Challenges and Characterization of Newly Targeted Upper Jurassic Carbonates, Agiba's Meleiha Field, Western Desert, Egypt

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Abstract

In Agiba's Meleiha field, shallow and deep targets are mainly Cretaceous and/or Jurassic clastics, while carbonate sections are not properly explored with appropriate success.

The Masajid Formation is described as a massive shallow marine carbonate sequence of Middle to Late Jurassic-Callovian/Kimmerdgian age. Recently, the Masajid Formation was determined to have significant potential through the detection of gas anomalies supplemented with petrophysical evaluation based on openhole logs (triple combo, microresistivity images, spectral gamma mineralogical analysis, etc.) that integrated with sidewall cores, petrographic, and X-ray diffraction (XRD) results.

This paper discusses the origin of the Masajid Formation, the criteria encouraged focusing on the Masajid, and the step-by-step methodology for evaluating the potential of Masajid carbonates in the Meleiha field.

Exploration of the Masajid Formation is challenging because of its intrinsic heterogeneities. These heterogeneities can be attributed to variable lithology, chemistry/mineralogy, pore types, and pore connectivity. These fundamental complexities are related to the geological processes controlling carbonate production and deposition, in addition to the diagenetic changes and their impact on reservoir quality.

The original complicated porosity-permeability system within the Masajid Formation is highly modified by secondary diagenetic processes and phases. The distribution and degree of dolomitization, fracture characteristics, and carbonate dissolution are the main post-depositional processes enhancing the reservoir quality of the Masajid Formation. They are geologically assessed and petrophysically evaluated using the available data set to control the reservoir quality within the Masajid Formation in the Meleiha field.

In the Meleiha field, this challenging carbonate succession was proven to be a promising hydrocarbon-bearing reservoir after conducting and integrating advanced technologies with a successful test.

Introduction

The Western Desert of Egypt is a well-known hydrocarbon province, especially its northern part, which comprises many proven mature and producing basins. Agiba's Meleiha Development Lease is located between the Matruh and Shushan basins within this area. This concession lies 65 km south of the coastal Marsa Matruh city, between latitudes 30° 36' to 30° 54' N and longitudes 27° 00' to 27° 18' E and covering an area of approximately 700 km^2.

The Meleiha Development Lease is operated by Agiba Petroleum Company, which is a joint venture between the Egyptian General Petroleum Corporation (EGPC) and IEOC-ENI. The Meleiha West Deep field is located at the west central part of the Meleiha concession as shown in **Fig. 1**. The area of this field is estimated to be approximately 3 km^2 and lies between latitudes 30° 45' to 30° 45' 40" N and longitudes 27° 03' to 27° 05' E.

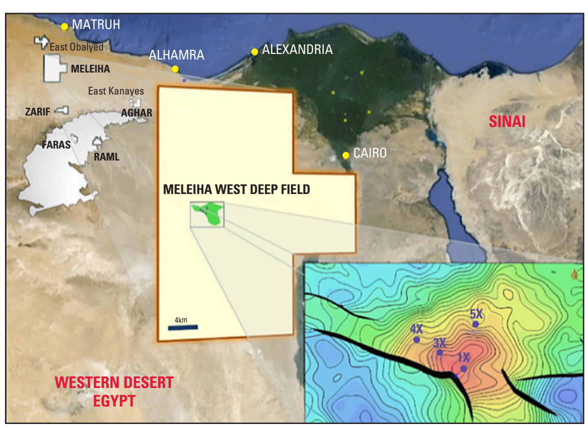


Fig. 1. *Location of the Meleiha West Deep field, including the studied wells on a structural contour map of the top of the Masajid Formation.*

Along the Meleiha concession, three clastic reservoirs were targeted including the oil-bearing Early Cenomenian Bahariya Formation, oil/gas-bearing Berriasian-Barremian Alam El Bueib member of the Burg el Arab Formation, and oil/gas-bearing Middle Jurassic (i.e., Khatatba Formation), which is known also as the main source rock charging these reservoirs.

Recently, the Middle to Late Jurassic carbonates (i.e., the Masajid Formation) were determined to be a potential reservoir in the Meleiha Development Lease. Thus, this study was conducted based on four wells (1X, 3X, 4X, and 5X) in the Meleiha West Deep field (Fig. 1) to highlight the Masajid origin, its diagenetic history, and the impact on the reservoir performance, and its hydrocarbon potential.

The Geological Setting of the Meleiha Concession

Throughout the north Western Desert, the main tectonic activity occurred during the Mesozoic and Early Tertiary. In the area of the Meleiha concession, these events are expressed by two major phases of faulting during the Late Jurassic to earliest Cretaceous and during the Late Cretaceous (Turonian) to Eocene. Within each phase, there probably has been a number of faulting events, in addition to which individual faults display isolated movement during the Early Cretaceous to Late Cretaceous (pre-Turonian).

Faulting style is predominantly extensional (normal), although strike slip movements must have occurred because of faulting trend variations. The degree of such movements might not be significant regionally; however, wrench or oblique slip fault movements might have contributed to the formation of structures proximal to the fault concerned and could have generated local compression (Keely 1994).

Faulting affected the area of the Meleiha concession during the Late Jurassic, resulting in subsidence and sediment accumulation. E-W and NW-SE trending faults are the main structural elements controlling the Meleiha concession during the Late Jurassic period, as illustrated in Fig. 1. Most of the faults were isolated fractures with tens of meters of displacements at the top Masajid Formation level. Reactivation of the Late Jurassic faults occurred during the Late Cretaceous tectonic event (Robertson et al. 1996).

From a stratigraphic point of view, the north Western Desert stratigraphic succession, as shown in **Fig. 2**, consists of four main depositional cycles. Each cycle began during an early low-stand phase of deposition and ended during a late high-stand phase of an eustatic sea-level transgression cycle. The transgressive phases correspond to the Upper Jurassic Masajid Formation, Lower Cretaceous (Aptian) Alamein Dolomite Member, Upper Cretaceous/Lower Tertiary Khoman Formation, and Middle Miocene Marmarica Formation separated by main regional unconformities. One of these major unconformities exists at the top of the Khoman Formation as the result of the regional Syrian Arc tectonic event.

Everywhere in NE Africa and the Levant, a major break separates the Jurassic and Cretaceous sequences—the "Cimmerian" event (Hirsch and Picard 1988). This event is believed to have occurred during the Mid-Tithonian to Mid-Berriasian interval. However, it coincides with a worldwide period of eustatic sea-level fall (Haq et al. 1987).

The Masajid Formation of Early/Mid-Callovian to Early Tithonian age was originally defined by Al-Far (1966) at Gebel El-Maghara, north Sinai (type section), and in the subsurface of the north Western Desert by Norton (1967). It overlies the Mid-Jurassic Khatatba Formation and underlies unconformably the Early Cretaceous Alam el Bueib Member of the Burg el Arab Formation as illustrated in Fig. 2. This unconformity (i.e., Cimmerian unconformity) signifies a period of uplift, tilting, partial erosion, and karstification of the Jurassic succession (Keeley et al. 1990; Keeley and Wallis 1991).

The variations in preserved thickness of the Masajid Formation in the north Western Desert are largely a function of the local variations in the severity of Cimmerian erosion.

Generally, the Masajid Formation in the Melehia concession consists of shallow-marine, thick massive limestones or dolomites with minor interbedded shales. The limestones are light brownish grey to brownish black and dusty to pale yellowish brown. They are locally slightly argillaceous and commonly coarsely crystalline. Dolomites commonly replace the limestones. Thin-interbedded subfissile shale layers are generally brownish black to grayish black and black color. In the present study, the Masajid Formation in the Melehia West Deep field is exclusively composed of secondary dolomites with rare remnants of the original algal skeletal inner-shelf limestones.

Available Data and Methodology

The workflow in this study to characterize the Masajid Formation in the Meleiha West Deep field is demonstrated in **Fig. 3**. The openhole triple combo and mudlog data recorded in the four studied wells (1X, 3X, 4X, and 5X) were analyzed and integrated with the rest of the available data set to categorize and characterize the Masajid Formation.

Borehole microresistivity image data were acquired in three wells (1X, 3X, and 4X) to identify and characterize the structural element that affected the Masajid reservoir. The wireline formation tester (WFT) points are recommended and selected based on the image interpretation regarding fracture characterization in Well_1X.

Fifteen sidewall core samples were examined in detail from Well_5X, covering the Masajid Formation. The selected plugs were visually inspected, and 15 thin sections were prepared and studied under a petrographic microscope to define the depositional orthochemical and allochemical components, as well as the diagenetic processes and their impact on the Masajid reservoir quality.

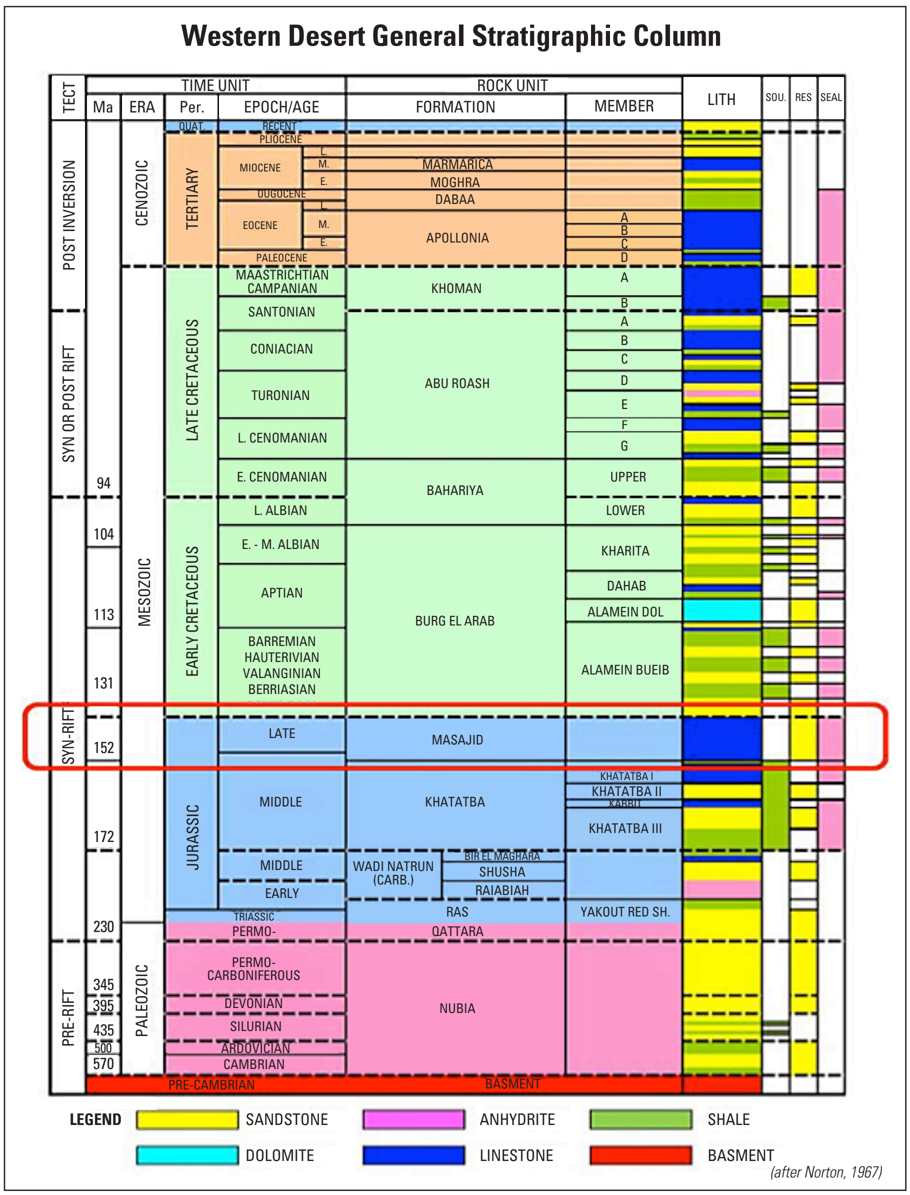


Fig. 2. *Stratigraphic succession of the Meleiha Development Lease, north Western Desert, Egypt.*

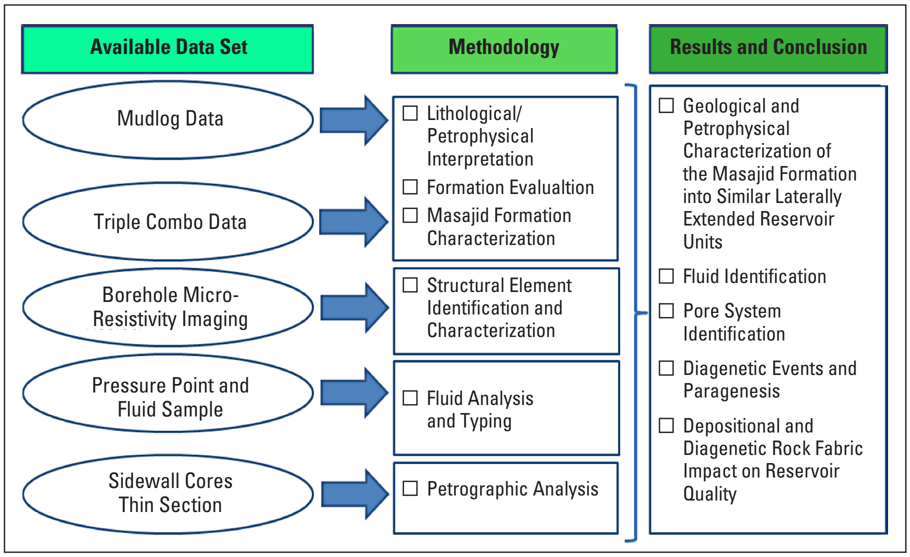


Fig. 3. *Study workflow to characterize the Masajid Formation in the Melehia West Deep field.*

The WFT in Well_1X documented the first pressure reading in this tight-carbonate reservoir, and fluid analysis was performed to clarify the ambiguity of the Masajid reservoir and to achieve concrete results regarding the fluid types in this formation. The recorded sample and fluid ID data analyzed designated the Masajid Formation as an oil/gas-bearing reservoir. The first well testing was performed in Well_3X, which provided actual information about the nature of the reservoir as well as its bearing fluids.

The Subdivision and Characterization of the Masajid Formation

The Masajid Formation in the Meleiha West Deep field has never been considered as a reservoir, and it was not completely drilled, except in one well, i.e., Well_1X, due to some restrictions in drilling programs besides it not being a primary target. The Masajid Formation has been studied in this well carefully to characterize and subdivide this formation into members having similar geological and petrophysical characteristics; subsequently, their lateral extension among the rest of the studied wells is then evaluated.

In Well_1X, which encompasses the complete Masajid Formation, it is subdivided based on the available openhole data set integrated with microresistivity images into two members—each member has its own geological and petrophysical characteristics (**Fig. 4**). The upper Masajid member is characterized by low density and PE response relative to the lower member, as well as relatively high resistivity. This is supported by petrographic results that conclude relatively more pore spaces and predominance of dissolution vugs and higher fracture frequency relative to the lower member (**Fig. 4-A**). On the other hand, the lower Masajid member is characterized by high density and PE response with relatively low resistivity, which was confirmed petrographically by the presence of high mechanical and chemical compaction structures/forms, i.e., frequent interlocked and concave/convex crystal boundaries and abundance of stylolites, in addition to the drastic reduction in the volume of dissolution karsitified vugs (**Fig. 4-B**).

The recognized well-defined upper and lower members of the Masajid Formation in the type section of Well_1X are correlated in the other three wells, i.e., 3X, 4X, and 5X, as shown in the structural correlation panel (**Fig. 5**) to define the lateral continuity of their lithofacies and their petrophysical characteristics along the studied Meleiha West Deep field. The correlation was mainly based on the available openhole data, including gamma, resistivity, PE, density, and neutron, in addition to the available pressure and total gas readings.

Masajid Reservoir Characterization

The Masajid reservoir architecture and porosity-permeability spatial distribution represent the combined effects and reflects multiple episodes of changes during burial history. It involves original rock fabric, mixed-origin pore systems, and reservoir fluid saturations.

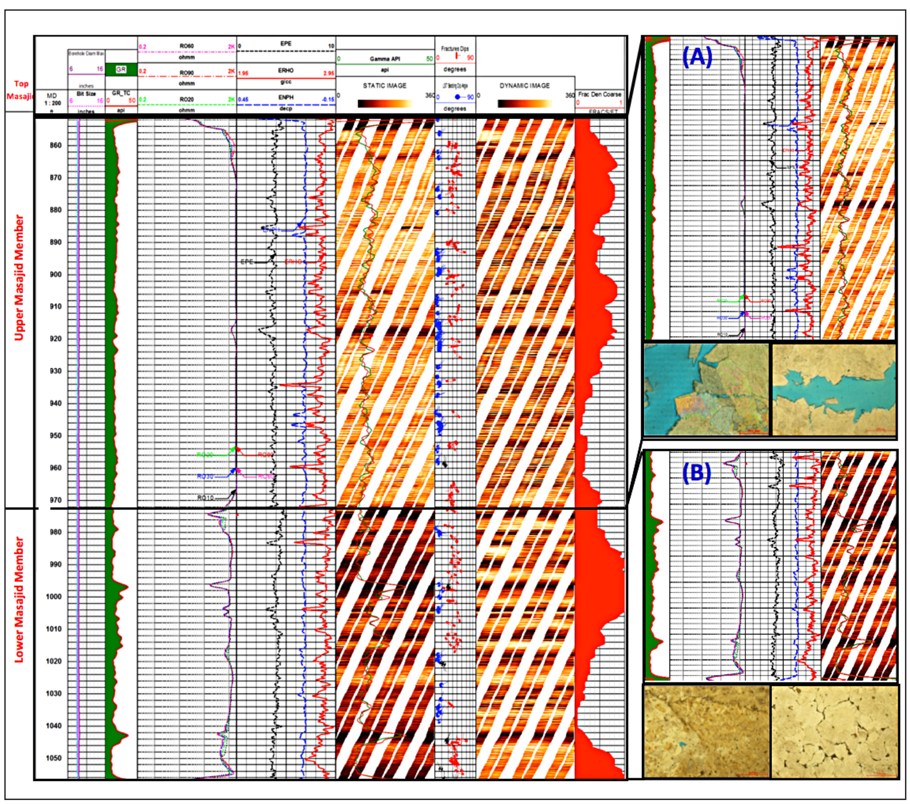


Fig. 4. *The type section of the Masajid Formation in Well_1X, Meleiha West Deep field with its upper and lower recognized members. (A) A snapshot of the upper Masajid member characterized by higher relative resistivity associated with relatively low density and PE responses confirmed by the abundance of connected dissolution vugs and fractures. (B) A snapshot of the lower Masajid member characterized by relatively low resistivity with high density and PE response, and supported by petrographic results indicative for a high degree of mechanical and chemical compaction.*

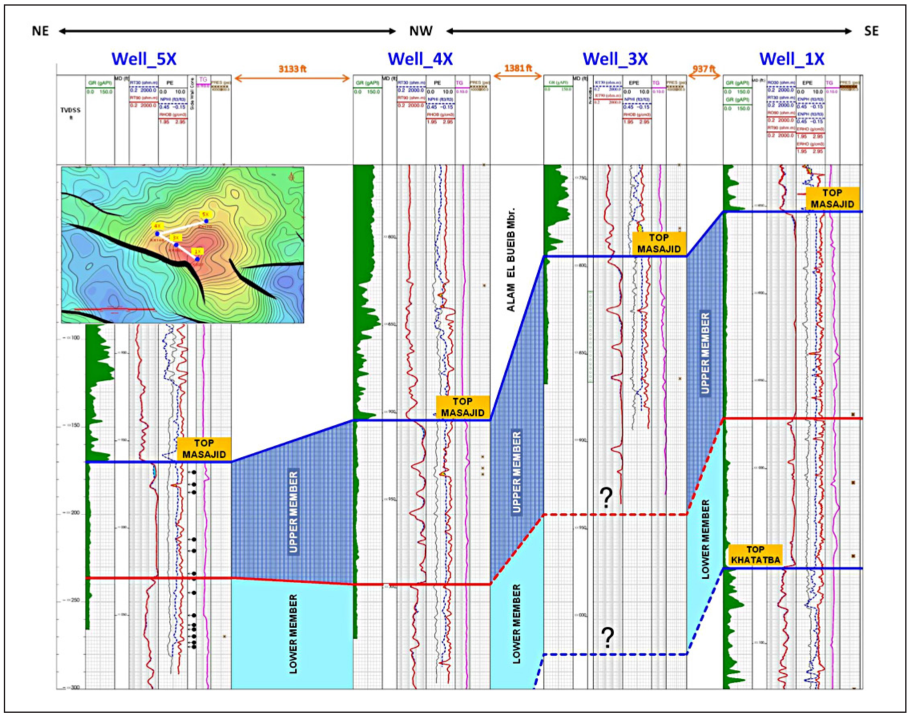


Fig. 5. *Structural cross section of the Masajid Formation in the Meleiha West Deep field, Meleiha concession, north Western Desert, Egypt.*

The original Masajid carbonate fabric was not easily distinguished, which could be explained by the excessive diagenetic processes that changed/masked the original rock fabric. The remnants of the original rock fabric are mainly composed of grain-dominated packstone to grainstone microfacies (**Plate 1-A**). The bioclastics are mainly algae; bryozoa and skeletal fragments embedded in micrite and glauconitic matrix. The skeletal grains are affected by aggrading neomorphism, and changed to microsparite and occasionally sparry calcite.

Diagenetic Processes and Evolution

Diagenesis is a continuing process that starts with cessation of sedimentation, and as time increases, the nature of precursor carbonate becomes more and more unlike the depositional texture (Lucia 2007). Numerous diagenetic processes have been identified contributing much to explain the highly heterogeneous rock fabric and reservoir quality within the Masajid Formation.

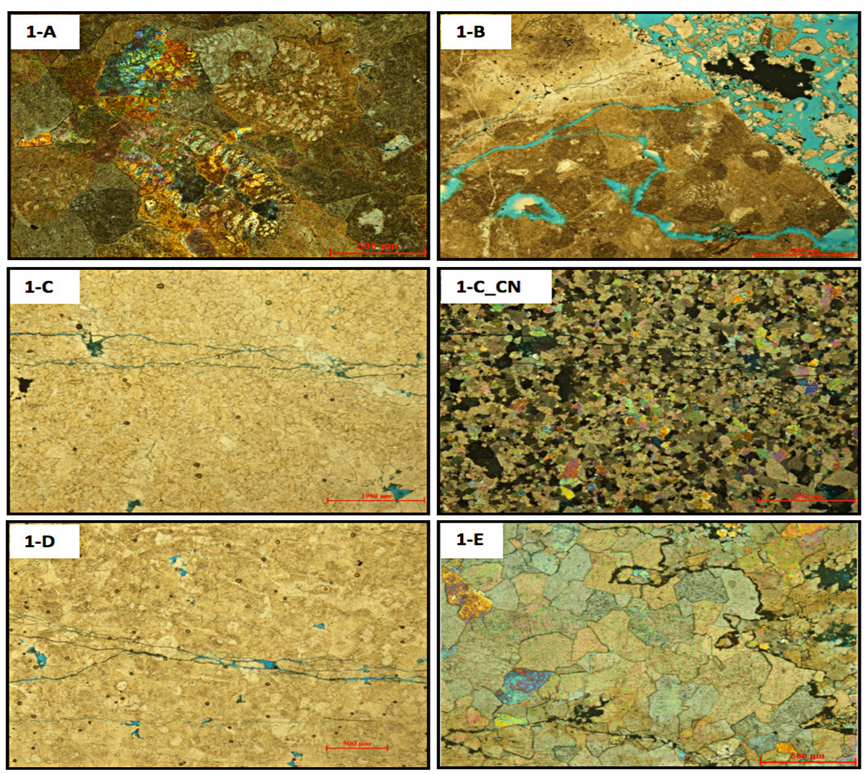
These diagenetic processes are firstly studied independently, although they are overlapping in time and place and have effect on each other.

The carbonate texture and rock fabric in the Masajid Formation has been studied carefully to elucidate the original depositional processes, as well as to predict the diagenetic history of both the rock matrix and the pore system, and the consequent petrophysical influences that affect and control the reservoir quality.

In this study, the most important data for the Masajid reservoir characterization are mainly based on openhole log interpretation, direct examination of sidewall core samples, and petrographic and XRD analysis, as well as the pressure, sample, and testing measurements.

Petrographic analysis is carried out on 15 thin sections representing 15 sidewall core samples along the Masajid Formation in Well_5X. It shows numerous processes of depositional and diagenetic events that generally formed heterogeneous rock fabric in the Masajid Formation. These rock fabrics are tied to the petrophysical parameters to identify the potentiality within the two separately recognized members.

It is worth mentioning that the variations in the preserved thickness of the Masajid members are largely a function of the local variations in the severity of “Cimmerian” erosion. Also, “Cimmerian” unconformity is controlling to a great extent the degree of dissolution and dolomitization of the Masajid reservoir.



N.B. CN: Crossed Nicole photomicrograph

Plate 1. *(A) photomicrograph of the packstone to grainstone microfacies that represent the remnants of the original rock fabric of the Masajid Formation; (B) Dissolution cavernous/vugs and channel fracturing promoting carbonate dissolution process; (C),(C)-(CN), (D), and (E) Early dolomitization phase characterized by fine-to-medium nonplanar dolomite consists of anhedral crystals that lack well-developed crystal faces. These xenotopic texture are closely packed with curved, lobate, serrated, or irregular crystalline boundaries. Open and/or partially filled with HC microscopic fractures dissecting the early dolomite phase.*

The main diagenetic processes recorded in the Masajid Formation and the paragenetic sequence will be discussed as follow:

Carbonate Dissolution/Karstification: It is a near-surface meteoric diagenetic process and commonly developed below unconformities, where small vugs and up to extensive caves may develop in the carbonate reservoir by karstification. This early diagenetic event affects the original depositional limestone rock fabric of the Masajid Formation through the permeability of the original packstones/grainstones, which allows the percolation of dissolving fluids. During the prolonged "Cimmerian" event, this process is promoted via excessive dissolution cavernous/vugs and channel fracturing, as shown in (**Plate 1-B**). The early formed dissolution cavernous/vugs are sometimes recognized to be partially filled with detrital clays as shown in (**Plate 1-C**).

Dolomitization: Generally, this diagenetic process changes the original rock fabric significantly and consequently increases the secondary porosity. If the rock has been dolomitized, however, the overprint of dolomite crystals often obscures the precursor limestone fabric (Lucia 2007). The studied openhole data, together with petrographic results of the acquired thin sections, shows that carbonates of the Masajid Formation in the studied wells have been subjected to a high/severe degree and multiple dolomitization phases. Due to the intensive dolomitization and presence of various ghost structures, it can be assumed that the dolomitization process replaced primary limestone types almost completely as "replacement dolomite."

Early Dolomitization: Phase possibly formed as the high magnesium-rich water find pathways along the permeability of the original packstones/grainstones fabric, as well as the connected network of early formed dissolution vugs and fractures resulted from the karstification process. The early dolomitization phase in the Masajid Formation is characterized by fine-to-medium nonplanar dolomite, consisting of anhedral crystals that lack well-developed crystal faces. These xenotopic textures are closely packed with curved, lobate, serrated, or otherwise irregular crystalline boundaries. This anhedral dolomite shows a lack of crystal faces and interlocked crystals that destroy porosity as shown in (**Plate 1-D**).

Fractures: These are formed as the result of brittle failure under mechanical stresses after the rocks have been lithified and mostly associated with tectonic features, such as folds, faults, and regional flexures. Fractures could be affected by later dissolution or cementation.

Fractured reservoirs, according to Nelson (2001), are reservoirs in which natural fractures have a significant effect on fluid flow, either in the form of increased reservoir permeability and/or reserves or increased permeability anisotropy.

In the Meleiha West Deep field, the structural contour map on top Masajid (Fig. 1) displays a major fault close to the studied wells, and these wells are located on a crested anticlinal structure. The major normal faults that dissected top Masajid are extending in a NW-SE to WNW-ESE trends. The borehole microresistivity imaging run in three wells (1X, 3X, and 4X) reveals that the Masajid Formation encompasses fault-related fractures, where the fracture intensity increases in wells nearby the fault, and these fractures have the same related fault trend, i.e., they are generally striking WNW-ESE (**Fig. 6**). The first successful sample point in Well_1X was recommended based on the fracture frequency recognized from image data; it reveals 0.28 g/cc pointing to the presence of gases as shown in **Fig. 6 (A)**.

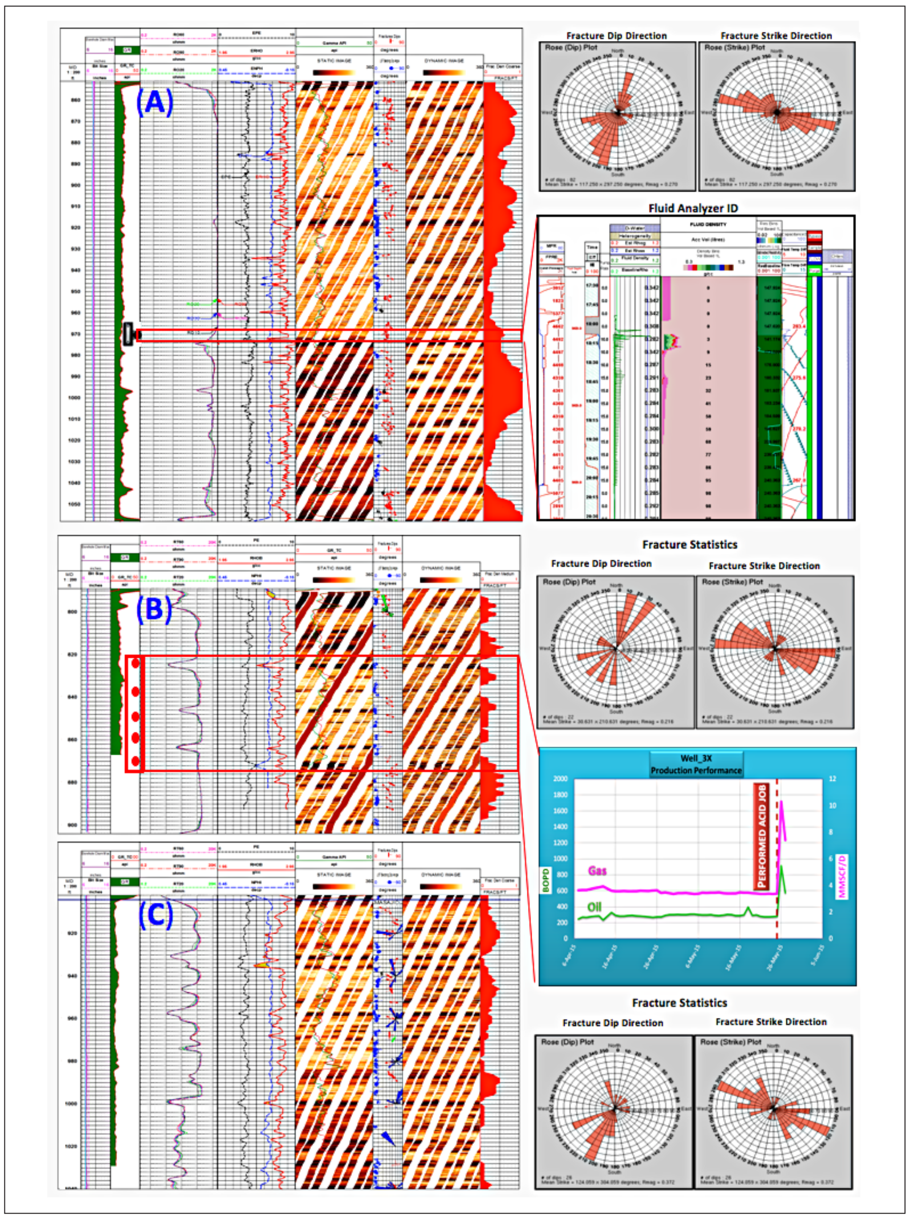


Fig. 6. *Masajid fracture characterization (orientation, distribution, and frequency) based mainly on microresistivity images and their relation with production data. For each well, the openhole logs are attached with static and dynamic images. The track between the images includes the picked fractures (red frac-poles), while the last track represents fracture frequency. Generally, all the recognized fractures exhibit a common WNW-ENE strike trend. (A) Well_1X demonstrates the location of WFT sample and fluid ID data, indicating the presence of gases. (B) Well_3X shows the tested interval (defined by solid red lines) and its gas and oil production performance. (C) Well_4X with its fracture statistics.*

The petrographic analysis performed in Well_5X shows common microscopic fractures that are generally open and partially filled with hydrocarbon (**Plate 1-C, D,** and **E**).

Compaction: Due to local intensive compaction, a considerable part of some carbonates might have been dissolved (disappeared), and only insoluble residues enriched in stylolite seams of varying thickness indicate their former presence. Also, former primary interparticle pore spaces might have been eliminated (Bathurst 1995; Lucia 2007; and Heap et al. 2014).

In this study, Masajid carbonates in the Meleiha West Deep field underwent mechanical and chemical compaction as their burial depth increases. The early diagenetic xenotopic to hypidiotopic dolomite crystals start to dissolve at point contacts to produce concave-convex and serrated contacts (**Plate 2-A**). Under thicker overburden, this chemical compaction generates discrete surfaces and reveals intensive interfingering, and are commonly separated by thin dark bands, which are interpreted as enrichments of insoluble residue and thus can be defined as stylolitic enrichments. The petrographic study resulted in the recognition of three kinds of stylolites within the Masajid Formation. These are (1) solution seams or wave-like stylolites. They are characterized by a smooth or undulatory pattern with a continuous coating of seam material along its surface (Plate 2-A). They appear to form during the early stage of chemical compaction. (2) Wispy seam or horsetail stylolites (**Plate 2-E** and **Plate 3-A**) may form significant fluid flow corridors. (3) Rectangular or high-amplitude stylolites (**Plates 2-C, C**+, and **D**) associated with the latest stage of stylolitization. Most of the seams are composed of black bituminous hydrocarbon residue, and also contain insoluble rock residue (clay minerals, quartz silt pyrite) as shown in **Plates** 2-A, **B**, C, D, and E.

Stylolites are common to very common in some parts of the Masajid Formation, especially in the lower member. The abundance of low-amplitude stylolites in some intervals through the Masajid reservoir results in a stylobrecciated and stylonodular fabric (Plates 2-A and B).

The abundance of stylolites in the Masajid Formation has a marked influence on the reservoir properties due to their contribution regarding permeability pathways. In this study, they are commonly described as positive parameters for the reservoir development, i.e., stylolites were favorable sites for the migration of hydrocarbons as demonstrated in Plates 2-B, E, and 3-A.

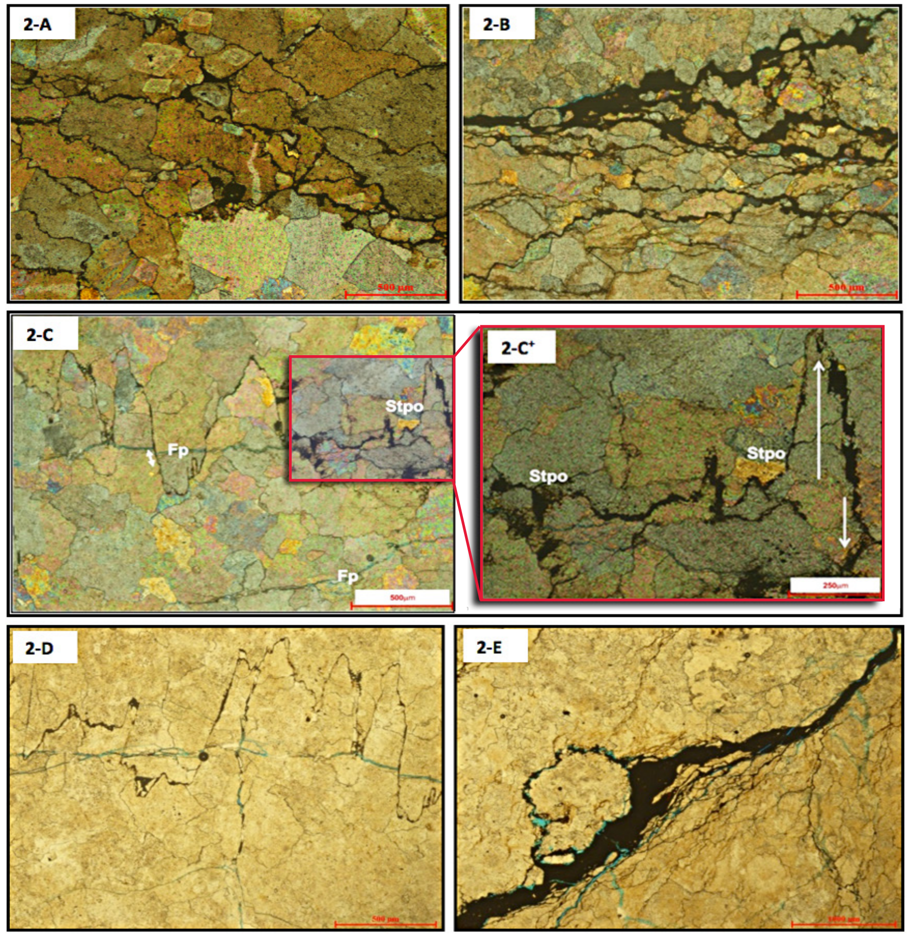


Plate 2. *(A) Photomicrograph of early diagenetic xenotoic to hypidiotopic dolomite crystals exhibit concave-convex and serrated contacts separated by thin dark solution seams demarcated low-amplitude wave-like stylolites. (B) Abundant low-amplitude stylolites result in a stylobrecciated and stylonodular fabric. (C), (C+), and (D) Late-stage high-amplitude stylolites. (E) Wispy seam or horsetail stylolites with black bituminous hydrocarbon residue.*

Late Dolomitization: As mentioned, dolomitization has been recognized as multiple phases that eventually almost make it difficult to identify the original fabric. This later-phase dolomitization is commonly identified with the predominance of idiotopic dolomite texture that's generally described with planar euhedral to subhedral relatively larger and brighter crystals with well-developed crystal facies with sharp boundaries as shown in (**Plate 3-B** and **C**). Most dolomite crystals of early diagenesis have a relativly dark appearance due to abundant tiny inclusions and possess small crystal size relative to the late-formed dolomite. Generally, dolomitization could generate, preserve, or destroy porosity. The detailed petrographic inspection reveals that the late-stage dolomite cement recorded in the Masajid Formation is well developed in the karstified caves and vugs, hence it reduces the early diagenetic dissolution porosity.

The petrographic analysis displays scarce microcrystalline silica pore filling (**Plate 3-D**) and nodular anhydrite crystals with prismatic texture (**Plate 3-E**) filling the dissolution vugs and invading the late diagenetic dolomite crystals. These minute anhydrites and tiny silica pore filling represent a small percentage of the bulk volume and have little effect on porosity or permeability.

Masajid Reservoir-Quality Prediction

The prediction of Masajid reservoir quality is a critical challenge for hydrocarbon exploration and field development. It should include the prediction of reservoir facies, their lateral and vertical distribution, and their porosity and permeability system for reserve calculations. The complicated porosity-permeability system within this newly discovered reservoir is one of the challenges to distinguish this reservoir.

Generally, the porosity types in the carbonate reservoirs are either fabric selective and/or nonfabric selective classes as mentioned by

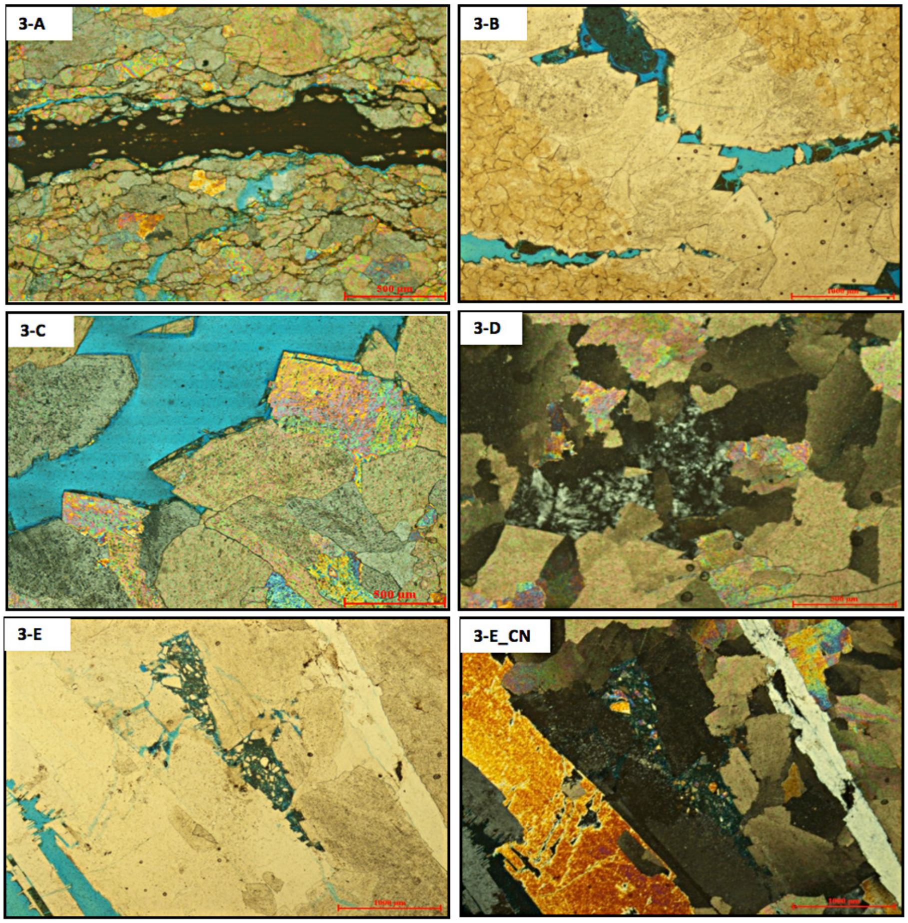


Plate 3. *(A) Stylobrecciated and horsetail stylolites filled with black bituminous hydrocarbons and insoluble rock residue; (B) and (C) Late-diagenetic large-planar euhedral and bright dolomite crystals filling the karstified vugs; (D) Tiny microcrystalline silica pore filling; and (E) Prismatic anhydrite crystals filling the dissolution vugs.*

Choquette and Pray (1970). The nonfabric selective pores are the most common and efficient types controlling the Masajid Formation in the Meleiha West Deep field.

Karstification, dissolution vugs, fracturing, early dolomitization, and pressure solution contribute much to enhance the porosity of the Masajid carbonate reservoir in the Meleiha West Deep field. On the other hand, several diagenetic processes diminish porosity and damage the reservoir quality, such as compaction as well as the cementation of the late-dolomitization phase. Fractures slightly improve the porosity, but they are an essential element for secondary enhancement of permeability.

The Masajid Formation in the Meleiha West Deep field is confirmed as one of the promising hydrocarbon-bearing reservoirs after the successful production test results in Well_3X. The test was performed along a 52-ft interval in the upper Masajid member (**Fig. 6-B**). The initial test results gave a production rate of 250 BOPD, 0% water cut, and the gas rate was 3.63 MMSCFD.

An acid job was performed in the same interval. Then, the production test rate was raised to 935 BOPD with 2.5% water cut, and the gas rate was 10.3 MMSCFD.

Conclusion

The Masajid Formation of Early/Mid-Callovian to Early Tithonian age overlies Mid-Jurassic Khatatba Formation and underlies unconformably Early Cretaceous Alam el Bueib Member of the Burg el Arab Formation. This unconformity, i.e., Cimmerian unconformity, is signifying a period of uplift, tilting, partial erosion, and karstification of the Jurassic succession. The Masajid Formation in the Melehia West Deep field is entirely composed of secondary dolomites with rare remnant of the original algal skeletal inner-shelf packstone/grainstone.

The variations in the preserved thickness of the Masajid Formation are largely a function of the local variations in the severity of "Cimmerian" erosion. Also, "Cimmerian" unconformity is controlling to a great extent the degree of dissolution and dolomitization of the Masajid reservoir.

The complete Masajid Formation is subdivided based on the available limited data set into two members. The promising upper Masajid member is characterized by lower density and PE response relative to the lower member, as well as relatively high resistivity. This is supported by petrographic results that display relatively more pore spaces and predominance of dissolution vugs and higher fracture frequency relative to the lower member. On the other hand, the lower member is characterized by the presence of high-mechanical and chemical compaction structures/forms, i.e., frequent interlocked and concave/convex crystal boundaries and abundance of stylolites, in addition to the drastic reduction in the volume of dissolution karsitified vugs.

The Masajid reservoir architecture and porosity-permeability spatial distribution represent the combined effects and reflect multiple episodes of changes during burial history.

The nonfabric selective pores are the most common and efficient types controlling the Masajid Formation in the Meleiha West Deep field. Karstification, dissolution vugs, fracturing, early dolomitization, and pressure solution contribute much to enhance porosity of the Masajid carbonate reservoir in the Meleiha West Deep field. Fractures slightly improve the porosity, but they are an essential element for secondary enhancement of permeability. On the other hand, several diagenetic processes diminish porosity and damage the reservoir quality, such as compaction as well as the cementation of the late-dolomitization phase.

The Masajid Formation in the Meleiha West Deep field, especially the upper member, is confirmed as one of the promising hydrocarbon-bearing reservoirs after the successful production test results.

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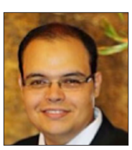

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