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Impact of Sedimentologic Diagensis on the Petrophysical Evaluation of the Reservoir Rocks in BED-1 Field, Western Desert, Egypt

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Authors' contributions

This work was carried out in collaboration among all authors. Author HA designed the study, performed the statistical analysis, wrote the protocol, managed the literature searches and wrote the first draft of the manuscript. Authors HA, MF and OME managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

Badr El-Din 1 (BED-1) field is one of the most prolific areas in the Western Desert and is a part of Badr El-Din Concession, 300 km west of Cairo, and to the west of Abu Gharadig Field. The available open hole well records contain complete logs in the form of composite (Gamma-Ray, Density, Neutron, Sonic and Resistivity of logs four wells. These wells are BED 1-2, BED 1-4, BED 1-10 St/1 and BED 1-11. The main objective of petrophysical analysis of Kharita and Bahariya reservoirs, was to evaluate the petrophysical characteristics and sedimentlogic diagnosis on hydrocarbon potentialities. The petrophysical evaluation of the Kharita and Bahariya reservoirs reveals that the shale volume, effective porosity, water saturation, hydrocarbon saturation and net-pay thickness vary from 2.20 to 9.50%, 11.70 to 26.50%, 19.70 to 52.60%, 47.40 to 80.30% and 3.20 to 61.98m respectively. The BED 1 field main reservoirs were deposited in distinctive environments, which affect the petrophysical characteristics. However, Bahariya Formation shows decreasing the shale volume and increasing the pay thickness in the northeast and south directions.

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Kharita Formation illustrate a discrease shale volume eastward and while increasing southeastward, by the pay thickness increasing eastward. The effective porosity and hydrocarbon saturation increasing in the same direction. Generally, the structural setting controls the distribution of the effective porosity and the hydrocarbon saturation of the BED-1 Field.

Keywords: Petrophysical analysis; reservoir characterization; logging analysis.

1. INTRODUCTION

The Western Desert of Egypt covers about 660,000 km^2 and comprises almost two-thirds of Egypt's whole area. Constituting 1000 to 1200 kilometers from the Mediterranean Sea shoreline extending to the north of the Sudanese border in the south by 600 to 800 kilometers east of the Nile valley to the Libyan border in the west. However, the exploration efforts were mainly concentrated in the northern part (latitude 28°) with lat of offshore areas' efforts. The Egyptian commercial accumulation of hydrocarbons (oil and gas) is divided territorially into three main petroliferous provinces; the Gulf of Suez, the northern Western Desert and the Nile Delta. Interestingly the oil and gas discovery in Egypt comes from the north of the Western Desert in the Nile petroleum province. BED-1 Field is a part of Badr El-Din Concession, 300 km west of Cairo and the west of Abu Gharadig Field (Fig. 1).

The Albian-Cenomanian Kharita and Bahariya formations are two of the most important oil-producing reservoirs in Egypt's Western Desert. The study area includes Badr El Din-1 (BED-1) Field at the center of Abu Gharadig Basin. Abu Gharadig Basin is of special interest, and the structure having been recognized as a major rift basin, which contains numerous faulted 'highs.' These structural features, in NE-SW oriented plunging anticlines, are believed to be NE – SW and NW – SE fault-controlled at depth and provide a range of reservoir possibilities Elsheikh et al. [1]. Many promising areas await detailed exploration and are virtually untested by drilling. A 1990 study concerning the petroleum resources of the Western Desert suggested that approximately 90% of oil and 80% of gas reserves have remained undiscovered Elsheikh et al. [1] and Abdelmaksoud et al. [2]. A generalized stratigraphic column in the northern Western Desert of Egypt is shown in (Fig. 2).

Source rocks for the Western Desert are typically shale sequences associated with the transgressive front of Upper Jurassic and the Upper Cretaceous carbonates. Few wells have been drilled into the strata located below the Mesozoic, and, as a consequence, information concerning the oil potential of Paleozoic rocks are scarce. The richest oil-prone kerogens are found within the Lower Devonian Zeitun Formation, while the gas-prone source rocks lie within the Carboniferous Dhiffah Formation. Black and bituminous shales, which are well known from the Silurian of Southern Tunisia and Algeria, may be at great depth. The general stratigraphic succession of the northern Western Desert of Egypt includes different sedimentary sequences, ranging in age from Pre-Cambrian to recent Said [3].

In spite of some anomalies, the total thickness increases progressively to the NNE from about 1829 m in the southern part to about 7620 m along the coastal area El Bassyouny et al. [5]. Generally, the stratigraphic section consists mainly of alternating depositional cycles of clastics (sandstone, siltstone, shale and clay) and carbonates due to several successive transgressions and regressions of the sea Rossi et al. [6]. Catuneanu et al. [7] have demonstrated that, the Bahariya Formation exhibits significant lateral and vertical changes of facies. As a result of that, A sedimentoligcal studies in the Bahariya Oasis was conducted giving rise to three major lithologic units. Unit one consisting of interbedded siltstones and sandstones (lower unit), while unit two is formed by cross-bedded amalgamated sandstone bodies (middle unit), and unit three is characterized by dark-colored ferruginous sandstones (upper unit). Eight distinct facies associations have been recognized, corresponding to changes in the clastic lithology, color, sedimentary structures and stratal stacking patterns. These facies associations reflect shifts in the paleo-depositional environments from the outer shelf (deepest marine facies recorded in the study area) to shoreface, coastal and fluvial (high and low energy systems).

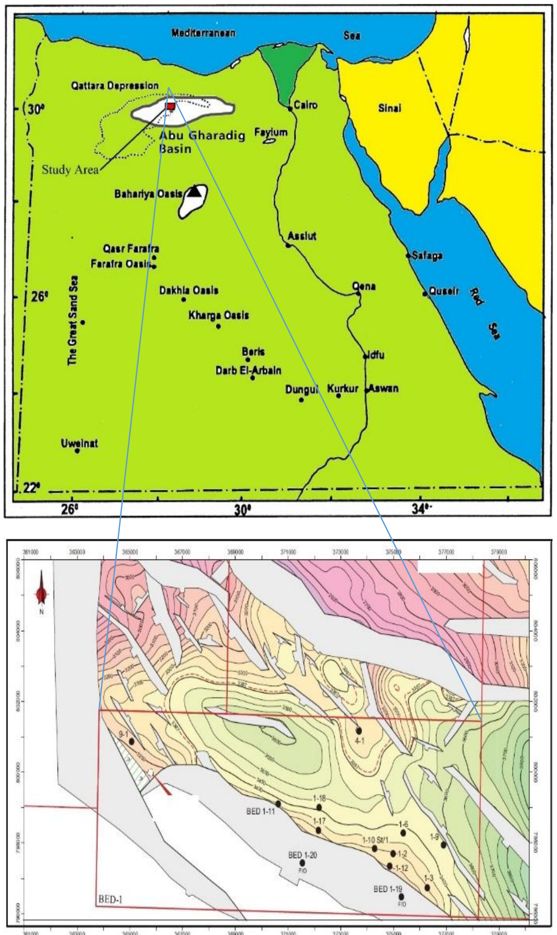

Fig. 1. Location map of the well in the Abu Gharadig Basin

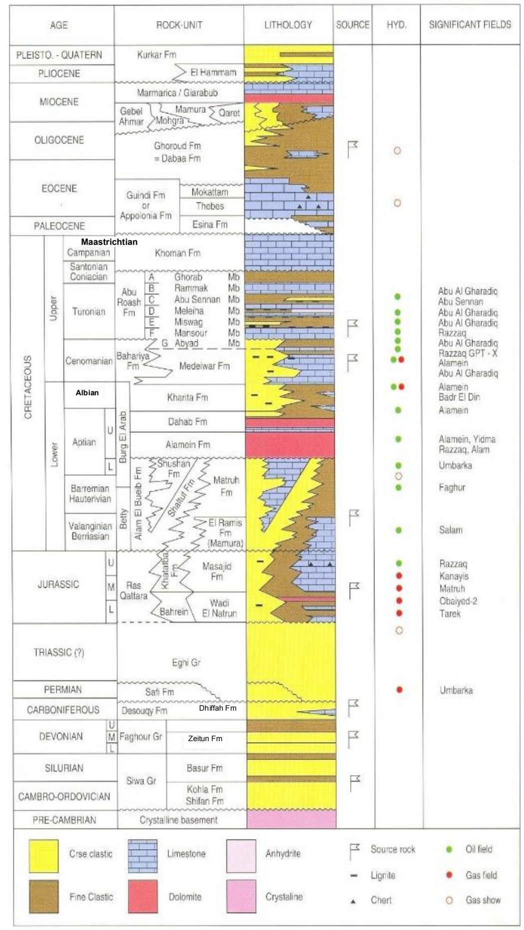

Fig. 2. Generalized stratigraphic column of the northern Western Desert [4]

Catuneanu et al. [7] described the Bahariya depositional environment as an overall transgression with coastal backstepping, comprising several coarsening-upward cyclothems and the deposition of fossiliferous glauconitic siltstones and sandstones. Hence, the environment was a shallow marine, with tidal fat to marine shelf settings. The sandstone samples' mineralogical composition from the Bahariya Formation. is mainly composed of quartz, kaolinite, plagioclase, and microcline. Muscovite, biotite, zircon, rutile and apatite, as well as diagenetic calcite, are present as accessory minerals. Several samples were investigated by scanning electron microscopy for detailed characterization of the pore space structures and Fe-rich cement minerals' occurrence and distribution Abuseda et al. [4].

2. METHODOLOGY

The main objective of the Kharita and Bahariya reservoirs study in petrophysical analysis, is to evaluate the petrophysical characteristics and hydrocarbon potentialities with a combination of a systematic data analysis. For this purpose, a complete well logging analysis, using the various open-hole logging data of four well logs (BED 1-2, BED 1-4, BED 1-10 St/1 and BED 1-11) was carried out to study their petrophysical parameters. The CPI is accomplished through the Techlog software of Schlumberger to evaluate the petrophysical parameters, while the construction of the iso-parametric contour maps was through Surfer 11 software.

2.1 Formation Temperature Determination

The formation temperature (FT) is determined by knowing four parameters; the formation depth (FD), bottom hole temperature (BHT), surface temperature (ST) and the total depth of the well (TD) as the following equation:

$$FT = ST + \left[\frac{BHT-ST}{TD}\right] FD \tag{1}$$

2.2 Shale Volume Determination

The shale volume is determined quantitatively, by applying different methods and techniques, using both the single and double-curved indicators. Shale volumes for the different reservoirs in the BED 1 field are estimated, using the single curve gamma-ray Log:

$$(V_{sh})_{GR} = \left[\frac{(GR-GR_{min}}{(GRmin_{max}}\right] \tag{2}$$

where; GR is the gamma-ray reading in the zone of interest, $(GR)_{min}$ is the minimum reading in clean sands or carbonates, $(GR)_{max}$ is the maximum reading in nearby 100% shale, and $(V_{sh})_{GR}$ varies from zero in clean sand to 1.0 in shale.

2.3 Porosity Determination

Porosity for different reservoirs in the BED 1 field is calculated using the density and neutron logs, and then the effective porosity are determined as follows;

Porosity from Density log:

$$\Phi = \left[\frac{\rho_{mat}-\rho_b}{\rho_{mat}-\rho_f}\right] - V_{sh}\left[\frac{\rho_{mat}-\rho_{sh}}{\rho_{mat}-\rho_f}\right] \tag{3}$$

Porosity from Neutron log:

$$\Phi N = \Phi N\, log_{cleanzone}$$
$$\Phi N = \Phi N\, log - V_{sh}\Phi N_{sh} shalzone \tag{4}$$

2.4 Estimation of the Total and Effective Porosities

Correcting the total porosity for the shale effect by determining effective porosity is important to remove the effect of shale content on the rock porosity reading. Eq. (3) was used to calculate the effective porosity ($Ø_{eff}$) in this study, as:

$$\Phi_{eff} = \Phi_T - V_{sh} * \Phi_{sh} \tag{5}$$

where; ($Ø_{eff}$) is the effective porosity (fractional), ($Ø_t$) is the total porosity from neutron or any method (fractional), (V_{cly}) is the volume of clay from the non-linear equation, or any (fractional), and ($Ø_{sh}$) is the neutron porosity reading in 100% shale.

2.5 Formation Water Resistivity Determination (R_w)

2.5.1 Pickett's method

Pickett likens clay to a porous rock, for which Archie's equation would apply: -

$$R_{sh} = \frac{Rw}{\Phi_{sh}^{m}} \tag{6}$$

This could also be expressed: -

$$LogR_{sh} = LogR_w - mLog\Phi_{sh} \tag{7}$$

2.5.2 R_{wa} method

The parent formation-water resistivity defined as:

$$R_{wa} = \frac{Rt}{F} \tag{8}$$

2.6 Water Saturation Determination

Water saturation (S_W) is the most important petrophysical parameter used for the evaluation of certain reservoirs. As soon as the water saturation S_W has been determined, accurate calculation and differentiation of the included hydrocarbon potentialities can be done. Water saturation is calculated, using different equations Berg [8]. Archie's Eq. (9) is used for the clean reservoir Archie [9] and the Indonesia model Eq. (10) is used in the relatively high shale volume reservoir Leveaux and Poupon [10]. Indonesia equation was used in this work.

$$S_w = \sqrt[n]{\frac{aR_w}{\Phi^m Rt}} \tag{9}$$

$$S_w = \frac{1}{Rt}\left(\frac{\sqrt{aR_w} * R_{sh}}{V_{sh}\sqrt{aR_w} + \Phi^{m/2}\sqrt{R_{sh}}}\right)^{n/2} \tag{10}$$

where; R_t is the deep resistivity, R_{sh} is the deep resistivity in shale (read from log) 2.5, R_w is the downhole water resistivity, ($Ø_{eff}$) = effective porosity, S_W = water saturation, S_{WE} = effective water saturation, a is Archie's exponent, m is the cementation factor, n is the saturation exponent, it is the gradient of the line defined on the plot.

3. RESULTS AND DISCUSSION

A detailed petrophysical evaluation has been performed for the four wells, that have a complete suite of logs. Included calculating the shale volume, effective porosity, water saturation, hydrocarbon saturation and net-pay thickness. Clavier et al. [11] method was used to estimate the volume of shale from the gamma-ray log. The Indonesian equation is applied for the water saturation calculation with Archie factors. A formation water resistivity (Rw) is calculated from Pickett's plot - porosity function of resistivity. (Table 1) summarizes the average petrophysical parameters to the Bahariya and Kharita formations of the selected wells in the BED -1 field.

3.1 Shale Volume Content

The shale volumes for the evaluation reservoirs of Kharita and Bahariya formations are defined using the single curve clay indicator of gamma-ray Log (GR). Thus, the average shale volume distributions for the different reservoirs in BED-1 Field range from 2.20 to 9.50%. (Table 1) shows the average shale volume distributions for the different reservoirs in BED-1 field.

3.2 Shale-type Distribution

The shale type is identified through Thomas Stieber plot, that shows the shale types in Bahariya Formation a dispersed to clean types (Fig. 3A), the most shale type in Kharita Formation is the dispersed type, with some samples are clean (Fig. 3B).

3.3 Porosity Determination

Porosity for the different reservoirs in BED-1 field is determined, using the density and neutron logs, and as a result the effective porosity distribution for the different reservoirs range from 11.70 to 26.50%. (Table 1) shows the porosity distribution for the different reservoirs in the BED-1 field.

3.4 Determination of the Formation Water Resistivity (R_w)

The water resistivity identified through Pickett's plot - porosity function of resistivity, for which Archie's equation would apply and the results are shown in (Table 2) for the clean water-bearing zones, the Rt approximate, the Ro (F R_w), so R_{wa} in these zones reads an essentially comparable value.

3.5 Determination of Water Saturation

Water saturation is determined, using the Indonesian equation, then the hydrocarbon saturation is determined. The Indonesian equation is one of the most popular and successful equations in common use, including a shale correction for the saturation calculation and the average water and hydrocarbon saturation distributions. It is applied for the different reservoirs in BED -1 field, giving that the water and hydrocarbon saturation range from 19.70 to 52.60% and 47.40 to 80.30%, respectively, as shown in (Table 1).

3.5.1 Cutoffs in BED -1 field

Table 3 determined the cutoff ranges for the shale volume content, porosity determination and water saturation in BED -1 Pay.

3.6 Lithology Determination

3.6.1 M-N (Tri-Porosity) cross plot

M and N values of the examined rock units are plotted in the M-N plot of Schlumberger charts (1979) to identify the mineral constituents.

$$M = \frac{\Delta t_f - \Delta t_{log}}{\rho bf_{log} X 0.01} \quad (11)$$

$$N = \frac{\Phi N_f - \Phi N_{log}}{\rho bf_{log}} \quad (12)$$

3.7 Dia-Porosity Cross Plot

Dia-porosity cross plots construction depends on a variety of combinations between the porosity tools (Δt, ρ_b and $Ø_N$) and the porosity derived from logs ($Ø_S$, $Ø_D$ and $Ø_N$). These plots are considered for identifying the lithology, gas, and secondary porosity.

3.8 Bahariya Formation

The M-N and neutron-density cross plot (Fig. 4A) show that, the rock components in Bahariya Formation are clastics (sandstone, siltstone, shale, and clay) and carbonates.

3.9 Kharita Formation

The M-N and neutron-density cross plot (Fig. 4B) shows that, the main rock components in Kharita Formation are sandstone, with some limestone and shales.

3.10 Petrophysical Characteristics

3.10.1 Vertical variations of the petrophysical parameters

Litho-saturation cross plots (Fig. 5) represent the combined litho-saturation cross plots of BED 1-2, BED 1-4, BED 1-10 St/1 and BED 1-11 wells. BED 1 Field contains two reservoirs, which are the Bahariya Formation and Kharita Formations. (Table 1) represents the petrophysical characteristics of these reservoirs.

3.11 Lateral Variations of the Petrophysical Parameters

3.11.1 Bahariya formation

Bahariya Formation shows southward decreasing of the shale volume and the northeast and south increasing of the pay thickness, due to the comparable increase of the sand clastic in the same direction. The effective porosity is 26.50% due southeast, and the hydrocarbon saturation increases in the same direction (Fig. 6A & 6B).

3.11.2 Kharita formation

Kharita Formation shows southeastward increasing of the shale volume and the comparable decreasing of the effective porosity. The effective porosity to be 16% due east and the hydrocarbon saturation increases due the same direction (Fig. 6A & 6B).

Table 1. It summarizes the average petrophysical parameters in the studied wells

Formation	Well Name	Average Shale Volume	Average Porosity	Average Water Saturation	Average Hydrocarbon Saturation	Net Pay
				(%)		m.
Bahariya Formation	BED 1-2	7.50	23.10	29.50	70.50	18.60
	BED 1-4	5.20	26.50	24.50	75.50	3.66
	BED 1-10 St/1	4.30	15.40	28.10	71.90	14.78
	BED 1-11	5.40	16.80	38.10	61.90	3.20
Kharita Formation	BED 1-2	2.20	16.00	19.70	80.30	29.00
	BED 1-4	9.50	11.70	20.60	79.40	61.98
	BED 1-10	4.30	13.00	25.60	74.40	10.82
	BED 1-11	3.10	12.10	52.60	47.40	52.60

Table 2. It summarizes the average a, m, n and Rw from Pickett's plot in the studied wells

	BED 1-2	BED 1-4	BED 1-10 St/1	BED 1-11	BED 9-1
a	1	1	1	1	1
m	1.47	1.53	1.6	1.56	1.53
n	2	2	2	2	2
Rw	0.21	0.17	0.13	0.15	0.17

Table 3. Determination of the cut-off ranges for the different reservoirs in BED -1 Pay

V_{sh}	Phi_{eff}	S_w
0 - 35	10 - 40	0 - 65

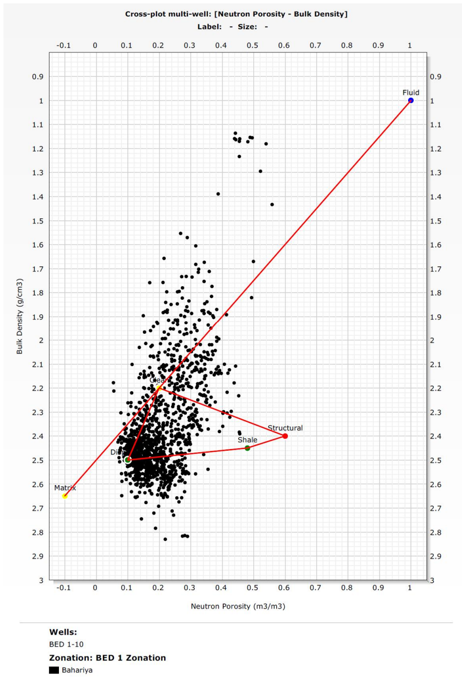

Fig. 3A. Shale types detection (Neutron Porosity VS Bulk Density) through Thomas Steiber Plot of Bahariya Formation

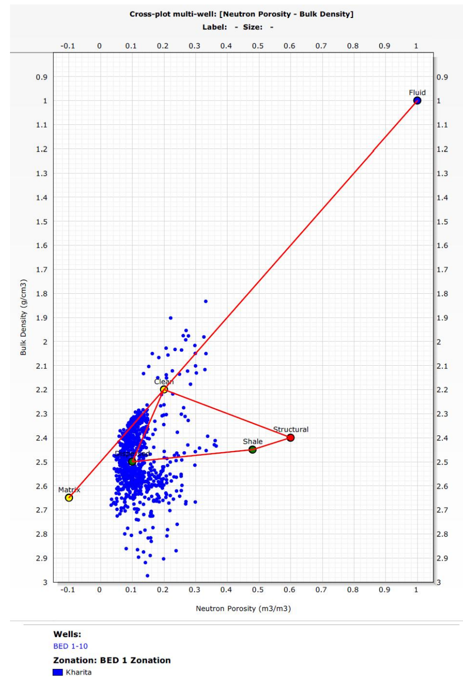

Fig. 3B. Shale types detection (Neutron Porosity VS Bulk Density) through Thomas Steiber Plot of Kharita Formation

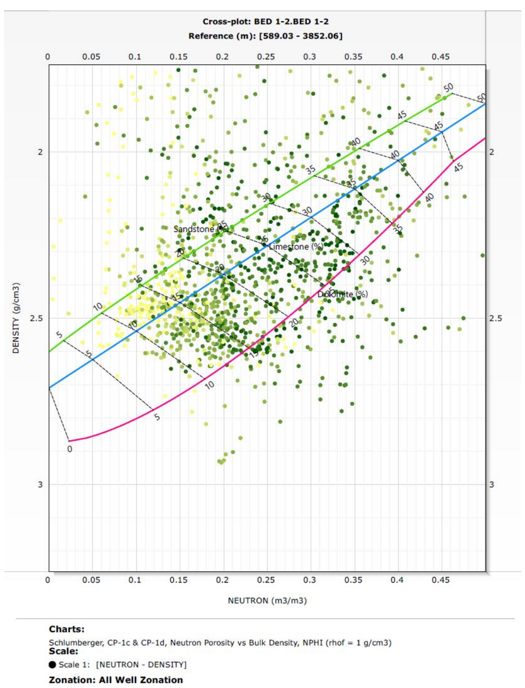

Fig. 4A. Neutron - density crossplots for Bahariya Formation

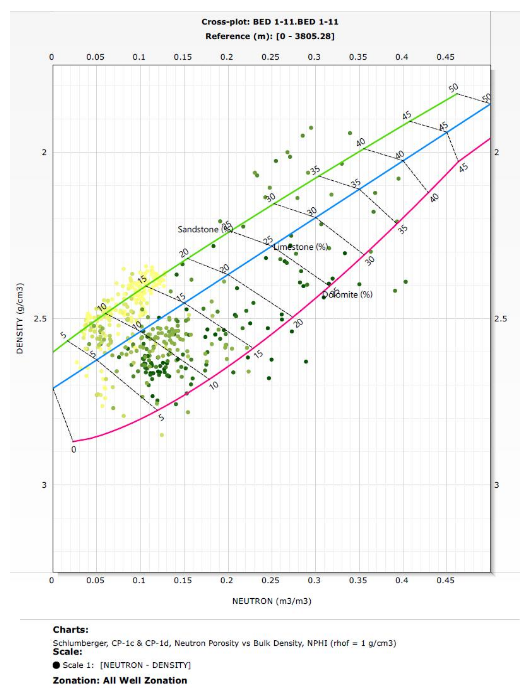

Fig. 4B. Neutron - density crossplots for Kharita Formation

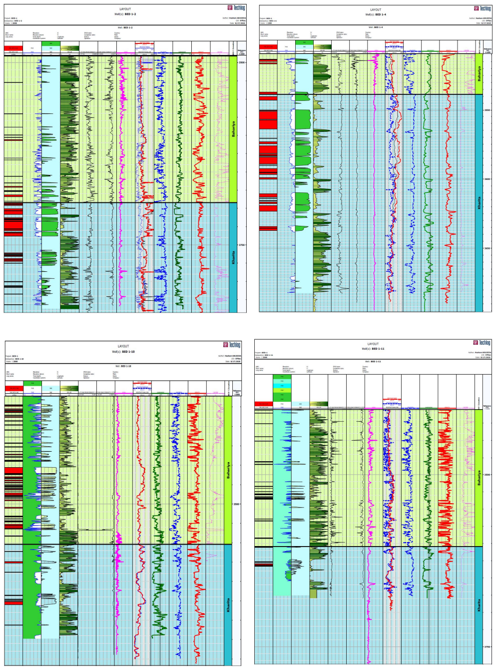

Fig. 5. Litho-Saturation Cross-Plot of BED 1-2, BED 1-4, BED 1-10 and BED 1-11 wells

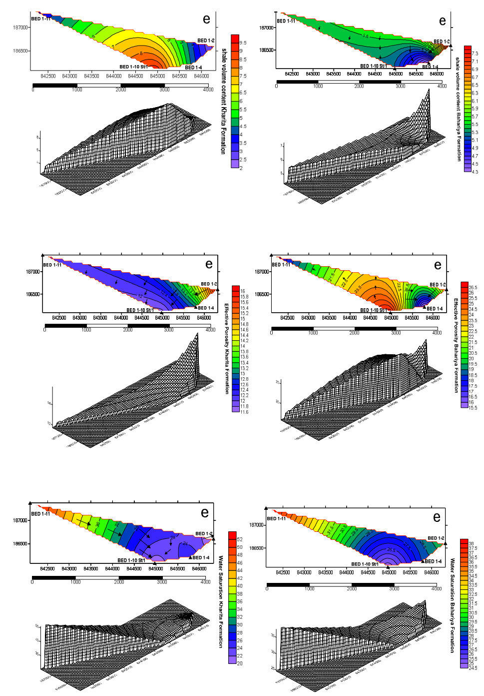

Fig. 6A. Distribution of BED 1-2, BED 1-4, BED 1-10 St/1 and BED 1-11 Petrophysical Parameters

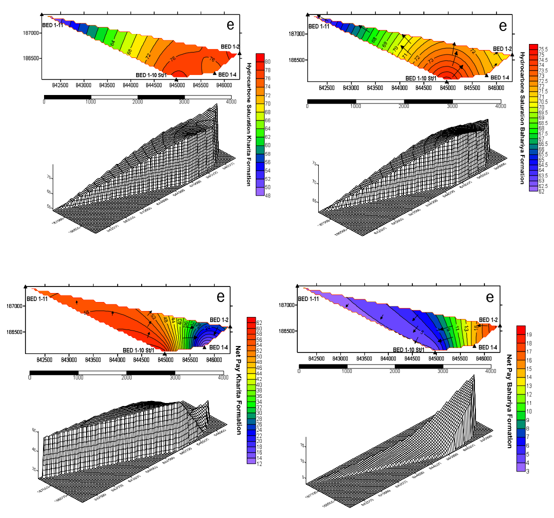

Fig. 6B. Distribution of BED 1-2, BED 1-4, BED 1-10 St/1 and BED 1-11 Petrophysical Parameters

4. SUMMARY AND CONCLUSIONS

BED-1 Field is one of the most prolific areas in the Western Desert. The available open hole well records contain complete sets of logs, as the composite well logs (Resistivity, Gamma-Ray, Density, Neutron and Sonic) of four wells. These wells are BED 1-2, BED 1-4, BED 1-10 St/1 and BED 1-11. Petrophysical evaluation of the Kharita and Bahariya reservoirs reveals that, the shale volume, effective porosity, water saturation, hydrocarbon saturation, and net-pay thickness vary from 2.20 to 9.50%, from 11.70 to 26.50%, from 19.70 to 52.60%, from 47.40 to 80.30% and from 3.20 to 61.98m, respectively. The main reservoirs in BED-1 field were deposited in distinctive environments, which have a clear effect on the petrophysical characteristics. Howere, Bahariya Formation show a decease in shale volume and by increasing the pay thickness toward the northeastern and southern direction. Kharita Formation shows the eastward decreasing of the shale volume and the eastward increasing of the pay thickness. The effective porosity and hydrocarbon saturation increasing due the same directions. Generally, the structural setting controls the distribution of the effective porosity and the hydrocarbon saturation of the BED-1 Field.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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