

The Lateral and Vertical Variations in Petrophysical Properties of Zubair Formation in the East Baghdad Oil Field

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Abstract

The Zubair Formation is one of the main producing formations in the East Baghdad oil field, which is considered one of the largest producing oil fields in central Iraq, with its oil reserves exceeding 10 billion barrels. The formation is subdivided into six parts according to lithological facies. This study aims to evaluate the petrophysical and geological characteristics of the Zubair Formation and to build three-dimensional models that show the distribution of these characteristics. Well logs data for three wells (EB-2, EB-4, and EB-16) were analyzed using the Interactive software (IP) to evaluate the formation's petrophysical properties. Porosity and permeability types were obtained by analyzing data from the three well logs. The results of two cross plots (Neutron Porosity-Density, and M-N) indicate that the lithology of the Zubair Formation is mostly sandstone, with small amounts of dolomite and limestone present in certain areas, and shale makes up a sizable portion of the volume (up to 50 %). In general, the Zubair Formation has a good total porosity (about 25% on average). Secondary porosity ranges from very low at the base to increasing towards the top of the formation. In contrast, effective porosity ranges from 0% to 15% depending on the shale content of the formation rocks. Permeability varies from low to high (2-600 md) depending on the porosity values and percentage of shale. The water and oil saturation of all formation units for the three studied wells ranged between (10-100 %). Three-Dimensional models of porosity, permeability, and saturation of water for the Zubair Formation have been made to view the distribution and variation of these properties in a three-dimensional view.

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1. Introduction

Well logging is one of the most widely used methods in petroleum engineering and geology because it has many advantages. It provides detailed information about many petrophysical and rock properties, and is much cheaper than coring or drilling. Many studies have used well log data to evaluate the petrophysical characteristics of hydrocarbon-containing formations. For example, Albeyati et al. (2021) assessed the petrophysical properties of the Balad Oilfield in Iraq by combining all available data, including petrographic image analysis (PIA), well logs (resistivity, density, and gamma rays), and core data (permeability and porosity). Al-Majid (2022a) used a so-called velocity deviation log (VDL) derived from a porosity log to detect the presence of hydrocarbons in the Haritha Formation, which is considered one of the productive formations in the Qayyarah oil field in northern Iraq. Al-Mawla et al. (2023) used well log data to estimate porosity types and the percentage of shale in the Bajawan Formation, a productive formation of the Kirkuk field in northern Iraq. Al-Juraisy and Al-Majid (2025) also determined the petrophysical properties and oil content of the Hartha Formation in the Qayyarah field in northern Iraq. They identified three zones in the formation relative to the percentage of oil.

1.1. Location

The East Baghdad Oil Field comprises several oil fields spanning over 1,000 km² and is situated east of the

Baghdad Governorate. Al-Mansurriya and Al-Suwayrah regions, respectively, constitute its northern and southern borders (Figure 1). The East Baghdad Oil Field extends more than 100 km from northwest to southeast, with some areas exceeding 10 km in width.

1.2 Geology

Structurally, the East Baghdad field is an anticline affected by numerous longitudinal and transverse faults, which led to its division into independent sections containing different oil and gas reservoirs. It led to the development of the Arabian Peninsula's largest oil and gas reserves. Many NW-SE-trending faults in the field produce oil that originates from the Early Cretaceous sandstone parts of the Zubair Formation, the Late Cretaceous Tanuma Formation, and the Late Cretaceous Khasib Formation (Sharland et al., 2001).

Stratigraphically, the Zubair Formation section includes many rock types, such as sandstone, carbonates, siltstone, and shale, deposited in marine and lagoon environments (Ali and Jassim, 2023). The Zubair Formation is one of the lower Cretaceous deposits, characterized by sandstone and shale that alternate, with a few thin layers of limestone in the upper portion of the formation. Its age is regarded as Berriasian-Valanginian. In the study area, The thickness of the Zubair formation is roughly 400m, and Figure 2 shows the stratigraphic section of the formations in the field (Al-Haleem, 2010).

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Figure 1. The location map of the study area with the locations of studied wells (Modified from Al-Ameri and Al-Obaydi, 2011)

According to the final geological report of the Central Oil Company in the East Baghdad oil field (IPC,1982), the Zubair Formation was divided into six units (from A to Z) depending on the rock content of each unit.

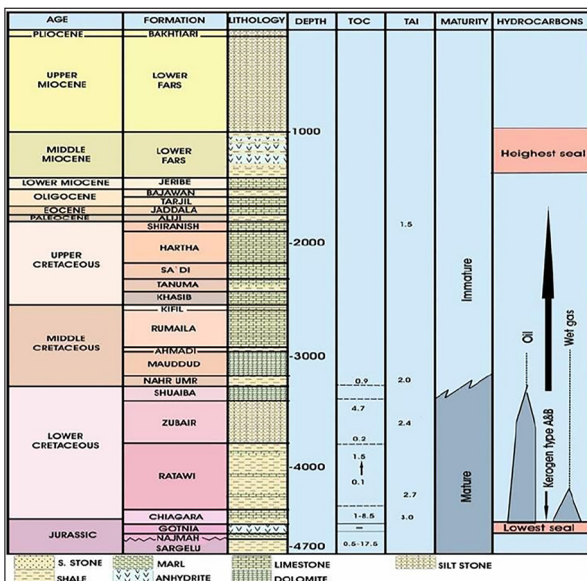


Figure 2. Stratigraphic section of East Baghdad Oil Field (Al-Haleem, 2010)

The primary aim of this study is to determine the amount of hydrocarbon in the Zubair Formation by analyzing petrophysical characteristics derived from well log data and creating three-dimensional models of these characteristics (porosity, permeability, and water saturation).

2. Materials and Methods

Well log data from three wells (EB-2, EB-4, and EB-16) in the East Baghdad Oil Field were used in this study, namely: Gamma ray, SP, porosity, and resistivity logs. All data used in this work were environmentally corrected to reduce the effects of mud cake, drilling mud, and other environmental factors. Many equations are used for calculating the required parameters and correcting them (Al-Majid, 2019, Al-Juraisy and Al-Majid, 2021, Al-Majid, 2021, Al-Majid, 2022a, Al-

Majid, 2022b, Boddy and Smith, 2009, and Ebrahim, et al, 2023) (Table. 1). Several computer programs (Interactive Petrophysics (IP), Techlog, Petrel E&P, and Neuralog programs) were used to facilitate and reduce the time spent in digitizing the data, preparing the data, well log analysis, data analysis, and results plotting.

Table 1. The measurement and correction equations used in this study

<p>Porosity calculation</p> $PHID = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \text{ --- (1)}$ $PHIS = \frac{\Delta Tlog - \Delta Tma}{\Delta Tf - \Delta Tma} \text{ --- (2)}$ $NPHID = \frac{NPHI + PHID}{2} \text{ --- (3)}$ $PHIsec = (NPHID - PHIS) \text{ --- (4)}$	<p>ρ_{ma}: density of the matrix (2.65 g/c³ for sandstone). ρ_f: density of the fluid (1 g/c³ for fresh water). ρ_b: reading of density log. Δt_r: fluid transit-time (189 μsec/ft for fresh water). Δt_{log}: sonic log reading of transit-time. Δt_{ma}: matrix transit-time (55.5 μsec/ft for Dolomite). Δt_f: density-porosity (using the density log data). $NPHI$: neutron porosity (using neutron log data). $PHIS$: primary porosity (obtained from sonic log data). $PHIsec$: secondary porosity. $NPHID$: neutron & density porosity.</p>
<p>Shale Volume calculation</p> $IGR = \frac{GRlog - GRmin}{GRmax - GRmin} \text{ --- (5)}$ $Vsh = 0.33 * [2^{(2 \cdot IGR)} - 1] \text{ --- (6)}$	<p>IGR: gamma-ray index. Vsh: volume of the shale. GR_{log}: reading of gamma-ray log, GR_{max}: the maximum gamma-ray value. GR_{min}: the minimum gamma-ray value.</p>
<p>Porosity corrections</p> $PHISc = PHIS - (Vsh \times PHISsh) \text{ --- (7)}$ $NPHIc = NPHI - (Vsh \times NPHIsh) \text{ --- (8)}$ $PHIDc = PHID - (Vsh \times PHIDsh) \text{ --- (9)}$ $PHIE = NPHID \times (1 - Vsh) \text{ --- (10)}$	<p>($PHISc$; $NPHIc$; $PHIDc$): corrected porosities ($PHISsh$; $NPHIsh$; $PHIDsh$): shale porosity obtained from different logs $PHIE$: the effective porosity.</p>
<p>M & N lithology parameters</p> $M = \left(\frac{\Delta t_f - \Delta t_{log}}{\rho_b - \rho_f} \right) * 0.01 \text{ --- (11)}$ $N = \frac{1 - NPHI}{\rho_b - \rho_f} \text{ --- (12)}$	<p>M and N: lithology parameters</p>
<p>Permeability and saturation equations</p> $K = 10000 * NPHID^{4.5} / Sw^2$ $Sw^n = \frac{a \cdot R_w}{NPHID^m \cdot Rt} \text{ --- (13)}$ $So = 1 - Sw^n \text{ --- (14)}$	<p>a: factor of the tortuosity (0.8 for sandstone). m: factor of the cementation (1.8 for sandstone). N: exponential of saturation (2 for sandstone). R_w: resistivity of formation water (obtained from Sp log). R_t: true formation resistivity (from resistivity logs); Sw: water saturation; So: oil saturation.</p>

3. Results

3.1. Lithology

Lithology is one of the important parameters in evaluating geological formations. In order to delineate the lithology of the Zubair Formation in the study area, two types of cross-plots were used:

3.1.1 Neutron Porosity- Density (NPHI-RHOB) Cross plot

Neutron Porosity-Density cross-plots were applied to determine the main rock component of the Zubair Formation in the three studied wells by observing the assemblages of points around rock types (sandstone, dolomite, and limestone). Most of the points are located near the sandstone line (Figure 3). From Figure 3, it is clear that the main component of the Zubair Formation in the three wells is sandstone, with limestone and dolomite percentages varying from one well to another. As for the shale, it increased in well EB-4 compared to the other two wells.

3.1.2. M-N Cross plot

The two factors (M and N), calculated using equations 11 and 12, respectively, are assigned to the three wells to apply the M-N cross-plot, which shows the basic mineral compositions in the Zubair Formation (Figure 3).

From the M-N cross plots above, most of the points gather around the site of silica, which is the main mineral

composition of sandstone. This concentration means that the main parts of the formation are sandstone, which is consistent with the results of the NPHI-RHOB cross plots. Also, from Figure 3, it can be seen that some points are located in the limestone and dolomite zones, indicating the presence of layers of limestone and dolomite within the Zubair Formation.

So, according to the analysis of Figures 3 and 4, the Zubair Formation is mainly composed of sandstone interspersed with some layers of limestone and dolomite.

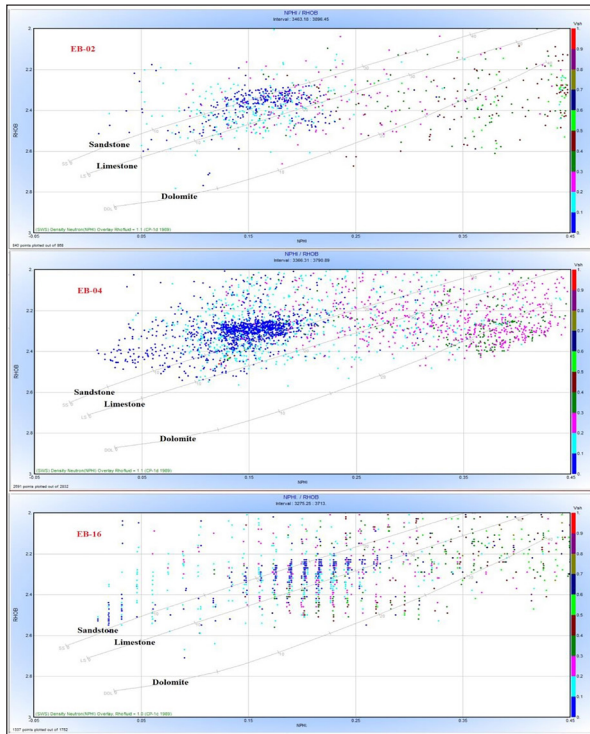


Figure 3. NPHI-RHOB cross plot applied on the three studied wells (EB-2, EB-4, and EB-16).

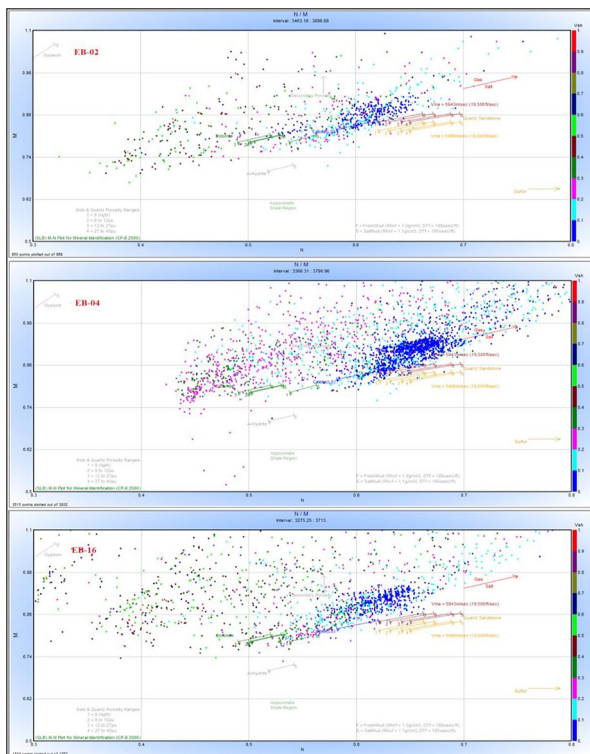


Figure 4. M-N Cross plot applied to the three studied wells (EB-2, EB-4, and EB-16).

3.2. Shale Volume

The shale volume (Vsh) is determinative in correcting porosity types and water saturation ratios based on shale content (Wahid et al., 2022). Vsh is calculated using the equations 5, and 6 respectively (Ajisafe and Ako, 2013). It is clear that there is an increase in the shale volume at the upper parts of the three wells, and in well EB-4 compared to other wells (figure 5).

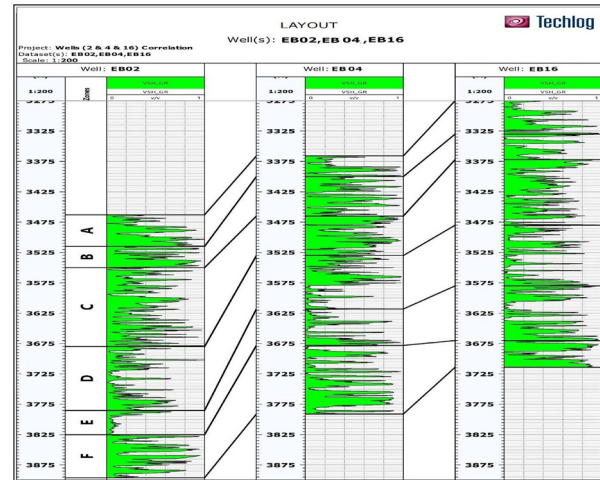


Figure 5. Shale volume of the three studied wells

3.3. Porosity

Three types of porosity have been calculated in this study:

3.3.1 Total porosity.

The total porosity (NPHID) values for wells EB-2, EB-4, and EB-16 have been calculated using equation 3. They are relatively high, reaching about 25%, especially in well EB-4, as its values are greater than those of the other two wells (Figure 6).

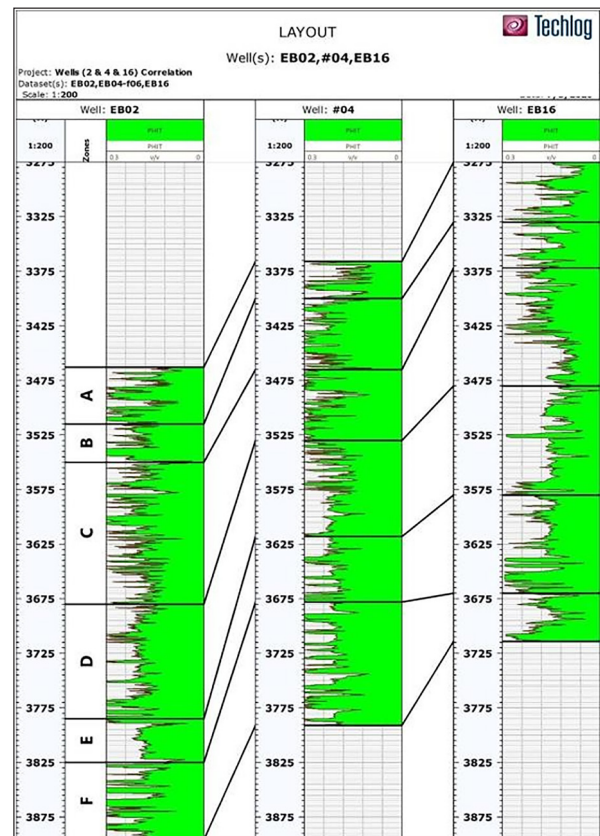


Figure 6. Total porosity values of the three studied wells.

3.3.2. Effective porosity

After accounting for the shale effect on total porosity, effective porosity (PHIE) values for the Zubair formation in the three studied wells are calculated using equation 10 (Figure 7). There was a close relationship between the total porosity values and the effective porosity values in the three wells

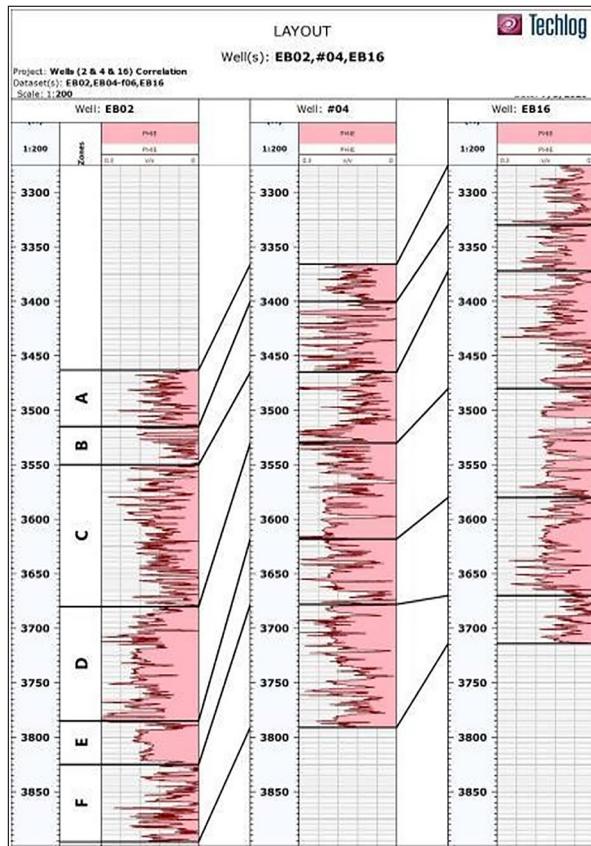


Figure 7. Effective porosity values of the three studied wells.

3.3.3. Secondary porosity

The secondary porosity values (PHIsec) are calculated using equation (4) as the difference between total and sonic porosities. The PHIsec values at wells EB-2 and EB-4 are almost equal in all units, while they are slightly larger in well EB-16 (Figure 8).

3.4. Permeability

The calculated permeability values for the three wells show that the highest permeability was observed in wells EB-4 and EB-16. The highest values (about 600 md) are observed at several units of well EB-4, while the lowest values are observed at most units of well EB-2. Figure 9 displays the three wells' permeability values.

3.5. Saturation

Determining water saturation (S_w) is an important characteristic that helps determine the amount of hydrocarbon in the oil reservoir (Mohammed et al., 2021). Water saturation is the fraction of the pore volume occupied by water. Improper calculation of water saturation leads to significant errors in the estimation of hydrocarbon saturation ($1-S_w$). There are several methods to determine water saturation, including dielectric measurements, nuclear measurements, the ratio technique (SP vs. R_{xo}/R_t), crossplots, F- overlays, Archie's equation, and shaly sand methods. In this study, Archie's formula was used to calculate the water and oil saturations

of the Zubair Formation (equations 13 and 14, respectively). The results demonstrated that the water saturation values of Zubair Formation range between (10% - 100%) (Figure 10). This means that the percentage of saturation with hydrocarbon ranges between (100% - 10%). The highest hydrocarbon saturation appears in the C unit, followed by the A unit. There is a clear increase in water saturation in well EB-16, accompanied by a decrease in oil saturation

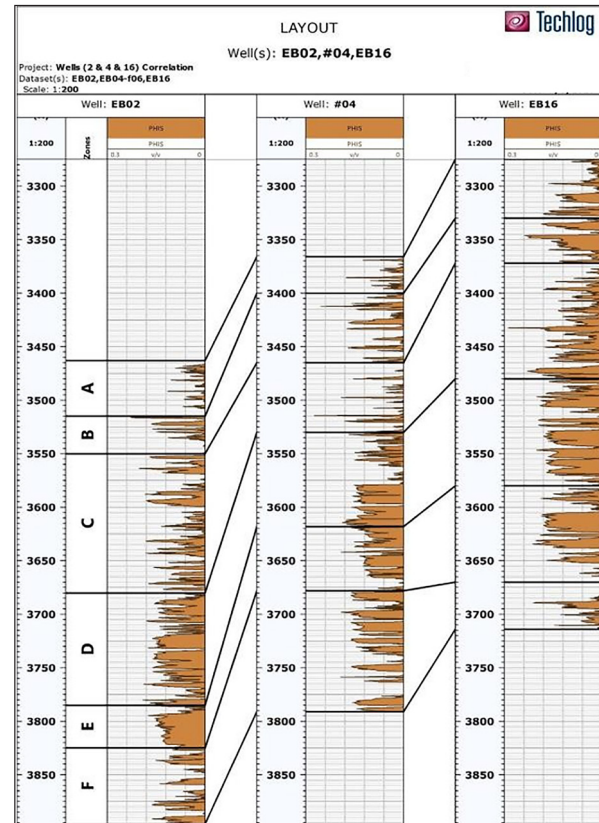


Figure 8. Secondary porosity values of the three studied wells in the study area

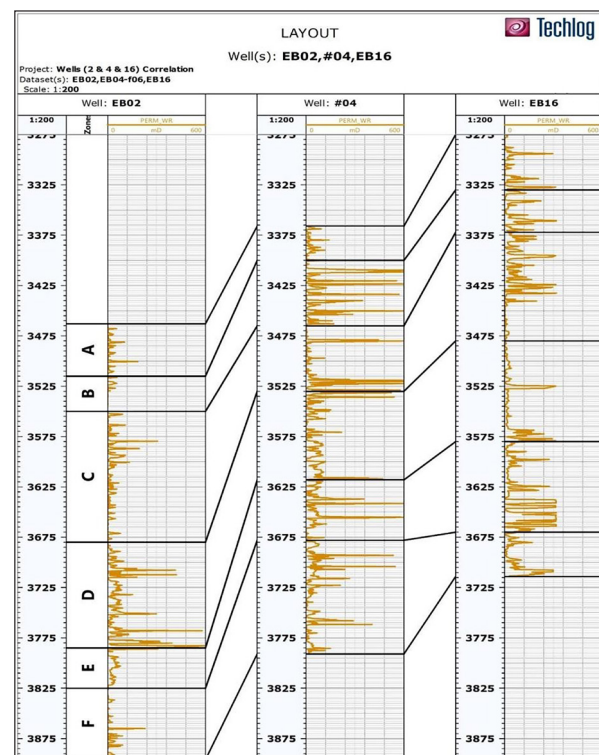


Figure 9. Permeability values for the three wells in the study area.

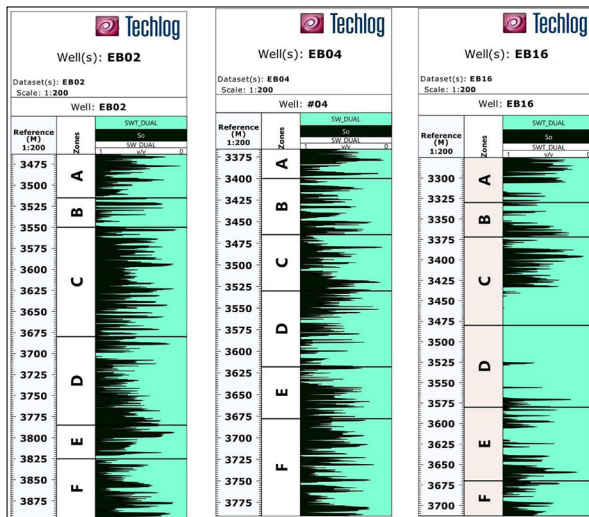


Figure 10. The saturation distribution in the three studied wells.

3.6. Petrophysical Modeling Process

Reservoir modeling in the oil and gas sector is the process of building a computer model of a petroleum reservoir to better estimate reserves, make field development decisions, forecast future production, install additional wells, and assess different reservoir management scenarios. A regular or irregular grid defines the array of distinct cells that make up a reservoir model, which depicts the reservoir’s physical space. Although 1D and 2D models are occasionally employed, the array of cells is typically three-dimensional. Each cell has values for characteristics including water saturation, permeability, and porosity.

The process of assigning petrophysical property values (permeability, water saturation, and porosity) to every cell in a three-dimensional grid is known as petrophysical property modeling. For simulating the distribution of petrophysical characteristics in a reservoir model, Petrel provides a number of algorithms. Geostatistical techniques were used to construct the petrophysics model. Based on the porosity, water saturation, and permeability measurements, which were adjusted and evaluated in the IP software, models of these parameters were constructed. To account for the volume of data at hand, the Sequential Gaussian Simulation algorithm was employed.

3.6.1. Porosity Model

Total and effective porosity models of the Zubair Formation were built based on results from porosity logs. Each unit is characterized by a specific range of porosity values (Figure 11).

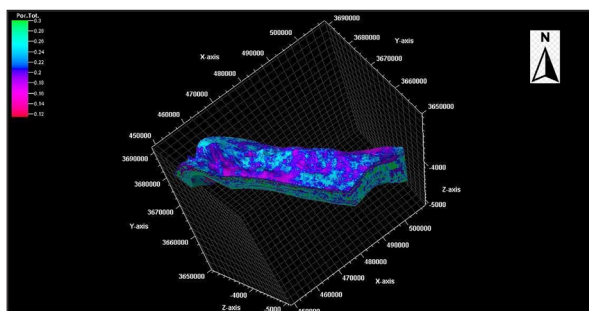


Figure 11. Total porosity model of Zubair Formation.

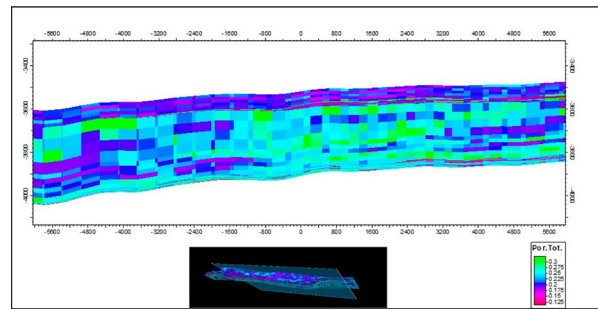


Figure 12. N-S cross-section shows the distribution of the total porosity of Zubair Formation.

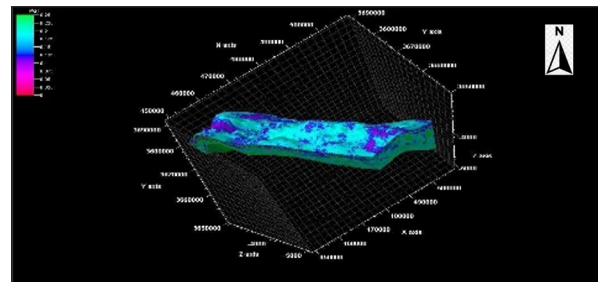


Figure 13. Effective porosity model of Zubair Formation.

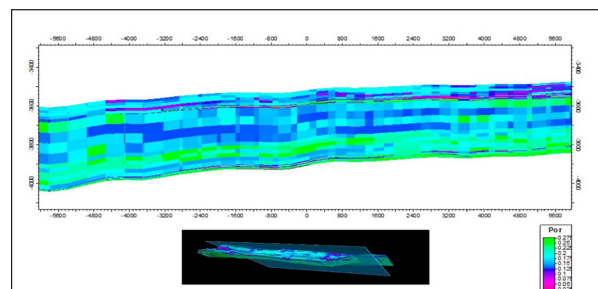


Figure 14. N-S cross-section shows the distribution of the effective porosity of the Zubair Formation

3.6.2. Permeability Model

Permeability is also considered one of the Petrophysical properties in formation evaluation. The method used to build the absolute permeability model was the Statistical Sequential Gaussian Simulation Algorithm, with normal score transforms and experimental variogram ranges calculated. The major direction azimuth is (-41°) as shown in Figure 15.

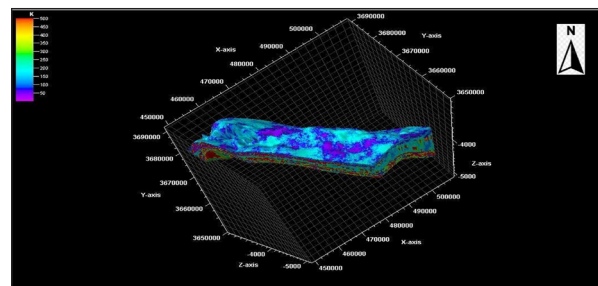


Figure 15. Permeability model of the Zubair Formation.

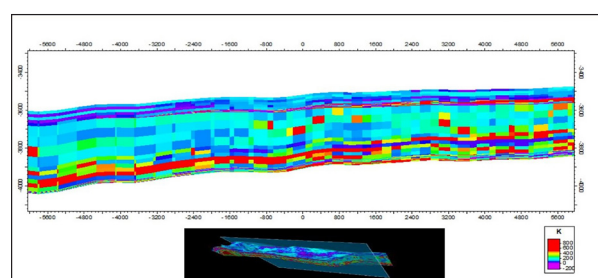


Figure 16. N-S cross sections shows distribution of the permeability of Zubair Formation

3.6.3. Water Saturation Model

One of the petrophysical characteristics used to evaluate a deposit is water saturation. Water saturation values are used to describe each unit. Models of water saturation, environment, and porosity were found to match (Figure 17).

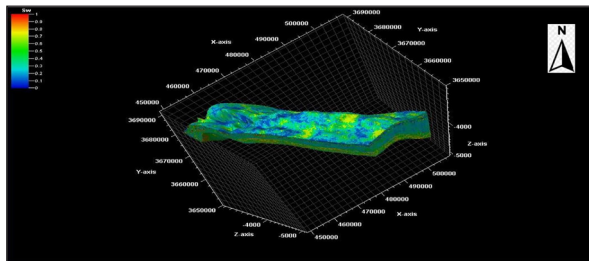


Figure 17. Water saturation model of Zubair Formation.

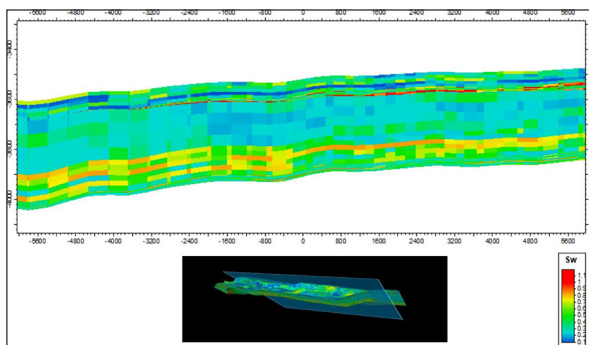


Figure 18. N-S cross-section shows the distribution of the water saturation of the Zubair Formation

4. Discussion

The Zubair Formation is considered lithologically complex, as it contains many rock types (Aqrabi et al., 2010). The proportions of these rocks vary from one region to another, and even within one region between one well and another (IPC, 1982). This variation in lithology is clearly observed in the large dispersion of points on the NPHI-RHOB cross-plot (Figure 3) and the M-N Cross plot (Figure 4). This variation led to a large variance and overlap in the petrophysical properties calculated for the three study wells. However, in general, by observing the values of the calculated petrophysical parameters, we can distinguish some evidence as follows:

Regarding the total porosity, it can be noted that there is, in general, an increase in this type of porosity in most parts of the bottom of the formation (Figures 11&12). This is perhaps due to the increase in the proportion of clastic sediments in this part of the formation, as reflected in the sand-to-shale ratio.

It can also be noted that the increase in total porosity at the bottom of the formation is accompanied by an increase in effective porosity (Figures 13 and 14), and permeability (Figures 15 & 16). On most sites, this increase may be related to the increase in the sandstone percentage.

Logically, an increase in water saturation indicates a decrease in hydrocarbon saturation (heavy oil at this site). The amount and method of oil distribution in the formation depend mainly on many factors, the most important of which are characteristics of the fluid and rock heterogeneity (Chioma et al., 2018). Therefore, it can be noticed that water

saturation increases from the lower to the upper part of the formation. This may be due to the density of water being greater than that of oil, and the presence of oil with water in some of the upper areas of the formation may be due to the close density match between the heavy oil present in the reservoir and the density of water. In this case, heterogeneity plays an important role in the amount and distribution of the fluids, as less-dense fluids (oil) can move and distribute within small pores, while more-dense fluids (water) are unable to move and distribute within small spaces. Because the Zubair Formation contains many different and overlapping rocks, which mainly include sand rocks with large pore sizes and shale rocks with small pores, we note that there is overlap in the zones and amounts of oil, water saturation in most parts of the formation (Figure 10)

5. Conclusions

According to the interpretation results of the wells' data for the three studied wells, we can conclude the following:

- The Zubair Formation rocks consist mainly of sandstone, with interbedded layers of shale, siltstone, limestone, and dolomite.
- The formation rocks generally contain a relatively high percentage of shale, which is randomly distributed throughout the formation and varies between approximately 40% and 100%, reaching 100% in some parts of the formation while not exceeding 1% in others.
- The total porosity of the formation can be considered good, as it ranged between 15% and more than 30% in most parts of the formation
- The permeability of the formation rocks varied greatly between parts of the formation and from one well to another, ranging from 0 to 600 md, perhaps due to variations in the proportion of low-permeability shale within these rocks.
- Formation porosity contains a good range of hydrocarbon saturation (10-100%), and the variability of this hydrocarbon saturation depends on the amount and type of porosity in the formation's parts.

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