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ORIGINAL ARTICLE

Reservoir characterization, in relation to the petrophysical modeling of Baharyia formation, Razzak field, northern western desert, Egypt

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Abstract The present work aims to investigate the reservoir characterizations of the Lower Cenomanian Baharyia Formation by creating isoparametic maps to calculate the petrophysical parameters and detect the favorable parts for oil accumulations using the available well logging data. Baharyia Formation is one of the main hydrocarbon sandstone reservoirs in the northern Western Desert of Egypt. About 90% of the Western Desert field produces form Baharyia sandstone Formation. This has been achieved through the analyses of the conventional wireline logs and petrophysical modeling. The Baharyia Formation comprises a complex of depositional lithofacies such as interbedded siltstone, shale, sandstones and pebbly sandstones. Petrophysical modeling of the Baharyia Formation was performed, based on the interpretation of complete wireline logs from five wells in Razzak oil field, north Western desert, Egypt. Petrophysical analysis accomplished, such as: shale volume, total and effective porosities, water saturation and hydrocarbon saturation, were deduced and utilized in the petrophysical subdivision of the Baharyia Formation. Relations between theses petrophysical parameters are established to define the implications of such parameters on the Baharyia Formation. Iso-parametric and litho-saturation crossplots are used to delineate variations in petrophysical parameters across the area. The obtained petrophysical results reveal that, the Baharyia Formation have a good reservoir quality, with high effective porosity values exceeding 18%,volume of shale about 30% and low water saturation values of 25%. The rock genetic types of the Baharyia Formation deduced form the log curve shapes proved that the Baharyia Formation was deposited from fluvial to marine environments passing through the tidal flood plain conditions. However, the lithology of the Baharyia Formation composed of sandstone, siltstone, shale and minor limestone inter-beds.

Highlights

- Baharyia sansdtone formation on of the most important reservoires in the Western Desert.
- The Petrophysical evaluation reveals good results of the ability Bahrayia Formation to produce oil.
- The fault framework are NW-SE and WNW-ESE normal faults.
- The pertoluem trap is an anticline trends NE–SW of the Cretaceous era.

Keywords Petrophysical model · Baharyia formation · Razzak field · Western desert

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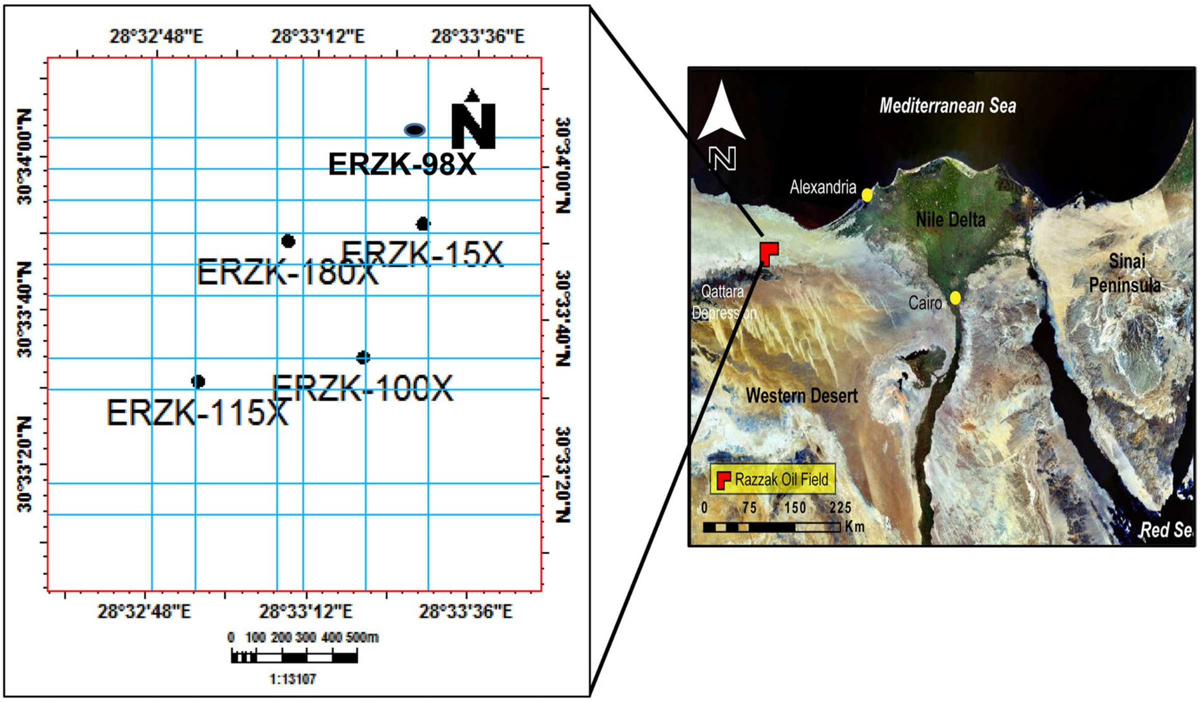


Fig. 1 Location map of the study area

1 Introduction

The study area is located at the north of the Western Desert of Egypt, about 150 km southwest of Alexandria (Fig. 1). It is lied between latitudes 30°24′ and 30°36′ N, longitudes 28°24′ and 28°36′ E. The Razzak field is a part of the Alamein basin, which is an ENE–WSW oriented basin, in the form of NNW–SSE tilted fault blocks. The Early Cenomanian Baharyia Formation was deposited conformably on top of the Albian Kharita Formation and is located stratigraphically below the Late Cenomanian–Turonian Abu Roash Formation. The contact between the Abu Roash and Baharyia Formation is easily recognized by the abrupt change in lithology, from clastic to non-clastic carbonate facies (Bosworth 1994). Petrophysical modeling is important for enhancing reserve estimation, determining future field development, placing additional wells, and predicting reservoir production (Abdel-Fattah et al. 2018). Reservoir models are constructed using available geological and geophysical data such as well logs, core, and seismic data. A reservoir model is a 3D visualization of the subsurface and includes horizons, zones, faults, and grid properties such as facies and petrophysical parameters. Remarkable variations of the petrophysical parameters are illustrated through the petrophysical model, exhibiting uniform and irregular changes of the stratigraphic features, and abrupt and irregular changes of the structural setting affecting the area.

2 Geologic setting

The northern Western Desert of Egypt represents, part of the unstable shelf of Northern Africa. It has been subjected to different tectonic regimes since the Paleozoic time, these have resulted in the construction of many sub-basins, faults and folds (Hantar 1990). The most predominant structural trends in the northern Western Desert of Egypt are the NW–SE to WNW–ESE related to the Early Cretaceous rifting of the relative motion of Africa with respect to Eurasia, based on the reconstruction of seafloor spreading data (Guiraud and Bosworth 1997). Jurassic rifting led to the development of NE–SW, NNE–SSW and ENE–WSW oriented normal faults and thickening of the Jurassic rocks against these faults, resulted from a stress pattern, which related to the opening of the North Atlantic ocean from Turonian times (90 Ma) to Paleogene (60 Ma). Also, strike-slip faults are present related to the lateral movement of the African plate sinistral during the Jurassic and dextral during the Late Cretaceous (Sultan and Halim 1988). Folds trends of NE–SW are related to compressional movements, which affected the area during the Late Cretaceous–Early Tertiary that related to the movement of the North African plate toward Europe. It resulted in the elevation and folding of major portions of the north Western Desert along an ENE–WSW trend Syrian arc system (Bosworth et al. 1999). Large-scale, northeast-trending asymmetric folds and associated extensional faults related to the Late Santonian shortening event corresponds with, the compression that swept across the entire African plate, coeval with a significant change in the poles of opening of the North Atlantic. This "Santonian event" is a prominent example of the role that, far-field compressional stresses, that induced inverted folds which, dissected by transverse (NW-oriented) normal faults. These folds and tilted fault blocks of the Jurassic/Cretaceous rifting form the main structural traps of the northern Western Desert (Moustafa 1988). (Fig. 2) shows the main stratigraphic units of the northern Western Desert of Egypt. Thicknesses of the encountered rock units in the north Western Desert increase towards the northeast, where four major sedimentary cycles occurred, with maximum and southward transgressions during the Carboniferous, Late Jurassic, Early and Late Cretaceous, Middle Miocene and Pliocene times. Maximum and northward regressive phases occurred during the Permo–Triassic and Early Jurassic, and continued till the Early Cretaceous. Again during the Late Eocene to Oligocene, with a final phase in the Late Miocene times. Source rocks of the north Western Desert are typically expressed by the shales accompanied with the transgression of the Upper Jurassic and Upper Cretaceous carbonates (Moustafa 2008). The Mesozoic source rocks include oil and gas-bearing formations, from the Middle Jurassic (Khatatba Formation). Reservoir rocks are composed of sand and limestone belongs to Lower Cretaceous (Alam El Bueib Formation) and the Upper Cretaceous (Baharyia and Abu Roash formations).Seal rocks are composed of shales, compacted limestone of Jurassic, Cretaceous, Eocene and Oligocene age. The Khatatba and Alam El Bueib formations have their own internal seals. The shales of the Abu Roash "G" Member represent the top seal above the Baharyia Sandstone reservoir. Traps are mainly of the combined stratigraphic-structural traps (EL Saharawi et al. 1992). Early stage of hydrocarbon generation during the Late Cretaceous for the AEB and Khatatba formations while the hydrocarbons migrated toward the Cretaceous source rocks after the Alpine tectonics, hydrocarbon accumulation and entrapping are tilted fault blocks and inverted fault and fold traps (Sarhan 2017).

3 Well logs data

The available well data for the present study that acquired by Khalda Company (KPC), are five wells (ERZK-15X, ERZK-100X, ERZK-115 X, ERZK-98X and ERZK-180X) in the form of check shot survey and well log data (Fig. 1), including gamma-ray, resistivity, sonic, neutron and density. These are used for the identification of lithologies and fluid types as well as the determination of shale volume, total and effective porosities and water and hydrocarbon saturations.

4 Petrophysical analysis

4.1 Shale volume

Shale volume calculation is crucial for the discrimination between reservoir and non-reservoir rocks. Gamma-ray, resistivity, neutron and neutron-density logs were used to calculate the shale volume. Neutron-density crossplot, as well as the shale volume-porosity crossplot were applied, the volume of shale of Baharyia Formation ranges from 40 to 60%.

4.2 Porosity

Neutron, density and sonic logs are commonly used in the calculation of pore volume within the rocks. Neutron log is directly related to fluids fully occupying the pore space (porosity), where the porosity of Baharyia Formation ranges from 17 to 20%.

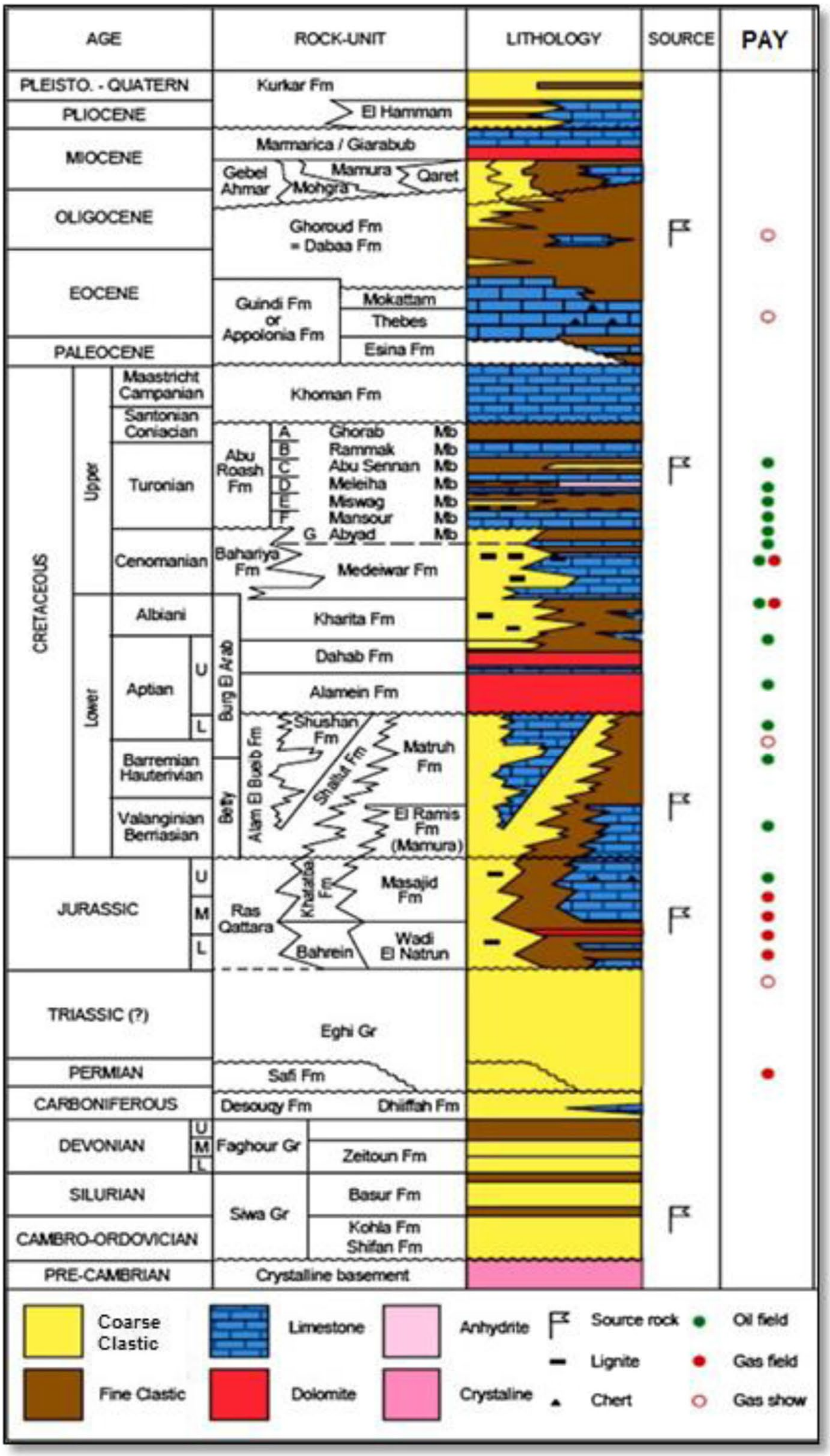


Fig. 2 Generalized lithostratigraphic column of the Western Desert (Abu El-Naga 1983)

4.3 Fluid saturation

Indonesian equation is one of best models to estimate SW in shaly rocks (VSH > 0) and it serves for the shale effect in its first part and for the clean formation effect (Archie's term) in the second part, water saturation (Sw) of Baharyia Formation ranges from 36 to 48%. While (Sh) hydrocarbon saturation reaches 52% to 64% by using the following equation: $Sh = (1 - Sw)$.

5 Rock genetic types

The shapes of well log curves is a basic tool, to interpret depositional faceis, especially gamma-ray, because log shapes is related to grain size of rocks (Selley 1978) Fig. 3. Recognizing the detailed rock genetic types in Baharyia Formation, using the log curve shapes of the gamma-ray log technique, facies analysis and reconstruction of facies patterns were performed, using the log curve shapes interpretation. The constructed vertical profiles of two borehole logs (ERZK-100X and ERZK-15X) data against the lithologic intervals of the Baharyia Formation define the depositional history and the different prevailing rock genetic types. Three main rock genetic types were recognized indicating deltaic sedimentation. Distributary channel fill Fig. 4 Stream mouth bar deposits and fluvial flood plain Fig. 5. Generally, the rock units are representing lower deltaic plains and deltaic fringes sediments, respectively.

After studying the gamma ray log curve shapes of the mentioned wells, there is a variation in depositional facies in each well, reflecting the paleo-depositional environment of the Baharyia Formation. ERZK-100X well genetic types had two depositional facies, according to the gamma-log from measured depth from 1800 to 1825 m, takes cylindrical shape, reflecting distributary channel fill depositional environment, serrated gamma-ray log curve shapes form 183 to 1850 m related to fluvio-marine depositional environments. ERZK-15X well genetic types had two depositional facies, according to gamma ray log curve shapes, funnel shape from 1920 to 1940 m, reflecting stream mouth bar deposits and serrated shape from 1940 to 1980 m, exhibiting fluvio-marine depositional environments. Well log analysis performed of the Baharyia Formation is found to consist of sandstone cemented by argillaceous and/or calcareous materials, siltstone, shale and minor limestone inter-beds. The Baharyia

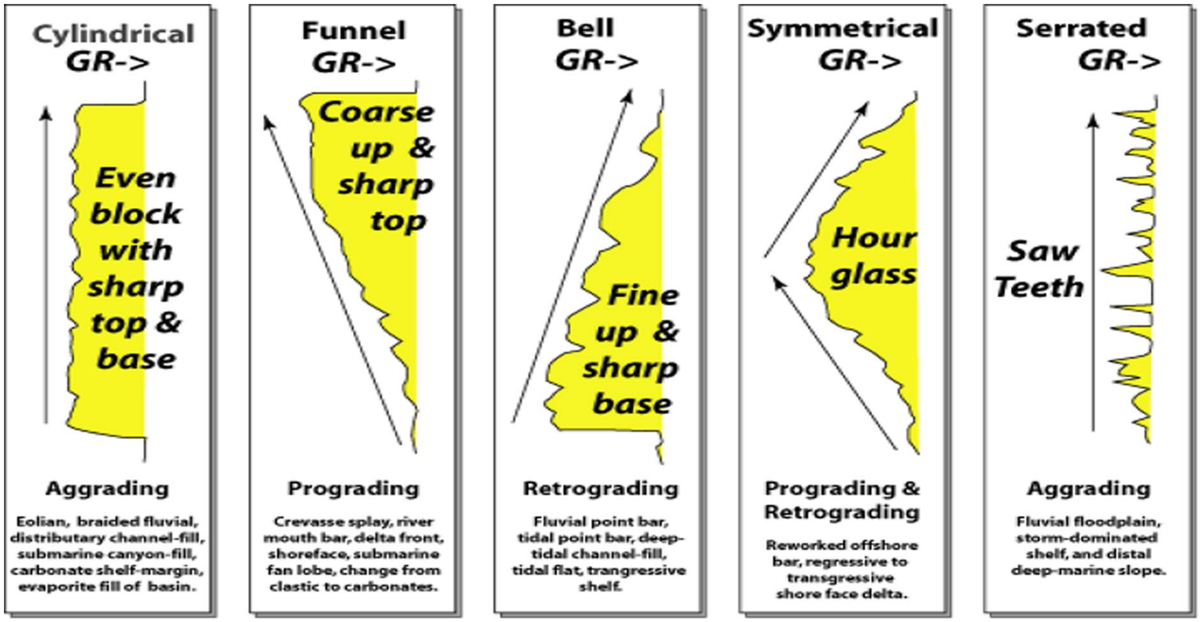


Fig. 3 General gamma ray response (Cant 1992)

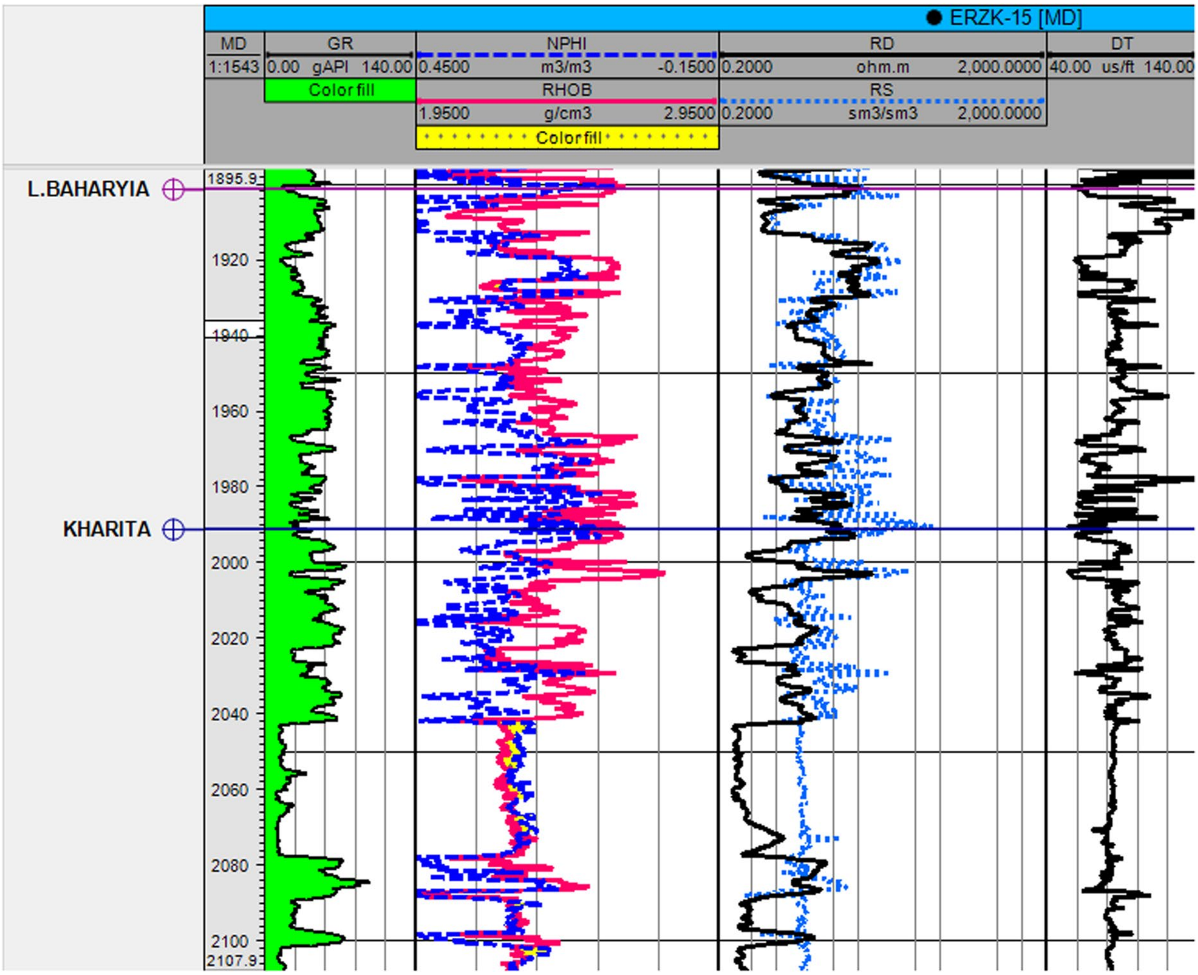


Fig. 4 GR cylindrical shape refer to distributary channel fill

reservoir is newly subdivided into three main zones according to the careful correlation of the log responses of the available logs; an upper shale-silt-carbonate lithofacies, a middle sand-silt lithofacies and a lower shale-silt lithofacies. These lithofacies form discontinuous bodies through the studied wells. Lateral and vertical facies changes within the Baharyia reservoir are noticed. Depositional facies are represented by continental fluvial to marine facies passing through the tidal flood plain conditions. (Moustafa 1988).

6 Litho-saturation cross plots

The litho-saturation crossplots of ERZK-15X and ERZK-180X wells show the vertical variation in the petrophysical and lithological properties within the Baharyia Formation (Figs. 6 and 7). ERZK-15X well shows a total gross thickness of the Baharyia Formation of 195 m, net sand about 115 m, a total porosity of the Baharyia Formation ranging from 0 to 25% with an average value of 14.48%, while the effective porosity ranges from 0 to 20%, with an average of 12.58%, the volume of shale is 50% and water saturation is 55%. ERZK-180X well shows a total gross thickness of the Baharyia Formation 280 m, net sand about 180 m, a total porosity of the Baharyia Formation ranging from 0 to 28%, with an

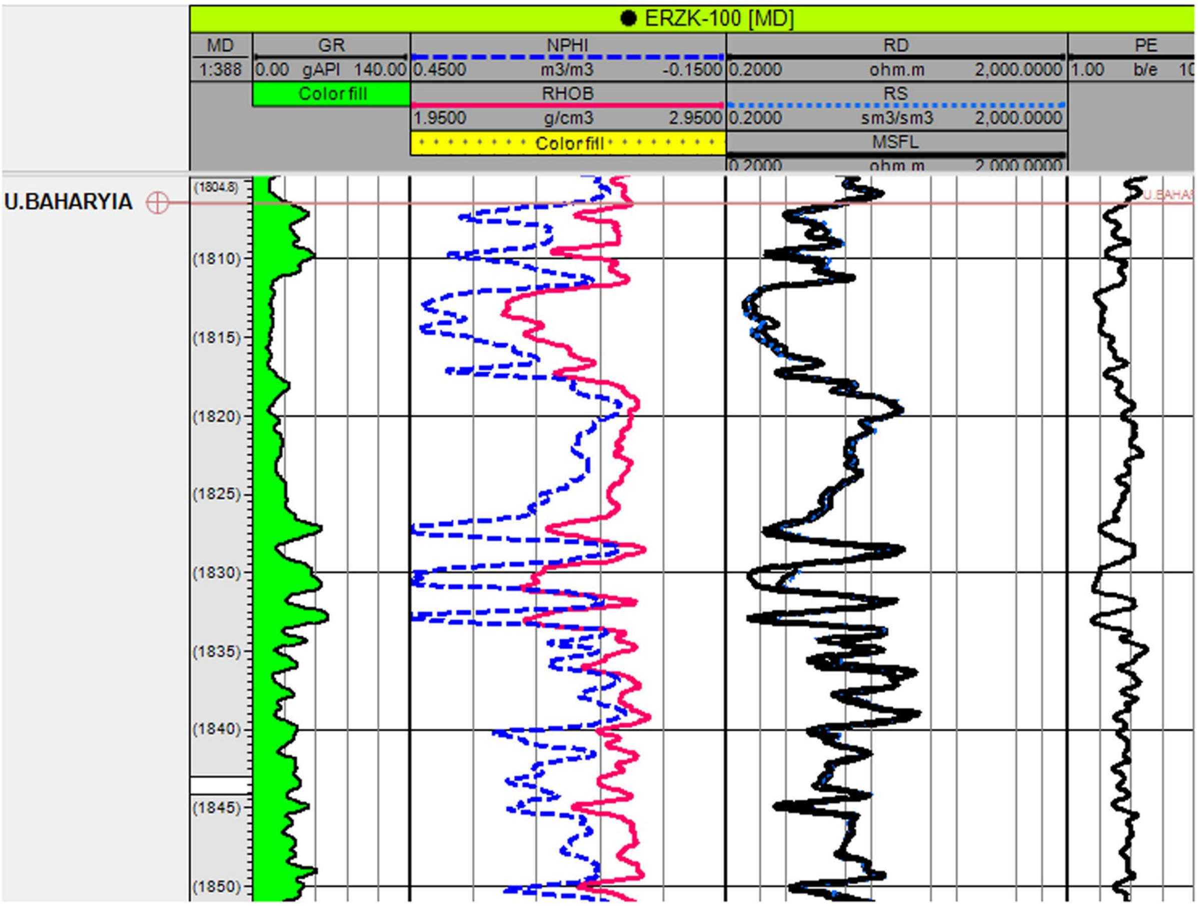


Fig. 5 GR cylindrical shape refer to mouth bar fill

average value of 17%, while the effective porosity ranges from 0 to 20% with an average value of 15%, volume of shale is 0% and the water saturation is 45%.According to well log evaluation of the Baharyia Formation revealed changing of the different petrophysical parameters is directly related to vertical and lateral facies changes, there is a relationship between porosity and depositional facies distribution (El Gezeery et al. 1972) the overall lateral and vertical changes of the petrophysical parameters are mainly related to changes in facies as the overall depositional model for the Baharyia Formation is that of a tidal flat dissected by channels trending South–North direction and passing seaward into tidal shelf sands and muds.

7 ISO-parametric distrubition

According to the wireline log evaluation, iso-parametric maps are constructed, to clarify the lateral variation in petrophysical parameters of Baharyia Formation these maps represent the concerned area, which is defined by well locations.

7.1 Total thickness and net-pay map of Baharyia formation

Figures 8 and 9 show the total thickness map and the net pay map of Baharyia Formation, where the thickness increases towards the middle part and decreases toward the southern part. This represents the basin depocentre at the middle part of the field and the thickness fades away toward southern direction. The Baharyia Formation attains maximum thickness

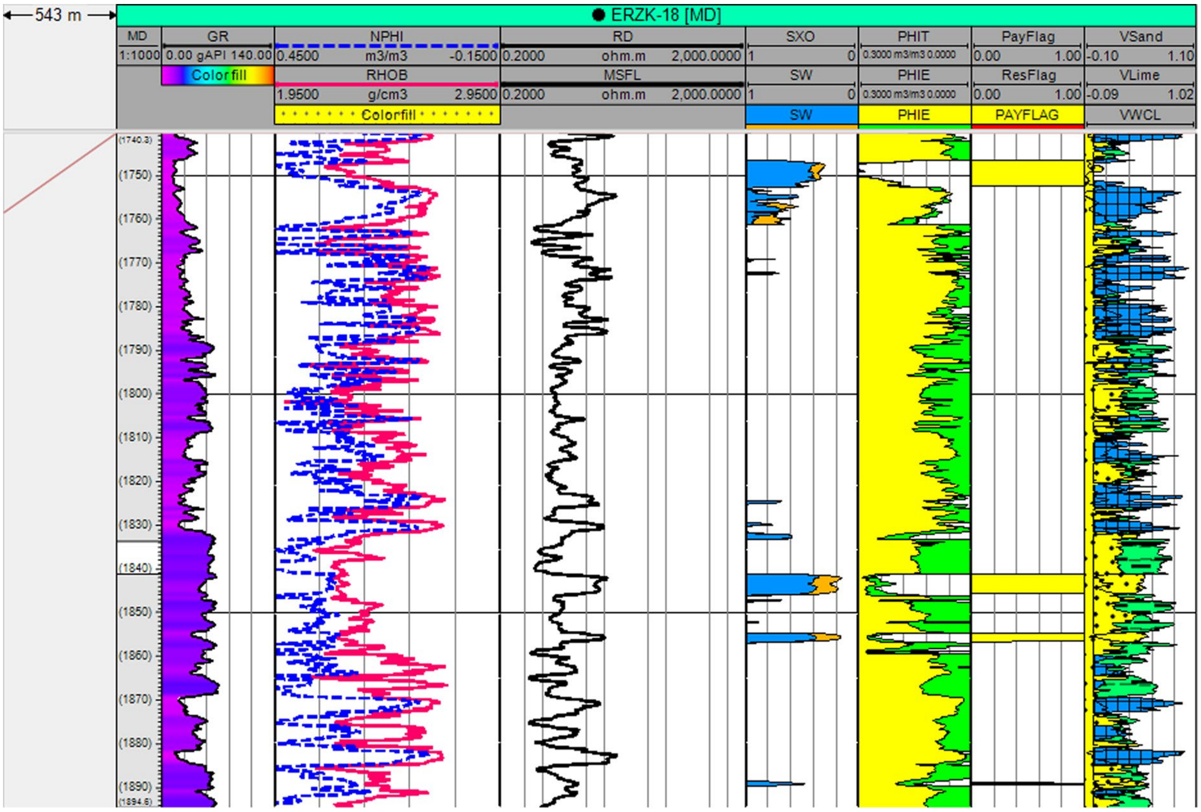


Fig. 6 Litho-Saturation crossplot of ERZK-180X well

about 250 m at ERZK-180X well and minimum thickness 100 m at ERZK-15X well. These, reflects that southward uplifting and northward subsidence, with remarkable NE–SW fault trend of the southern region high.

7.2 Shale volume map

Figure 10 reveals the shale volume map of Baharyia Formation, the shale volume increases toward the northern direction and decreases at the middle. This affects the effective porosity of the reservoir in the north part and increases in the middle part. The maximum shale volume is detected at ERZK-98X well and minimum shale volume at ERZK-180X well. This, reflects continental shelf depositional regime in little moving water with maximum depth 200 m in the northeastern direction.

7.3 Sand volume map

Figure 11 exhibits the sand volume map of Baharyia Formation, that increases in the middle parts and decrease towards the north east direction, so effective porosity will give good results in the middle part. The maximum sand distribution is detected at ERZK-180X well and minimum sand distribution at ERZK-98X well. These, reflects that sandstone deposited in the middle part in a relatively low-energy restricted marine setting.

7.4 Limestone volume map

Figure 12 shows limestone volume map of Baharyia Formation, increases in the northern and southern parts and fades towards the middle part. The maximum limestone distribution is detected at ERZK-180X well and minimum limestone distribution at ERZK-98X well. These, reflects that Baharyia

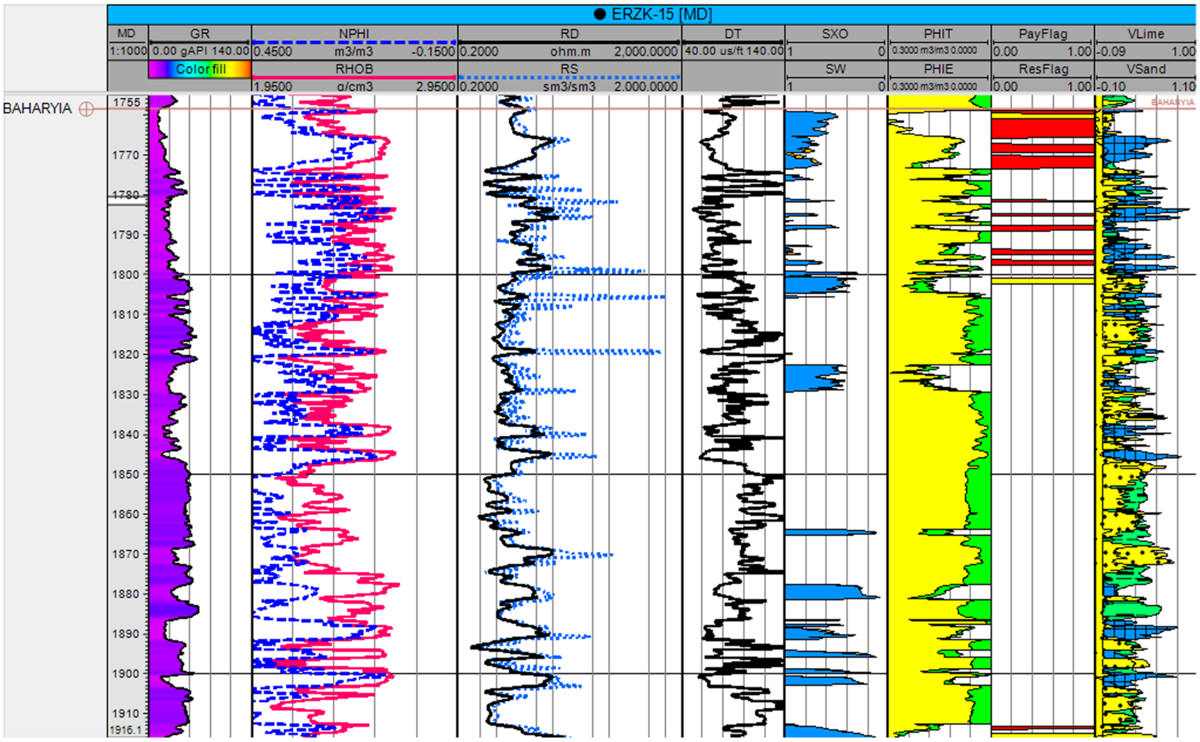


Fig. 7 Litho-saturation crossplot of ERZK-15X well

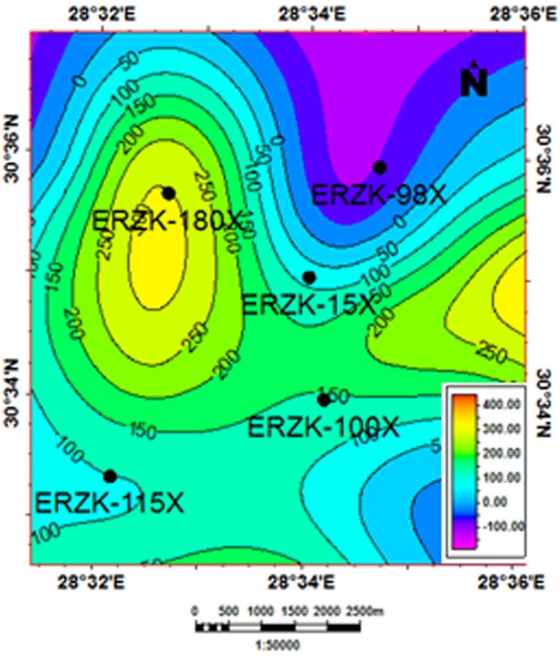


Fig. 8 Baharyia total thickness map

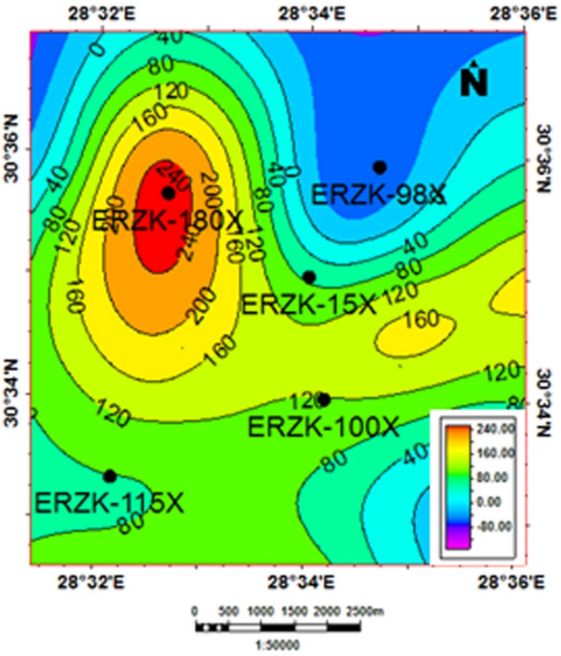


Fig. 9 Baharyia net pay thickness map

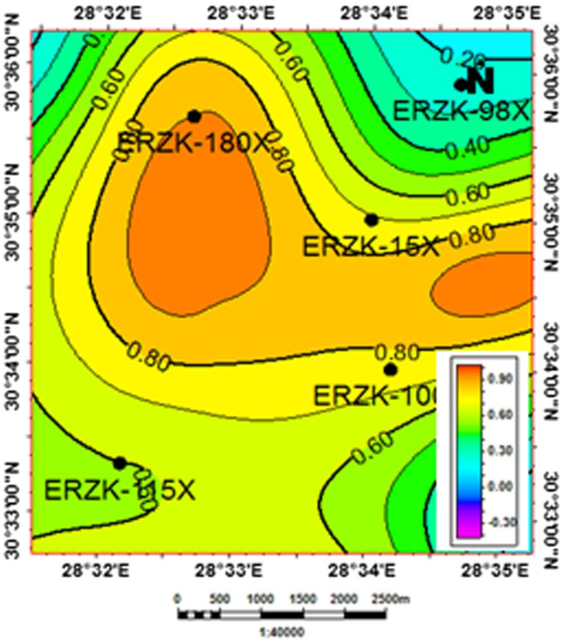


Fig. 10 Baharyia sandstone distribution map

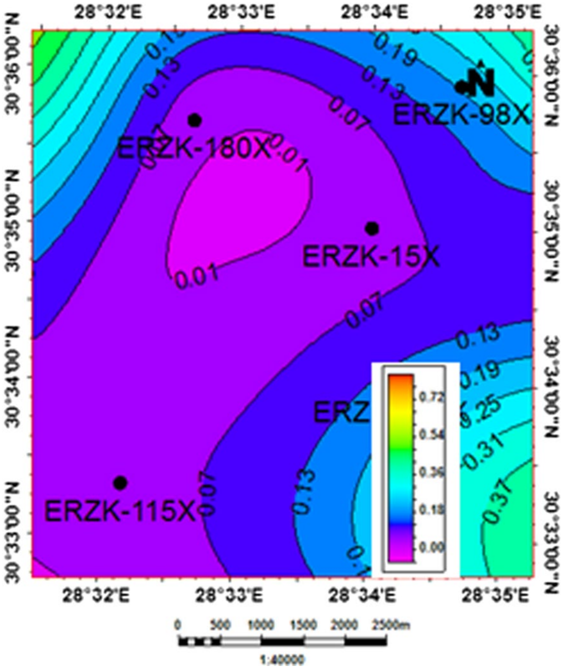


Fig. 12 Baharyia limestone distribution map

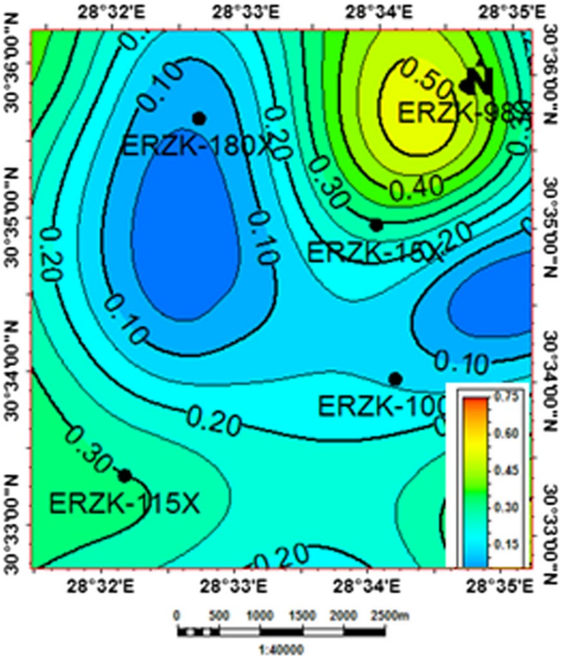


Fig. 11 Baharyia shale volume distribution map

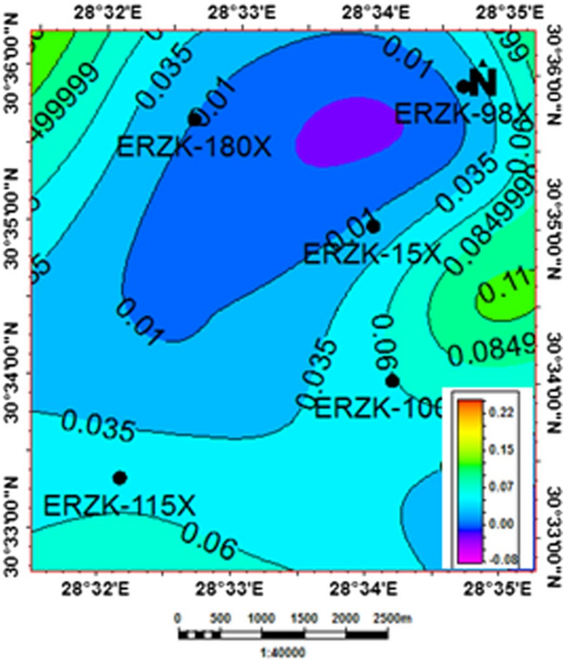


Fig. 13 Baharyia matrix distribution map

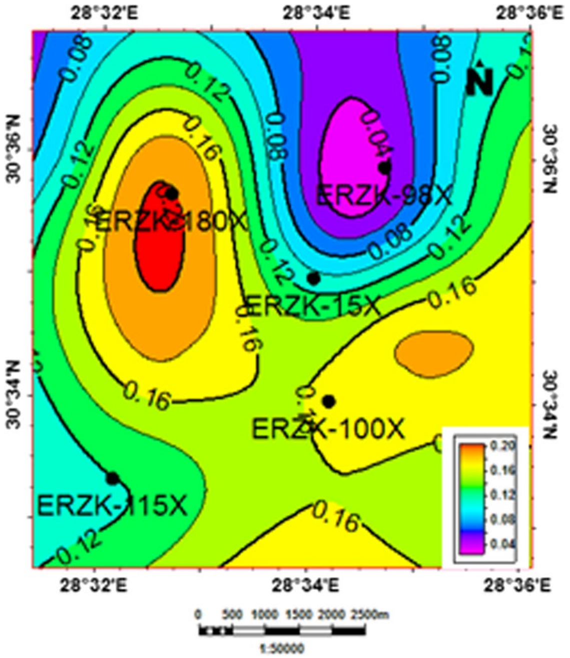


Fig. 14 Baharyia total porosity map

Formation deposited in the northeastern in open marine environment.

7.5 Matrix volume map

Figure 13 shows matrix volume map of Baharyia Formation, increases in the northern and southern parts and fades towards the middle part. The maximum matrix distribution is detected at ERZK-180X well and minimum matrix distribution at ERZK-98X well. These, reflects that Baharyia Formation matrix distribution varies due to variation of depositional environments from fluvio-marine to relatively deep marine environment.

7.6 Total and effective porosity map

Figures 14 and 15 shows total and effective porosity maps of Baharyia Formation, increases in the western parts and decrease towards the northeastern direction, so best drilling results would be in the western direction. These, also, elucidate the eligible effect of structural activities in form of secondary porosity on the implicated porosity regime.

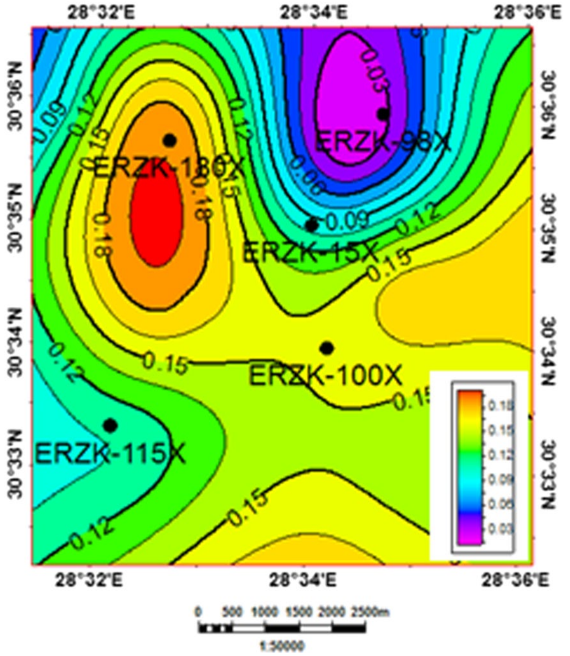


Fig. 15 Baharyia effective porosity map

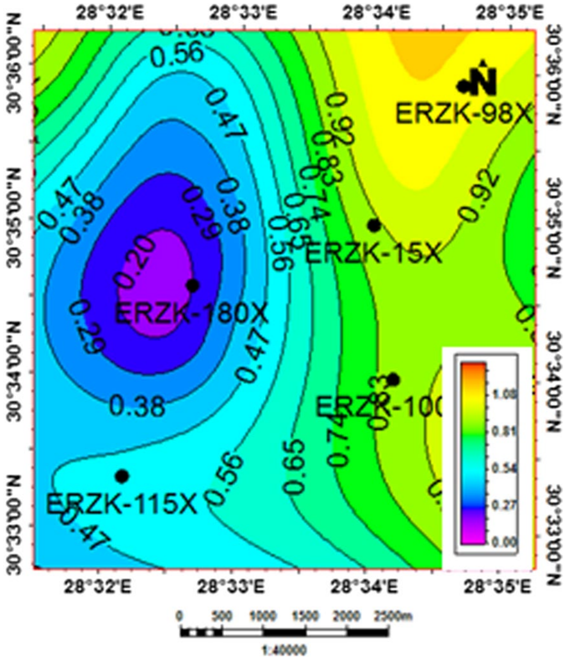


Fig. 16 Baharyia water Saturation map

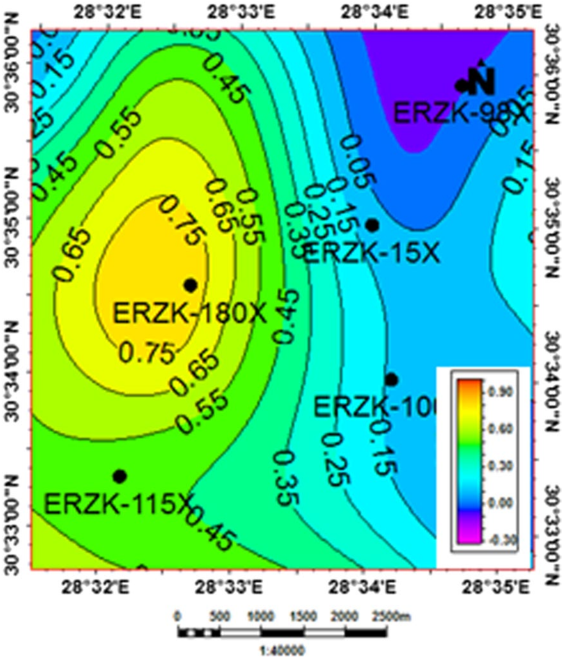


Fig. 17 Baharyia hydrocarbon Saturation map

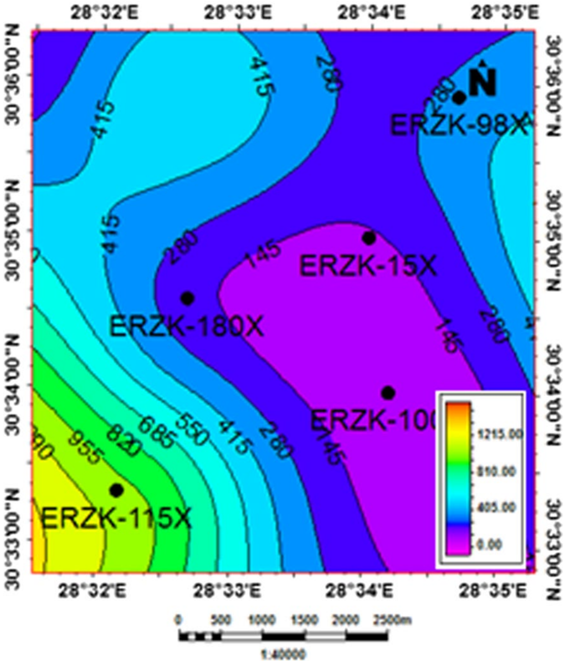


Fig. 18 Baharyia relative permeability

7.7 Water saturation map

Figure 16 shows matrix volume map of Baharyia Formation, increases in the northern and southern parts and fades towards the middle part. The maximum values detected in the eastern direction and minimum values in the western direction. Theses indicates that, the water saturation implications of the western parts of the studied area are more potentials than its central and eastern parts.

7.8 Hydrocarbon saturation map

Figure 17 shows matrix volume map of Baharyia Formation, increases in the northern and southern parts and fades towards the middle part. The maximum values detected in the western direction and minimum values in the eastern direction. Theses indicates that, the water saturation implications of the western parts of the studied area are more potentials than its central and eastern parts.

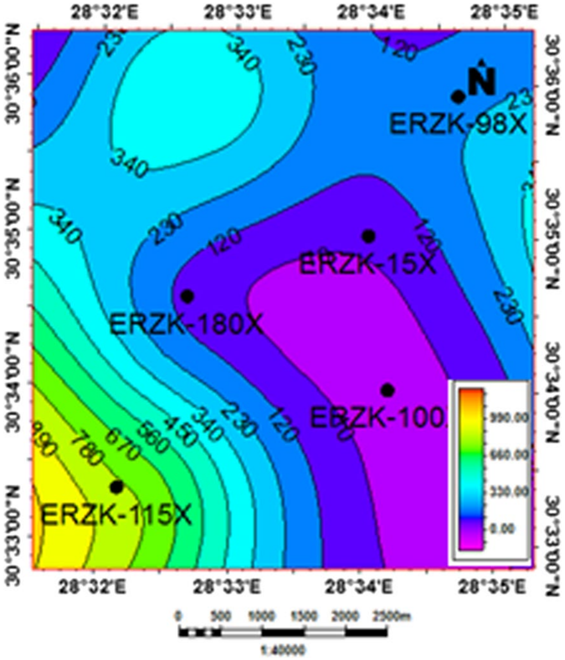


Fig. 19 Baharyia absolute permeability

7.9 Permeability maps

Figures 18 and 19 shows both average absolute and relative permeability's of the Baharyia Formation, the flow capacity of hydrocarbons has its highest values in the western part of the studied area and increase northward of the former unit and decreases eastwards. This means that the reservoir permeability is a more complex function depends not only the total water saturation and effective porosity, but also on the integrated conditions. Also, the average relative permeability of the Baharyia Formation shows the highest flow capacity in the western parts and lowest in the eastern parts. These, reflects that, the comparable variation of the conditions fullfilling the permeability regime against water, with those of the other hydrocarbon constitutes. (Abdine and Deibis 1972).

8 Petrophysical modeling

The calculated petrophysical parameters of the reservoir (such as porosity, water saturation and net to gross pay thickness) are distributed spatially in 3D grid form. Facies modeling is a process in which, facies can be distributed. It requires, a scale-up of well logs as a pre-requisite and includes several log types either continuous logs (porosity, permeability etc.) or discontinuous logs (facies) Fig. 20. The integration of well logs and core is important in determining the lithology and paleoenvironment of the subsurface. Channel sand facies including, sandstone and slightly argillaceous to slightly calcareous sandstone. The cross bedded and pebbly sandstones indicates, a high energy tidal channel environment. The presence of dark carbonaceous matter in the sandstone indicates, that these channels were near deltaic to tidal flat mixed environments (Selley 1978). Flood Plain Facies including, siltstone to argillaceous and sandy siltstone. The silty mudstone indicates, deposition in a mud flat setting. Lagoonal mud facies including, shale and silty to calcareous shale. These facies are represented by the carbonaceous mudstone in the. It is related, to deposition in a low energy marsh environment. Marine Carbonate Facies including, limestone and dolomite indicate, deposition in a marine environment. The effective porosity is calculated from neutron and density logs in each well and it represents the actual storage capacity of the rock.

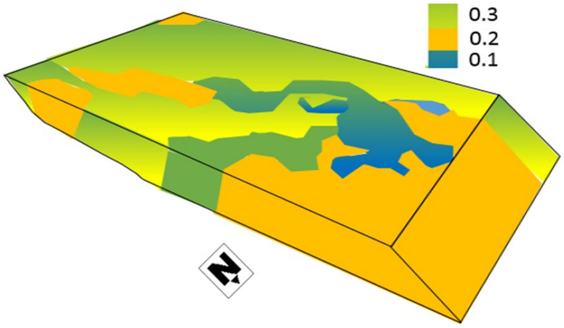
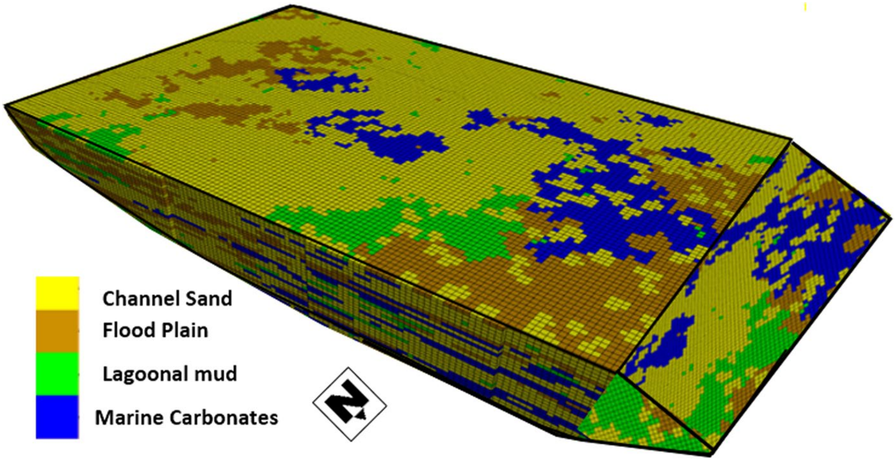


Fig. 21 Baharyia Formation petrophysical model

Fig. 20 Baharyia Formation facies model



The porosity of sandstone reservoirs of Baharyia Formation averages 10–22%.

8.1 Geologic model

Finally, after integration the constructed facies model and effective porosity petrophysical model, a geologic model established for the study area of the north Western Desert. It's obvious, that there is a remarkable variations of petrophysical parameters of the illustrated geologic model, exhibiting uniform changes representing stratigraphic features and abrupt changes of the structural setting affecting the area. The stratigraphic facies model of the Baharyia Formation for the sand channels oriented in N–S to NE–SW directions and were, deposited in a lagoonal mud setting affected by tides in a marine environment shows different facies settings (Fig. 21). The western direction is dominated by fine to medium grained friable sand with free kaolinite, which indicates deposition in a continental to near-shore environment. This is followed by deposition of siltstone and shale with free pyrite in a marginal marine environment. Most of the area has a mixture of fluvial, deltaic, and marine facies (Othman and Metwalli 2000). The dominance of marine carbonate facies to the east and sand facies to west indicates. Sand facies are thin, ranging from 10 to 40 ft. Structurally the structure type is a three-way closure, also termed faulted anticline, and three structures are distributed, the major fault s downthrown to the north. There is a major anticline on the large easternmost structure this anticline trends NE–SW and is dissected by normal faults that are downthrown to the north and south (Moustafa 2008). The trend of these faulted anticlines is most probably synchronous with the lower part of the Alpine orogeny that produced the Syrian arc system of folding and dip-slip faulting (NE–SW) during the Middle Mesozoic to Late Mesozoic (Abu El-Ata 1988). These types of structures are common oil and gas traps in the northern Western Desert of Egypt (Sarhan 2017). Figure 22.

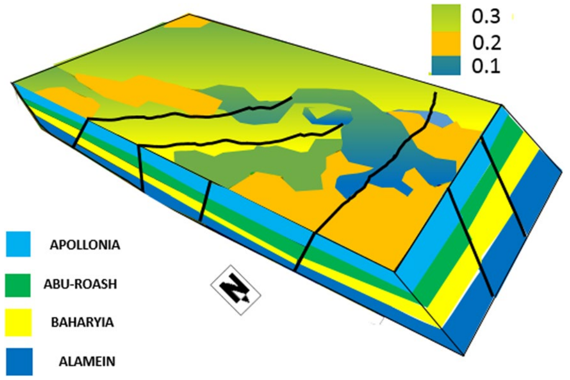


Fig. 22 Geological model of the study area

9 Summary and conclusions

The petrophysical properties of the Baharyia Formation in the study area have been evaluated, using a complete wireline log suite extracted from five wells (ERZK-15X, ERZK-100X, ERZK-115 X, ERZK-98X and ERZK-180X). The lithologic distrubtion predicted from log data exhibits the lithology of the Baharyia Formation is dominated by sandstones intercalated with calcareous shale. The petrophysical well log results volume of shale of the Baharyia Formation ranges from 40 to 60%, porosity of Baharyia Formation ranges from 17 to 20%, fluid saturation ranges from 36 to 48%. Petrophysical relationships was integrated, to predict the permeability from porosity relationships for the two wells (ERZK-15X, and ERZK-180X), permeability results in ERZK-180X well is better than ERZK-15X well. The litho-saturation crossplots of ERZK-15X and ERZK-180 wells show the vertical variation in the petrophysical and lithological properties within the Baharyia Formation ERZK-15 well shows total gross thickness of the Baharyia Formation of 195 m, net-sand of 115 m, total porosity of the Baharyia sediments ranges from 0 to 25% with an average value 14.48%, while the effective porosity ranges from 0 to 20% with an average value of 12.58%, volume of shale is 50% and water saturation is 55%. ERZK-180X well shows the total gross thickness of the Baharyia Formation of 280 m, net sand about 180 m, the total porosity of the Baharyia sediments ranges from 0 to 28% with an average value 17%, while the effective porosity ranges from 0 to 20% with an average of 15%, volume of shale is 0% and water saturation is 45%. In the meantime, the spatial distribution of the weighted petrophysical parameters is also represented by a number of iso-parametric maps. These maps illustrate, the reservoir characterizations (net-pay thickness, net-gross thickness, volume of shale, effective porosity, water and hydrocarbon saturation, and give better drilling results at the middle part of the area, while the productivity fades toward the northeastern and southern direction and southwards. Building a 3D model is the final result of seismic interpretation, well correlation using available well log and core analyses. The process of building a model is time consuming but can be updated easily. Petrophysical model shows the structural type is a three-way dip closure, intervened by faults, also termed faulted anticline. Also, three linear structures (faults) are distributed, in which the major faults downthrown toward the north. There is a major anticline capped the large easternmost structure. This anticline trends NE–SW of the Cretaceous and is dissected by of NW–SE and WNW–ESE normal faults of the Tertiary that, are downthrown majority to the north and minority to the south. Facies modeling showed multiple the stratigraphic facies model of the channel sand facies including sandstone and slightly argillaceous sandstone Baharyia Formation is established for the sand channels oriented in the N–S to NE–SW directions, Flood Plain Facies including siltstone to argillaceous sandstone lagoonal mud setting affected by tides in a marine environment, showing varying facies settings. The dominance of marine carbonate facies limestone and dolomite to the east and sand facies to the west indicates sand facies.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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