Reservoir properties and petrophysical analysis of the Late Miocene Abu Madi Formation in the Abu Qir Bay Area, West Nile Delta, Egypt

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Abstract
The Abu Qir Bay area is on the offshore western part of the Nile Delta. It is divided into three fields namely: North Abu Qir, Abu Qir, and West Abu Qir. The main reservoir in the Abu Qir Bay area is Abu Madi Formation, which represents the Miocene rocks. The current uses conducting advanced conventional petrophysical techniques for determining the reservoir properties of the Abu Madi Formation. The wireline log data is commencing four wells drilled in the study area namely: North Abu Qir-7x, West Abu Qir-1x, Abu Qir-1x, and Abu Qir-13x. The interpreted lithologic data of the studied wire-line logs shows that the Abu Madi Formation’s main lithology consists of sandstone interbedded with some amounts of shale and thin lamina of limestone and anhydrite. Based on the interpreted well logging records, the Abu Madi Formation can be subdivided into three members: The Upper, Middle, and Lower Abu Madi members. The main target is the Upper Abu Madi members with shale volume varying from 8 to 12% with an average of 10%. The Middle Abu Madi member which is considered the second target has a shale volume ranging from 9.5 to 13.5% with an average of 11.5%. The thickness of the Abu Madi Formation ranges in the four drilled wells varies between 67.61 and 167.63 m with an average of 117 m. The petrophysical evaluation displays two important pay zones, and they belong to the Upper and the Middle Abu Madi members. The average porosity and hydrocarbon saturation values of both members indicate that Abu Madi is a very good reservoir. The southwestern area near West Abu Qir-1x well was found a good place for any upcoming appraisal, particularly for the upper Abu Madi reservoir future development.

Keywords Reservoir analysis · Petrophysical parameters · Miocene reservoir · Abu Madi · Formation · Abu Qir Bay field · West Nile Delta

Introduction
The Nile Delta is regarded as the most significant gas province in Egypt, as its sedimentary succession seems to shelter a rich gas potentiality reach of about over forty TCF (Trillion Cubic Feet) of the proven reserve, (Sarhan 2015; Mahmoud et al. 2017). The Nile Delta makes up an irregular triangle bordered by the two River Nile branches, Rosetta, and Damietta. The Rosetta branch is in the western part and the Damietta branch is in the eastern part. The delta extends about 250 km parallel to the Mediterranean shoreline and continues to a peak of 160 km from north to south that considers one of the biggest fan-shaped delta (Said 1990).

It is a type of passive margin sedimentary basin along the eastern Mediterranean Levant Sea (Dolson et al. 2005). The fan-shaped delta cone accumulates a huge thickness of mainly fine terrigenous shale and sandstone with occasional anhydrite, which started deposition in the Paleogene, which may reach 6 km (Abu El Ella 1990; Abdel Aal et al. 2000). The stratigraphic succession of the Nile Delta ranges in age from the Oligocene to the Recent (Fig. 1).

The composite stratigraphic section of the Nile Delta represents an expanded variety in both amounts thickness and types of sedimentary facies of coarse sandstone and gravel of channel deposits and fine detrital mudstone and claystone of mainly over bank and floodplain deposits (Said 1990; Eysa et al. 2015). A uniform increase in thickness is recorded from the south to the north (Harms and Wray 1990).
EGPC (1994) and Issawi et al. (1999) divided the offshore stratigraphy section of the Nile Delta into two main rock units as follows from base to top: (A) The sandy shale sequence from the Langhian to Missniaen rock unit of Moghra (sandstone), Sidi Salim (shale), Qawasim (sandstone) and Rosetta (anhydrite) Formations. (B) The shaly sandstone sequence from them the Zanclean to Holocene comprises Abu Madi (sandstone), Kafr El-Sheikh (shale), El Wastani (sandstone), MitGhamr (sandstone shale interbedded), and Bilgas (shale with sand lenses) formations.

The younger sequence is uniform in thickness overlain, an unconformity upon the older sequence of wedge shape sequence taped at the south and thick toward the north.

The Abu Madi Format represents the base of the upper sequence. It is unconformably overlain, by either the Quasim Formation toward land at the south or Rosetta Formation toward the sea at the north. Subsurface record of drilled data of Abu Madi-1 well type section it reaches 222 m of thick bodies reservoir of sand with interbedded thin shale of maximum recorded thickness of 1400 m in Ras El-Barr subsurface wells (Issawi et al. 1999; Tawdros 2001).

The Abu Qir Bay area is on the offshore western part of the Nile Delta and is divided into three fields namely: North Abu Qir, Abu Qir, and West Abu Qir. Figure 2 shows the study area that lies between longitudes and latitudes in order of 30° 04′ E, 30° 18′ E, and 31° 20′ N to 31° 36′ N. The main reservoir in the Abu Qir Bay area is Abu Madi Formation, which represents the target for reservoir evaluation in the present study.

In general, the reservoir is a volumetric oil or gas accumulation in a porous and permeable rock; this rock is mostly of sedimentary origin (Okotie and Ikporo 2019). The most basic concern for the analysis of a specific reservoir is the spatial distribution of its petrophysical parameters measurements of the reservoir rocks and the fluid properties that are affected by those quantities (Towler 2002). To visualize the opportunity of rock to be considered as a reservoir, the application of wireline logs tools is important for characterizing such a reservoir. This process enabled us to determine the main reservoir parameters such as porosity, permeability, and water saturation.

Because of limited data about the lithological and petrographic characterization of core concern Abu Madi Formation, petrophysical evaluation of the wireline log data has always been used for the identification of hydrocarbon reservoirs. This petrophysical characterization is done by using many tools such as gamma-ray to determine the volume of shale and used to divide Abu Madi Formation, resistivity to determine the type of fluids and the water saturation, and density-neutron logs to evaluate the formation porosity. The creation of some cross plots such as neutron-density cross-plot and Picket plot helps in calculating the lithology, porosity, and formation water resistivity of a specific reservoir (Kupecz et al. 1997).

Accordingly, the principal purpose of the current study is evaluating of the Abu Madi hydrocarbon reservoirs in the study field. The conventional quantitative interpretation of the petrophysical reservoir parameters for four wells including the shale content, effective porosity, and water saturation helps in the reservoir’s assessment quality. Construction of the litho-saturation cross-plots and the distribution parameters maps (effective porosity, net pay, water saturation) have been completed for representing the vertical and the lateral
distributions of the various iso-parametric maps which are useful techniques in reservoir characterization.

**Geologic setting**

The Nile Delta basin is a part of an unstable shelf that expands from the northern boundary of the Western Desert to North Sinai attaining over 80 km (Kamel et al. 1998). It is subdivided into two geologic sub-basins separated by block faults and accompanies a thick sedimentary sequence over a high basement relief (Sarhan and Hemdan 1994; El-Heiny and Enani 1996) the northern offshore sub-basin, and the southern onshore sub-basin (Fig. 3). The flexural zone (Hinge Zone) which was developed before the Miocene time and affected the Nile Delta is the major structural feature in oriented faults in the E–W direction (Harms and Wray 1990). The other three main faults trends are NW–SE and NE–SW, and N–S directions (Meshref 1990; Sestini 1995).

The offshore Nile cone is characterized by a huge of Tertiary sediments of mainly terrigenous siliciclastic rock (Dolson et al. 2001). The wave-dominated Nile Delta today was suggested to be a tide-dominated delta, where the river mouths hit the sea in areas cluttered by large tidal ranges during a Miocene time. The Delta shape is extensively reworked and reconstructed by the daily ebb and flood tidal currents (Zeydan 2005; Leeder 2012). During the Messinian crisis, the seawater dropped to a hundred meters rejuvenated.
several river channels to run upon the shelf-slope and made a submarine fan at end of the channel courses seaway (Issawi et al. 1999).

The tectonic evolution in the study area is subjected to three stages of deformation (Mostafa 2020). The first one is related to divergent tectonic starting in the middle of Triassic time and ending in the Early Cretaceous time opening the Neo-Tethys in between Afro-Arabian and Eurasian Plates. This phase is responsible for the NE–SW faults perpendicular to the NW–SE transform movements in Delta Basin (Harms and Wray 1990; May 1991; EGPC 1994). The second phase is another extension one called Cretaceous–Early Tertiary rifting related to the opening of the South Atlantic Ocean and is responsible for E–W and NW–SE normal faults (Sestini 1995; Saleh 2013). Tectonic phase in the present-day is convergence initiated at late-Cretaceous till recent and changes its trend with time started by NW–SE faults change in Miocene time to being N–S faults trend (Moustafa 2002).

Materials and methods

The wireline logs data of four wells, namely North Abu Qir-7x (NAQ-7x), West Abu Qir-1x (WAQ-1x), Abu Qir-1x, and Abu Qir-13x (Fig. 2), include Caliper CL, Gamma-ray (GR), Formation Density RHOB, Neutron Porosity NPHI and NPOR, Sonic DTL and Resistivity shallow and deep logs LLS, LLD; this data was collected by Abu Qir Petroleum Company, Egypt.

The available electrical logs were logged in by turning the field analogue prints into digital data by taking readings from the prints in an equal interval of 0.5 m. These readings were plugged into the computer for the analyses and then be uploaded by the Techlog program (Techlog 2015) which facilitated plotting various litho-density cross plots and calculating the different reservoir parameters.

Discussion and results

The obtained results from the applications of the various petrophysical techniques are listed and displayed as well as their interpretation from the author’s point of view is given below.

The lithological components estimation

The available logs for determining lithology are gamma-ray, density, neutron, and sonic logs. Several cross-plots such as density-neutron and gamma-ray are used through the Techlog (Petrophysics software) for lithology identification (Fig. 4) which are displaying the neutron-density cross-plots of the Abu Madi Formation for the four included wells in the study area.
The essential components extracted from the cross-plots of the upper Abu Madi unit are pure sandstone in Abu Qir-1x, and it is sand intercalated with shale for NAQ-7x, WAQ-1x, and Abu Qir-13x. Lower Abu Madi is mainly composed of shaly sand in all wells.

Fig. 4 Neutron-Density cross-plot of Miocene Pay zone (Abu Madi formation)
Porosity and the volume of shale determination

The porosity is defined as the ratio of the volume of pore spaces in a certain rock to the absolute volume of that rock (Cannon 2016). In the current work, the porosity was determined from the sequence of the density porosity $\phi_D$ and the neutron porosity $\phi_N$. The density porosity can be measured by the equations:
The value of the total porosity ($\phi_t$) is calculated by using the following formula:

$$\phi_t = \frac{\phi_N + \phi_D}{2}$$

As for the effective porosity ($\phi_e$) estimation, the volume of shale ($V_{\text{Sh}}$) is necessary for the effective porosity determination according to the following equation:

$$\phi_e = \phi_t * (1 - V_{\text{Sh}})$$

It could evaluate the shale volume from the gamma-ray log depending on the gamma-ray index ($I_{GR}$) according to (Clavier et al. 1971) as:

$$V_{\text{Sh}} = 1.7 - [3.38 - (I_{GR} - 0.7)^2]^{0.5}$$

$I_{GR}$, the gamma-ray index can be calculated from the gamma-ray log:
where $\text{GR}_{\text{log}}$ = reading of gamma-ray log; $\text{GR}_{\text{min}}$ = gamma-ray minimum reading; $\text{GR}_{\text{max}}$ = gamma-ray maximum reading.

**Water saturation determination**

Water saturation ($S_w$) is a term that is applied for the measurement of pore volume filled with water; it can be calculated according to Archie’s Equation:

$$\text{I}_{\text{GR}} = \frac{\text{GR}_{\text{log}} - \text{GR}_{\text{min}}}{\text{GR}_{\text{max}} - \text{GR}_{\text{min}}}$$

(5)

$$S_w = \left( \frac{R_t}{R_w} \right) \cdot \Omega^m \cdot \phi^n$$

(6)

where $R_w$ = formation water resistivity measured in Ohm; $R_t$ = resistivity of the invaded formation; $\phi = \text{porosity}$; $m = \text{cementation factor}$ and $n = \text{saturation exponent}$.

By taking the deep resistivity tool readings as ($R_t$); furthermore, using $m = (1–2)$ and $n = 2$, the formation resistivity of water ($R_w$) values can be calculated clearly from the Pickett plot of a known water-bearing section of the targeted formation. The Pickett plot is showing the relation between log ($R_t$) vs. log($\phi$) and ($R_w$) may be read from the intercept of the line with the ($R_t$) axis (Rider 1986). Figure 5 shows
the Pickett plot of the Sidi Salem Formation, and the Lower Abu Madi Unit are represented, respectively.

**Litho-saturation cross-plots**

The vertical variations of lithology, porosity, water saturation, and the net pay of the Abu Madi Formation are presented as litho-saturation cross-plots for each Well side by side with different logging tools tracks. Figure 6 is representing the North Abu Qir-7x litho-saturation cross-plot. It shows that the lithology of the Abu Madi Formation is sandstone interbedded with shale. The upper Abu Madi Unit is the pay interval which extends from 3058.966 m to the depth of 3089.428 m (TVDSS) true vertical depth subsea with net pay thickness equals 11.613 m having a porosity of 21.8%, water saturation of 53.9%, and shale volume 9.5%.

The resistivity of water value $R_W = 0.08457$ Ohm at $m=1.81524$ and $n=2$. The clean sand region which is represented by the yellow color in the litho-saturation cross-plot in the Upper Abu Madi Unit refers to the Miocene reservoir pay zone and the average porosity in this interval approximately equals 19.5%. In West Abu Qir-1x well, the
Fig. 9  Petrophysical evaluation of Miocene reservoir (Abu Madi formation) in Abu Qir 13x well

Fig. 10  Stratigraphic correlation in the direction from North to Southeast
The main lithology of the Abu Madi formation is sandstone with some shales and some anhydrite strings (Fig. 7). Abu Madi Formation is divided into Upper Abu Madi, Middle Abu Madi and Lower Abu Madi sands in West Abu Qir-1x Well. There are two pay intervals in West Abu Qir-1x; the first is in Upper Abu Madi and extends from 2773.45 to 2797.225 m TVDSS with net pay of 23.47 m having a porosity of 24%, water saturation of 21.2%, and shale volume 8%. The second one lies in the Middle Abu Madi Unit between 2797.225 and 2837.53 m TVDSS with net pay of 9.601 m having a porosity of 23.6%, water saturation of 49.3%, and shale volume of 13%. The Pickett plot gives $R_w = 0.234$ Ohm when $m = 1.05$ and $n = 2$.

By moving down to Abu Qur-1x well as displayed in (Fig. 8), Abu Madi Formation lithology comprises sandstone, siltstone, and shale with bodies from anhydrite. There is only one pay interval in this well which starts at depth 2452.8 m and continues to 2469.52 m TVDSS. The net pay thickness is 12.431 m with a porosity of 26.3%, water saturation of 41.7%, and shale volume is 12%. Water resistivity $R_w = 0.182$ Ohm where $m = 1.28$ and $n = 2$. The average

![Fig. 11 Structure correlation in the direction from North to Southeast](image_url)
porosity of the clean sandstone of the Miocene reservoir equals 26%.

Abu Madi Formation along the section of Abu Qir-13x well is mainly sandstone with some shale and anhydrite (Fig. 9). Two pay intervals appear here; Upper Abu Madi Unit starts from 2489.85 m and extends to 2505.54 m TVDSS with a net pay thickness equal to 3.962 m. It has a porosity of 26.1%, water saturation of 36.6%, and shale volume of about 11%. The second pay interval is the Middle Abu Madi Unit which begins from 2505.54 m and reaches 2557.6 m TVDSS with a net pay thickness of 3.2 m. Its porosity value is 24.2% and the water saturation is 58.8% while the shale volume is 13.5%. The calculated water resistivity is $R_w = 0.194 \text{ Ohm at } m = 1.33445$ and $n = 2$.

Well to well correlation

Well to Well correlation is a technique used to define the reservoir geometry along a specific section. Figure 10 represents the correlation panels starting from the NAQ-7x well and ending at Abu Qir-13x well passing through the two wells WAQ-1x and Abu Qir-1x. These correlations are
Fig. 13  The Net Pay map of Upper Abu Madi Unit

Fig. 14  The Water Saturation map of Upper Abu Madi Unit
established based on the patterns of gamma-ray and the lithological tracks of the four studied wells. A meticulous look through these panels shows the level of correlativity between the successive formations and the reservoir sand levels across the wells.

Structurally, Abu Madi Formation is shallower in the southeastern part (in Abu Qir-1x well) and appears deeper in the central part of the study area (in NAQ-7x well). It is moderate in depth at (Abu Qir-1x). The subsurface variations in depth could be interpreted as due to an existing uplifting block (horst like structure) which is bordered by two faults throw in the northern and southeastern parts of the area (Fig. 11).

The thickness of the Abu Madi Formation decreases significantly from the southeastern part at (Abu Qir-1x) and increases due to the north-central area at (NAQ-7x), which might reflect an accumulation of sediments in tectonic subsidence and a transgression fluvial environment.

**Iso-parametric maps of the petrophysical parameters**

The horizontal distribution maps which represent the lateral distribution of the petrophysical analyses result in the study area called iso-parametric maps. These maps include the thickness map (isopach) of net pay and the parameters petrophysical maps (effective porosity \( \Phi_e \) and water saturation \( S_w \)). Figure 12 shows the effective porosity is increasing in the southern-eastern parts of (Abu Qir-x and Abu Qir-13x) wells. This might be because of the compactness of the deeper northern Abu Madi sands of NAQ-7x which reduces the pore spaces.

The net pay interval thickness of the Abu Madi Formation is assumed to decrease in the eastern parts of the study area reaching the zero value, and it is relatively increasing in the central and northwestern parts (NAQ-7x). It displays the maximum increase in the southwestern parts of (WAQ-1x). Water saturation is observed to behave differently; it is increasing rapidly in the northern areas in (NAQ-7x) and in the southeastern parts of (Abu Qir-1x). It shows a rapid decrease in the south-western area in (WAQ-1x).

The southwestern part area near (West Abu Qir-1x) is a good promising zone for any future hydrocarbon development in the study area with sufficient net pay thickness and high effective porosity and low water saturation.

**Conclusion**

The petrophysical analysis results in the study area obtained from the geophysical and geological aspects reveal some criteria about the Abu Madi Miocene reservoir. The upper Abu Madi members are composed of pure sandstone, whereas the lower member composed of an alternation of sandstone and shale.

The litho-saturation cross-plots and the iso-parametric maps (Figs. 12, 13, 14 and 15) show that the effective porosity is increasing in the southern-eastern parts of (Abu Qir-x and Abu Qir-13x) wells, and this is because of the compactness of the deeper northern Abu Madi sands of NAQ-7x which reduces the pore spaces.

The net pay interval thickness of the Abu Madi Formation is assumed to decrease in the eastern parts of the study area reaching the zero value, and it is relatively increasing in the central and northwestern parts (NAQ-7x). It displays the maximum increase in the southwestern parts of (WAQ-1x). Water saturation is observed to behave differently; it is increasing rapidly in the northern areas in (NAQ-7x) and in the southeastern parts of (Abu Qir-1x). It shows a rapid decrease in the south-western area in (WAQ-1x).

The southwestern part area near (West Abu Qir-1x) is a good promising zone for any future hydrocarbon development in the study area with sufficient net pay thickness and high effective porosity and low water saturation. The authors are highly recommending detailed non-conventional and depositional modeling studies for the south-western region of the study area, supporting their conclusion for any upcoming appraisal for that region.
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