone and grainstone and wackestone carbonate facies interstatified with thin grey and carbonaceous shales and silts representing the oscillatory depositional conditions. Vertical aggradation and lateral growth of the carbonate platform was witnessed in cyclic manner in response to the changing accommodation space under oscillating sea level changes. The Late Oligocene-Early Miocene boundary represents a predominantly shale-Carbonate interface and represents a major sequence boundary, mapped as H3CGG horizon in seismic data. During the earliest part of the Carbonate cycle under HST system tract, a major relative sea level fall is witnessed (~ 170 m; Dave et.al 2004). Clastic system with southwesterly influx from the northern Tapti-Daman area, bypassed a major part of the Heera-Panna-Bassein platform into shelf edge and slope through a narrow corridor around the Murud depression, which portioned the carbonate depositional system in to two separate sub areas. One in and around the Mumbai High Platform and another one in the Ratna area. A northward carbonate depositional tongue extended from Ratna area into the eastern homocline up to Neelam sector. This is included under Ratnagiri formation inLithostratigraphic classification. The mixing of the Carbonate and clastic sediments did take place in the northern corridor between the Mumbai High platform and median axis of the clastic supply flowing from Tapti-Daman block. Mixed lithologies of limestone-silt, sandstone, shale and claystone were deposited in Panna-Bassein and Tapti-Daman Blocks grouped under Mahim Formation.

Cyclic carbonate sedimentation under regressive phase continued till ~21 ma with development of high-quality carbonates deposited over Mumbai High platform. This event is marked as Maximum Regression Surface. However, thereafter sea level started rising again and carbonate sedimentation continued under transgressive system tract till ~ 16 ma which is recorded as maximum flooding surface 90 and in seismic that is mappable as H2B horizon(figure 11). During the regression phase there are isolated carbonate build ups and reefoidal bodies are developed over the structural paleo highs and newly formed inverted structures.

Langhian and Serravallian Stages of Middle Miocene spanning from 15.97 ma to 11.8 ma are represented by a full regression-transgression cycle bound at the bottom and top by two flooding surfaces FS90 and FS100, which coincide with two prominent markers namely H2B and H1A respectively. A well-developed carbonate sequence was deposited during the period over Mumbai High platform and surrounding areas. The lower part of that is formed during the regressive phase whereas the top part of the carbonate was deposited under transgressive phase. Maximum regression surface MRS100 (Dave et.al 2004) is recorded at 13.6 ma which coincides with another

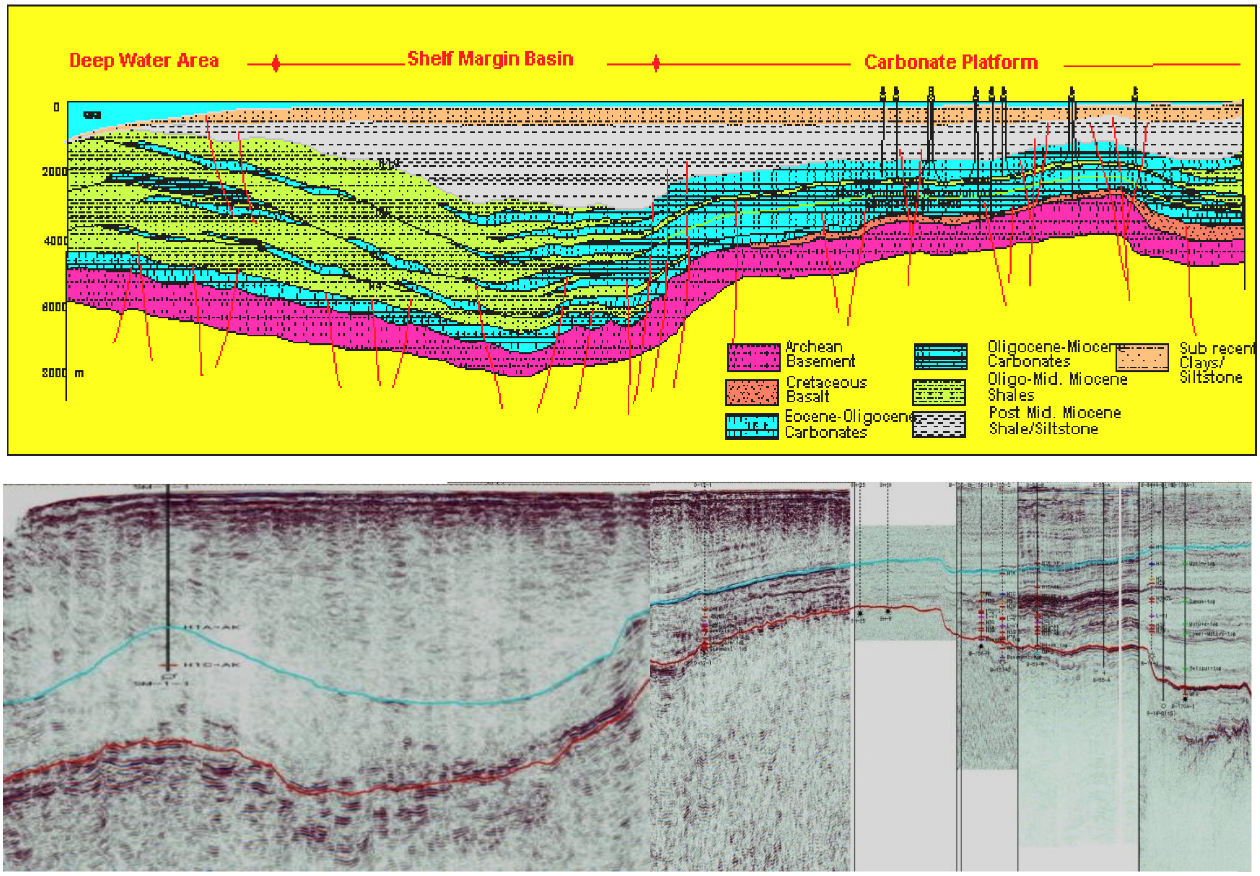


Figure-11 Upper Panel - Seismo geological section across Mumbai High-DCS Block showing multicyclic Oligo-Miocene carbonate deposition over the platform area and its lateral facies transition into shales in the shelf margin sub basin and shelf edge. Lower Panel: Composite mosaic of seismic sections along the same profile.(Dave et al, 2004)

prominent marker H1C in the seismic. Carbonates of this cycle were deposited under middle to outer shelf environment and are included under Bandra Formation in Lithostratigraphy. In Ratnagiri area the equivalent Carbonates are grouped under Ratnagiri formation. If we compare the paleogeography with the Middle Miocene time, over all clastic influx has increased in the basin with much wider influence over the carbonate sedimentation. As a result, spatial extent of the carbonate development is reduced, and these are much dirtier and tight as compared to underlying cycle. Better net to gross carbonate percentages is seen on the western periphery of the Mumbai High and adjoining shelf margin and Ratnagiri areas. The Carbonate factory appears to be in drowning phase with terminal collapse. Silt-Claystone-shales and marl assemblage deposited over Panna-Bassein-Heera platform and Tapti-Daman Block are included in Tapti Formation in Lithostratigraphic classification. Generally, the arenaceous clastics are more abundant and widespread in Tapti-Daman Block, however isolated discrete sand lenses and carbonate streaks are embedded with in finer clastic matrix in the Panna-Bassein-Heera platform as well as areas closer to Central graben. This period generally marks the end of the carbonate sedimentation in the basin as carbonate factory eventually collapses under the heavy clastic influx and sharp rise in the sea level at ~11.60 ma which is coinciding with H1A. Collision and Sharp rise of the Himalayas along the northern margin of India created a new climate cycle with high precipitation and heavy sediment discharge in the terrestrial drainage system, which eventually was reflected in western offshore basin as well. Overlying shale, clays, and silt of clastic Chinchini formation is testimony of the same process. Heavy load of the clastic sediments led to the shelf edge progradation and adopting the present-day configuration. The Mio-Pliocene boundary is marked by CII 100 (Dave et.al.2004) with shales grading into unconsolidated clays and silt. Within Upper Miocene some isolated carbonate bodies are formed on the shelf edge in form of build-ups, reefal growth and associated fore reef bioclastic assemblages.

Miocene carbonates exposed in the Kutch onland were studied for comparison. Upper Vijhanian Carbonate sequence in Khari Nadi Section, exhibits close similarities in the lithological and bio-assemblage with L-III Carbonates of Western Offshore and represent their close time analogues (**Figure 12**). Outcropping section shows alternating layers of highly bioturbated wackestone/ packstone and tight & compact micritc and sparitised layers. The bioturbated layers show preferential leaching patterns and vuggy/cavernous porosity development (figure 12). Radiating burrow patterns are also seen in the carbonates.

Depositional Cyclicity in Mumbai High Carbonates

Multi cyclic and continued carbonate sedimentation has taken place over Mumbai High Platform right from Late Oligocene to Mid Miocene period, which was primarily controlled by the changing relative sea level ,

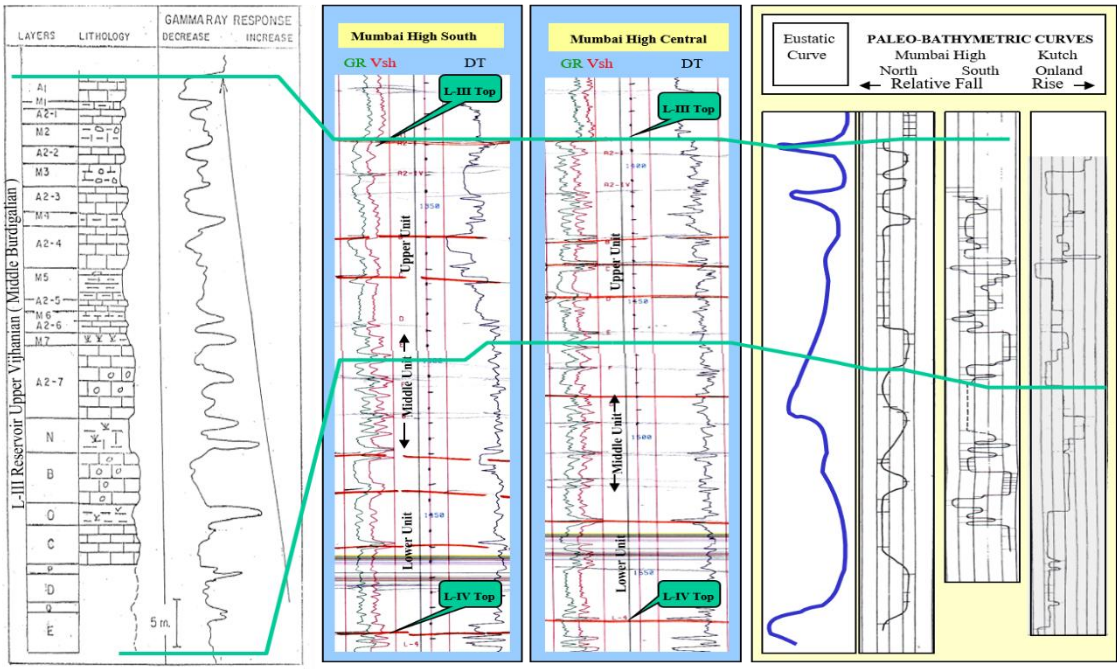


Figure-12 Depositional Cyclicity pattern seen in the L-III (Miocene) Carbonates with corresponding log signatures and relative Sea level changes (Nrendra K Verma et al,2001))

accommodation rates, and changing equilibrium between the active carbonate factory and clastic supply influx from north. Preferential, thicker, and cleaner carbonate growth is witnessed during this period over the platform as compared to surrounding areas in the Panna-Bassein-Heera Block and western shelf margin Block, which was apparently due to better bathymetry conditions prevailing over the Mumbai high with reference to the surrounding lower areas. After the cessation of the carbonate factory in the Middle Miocene, Mumbai High was also covered by the marine shales, silt, and unconsolidated clays of Chinchini formation along with the entire basin. Seismic data exhibits high amplitude reflector packs against the cyclic carbonates with strong basement reflector, showing the basin floor geometry. In the areas with dominant shales and silt, weaker reflectors and transparent seismic zones are seen. Six well defined Limestone reservoir units namely LI, LII, LIII, LIV, LV and LVI, interspersed with the intervening shale layers of varying thickness have been identified over the Mumbai High structure, LV & LVI are the part of the Late Oligocene Panvel Formation, whereas LIII & LIV are embedded in Early Bombay formation and LI & LII form the part of Middle Miocene Bandra formation. Out of these reservoir units, LIII is the most prolific and well-studied with 12 subunits mapped and defined based on the well log signatures. These are A1, A2-1 to 7, B, C, D, E and inter stratified by shale layers named as M1-7, N, O, P, & Q (**Figure 12**). These limestone subunits are mapped as para-sequences with consistent log and petrophysical signatures over Mumbai high . LIII top is a good marker on Logs and seismic as Carbonate-Shale boundary and it is a pronounced unconformity. A1, and seven layers of A2 are mapped as individual flow units based on the well log signatures and lithological attributes for the development and production activities of the oil and gas from these reservoirs and such correlation mapping was extended over the Mumbai High north and south with respective log signatures and thickness trends (**Figure 12**). However, such correlation resulted into complications and surprises in the production behavior from different layers in terms of overall flow rates in the drilled well and oil water contacts as seen in the wells. Premature water breakthrough was observed in many places which questioned the 3D integrity of such unit correlation over the Mumbai high field. This created a serious setback in the production strategy and overall recovery from the sole super giant oil field.Detailed seismo geological analysis reveals repeated Keep-Up and Catch-Up cycles leading to the vertical and lateral growth of the platform during Oligo-Miocene period. (**Figure 13**). Repeated exposure of the platform and leaching/ bioturbation resulted into the layered porosity development (**Figure 14**).

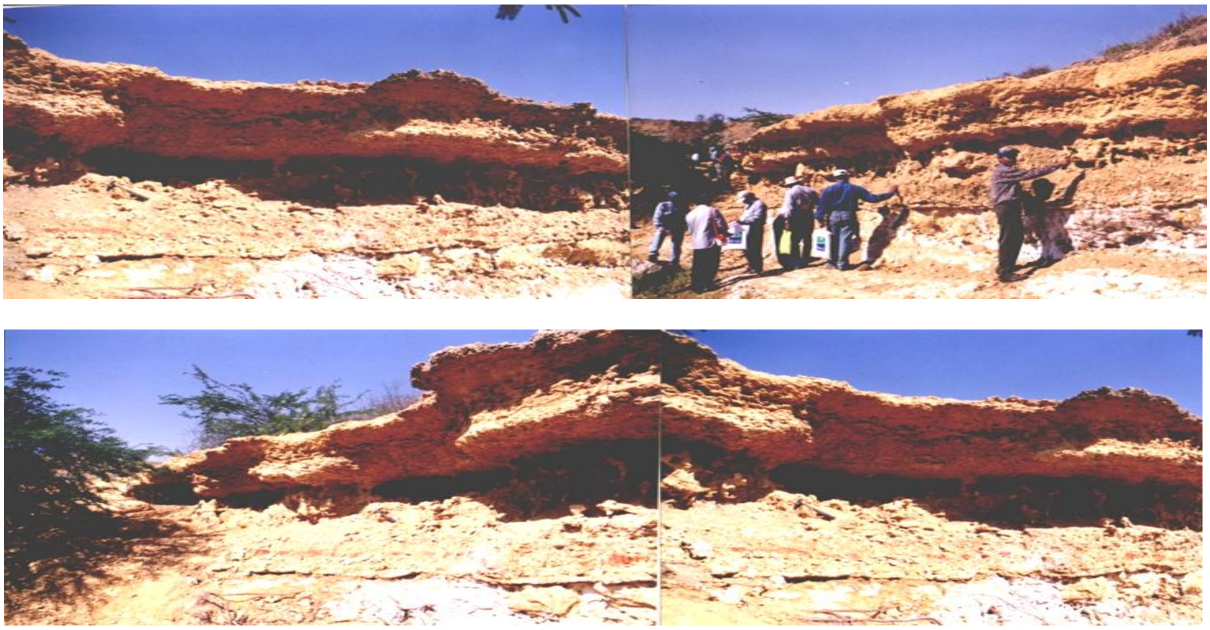
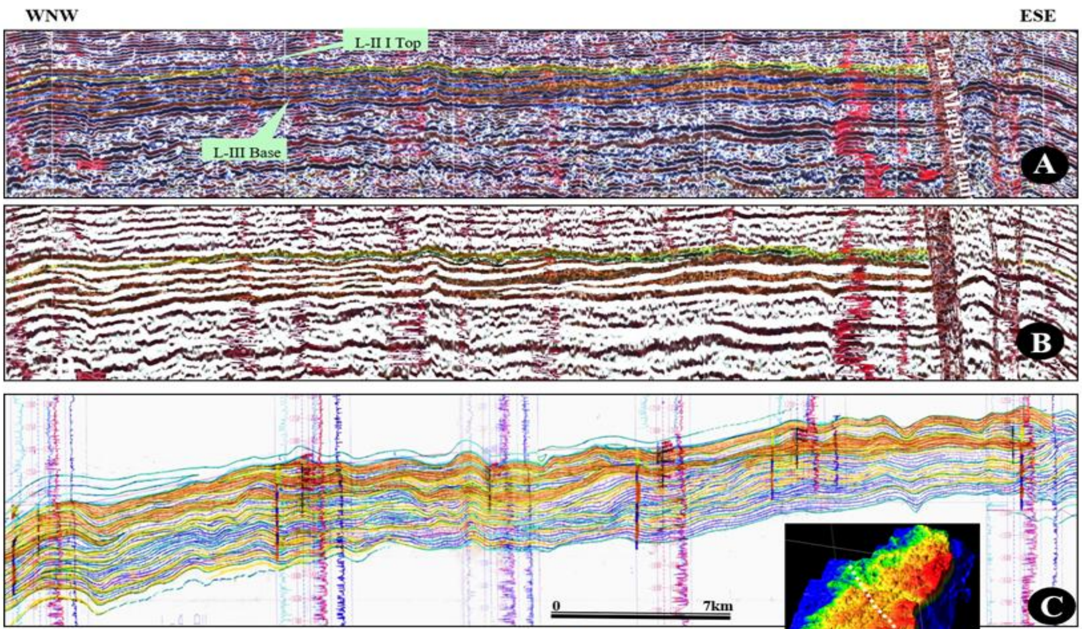


Figure -12 Photo-mosaic showing outcropping Upper Vijhanian Carbonate sequence in Khari Nadi Section, Kutch Onland. The sequence exhibits close similarities in the lithological and bio-assemblage with L-III Carbonates of Western Offshore and represent their time equivalent.showing alternating highly bioturbated wackestone/ packstone and tighter micritc and sparitised layers. The bioturbated layers showing preferntial leaching and vuggy/cavernous porosity development.



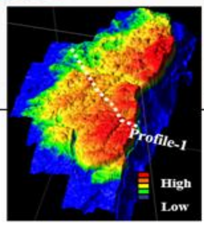


Figure -13Seismic Profile, and seismo geological section across Mumbai High Field showing the depositional cyclicity of Oligo-Miocene Carbonates with vertical and lateral growth patterns reflecting the repetition of Keep-Up and Catch-Up cycles of Carbonate sedimentation over Mumbai High.

Figure-14 Field Photographs of Vinjianian Carbonate in Kutch On land (Analogues of L-III carbonates of Mumbai High)showing Interstratified Layers of: Highly Bioturbated Carbonates- Non-bioturbated wackestone/ packstones Argillaceous/Micritic Limestone Shale/Clay horizons. Right panel shows the zoomed image of intergranular porosity created by bioturbation.

Concurrent Silici-Clastic Sedimentation Analogues

As described in the foregoing paragraphs, there was continued influx of silici-clastic sediments from northern Tapti-Daman Block which was being fed from the terrestrial drainage of Narmada-Tapti rivers. Tapti - Daman Block occupies the marginal marine mouth region of the Narmada-Tapti river system and its spatial geometry mimics the funnel shape estuarine embayment (Figure 2), which channelized the clastic sediment load in to the Mumbai offshore basin in impulses giving rise the inter-tonguing transition between the predominantly carbonatesedimentation over Panna-Bassein-Heera and Mumbai High platforms and clastic sedimentation in the Tapti-Daman Block during Early Eocene to Middle Miocene. Tectonic elements like east-west running Diu faults and other major faults embedded in the basin’s structural fabric controlled the accommodation space creation as well as carbonate-clastic sediment equilibrium. It was dynamically adjusted to account for the eustatic sea level changes, productivity of the carbonate factory in the shelf-slope region and over all sediment influx from the terrestrial provenance and ultimately molded the entire stratigraphic column into the existing form.

During the Paleogene carbonate cycle, Panna and Belapur-Diu formations were deposited as clastic analogues of Devgarh and Bassein carbonates. As described earlier, Devgarh carbonate cycle was developed during the Panna sedimentation in the marine shelf conditions in down dip areas of the shelf like in Murud depression and shelf margin basin, and during the same period, marginal marine or fluvial sedimentation occurred in rest of the basin. In Tapti-Daman and central-Vijaydurg grabens higher thickness was deposited and arenaceous clastics were preferentially deposited in proximity of the graben shoulders and other similar locales. With marine incursion impulses and continued sedimentation created swampy areas in cyclic recurrence which led the coal and carbonaceous shale deposition within Panna sedimentary sequence.

After a pronounced hiatus a major sea level rise in Early Eocene established the Bassein carbonate cycle over entire part of the Panna-Bassein-Heera platform which spread to shelf margin and Mumbai High DCS block excepting Mumbai High Structure. However, Diu and Tapti-Daman block were under clastic sedimentation during this period and Belapur and Diu formations were deposited in these areas. In shelf margin block also clastic Belapur sediments were deposited as bathymetry was not favorable for carbonate formation in these areas.

In the next cycle, when Mukta and Heera sedimentation occurred in the Panna-Bassein-Heera platform, Tapti-Daman area received high sediment load and thick Mahuva clastic cycle was deposited. Eustarine and tidal-intertidal deltaic environment prevailed in the Tapti-Daman segment which resulted in discrete and lenticular sand bodied embedded in predominantly finer clastic sediments. Incidentally, these sands have been proven to hold significant quantities of gas in Tapti-Daman.During Late Oligocene cycle comprising carbonates of Panvel formation in the shelf margin block and Alibagh finer clastics with minor carbonates over rest of the platform areas, Tapti-Daman region received large quantities of arenaceous clastics along with subordinate shale-silt and clays, which were deposited under tidal and wave deltaic set up (**Figure 15**).

Mahim and Tapti formations were deposited in Tapti-Daman block during the Early and Middle Miocene carbonate cycles of Mumbai High platform during which LV & LVI and LIII & LIV were deposited, respectively. Mahim sedimentation was under rising and High Stand Systems tract and represent predominantly finer clastics as compared to Tapti formation which was deposited during the regressive and Low Stand systems tract with considerable arenaceous facies. Late Miocene onwards mostly shale, silt and claystone are deposited in the entire basin under the rising sea level. However, relatively more arenaceous contents are seen in the Tapti-Daman region owing to the proximity to the provenance.

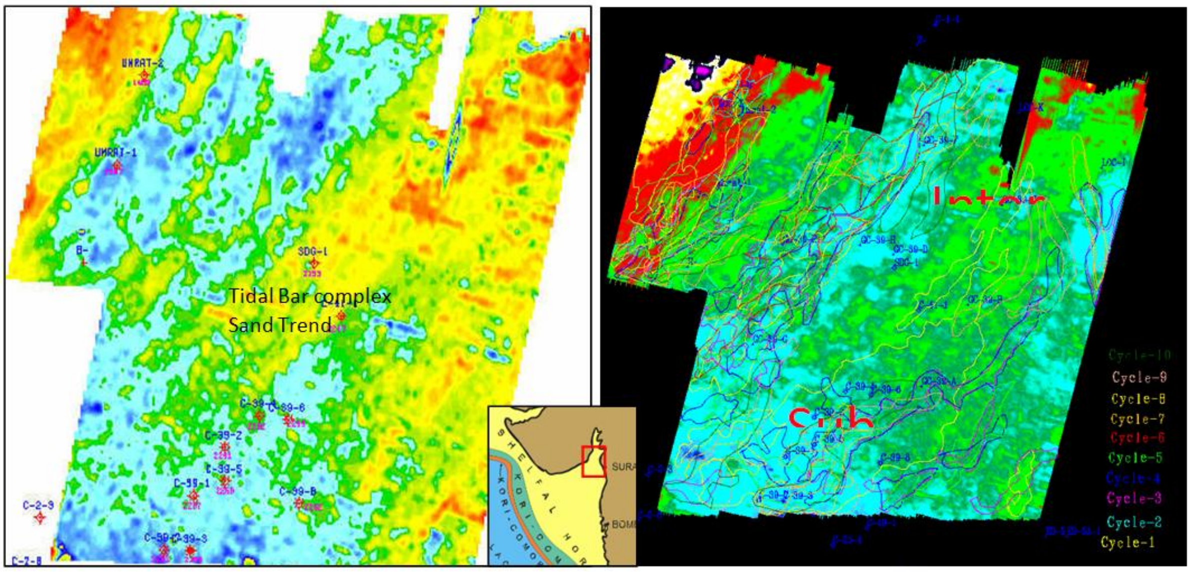


Figure-15 Left Panel: Seismic Attribute Maps showing the Estuarine- tidal deltaic complex developing in the Tapti-Daman Block, Cambay Gulf Area of Mumbai Offshore Basin during Oligo-Miocene period. Right Panel : Successive cycles of migrating channel complexes are mapped by stratal slicing of seismic data and overlayed on the seismic attribute Map.

Carbonate Cyclicity and Hydrocarbon Migration and Accumulation

Early Middle Miocene carbonates (LIII) of Mumbai High are the most prolific oil reservoirs of India forming the primary reservoir sequence of Mumbai High. These are the layered carbonates deposited under the oscillating sea level constituting the repeated Keep-Up and Catch -Up cycles. Repeated exposures of the depositional surface have resulted in extraordinary porosity and permeability development which characterize its prolific oil and gas production. Cyclic vertical and lateral growth of the Mumbai High platform has resulted into oblique stratification in the Oligo-Miocene sequence and its not a layer parallel internal geometry which has been hitherto believed by most of the workers. Detailed seismo-geologcial analysis has revealed the oblique stratification as its internal geometry and successive carbonate layers are time diachronous from crestal apart to the flank of the platform.

Concurrent changes in the relative sea level and influx of the clastic sediments from the Cambay Gulf or Tapti-Daman block area has governed the siliciclastic ratio over the platform in the cyclic manner providing the layers of shales and marl sandwiched with in the carbonates. It provides the local seal layers as baffles and obstruct the free vertical flow during the migration and thus have played important role in the hydrocarbon accumulation.

Paleogene carbonate cycle comprising the Devgarh-Bassein-Mukta formation is prolific hydrocarbon producer in the entire Mumbai Offshore basin, although the Devgarh carbonates are tighter and don't have significant porosity development as these are deposited in the relatively lower energy and were seldom exposed to the surface due their deeper bathymetric locations. On the contrary, Bassein and Mukta Carbonate cycles were subjected to repeated exposures and thereby developing multilayered porosity development and hydrocarbon charge. Number of depositional lows including B-172, B40, B-55, Neelam and several others in Tapti-Daman area like North Tapti, Mid Tapti,Umrat, etc have been affected by the Northeasterly strike-Slip fault movement and have been structurally inverted to provide secondary hydrocarbon traps and or redistribution of the earlier charge in to later formed structures.

Simultaneous strike-slip movements in NE-SW and ENE-WSW trends have created local structural inversions in the entire basin which are genetically driven by the Mid oceanic spreading in the Arabian Sea. Earlier workers believed that Narmada-Son Leneament has been the primary driver of the Northeasterly strike Slip movement, whereas the present study has revealed that lateral movement along Narmada-Son Lineament is an outcome of the mid oceanic spreading related transform faulting rather than a genetic driver of such movement in Mumbai Offshore basin.

Dominant NE linear structures developing all over the basin have created a preferential carbonate sedimentation locale during Oligo-Miocene period due their bathymetric advantage into photic zone as compared to surrounding lows.

Subordinate volumes of hydrocarbons are accumulated in the rift and early drift clastic sequence named as Panna formation, which also depicts repeated cyclicity patterns with coal-shale-sand and carbonate deposition under marginal marine to shallow marine environment.

II. Conclusions

Two mega carbonate cycles evolved with the oscillating sea level changes and an active strike-slip regime constitute the Paleogene-Neogene sequence of Mumbai Offshore basin. Sequential activation of the carbonate factory over the Panna-Bassein-Heera platform area during Paleogene and there after over Mumbai High platform and shelf margin area during Neogene period has been structurally controlled by the passive margin processes like margin subsidence and cooling. Sea level oscillations have created oblique stratification over the Mumbai High platform in Miocene Carbonates depicting typical footprints of repeated Keep-Up and Catch-Up cycles. Multiple sea level oscillations and exposures of the depositional surface has resulted into multilayered porosity development both in Panna-Bassein and Mumbai High Platform.

Continued northeasterly strike-slip movement driven from the mid oceanic spreading in the Arabian sea has led to development of typical flower geometries of various magnitude and temporal signatures, which has obliterated the older hydrocarbon traps and created secondary accumulation locales in Paleogene carbonates. Due to uprise of the linear inversion structures, created due to strike slip movements, preferential carbonate deposition has occurred over these structures because of bathymetric advantages. However, these shallow carbonates pose a serious imaging issue in seismic data because of velocity inversions and need careful handling.

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