Decoding Early Oligocene Carbonates: Facies Associations, Sequence Stratigraphy, and Reservoir Potential in N & N-W of Heera, Mumbai Offshore

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Sequence stratigraphy, depositional facies, diagenesis petrography, Early Oligocene, Mumbai Offshore

Abstract
The study aims to determine the depositional facies, high resolution sequence stratigraphy and diagenetic processes of Early Oligocene carbonates in N & N-W of Heera, Mumbai Offshore. Foraminiferal assemblage and microfacies from cores of Well A, B, C, D and E are indicative of facies association related to four depositional environments i.e., restricted inner lagoons-tidal flats, shallow open lagoons, high energy carbonate bars-shoal complex and deeper mid-ramps of a westerly dipping homoclinal carbonate ramp. Two high frequency (4^{th} Order) depositional sequences bounded by sequence boundary, DS1 and DS2 displaying hierarchical stacking pattern are identified and correlated across wells. Furthermore, the study highlights the influence of vadose zone diagenesis resulting from short diastems/subaerial exposure. This diagenetic process has led to the development of favorable porosity in the highstand systems tract (HST) carbonates and effecting the underlying transgressive systems tract (TST) sediments in Well D, C, and E. Vadose zone diagenesis effect during short diastem/ subaerial exposure have rendered good porosity due to dissolution in HST carbonates and occasionally effected underlying TST sediments (Well D, C and E). By mapping and correlating the sequences, the study identifies thin carbonate bars that hold potential as reservoirs. These carbonate bars are envisaged to extend along Wells E, D, and C in northwest-southeast trend. Furthermore, a more pronounced development of these carbonate bars, oriented in the same direction, and are anticipated towards the western extent of the study area.

Introduction

This paper deals with the Mukta Formation, an Oligocene carbonate succession in the north and northwestern Heera field, Western Offshore Basin, Wester Western Offshore Basin on the Western Continental Margin of Indian (Figure 1). The carbonate sediments in the study area offer an opportunity to investigate the relationship between sedimentary facies and sequence stratigraphy of a carbonate platform.

The Mukta Formation is a significant carbonate reservoir in the basin and comprises primarily limestone and dolomitic limestone with interbedded shale.

This paper reports on a sedimentological study of conventional cores from Mukta Fm. whose results could contribute to a better understanding of the subsurface facies distribution. The main objectives of this research were focused on (1) a description of the facies and their distribution on the Early Oligocene carbonate platform, (2) the paleoenvironmental reconstruction of the carbonate platform, and (3) the origin of sequences that developed in the study area mainly based on the distribution of the foraminifera, (4) Effects of diagenesis on the carbonate reservoir.

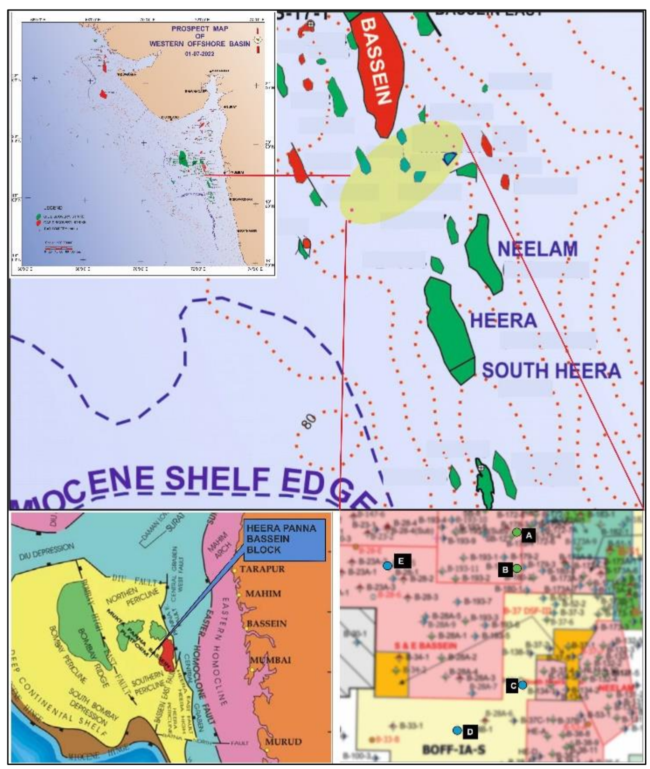

Fig. 1: Location map

General Geology

Notably, Heera field has proven hydrocarbons in the Basement, Early Paleocene-Late Eocene, and Early Oligocene intervals. Bombay High East Fault marks the western boundary of Heera Panna Bassein Block while the Vijaydurg graben forms the southern limit of the area. The major tectonic elements are oriented in NNW-SSE and NW-SE, NE-SW and ENE WSW. The central graben is the major depocenter, which has accommodated more than 4km sediments lies to the east. To the south west of Heera Panna Bassein, platform gradually deepens and forms the Murud Low.

Cenozoic sedimentary (variable thickness from 2.5 to 4.3 km) sequence ranging from Paleocene to Recent. The Deccan Traps of Late Cretaceous Early Paleocene age forms the technical basement of the region, though, at places especially at paleo-highs, the Archean basement has also been encountered. The Panna Formation of Late Paleocene to Early Eocene age non-conformably overlies the Deccan trap basalt Precambrian granitic-gneiss. It is bounded by H5 marker corresponding to the Basement top at the bottom and H4 seismic marker at the top. Middle to Upper Eocene Bassein Formation, consists of carbonates with minor shale units. It unconformably overlies the Panna Formation H3B seismic marker marks the top of Bassein Formation. The B Lower is a shale- carbonate interface which divides Bassein formation into two units, i.e., Lower Bassein Unit between H4 and B Lower markers and Upper Bassein Unit between B Lower and H3B markers. The Mukta Formation between H3B at bottom and H3A at top unconformably overlies the Bassein Formation. The overlying Heera Formation is bounded by H3A at bottom and H3G at top. Mukta and Heera formations are of Lower Oligocene age and contain limestone and shale alternations. The Upper Oligocene Alibag Formation between H3G and H3CGG is dominantly shaly unit with minor limestone streaks. A thick argillaceous sequence between H3CGG and H1C with thin limestone bands of Lower Miocene age overlies the Alibag Formation and is called the Mahim/ Bombay Formation. This, in turn, is overlain by the shale and thin limestone of Tapti Formation, between H1C and H1A, markers. Post Middle Miocene shale and claystone of Chinchini Formation, between H1A and water-bottom mark the end of carbonate sedimentation in the basin except over the isolated banks, some of which continue to grow even today.

The Cenozoic column is divisible into two genetic stages: Syn rift (during Paleocene) and Post rift (Post Paleocene). Organic rich shales of Panna Formation acted as main source rock for Bombay Offshore Basin. Panna sandstones (Paleocene to Lower Eocene) and Bassein carbonates (Middle to Late Eocene) and Mukta carbonates (Lower Oligocene) are the three major hydrocarbon producing formations of the HPB sector. Figure 2 shows the generalized stratigraphic column of the region.

In the study area lying North and Northwest of Heera field, the Early Oligocene carbonates of the Mukta Formation (with a thickness ranging from 24-79m) are observed to unconformably overlie Middle-Late Eocene sediments. The focus of this study is to analyze bio-litho-microfacies of cores to interpret the depositional environment, high-frequency sequence stratigraphy, and diagenesis processes, with the aim of characterizing the reservoir.

Methodology

In this study, sedimentological attributes including megascopy, litho-microfacies, textural characteristics, and sedimentary structures were analyzed in six conventional cores retrieved from Wells A, B, C, D, and E. The purpose was to gain insights into the depositional environment and diagenetic processes. X-ray diffraction (XRD) analysis was conducted to examine the mineralogy of the samples.

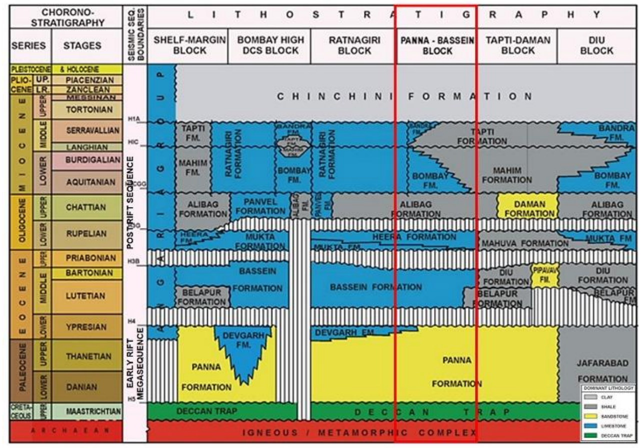

Fig. 2: Generalized stratigraphy

Biostratigraphic studies focused on the analysis of benthic foraminifers, providing valuable information on paleobathymetry and the environmental conditions prevailing during deposition.

The identification of depositional sequences, systems tracts (transgressive systems tract and highstand systems tract), and significant stratigraphic surfaces such as the maximum flooding surface and sequence boundary was accomplished through the analysis of stacking patterns of parasequences and the hierarchical nature of sedimentary cycles. Furthermore, correlation of these identified features was established across the different wells studied.

Facies analysis and Depositional history

Based on the microfacies and associated biofacies, textures, lithology and, sedimentary structures, five facies association (FA) are identified representing deposition in Tidal flat (A), Restricted lagoon (B), Mixed Lagoon (C), Open Lagoons (D), Shoal complex (E). Facies analysis and those comparisons with modern and ancient environments indicate that the Mukta formation was deposited inner to middle ramp setup within a homoclinal ramp (Fig. 7.). A detailed description of each of these lithofacies is given below

A. Inner shelfal lagoon-Tidal flats

The following microfacies representing deposition in tidal flat and inner lagoons were identified (Fig. 3A-F)

1. **Dolomitized mudstone**: The microfacies is with low diversity and a limited fossil yield. The micritic matrix exhibits intense replacement by non-mimetic dolomite, occurring as fine to medium-grained euhedral rhombs dispersed throughout the matrix. Occasional occurrences of pyrite and ferruginous specs/streaks are also observed within the microfacies.
2. **Sideritic dolomitized mudstone** is brownish black, moderately hard, fissile, feebly-non calcareous, highly carbonaceous (streaks, lenses and fine laminations) and pyritized.

3. **Miliolitic peloidal bioclastic wackestone** -Fossils grains consist of miliolids, abundant peloids few algal oncoids, small nummulites and very fine grained-silt sized bioclast in inhomogeneous peloidal micritic matrix.
4. **Bioclastic foraminiferal wackestone to mudstone-** Few sparitized grains are seen floating in micrite.

Interpretation: Presence of mud supported limestone microfacies, carbonaceous matter, siderite nodules, low faunal assemblage and presence of miliolids indicate low energy restricted conditions. Additionally, algae, abundance of peloids and bioturbations indicate deposition in low energy inner lagoons to mud rich tidal flats.

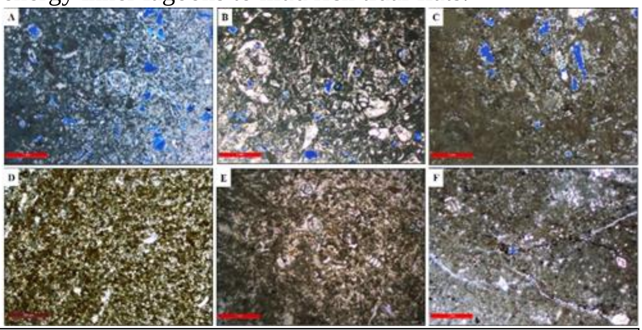

Fig.3 (A-f): Photomicrographs showing microfacies types in tidal flat environment-A. Miliolid bioclastic wackestone (Well A, CC-2 Depth 1798.60m); B.Bioclastic foraminiferal wackestone to mudstone (Well A, CC-2 Depth 1798.87m); C. Peloidal bioclastic wackestone (Well A, CC-2 Depth 1799.40m); D. Dolomitic mudstone to wackestone (Well B, CC-2 Depth 1616.45 m); E. Miliolitic bioclastic wackestone (Well B, CC-2 Depth 1622.37 m); F. Foraminiferal bioclastic mudstone to wackestone (Well C, CC-2 Depth 1657).

B. Outer lagoon (Inner ramp)

Following are the dominant microfacies representing outer lagoon environment (Fig. 4A-H).

1. **Bioturbated coralline foraminiferal wackestone-** Solitary coral grains, algal fragments, bryozoan and foraminifers are seen in micrite. The skeletal framework is sparitized and occasionally bored by benthics, whereas the chambers are filled with micrite. Poor porosity.
2. **Nummulitic lepidocyclina foraminiferal wackestone- packstone-** Both larger and smaller forams (Nummulites, N.fitcheli, lepidocyclina, rotalid), bioclast and shell fragments are observed in micrite. Fossil test shows well preserved aragonitic fabric. Glauconite is present as fillings and pellets. Presence of few minute vugs result in poor porosity.
3. **Nummulitic wackestone-packstone-** Smaller and larger forams (dominantly Nummulites), bioclasts are present in micritic matrix which is dolomitized. Disseminated pyrite specks are also seen. Porosity is good exhibited by intraparticle pores, molds and vugs.
4. **Bioclastic algal -peloidal wackestone-** Fossils (forams, bioclasts and peloids) are embedded in lime mud matrix. Partial sparitization of few bioclasts is observed. At places calcite cementation is observed.
5. **Algal foraminiferal wackestone-** Fossils are micritic, occasionally sparitized and consist of foraminifers, bioclasts and algae embedded in partially sparitized matrix. Occasionally bioclasts are fractured. Stylolaminations filled with argillaceous content is seen.

Interpretation: Mud supported limestone microfacies

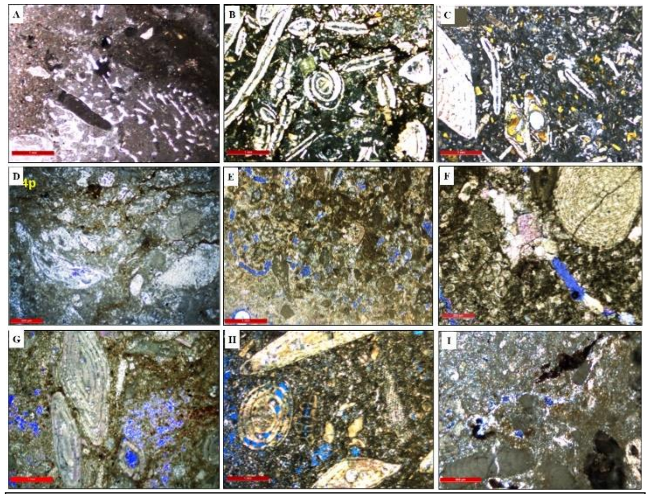

Fig.4 (A-I): Photomicrographs showing microfacies types in Outer Lagoon-A. Bioturbated coralline foraminiferal wackestone (Well E, CC-1 Depth 2080m); B. Nummulitic lepidocyclina foraminiferal wackestone- packstone (Well E, CC-1 Depth 2083m); C. Nummulitic wackestone-packstone (Well E, CC-1 Depth 2084.4m); D. Bioclastic algal wackestone (Well E, CC-1 Depth 2087m); E. Bioclastic peloidal wackestone (Well A, CC-2 Depth 2091.10m); F. Foraminiferal bioclastic wackestone (Well A, CC-2 Depth 2094.5 m); G. Dolomitic nummulitic bioclastic wackestone (Well B, CC-2 Depth 1616.30 m); H. Nummulite wackestone (Well B, CC-2 Depth 1617.17 m); I Algal foraminiferal wackestone (Well C, CC-1 Depth 1657.82 m).

indicate deposition in low energy. The foraminiferal assemblage is dominated by larger benthic foraminifera such as abundant Nummulites, N.fichtelii, Lepidocylcina sp., rotaliid and few miliolids suggest open marine conditions in bathymetry ranging from 10-20m. Local transportation is indicated by bioclasts. Fluctuations in environment open marine to lagoonal is indicated by mixed faunal assemblages consisting of Nummulites (open marine) and miliolids (restricted environment). In addition, corals and bryozoan indicate presence of patchy reef.

Glauconite pellets and burrows are also observed indicating low energy and low sedimentation rates. Hence the depositional environment can be concluded to be outer lagoon with open marine conditions.

Carbonate bars (Mid ramp):

The high energy microfacies such as nummulitic packstone (Fig. 5A-1),

1. **Bioclastic foraminiferal packstone-** Smaller foraminifera, bryozoa, bioclast, peloids, algal and shell fragments are packed with occasional minor micritic matrix. Blocky calcite and dolomite are seen at places.
2. **Nummulitic glauconitic grainstone-** Large Nummulites (>1mm) are the dominant framework grains and are packed in minor micro-spritized matrix. Compaction has resulted in sutured grain boundary and

internal fracture. The nummulite chambers are filled with glauconite.

3. **Coralline boundstone-** The skeletal framework of the corals is completely sparitized to blocky calcite whereas the coral chamber is filled with micrite. Dolomite is also observed at places.
4. **Nummulitic packstone to grainstone-** Larger foraminiferal grains of Nummulites, Spherogypsina, Lepidocyclina along with algal frag-ments and bioclast are densely packed. Matrix if any (packstone facies) is composed of micro-spars and minute dolomite rhombs. Intense compaction is observed in the grainstone facies resulting in sutured grain boundary and microfractures within grains.
5. **Nummulitic operculina packstone-** Larger foraminifers such as Nummulites, Spherogypsina, Operculina along with algal fragments and corals are packed in micrite. The grains are sparitized.
6. **Lepidocylcina algal packstone-** Partially sparitized lepidocyclina, bioclasts and algal filaments are packed in minor micritic matrix. At places the grains are sparitized. Porosity is moderate to good rendered by intra-particle and several vugs.

Interpretation: The lack of mud, grain supported fabric, abundance of Nummulites, Lepidocyclina, Operculina, spherogypsina etc. that thrive in oligotrophic open marine environment, presence of bioclast indicate high energy depositional environment in carbonate bars/shoals. In addition, corals and bryozoan indicate presence of patchy reef. Glauconite are formed in low energy and low sedimentation sub anoxic environment. However, the presence of glauconite as fill in fossil chambers in such high energy facies suggest that it is diagenetic.

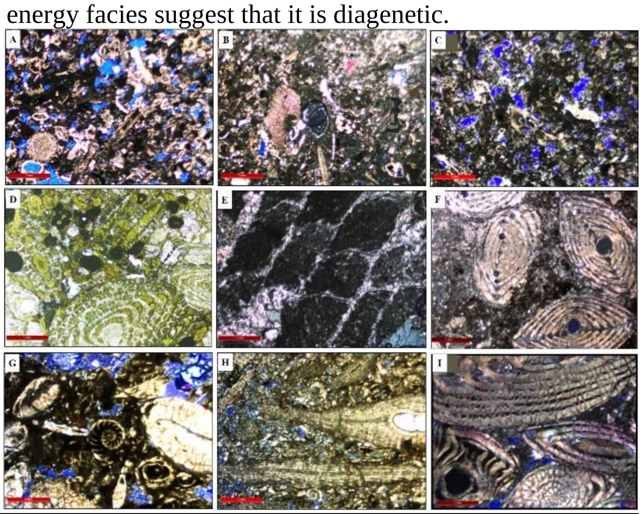

Fig.5 (A-I): Photomicrographs showing microfacies types in Carbonate Bars- A. Bioclastic foraminiferal packstone (Well E, CC-2 Depth 2088m; B. Foraminiferal bioclastic packstone (Well E, CC-2 Depth 2089m); C. Foraminiferal bioclastic packstone (Well E, CC-2 Depth 2090m); D. Nummulitic glauconitic grainstone (Well D, CC-3 Depth 2019.56 m); E. Coralline boundstone (Well C, CC-1 Depth 1650.21 m); F. Nummulitic packstone (Well C, CC-1 Depth 1650.21 m); G. Nummulitic operculina packstone (Well D, CC-3 Depth 2015.85 m); H. Lepidocylcina algal packstone (Well D, CC-3 Depth 2016.9 m); I. Nummulitic grainstone (Well D, CC-3 Depth 2018.10 m).

4. Deeper mid ramp.

This environment is represented by dark grey, moderately hard, highly fissile and calcareous shale occurring in sharp contact with Nummulitic packstone and grainstone. The immediate association of low energy calcareous shale with high energy midramp carbonate shoals and presence of thin glauconitic, sideritic, pyritized and bioturbated grainstone (Fig. 5) beds (representing condensed section at MFS) in shale indicate deposition in deeper mid ramp.

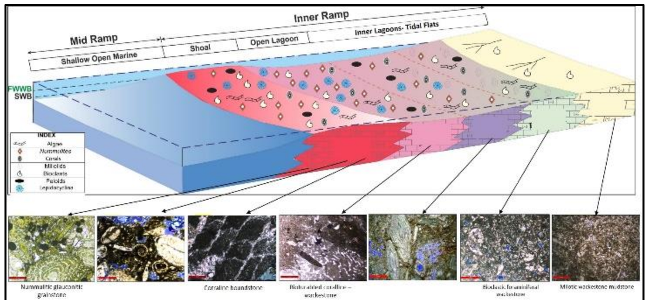

Fig. 6. Depositional model and distribution of facies association (FAs) in Mukta Formation

SEQUENCE STRATIGRAPHY

The Early Oligocene carbonate platform in the study is characterized by stacks of Transgressive-Regressive cycles of variable thickness is the result of short term oscillation in sea level. The litho-biostratigraphic analysis of the wells showing temporal changes in lithofacies, depositional setup, diagenesis and porosity is represented in Fig 12-13.

Depositional sequences, systems tracts and stratigraphic surfaces of the Early Oligocene are identified according to the stacking pattern and sedimentary cycles. The identified stratigraphic surfaces (maximum flooding surface and sequence boundary) have been correlated across wells. In instances where sedimentological data control is lacking, electro-log signatures are utilized as additional support for correlation. Two depositional sequence (DS) were identified and are discussed in detail below.

Depositional sequence 1 (DS1)

This sequence overlies a subaerial unconformity (Mid-Late Eocene top). A retrograding stacking pattern is identified, characterized by the successive occurrence of inner lagoon, outer lagoon, carbonate ramp, and deeper mid-ramp facies. This arrangement signifies the presence of a transgressive systems tract (TST) within the sequence, which is indicative of a rise in relative base level. In Well C, the TST culminates with high-energy packstone facies associated with carbonate bars, while Wells E and B show a facies transition from inner lagoon to outer lagoon environments. The maximum flooding surface (MFS) of this unit is marked by the presence of mid-ramp shales and glauconitic, sideritic, pyritized, and bioturbated grainstone beds in Well D, which represents a condensed zone.

The overlying Highstand systems tract (HST) deposited during a gradual rise in base level, and characterized by an aggradational/progradational stacking pattern. In Well D, the HST initiates with deposition in carbonate bar/shoal deposition, and concludes with inner restricted lagoon deposition in Wells B and E, indicating a shallowing up trend. The termination of the HST is marked by a diastem, indicating subaerial exposure. Compared to the TST, the HST is relatively thinner (approximately 5m). The due to vadose zone diagenetic process resulting from subaerial exposure has significantly impacted both the HST and the underlying TST, leading to the development of favorable porosity reservoirs within the carbonate bars of Wells D and C.

Depositional sequence 2 (DS2)

The transgressive systems tract (TST) of this sequence is positioned above the sequence boundary of DS1 and commences with the deposition of lithofacies representing inner lagoon, outer lagoon, and carbonate bars, displaying a retrograding stacking pattern in wells E and B. The subsequent highstand systems tract (HST), characterized by a shallowing trend, comprises outer lagoon facies towards the western portion (Well E) and a transition from outer lagoon to inner lagoon facies towards the eastern part (Well B). The depositional sequence culminates with a sequence boundary associated with subaerial exposure at the top of the Early Oligocene.

The variations in depositional lithofacies within this sequence are comparatively less pronounced compared to the previously identified DS1. This suggests intermittent base level fluctuations that resulted in minor shifts in the depositional environment. However, the limited availability of sedimentological data across most parts of the study area restricts a comprehensive analysis of this sequence, with detailed information only available for the northern section encompassing wells E and B.

DIAGENESIS

Based on the analysis of diagenetic features, several diagenetic environments including the meteoric phreatic zone, mixing zone, and vadose zone have been identified. The predominant diagenetic process observed in the studied area is sparitization, characterized by coarse blocky calcite, indicating diagenesis in a freshwater phreatic zone. Additionally, the presence of dolomite, commonly observed in the highstand systems tract (HST) of wells E and B, suggests the influence of a mixing zone in the northern region of the study area.

The occurrence of gypsum along with siderite in wells D, C, and B indicates reducing hypersaline shallow conditions prevailing in tidal flats and lagoons within the HST, particularly near the sequence boundary. This interpretation is supported by the widespread pyritization observed in most of the wells. Occasional bioturbations, primarily observed in the transgressive systems tract (TST) and maximum flooding surface (MFS) zones of wells B, HWD-1, and D, indicate intermittent cessations of sedimentation, which are common in shallow restricted environments.

Glauconite, present in wells E and D, is indicative of its formation in passive shelf-margin environments within the mid-ramp settings characterized by sediment-starved conditions, low terrigenous sediment input, favorable substrates, high organic activity, and suitable physical-chemical conditions. Occasional oxidization of glauconite suggests intermittent periods of subaerial exposure.

Well-developed porosity zones are observed in wells E and D, particularly within the carbonate bars, attributed to dissolution processes in the marine vadose zone. The major porosity types resulting from dissolution include vugs, molds, interparticle pores, and solution channels.

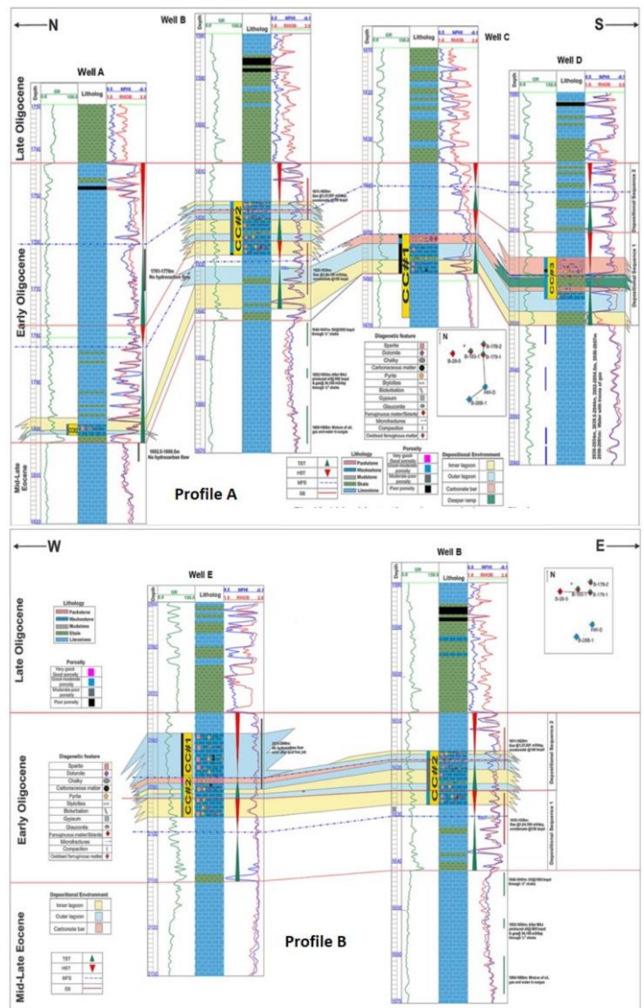

Fig. 7. Correlation profile

7. CONCLUSION

The study area encompasses Early Oligocene carbonates that unconformably overlie Middle-Late Eocene sediments. These carbonates were deposited within a shallow marine environment characterized by a homoclinal ramp setting, with bathymetry ranging from 0 to 30 meters. Intermittent thin shale intercalations within the succession indicate periodic interruptions in carbonate sedimentation, potentially associated with deposition in deeper mid ramp areas.

The predominant microlithofacies identified is mud-supported bioclastic foraminiferal wackestone, indicating a prevailing low-energy lagoonal environment throughout most of the Early Oligocene. However, sporadic variations in the depositional environment are inferred, manifesting as shifts from restricted inner lagoons and mid ramp carbonate bars to deeper mid ramp settings.

Notably, thin carbonate bars, measuring 5-10 meters in thickness, are observed towards the western and southern regions along Wells E, D, and C suggesting the presence of a weak barrier system oriented parallel to the paleo shoreline. Consequently, this barrier system has influenced the development of shallow open lagoons in the eastern part of the study area (Wells A and B). Toward the northeast (Well A), a further restricted conditions are observed, characterized by mudstone and dolomitic-rich facies within the inner lagoons.

Vadose zone diagenesis, occurring during brief periods of diastem or subaerial exposure, has significantly impacted the porosity characteristics of the highstand systems tract (HST) carbonates. Notably, this diagenetic process has occasionally extended into the underlying transgressive systems tract (TST) sediments, resulting in the formation of favorable porosity reservoir facies (Wells D, C, and E) through dissolution mechanisms. The thin carbonate bars, exhibiting distinctive porosity attributes, hold promising potential as hydrocarbon reservoir facies.

Spatially, the presence of thin carbonate bars is anticipated to follow a northwest to southeast trend, extending along Wells E, D, and C. Additionally, a more pronounced development of these carbonate bars in the same orientation is expected in the western portion of the study area.

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