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Original Article

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Abstract

Petrophysical evaluation of the lower Bahariya sediments was performed based on comprehensive interpretation of complete wireline logs suite from two wells in Salam oil field, southwest Shushan basin in the north Western Desert, Egypt. Several petrophysical parameters such as shale volume (V_{SH}), total and effective porosities (PHIT, PHIE), water saturation (S_W) and hydrocarbon saturation (S_H) were deduced and utilized in the petrophysical subdivision of the lower Bahariya sediments. Neutron versus density, matrix volumetric versus matrix grain density and M-N crossplots revealed that quartzose sandstone is the dominant matrix component within the lower Bahariya sediments. Additionally, the litho-saturation crossplots typified the presence of oil-bearing intervals often associated with the quartzose sandstones with minimal contents of silts and clays. Dispersed and laminated clays are detrimental to the reservoir quality by obstructing the pore spaces and thus reducing the hydrocarbon flow storage and flow capacities. The obtained petrophysical results reveal that the lower Bahariya sediments have a good reservoir quality with high effective porosity values exceeding 18% and low water saturation values ~ 35%. The upper part of the lower Bahariya sediments hosts the most promising reservoir intervals which should be considered during future exploration and development of the oil fields in the study area.

1. Introduction

The study area locates in the north Western Desert which is considered as one of the most prolific petroleum provinces in Egypt (Fig.1). The target of this study is the lower part of the Bahariya Formation which hosts the most promising reservoir intervals in the north Western Desert with high rates of petroleum production. In addition to its reservoir potential, the sediments of the lower Bahariya constitute some organically-rich hydrocarbon source intervals (Dolson et al., 2001; Mansour et al., 2020). Bahariya Formation was informally subdivided into upper and lower units that were deposited under fluvio-marine to shallow marine conditions with strong tidal influence at the beginning of the upper Cretaceous transgression (Watkins et al., 2002; Wehr et al., 2002; and Metwalli et al., 2000; El Bassyouny, 2004; Catuneanu et al., 2006 Abdelmaksoud et al., 2019). The lower Bahariya unit contain clastics sediments that were deposited in fluvial and fluvio-marine conditions, and therefore hosts several intervals with high degree of reservoir heterogeneity. The main objectives of this study are to determine the reservoir lithology, fluid saturation and porosity, determination of cutoffs and identify the different reservoir parameters that characterize the pay zones.

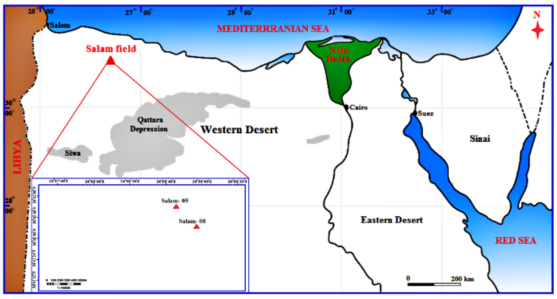

Fig. 1. Location map of the Salam Field (Shalaby et al. 2014).

2. Geologic setting

The geological and drilling studies revealed the presence of a dense subsurface lithostratigraphic column, varying in age from the Paleozoic to the Recent (Fig.2). The post-Palaeozoic succession includes four main cycles of tectono-sedimentary distinguished by unconformities, crossing to the

Middle Jurassic, Lower Cretaceous, Upper Cretaceous, and Eocene to Miocene. Each of these cycles starts with fluvio-deltaic siliciclastics and ends with marine carbonates (Sultan and Abdelhalim, 1988; May, 1991; EGPC, 1992; Shalaby et al. 2013).

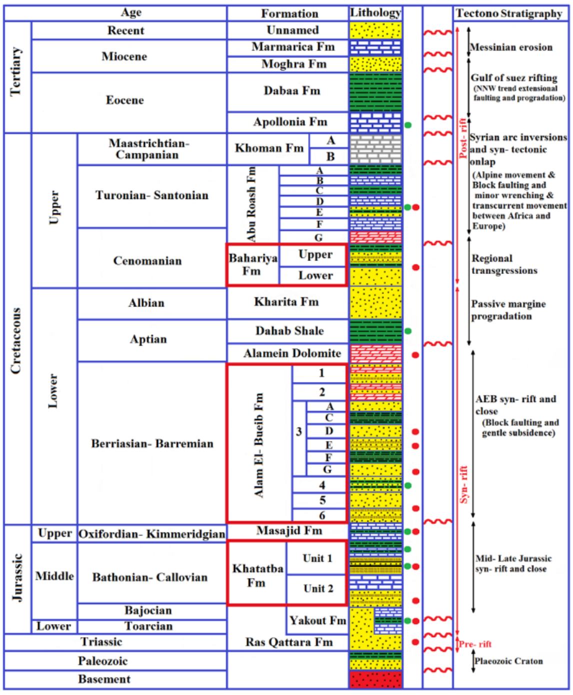

Fig. 2. Generalized lithostratigraphic column of the Shushan basin (Wescott et al. 2011).

The north Western Desert, where the study area is located was initially formed mainly by the vertical movement of basement blocks. They are dominated by parallel, elongated, tilted fault blocks, producing horst and half-graben structures associated with the erosion of the upthrown blocks (Shalaby et al., 2013; Barakat, 2017; Mahmoud et al., 2019). Shushan basin is suited within the tectonic zone of the unstable shelf that was tectonically active throughout most of the Paleozoic to Early Cenozoic period, where the Late Jurassic to Early Cretaceous rifting, Mid-Cretaceous (Aptian) uplift and erosion, and Late Cretaceous to Early Tertiary shear and compression have occurred (Said, 1962; Marfil et al., 2003). During the Late Jurassic- Early Cretaceous, Shushan basin was formed as a sequence of opening of Neo-Tethys ocean to the north as a NE- SW extensional basin, receiving only continental and fluvio-lacustrine sediments and later converted into a pull-apart basin during the Late Cretaceous as a result of the rifting and separation of the North African plate from European plate (Meshref and Hammouda,1990; EGPC, 1992; Meshref, 1996; Metwalli and Pigott, 2005; Al-Sharhan and Abd El- Gawad, 2008;Shalaby et al., 2012; Barakat, 2017).

3. Materials and Methods

This study is established based on well log data from two exploration wells, Salam-05 and Salam-08. The well log evaluation has been accomplished using Interactive Petrophysics software (IP) version 3.6. Well log data include gamma ray, resistivity, sonic, neutron and density, which were used for identification of lithology and fluid type as well as determination the shale volume, total porosity, effective porosity, water and hydrocarbon saturations.

3.1. Shale volume calculation

Accurate estimation of the shale volume is essential for the petrophysical evaluation clastic reservoir rocks. Shale volume calculation is crucial for elimination the effect on logging responses and discrimination between reservoir and non-reservoir rock. Gamma ray, resistivity, neutron and neutron-density logs were used to calculate the shale volume. The average value of shale content from these methods is approximately equal to its actual value (Hakimi, et al. 2012). Neutron- density crossplot as well as shale volume- porosity crossplot (Thomas and Stieber, 1975) are used to understand the distribution and type of shale and its effect on reducing the pore space. The cutoff of shale is determined to be 50% which means that rocks with more that 50% of shale content are evaluated as non-reservoir rock, while rocks that have less than 50% of shale content are regarded as reservoir rock.

3.2. Porosity calculation

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), density log is a function of density of the matrix, porosity and the density of the fluid in pores, while sonic log is related to the clean compacted rocks (primary porosity). Total and effective porosity (PHIT and PHIE) are calculated by using the neutron density- initial porosity model. Neutron density porosity- sonic porosity crossplot is used to identify the porosity type. To differentiate between porous and non-porous sand intervals, a 10% porosity cutoff which is the lowest effective porosity which allow oil flow is applied.

3.3. Fluid saturation

Indonesian equation is used to calculate the water saturation as it serves for the shale effect in its first part and for the clean formation effect (Archie's term) in the second part, while hydrocarbon saturation is calculated by using the following equation:

$$S_h = (1 - S_w) \qquad (1)$$

Where; S_h is the hydrocarbon saturation and S_w is the water saturation. Also a 50% water saturation cutoff is used to differentiate between the pay and non- pay zones.

. Data analysis was completed using detection software and the formula $2^{-\Delta\Delta Ct}$ method for relative quantization.

4. Results and discussion

4.1. Discrimination of the reservoir lithologies

The lower Bahariya unit consists mainly of fine to coarse-grained sandstone alternated with siltstone and mudstone. Sandstones are mostly glauconitic and ferruginous likely deposited in braided fluvial channels (Khalifa and Catuneanu, 2008; Catuneanu, et al. 2006). Whilst, the mudstone and siltstone facies represent the floodplain deposits. Plotting the bulk density versus the apparent matrix density differentiates the lower Bahariya sediments based on their mineralogical composition and porosity (Fig.3A).

Several sandstones types were recognized including the quartzose sandstones having an average matrix density of 2.67 g/cm^3 and average clay volume of 8 %. Glauconitic sandstones have average matrix density of 2.77 g/cm^3 and average clay volume of 25.6 %, whereas the calcareous and ferruginous sandstones are discriminated by their elevated average matrix density of 3.07 g/cm^{3,} and they have a wide range of clay volume.

Neutron versus density crossplot (Fig. 3B) shows that sandstone is the main lithology in the lower Bahariya with some interbeds of calcareous shale which are plotted close to the dolomite line.

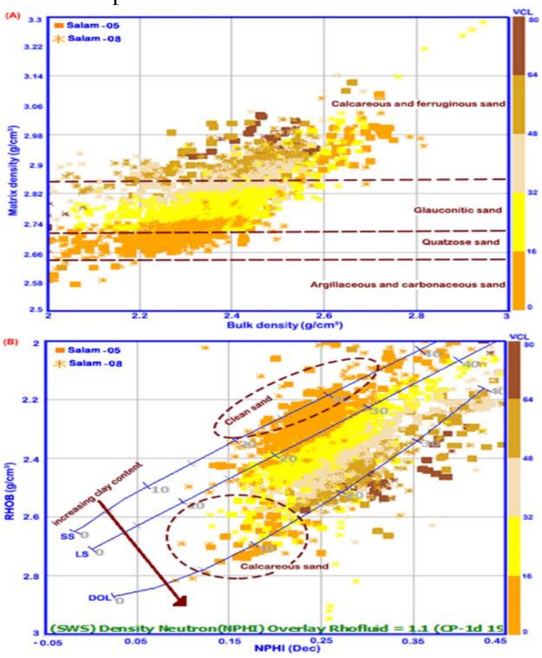

Fig.3. (A) Bulk density- Matrix density crossplot, neutron- density crossplot for lithological identification (B).

Quartzose sandstones exhibit neutron values ranging from 15% and 30% and density values from 2 to 2.5 g/cm^3. Calcareous sandstones were plotted between the limestone and dolomite lines, whereas the glauconitic and ferruginous sandstones are often clustered below the dolomite line. Matrix volumetric versus matrix grain density crossplot (Fig.4A) confirms the abundance of quartzose sandstones in the lower Bahariya sediments with matrix grain ranges from 2.65 to 2.71 g/cm^3 and matrix volumetric of 6.4 to 10 barns/cm^3 with K- feldspar having matrix density less than 2.65 g/cm^3 and traces of heavy minerals and anhydrite with matrix density from 2.9 up to 3 g/cm^3 and matrix volumetric ranging from 13.6 to 16 barns/cm^3. Clay volume increases below the dolomite line extents to illite clay minerals exhibiting the highest clay content up to 64-80%. Calcite content increases towards the calcite point with an average matrix density of 2.71 g/cm^3 and average matrix volumetric of 13.6 barns/cm^3, while dolomite content increases towards the dolomite region with matrix density up to 2.84 g/cm^3 and matrix volumetric of 8.8 barns/cm^3. The M-N cross plot (Fig.4B) also confirm the abundance of clean quartzose sandstones in lower Bahariya sediments with clay volume ranges from 0 to 16%. Some points are scattered upward due to the occurrence of secondary porosity in the calcareous sandstones.

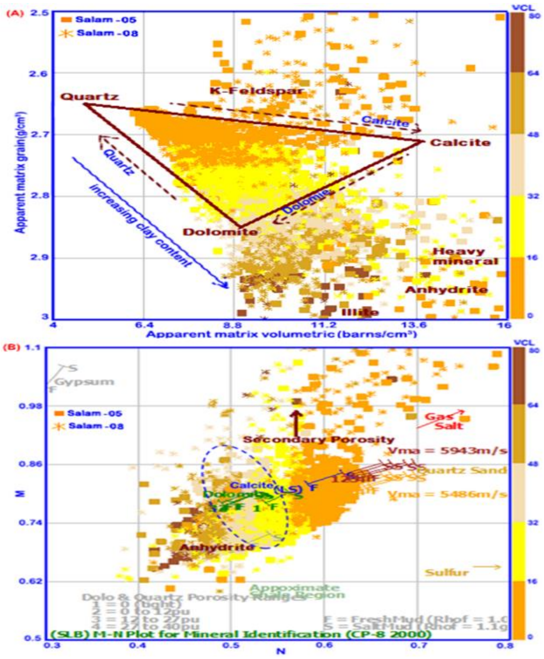

Fig. 4. (A) Apparent matrix volumetric as a function of apparent matrix grain density plots, M-N plot (B) showing mineralogical component of lower Bahariya.

4.2. Clay distribution and impact on reservoir quality

The crossplot of neutron porosity versus density porosity shows that clays are mostly distributed within the sand in laminated and dispersed forms with slight effect of heavy minerals. Some samples mainly of quartzose sandstones are shifted upwards due to the effect of hydrocarbons (Fig.5A). According to the model of Thomas and Stieber (1975), the sandstones containing laminated clays have PHIE>10% with clay volume <50%, reflecting a minimal effect on pore space reduction with a considerably low water saturation, while the occurrence of dispersed clays often reduce the PHIE of the sandstones to less than 10%. The presence of even a small content (<30 %) of dispersed clays in the sandstones would reduce the PHIE to less than 10% and increase the water saturation up to 80% reflecting its significant detrimental impact on the sandstones' reservoir quality (Fig.5B).

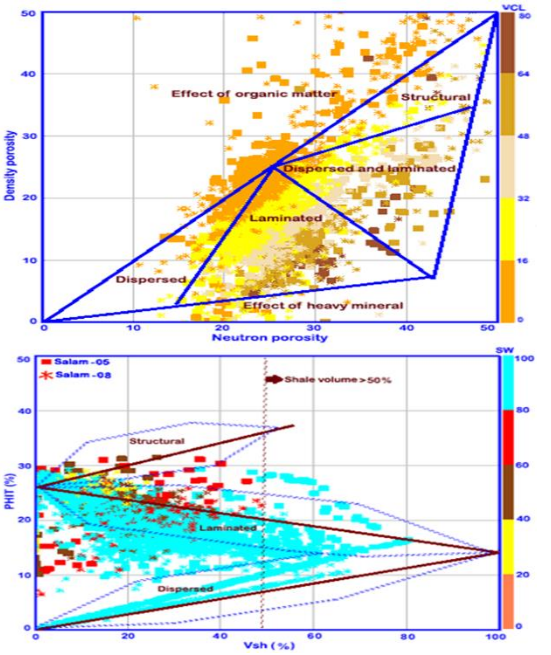

Fig. 5. Neutron porosity- density porosity crossplot accompanied with shale volume showing the distribution and type of shale within sand (A),Thomas- Stieber model of shale distribution accompanied with water saturation showing the effect of shale form on porosity and water saturation (B).

4.3. *Petrophysical evaluation of the lower Bahariya sediments*

The litho-saturation crossplots of Salam-05 and Salam-08 show the vertical variation in the petrophysical and lithologic properties within the lower Bahariya sediments (Figs. 6A, B). The total porosity of lower Bahariya sediments ranges from 0 to 31.21 % with an average values of 17.84 and 14.48 % for Salam-05 and Salam-08 respectively, while the effective porosity ranges from 0 to 29.26 % with an average effective porosity of 12.58 and 10.77 % for Salam-05 and Salam-08 respectively. The vertical distribution of porosity shows upward increase in the values, and the highest values often coincide with minimal content of clays (Figs. 6A, B).

The porosity type is commonly determined by plotting neutron-density porosity versus sonic porosity (Fig. 7). The plot reveals the abundance of intergranular porosity particularly in the quartzose sandstones and secondary porosity in the calcareous sands.

Shale volume ranges from 0 to 80.6 % with an average value of 26.02 and 23.33%, respectively in Salam-05 and Salam-08 wells. Shale is distributed mainly in a laminated and dispersed form and thus reduces the pore space. Lower Bahariya formation exhibits higher water saturation values compared to hydrocarbon saturation with an average values of 88.25 % and 11.75 % in Salam-05 well and 92.43 % and 7.57 % in Salam-08 well. The highest values of water saturation are often associated with the sandstones containing dispersed clays, while the lower mainly correlates with the structural and laminated shale. Water saturation generally decreases upward until reaches its minimum values at the top with a minimal clay content of laminated shale. Cutoffs of 10%, 50% and 50% for porosity, water saturation and shale volume are applied to differentiate between pay and non-pay zone intervals (Table 1).

Table 1. Petrophysical parameters of lower Bahariya pay zone for the studied wells.

well	Top (ft)	Bottom (ft)	Gross (ft)	Net (ft)	Net/Gross	Av PHI (%)	Av SW (%)	Av Vcl (%)
Salam-05	5900	6542	642	53	0.083	0.215	0.361	0.115
Salam-08	5894	6544	650	2.25	0.011	0.188	0.478	0.169

The pay zones occur at the top of lower Bahariya where the quartzose sandstones dominate in both wells with average porosity of 21.5 % and 18.8, average shale volume of 11.5% and 16.9 %, and average water saturation of 36.1% and 47.8 % for Salam-05 and Salam-08, respectively.

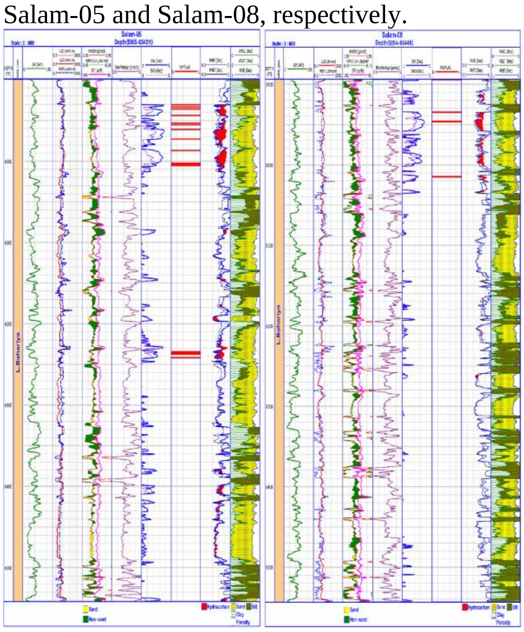

Fig. 6. Vertical distribution of the different petrophysical parameters in the lower Bahariya sediments of Salam-05 well (A) and Salam-08 (B).

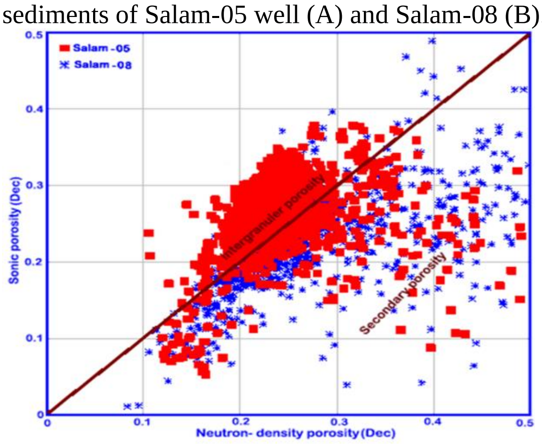

Fig. 7. Neutron- density porosity versus sonic porosity showing type of porosity.

Conclusion

The petrophysical properties of the lower Bahariya sediments in Salam oil field have been evaluated using complete wireline log suite from two wells (Salam-05 and Salam-08). Bulk density, apparent matrix density and apparent matrix volumetric data reveal that the lithology of lower Bahariya formation is dominated by sandstones intercalated with calcareous shale. The sandstones were discriminated into three types namely, the quartzose, glauconitic and calcareous, ferruginous sands. Quartzose sandstones have the best petrophysical properties in terms of effective porosity and fluid saturation. Clays are distributed in sand mainly in laminated and dispersed forms. Laminated clays induce a minimal effect on the pore volume, whereas dispersed shale significantly reduces the pore volume however increases the water saturation probably due to their elevated contents of irreducible water saturation. Porosity in lower Bahariya is mainly intergranular particularly in the quartzose sandstones. Hydrocarbon pay zones with water saturation values less than 50% are often present at the upper part of the lower Bahariya sediments where the quartzose sandstones of the braided fluvial channel are dominant. Future exploration in the study area should target the fluvial quartzose sand beds which are commonly present at the top of the lower Bahariya and are often capped by the floodplain shales.

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