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# 3D Static Reservoir Modeling of the Bahariya Reservoirs in parts of the Shushan Basin, North Western Desert, Egypt

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## ABSTRACT

The Khalda Oil Field is one of the most productive in the Shushan basin; two dry wells were recently drilled in the study area's northern and southwest corners. The primary goal of this study is to assess the potential of the Bahariya reservoir in the Khalda Oil field and to express the geological, petrophysical, and structural features through maps and cross sections. The Upper and Lower Bahariya members were evaluated as hydrocarbon-bearing sandstone reservoirs using a complete set of well logs from eight wells and thirty 2D seismic lines. The NW-SE fault trend is clearly defined by the interpretation of the depth structure contour maps. The quantitative computer-processed interpretation of petrophysical characteristics such as lithology, net pay, effective porosity (eff), the volume of shale (Vsh), water saturation (Sw), and hydrocarbon saturation (Sh) is obtained. All of these findings are represented in a 3D geological model. 3D static reservoir modelling of the Bahariya reservoirs using seismic and well data can be an important part of an overall strategy for oilfield development and locating a new drilling location. A 3D integrated reservoir model was run on eight wells to simulate the subsurface structural setting, petrophysical modelling, and facies distribution modelling of the Cretaceous Bahariya reservoir, which is the study's main oil-bearing reservoir. In the Late Albian (Lower Bahariya), Early Cenomanian, the various structural depth maps and structural cross-sections extracted from the 3D structural model show 11 dip-faults that are primarily normal faults with dominated NW-SE trends (Upper Bahariya), Facies and petrophysical cross-sections extracted from the 3D model show the lateral extension of these properties and their thickness variation through the reservoir zones. The combination of geological structures, accurate facies, and petrophysical evaluation provides an excellent framework for planning appropriate drilling campaigns for Khalda oil field exploration and development.

## 1. Introduction

Khalda oil field is situated in the northeastern boundary of the Shushan basin between latitudes: 30°, 51’ - 30°, 48' N

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and longitudes: 26°,42' - 26°, 48' E, about 450 km west of Cairo, and about 70 km south of the Mediterranean coast Fig. (1). It was discovered in November 1980 by drilling Khalda-1X well. In 1984, Khalda-2 well was drilled and proved the southern extension of Khalda Field. In the area of study, up to the present, all commercial and non-commercial hydrocarbon accumulations have been found in the Cretaceous formations [2, 3, 4]. The Cretaceous sediments in the study area have great importance in the exploration activities due to their wide areal distribution, great thicknesses, and their facies characteristics. The Northwestern Desert, encompassing Shushan Basin, has a Paleozoic to Tertiary geologic sequence Fig. (2). It is made up of clastic and carbonate sequences that alternate [6]. The Bahariya Formation is the most promising oil-bearing reservoir in Khalda Oil Field. The primary reservoir producer in the Khalda concession is the Lower Bahariya, whereas the secondary producer is the Upper Bahariya [7]. It is primarily composed of sandstone facies accumulated in a transgressive shallow marine coastal depositional setting, with some neritic shales and thin carbonate interbeds. The thickness of the Upper Bahariya Member is several hundred feet and is mainly composed of shale and thin beds of limestone, whereas the Lower Bahariya Member is thick and composed of sandstone and shale interbeds. Thick organic-rich sediments were deposited under favourable conditions for oil generation at the depocenters of the Cretaceous basins such as the Shushan basin. The structure on top Bahariya Formation is an oval anti-cline, dissected by NW-SE trending normal faults. Minor faults (< 50 ft. throw) offset the Bahariya Formation and isolate the pay zone into several fault blocks within the field. Shushan Basin lies to the south of Matruh Basin and shows the effect of ENE-WSW and WNW-ESE oriented faults on the basin architecture. Like Matruh Basin, Shushan Basin witnessed Jurassic and Early Cretaceous extension followed by Late Cretaceous-early Tertiary inversion [8]. NE-SW and NNE-SSW oriented inversion anticlines, as well as tilted fault blocks bounded by WNW-ESE and NW-SE; oriented normal faults form the main structural traps in the basin. According to [9], the Shushan basin is currently regarded as one of the most significant petroliferous basins as it has numerous clastic reservoirs [9] (Mahmoud et al., 2019). The hydrocarbons have been trapped in the shushan basin within structural traps that follow the Syrian Arc structural trend. These traps are formed as fault blocks, and three to four-way closure structures [10, 11, 12].

## 2. Data Base and Methods

Fig. (3) shows both geological and geophysical data acquired from Khalda Petroleum Company (KPC) and Egyptian General Petroleum Corporation (EGPC). Eight borehole petrophysical logs (gamma ray, density, acoustic, neutron, and resistivity logs).

The geophysical data includes thirty 2D seismic lines with check shot records for Khalda-21 well. The selected logs of eight wells were applied for the subjective and quantitative examination, confirmation of petrophysical parameters, and oil potentiality in the Khalda oil field. Various maps for the reservoir's properties were created and helped in the modelling step. Seismic interpretation represents the backbone of structural modelling.


**Fig. 1:** Location map of the Khalda Oil Field and the Coastal Basins in the north Western Desert, Egypt [1].

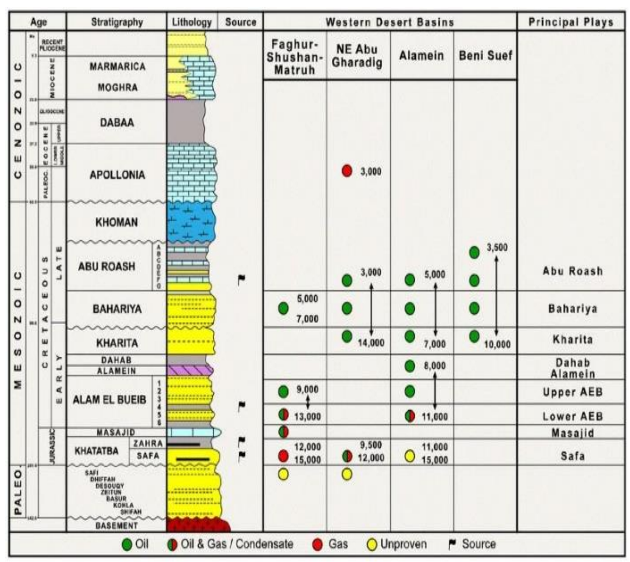



**Fig. 2:** The Lithostratigraphic column of the Western Desert of Egypt shows the main basins and principal plays [5].

The primary step in seismic interpretation is to establish the connection between seismic reflections and stratigraphy [13]. The seismic interpretation workflow in Fig. (4) starts with collecting the seismic data and checking its quality and then the good thing, the fault and horizon interpretation, and the time-to-depth conversion process was applied to enable mapping the structural setting of the Khalda structure. The petrophysical evaluation was conducted through the following steps. First, the reservoir lithologies of Bahariya have been identified using cross-plots. Then, the petrophysical parameters (net-pay thickness, PHIE, Vsh, Sw, and Sh) of the reservoirs have been estimated by computer-processed interpretation (CPI).

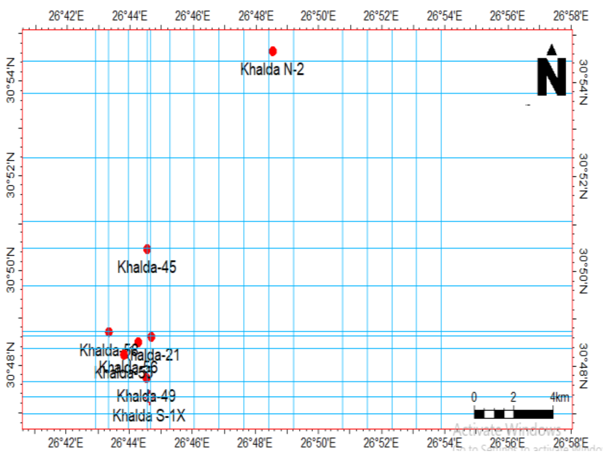



**Fig. 3:** Base map of seismic lines and wells in the study area.

The reservoir model of Bahariya reservoirs is used to represent the shape of the structures, the workflow used to model the Bahariya reservoirs in the Khalda field consisted of three types of modelling based on the interpretation of the seismic and well logs. The evaluation of the hydrocarbon potentiality of the Shushan Basin and Khalda oil field are investigated in recent studies [14, 15, 16].

## 3. Results and Discussions.

### *3.1. Seismic Interpretation.*

Depth structure maps Fig.s (5, 6) at the top of Upper and Lower Bahariya reservoirs reveal that: The research area is dissected by a group of eleven faults extending from northwest to southeast (NW-SE) direction. The depth values for the Upper and Lower Bahariya Formation lie between 5043.43 to 6282.5 ft and 5189.88 to 6449.83 ft respectively obtaining their maximum value towards the northern part and southwestern portion of the research area. Folding and faulting play a prominent role in the definition of the structural setting on the mapped tops. The oval anticline on top of the Bahariya Formation is cut by NW-SE trending normal faults. A three-way structural closure has been appeared in the north part forming some faulted anticlines.

### *3.2. Subsurface Evaluation*

The depositional environment and expected direction of the paleo-shoreline will be revealed by illustrating the subsurface geology of the Khalda field with various lithological maps. Many geologic studies aim to depict the paleogeography of a given area at a specific geologic time. Isopach map of Upper Bahariya Formation, Fig. (7) illustrates an increase in the north, northwest and southwestern parts obtaining its highest value at Khalda-21 and Khalda n-2 wells with 202.4 and 202 ft and decreases in the west and southwestern parts gaining its minimal value at Khalda-45 and Khalda S-1x well with 172.22 and 178 feet; and isopach map of Lower Bahariya Formation, Fig. (8) indicates an increase in the central and southeastern parts getting its maximal value at Khalda-21 well with 797.86 ft and decreases in western part obtaining its minimal thickness at Khalda-58 well with 181.31 feet.

The sand/shale proportion map of the Upper Bahariya Formation, Fig. (9) shows that the proportion increases in the southern portion, reaching a maximum value at Khalda-49 and KhaldaS-1x wells, while it decreases in the northern portion, reaching a minimum value at Khalda-45 and KhaldaN-2 wells. In the Lower Bahariya Formation, Fig. (10) shows that the ratio increases in the southern and central portions, reaching a maximum value at Khalda-21 and Khaldas-1x wells and decreases in the north and southwestern parts getting its minimal value at Khalda 53 well.

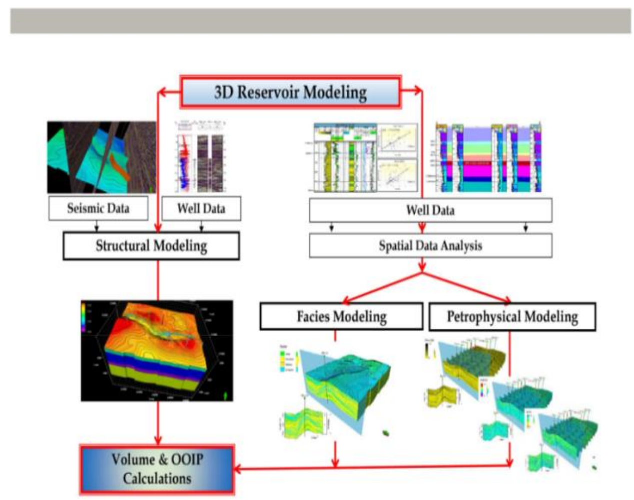



**Fig. 4:** Simplified workflow for 3D static reservoir modeling of Bahariya reservoirs in Khalda Oil Field, Western Desert, Egypt.

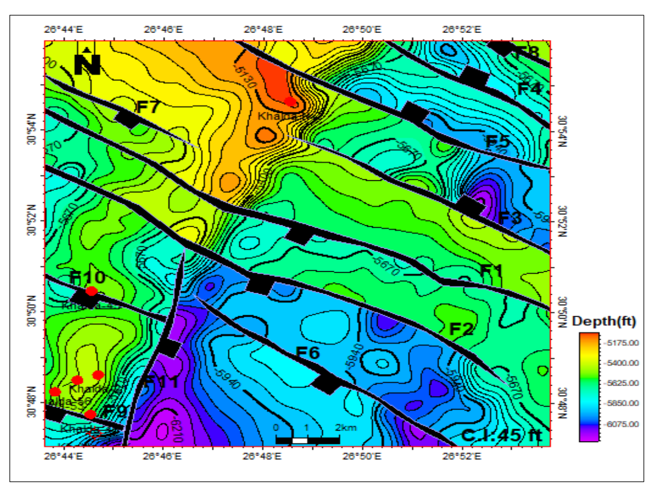



**Fig. 5:** Depth structure contour map on top of Upper Bahariya Reservoir.

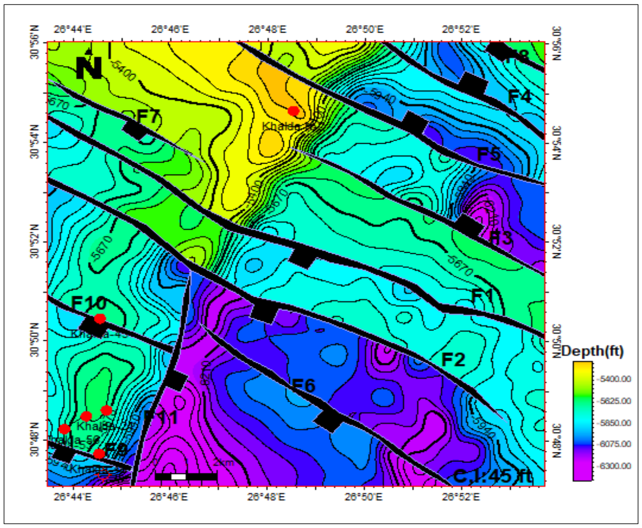



**Fig. 6:** Depth structure contour map on top of Lower Bahariya Reservoir.

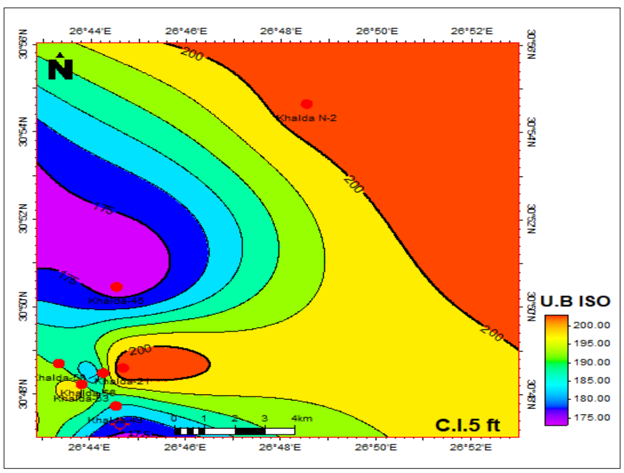



**Fig.7:** Isopach map of Upper Bahariya Formation.

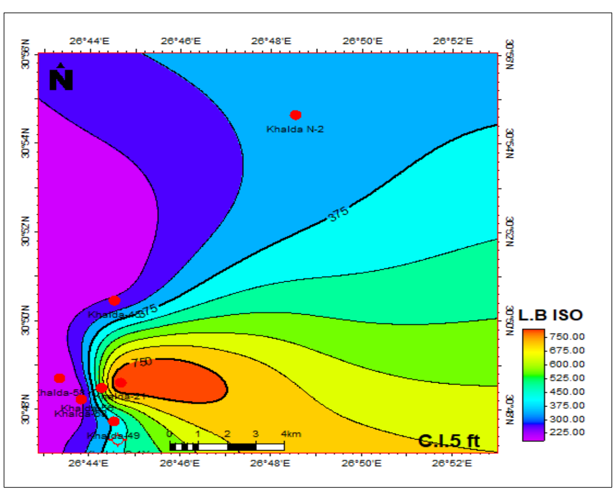



**Fig.8:** Isopach map of Lower Bahariya Formation.

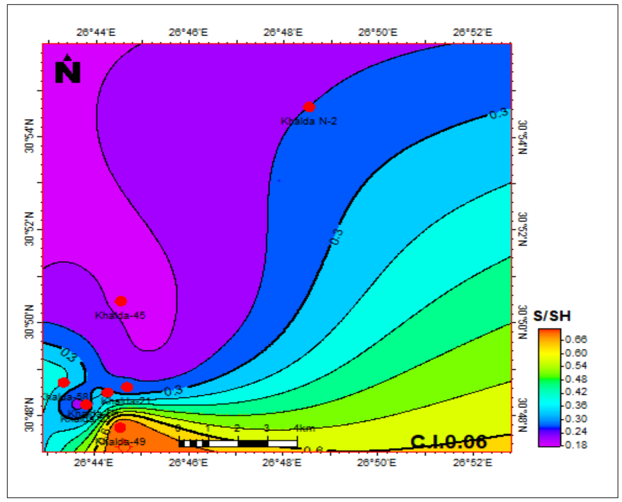



**Fig.9:** Sand/shale ratio map of Upper Bahariya Formation.

*3.3. Petrophysical Evaluation.*

For the present study, a complete set of borehole logs were released for five wells in Khalda Field (Kh-49, Kh-53, Kh-45, Kh-56, Kh-58, Kh-21x, and Kh-S-1 × wells) crossing the Bahariya Formation including resistivity logs, neutron, density, PEF, and gamma-ray logs. The petrophysical analysis includes lithologic definition based on a set of X–Y cross-plots for the petrophysical parameters, and the litho-saturation vertical plot, and the contour maps of the

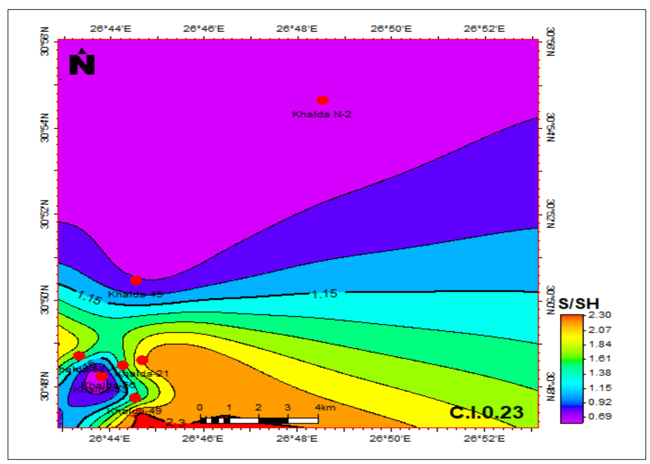



**Fig.10:** Sand/shale ratio map of Lower Bahariya Formation.

The sandstone map of the Upper Bahariya Formation, Fig. (11) indicates an increase in the southern portion, reaching its highest value at KhaldaS-1x well with 89.38 feet, and decreases in the northern part at Khalda-45 well with 17 feet, while the sandstone map of the Lower Bahariya Formation, Fig. (12) indicates an increase in the southern portion, reaching its highest value at Khalda-21 well with 379.5 feet, and decreases in the Southwestern part gaining its minimal value at Khalda-53 well with 39.5 feet.

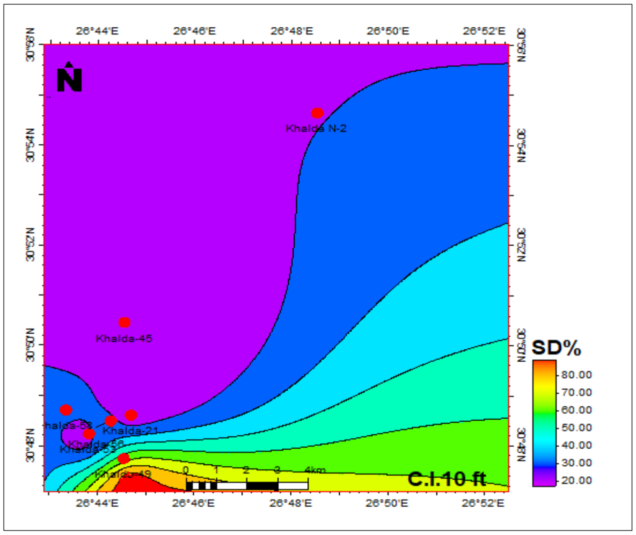



**Fig.11:** Sand ratio map of Upper Bahariya Formation.

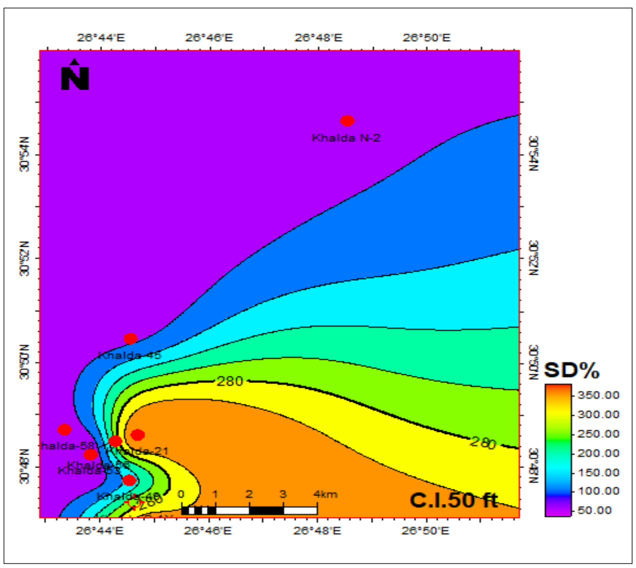



**Fig.12** Sand ratio map of Lower Bahariya Formation.

petrophysical parameters in the different wells [17, 18]. In this regard, the available well log data of the studied wells have been evaluated using the IP3.6 (Inter-active Petrophysics); it is a proficient software applied to process and present the petrophysical well logging data as a function of depth and as a set of X–Y plots. The borehole and the environmental conditions were considered during the processing these petrophysical data using the Schlumberger charts [19, 20, 21, 22, 23].

*Lithology Identification.*

Different methods were applied simultaneously to determine the lithology including the Density-Neutron, and the M–N lithology identification cross-plots which were recommended by many authors [24]. Estimating the M and N values are based on the apparent matrix density (Δma) and the apparent transit time of rock matrix (Δtma) as follows.

$$M = [\,(\Delta tf - \Delta tlog\,) / (\,\rho b - \rho f\,)\,] * 0.01 \qquad (1)$$

$$N = (\varnothing nf - \varnothing n\ log) / (\rho b - \rho f) \qquad (2)$$

where: ΔTf is the transit time of the saturating fluid, ΔTLog is the transit time log reading, ρLog and ρf are the density log reading and the fluid density, respectively, ØNf is the neutron porosity of the saturating fluid, and ØNLog is the porosity log reading.

*Shale volume determination (Vsh).*

The shale volume of the Bahariya Formation has been calculated using different techniques following [25, 26], and the most actual values were recorded as follows

$$vsh = 0.083 \times (23.7 \times (GRLog - GRmin) / (GRmax - GRmin) - 1) \qquad (3)$$

*Porosity estimation*

The effective (Øe) and total porosity ($\varnothing_T$) values were calculated using the density-neutron values [19] as follows.

$$\varnothing_e = \varnothing_T\,(1 - vsh) \qquad (4)$$

$$\varnothing_T = (\varnothing_{Nlog} + \varnothing_{Dlog}) \qquad (5)$$

where: $\varnothing_{NLog}$ and $\varnothing_{DLog}$ are the neutron and density porosities.

*Water saturation (Sw)*

Due to the complexity of the reservoir lithologies and properties, different equations have been widely applied to determine the water saturation (Sw). Among these, the Simandoux's and the Indonesian equations are the most appropriate for the argillaceous clastic sequences (Vsh > 10%) like the Bahariya Formation [27, 28].

$$SW = (A.RW) / (2.\ \varnothing^{M}).\ \{SQRT[(VSH / RSH)2 + ((4 * \varnothing^{M}) / (A.RW.RT\ )] - (VSH/RSH)\} \qquad (6)$$

The total gross thickness of the Bahariya Formation including its upper and lower members is estimated as 172.55–797.86 ft in the studied wells Tables (1, 2). The petrophysical analysis of the estimated net-pay thickness, including the shale volume, the effective values, and the water saturation, indicates the minimum clay volume in Upper Bahariya Formation is in well KhaldaN-2 with a value of 0.13 while the maximum is 0.30 in well Khalda-58 with an average of 0.23. For Lower Bahariya Formation, the minimum clay volume is 0.12 in wells KhaldaN- 2, and the maximum is in Khalda-45 and KhaldaS-1X wells with a value of 0.43 and the average is 0.26. The effective porosity ranges between a minimum of 0.15 in well Khalda-45 and a maximum of 0.30 in well Khalda-21 and averaged 0.18. In Lower Bahariya Formation the minimum value of total porosity is 0.16 in well KhaldaS-1X and the maximum value is 0.32 in Khalda-21 well giving an average of 0.20.

**Table 1:** Petrophysical output data of Upper Bahariya Formation

| Wells | Net Pay (ft) | $V_{sh}$ (%) | $\phi_e$ (%) | $S_w$ (%) | $S_h$ (%) |
|---|---|---|---|---|---|
| KH S-1x | 0 | 21 | 19 | 96 | 4 |
| KH-21 | 21 | 22 | 30 | 41 | 59 |
| KH-45 | 14 | 26 | 15 | 66 | 34 |
| KH-49 | 50.25 | 29 | 19 | 48 | 52 |
| KH-53 | 15 | 17 | 16 | 54 | 46 |
| KH-56 | 27.25 | 27 | 16 | 57 | 43 |
| KH-58 | 26.75 | 30 | 17 | 55 | 45 |
| KH-N2 | 0 | 13 | 16 | 80 | 20 |

**Table 2:** Petrophysical output data of Lower Bahariya Formation.

| Wells | Net Pay (ft) | $V_{sh}$ (%) | $\phi_e$ (%) | $S_w$ (%) | .$S_h$ (%) |
|---|---|---|---|---|---|
| KHS-1X | 2.75 | 43 | 13 | 47 | 53 |
| KH-21 | 46 | 27 | 31 | 35 | 65 |
| KH-45 | 5 | 43 | 13 | 55 | 45 |
| KH-49 | 55 | 26 | 21 | 33 | 67 |
| KH-53 | 0 | 18 | 15 | 91 | 9 |
| KH-56 | 35.75 | 26 | 15 | 44 | 56 |
| KH-58 | 20.50 | 20 | 18 | 48 | 52 |
| KH-N2 | 0 | 12 | 17 | 88 | 12 |

The effective porosity is minimum (0.13) in well KhaldaS-1X, and is maximum (0.31) in well Khalda-21 with the average value 0.17. Water saturation in the Upper Bahariya is averaged 0.62 with a minimum value of 0.41 in well Khalda-21 and a maximum value of 0.96 in well KhaldaS-1X. The minimum value of water saturation in Lower Bahariya Formation is 0.33 in well Khalda-49 and the maximum value is 0.91 in well Khalda-53 giving an average of 0.55. In the current study the Neutron- Density, M-N cross plots and Litho-saturation cross plots of Khalda wells Fig.s (13, 14, 15, 16) reveal that Bahariya Formation consists of shale, siltstone, limestone and sandstone streaks. The pore spaces of the sandstone are filled with water, residual and movable hydrocarbons. The lower Bahariya Formation is relatively sand rich succession of fine to medium-grained sandstone and mudstone that indicate deposition in an estuarine to shallow-marine environment with strong tidal influence and has been recognized as the primary reservoir unit in the Khalda Concession.

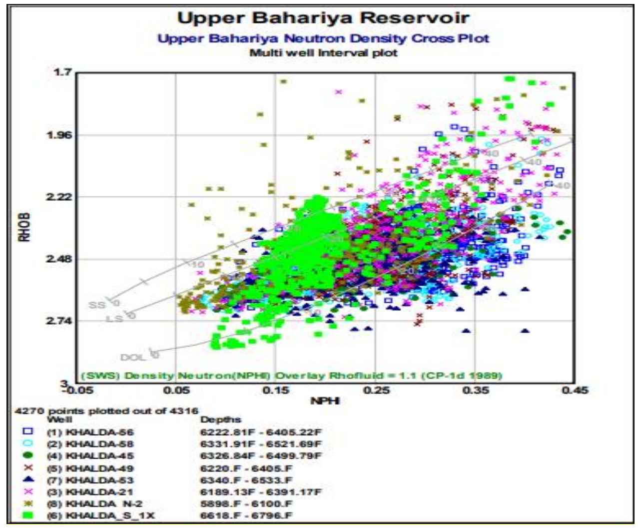



**Fig.13:** Neutron-Density crossplot of Upper Bahariya Formation in the studied wells.

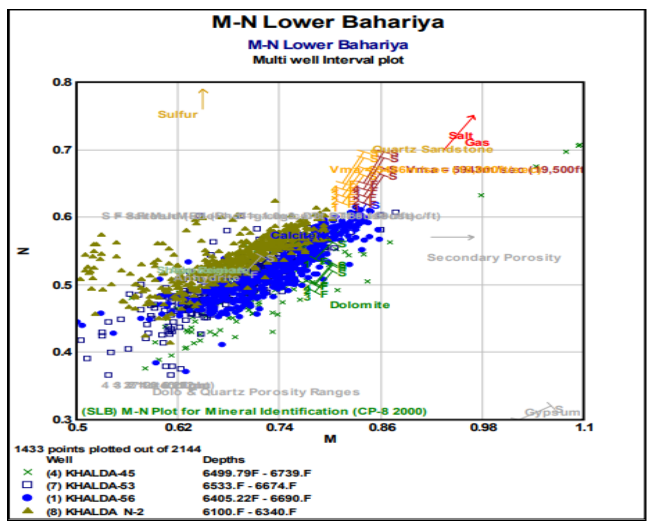
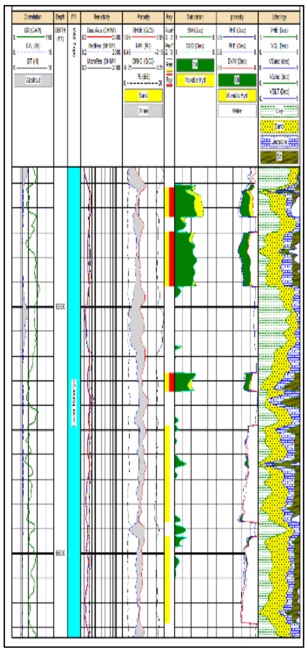


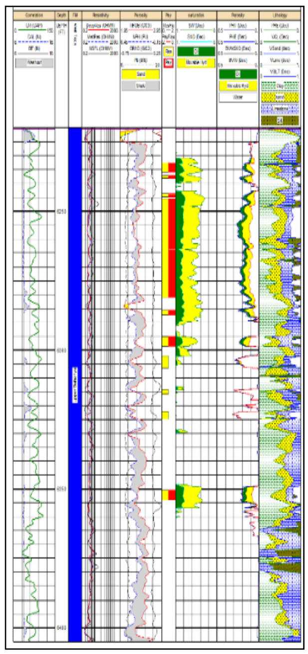

**Fig.14:** M-N crossplot of Lower Bahariya Formation in the studied
wells.

*3.4. Reservoir Modelling.*

The primary goal of 3D modelling is to obtain a 3D analysis and understanding of the geological structure. The essential components of constructing a structural reservoir model are the interpreted fault pattern and structural horizons of the hydrocarbon accumulation [29, 13]. Fig. 17

shows that anticlinal features are represented by the most uplifted areas for Upper and Lower Bahariya respectively which constitute the most trapping in the study area. This feature occupies the western, southwest, and northern parts of the area. The dipping of this anticline is steeper to the East and South and gentler to the West and North, other minor anticlinal features are shown in the eastern and Northeastern corners of the area.





**Figs. 15: (left) and 16 (right)** Computer processed interpretation plot for Khalda-58, 49 wells.

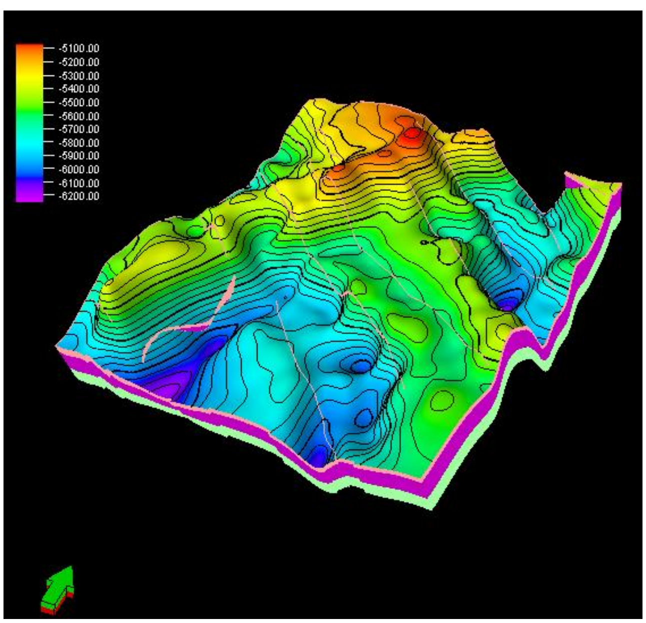



**Fig.17:** Interpreted 3D Structural model.

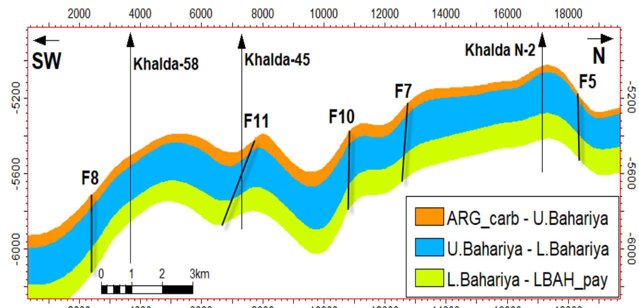



**Fig. 18:** Northeast–Southwest (N–SW) structural cross section.

On the other hand, synclinal features are shown in the area in the south and east parts. The lateral extension of reservoir zones and their thickness variation, including faults, are shown in the structural cross-sections generated from the 3D structural model Fig. (18).

The region of study is affected by eleven normal faults directed to N-SW passing through all studied formations, these faults divide the pay zone into multiple fault blocks inside the field. The general dipping of the mapped horizons is to the south and northeastern portions of the research area. Combinations of faults and folds characterize the major structures of the study area.

Four fundamental facies are defined in this thesis which characterizes the depositional mode of the Khalda oil field: (Limestone, Shale, Siltstone and Sandstone). The Bahariya reservoir was deposited first under fluviatile conditions that later changed to estuarine as flooding continued. Sands are variable, being made up of coarse-grained, cross-bedded sandstones that are seemingly non-fossiliferous to fine-grained, well-bedded, ferruginous classics that carry a large number of vertebrate fossils. The additional section may include dolomite, sandy dolomite and calcareous grits that are rich in fossils. The Upper Bahariya section consists of 30.8% siltstone, and 20.0% sandstone, with 24.2% limestone and 25% shale intercalation. The Lower Bahariya consists of 46.5% sandstone, 22% limestone, and 10% siltstone with 21.5% shale intercalation. The moderately sorted sandstone is both coarser and a little cleaner than in the Upper Bahariya, and the gross sand interval increases from the Upper Bahariya Figs (19, 20).

A petrophysical reservoir model aims to provide a complete set of continuous reservoir parameters (i.e. clay volume, porosity and water saturation). Fig. (21) shows the shale volume distribution which reveals that shale volume reaches a minimum of 13% at the Khalda N-2 well and a maximum of 30% at the Khalda-58 well. The shale volume increases towards the west and falls in the rest of the reservoir, with the lowest value of 12 per cent at the Khalda N-2 well and the greatest value of 43 per cent at the KhaldaS-1X well in the Lower Bahariya reservoir. The value rises in the south, center southern, and northwestern sections of the area, while it falls in the north, east, southeast, and southwest.

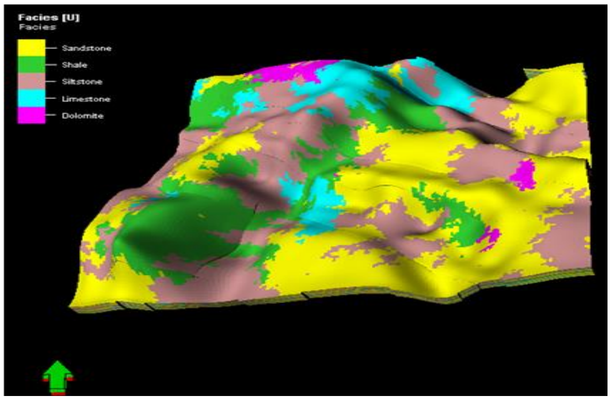



**Fig. 19** 3D facies modeling of Bahariya reservoir in the study area.

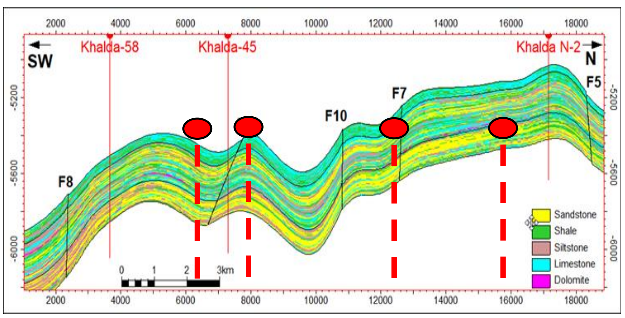



**Fig. 20:** (N–SW) cross-section illustrating facies distribution in the study area with new prospect locations.

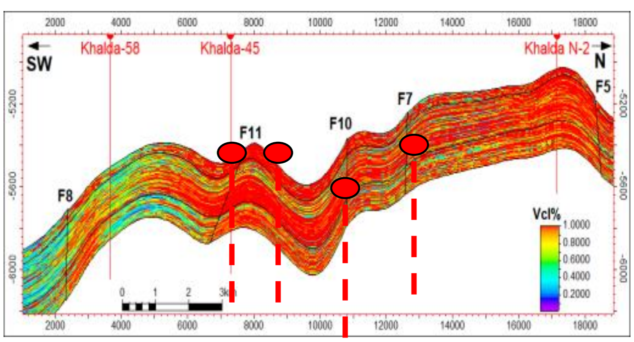



**Fig. 21:** N-SW cross-section illustrating clay volume distribution in the main reservoirs in the study area with new prospect locations.

The effective porosity in the Upper Bahariya reservoir shows an increase toward central southern and south directions, where it reaches 30% at Khalda-21 well and drops in the north, northeast, northwest and southwest parts to reach 16% at Khalda-53, 56 and Khalda N-2 wells. On the other hand in the Lower Bahariya indicates a rise in the center, east, and southeastern directions, reaching 21 per cent at the Khalda-49 well, and a decline in the north, west, and southwestern directions, reaching 13 per cent at the KhaldaS-1X and Khald-21 wells Fig. (22).

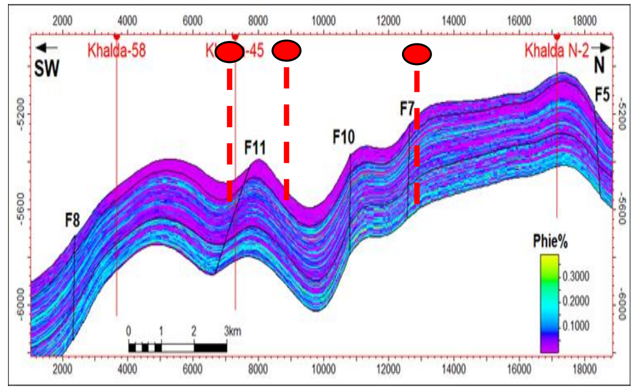



**Fig. 22:** N-SW cross-section illustrating effective porosity distribution in the main reservoirs in the study area with new prospect locations.

## Conclusions

According to current research, subsurface and petrophysical investigations have been used to evaluate the hydrocarbon potential of the Bahariya Formation in the Khalda oil field. Depositionally, the Upper Bahariya Formation exhibits a shallow marine to deep marine environment in the east, whereas the Lower Bahariya Formation exhibits a shallow marine environment. The majority of the Bahariya reservoir is composed of shale, sandstone, and siltstone, with limestone and dolomite streaks.

The structural framework delineation of the studied petroleum system in the Khalda field is greatly influenced by folding and faulting. The integration of seismic interpretation, petrophysical analysis, and structural modelling reveals four prospective locations. The proposed locations are positioned as being in structurally high areas that would be suitable for oil and gas accumulations, the facies distribution in that location is sandier, and the reservoir exhibits fair reservoir properties, confirming our structure and demonstrating the up-dip for these locations. Furthermore, petrophysical cross sections show good parameters for drilling wells, with effective porosity values of 14% and 20%, and water saturation values of 20% and 40% for the proposed locations. With increased net pay thickness and average effective porosity, as well as a decrease in water saturation, this analysis shows that the southern and southwestern portions of the studied area are the best for future development.

As a result of the subsurface and petrophysical assessment for this area, the maximum production will be allied in the southern and southwestern parts of the studied area. As a result, more drilling activities in these areas are recommended for further development. According to the 3D structural model, anticlinal features are represented by the most uplifted areas in the Upper and Lower Bahariya Formations, which account for the majority of trapping in the study area. As a result, four new locations for prospective wells in the Khalda oil field are proposed.

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