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Sequence Stratigraphy, Depositional Environments and Reservoir Characterization of Oligo-Miocene Carbonates of Well X in DCS area, Mumbai Offshore

Abstract
Integrated sedimentological and biostratigraphic studies of cores, side wall cores and cuttings of Late Eocene to Middle Miocene succession of well X in the DCS area have been carried out to understand vertical distribution of sedimentary facies, their depositional environment, diagenesis and reservoir characterization. The Late Eocene carbonates are represented by high energy packstone facies of a shallow shelf. With the progradation of shelf during Oligocene-Middle Miocene, the shallow shelf was succeeded by lagoonal setup. A renewed marine transgression at the beginning of Late Miocene witnessed rise in bathymetry from 10-20m to 40-80m resulting in shut down of carbonate factory and beginning of clastic deposition represented by marine shales of Chinchini Formation. The depositional environment oscillated between open to restricted lagoonal environment of inner-middle shelf setup during Oligo-Miocene. The development of primary porosity in sediments deposited in platform interior (lagoonal environment) is poor. Good reservoirs are seldom formed in this environment. Based on sequence stratigraphic analyses incorporating litho-microfacies, biostratigraphy and electrolog data, high frequency T/R cycles have been mapped in the studied interval. The most common diagenetic phenomenon in the Oligo-Miocene carbonates is sparitization. It has resulted in destruction of both primary and secondary porosity rendering poor reservoir quality. Early phase dolomitization, bioturbations and stylolaminations indicating late stage chemical compaction have also adversely affected the porosity. Nonetheless, selective dissolution, especially at the top of the T/R cycles, has resulted in good secondary porosity in the form of vugs, molds, solution channels and intercrystalline pores rendering good reservoir quality.

Introduction
The Deep Continental Shelf, west and south of Mumbai High hosts Cenozoic clastics and carbonates that have been extensively explored for hydrocarbons, especially the carbonates of Oligocene and Miocene ages. These carbonates show frequent facies changes both in space and time. The sedimentological and biostratigraphic studies were carried out on well X with an objective to demarcate age boundaries, litho-microfacies analyses, infer environment of deposition, evaluate T-R cycles within sequence stratigraphic framework and diagenetic study for reservoir characterization of Oligo-Miocene succession.

Methodology
Foraminiferal biostratigraphic studies were carried out on all the cores and cutting samples in the interval 3150 m- 1675m to determine the age boundaries, hiatuses, environment of deposition and paleobathymetry. The 'Last Occurrence' level of the index fauna is considered for the demarcation of age boundaries. In case of its absence or poor sample control, the faunal assemblage as a whole is taken into consideration along with change in electro-log motifs in deciphering the age boundaries. Sedimentological studies included detailed megascopic, microfacies analyses and X-Ray diffractometry (XRD) studies to bring out lithological variations, mineralogical composition, environmental interpretation and reservoir characterization of the studied succession.

Observations and depositional history
The Oligo-Miocene carbonates of well X represent
deposition in lagoonal complex of platform interior on rimmed carbonate platform. The lithofacies and biostratigraphy data have been utilized to demarcate the microenvironments. The facies zones present in lagoonal setup of platform interior (Fig.1) are open shelf carbonate sand flat / bank (at the edge of the rimmed shelf), open lagoonal environment and restricted lagoon. The temporal variation of these facies zone is discused below.

Oligocene

The Early Oligocene succession is represented predominantly by carbonates with intercalated shale. Algal foraminiferal packstone and wackestone represent major microfacies of the succession (Fig.2). Towards the top, it is mainly wackestone with occasional mudstone. The matrix is highly sparitised. Porosity is poor to moderate represented by vugs, intra-particle pores and molds. Intercrystalline porosity is present at places. Stylolites filled with argillaceous matrix are also present.

The foraminiferal assemblage includes *Heterostegina* sp., *Elphidium* sp. *and Rotalia* sp. It suggests 5-10m bathymetry.

Presence of foraminiferal packstone and wackestone, occasional occurrence of mudstone with smaller benthics in shallow bathymetric condition suggest deposition in an open lagoonal setup of platform interior.

During Late Oligocene, the study area experienced predominant carbonate sedimentation with occasional intercalations of shale, carbonaceous shale and coal towards the upper part. Thick Late Oligocene succession is represented by algal foraminiferal packstone to wackestone, coralgal- foraminiferal packstone, dolostone and at places interlayered mudstone or carbonaceous shale, shale and coal (Fig.3). Porosity is moderate to poor and at places, presence of vugs, solution channels, intercrystalline pores and molds result in enhancement of porosity. Carbonaceous matter is present as fillings in stylolites and as specks and lenses.

The faunal assemblage represents *Grybowskia tandoni, Heterostegina* sp., *Lepidocyclina* sp., *Spiroclypeus* sp., *Pararotalia* sp., *Elphidium* sp., *Rotalia* sp., *Floridus* sp., *Biloculina* sp., *Borelis* sp., *Operculina* sp., *Discorbis* sp., miliolids and ostracods suggesting a bathymetry of 5-15m.

Presence of foraminiferal algal packstone-wackestone, mudstone, bioclastic packstone with occurrence of occasional coralgal foraminiferal packstone suggests open lagoonal depositional setup which becomes restricted lagoonal towards the top of the succession evidenced by occurrence of shale, carbonaceous shale, coal and dolostone at places.

The isochronopach map of Oligocene (Fig.4) shows a distinct linear shelf edge oriented in NW-SE direction. The well X lies behind the shelf edge which corraborates a lagoonal setup of a rimmed platform.

Miocene

The Early Miocene succession is dominantly represented by carbonates. Shale and carbonaceous shale intercalations occurs towards the top. The carbonate deposition commenced with the low energy mudstone facies and gradually became packstone to wackestone. A conventional core CC#4 (2210.36 m to 2219.36m) represents the top of the succession which is characterized by foraminiferal bioclastic packstone and packstone-wackestone. Fossils are highly sparitised and packed in micritic matrix. Minute specs of pyrite and carbonaceous matter are disseminated throughout the core. The overall porosity of the succession is poor to moderate.

At the beginning of Early Miocene, foraminiferal frequency and diversity was more as compared to the rest of the succession and gradually becomes very poor to poor. This implies, the bathymetry initially varied between 10 to 20m and becomes shallower that is 5 to 10m for the rest of the succession.

The faunal assemblage includes *Miogypsina indica, Heterostegina* sp., *Sphaeogypsina* sp., *Lepidocyclina* sp., *Archaias* sp., *Elphidium* sp., *Cribroelphidium* sp., *Amphistegina* sp., *Marginopora* sp., *Operculina* sp., *Discorbis* sp., miliolids and ostracods etc.

Presence of low energy mudstone (Fig.5) along with wackestone and packstone at the bottom of the succession suggest open lagoonal environment. Towards the top packstone to wackestone inter-layered with thin laminae of mudstone, shale and carbonaceous shale indicates restricted lagoonal depositional condition. Similar depositional conditions continued to prevail during Middle Miocene.

The Middle Miocene succession is represented mainly by carbonates with thin shale intercalations with occurrences of carbonaceous shale towards the bottom. Beginning of the succession is marked by the presence of packstone to wackestone facies (Fig.6) with minor mudstone and intercalations of shale and carbonaceous shale and rarely coal. Three conventional cores CC#3 (1990-1999 m), CC#2 (1880-1889 m) and CC#1 (1721.23-1730.23) were cut in Middle Miocene succession. Algal coral boundstone and floatstone fragments in carbonate mud with shale intercalations along with packstone and mudstone represents CC#3 and CC#1. CC#2 is represented mainly by bioclastic packstone to wackestone. Bathymetry throughout the interval fluctuated between 5 to 15 m. A rise in bathymetry between 10 to 20 m has been observed towards the top of the succession. Beginning of Late Miocene is marked end of carbonate deposition. This was followed by deposition of finer clastics (shale) in bathymetry of 40-80 m.

During Miocene, carbonate deposition continued and the platform expanded and prograded the SW direction. The progradation of shelf edge is also evident from the isochronopach map of Early and Middle Miocene epoch (Fig.7).

Sequence Stratigraphy and Trangressive-Regressive (T/R) cycles in Oligo-Miocene Carbonates

The Oligo-Miocene carbonate platform in the well X is characterized by stacks of high frequency T/R cycles of variable thickness. Each cycle begins with low energy mud supported facies (with fining upward, retrograding stacking pattern) and ends with prograding/aggrading high energy grain supported facies. At places, the cycles culminate into short duration subaerial exposures. The cyclicity of carbonate sedimentation in shelf settings, causing variation in cycle thickness, is the result of short term oscillation in sea level. The litho-biochronostratigraphic analysis of the well shows temporal changes of cycle characteristics with lithofacies, depositional setup, diagenetic changes and porosity trends.

Based on lithomicrofacies analysis, biostratigraphy and electrologs, high frequency cycles are mapped in well X. One, seven, four and seven cycles have been identified in Early Oligocene, Late Oligocene, Early Miocene and Middle Miocene, respectively (Fig 8). It has been observed that porosity is good at top of the cycles of Late Oligocene and cycle 1 of Early Miocene. Here selective dissolution has resulted in vugs, molds, solution channels and intercrystalline pores creating secondary porosity.

Diagenesis

Diagenesis plays a pivotal role in the porosity evolution of carbonates. These diagenetic changes are influenced by sediment composition, grain size, ambient fluid compositions and sea level changes. Therefore by evaluating the diagenetic events within sequence stratigraphic framework (high frequency T/R cycles), the porosity becomes more predictable for inferring reservoir characteristics.

In the present study, major diagenetic events include sparitization, dissolution, pyritization and dolomitization at places. Sparitization destroys porosity in most cases and occurs due to precipitation of calcium carbonate during diagenesis. Sparitization observed in carbonates of well X is inferred to be of marine (fibrous spar), meteoric phreatic zone (blocky and isopachous) and burial environment (drusy and equant). It is the most widespread diagenetic feature that is omnipresent in carbonates from Late Eocene to Middle Miocene.

Another significant event is intermittent short duration sub aerial exposures. This results in dissolution and leaching of the sediments. Chalky nature and secondary porosity creation are diagenetic features associated with subaerial exposure. In well X, subsequent cementation (many generations of cementation observed at places) has resulted in secondary porosity destruction. Nevertheless few cycle tops especially during Late Oligocene and Early Miocene exhibit porosity preservation rendering good reservoir potential.

Dolomitization is commonly believed to be critical to porosity preservation. Thin cycles deposited especially during highstand are often preferably dolomitized either by restricted seawater or tidal flat circulation. However, in this case dolomitization is commonly observed during transgression which has been felicitated by hypersaline waters of restricted lagoonal environments. The porosity has been destroyed due to early phase dolomitization resulting in poor reservoir conditions. The porosity distribution in carbonates is altered systematically during sub aerial exposures and meteoric diagenesis.

Other diagenetic features such as stylolaminations (ranging from wispy, anastomosing and seams of stylolites) present in most carbonates of the studied section are filled with argillaceous or carbonaceous matter. The presence of stylolite indicates late stage chemical compaction during diagenesis. This results in porosity occlusion and reduction in permeability thereby reducing reservoir quality.

Bioturbation in the form of tubular burrows are commonly observed in Middle Miocene (CC#3 and CC#1). The bioturbated sediments exhibit poor porosity except where the burrows are open or partially filled.

An integrated chart in Fig 8 summarizes the T/R cycle, depositional and diagenetic history of Oligocene- Miocene carbonates of well X.

Conclusions

The Oligo-Miocene succession in well X is represented by carbonates deposited in lagoonal environment of platform interior. Detailed analysis of litho-microfacies and biostratigraphy helped in further refining of the microenvironments for the succession. During Early Oligocene to lower part of Late Oligocene, open lagoonal setup was prevalent whereas during major part of Late Oligocene the environment remained restricted. During the beginning of Early Miocene, the environment once again became open lagoonal, which later became restricted and continued to be so in Middle Miocene. The carbonate platform ceased to grow during Late Miocene which witnessed deposition of fine clastics (thick shale) and gradual rise in bathymetry from 10-20m to 40-80m. Vertical distribution of sedimentary facies and their interpreted depositional environments indicate a regressive phase from Late Eocene to Late Oligocene, transgression from Late Oligocene to Early Miocene and again regressive in Middle Miocene. Transgression commenced in Late Miocene which resulted in deposition of finer clastic and cessation of growth of carbonate platform. The development of primary porosity in sediments deposited in lagoonal environment of platform interior is poor. Good reservoir rocks are seldom formed in this environment. Based on sequence stratigraphy with incorporated litho-microfacies, biostratigraphy and electrolog data, high frequency T/R cycles have been mapped. The major diagenetic sedimentary feature includes sparitization, dolomitization, stylolaminations, bioturbation, pyritization, and selective dissolution resulting in chalky nature and porosity creation at places. The most widespread and common diagenetic phenomena in the Oligo-Miocene carbonates is sparitization. It has resulted in destruction of both primary and secondary porosity rendering poor reservoir quality to the Oligo-Miocene carbonates. Early phase dolomitization (from hypersaline restricted lagoon waters) has also resulted in porosity occlusion. The other diagenetic features that have adversely affected reservoir potential include stylolaminations and bioturbations. At certain intervals, especially at the top of cycles of Late Oligocene and cycle 1 of Early Miocene, selective dissolution has resulted in vugs, molds, solution channels and intercrystalline pores creating secondary porosity and good reservoir quality.

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