Hydraulic Flow Units of Some Studied Bahariya Samples: Abu Gharadiq Basin, W. Desert, Egypt

Abdel Moktader A. El Sayed 1, Mohamed El Bagoury 2, Nahla A. El Sayed 3, Ayman Shebl 1
1Department of Geophysics, Faculty of Science, Ain Shams University, Egypt
2Badr El Din Petroleum Company, Cairo, Egypt
3Department of Exploration, Egyptian Petroleum Research Institute, Egypt
moktader@sci.asu.edu.eg

Abstract. Hydraulic flow units and rock types in the Middle and Lower Bahariya Formation encountered in different drilled wells in NEAG-1 field were investigated. These are governed by lithologic variations and flaser laminations characterizing the Bahariya deposits, while they have a direct impact on sedimentation and digenetic process. The measured pore throat radius ($r_{35}$) using mercury injection capillary pressure (MICP) technique were used to develop self-reliant trend lines with reliable formula derived from laboratory petrophysical measurements. Petrographic investigations were used for outlining mineralogy, porosity types and mode of occurrence of formation fines. X-ray diffraction technique (XRD) of bulk samples was used for detecting rock forming minerals, mineralogy of cementing materials and their quantitative dominance in the pore spaces of the studied Bahariya sandstone samples. The Primary and secondary porosity either interparticle or intraparticle are controlling by pore space architecture while, four reservoir rock types (T-1, T-2, T-3 and T-4) are detected. Each rock type reflects different sedimentary environmental agent, degree of digenesis and variation in mineralogy. The calculated equations predict that up to 85% of measured permeability data demonstrate 10 hydraulic flow units which reveal the value of $r_{35}$ standing between 0.2µm and 3.11µm. The relationship between helium porosity and nitrogen permeability for the studied samples are supported by high coefficients of correlation ($R^2 = range 0.75$ to $0.85$) allowing reservoir characterization and permeability prediction from measured average porosity of each reservoir rock type. Different empirical relationships were constructed in order to facilitate hydrocarbon exploration and development in the Neag-1 oil field in the Egyptian Western Desert.

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 [1] in the Bahariya Formation encountered in the Salam and Khalda oil fields. [2] Investigated poison’s ratio versus reservoir 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 [3]. Authors [4-8] studied the seismic velocity behavior and NMR derived reservoir parameters and their significances on the hydrocarbon production.

The present study is dealing with NEAG-1 oil field which is located 150 Km W-SW of town Cairo [9] ‘figure 1’, in the north eastern part of Abu Gharadig basin. From a lithological point of view, the Bahariya Formation exhibits significant lateral and vertical facies changes [9, 10 and 3]. Evaluating the shale sand of the Bahariya and identification the main factors controlling pore volume distributions, and reservoir mineralogy are the scope of the present work, while the study of reservoir rock types and hydraulic flow units of the Bahariya Formation are objects too.

![Figure 1 Location map of the study area](image)

Neag-1 field structure is mainly a complex fault of three-way dip closures at top Bahariya level as Faulted anticlines [9]. Al Fadl and Al Qadr structures are two separate blocks trending to the northeast. Both structures are similar in structural style and separated by normal faults of + 200 m throw. The reverse fault bounding the field from north was resulted from compressional tectonic forces of the late Cretaceous age known as Syrian arc deformation of northeast-southwest trending folds [11]. The Lower / Middle Bahariya sand reservoirs are interpreted to be deposited in a shallow marine / marginal marine depositional environment. The reservoir section is subdivided into two units by lateral extended geo-markers. The reservoir properties are varying in the upper and lower part of Bahariya [3].

2. Methodology

The routine core analysis was done for 423 plugs to determine the main petrophysical data as helium porosity, permeability (measured on horizontal and vertical samples), and this data set collected from three different wells that covers the whole section of the Bahariya reservoir. 57 core samples were selected for thin section investigation, 18 samples for XRD to cover different types of litho-facies of most reservoir rock types. Effective pore radius was done for only 8 samples.
2.1. Porosity and Permeability Measurements:
Porosity is measured using Helium porosimeter with matrix cup core holder for grain volume ($V_g$) estimation [12]. Porosity ($\Phi$) is calculated by the following equation:

$$\Phi = (1.0 - V_g) / V_b$$  \hspace{1cm} (1)

where:
- $\Phi$ is the porosity fraction,
- $V_g$ is the grain volume cm$^3$,
- $V_b$ is the bulk volume of the sample in cm$^3$.

The gas permeability is measured using core Lab permeameter followed methods adopted by [12]. Gas permeability measurements were conducted with Hassler type core holder in which samples (approximately 2.5 cm in diameter and 5 cm in length) were subjected to dry Nitrogen gas with pressure of 1378.9514 kPa. The permeability is calculated by the following formula:

$$K = (C.Q.hw.L^2) / 200 V_b$$  \hspace{1cm} (2)

where:
- $K$ is gas permeability, mD,
- $L$ is the length of the sample, cm,
- $hw$ is the orifice manometer reading, mm,
- $Q$ is the orifice value, cm,
- $c$ is the value of mercury height, mm, and
- $V_b$ is the sample bulk volume, cm$^3$.

2.2. Pore throat radius measurements:
The pore throat radius is calculated from capillary pressure measurements. The capillary pressure ($P_c$) was calculated using the equation

$$P_c = \frac{2\sigma \cos \theta}{r}$$  \hspace{1cm} (3)

where:
- $\sigma$ = surface tension of Hg (485 dynes/cm),
- $\theta$ = contact angle of mercury in air (1400),
- $r$ = radius of pore aperture for a cylindrical pore, $\mu$m.

The effective pore radius ($r_e$) is calculated using the equation adopted by [13];

$$r_e = 107.6 / P_c$$  \hspace{1cm} (4)

where: $r_e$ is the effective pore radius ($\mu$m) and $P_c$ is capillary pressure (psi).

2.3. Thin section preparation
Thin sections technique was performed for 57 selected sandstone samples. Involved vacuum impregnation with blue-dyed resin to facilitate the recognition of porosity and staining with a mixed Alizarin Red-S and potassium ferric-cyanide solution to allow the identification of the carbonate minerals. In addition, samples were stained with a sodium cobalt nitrite solution to aid the recognition of alkali feldspars. The focus on the reservoir-related aspects for each rock type by the bulk samples examination under binocular microscope.

2.4. X-Ray diffraction analysis
XRD analysis was done for whole rock sample. The sample splits have been “micronised” before subjected to XRD analysis in order to obtain quantitative results about mineral components for some selected samples.
The maximum intensity of each identified mineral has been measured and compared to a standard intensity obtained for a pure sample of that mineral.

3. Results and Discussions

3.1. Storage capacity and flow capacity properties

The measured porosity and permeability are ranged from 2.5 to 32 % and 0.01 to 874 mD respectively. Storage capacity property and flowing capacity plot ‘figure 2’ were performed in-order to outline porosity cut off value, permeability distribution and identifying different rock types as well. The first observation from this plot shows that helium porosity of less than 10 % is represented by a storage capacity of (2 %) and flowing capacity less than 0.1 %, while porosity value of more than 10% is represented by more than 95% of both the storage and flowing capacities of the studied samples. On the other hand, the whole capacity range can be classified into four segments representing four reservoir rock types respected to their pore space framework as follows;

- **Type-1:** It is characterized by porosity ranging from 10 % to 19 % and representing approximately 30 % of storage capacity and 2.5 % of fluid flow capacity.

- **Type-2:** It is characterized by rock porosity ranging from 19 % to 23.2 % and representing 32 % of storage capacity with 9.4 % of fluid flow capacity.

- **Type-3:** It is characterized by rock porosity more than 23.2 % up to 25.8 % and representing approximately 18 % of reservoir storage capacity and 24 % of fluid flow capacity.

- **Type-4:** It is characterized by rock porosity more than 25.8 % and representing 18 % of reservoir storage capacity and approximately of 64 % of fluid flow capacity.

![Figure 2. Storage and flow capacity versus porosity](image-url)
3.2. Petrographic Investigations

The Petrographic analysis is used to identify rock texture, mineralogy and digenesis. The relative abundance (in % by volume) of both detrital and authigenic components were performed for some selected samples. The pore spaces that were determined by point counter could be used for achieving a reasonable petrographic classification for the obtained rock types and determination of diagenetic aspects of the studied reservoir rock. The mineralogical investigations showed that the studied Bahariya Formation is mainly consists of sandstone (up to 60 - 90 %) generally well sorted, very fine lower to fine sand that ranged from 62 to 125 µm in size. The detrital components are dominated by monocrystalline quartz; glauconitic pellets (4 - 37 %). The feldspars (4 - 14%), detrital clays (1.5 - 17 %) are appeared as pore-filling and grain-coating shape, while, minor polycrystalline quartz, phosphatic fragments, micas and accessory minerals are present. The authigenic components include pore filling dolomite, siderite, Kaolinite, illite with rare barite and quartz cements are shown (Figure 3).
3.3. Permeability and Mineral Pore filling:
The permeability is affected by mineral pore fillings of different types. It decreases by increasing the amount of filling minerals ‘figure 4’. This relationship is controlled by a reliable equation which characterized by high coefficient of correlation ($R^2 = 0.74$);

$$K = 446581.0 \text{ Pf}^{-4.05}$$

(5)

Where: $K = \text{permeability, mD and Pf = Pore filling minerals, \%}$

![Figure 4. Permeability and pore filling relation](image)

3.4. $R_{35}$ and permeability model
The mean hydraulic radius ($r_{50}$) of the studied samples versus sample permeability ‘figure 5’ gave a chance for developing new approach solving the anisotropy of the Bahariya reservoir rocks. The SPSS software was used to calculate the following relation;

$$\text{LOG } R_{35} = ((0.249*\text{LOG (K)}) + ((0.256*\text{LOG (Ø)})))-(0.511) \quad \text{where } R^2 = 0.98$$

(6)

Equation (6) was applied on both porosity and permeability for 380 core samples obtained from the Bahariya Formation. The resulted $R_{35}$ was sensitive to permeability variations than porosity as shown in ‘figure 6’.
3.5. Hydraulic flow units:
The Bahariya reservoir shows ten hydraulic flow units ‘figure 6’ where, HFU-10 represents the best reservoir qualifications and the HFU-1 is the worst one. In general, wake sandstones have smallest pore radius than arenite sandstone. The gradual increase of pore radius is resulted from the increase of mineral solution. The secondary porosity resulted from reservoir diagenesis establishing a dramatically enhancement of its permeability (e.g. samples- 3R and 4R ,figures 5&6).

---

**Figure 5.** Permeability versus R\(_{35}\) derived from (equation-6) new model

**Figure 6.** Flow units of Bahariya reservoir in the study area
The contribution of different pore throat sizes in the Bahariya flowing capacity (Figure 7) is represented mainly by a bimodal distribution histogram. The first mode = 0.63 μm and presenting 28.3% HF, while the second mode = 1.96 μm and 16.3% HFU. Figure 8, shows a relation between flowing capacity and storage capacity of the Bahariya reservoir. The deflection points indicate new flow units which are merged into four major reservoir units, figure 8.

**Figure 7.** Polygon showing Bahariya reservoir Flow units

**Figure 8.** Storage capacity versus flowing capacity of the Bahariya reservoir in study area
4. Conclusions

- Dissolution and cementation is considered as pore framework controls in the Bahariya reservoir rocks.
- Four rock types preserving different levels of diagenesis related to mode of occurrence of formation fines have been distinguished.
- The obtained empirical relation (eq.6) characterizing with high coefficient of correlation \( R^2 = 0.98 \) is used to calculate robust relations between porosity and permeability indicating different flow zones.
- The mean hydraulic radius \( R_{50} \) could be used instead of \( R_{35} \) in case of the presence of flaser laminas in the Bahariya reservoir rocks in order to solve flow zone problems.
- The hydraulic flow cross-plot indicates more than 10 hydraulic flow units indicating the anisotropy of the Bahariya reservoir north east Abu Gharadig field.

Acknowledgments:
Authors acknowledge EGPC and Bapetco of Egypt for the permission to use the technical data. Special thanks to our colleges in Ain Shams University and Bapetco exploration department.

References
[1] El Sayed, A.M.A., Mousa, S.A., Higazi, A., and Al-Kodsh, A. “ 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, 1993.
[2] El Sayed, A.M.A., El Batanony, M. and Salah, A. “ Poisson’s ratio and reservoir fluid saturation: Upper Cretaceous, Egypt.” Istvan L. (ed.): Challenges of an Interdisciplinary Science-Akademiai Kiado, Budapest, Progress in Mining and Oil Field Chemistry, Siofok: Vol.1., pp. 47-54, 1999.
[3] Matthias, H., Weller, A., Sattler, C., Debschütz, W., El-Sayed, A. M. A” A complex core – log case study of anisotropic sandstone, originating from Bahariya Formation, Abu Gharadig basin, Egypt. Petrophysics 50 (6), 478–497, 2009.
[4] El Sayed, A. A. and N. A., El Sayed, “Petrophysical modeling for the Bahariya Formation, Egypt.” Procedia earth and planetary science 15, p 518-525, 2015.
[5] El Sayed, A. A., Nahla A. El Sayed. “Petrophysical Properties of Clastic Reservoirs Using NMR Relaxometry and Mercury Injection Data: Bahariya Formation, Egypt.” International Journal of Geophysics and Geochemistry. Vol. 3, No. 3, 2016, pp. 28-32.
[6] El Sayed, A. A., Abuseda, H., El Sayed, N.A., “ Petrophysical study of Szolnok Formation, Endrod gas field, Hungary”, Egyptian Journal of Petroleum (2017) 26, 189–202.
[7] El Sayed, A. A., Nahla A. El Sayed “Petrophysical Study of Szolnok Formation, Endrod Gas Field, Hungary” IOP Conf. Series: Earth and Environmental Science 95 (2017) 032036 do i: 10.1088/1755-1315/95/3/032036
[8] El Sayed, A. A., and Nahla A. El Sayed “Impact of Reservoir Fluid Saturation on Seismic parameters: Endrod Gas Field, Hungary” IOP Conf. Series: Earth and Environmental Science 95 (2017) 032028 do i: 10.1088/1755-1315/95/3/032028
[9] Bakr A., Le Varlet X, Postuma W, Karaaly H, “ Fast-track maturation and development of the Al Fadl & Al Qadr Fields, two new discoveries, NEAG East, Western Desert, Egypt.” Badr Petroleum Company, SPE 128009. 2010.
[10] Catuneanu, O., Khalifa, M. A., and Wanas, H. A. “Sequence Stratigraphy of the Lower Cenomanian
Bahariya Formation, Bahariya Oasis, Western Desert” Egypt: Sedimentary Geology, vol. 190, 1-4, p. 121-137, 2006.

[11] Abdel Aal, A.A., and Mustafa, A.R.” Structural framework of the Abu Gharadig basin, Western Desert, Egypt.” 9th E.G.P.C. Conf., Cairo, p 37, 1988.

[12] El Sayed, A. A.” Geological and petrophysical studies for Algyő -2 reservoir evaluation, Algyő oil and gas field, Hungary, Ph.D. Thesis, Hungarian Academy of Science, Budapest, 1981.

[13] El Sayed A.M.A, Inter-correlation of capillary pressure derived parameters for sandstones of the Tortel Formation, Hungary, Geophysical transactions 1994, Vol. 39 no1 p 77-87.