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Integrated the Core Analysis Data, Image logs, and Conventional Logs to Understand the Reservoir Rock Type of the Mauddud Formation

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Abstract

Inner ramp carbonates with dolomitic limestone make up the Late Albian Mauddud reservoir in Arabian plate. The age of the Mauddud Formation is Albian–Early Cenomanian, and it overlies the Nahr-Umr Formation and the Ahmadi Formation. The depositional environments range from subtidal to lagoon and shoal environments. The main goal of this study is to integrate all the available information to recognize different rock types within Mauddud reservoir. Due to the limited core available in Mauddud reservoir, the rock types have been identified mainly based on the Full-bore formation micro imager tool. The formation micro imager readings were compared and calibrated by available core data and conventional well logs (Density Neutron).

This study concludes that there are three rock types were recognized within Mauddud reservoir: The first rock type is grainstone, which is characterized by having relatively higher porosity and permeability than rock types one and two (porosity is more than 15 pu and permeability is more than 1 mD). The second rock type is wackestone to packstone with a porosity value of between 10% and 15% and a permeability range of 0.1–1 mD. This rock type image reflection generally shows mixed laminated and fine mottled size image facies that is shown in the lagoon environment. Finally, the third one is Cemented Wackestone and Packstone which is characterized by having low porosity and permeability ($\Phi<10\%$, perm<0.1 md). The image reflection of cemented wackestone and packstone is almost like a massive image reflection. This rock type usually reflects the intertidal environment.

Keywords: Reservoir Rock type, Lithofacies, Image facies, Image log, Mottled.

1. Introduction:

A shallow-water carbonate Mauddud Formation may be founded across the Arabian Gulf's subsurface. Inner ramp carbonates with dolomitic limestone make up the Late Albian. It was first defined in Qatar and has been recognized in the United Arab Emirates and Oman in the southern

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Gulf. In terms of regional dispersion and thickness, the Mauddud Formation is a significant geological formation in the Arabian basin. Moreover, since the 1940s, the formation has produced considerable amounts of oil in northwest Iraq and Bahrain, and it may include further oil in other potential locations. Henson reported the Mauddud Formation for the first time in an undocumented report from the Dukhan-1 well in Qatar in 1940 [8]. "Limestone, light gray, grainy, mostly of rather moderate porosity excluding the bottom several feet, which are rather marly," explains the formation. The abundance of fine calcareous debris causes most of the limestone to appear silty. [8] published the first official description of the type section of the formation in Qatar, defining it as foraminiferal limestone ranging from lime mudstone at the bottom to wackestone, pellet and skeleton packstone, and wackestone at the top. In such horizons, the formation is dominated by Orbitolina and Trocholina tests [9]. The Mauddud Formation consists of rudist grainstone and packstone with peloidal, Orbitolina-bearing limestone in northern offshore zones [3]. The transition from the Nahr Umr's clastic rocks constitutes the Mauddud Formation, which lays conformably on the Nahr Umr Formation. The lower marly section of the Mauddud Formation comprises a transitional zone between the Nahr-Umr clastic sand the limestones appropriate to the so-called “Upper Mauddud" in the subsurface north region. The Ahmadi Formation is the overlying formation in the type locality, and its contact is similarly conformable and marked by a sharp gamma-ray peak [3].

In subsurface reservoirs, the core is usually taken because it provides a high-resolution database on which to collect sedimentological, diagenetic, and reservoir quality observations. As a result, it provides the essential building elements for creating a reservoir model. Core recovery from subterranean reservoirs is, however, exceedingly costly, and as a result, it is frequently limited in scope. In subsurface reservoirs, traditional wireline logs such as gamma ray, neutron, density, resistivity, and sonic logs are frequently collected with the goal of characterizing the reservoir rock (quantification of porosity, hydrocarbon saturation, etc.). This dataset includes the whole reservoir; however, it is especially useful at uncored intervals when data is limited. Conventional wireline logs frequently reveal lithological heterogeneity within a rock sequence, but texture variability is typically difficult to interpret accurately [1]. This is especially problematic in limestone reservoirs, where the lithology is often consistent throughout and reservoir quality was determined by differences in carbonate textures and/or calcite cementation activity.

Open Access
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Borehole image logs are a type of digital log that represents the physical attribute (electronic resistivity or acoustic impedance) of borehole walls [7]. Electrical borehole image measurement and interpretation give continuous oriented images with very high vertical resolution up to 5 mm of the borehole wall. Borehole imaging technologies add greatly to geological knowledge and interpretation of recorded intervals [7]. Borehole imaging technologies might identify sedimentological and structural characteristics up to a few millimeters in resolution [10]. Full-bore Formation Micro Imager (FMI), the advancement of the FMS tool, comprises four holding pads linked to two orthogonal arms, with each pad having an attached flap. As a consequence, the FMI could well be run in either 8-pad mode (using both the pads and flaps) or 4-pad (FMS) mode (using only the four pads). Each pad/flap has 24 buttons and is also in touch with the borehole wall. The 192 electrodes, which are arranged on four pads and four extendable flaps, yield 192 microresistivity curves that can be used to generate a computer-generated "image" of the wellbore wall. Borehole images are commonly utilized to complement core data in reservoirs where sedimentary features, which include cross-bedding, are prominent. Borehole images can offer not only a cheaper dataset with more stratigraphic coverage for sedimentological definition than the core, but they can also provide paleo currents orientation data, which is important for understanding the architecture of geo-bodies in the subsurface [4] [6]. Sediment homogenization caused by bioturbation and other processes can result in a lack of sedimentary features in limestone reservoirs. There have been few studies on the sedimentological uses of borehole images in such reservoirs.It seems that you are referring to a study in the field of petroleum geology. The study suggests that hydrocarbon-producing zones are commonly found in clean carbonate lithologies located in the upper part of the Mauddud Formation. However, the wireline log signatures obtained from these carbonate reservoirs are not unique, making it difficult to determine their texture and reservoir quality accurately without core samples.To address this challenge, the study proposes using borehole images from one well in the Mauddud Formation to gain a better understanding of the reservoir's texture and quality. Borehole images provide high-resolution data that can help identify features such as fractures, vugs, and porosity, which are critical in evaluating the reservoir's productivity. By using borehole images, the study hopes to improve the accuracy of wireline log interpretation, which can help geologists and engineers make informed decisions regarding reservoir development and production. Overall, this study highlights the importance of using multiple data sources and techniques to fully understand subsurface reservoirs in the oil and gas industry. The appears that the study aims to characterize the sedimentological properties and

Open Access
No. 41, December 2023, pp. 1-15

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reservoir quality of the carbonate deposits in the Mauddud Formation using FMI (Formation Micro-Imager) data. The FMI data is calibrated with core observations, which is a common practice in petroleum geology to ensure that the data obtained from well logging tools match the properties of the rocks sampled from the reservoir.

The ultimate goal of the study is to understand and predict the depositional and reservoir architecture of the Mauddud Formation using log-based datasets only. This means that the study aims to use wireline logs, which are commonly used in the oil and gas industry, to infer the depositional environment and the quality of the reservoir.

To achieve this goal, the study may use various techniques such as facies analysis, petrophysical analysis, and image analysis to interpret the FMI data and correlate it with the wireline logs. By doing so, the study may provide insights into the depositional history of the Mauddud Formation and identify the factors that control the reservoir quality. This information can be crucial for oil and gas exploration and production companies to optimize the development and production of the reservoir.

2. Geological settings

The Mauddud formation lays between two shale members; the lower contact is overlaying the upper Nahr Umr clastic formation shale member and the upper contact is underlaying the lower Ahmadi shale. The formation depositional environments progress from intertidal to foreshoal environments. Benthic foraminifera are a significant fauna group. The *Orbitolina* bearing limestone is a major lithology over the Arabian plate. The second common association is rudist grainstone in the upper part of the Mauddud formation figures 1&2. The other bioclastic fragments like echinoderms, algae, and mollusks are also described in the Mauddud formation.

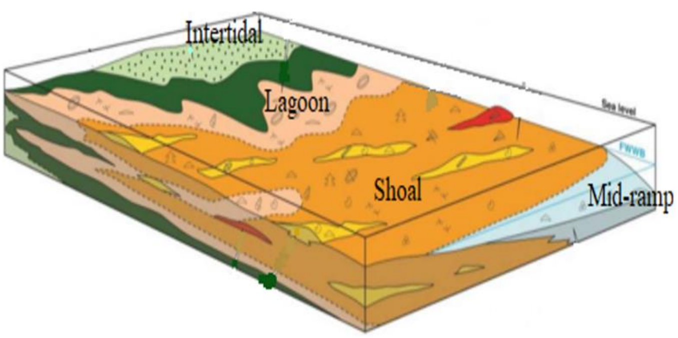

Fig. (1): Depositional Model of Mauddud Formation Modified from [2].

Open Access
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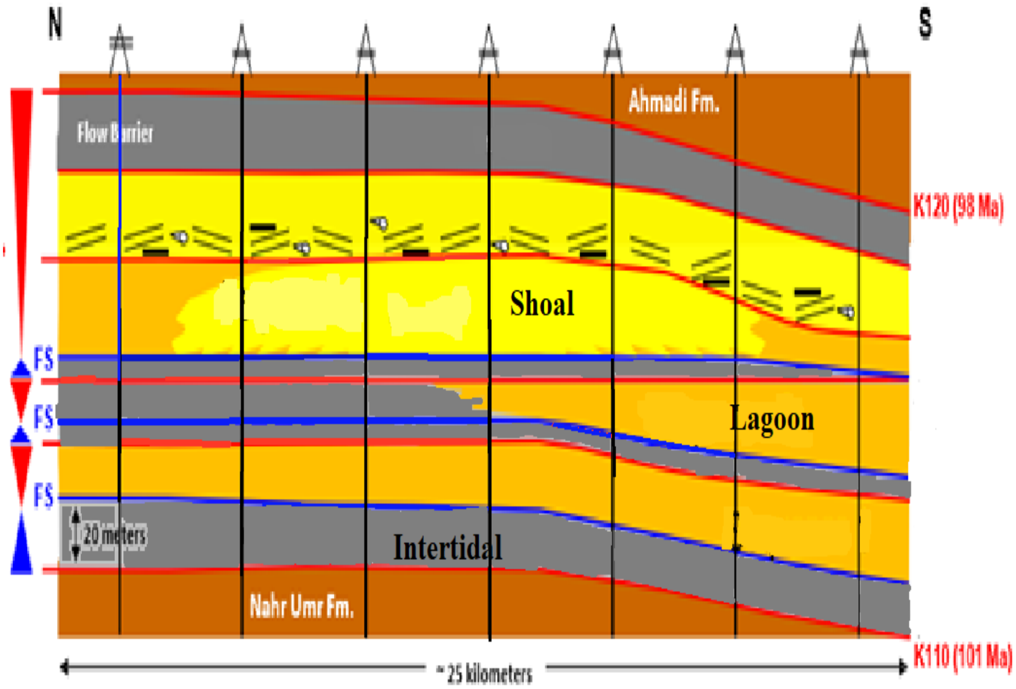

Fig. (2): Vertical Profile for the Depositional Environment of Mauddud Formation and correlation section.

3. Methodology

The core data. In the study well, 132m of core is available through the Mauddud Formation, which has a total thickness of 132m. All reservoir zones of the Mauddud Formation are covered by the cored interval. There are additionally 32 porosity and permeability core plug data available from the research well's cored interval. The sample density is higher in the carbonate lithologies, which are the focus of the investigation. These measurements cover the whole cored Mauddud stratigraphy. Logs of wirelines and borehole images (BHI). Throughout the Mauddud Formation, conventional wireline logs like as gamma ray, caliper, neutron, density, and resistivity are accessible. In the research well, FMI logs of commonly accepted quality are provided throughout the Mauddud Formation. This section outlines the method for determining the FMI predictability of the sedimentological make-up and reservoir quality. To comprehend the predictability, it is necessary to first characterize the Mauddud Formation's sedimentological make-up, diagenetic overprint, and reservoir quality properties. It should be noted, however, that this characterization is not the primary focus of this study and is only summarized here for predictive purposes. Correction and quality control might be used to acquire and load the raw image data (dlis file). (1) Inclinometer QC and correction are the primary processes in the workflow for processing the picture log data. (3) Image generation, (4) Equalization and Normalization, and (2) Speed

Open Access
No. 41, December 2023, pp. 1-15

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E- ISSN: 2710-1096

Optimization The high-resolution magnetometer and accelemeter are used to calibrate the inclinometer QC and correction. The velocity of the logging tool may or may not be steady over the whole wellbore depending on the cable speed correction made during the survey. Wellbore issues that must handle during speed correction include washout, breakout, and excessive pad pressure [10]. The raw image curve is obtained at the image production stage by combining the adjusted speed image pads data. Equalization is the final phase.

3.1 Lithofacies

According to Dunham (1962) the lithofacies of Mauddud Formation that related with environments energy from low to high energy level. The main lithofacies that common in the formation are:

A- Laminated mudstone

Rarely bioclastic fragments and argillaceous almost laminated layers. The bioclastic contents are rare fragments of bivalves, algal fragments, benthic foraminifera fragments.

B- Lagoonal wackestone

This microfacies is reflected the low lagoon environment level and commonly bioturbated. The allochem assemblage of this microfacies main grains are algal fragments, prealveolinids orbitolinids and miliolids (Figure 2A).

C- Shoal bioclastic packstone

This microfacies are dominated by grain contents skeletal or non-skeletal grains, the skeletal grains which common in this lithofacies are benthic foraminifera (miliolids, prealveolinids, trocholinids and algae green or red algae). The non-skeletal grains are peloids and coated grains. This lithofacies represent the high energy level (Figure3B)

D- Grainstone -Rudstone lithofacies

This lithofacies represent the highest energy level clean lithofacies abundant by skeletal fragments (rudist, echinoderms, bivalves and benthic foraminifera). Whilst, the non-skeletal fragments are peloids and coated grains (Figure 3 C&D).

The lithofacies association that detected in Mauddud formation the mudstone and wackestone are dominated in lower part of the formation, which reflected the intertidal or lagoonal environments, while, the packstone, and grainstone lithofacies are dominated in upper part of the formation.

Open Access
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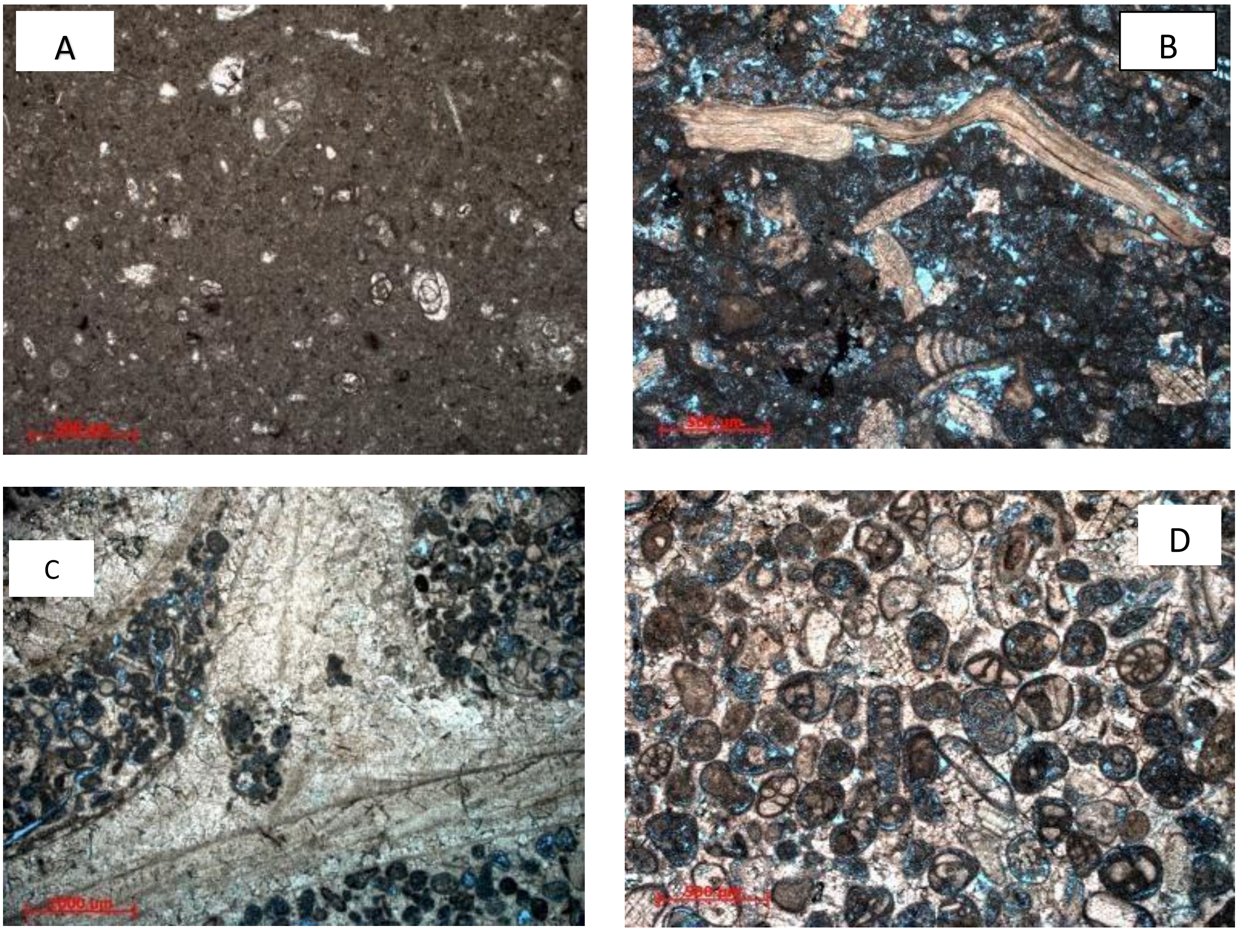

Fig. (3): Mauddud Formation Lithofacies

A- Lagoonal wackestone
B- Shoal bioclastic packstone
C- Rudstone lithofacies
D- Grainstone lithofacies

3.2 Image facies reflection

The image facies of Mauddud Formation interpretation based on micro resistivity full-bore imager that reflect the rocks and fluid characterizes. The FMI patterns that show in the Mauddud Formation are:

A- **Resistive:**

When using traditional logging techniques, a resistive log response represents the high resistivity values from substances like hydrocarbons or low-porosity matrices (non-invaded and resistive substances like anhydrite). Typically, light hues, beginning with white, reflect off of resistive materials [5].

Open Access
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B- Conductive:

Low resistivity measurements in marls, clays, and shales are recorded in conventional logs. They are indicated by darker colors in image logs (often black). When saturated with drilling fluids, however, vugs or high-porosity zones are also reflected as conductive.

C- Mottled Image Facies:

Mottled: Mottles can be defined as the alternation of resistive and conductive patterns caused by different grain sizes. Irregularly formed mottles show grain sociations from moderate-to-high-energy settings. Mottled-image facies are a kind of microfacies that includes bioclastic packstone, coral floatstone, rudstone, and breccias with variable-sized clasts or bioclasts. Massive mottles reflect large benthic shells as resistive reflections on a high-porosity, conductive backdrop, whereas small mottles reflect small skeletal bioclasts. A conductive background with resistant grains, on the other hand, may suggest a high-porosity background with carbonate grains invaded by drilling fluids. Big mottles in the porous matrix often identify large bioclastic skeletal grains Table (1).

D- Laminated Image Facies:

This image pattern has thin, regularly layered conductive and resistive patterns of approximately consistent thickness. Laminated-image facies are generally found in low-energy environments where mudstone and wackestone microfacies dominate. The argillaceous limestone deposits from the restricted environments represented by this pattern feature rare bioclast fragments Table (1).

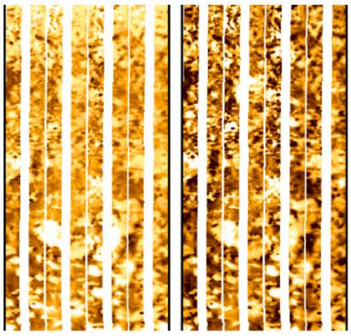
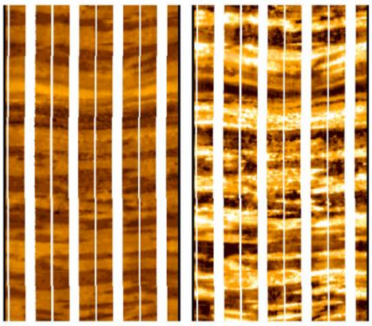
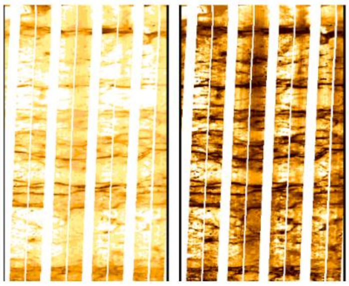
E- Massive Image Facies:

Matrix and/or earlier calcite cements may be replaced with dolomite. Cements are made of late dolomite. Micritization, isopachous cements, dissolution, common blocky and neomorphism cements, and compaction are some of the terms used to describe these processes. The massive image reflection is resistive pattern due to low porosity and non-invasion by drilling fluid table1.

Open Access
No. 41, December 2023, pp. 1-15

P- ISSN: 2220-5381
E- ISSN: 2710-1096

Table (1) Interpretation of Lithofacies between the Core and Image Facies

Image facies	Image pattern	Slapping core	Discerption
Mottled Image Facies			Resistive and conductive patterns high porous, highly invaded drilling fluid inside the formation. the resistive large size mottled reflected the size of bioclast fragments
Laminated Image Facies			Resistive and conductive planner patterns due to alteration clean and argillaceous layers
Massive Image Facies			Low porosity and lack of invasion cause an always resistant pattern. Reddening, aragonite dissolution, and bioclast micro solicitation Cement and matrix replacement using dolomite. Calcite cements, late leaching.

4. Results and Discussions

4.1 Image Facies Interpretation

The mottled image facies is a major image lithofacies that is present in the Mauddud formation. The resistive mottling shows bioclastic fragments. The matrix contents were reflected by the surrounding environment, which exemplified the conductive. The shape and size of mottled varieties depend on fragments of bioclastic (Figure 4). The conductive result was when the drilling fluid invaded the porous or vugs between the grains. This pattern characterized the upper part of the Mauddud formation. The second image facies that is expressed in the Mauddud

Open Access
No. 41, December 2023, pp. 1-15

P- ISSN: 2220-5381
E- ISSN: 2710-1096

formation is the massive image facies. A compact limestone with low porosity values due to the cementation process that happens in restricted environments. The massive pattern usually has a resistive image shape. The last image pattern that shows in the Mauddud Formation image facies is a laminated image that represents the argillaceous environments (intertidal and restricted lagoon). This image facies pattern as planned limestone bedding rich in clay.

4.2 Data Integration

The integration between conventional wireline and FMI to understand the reservoir chartists the sedimentological properties of diagenetic texture have been understood by data integration. Figures 5, 6, and 7 show the plot between density-neutron and gamma-ray neutron codded by image facies. Figure 7 shows the relation between core data porosity and permeability codded by image facies. The mottled image facies mostly have a widespread range of equivalent density-neutron and low gamma-ray neutron plots (Figures 5 and 6). The massive image facies show high density values and low neutron values. The gamma-ray neutron plot shows a wide range of data. The laminated image facies show a wide range for both density-neutron and gamma-ray neutron plots. The core data (porosity permeability relationship) shows reservoir rock quality as below:

The mottled image facies has a wide porosity range; this ranges from medium porosity to good porosity (10 to 24 pu). Also, the permeability ranges from 0.5 to hundreds of micro diameters. These values reflect mixed and macropore types of vugs and good reservoir quality. The mottled pattern has good rock reservoir quality due to grainstone and packstone lithofacies that are characterized by a high energy level and dissolution digenesis process. The massive image facies is characterized by a low porosity range of less than 10 pu and small permeability values of less than 1 milli Darcy. The pore system for this image facies consists of equivalent micropores. The dominated lithofacies for the massive pattern are the wackestone and mudstone lithofacies, low energy level, and the cementation process, which is the main diagenesis process controlled in this image pattern. The laminated pattern ranges between 10 to 15 pu porosity values and about 1 milli Darcy permeability values. This pattern reflects the mixed reservoir pore system. The main dimensional process is the compaction process.

According to image facies architecture and lithofacies, the reservoir rock type can be divided into:

- RRT1: This rock type includes mudstone and wackestone with low porosity and very low permeability values because of the cementation process, which results in microporous and low reservoir quality. This reservoir rock type dominates this massive image pattern. The porosity values are less than 10% and the permeability values are between 0.1 and 10 md.

- RRT2: This rock is a combination of wackestone, packstone, and a mixed pores system. This rock type represents mixed-character rock quality with medium porosity and low permeability properties. The fine mottled image and laminated image patterns are most dominant in this reservoir rock type. The porosity values range between 10–15% and the permeability values range between 0.1–1 md.
- RRT3 includes grainstone, rudistone facies, and a vuggy porous system. This reservoir rock type represents high rock quality characteristics with high porosity and permeability properties. The mottled image facies is the dominated image facies for this rock type. The range of porosity is > 15 % and permeability values are more than 1 md.

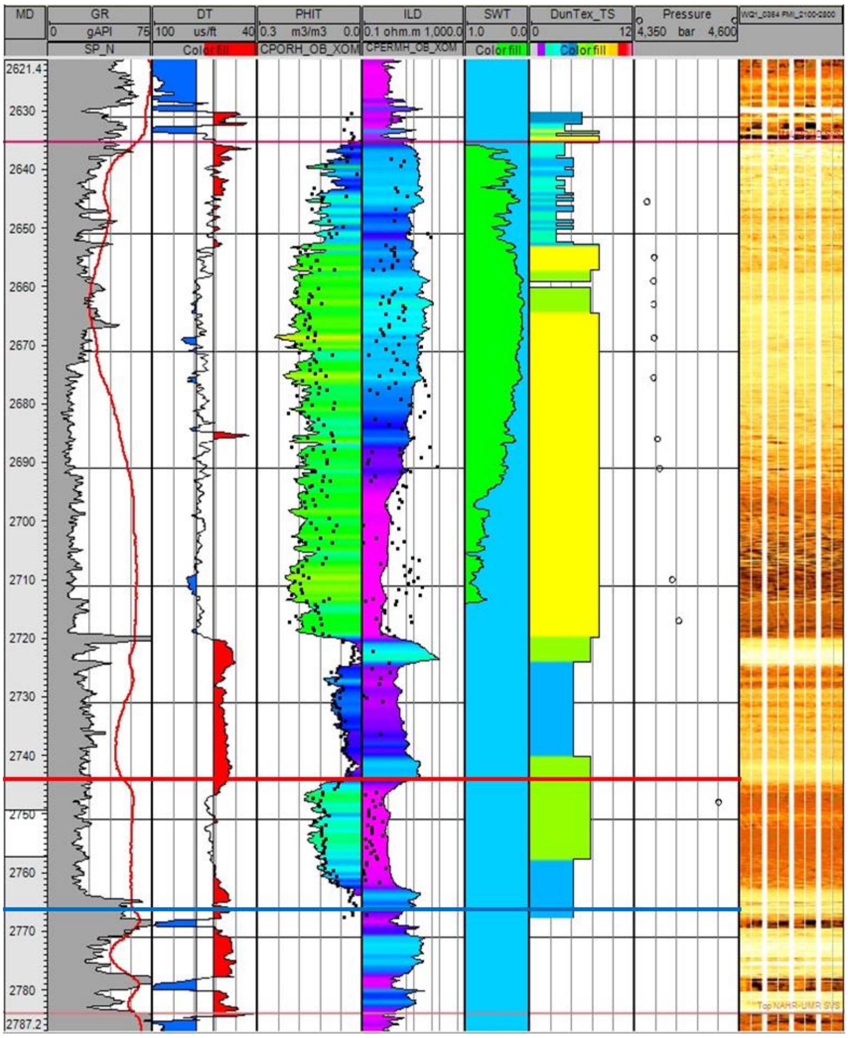


Fig. (4): The Image Facies Distribution in Well Study

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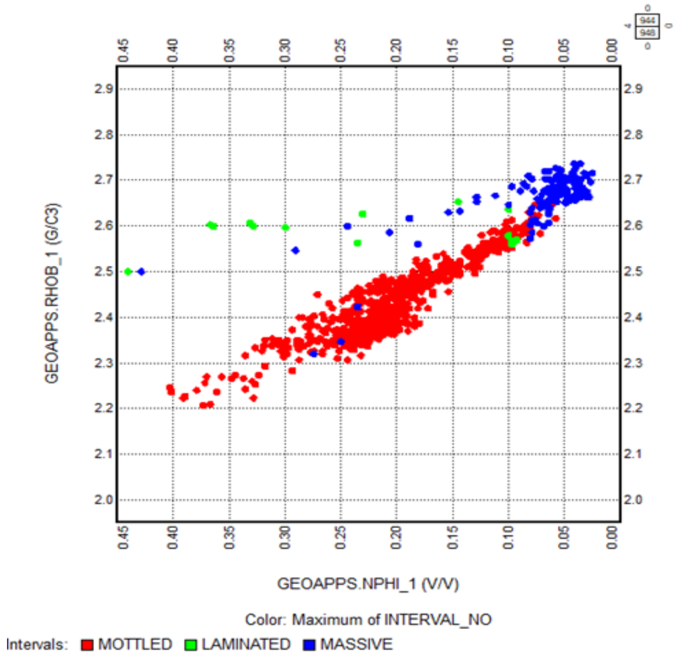

Fig. (5): Neutron-Density Cross Plot of Study Well

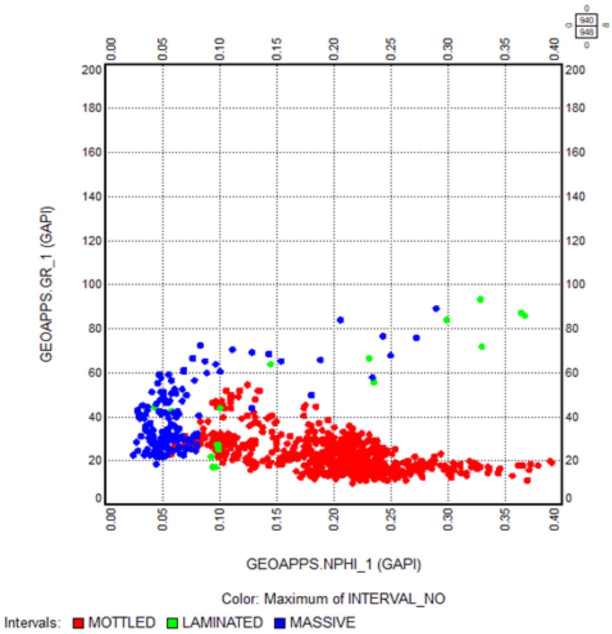

Fig. (6): Neutron-Gamma Ray Cross Plot of Study Well

Open Access
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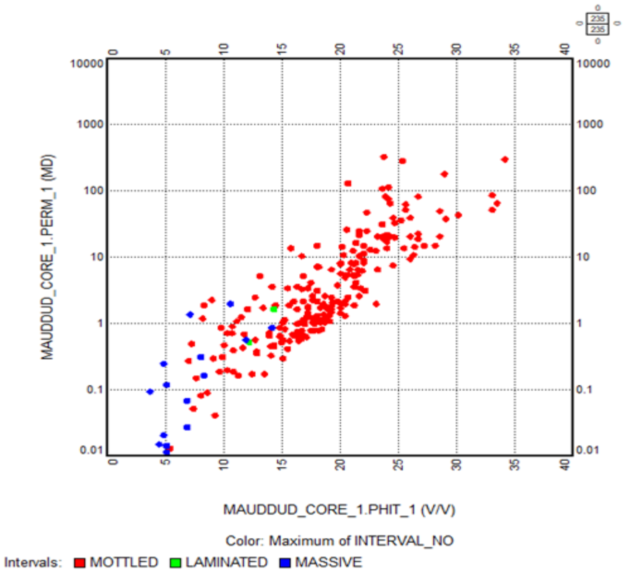

Fig. (7): Porosity -Permeability and Reservoir Rock Type Cross Plot of Study Well

5. Conclusions

The Mauddud formation has been deposited in shallow water environments. The lower parts of the formation environments are the intertidal and lagoon, while the upper part is mostly a shoal environment. The intertidal and restricted lagoon reflect the quiescent environment that is rich in clay content, and the major diagenesis process is cementation. The cement and clay content drove low porosity and low permeability values. The density log values are increased while the neutron values become near zero. Based on core-calibrated FMI logs, an image facies scheme was created. This design clearly demonstrates connections to the sedimentological make-up of the Mauddud Formation in the research well. From these data, the massive image facies is the major image facies that is represented in the lower part of the formation. The reservoir rock type3 with the massive image facies is the opposite of the non-reservoir rock type with porosity values of less than 10 pu and permeability of less than 0.1 md. The open lagoon is characterized by alternative beds that decrease in density values while the neutron values increase. The image lithofacies ranged between laminated and fine-mottled image facies. The reservoir rock type 2 is categorized in this image facies that have porosity values of between 10-15 pu and permeability of between 0.1-1 mD. The upper part of the formation is characterized by good porosity values and high permeability. The mottled image facies is the major image facies. The reservoir rock type 1 is considered in this image facies with porosity values of more than 15 pu and high permeability values of more than 1 md.

Open Access
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