Petrophysical Properties of Clastic Reservoirs Using NMR Relaxometry and Mercury Injection Data: Bahariya Formation, Egypt

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Abstract. The Bahariya Formation is a sedimentary sequence, which was deposited under fluvial to shallow marine conditions at the beginning of the Upper Cretaceous (Cenomanian) transgression in the Western Desert of Egypt. Thirty sandstone core samples, obtained from the Bahariya Formation, are conducted to NMR measurements and the relaxation time $T_2 = 100 \mu s$ and $600 \mu s$ were estimated. Application of a model related core-porosity and transverse relaxation time ($T_2$) measured from NMR spectrum; the cementation exponent of Wyllie’s type is outlined with high accuracy. Consequently, the water saturation and hydrocarbon saturation will be significantly enhanced. The irreducible water saturation ($S_{wirr}$) calculated from the mercury injection capillary pressure (MICP) measurements is related to the normalized area under $< 4 \mu s$ of transverse relaxation time ($T_2$) and a regression model is calculated with a reliable coefficient of correlation permitting calculation of ($S_{wirr}$) with high accuracy. Lithologic laminations presented in some intervals of the Bahariya Formation have great consequences on both the Mercury injection capillary pressure (MICP) measurements and nuclear magnetic Relaxometry ($T_2$) as well. Thin sections and SEM-micrographs were made for some selected core samples in order to recognize petrography and mineralogy of the Bahariya sandstones. Glauconitic, mica, zircon, rutile and pyrite minerals are predominant in the laminated sandstones intervals.

1. Introduction

The Bahariya Formation is a sedimentary sequence, which most likely deposited in a Tidal flat - lagoon environment at the beginning of the Upper Cretaceous (Cenomanian) transgression in the Western Desert of Egypt. Barrier bar, stream mouth bar, point bar, and distributary channel sand bodies were detected (El Sayed et al., 1993) in the Bahariya Formation encountered in the Salam and Khalda oil fields. El Sayed et al. (1999) investigate poison’s ratio versus fluid saturation relations. Regarding to its hydrocarbons potentiality, the Bahariya Formation is counted among the most important hydrocarbon reservoirs in the Western Desert. Thus, a better understanding of the Petrological and petrophysical characteristics of the Bahariya reservoir sandstones is inquiry (Matthias et al., 2009).

The Bahariya studied samples display fine grained sandstones with different numbers of black lamination or flaser bedding, (Figure1) parallel to the sedimentary bedding and partly imbedded...
particles. Subsequently, many authors (Athmer et al., 2007; El Sayed, 2011; and El Sayed, et al, 2015) have studied the petrology and some petrophysical properties of the Bahariya core samples.

Wang et al. (2014) introduce a novel cementation exponent (m) prediction model, which is relevant to porosity (Ø, %) and logarithmic mean of NMR transverse relaxation time (T2LM, % of total area) spectrum. Based on the analysis of the core test results of Wang et al., (2014), He established a regression model as:

$$m_{NMR} = \frac{(-1.262-(0.047 \ln T_{2LM}))}{\ln \theta} - 0.905 \quad R^2=0.91 \quad (1)$$

Where: (R) is the correlation coefficient. Equation (1) shows that the value of correlation coefficient is close to 1.0, which indicates that the cementation exponent (m) can be calculated from NMR logs precisely. This model is tested, in the present work, and proves its applicability at more than T2 value for both the Bahariya and Szolnok sandstone reservoirs at T2 >33 ms up to 600 ms. Application of this model increases the accuracy of water saturation obtained values and then, hydrocarbon saturation will be significantly improved. The irreducible water saturation (Swirr) calculated from MICP results are assumed to be function of the clay bound water (CBW) calculated from the T2-distribution curve (< 4.0 ms). While, the bulk volume irreducible (BVI) is related to the magnetic susceptibility (k) for the Bahariya laminated and non-laminated samples and represented by:

$$\ln(k) = 2.604*\text{BVI}+2.585 \quad (\text{for laminated sandstones}) \quad R^2 = 0.42 \quad (2)$$

$$\ln(k) = 3.458*\text{BVI} + 1.834 \quad (\text{for non-laminated sandstones}) \quad R^2 = 0.62 \quad (3)$$

The target of the present research work is to delineate Inter-correlations among some sandstone reservoir derived parameters from NMR measurements and the same parameters derived from mercury injection capillary pressure (MICP) tool or laboratory conventional tests like porosity. In addition, the effect of core sample orientation (horizontal or vertical to the formation bedding plane) on the T2-distribution curve-shape was objective as well.

2. Methodology

Sohxlet extractor with different organic solvents cleaned the studied samples prior to porosity, NMR and MICP measurements. The samples were dried in an electric oven and then weighted using digital balance to 0.0001g. Porometer -2000 is used MICP test. The mercury injection capillary pressure (MICP) curve consists of at least 30 pressures versus injection volume measurements that are roughly logarithmically spaced between <5.0 psi to >30kpsi air/mercury pressures. For the purpose of
comparing NMR and MICP data, mercury capillary pressure $P_c$ (in psi) was converted to pore radii ($r$, in μm) using Washburn equation:

$$r = 0.29 \sigma \cos \Theta / P_c$$  \hspace{1cm} (4)

Where the interfacial tension $\sigma = 480$ dyne/cm and contact angle $\Theta = 140^\circ$.

The samples were then vacuum-pressure saturated with NaCl brine whose concentration was adjusted to approximate the formation water salinity of the Bahariya Formation penetrated in Bed-1 field (0.56 g/l). Proton NMR measurements were made for all studied samples at 100% brine saturation. $T_2$ measurements were made in a homogeneous magnetic field using CPMG method with phase alteration and an interecho spacing $TE = 0.5$ ms. A sufficient number of echo trains were measured and stacked to achieve a minimum signal-to-noise ratio of 200:1 (300:1 type). $T_2$ distributions were computed by fitting the stacked echo trains for partial porosity amplitudes corresponding to 51 per selected values of $T_2$ spaced logarithmically between 0.1 and 10,000 msec. using the algorithm developed by Prammer (1994). In order to place all distribution on a common scale, MICP pore radii were converted to an equivalent $T_2$ value according to equation published by Marschall et al, (1995);

$$\frac{1}{T_2} = \frac{V_{pore}}{T_{2, bulk}} + \frac{\lambda s}{T_{2, surface}} = \rho_e \frac{S}{V}$$  \hspace{1cm} (5)

Where $\rho_e$ is the effective surface relaxivity, μm/sec.; $V_{pore} = V$ = is the rock pore volume, cm$^3$; $T_{2, bulk}$ = for bulk sample; $S = is$ sample surface area, cm$^2$. For cylindrical tube pores, then $(S/V) = (2/r)$, and by substituting the surface to volume ratio by its equivalent $(2/r)$ in equation (5) then:

$$T_2 = \frac{((1000 \ r)}{2 \rho_e}$$  \hspace{1cm} (6)

Marschall et al, (1995) stated that the average value of specific relaxivity ($\rho_e$) for clean sandstone is found to be $= 14.0$ and for shale sandstone $= 16.0$, while it is equal to 9.5 for carbonate facies. In the present work, It is assumed to be $(\rho_e = 15.0)$ for the studied sandstone samples obtained from both the Bahariya and the Szolnok formations. The Pore radius ($R_{NMR}$) in the present study, is calculated using equation (6), while the cementation exponent ($m_{NMR}$) is calculated using equation (1).

### 3. Results and Discussion

#### 3.1. Change of $T_2$ –Spectra with Sample Lamination

The spectra of $T_2$ – distributions are changing according to the density of the flaser lamination from horizontal direction of sample cutting into vertical one (Figure 1).
Changes are increases between horizontal (parallel to the bedding plane) and vertical one with increasing lamination (Figs. 2a and b). This change in the $T_2$-distribution curve-shape is equals to $T_2$-anisotropy shown in positive laminated sandstone samples obtained from the Bahariya Formation.

![Figure 2b: $T_2$-Distribution of samples 49H (-L) and 49 V (-L)](image)

3.2. NMR Porosity versus Conventional Porosity and CBW

Porosity data measured by saturation method has been related to its synonymous NMR porosity (Figure 3). This relationship shows close correlation ($R = 0.973$ for Bahariya samples from Egypt and $R = 0.985$ for Szolnok samples from Hungary) for the two types of sandstone reservoirs. These relations prove that porosity from NMR-logs is analogous for porosity calculated from core analysis tests. The NMR-porosity is related to the clay bound water (CBW) calculated from the relaxation time ($T_2$) and considered as a function of $< 4$ ms area percentages from the total area under $T_2$-spectra (Figure 4).

![Figure 3: Lab. Porosity versus NMR-Porosity](image)

The obtained high coefficient of correlation permit the prediction of clay bound water (Irreducible water saturation) using rock porosity calculated either from conventional core analysis or from NMR-tools. These relations are represented as the regression line equations:

- CBW = -3.431$\phi$ + 97.94 \hspace{1cm} R = 0.90 \hspace{1cm} (for clean non-laminated sandstones) \hspace{1cm} \(7\)
- CBW = -2.132$\phi$ + 72.92 \hspace{1cm} R = 0.877 \hspace{1cm} (for shale and/or laminated sandstone) \hspace{1cm} \(8\)
3.3. Porosity versus Cementation Exponent

Using equation (1) derived by Wang et.al, (2014), the cementation exponent (m) is calculated and related to rock porosity (Figure 5). Two sandstone types (Bahariya and Szolnok) are plotted. Most of the Bahariya sandstone is shale and laminated while, Szolnok sandstone is clean, non-laminated and of high porosity.

![Figure 4: Clay bound water (CBW), % versus NMR-Porosity (red points for Szolnok sandstone and blue points for Bahariya samples).](image)

The relationships are very close and characterized with high coefficient of correlations (R = 0.71 and 0.76 for Bahariya and Szolnok respectively), and they are:

\[ m = 0.052\Phi + 0.82 \quad \text{for Bahariya formation (9)} \]
\[ m = 0.514\ln(\Phi) + 0.084 \quad \text{for Szolnok formation (10)} \]

![Figure 5: Wyllie’s Cementation Exponent versus Porosity for both Bahariya (blue) and Szolnok (red) formations.](image)
3.4. CBW versus Swirr
An attempt was made to relate the data of irreducible water saturation, calculated from MICP, to the T2<4ms % of the total area under T2-spectra (Figure 7). The reliable coefficient of correlation (R = 0.801) calculated for this relation indicates that regression line equation is very useful to delineate the irreducible water saturation from NMR-logs as:

\[ T_2 = 62.7 \ln (Sw_{irr}) - 126.8 \quad R = 0.801 \]  \( (11) \)

Where: (Sw_{irr}), % is irreducible water saturation and T2<4ms; % of the total area under T2-spectrum.

![Figure 6: Relationship between Sw_{irr},% (MICP) versus T2<4.0 ms , % of total area under T2 (NMR)](image)

4. Conclusions
- Cementation exponent (m) increases with porosity increasing and it could be outlined with high precision from either conventional or log porosity using equations (9 and 10) for shale laminated and clean sandstones respectively.
- The Irreducible water saturation (Sw_{irr}) can be calculated from NMR-tools with high accuracy using the empirical equation (11), and from porosity using equations (7 & 8).
- The T2- spectra curve-shapes depend on the direction of sandstone lamination.
- Clay bound water (CBW) can be calculated from porosity for shale rich or clean sandstone by using equations (7 - for clean and 8 - for shale-rich sandstone), while Capillary bound water (BVI) could be outlined from magnetic susceptibility using equations (2 and 3) for shale rich and clean sandstone respectively.

References
[1] Athmer, W., Weller, A, El Sayed, A.M.A., 2007, Petrological characterization of the Bahariya Formation, Egypt. 2nd International Conf. on the Geol. of Tethys: V.1:179-184.
[2] El Sayed, A.M.A., Mouse, S.A., Higazi, A., and Al-Kodsh, A., 1993. Reservoir characteristics of the Bahariya Formation in both Salaam and Khalda oil fields, Western Desert, Egypt. E.G.S.Proc., 11th Ann. Mtg., 11:115-132.
[3] El Sayed, A.M.A. El Batanony, M and Salah, A., 1999. Poisson's ratio and reservoir fluid saturation: Upper Cretaceous, Egypt. Istvan Lakatos (Ed.): Challenges of an interdisciplinary science, Akademia Kiado, Budapest-progress in mining and oil field chemistry, Vol.1:47-54.
[4] El Sayed, A.M. A., 2011. Thermophysical study of sandstone reservoir rocks. Journal of Petroleum Sciences & Engineering, 76:138-147
[5] El Sayed, N.A., and A.M.A. El Sayed, 2015. Petrophysical modeling of the Bahariya
Formation, Egypt. Procedia Earth and Planetary Science

[6] Matthias, H., Weller, A., Sattler, C., Debschütz, W., El-Sayed, A.M.A., 2009. A complex core – log case study of an anisotropic sandstone, originating from Bahariya Formation, Abu Gharadig basin, Egypt. Petrophysics 50 (6), 478–497.

[7] Marschall, D., J.S. Gardner, D. Mardon, G.R. Coates, 1995. Method for correlation NMR relaxometry and mercury injection data. Sea - Conference, paper no. 9511.

[8] Prammer, M.G. 1994 NMR pore size distribution and permeability at the well site. SPE 69th Annual Tech. Conf. and Exhibit. Proceedings, paper no. 28368.

[9] Wang, L., Zhiqiang M., Yujiang S., Qin’e T., Yumei. , Yong S., 2014. A Novel Model of Predicting Archie’s Cementation Factor from Nuclear Magnetic Resonance (NMR) Logs in Low Permeability Reservoirs. Journal of Earth Science, Vol. 25, No. 1, p. 183–188